CHAPTER 206

MULTIPLE BAR FORMATION BY BREAKER-INDUCED VORTICES: A LABORATORY APPROACH

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ABSTRACT: Using a two-dimensional wave flume and a two-video-camera system, mechanism and process of multiple bar formation were investigated in the light of breaker-induced vortices. A fixed-bed experiment revealed that (1) the vortex formed at the wave break point can be classified into three: oblique, A-type horizontal, and B-type horizontal vortices; (2) the vortex formed in the surf zone is always oblique; and (3) the location of a vortex reaching bottom can be described by wave properties and the bottom slope, and its water depth can be expressed by breaker height alone. A movable-bed experiment indicated that bars are initiated by the vortices rcaching bottom in the surf zone; the number of bars formed coincides with the number of such vortices. Suspension of the bottom sediment due to vortex action and the mean-drift-velocity pattern can play an important role in multiple bar formation; mechanism for break-point bar formation is "convergence", while that for inner bar formation is "congestion". Two major modes for the development of multiple bars were found: simultaneous and successive: these depend on the interaction of vortex action and topography in the surf zone. Multiple-bar features such as trough spacing and crest depth could be explained from vortex features found through the fixed-bed experiment.

INTRODUCTION

Major hypotheses regarding multiple bar formation are: the wave breaking hypothesis (e.g., O'Brien, 1968; Dhyr-Nielsen and Sorensen, 1970; Exon, 1975; Dolan and Dean, 1985; Sunamura and Takeda, 1993), and standing wave hypothesis (e.g., Suhayda, 1974; Short, 1975; Bowen, 1980; Katoh, 1984; Aagaard, 1991). In both hypotheses, no clear explanation on multiple bar formation has been provided

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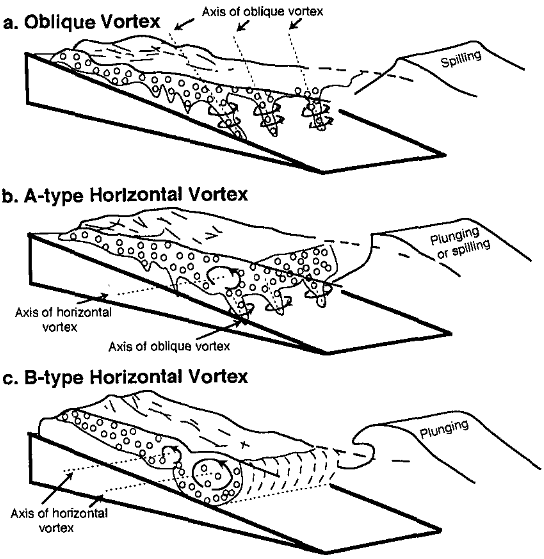

Fig. 1 Three vortex types

based on sediment dynamics.

With the recent progress of measuring techniques of flow velocity, studies from a micro-scopic point of view have been conducted with the purpose of elucidating the nearshore hydrodynamics. Nadaoka et al. (1987, 1988) found the presence of "oblique vortex" in the surf zone under spilling breaker conditions, and reconfirmed that this oblique vortex induced sediment suspension in the surf zone. Although they have not noted the interaction of the oblique vortex and bar formation, it is suggested that such sediment suspension could influence the net sediment movement in the surf zone resulting possible bar formation.

This study, conducted in the laboratory from the standpoint of the breaking-wave hypothesis, attempts to investigate the possibility of vortices induced by breaking wavcs to form multiple bars.

FIXED-BED EXPERIMENT ON BREAKER-INDUCED VORTICES REACHING BOTTOM

In order to examine the characteristics of vortices produced by breaking waves, an experiment was conducted setting up a 1/10 or 1/ 20 uniform steel bottom in a wave flume (12 m long, 0.2 m wide, and 0.4 m deep) equipped with a regular-wave generator. The period of waves ranged from 0.6 to 2.4 sec and the height of

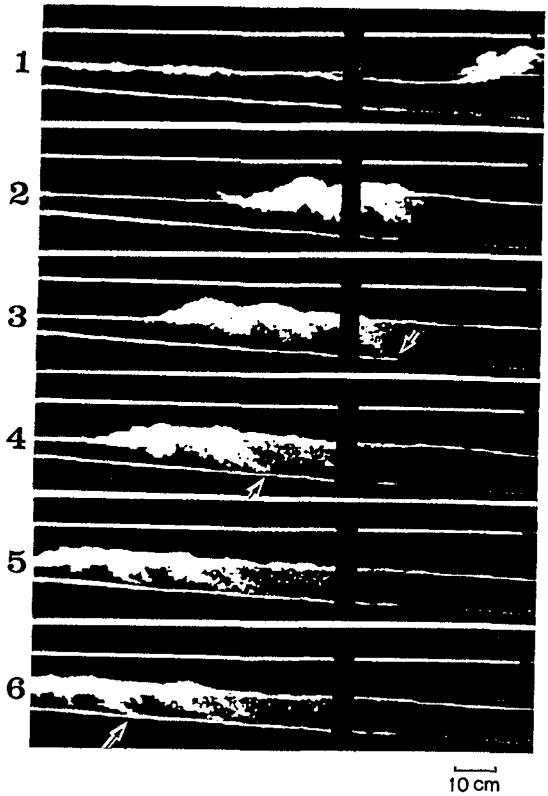

Fig. 2 Development of triple vortices reaching bottom (H_b=11cm, T=1.2s, tan β =1/20)

breaking waves from 5.0 to 14 cm. To examine the characteristics of vortices developed in the whole surf zone, two video cameras were set up beside the flume One was placed normal to the side of a glass window of the flume, and the other was installed with an angle of 30 degrees at the offshore side of the wave break point. The three-dimensional characteristics of vortices were examined on reproduced video pictures using both breaker-induced air bubbles and neutrally buoyant particles (1.2mm in diameter) as tracers.

Vortices formed just after wave breaking are classified into three types according to the direction of vortex axis: oblique vortex and two types of horizontal vortex, i.e., A-type and B-type horizontal vortices (Zhang and Sunamura, 1990). The oblique vortex is like a tornado that has an obliquely stretched axis of rotation (Fig. 1a). The B-type horizontal vortex looks a cultivator that has a horizontal axis of rotation (Fig. 1c). The A-type horizontal vortex is a hybrid between horizontal and

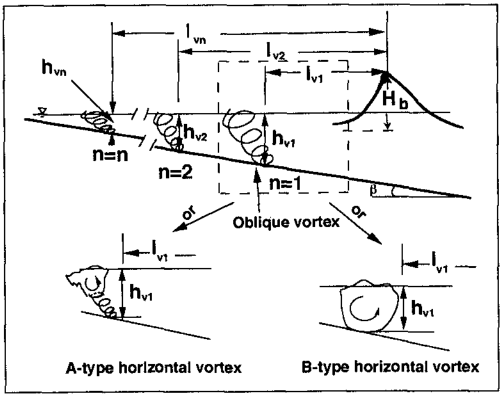

Fig. 3 Definition sketch of location of vortices reaching bottom

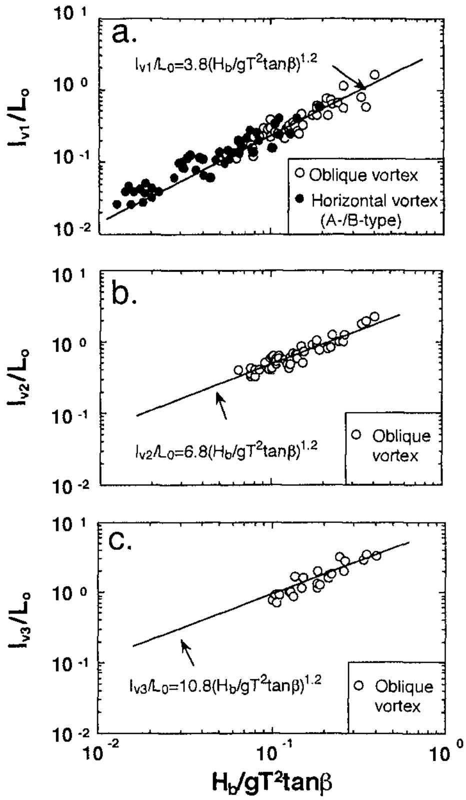

Fig. 4 Relationship between $H_b/gT^2\tan\beta$ and l_{vn}/L_o

oblique vortices (Fig. 1b). Namely, the horizontal vortex forms first in the upper part of water column and then it changes to the oblique vortex. Considering that a vortex which is stretched to reach bottom play a very important role in sediment motion and resulting topographic change, we focused on this kind of vortices.

The experiment showed that the vortices reaching bottom are not only formed at the wave break point, but also in the whole surf zone depending on experimental conditions. Figure 2 is an example of a sequence of video-pictures that show developmental processes of the triple vortices reaching bottom. The time between one stage to the next is 0.3 sec. The first oblique vortex develops at Stage 2 just after wave breaking (spilling breaker) and it touches the bottom as indicated by the arrow at Stage 3. As the bore propagates, the second oblique vortex develops inshore and reaches bottom at Stage 4, and finally the third oblique vortex reaching bottom forms further inshore at Stage 6 as indicated by the arrow. The vortex strength tends to decrease with increasing distance from the wave break point.

Results obtained through the present experiment indicate that the first vortex, i.e., the vortex formed just after wave breaking, is an oblique vortex or an A-type or a B-type horizontal vortex depending on experimental conditions, but the vortex or vortices in the surf zone are always oblique. It was also observed in this experiment that the vortices not reaching bottom appeared when the breaker height was extremely small.

The location and water depth when the first vortex touches the bottom were almost constant with time, whereas those of vortices reaching bottom in the surf zone slightly fluctuated with waves. Average location and depth were measured by reproducing video-pictures for six consecutive waves.

The average horizontal distance from the break point to the location of the vortex reaching bottom, counting from the first vortex (n=1), is denoted as l_{vn} (Fig. 3). Data were analyzed using three dimensionless quantities, l_{vn}/L_o, H_b/gT^2, and $\tan\beta$, where L_o is the deep-water wavelength, H_b, is the breaker height, T is the wave period, and $\tan\beta$ is the bottom slope. These three quantities are the same that Sunamura (1985) used to analyze the data of the location of the deepest penetration of breaker-produced bubbles in the surf zone.

Figure 4 shows the result of analysis. From the equation written beside the straight line in each graph, it is anticipated that the location of the n-th vortex can be described by

$$l_{vn}/L_o = A(H_b/gT^2\tan\beta)^{1.2} \tag{1}$$

where A is a dimensionless coefficient that varies with the value of n as shown in Fig. 4. To obtain the relationship between A and n, A is plotted against n in Fig. 5; the line in this figure can be expressed by

$$A = 3.98\ n^{0.86} \tag{2}$$

One obtains the following relation:

$$l_{vn}/L_o = 3.98\ n^{0.86}(H_b/gT^2\tan\beta)^{1.2} \tag{3}$$

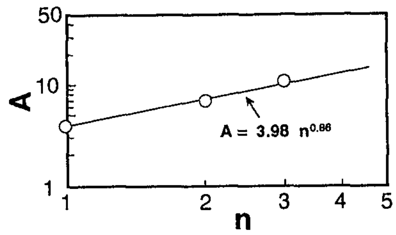

Fig. 5 Relationship between *A* and n

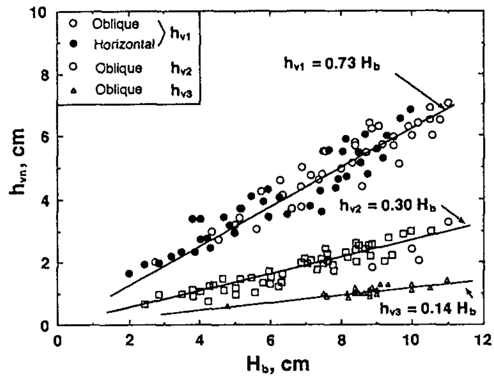

Fig. 6 Relationship between breaker height and water depth for vortex reaching bottom

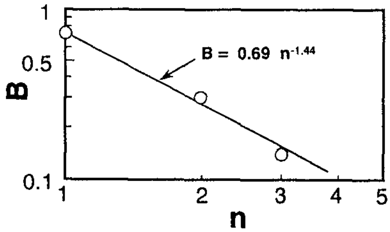

Fig. 7 Relationship between *B* and n

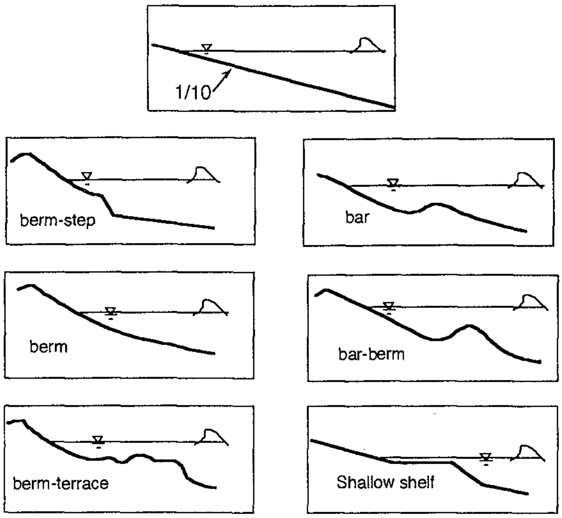

Fig. 8 1/10 uniform and six non-uniform beach profiles used as the initial boundary condition for movable-bed experiment

This equation allows us to predict the position of multiple vortices which can touch the bottom.

Denoting the water depth of the n-th vortex reaching bottom as h_{vn} (Fig. 3), Fig. 6 shows the relationship between breaker height and water depth of 1st, 2nd, and 3rd vortices. It is easily anticipated from the equations in this figure that the case of the n-th vortex can be described by

$$h_{vn} = B\, H_b \tag{4}$$

The values of B are plotted against n in Fig. 7, and the line in this figure is given by

$$B = 0.69\, n^{-1.44} \tag{5}$$

The following relation can be written:

$$h_{vn} = 0.69\, n^{-1.44} H_b \tag{6}$$

Prediction of the water depth of multiple vortices reaching bottom is possible by the use of this equation.

MOVABLE-BED EXPERIMENT ON BAR FORMATION DUE TO BREAKER-INDUCED VORTICES REACHING BOTTOM

An experiment was conducted using 1/ 10 uniform beach profile and six kinds of non-uniform profiles as the initial boundary condition set up in the same wave flume as used before. Figure 8 is a schematic illustration of the seven initial beach profiles, of which "1/10" and "shallow shelf" were artificial and the remaining five were formed by waves (Zhang, 1994). To examine the vortex characteristics and vortex-topography interaction, the two-video camera system was again used. Changing the combination of these initial beach slopes, the grain size of beach material (0.22, 0.69, 1.3, and 2.4 mm), wave period (0.7, 0.8, 0.9, and 1.0 sec), and breaker height (5.0~10cm), 61 experiment runs were conducted. As the breaker height, the value measured at the initial stage where no significant topographic change occurred was adopted in this study. Waves continued to act until no significant development of the break-point bar occurred. This stage is defined as the equilibrium; the time required for it ranged from thirty minutes to two hours depending on experiment runs. The beach topography was measured at the center of the flume by an automatic profiler every five minutes as a general rule.

The result showed that multiple bars were formed depending on the experiment conditions. It was found that (1) the bar formation is closely associated with the action of vortices reaching bottom, (2) the number of bars formed coincides with that of such vortices, and (3) the shape of initial morphology greatly affects the mode of multiple bar formation. Two major modes will be illustrated below.

Simultaneous and Successive Modes for Multiple Bar Formation

Figure 9 shows an example of simultaneous mode of double bars. The initial morphology was a berm profile. During the first 5-minute wave action, two bars started to form at the same time by two oblique vortices reaching bottom,

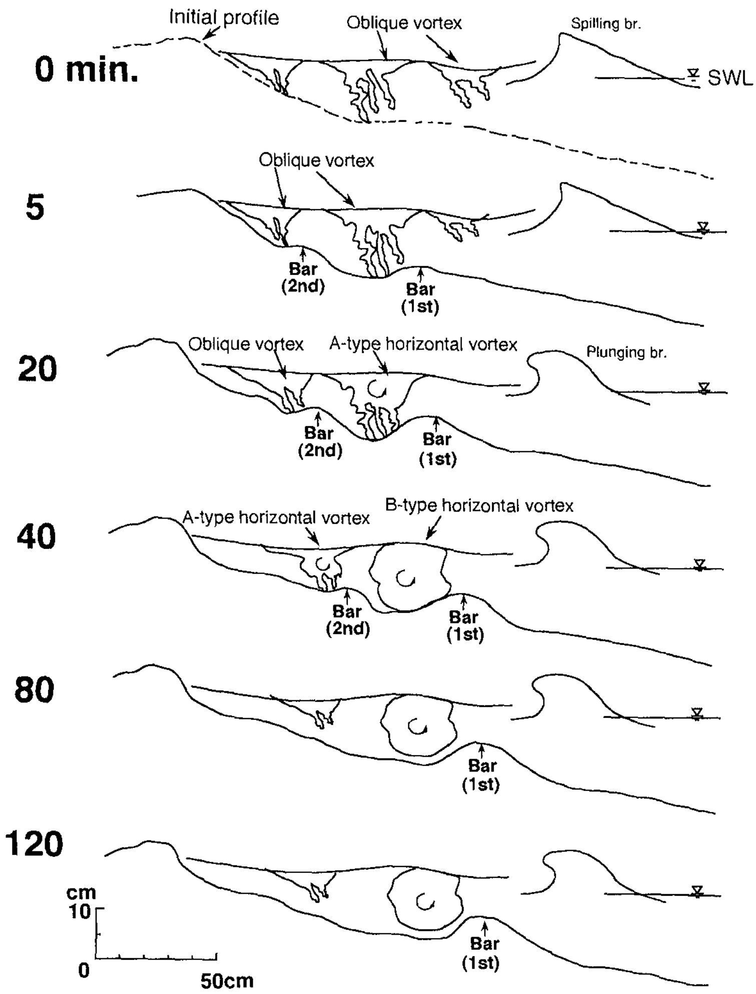

Fig. 9 An example of simultaneous development of double bars

respectively. The break-point bar, located offshore, grew to a large bar; then the breaker type changed from spilling to plunging, which resulted in the change of vortex type from the oblique vortex to the A-type and finally to the B-type horizontal after 40-minute wave action. At the same time, the vortex type near the inner bar changed from the oblique to the A-type horizontal vortex. After 80 minutes, the breaker-point bar attained the equilibrium with the B-type horizontal vortex having no significant force to further scouring of the trough, because the trough was too deep for the vortex to reach bottom any more. The inner bar disappeared after 80

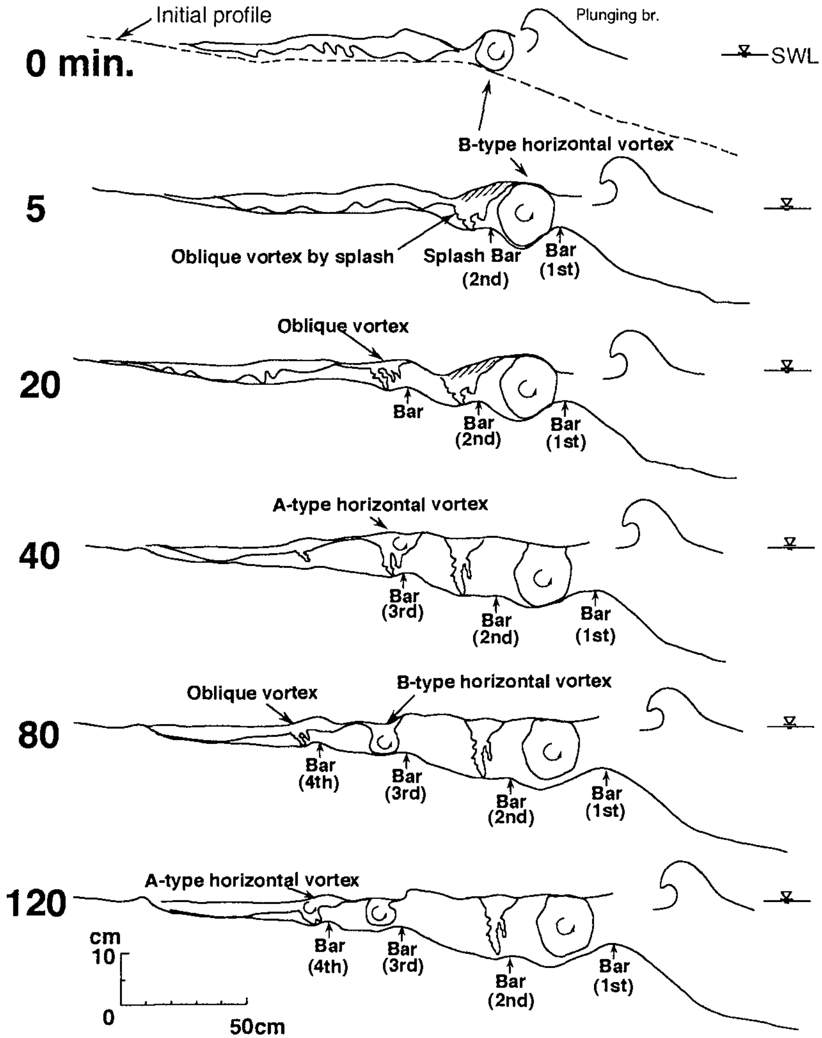

Fig. 10 An example of successive development of quadruple bars

minutes due probably to the decrease in force of the inshore vortex, which has already changed from the A-type to the oblique vortex at the stage of 80 minutes. In the present experiment, this type of bar development, i.e., simultaneous occurrence of bars, was observed in the cases in which the initial morphology was a berm or a berm-step. Simultaneous occurrence of multiple vortices acting on the bottom is

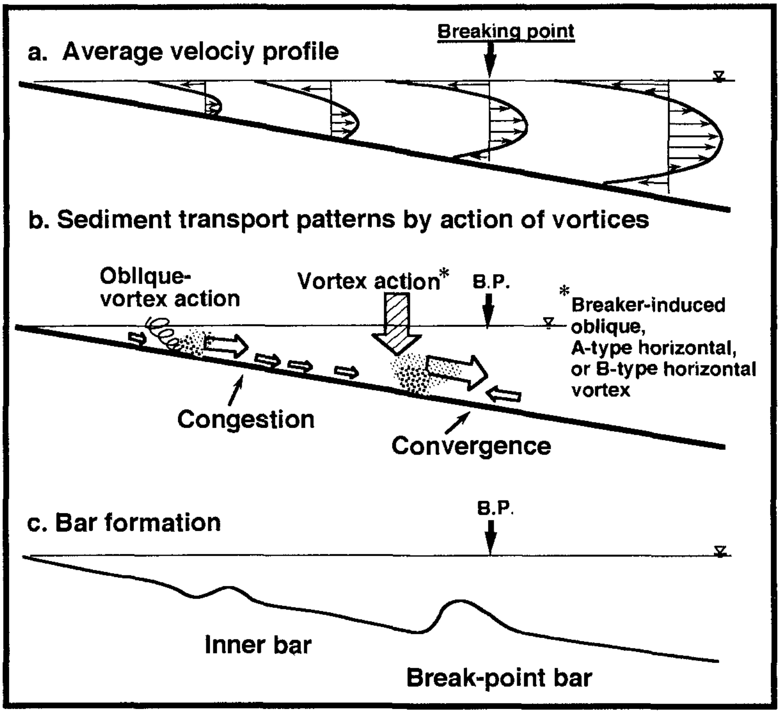

Fig. 11 Formative processes of inner and break-point bars at the initial stage. (a) Average drift velocity profile in the surf zone; (b) different patterns of sediment transport by the action of vortices; and (c) formation of inner and break-point bars

necessary for simultaneous bar development.

Figure 10 shows an example of successive development of four bars. The initial morphology had a profile of a shallow shelf. During the first 5 minutes, the break-point bar was formed by the B-type horizontal vortex due to plunging breakers, and the second bar was formed inshore almost simultaneously by the action of oblique vortex produced by the strong shear flow of rushing bores induced by splash of the plunging breakers. At 20 minutes, the third bar appeared by the action of oblique vortex occurred further inshore. At 40 minutes this oblique vortex changed to the A-type horizontal vortex, which finally changed to the B-type horizontal vortex at 80 minutes. At the same time the second breakers were observed above the third bar. At this stage, the fourth bar was formed most landward by the oblique vortex. Finally, the equilibrium state of four bars was achieved when most vortices did not touch the bottom. This type of bar growth was observed in the cases in which the initial morphology was a shallow shelf.

As illustrated in Fig. 10, the multiple bars are formed successively from the wave break point to the inshore zone due to the coupling between the vortex action and nearshore topography. As the third bar clearly indicates, the order of change in vortex type occurring there is from oblique to A-type and finally to B-type horizontal vortices due to the interaction between bar growth and change in breaker type.

The present experiment showed that the second bar, as shown in this case (Fig. 10), was initiated by the vortex action induced by splash of plunging breakers, and it was always located deeper than and closer to the first bar. This type of bar is called a "splash inner bar" in this paper. A splash inner bar often occurred when plunging breakers acted on the beach.

Difference in Formative Processes Between Inner and Break-point Bars

Figure 11a shows the average drift velocity profile in the surf zone induced by spilling breakers which may form bars; this result is obtained from the result of float observation in this study and supplemented by the results of studies by Pae and Iwagaki (1984), Svendsen (1984), and Wang et al. (1984). The average velocity is found to direct onshore in the upper layer of water column, and offshore in the middle to bottom layers within the surf zone, where the middle layer has higher offshore velocity than the bottom. The onshore velocity occurs near the bottom in the offshore zone including the break point.

Figure 11b shows two modes of net sediment transport under the action of vortices. One is the "congestion" in the surf zone. Sediment particles lifted by the vortex occurring inshore are more rapidly transported by the higher offshore velocity, whereas the sediment particles located adjacent to the vortex but not lifted by the action of the vortex are transported by the lower offshore velocity without suspension. The difference in sediment particle velocities directed offshore causes congestion. The other mode of sediment transport is the "convergence" near the wave break point. Sediment particles suspended by the action of the breaker-induced vortex are transported offshore by offshore-directed drift velocity, whereas sediment particles rested on the bottom seaward of the break point may be transported onshore by the onshore-directed drift velocity near the bottom. Convergence of transported sediments occurs immediately seaward of the place where the vortex acts on the bottom.

Figure 11c illustrates the inner bar formation by congestion, and the break-point bar formation by convergence. Sediment grain size that controls the height of suspension is also important in multiple bar formation. Sediment particles suspended by the surf-zone vortex would be transported to the break point to form the break-point bar, if the fall velocity of the sediment is too low to settle down immediately seaward of the vortex. In this case no inner bars would form.

RELATIONSHIPS BETWEEN CHARACTERISTICS OF MULTIPLE VORTICES AND MULTIPLE BAR FEATURES

Figure 12 shows the relationship between vortex spacing (defined in this figure) calculated using Eq. (3) and the observed trough spacing using bar-profile data of small-scale experiments (the present experiment and Yokotsuka, 1985) and

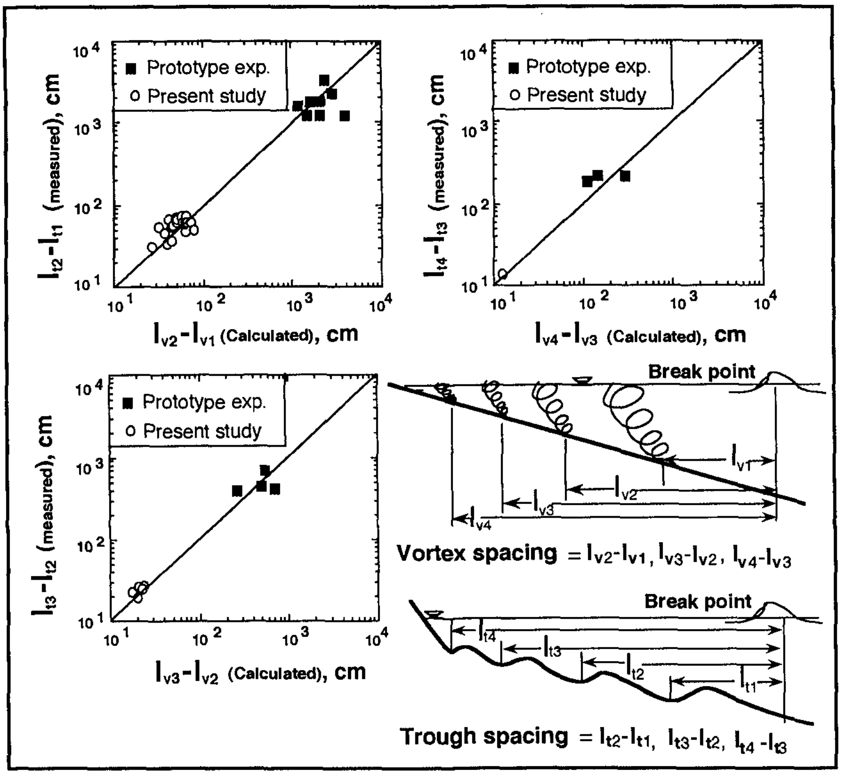

Fig. 12 Comparison of calculated vortex spacings and measured bar-trough spacings

the existing prototype experiments (Sunamura and Maruyama, 1987; Kraus and Larson, 1988), except the "splash inner bar". This figure illustrates that the calculated value of vortex spacing is almost equal to the observed value of trough spacing. In the calculation using Eq. (3), a problem is how to evaluate $\tan\beta$ for the case of non-uniform beach profiles. Considering that the wave breaking is crucial for multiple bar formation, the average beach slope shoreward of the wave break point, i, was used for $\tan\beta$. The average slope i is defined as

$$i = 2h/l \tag{7}$$

where h and l are the average water depth and the width of the surf zone (from the wave break point to the still-water line), respectively. The average depth h is given by

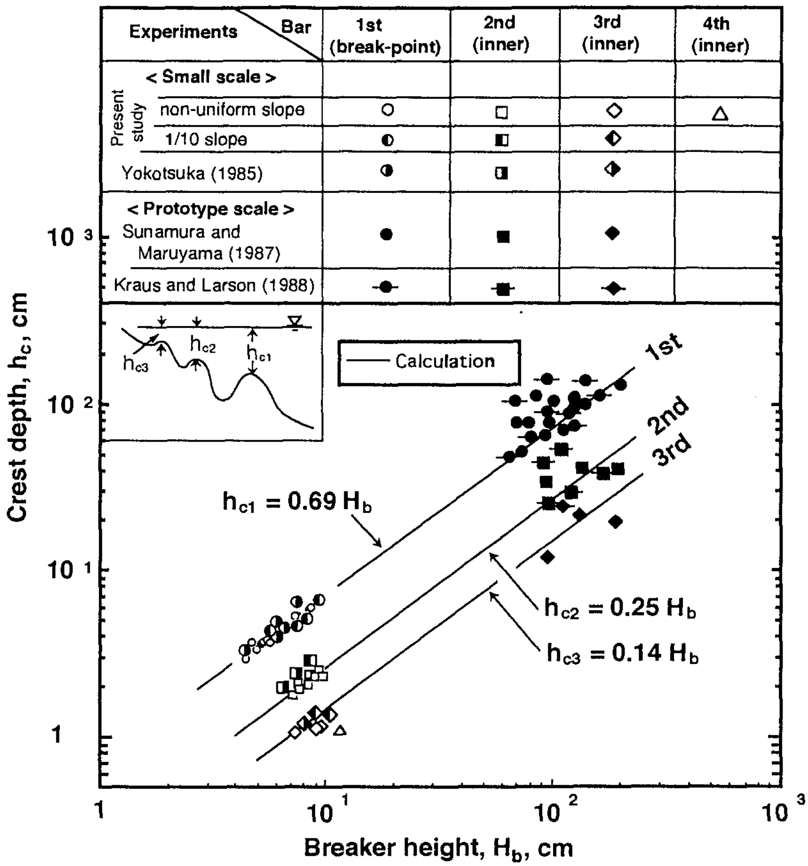

Fig. 13 Relationship between bar-crest depth and breaker height

$$h = \frac{1}{l}\int_0^l h(x)\mathrm{d}x = S/l \tag{8}$$

where S is the cross-sectional area of the surf zone. From Eqs. (7) and (8), we have

$$i = 2S/l^2 \tag{9}$$

The relationship between the breaker height and the water depth at the crest of n-th bar is shown in Fig. 13, using data of the above-mentioned small-scale and prototype experiments; data of the "splash inner bar" were again excluded. It was found that the water depth of bar crest is independent of time and is almost equal to the water depth where the vortex reaches bottom at the initial stage (Zhang, 1994). Assuming that the water depth of vortex reaching bottom is equal to the water depth of bar crest, the following equation is obtained from Eq. (6):

$$h_{cn} = 0.69\, n^{-1.44} H_b \tag{10}$$

where h_{cn} is the water depth of n-th bar crest. The straight lines in this figure are the result of calculation by use of this equation substituting n=1, 2, and 3. It is seen that calculation and experiment are in fairly good agreement.

CONCLUSIONS

(1) Bars are only formed by the vortices reaching bottom; the number of bars formed coincides with the number of vortices reaching bottom. The occurrence of vortices reaching bottom in the surf zone is crucial for the multiple bar formation.
(2) Average drift velocity and sediment suspension due to vortex action can play an important role in bar formation. The mechanism for break-point bar formation is " convergence"; however, that for inner bar formation is "congestion"(Fig. 11).
(3) Multiple-bar features such as trough spacing and crest depth can be explained from vortex features found through a fixed-bed experiment (Figs. 12 and 13).

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