CHAPTER 54

VORTEX FORMATION IN PLUNGING BREAKER

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ABSTRACT

By a flow visualization of a plunging breaker on 1/20 slope beach in a wave tank, an existence of 2nd and 3rd horizontal vortices(Miller, 1976) and slanting vortex(Nadaoka et al., 1986) is confirmed. A MAC method is applied to simulate a violent motion after an impinging of a jet from a crest of a plunging breaker on the trough surface. The calculated maximum water particle velocity in the jet is found to reach three times the linear long wave celerity. Values of circulation of the first four horizontal vortices are calculated and their changes in time are discussed.

INTRODUCTION

Recently the turbulence generated by wave breaking was measured in wave tanks by several researchers (for example, Stive(1980) and Sakai et al.(1982)). Several facts on the turbulence were clarified. The steady current, undertow, was also explained to some extent(Buhr Hansen and Svendsen, 1984). These are useful for our understanding of the so-called inner region of surf zone. In this region, the motion is rather mild.

In the outer region, however, the motion changes very rapidly. The vortex-like motions generated by wave breaking are not yet clarified so much. Especially, the plunging breaker generates large-scale vortex-like motions. This vortex-like motion is important for the sediment movement in the surf zone.

Miller(1976) suggested that several vortices were generated in the shoreward direction. Peregrine(1983) discussed three kinds of possibility for the penetration of plunging water into and the splash from the front trough surface. Nadaoka et al.(1986) pointed out that the vortex having a horizontal axis (horizontal vortex) was unstable and a vortex having a slanting axis (slanting vortex) was developed. Basco(1985) showed a schematical figure of a plunging breaker which contained one horizontal vortex.

In this paper, at first, an existence of the 2nd and 3rd horizontal vortices and the slanting vortex in surf zone suggested by Miller and

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Nadaoka et al. respectively is examined by a flow visualization on a beach in a wave tank. Secondly, the detail of an impinging of a plunging water upon and a splash from a front face of wave is discussed by using a numerical simulation. The water particle velocity in and around the jet and the circulation of several horizontal vortices are also discussed.

FLOW VISUALIZATION OF HORIZONTAL AND SLANTING VORTICES

A wave tank, 27m long, 50cm wide and 70cm high, in Dept. of Civil Eng., Kyoto Univ., was used. A beach of 1/20 slope was installed in the wave tank.

The experimental conditions are listed in Table 1. i is the beach slope, T the wave period, h_b the still water depth at the breaking point, H_b the breaking wave height, W the width of the surf zone and H_0/L_0 the calculated deepwater wave steepness. The water depth in the uniform depth part was 35cm.

Table 1 Experimental conditions

i	T (sec)	h_b (cm)	H_b (cm)	W (cm)	H_0/L_0
1/20	1.82	15.5	13.5	310	0.021

Pictures of the water motion in the surf zone was taken through the glass side wall of the tank with a video camera and a 35mm still camera. Fig.1 shows the surf zone and the region in which the picture was taken. "b.p." means the breaking point, and "p.p." the plunging point.

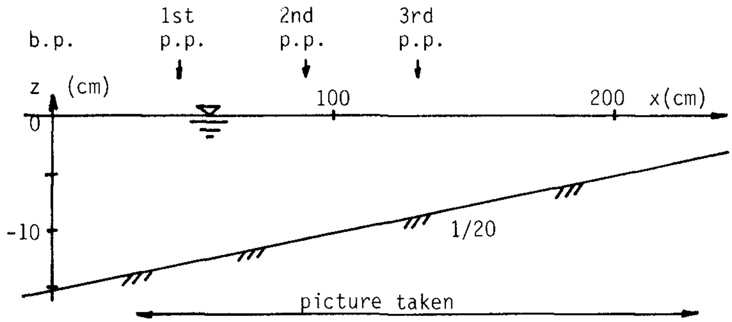

Fig.1 Surf zone and region in which picture was taken

The water motion recorded in a video film was observed carefully by using air bubbles as the tracer. Photo 1 shows a large overturning water mass from the crest. After this overturning mass hits the trough surface, a very violent splash occurs(Photo 2). A part of the overturning mass penetrates into the water body of the trough, and generates a large vortex-like motion having an horizontal axis(Photo 3).

Photo 4 shows a white region in which many air bubbles are contained in the surf zone. The black part is a part of a vertical steel element connecting two neighbouring glass plates of the tank. The upper picture was taken a little bit earlier than the lower one was. The wavy lower edge of this white region indicates an existence of the 2nd and 3rd horizontal vortex-like motions.

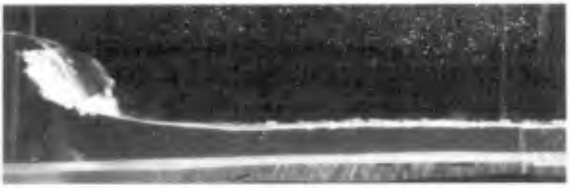

Photo 1 Large overturning mass from crest

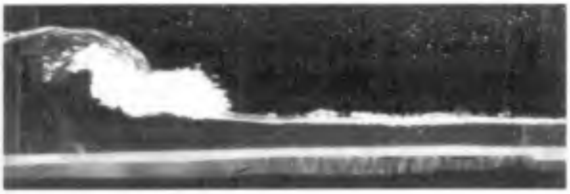

Photo 2 Splash from trough surface

Photo 3 Large horizontal vortex

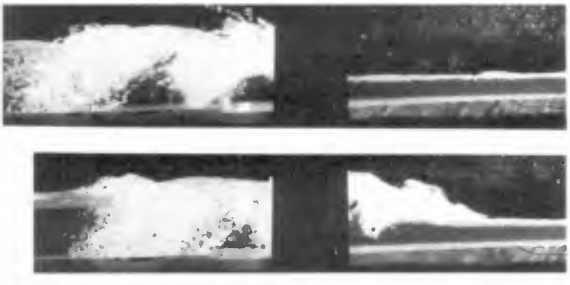

Photo.4 2nd and 3rd horizontal vortices

Photo. 5 shows a picture of a plunging breaker taken from its back. Two or three tails of the white region are seen in the transverse direction of the tank. This indicates an existence of the slanting vortex.

Photo.5 Slanting vortex

MAC METHOD

Physical experimental methods have their limitation for investigating the detail of structure in the outer region, due to the very rapid motion of wave breaking and the entrainment of a lot of air bubbles. An alternative method is numerical experiment.

For the overturning of water mass from wave crest, already many numerical computations have been done. One example is New et al.'s computation(1985)(Fig.2). They calculate a deformation of a overturning water mass, the water particle velocity and acceleration in this water mass, until the tip of overturning mass touches the trough water surface. But after the overturning mass touches the trough water surface, such a calculation fails to simulate the motion. This is because the calculation is based on a potential flow assumption.

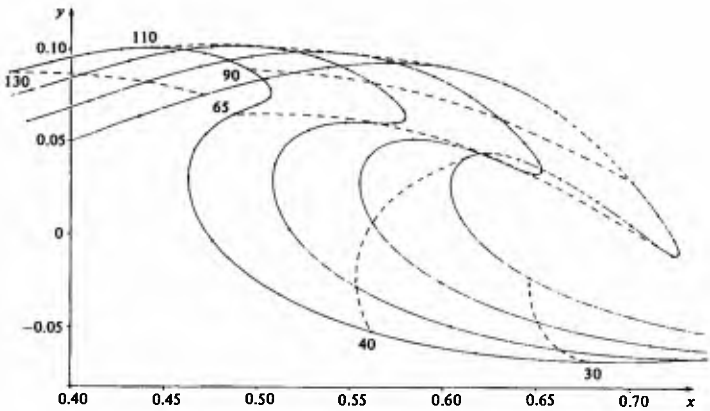

Fig.2 Numerical simulation of overturning mass from crest (New et al., 1985)

Here we used the so-called marker and cell method, "MAC method", to simulate a motion after an overturning mass touches the trough surface. In this method, the full Navier-Stokes equations are calculated. Therefore, the strong shear flow generated by the overturning jet can be calculated. Due to computational limitation, the calculation was done in two dimensional space, a vertical plane. So, the vortex having a slanting axis can not be calculated, because this vortex is generated due to a three-dimensionality of flow. Still, this calculation is expected to simulate the strong shear between the overturning jet and the trough water, the splash and the horizontal vortices.

The used MAC method is the so-called SMAC method(Takemoto et al., 1981). The surface conditions in the numerical model are rather of original type. As the initial conditions, a numerical result computed by Takigawa and Iwagaki(1983) with a finite element method(their figure No.7,(b)) was used(Fig.3). They calculated a propagation on a beach of 1/20 slope of a wave generated by a wave board in a wave tank. The calculation was stopped before the front face of wave becomed steep and the calculation becomed unstable. The conditions of Takigawa et al.'s computation are listed in Table 2. So the breaker type is plunging.

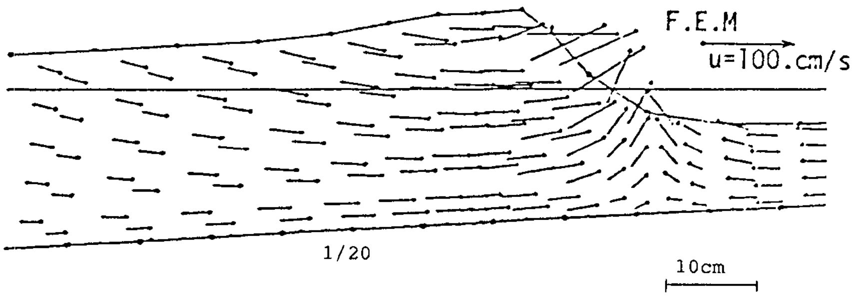

Fig.3 Initial wave profile and water particle velocity of numerical simulation (Takigawa et al., 1983)

Table 2 Conditions of Takigawa et al.'s computation(1983)

i	T (sec)	h_b (cm)	H_b (cm)	H_0/L_0
1/20	2.5	13.5	11.0	0.008

The cell is a rectangle of 1.0cm(Δx) x 0.5cm(Δy)(Fig.4). The time step Δt of the calculation is 0.0025sec. To take into account the existence of beach, the x-axis is taken parallel to the beach face. So the y-axis is not vertical, and the gravity has a x component. The computation region is 92 times 1cm long in x direction and 50 times 0.5cm high in y direction.

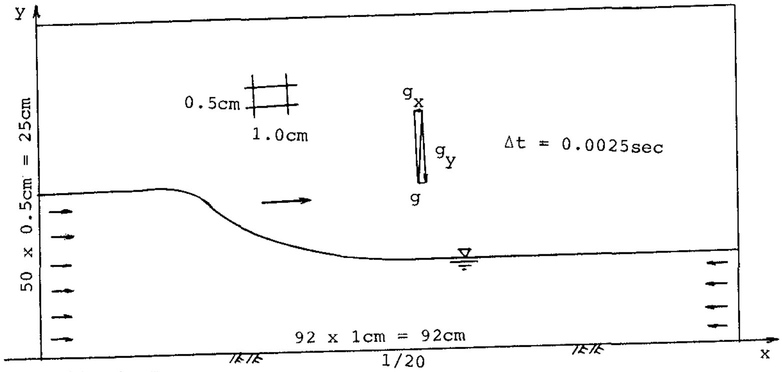

Fig.4 Region and conditions of numerical simulation

RESULTS OF NUMERICAL SIMULATION

Fig.5 shows a result of numerical simulation. The upper figure shows a vector arrow of the water particle velocity and the lower figure shows the location of the markers.

The figure (1) shows the initial condition. The crest height from the bottom is about 22cm. The linear long wave propagation velocity $\sqrt{gh}$ is about 110cm/sec. The maximum velocity in x direction is also about 110cm/sec and equal to the linear propagation velocity.

From the left and right boundaries, uniform currents in x direction flow into the region. This is not the real situation, but it is thought that the difference between the uniform current and the real flow situation does not influence the flow pattern near the plunging point during one run of computation (about 60 time steps).

The figure (2) shows the calculated result of about 0.3sec later. The computation region is shifted 30cm to the right. The uniform inflow current velocity was changed according to the result of calculated velocity at the final time step of the first run. The lower figure shows an existence of the overturning water jet from the crest. The air tube between the overturning jet and the front water surface looks smaller than the real one and the computed result based on potential flow assumption(Fig.2). This can be improved by decreasing the size of cell. Fig.6 is a result in the case of Δx = 0.5cm. The shape of the overturning jet becomes more realistic.

The figure (3) shows the result of 0.4sec later. The jet touches the trough surface, and rebounds. The upper figure shows that the velocity of rebounding and splashing water is very high.

The figure (4) shows the result of about 0.53sec later. The second touching and the second rebound or splash occur. The velocity direction is opposite between the upper jet and the lower trough water. Between these two water bodies, a strong shear exists. Two horizontal vortices

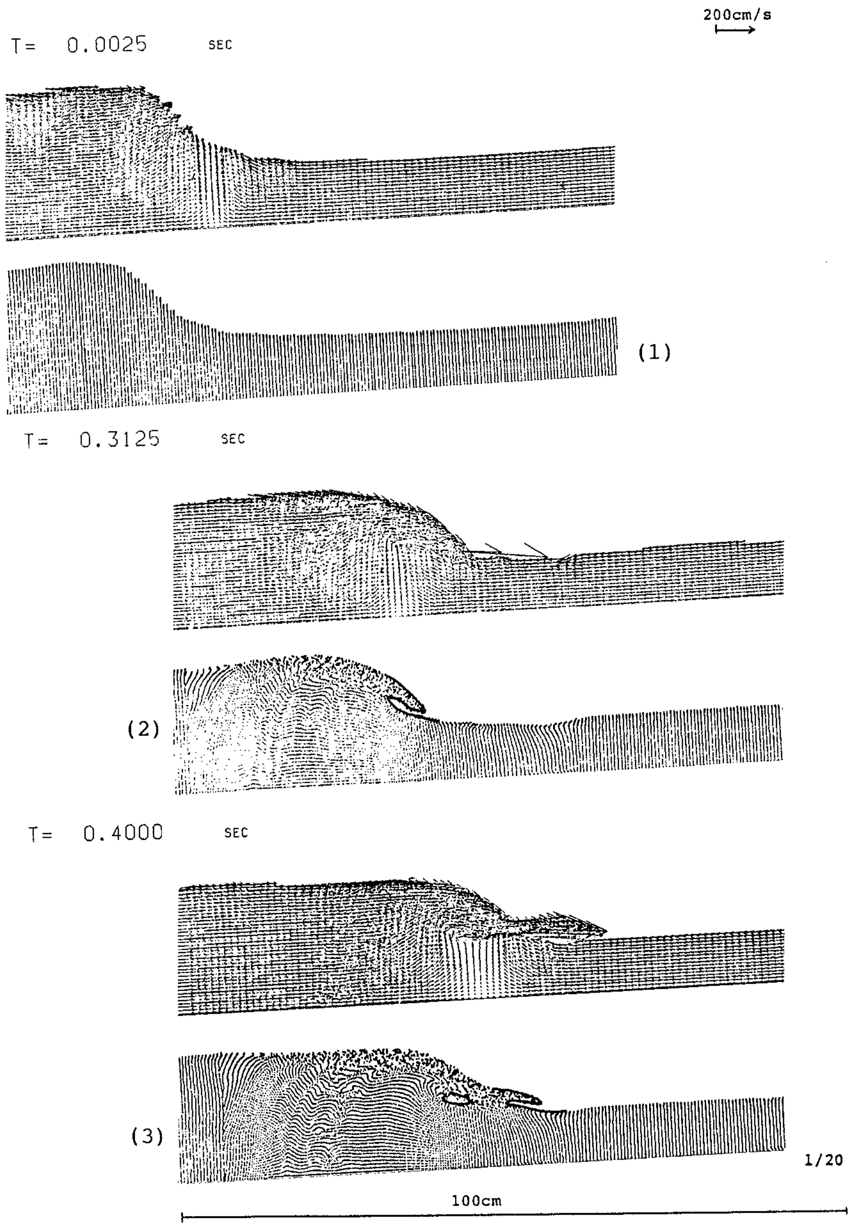

Fig.5,(1)-(3) Result of numerical simulation

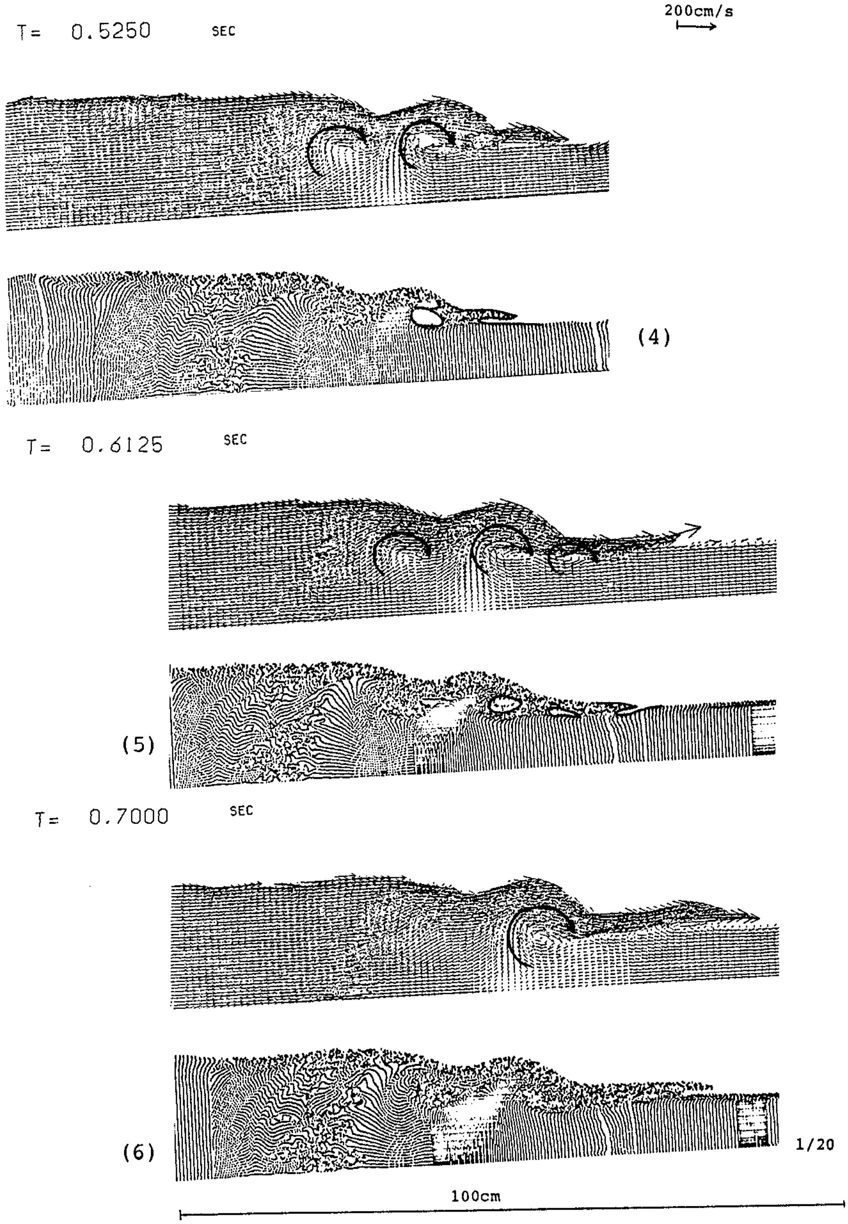

Fig.5,(4)-(6) Result of numerical simulation are found. They have a horizontal axis rotating clockwise.

The figure (5) shows the result of about 0.61sec later. The computation region is shifted again 25cm to the right. The uniform inflow current velocity was changed again. The third touching and the third splash occur. Totally three horizontal vortices are found.

The figure (6) shows the result of 0.7sec later. Still one large horizontal vortex exists.

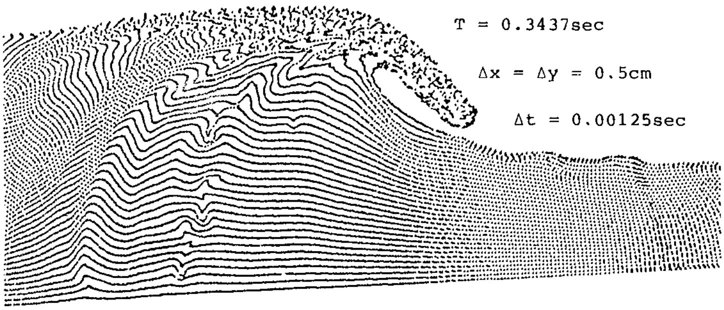

Fig.6 Improvement of shape of overturning jet by decreasing cell size

Photo 3 shows a splash on a 1/20 slope beach in a wave tank, taken from the side of the tank. The wave period is 1.8sec, and the deep-water wave steepness is 0.021(Table 1). So we can not compare this photograph with the calculated results directly. But the splash height in the wave tank is higher than that of the calculated result.

One reason is that the cell size is too large to take into account the existence of small water drop. Also as seen in Photo 3, under the crest, a lot of air bubbles are entrained into the water. The air entrained region reaches near the bottom. This air bubble entrainment is also not reproduced by the numerical calculation.

So, this numerical computation does not simulate the real motion. But, for our understanding of the very rapid motion after wave breaking on beach, these numerical results are useful. In particular, the numerical computation can calculate the instantaneous high speed velocity of water particle. Also the instantaneous value of circulation of the horizontal vortex can be calculated.

DISCUSSIONS

(1) water particle velocity

The maximum water particle velocity in the x direction at the initial condition(Fig.5,(1)) is about 110cm/sec and occours at the steep front face of the wave. The linear long wave propagation velocity $\sqrt{gh}$ is also about 110cm/sec.

At about 0.15sec later(the result not shown here), it increases to 140cm/sec, and its position is still located at the steep front face. Mizuguchi et al.(1986) measured a velocity field of breaking waves on a beach of 1/20 slope in a wave tank with a laser-doppler velocimeter. A maximum velocity before plunging normallzed by $\sqrt{gh}$ red from their figure is about one. This is comparable with our numerical result.

At 0.29sec later(not shown here), the tip of jet has not yet touches the trough surface. The maximum velocity is about 200cm/sec, and located at the lower surface of the jet. New et al.(1985) said in their paper that the horizontal velocity in the jet are between 1.5 and 2 times the phase speed of the linear wave. In this case, the linear long waves propagation velocity is about 110cm/sec. So our computation result agrees with their result.

Fig.7 shows a contour of water particle velocity in the x direction in and around the jet at 0.33sec later. This instance is just after the first jet touching on the trough surface. Notice that the x direction does not coincide with the horizontal direction. At the tip of the jet, a maximum velocity of more than 300cm/sec occours. It is not easy to find the maximum velocity after plunging from Mizuguchi et al.(1986)'s figure. But the normalized value seems to be still one.

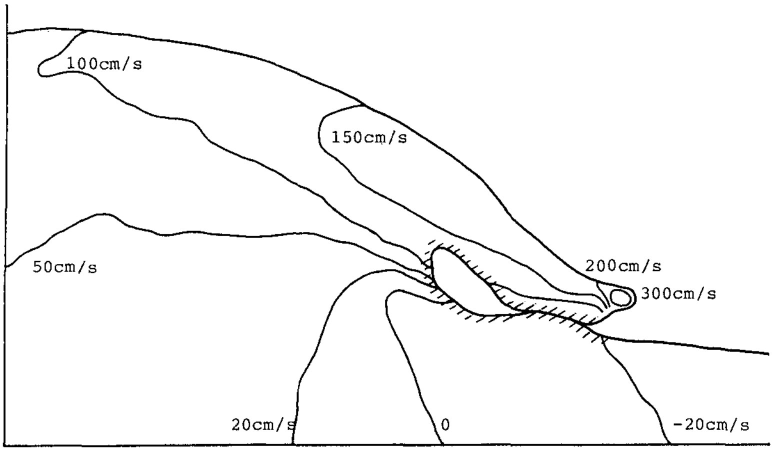

Fig.7 Contour of x component of water particle velocity in and around jet at 0.33sec later(just after 1st jet touching on trough surface)

Jansen(1986) also measured a velocity field in the jet by using fluorescent particles as tracer in a wave tank. From their figure 11, it is found again that the normalized maximum velocity is about one. In our result, the value of $\sqrt{gh}$ is 110cm/sec, and the maximum velocity is more than 300cm/sec. So the normalized value is about 3. It is thought that the experimentally measured values are underestimated.

Fig.8 shows a similar contour at about 0.47sec later. At this instance the second jet touching on trough surface already finished. The x component of water particle velocity in the jet is still large(about 200cm/sec) in its upper region. But it is small compared with that at the tip at 0.32sec later(Fig.7). It is found that the water particle velocity in the jet decreases gradually in the jet touching and splash process.

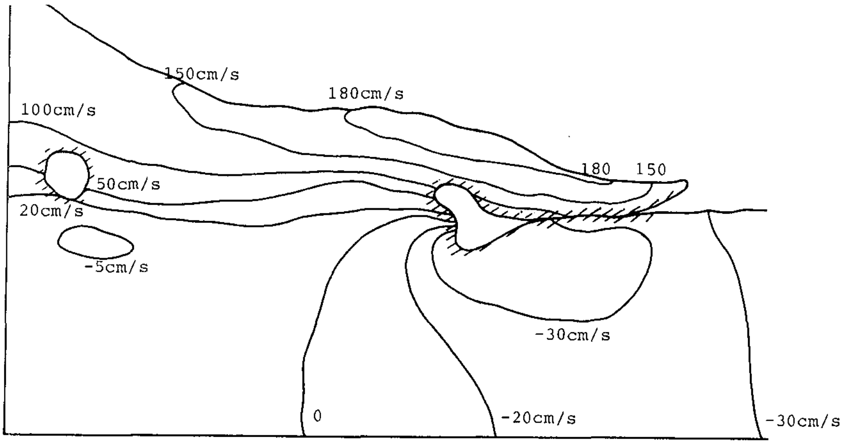

Fig.8 Contour of x component of water particle velocity in and around jet at 0.47sec later(after 2nd jet touching on trough surface)

(2) circulation of horizontal vortices

As seen in Fig.5, several large horizontal vortices are generated between the jet and the lower trough water. Values of circulation of these vortices are calculated. The closed path for the circulation calculation is determined rather arbitrarily.

Fig.9 shows the result. The instance when the vortex is generated is difficult to determine exactly from the figure of marker location. Arrows indicate a possibility that the vortex may be generated earlier. From the figure, it is found that the value of circulation reaches near 2000cm^2/sec. The circulation of the first vortex decreases gradually, while that of the second vortex grows at first and then decreases. The third and fourth vortices are not so large compared with first two vortices.

Value of circulation of a horizontal vortex was calculated also by Shibayama et al.(1982) using experimental data. The wave period was 1.24sec, deepwater wave height 3.8cm, deepwater wave steepness 0.016, and the initial slope of a movable bed 1/20. They calculated the circulation from a velocity field which was determined from movement of polystyrene particles. From their figure 5, it is found that the value of circulation is at most 120cm²/sec. The conditions of their experiment are different from those of our numerical simulation. So a direct comparison is impossible.

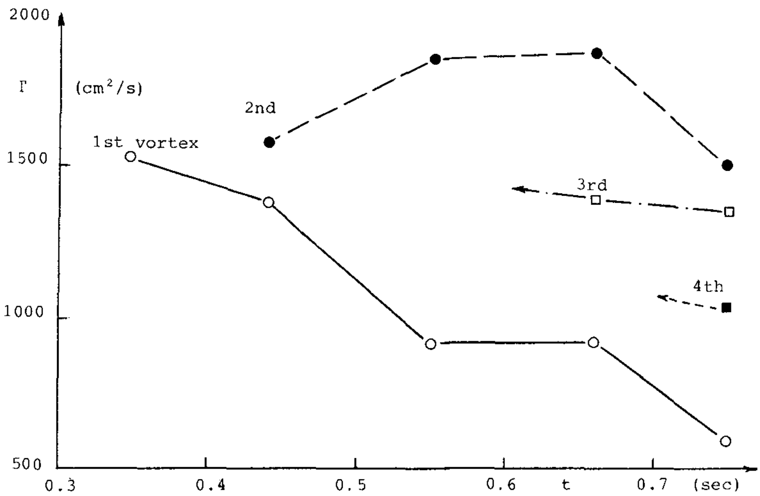

Fig.9 Circulation of four horizontal vortices

CONCLUSIONS

(1) By a flow visualization of a plunging breaker on a 1/20 slope beach in a wave tank, an existence of the 2nd and 3rd vortices suggested by Miller(1976) and the slanting vortex suggested by Nadaoka et al.(1986) is confirmed.
(2) A MAC method is applied to simulate a violent motion after an impinging of a jet from a crest of a plunging breaker on the trough surface. Although the numerical simulation can not reproduce the high splash, the deep air bubble penetration into the trough water and the slanting vortex, it can reproduce the high speed jet on the trough surface and the several horizontal vortices.
(3) The calculated maximum water particle velocity in the jet reaches three times the linear long wave celerity just after the impinging of the jet on the trough surface.
(4) The calculated circulation of the first horizontal vortex decreases gradually. The calculated circulation of the second one is larger than that of 1st one. It increases at first and then decreases. The values of circulation of the third and fourth horizontal vortices are smaller than those of the first and second ones, and become smaller in this order.

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