CHAPTER 304

A STUDY ON FLOW STRUCTURE AND SUSPENDED SEDIMENT CONCENTARTION OVER SEAWEED BED

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ABSTRACT

Numerical calculation of flow structure and the suspended sediment concentration over seaweed bed under surface wave is conducted using the k-ε turbulence model. Velocity distribution and suspended sediment concentration over seaweed bed, which is made of a plastic sheet, are measured by use of the electromagnetic current meter and a turbidity meter, respectively.

The characteristic phenomenon such as the vortex formation over seaweed bed is simulated and the calculated vertical profile of suspended sediment concentration is similar to that of experiment. The value of drag force coefficient of seaweed is a few times larger than that of rigid seaweed.

I. INTRODUCTION

Seaweed bed in the sea is an important ground for fishes and shellfishes as nursery ground. So method for artificial seaweed bed creation and technique for selecting appropriate site have been studying. But there are many problems to be resolved. One of them is to understand the mechanism of sediment transport induced by the wave motion and the seaweed motion. The seaweed acts against the water body in motion as the drag force, and the flow mechanism is so complicated by that.

Also a study on wave attenuation and control of sediment transport by using the flexible artificial seaweed a like plastic sheet have been investigated recently. This paper presents an experimental approach and a numerical approach on a study of the flow mechanism and the concentration profile of suspended sediment over seaweed beds.

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II. EXPERIMENTAL METHOD

The experiment was performed in a water tank which was 18m long, 0.6m wide and 1.0m high. Since the seaweed motion in the field is very complicated, an artificial flexible roughness element like a plastic sheet is used as the seaweed in this experiment(from now on, it is called seaweed). The plastic sheet is cut at space of 1mm to 10cm in the length, being placed at the bed. Number of seaweed and its settling space were made to change and eight test runs were performed as summarized in Table 1.

For each of the eight test run, capacitance wave gages were used for the measurement of the free surface elevations, the electromagnetic current meter for that of velocity and the turbidity meter for that of suspended sediment concentration. Sand with diameter of 0.014mm was used as bed materials. The bed material was placed in a uniform thickness of 8cm at the tank bottom, about 2.5m long and 0.4m wide. Also the natural frequency of used seaweed is measured by using the oscillating plate, and its value is between 4.5 and 5.5Hz. The output voltages of their measured values were transmitted to personal computer. In table 1, "u" stands for horizontal velocity, "w" for vertical velocity, "c" for concentration, "H" for wave height and "S" for settling space of seaweed. In the follow figures, the settling position of seaweed is marked as " ↑ " and the wave phase is set to be zero when the flow direction over the seaweed on the offshore side is changed from offshore to onshore.

Table-1 Experimental Conditions

Run	*H (cm)*	*Depth (cm)*	*Period (sec)*	*S (cm)*	*Number Seaweed*	*Item*
1	4.1	30	1.22		1	u, w
2	3.6	21	1.22		1	u,w,c
3	7.3	21	1.22		1	c
4	4.8	21	1.22	10	2	u,w
5	1.1	21	1.72	10	2	u,w,c
6	3.9	21	1.22	10	3	u,w
7	4.6	21	1.22	20	2	u,w
8	4.3	21	1.22	20	3	u,w

III. EXPERIMENTAL RESULTS

3.1 Velocity vector

Figure 1(a) and 1(b) shows the measured velocity over the seaweed without its motion at the wave phase of t/T=0.25 for run No.2 and over the seaweed with its motion at that of t/T=0.5. A blank space in fig.1(b) shows no data because of the limitation in measurement system. It is thought that formation of vortex over the vertical plate(like fig.1(a)) under the wave motion is seen at the wave phase of a wave crest. Meanwhile the vortex in fig.1(b) with the seaweed motion is formed over seaweed beds at the wave phase when the flow direction change from onshore to offshore. There is a phase lag of $\pi/2$ on the formation of vortex between both fig.1(a) and (b) and the location of vortex formation in fig1(b) is lower than that of fig.1(a), and after the vortex in fig.1(b) is expected, following the motion of the free surface.

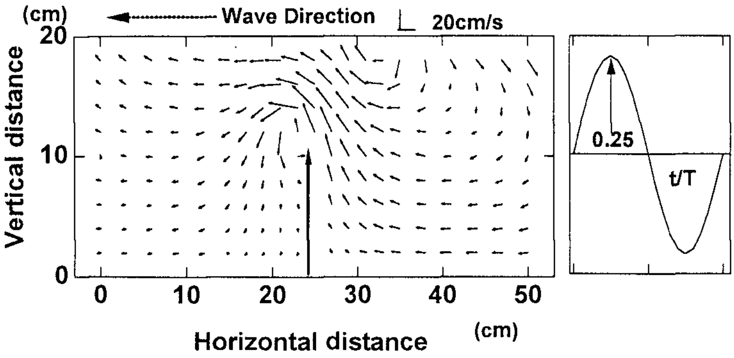

Fig.1(a)Velocity profile over seaweed without motion for run 2

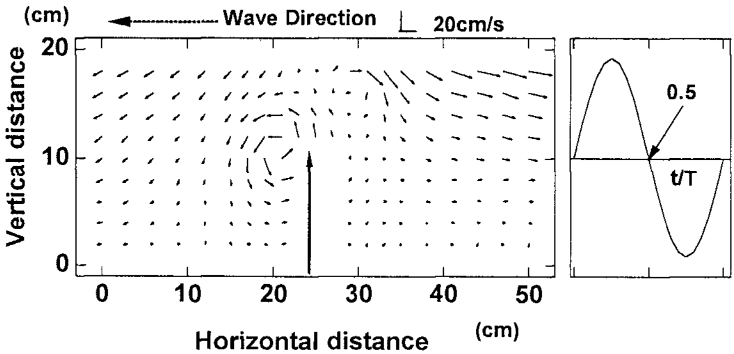

Fig.1(b) Velocity profile over seaweed with motion for run 2

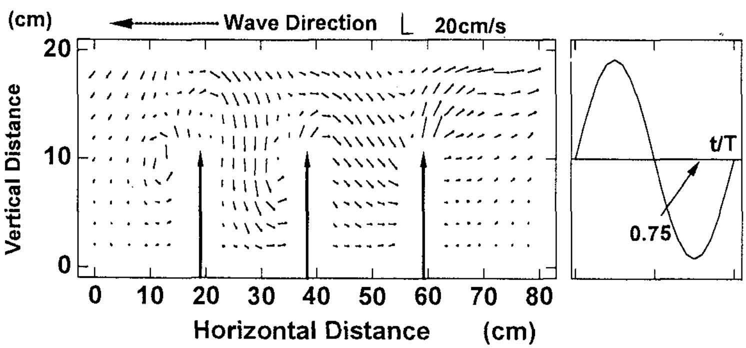

Fig2.Velocity profile over three seaweed with motion for run 8

Figure 2 show the velocity profile for run No.8. The vortex formation is not seen clearly near the top of seaweed. The counter clockwise vortex, however, is formed over the seaweed bed in the onshore side when the flow direction changes from onshore to offshore and its scale is smaller than that of fig.1(b). Also the other clockwise vortex around there is seen. It is thought that the flow filed produced by the seaweed motion before the half period forms a wavy boundary layer along the top of seaweed, producing this clockwise vortex.

3.2 Steady velocity

Figure.3 shows the measured velocity averaged over a wave period for No.8. The flow profile near the top of seaweed is oscillated wavy. The velocity toward upward direction just over seaweed and the velocity toward downward direction between the seaweed are seen,

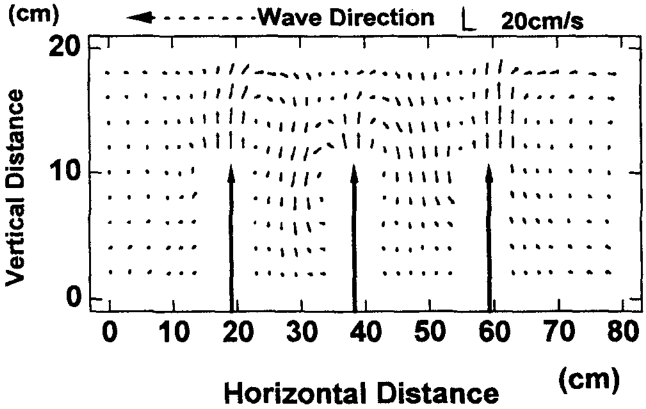

Fig.3 Steady velocity over seaweed for run 8

respectively, so that these flows form a set of circulation flow, having a large scale which compares with the scale of depth. It, therefore, has a effect on the suspension mechanism of sand particles close to the bed among the seaweed. These phenomena are seen in the case of run No.7,too. No vortex, however, is formed for run 4 and 5 in which the distance between both seaweed is half of run 7 or for run No.1,2 and 5 in which the number of seaweed is only one.

3.3 Suspended sediment concentration

It is known that there are three types of the distribution patterns of sediment concentration in the vertical direction, i.e. concave, convex and linear. Under non-breaking wave field, a region of high concentration is produced close to the bed due to the separated vortex over sand ripples and away from the bed surface the mean value of concentration is decreasing.

Figure 4 shows the vertical distribution of mean concentration for run 3 and in which the numbers show the distance from the settling position of seaweed. The distribution patterns of present study, as shown in fig.4, are concave with the turning point in the middle of depth, away from there all profiles reach a constant value. Those are not seen under non-breaking wave condition. Because no turbulent kinematics energy is supplied from the upper layer unlike the breaking wave and the flow filed by wind shear stress(e.g., Nielsen 1985; Tsujimoto et al.1995). It is thought that the turbulent kinematic energy generated by separated vortex near the top of seaweed can picks up the sand particles from the bed. Especially the separated vortex on the onshore side is conspicuous, having a large scale in space, so that it exerts the major effects on the suspension mechanism of sand particles. Also sand ripples have been formed at the bottom through eight runs.

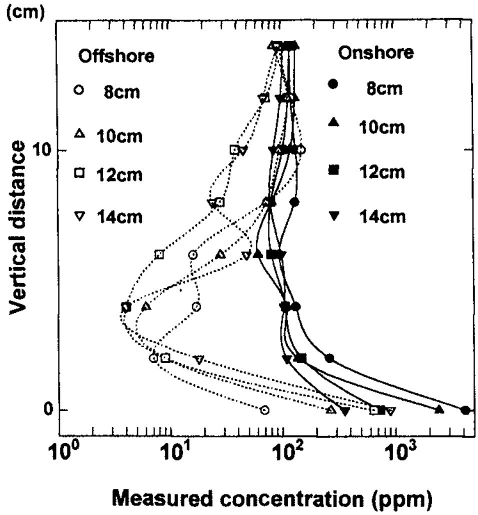

Fig.4 Measured mean concentration of suspended sediment

IV. NUMERICAL APPROACH

4.1 Previous study

Although there are many studies on the flow field with the substance in motion like seaweed, few have considered the mechanism of turbulent flow and sediment transport under wave motion. Asano et al.(1988) investigated the wave damping by using the artificial vegetation. Tsujimoto(1992) studied the mechanism of turbulent flow over an artificial seaweed field using the k- ε turbulent model. The agreement between the calculation and experiment, however, is not satisfactory.

These approaches are characterized by considering the effects of seaweed in the momentum equation as drag force. To calculate the turbulent flow filed over the seaweed bed, the turbulent productions and its dissipation by the seaweed motion should be modeled. There, however, is less knowledge on the production mechanism of turbulence over the seaweed bed under the wave motion and it is not easy for accurate determination on drag coefficient when drag force is adapted in the momentum equation.

4.2 Basic equation

The basic equations describing fluid motion consist of the continuity equation, momentum equations, diffusion equation of suspended sediment and conservation for

turbulent kinematic energy k and its dissipation rate ε. These equations are the same equations as author's used(1991) on calculation of suspended sediment over sand rippled and the effects of seaweed motion includes directly in the calculated grid without estimating that as drag force. These equations are written as follows:
For the continuity

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0 \tag{1}$$

For the momentum equation in x-direction

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uw}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial z^2}\right)+\frac{\partial}{\partial x}\left(2\nu_t\frac{\partial u}{\partial x}\right)+ \frac{\partial}{\partial z}\left(\nu_t\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right) \tag{2}$$

For the momentum equation in z-direction

$$\frac{\partial w}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial w^2}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial z^2}\right)+\frac{\partial}{\partial z}\left(2\nu_t\frac{\partial w}{\partial z}\right)+ \frac{\partial}{\partial x}\left(\nu_t\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right) \tag{3}$$

For the diffusion equation of the suspended sediment

$$\frac{\partial c}{\partial t}+\frac{\partial uc}{\partial x}+\frac{\partial wc}{\partial z}=-\frac{\partial}{\partial x}\left(\left(\nu+\frac{\nu_t}{\sigma_t}\right)\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial z}\left(\left(\nu+\frac{\nu_t}{\sigma_t}\right)\frac{\partial c}{\partial z}\right)+\frac{\partial w_o c}{\partial z} \tag{4}$$

For k-equation

$$\frac{\partial k}{\partial t}+\frac{\partial uk}{\partial x}+\frac{\partial wk}{\partial z}=-\frac{\partial}{\partial x}\left\{\left(\nu+\frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right\}+\frac{\partial}{\partial z}\left\{\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial z}\right\}+P-\varepsilon \tag{5}$$

For ε-equation

$$\frac{\partial \varepsilon}{\partial t}+\frac{\partial u\varepsilon}{\partial x}+\frac{\partial w\varepsilon}{\partial z}=-\frac{\partial}{\partial x}\left\{\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right\}+\frac{\partial}{\partial z}\left\{\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}\right\}+ C_{1\varepsilon}\frac{\varepsilon}{k}-C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{6}$$

$$P=2\nu_t\left\{(\partial u/\partial x)^2+(\partial w/\partial z)^2\right\}+\nu_t(\partial u/\partial z+\partial w/\partial x)^2 \tag{7}$$

$$\nu_t=c_\mu\frac{k^2}{\varepsilon} \tag{8}$$

where x and z are the horizontal axis and the vertical axis, respectively, u and w are velocity in x and z direction, p is the pressure, ρ is the fluid density, ν and ν_t the molecular and eddy viscosities, c is the suspended sediment concentration, w_0 is the fall velocity of the sediment particle and the constants in these equations are set at the values proposed by Rodi(1980) as given as follows:

$$C_\mu = 0.09, C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, C_{3\varepsilon} = 1.00, \sigma_k = 1.00, \sigma_\varepsilon = 1.3, \sigma_t = 1.00 \tag{9}$$

The natural frequency of seaweed is different from that of the experimental wave, so that the oscillation period of seaweed was set to be the same as wave's. The seaweed motion should be coupled from the wave motion in a strict sense, but the experimental value of velocity of seaweed motion are used herein.

There is no relative velocity in the normal direction to the surface of seaweed, and it is given by the following equation;

$$Vn = V'n \tag{10}$$

where n is a unit vector in the normal direction to the seaweed surface, V is the velocity of water particle and V' is the velocity of seaweed motion. The values of V' are given by the displacement of seaweed per a second in the horizontal direction. The displacement of seaweed in the vertical direction is assumed so small that the vertical velocity can be neglected. The boundary conditions at seaweed surface on the turbulent kinematic energy k and its dissipation rate ε are the same as that at the bottom and the concentration is set to be zero there. Other boundary conditions are the same as author's(1991).

4..3 Method of calculation

The conditions of calculation are equivalent to that of the experiment as given in Table 1. Forty elements in the vertical direction are used and the number of element in the horizontal direction is changed from forty to one hundred twenty depended on number of seaweed and a fine mesh scheme is employed near the seaweed. The calculation was conducted to investigate the effect to the flow structure when the phase lag between the wave motion and the seaweed motion and the height of seaweed were changed.

V. CALCULATED RESULTS

5.1 Steadv flow

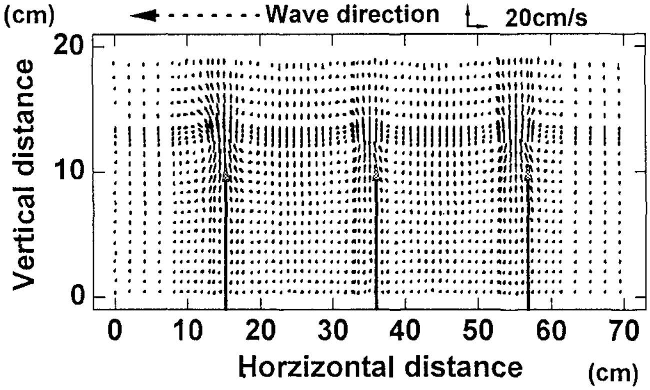

Fig.5 Calculated steady velocity

Figure 5 shows a steady velocity for run 8. The wavy flow near the top of seaweed and the vertical circulation flow between the seaweed are seen as shown in the experimental results(e.g. figure 3). These values are about 20cm/sec and approximately the same value as the experimental one. The calculated values of vertical downward direction, however, are smaller than the experimental values.

5.2 Velocity profile and suspended sediment concentration

Figure 6(a)and(b) show the calculated results on velocity and concentration for run 6. The separated vortex is not seen at the wave phase when a wave crest passes over the seaweed and the wavy flow is only formed near the top of seaweed. So the value of suspended sediment concentration is still low. The suspended sediment cloud is transported from the offshore side to the top of seaweed, but it has little sand particle. A small separated vortex is formed near the top of seaweed for fig.6 (b), but the suspended sediment between the seaweed could not be transported to the upper layer.

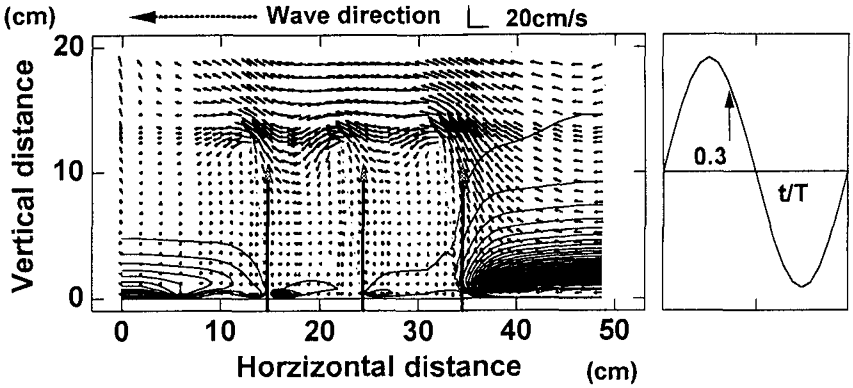

Fig.6(a) Calculated velocity and suspended sediment concentration for run 6

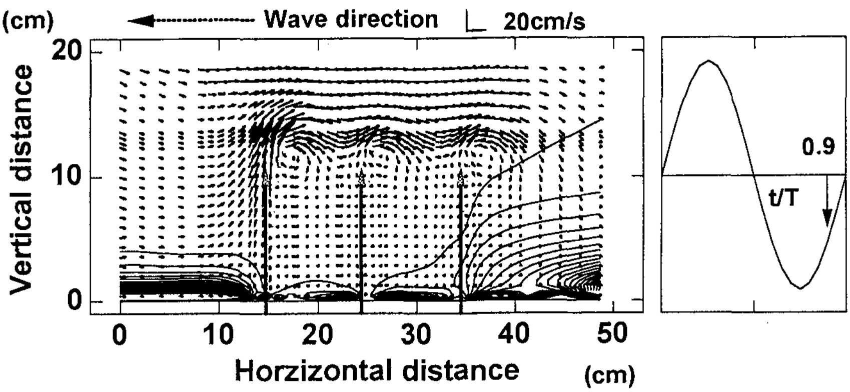

Fig.6(b) Calculated velocity and suspended sediment concentration for run 6

Figure 6(c) shows the calculated results at the same wave phase as that of figure 6 (b) for run 8. The settling space of seaweed in this figure is two times longer than that of figure 6(b). Since the separated vortex grows easily in size, much suspended sediment are transported to upward from the bed. The results of this figure gives an evidence that the settling space of seaweed is very important for suspended sediment transport.

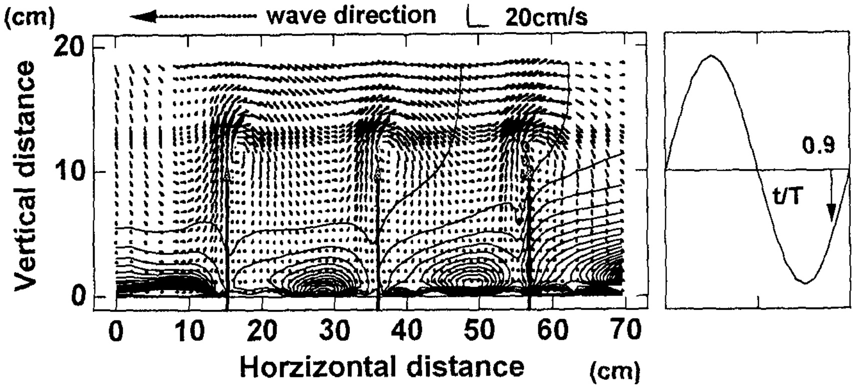

Fig.6(c) Calculated velocity and suspended sediment concentration for run 8

5.3 Suspended sediment concentration

Figure 7 shows the calculated vertical distribution of suspended sediment concentration averaged over a wave period, in which the number shows the distance from the position where the seaweed is located. The value of suspended sediment concentration close to the bed is lower than that of experiment, as the effects of sand ripples are not considered in the present calculation. The calculated results around the top of seaweed are close to the experimental values.

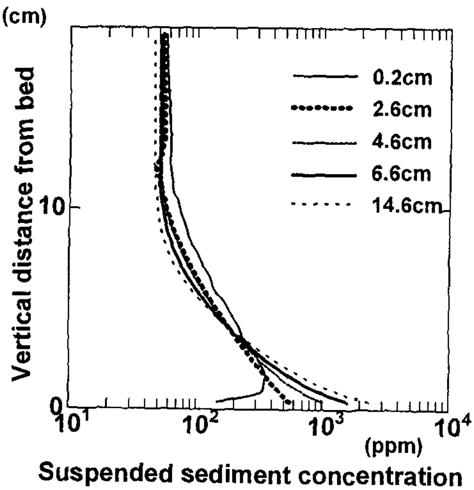

Fig.7 Calculated mean suspended sediment concentration for run 2

The suspended sediment concentration decreases lineally with increasing distance from the bed, whereas away from there it attains a constant value and the distribution pattern is concave. Also a certain level where the slope of the vertical distribution of the sediment concentration changes is approximately equal to the height of seaweed.

5.4 Vorticity

The experimental distribution of vorticity is shown in figure 8 for run 2. The vortex with negative sign at the preceding half period and the vorticity with positive sign at the next half period are seen near the top of seaweed.

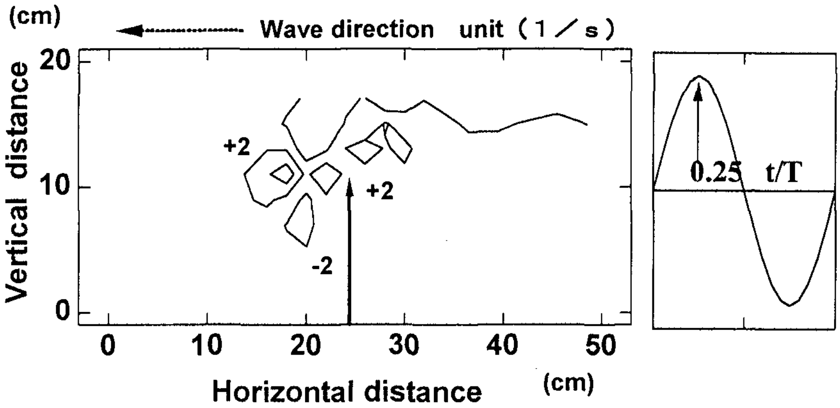

Fig.8 Contour lines of measured vorticity for run 2

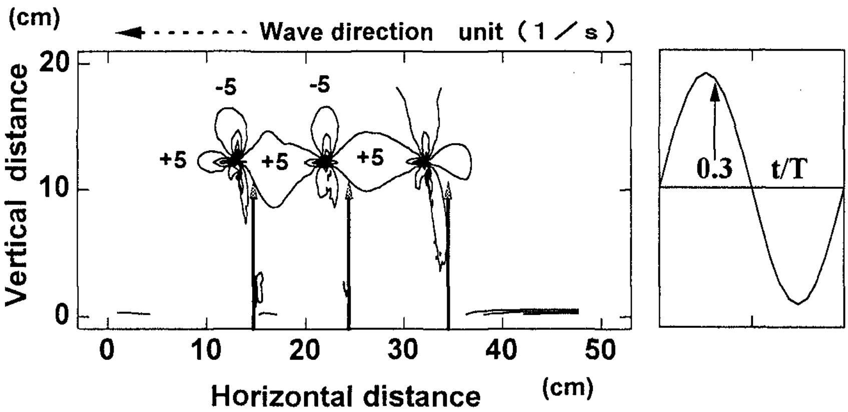

Fig.9 Contour lines of calculated vorticity for run 6

It is thought that the vorticity with positive sign is dominant at this phase; but the seaweed is oscillated at the same frequency of that of water particles toward the same direction, and the vorticity with positive sign are produced late. The similar results are obtained in the present calculation(no figure). The calculated results are shown in figure 9 for run 6. Each vorticity are combined among the seaweed, and they does not grow in size.

5.5 Coefficient of drag force

In the present study the effect of seaweed to the flow mechanism is considered by given the velocity of seaweed motion to calculated mesh. The seaweed field should be considered as the drag force averaged in space in the field, and the estimation on the coefficient of drag force are very important.

Hydrodynamic force F(t) at the each wave phase is calculated by integrated the calculated hydraulic pressure along the seaweed surface, being separated into the drag force and the inertia force as shown eq.(11).

$$F(t) = \frac{1}{2} C_D \rho A u(t)|u(t)| + C_M \rho V \frac{\partial u(t)}{\partial t} \tag{11}$$

in where u(t) is the horizontal velocity just over seaweed close to the free surface, C_D is the coefficient of drag force, C_M is the coefficient of inertia force, A and V are the reference area and volume, respectively. As shown by Ishida(1988), the values of C_D and C_M are assumed to be constant between the adjacent phase and eq.(11) is solved by using the simultaneous equations.

Figure 10 shows the variation of the horizontal velocity and the coefficient of drag force over both the seaweed and the fixed seaweed for run 2. The coefficient of drag force reaches the biggest value at the wave phase when the flow direction changes from onshore to offshore and constant value at other wave phase. Also its value over the seaweed is bigger than that over the fixed seaweed. The drag coefficient C_D is changeable at the each phase, varying from the used value of horizontal velocity. The drag coefficient C_D is generally estimated by the number of the Keulegan-Carpenter number at the wave phase when the wave crest or the wave trough passed over the reference point, when the drag force become maximum.

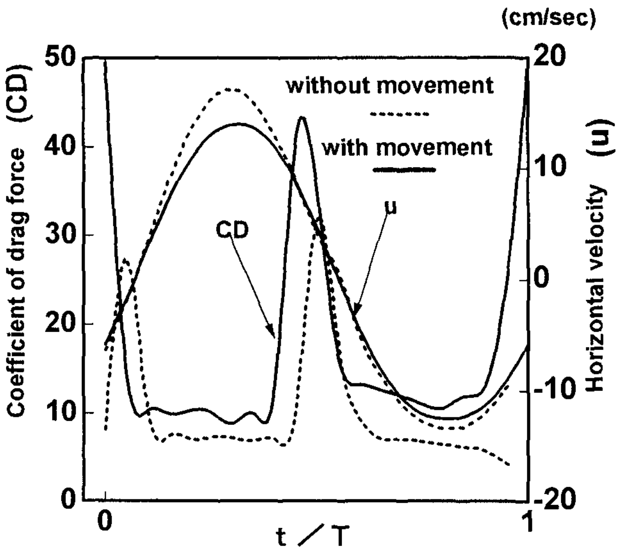

Fig.10 Time history of drag force and horizontal velocity

It is shown through the experiment that the wave phase lag between the seaweed motion and the wave motion is $\pi/2$. The wave phase lag is varied from the wave condition and kinds of seaweed. Figure 11 shows the relationship between the drag coefficient C_D and K.C. number when the wave phase lag between the seaweed motion and the wave motion is changed from 0 to $3\pi/2$. With increasing the value of KC number, the value of KC number attains to about 5. That is similar to Ishida's results, who measured the wave force acting on a pile structure.

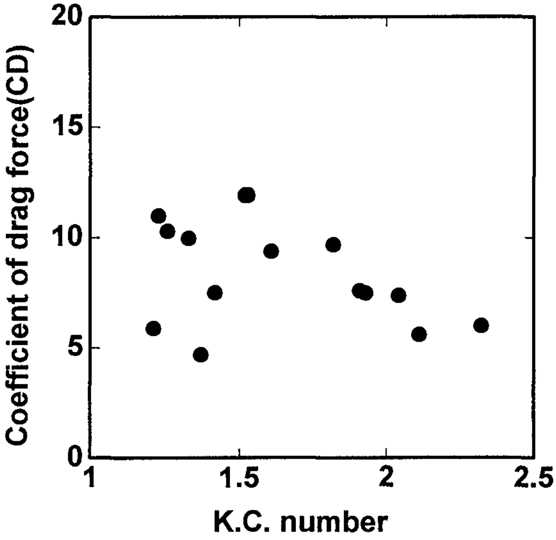

Fig. 11 Drag coefficient and KC number

VI. CONCLUSIONS

The seaweed bed is made of a plastic plate which is oscillated symmetrically with the wave motion and the flow mechanism and suspended sediment concentration over the seaweed bed were investigated by an experimental approach and a numerical simulation. The wavy flow near the top of seaweed and the vertical circulation flow which compared with the scale of water depth are produced by the seaweed motion, respectively. As the separated vortex is formed at the middle of depth, the value of suspended sediment concentration reaches a constant one or increase by the turbulence kinematics energy. That can not be seen under the non-breaking wave.

The turbulent calculation considered the existence of seaweed in the calculated mesh showed as follows:

1) The separated vortex over the seaweed is formed later than that over the fixed seaweed.
2) The value of suspended sediment concentration attains a constant value away from the bed.
3) The settling space between the seaweed and the wave phase lag between wave

motion and seaweed motion have a major effect on the flow mechanism.

4) The value of drag coefficient C_D of seaweed estimated as the drag force is several times lager than that of a plate(2.01).

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Reference

Asano T., S. Tsustui, and T. Sakai(1988):Wave damping characteristics due to seaweed,Proc.35th Coastal Eng. Conference in Japan,pp.138-142(in Japanese).

Ishida, H. and Tamura K.(1988):Coefficient of drag force of a pile structure under separated flow ,Proceeding. of JSCE,No.393,II-9,pp.120-130(in Japanese).

Nilesen P.(1984):Field measurement of time-averaged suspended sediment concentration under waves, Coastal Engineering,Vol.8,pp.51-72 .

Tsujimoto G., N. Hayakawa, M. Ichiyama, Y. Fukushima and Y. Nakamura(1991) :A study on suspended sediment concentration and sediment transport mechanism over rippled sand bed using a turbulence model, Coastal Engineering in Japan,Vol.34,No.2,pp. 177-189.

Tsujimoto G.(1992):Flow and suspended sediment concentration over seaweed field, Proceeding Coastal Eng. of JSCE,Vol.39,pp.276-280(in Japanese).

Tsujimoto G. and H.G.Stefan(1994):Simulation of sediment resuspension transport by wind driven current in a shallow lake, Research Reports of Kobe City College of Technology No.32,pp.65-72.