CHAPTER 15

Coherent Eddies Induced by Breakers on a Sloping Bed

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Abstract

The separation of boundary layer occurs periodically near a breaking point when incident waves climbing up a sloping bed are about to break. Not the breaker but the separation forms an unsteady coherent eddy, which suspends a large amount of bed material. A row of steady vortices has been found along the water surface of an offshore zone. Its formation is due to the shear instability between shoreward steady flow induced near the bed and offshore steady flow near the water surface. Moving in the offshore direction, the steady vortices repeat amalgamation each other and increase their intervals at the order of mean water depth. They decay after reaching to the region where the shear rate is not enough between the two steady flows. This shear instability may be excited by the periodic separation of boundary layer.

1. Introduction

Recently, the velocity in nearshore zone has been measured vigorously through field and laboratory investigations in order to reveal the mechanism of suspension and sediment transport or to understand the process of water exchange between nearshore zone and offshore. Many researchers (e.g., Mizuguchi, 1986 ; Okayasu, et al., 1986) have the idea that turbulence by breakers lifts up much bed material, and their attention has focused on coherent eddies in surf zone. Miller (1976) showed the formation of breaker vortices on basis of the pattern of entrained air bubbles. Kaneko(1985) confirmed their formation by tracing the paths of polystyrene beads. Nadaoka(1986) has suggested the existence of oblique eddies from bubble patterns. However, the question that the flow drawn schematically by him forms truly in surf zone will remain until it becomes clear that the ensemble-averaged behavior of individual tracers has such a coherent, rotational structure.

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We often observe that a large amount of bed material has been already rolled up at the breaking point when incident waves are about to break. The purposes of this paper are to reveal experimentally the mechanism of this suspension and to show the qualitative characteristics of a vortex train induced in an offshore zone, which has been supposed to be irrotational flow region.

2. Experimental Methods

Figure 1 shows schematically an experimental apparatus. The wave tank was 12 m long, 0.4 m deep and 0.15 m wide. It was made of transparent acrylic plates and equipped with a sloping bed. Two-dimensional regular waves were formed by oscillating a flap. The behaviors of flow were observed near a breaking point and in offshore zone.

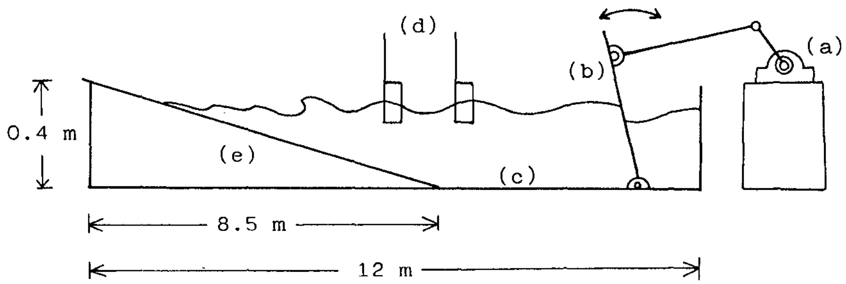


Figure 1. Experimental apparatus.
(a) Motor; (b) wave generator; (c) wave tank;
(d) wave gauges; (e) sloping bed.

Near the breaking point, turbulent flow by a plunging breaker was investigated by means of both velocity measurement and flow visualization. The slope θ of the bed was 0.056 and the wave period T was 1.3 s. Figure 2 shows the measuring points and the level of wave crest. The points P.P. and B.P. indicate the plunging point and breaking point, respectively. The velocity measurement was carried out by using a single-component Lazer-Doppler velocimeter of forward scattered fringe mode. Therefore, the horizontal and vertical velocities had to be measured separately under the same hydraulic conditions. Two capacitance-type wave gauges were used for the measurement of wave profiles. One was placed right above the measuring point of velocity and the other was fixed at an offshore position. Signals from the L.D.V. and wave gauges were recorded simultaneously by a data recorder. They were digitized;the sampling time and number were 8/1000 s and 16,384, respectively. Flow patterns were visualized by using granules of aniline blue, condensed milk and saw dust as a tracer.

The flow in offshore zone was observed only by means of flow visualization. The value of θ was 0.043. The period T ranged from 0.55 to 2.0 s. Granules of aniline blue were used as a tracer and were scattered on the water surface of

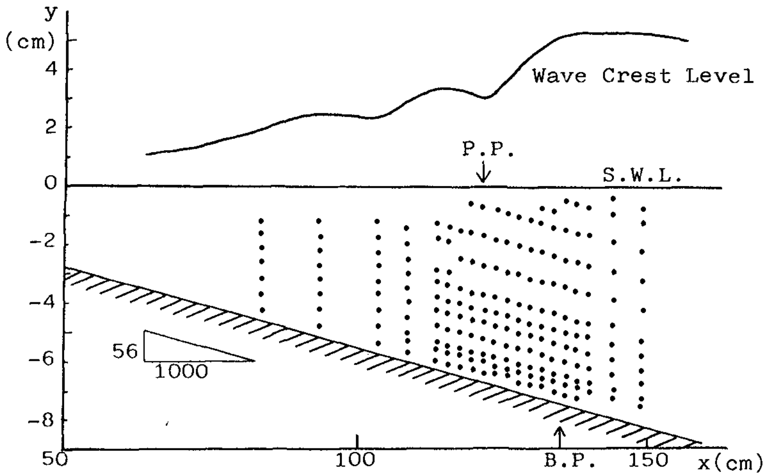
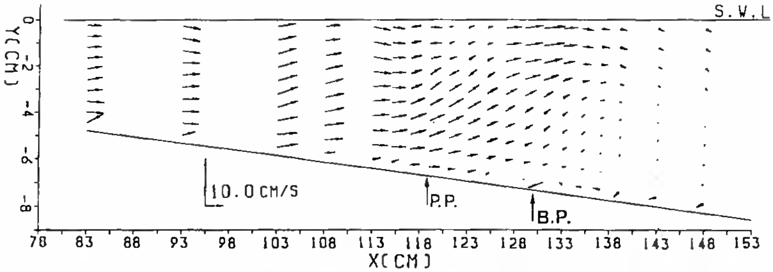


Figure 2. Measuring points and wave crest level.(P.P. indicates the punging point and B.P. the breaking point.)

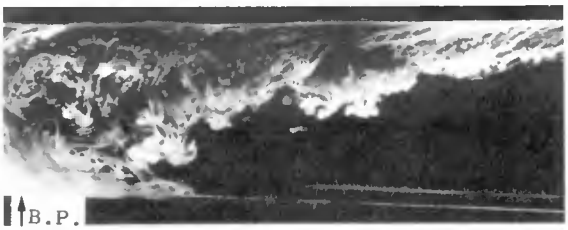
the offshore zone. All the flow patterns were photographed instantaneously through a side wall of the tank by using a 35mm camera, which was at rest with respect to it. The offshore side is on the right in all these photos.

3. Results and discussion

Figures 3(a) to (d) show the patterns of secondary steady flow induced near the breaking point. Mean velocity vectors are drawn in figure 3(a). The steady flow rises at the breaking point and runs along the water surface. Shoreward steady flow forms along the boundary layer of the offshore zone (e.g., Longuet-Higgins 1953). It is therefore seen that the breaking point is a separation point of the steady flow. Figure 3(b) shows a lift-up pattern of condensed milk immediately after the start of oscillation. The tracer was precipitated beforehand near the breaking point. Here, t is the time elapsed since the start of oscillation and T the wave period. A large amount of the tracer is lifted up at the breaking point without running down along the bed of the offshore zone, and it is transported along the water surface. This pattern agrees well with that shown in figure 3(a). Figure 3(c) was taken when $t/T = 92$. A row of vortices with the clockwise rotation is seen in the offshore zone. The formation mechanism and formation region of this vortex train will be discussed later in detail. Figure 3(d) is a close-up view of the boundary layer separation. Aniline blue dye was used as a tracer. The dye dropped on the bed of the offshore zone is transported onshore by the shoreward steady flow

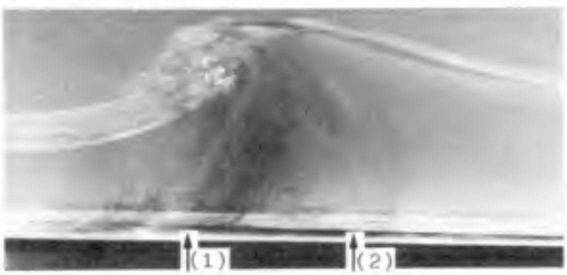


(a)



(b)

(c)



(d)

Figure 3. Steady flow patterns induced near the breaking point. (Arrow (1) indicates the separation of boundary layer and arrow (2) the trace of dye along the bed.)

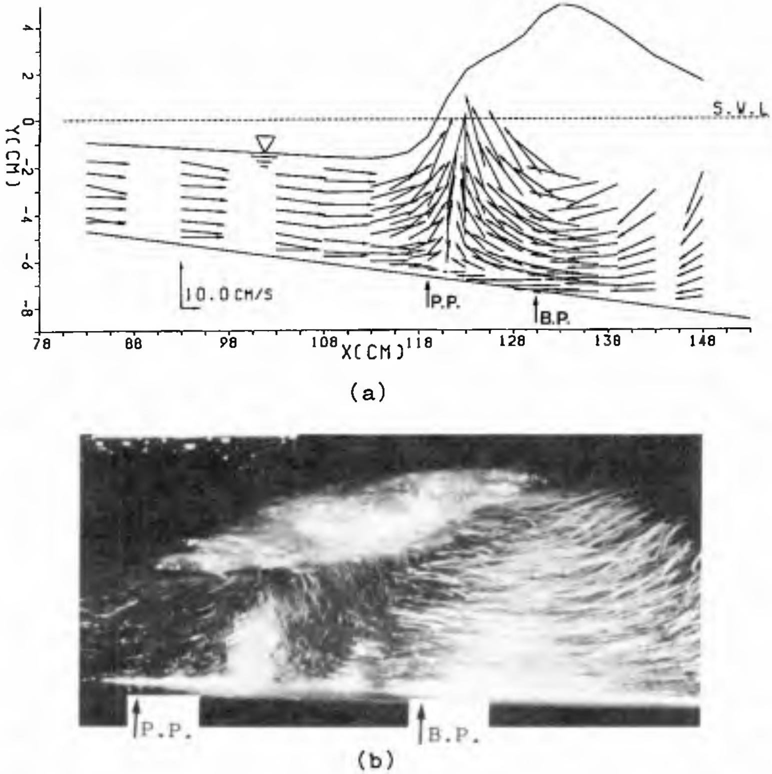


Figure 4. Velocity and flow patterns when an incident wave is about to break. Scale bar is 10 cm.

along the boundary layer, and separates at the breaking point just before breaking. It should be noted that the run-up of tracer along the bed is not observed in surf zone owing to the separation. This visualized result supports also the pattern shown in figure 3(a).

Figure 4(a) shows the ensemble-averaged velocity pattern at a phase just before breaking. Strong upward orbital motion is seen at the front of wave crest. Figure 4(b) is taken at almost the same phase as figure 4(a). Saw dust is lifted up owing to both the separation of boundary layer and the orbital motion.

Figure 5(a) is the ensemble-averaged velocity pattern at a phase immediately after breaking. Arrow (1) indicates a flow pattern induced by plunging. It should be emphasized that the flow does not form a complete rotational pattern since its direction is shoreward near both the bed and water surface. Arrow (2) indicates a vortical pattern with the clockwise rotation. The formation of this coherent eddy is closely related to the separation of boundary layer. From these reasons, therefore, it may properly be called the 'backwash vortex', which was found by one of the authors(1979, 1981). Figure 5(b) shows an instantaneous

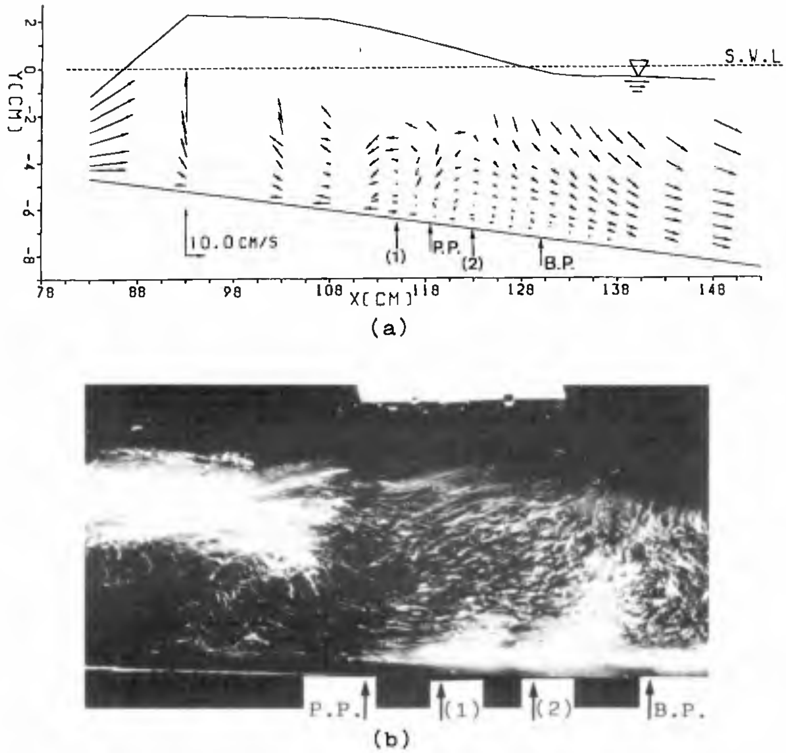
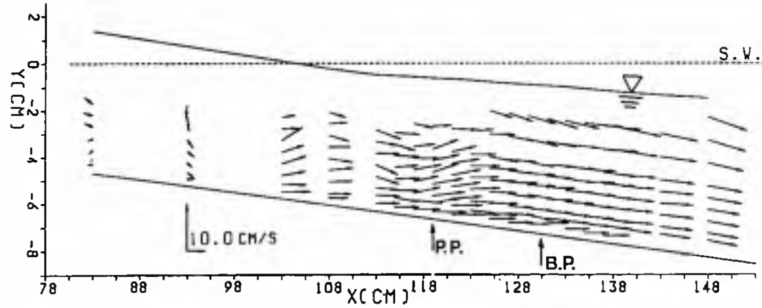


Figure 5. Velocity and flow patterns immediately after breaking. Scale bar is 10 cm.

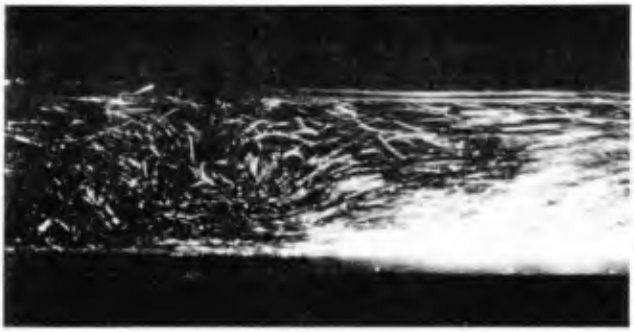
flow pattern at almost the same phase as that of figure 5(a). Two lift-ups of saw dust are seen as indicated by arrows (1) and (2). The lift-up shown by arrow (1) seems to be due to plunging breaker. On the other hand, considering that the suspension shown by arrow (2) has the clockwise rotation and forms near the breaking point every wave period, we can guess that it is generated by the backwash vortex.

Figures 6(a) and (b) show velocity and flow patterns, respectively, when a wave trough passes through the breaking point. Both the patterns agree well and the coherent suspensions have been already wiped out by the orbital motion.

Now, let us discuss about the vortex train appearing in offshore zone. Figure 7 shows a steady flow pattern induced along the water surface of offshore zone. The breaking point was at 0.68 m shoreward from the position E and the intervals between adjacent positions was 0.5 m. A wavy flow pattern is seen in the top photo. Between the positions D and B, the wavy pattern develops to a row of vortices with the clockwise rotation. Their intervals increase with the increase of water depth. As shown in the bottom photo,



(a)



(b)

Figure 6. Velocity and flow patterns when a wave trough passes through the breaking point.

the vortical pattern disappears in the region seaward from B. In the following discussion, this vortex will be called an 'offshore vortex'.

In figures 8(a) to (f), the process is shown in which the intervals of offshore vortices increase in the seaward direction. Here, t is the time passed from the photographing of figure 8(a). Let us focus attention on the two offshore vortices indicated by the arrows. Moving in the seaward direction, the two vortices approach gradually each other as shown in figures 8(b) to (d). Figure 8(e) shows that they have become one offshore vortex after their amalgamation. In figure 8(f), we can see the offshore vortices rearranged at the intervals of the order of mean water depth.

Let us consider about the formation region of the offshore vortex train. It may be expressed by the following function.

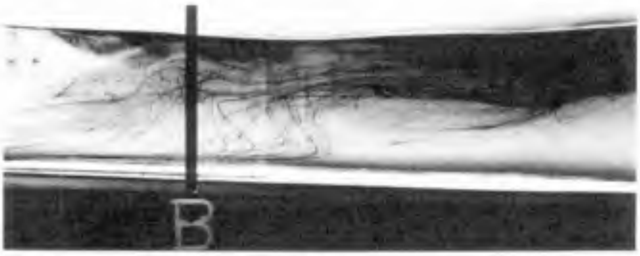
$$\text{Formation region} = f(h, L, H, T, C, g)$$

Here, h is the mean water depth, L the wavelength, H the wave height, T the wave period, C the phase velocity of incident waves and g the acceleration of gravity. In this

(a)

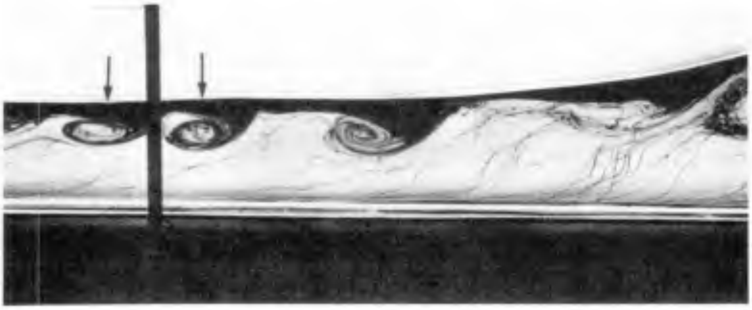
(b)

(c)



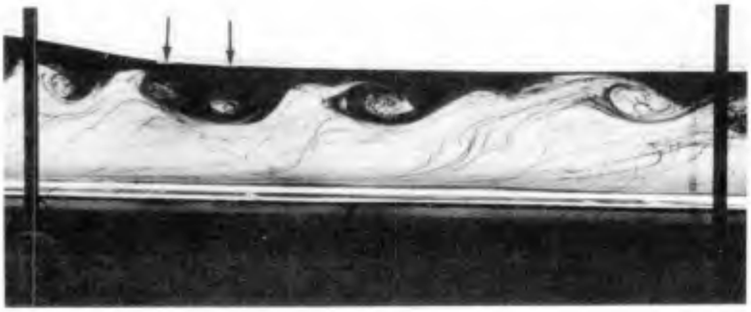
(d)

Figure 7. Local patterns of a vortex train in offshore zone. (The mean water depths are 7.9 cm at E, 10 cm at D, 12 cm at C and 14 cm at B.)



(a)

(b)



(c)

Figure 8. (a)-(c). For caption see next page.

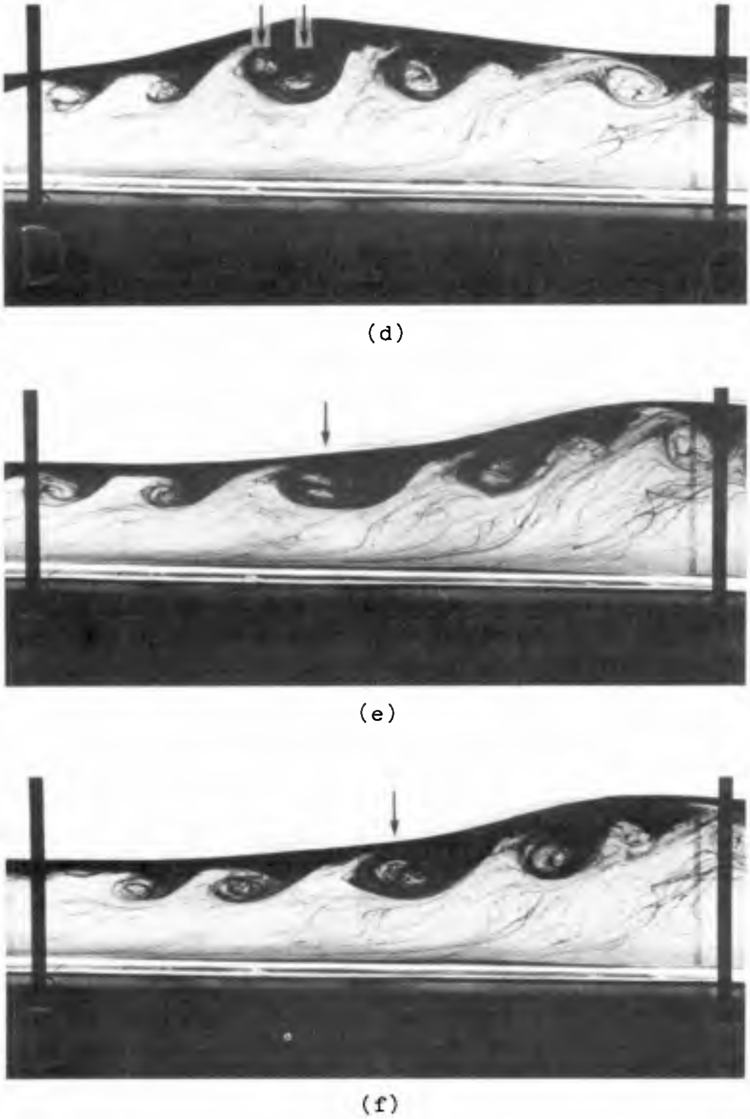


Figure 8. Increase-process of intervals of offshore vortices. The interval between D and C is 0.5 m.
(a) t/T=0; (b) t/T=12; (c) t/T=23;
(d) t/T=26; (e) t/T=30; (f) t/T=38.

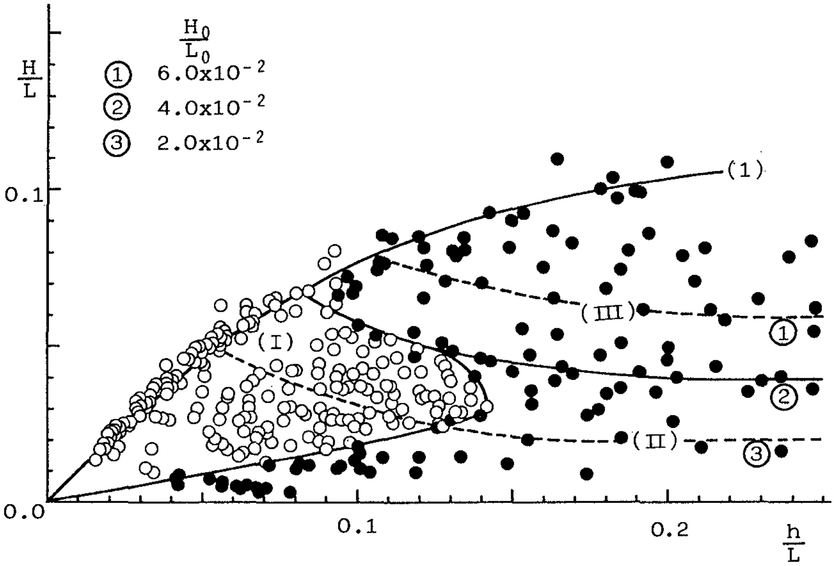


Figure 9. Formation region of offshore vortices.

expression , it has been assumed that the bed slope and the kinematic viscosity of fluid are constant. If the relation of C = L/T and the dispersion relation are taken into account, the function is simplified as g(h, L, H, g). Therefore, non-dimensional quantities to describe the formation region become h/L and H/L.

In figure 9, the formation region is examined by plotting H/L against h/L. The parameter H_0/L_0 is the steepness of deep water waves. The open circles indicate the formation of offshore vortices and the solid circles mean that the vortices are not observed. Regions (I), (II) and (III) are bounded by the solid lines. Line (1) expresses an empirical relationship between wave height and mean water depth at breaking points. Region (I) is the formation region of the vortex train. Region (II) indicates the region where the offshore vortices decay as shown in the bottom photo of figure 7. In region (III), no laminar vortical pattern is observed because of the strong diffusion due to high steepness of waves.

Figure 10 shows schematically the flow patterns induced in the offshore zone on the basis of the qualitative results mentioned above. The backwash vortex forms periodically near the breaking point owing to the separation of boundary layer. In the offshore zone, the train of offshore vortices develops in the seaward direction from the breaking point. Its formation is due to the shear instability between the shoreward and seaward steady flows, which are indicated by the arrows. This instability may be excited by the periodic separation. The offshore vortices increase their intervals as they move in the seaward direction. However, they decay after reaching to the region where the shear rate is not enough between the two steady flows.

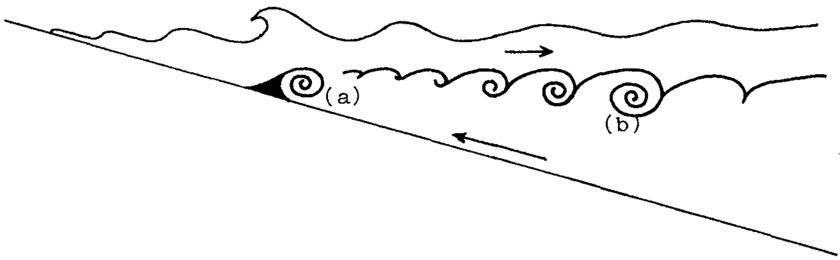


Figure 10. Schematic diagram of coherent eddies induced by breakers.
(a) backwash vortex; (b) offshore vortices.

In conclusion, the authors suggest that the separation of boundary layer near the breaking point and the offshore vortex train would be very important in the process of nearshore sediment transport.

Acknowledgments

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