CHAPTER 111

SEDIMENT TRANSPORT DUE TO BREAKING WAVES

Tomoya Shibayama, A.M. ASCE *
Akihiko Higuchi ** and
Kiyoshi Horikawa, M.ASCE***

ABSTRACT

In the surf zone, the agitation of the bed materials by breaking waves is strong and the suspended sand concentration in the vicinity of the wave plunging point is extremely high. Sand movement in this region was observed and sand concentration was measured in a wave flume. The sand movement in the region was divided into the following two categories: 1) sand suspension due to the large vortex which is created by wave plunging, and 2) sand deposition under turbulent flow. The condition for exciting this suspension process was considered and the result was well explained by the two parameters which are the deep water wave steepness and the bottom slope. Then a numerical model of the sediment suspension process was formulated and the process was well simulated by the model.

1.INTRODUCTION

In recent years, many attempts have been made to formulate cross-shore sand transport and resultant beach transformation. However many of these treatments are based of oscillatory wave motion and the resultant bed shear stress. In order to analyze sand transport within the surf zone more precisely, the dynamics of breaking waves must be understood more clearly. In the surf zone, agitation due to wave breaking lifts the bed material and places it into suspension and the suspended sand concentration in the vicinity of the breaking point is extremely high. Fig. 1 shows the schematic view of the sand movement process in this region. The purpose of the present paper is to describe the nature of sand movement under breaking waves.

The present work was stimulated by the following two studies. Dean (1973) treated the problem of sand suspension at the wave breaking point and gave critical values of two parameters which govern the sand

---

* Associate Professor, Dept. of Civil Engineering, University of Tokyo, Bunkyo-ku Tokyo 113 Japan
** Engineer, Penta-Ocean Construction Co., Ltd.
***Professor, Dept. of Civil Engineering, University of Tokyo

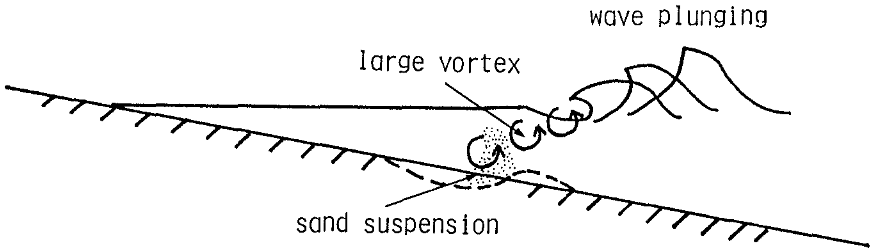

Figure 1: Schematic View for Sand Suspension due to Wave Plunging.

transport direction at the wave breaking point. The two parameters are the wave steepness and the ratio of fall velocity to wave period. Sawaragi and Iwata (1974) investigated the mechanism of wave breaking and reported the nature of plunging waves. They described the physical mechanism of the "horizontal roller" which is the large vortex created by the wave plunging. In the present study, the sand suspension process will be explained in relation to the action of the large vortex.

2. CONDITIONS FOR SEDIMENT SUSPENSION

Wave breaking over a movable bed sometimes results in sand suspension due to agitation caused by the wave plunging. In order to determine the condition when this kind of sand suspension occurs, laboratory experiments were performed for a wide range of flow conditions. In the experiment, two wave flumes, termed A and B, were used. Flume A was 11 m long, 0.2 m wide and 0.3 m deep. Flume B was 25 m long, 0.8 m wide and 1.5 m deep. Sand with median diameter 0.2 mm was used for bed material. In both flumes, sand was placed to form an initial beach profile of uniform slope. The conditions of the experiments performed are summarized in Table 1 together with the conditions of Shibayama and Horikawa (1982).

In order to investigate the water particle movement, polystyrene of diameter 1 mm or 2 mm and specific gravity 1.02 were injected into the water. The motion of sand particles and polystyrene particles in the vicinity of the breaking point was recorded using a 16 mm movie camera. By analyzing the film, the motion of sand particles and the characteristics of the large vortex could be examined.

From the observation, the effect of large vortex itself to sediment suspension, not the small scale turbulence, was found to be the main mechanism to cause the sand suspension at the wave plunging area. Fig. 2 shows the critical values of the bottom slope and deep water wave

Table 1: Experimental Conditions.

Case	Wave Period $T(s)$	Deep Water Wave Height H_0 (cm)	Deep Water Wave Steepness H_0/L_0	Initial Slope i_0
(a) Present Work				
A-1	0.65	5.33	0.081	0.05
A-2	0.73	5.22	0.063	0.05
A-3	0.80	4.81	0.048	0.05
A-4	0.60	5.35	0.095	0.067
A-5	0.61	5.37	0.093	0.067
A-6	0.65	5.33	0.081	0.067
A-7	0.71	5.19	0.066	0.067
A-8	0.82	4.82	0.046	0.067
A-9	0.60	5.35	0.095	0.1
A-10	0.61	5.12	0.088	0.1
B-1	3.00	4.50	0.0032	0.05
(b) Shibayama and Horikawa (1982)				
A-11	1.62	3.0	0.0073	0.05
A-12	1.42	3.4	0.011	0.05
A-13	1.24	3.8	0.016	0.05
A-14	1.00	2.8	0.018	0.05
A-15	1.00	4.4	0.028	0.05
A-16	0.87	4.0	0.034	0.05
A-17	0.78	6.6	0.069	0.05
A-18	0.67	7.6	0.11	0.05
B-2	1.52	8.7	0.024	0.1
B-3	1.51	10.9	0.031	0.1
B-4	1.50	12.5	0.036	0.1
B-5	1.50	15.7	0.045	0.1

steepness for the creation of a large vortex due to wave plunging. The result of Sawaragi and Iwata (1974) are also shown in the figure. The solid line in the figure defines the boundary between the large vortex and no-large vortex region. The dashed line in the figure shows values of the similarity parameter, I_r, (Battjes, 1975) defining the transition between spilling and plunging breakers, given by $I_r = i_0/(H_0/L_0)^{1/2} = 0.5$ (dashed line in the figure) where i_0 is the initial bottom slope and H_0/L_0 is the deep water wave steepness. As seen from the figure, the two boundaries are different. The customary definition of wave breaking type was based on surface profile appearance at the point of breaking. However from the view point of sediment suspension, it is more important whether a breaking wave produces a large vortex or not. The solid line is more important than the dashed line for describing sand movement in the wave breaking area.

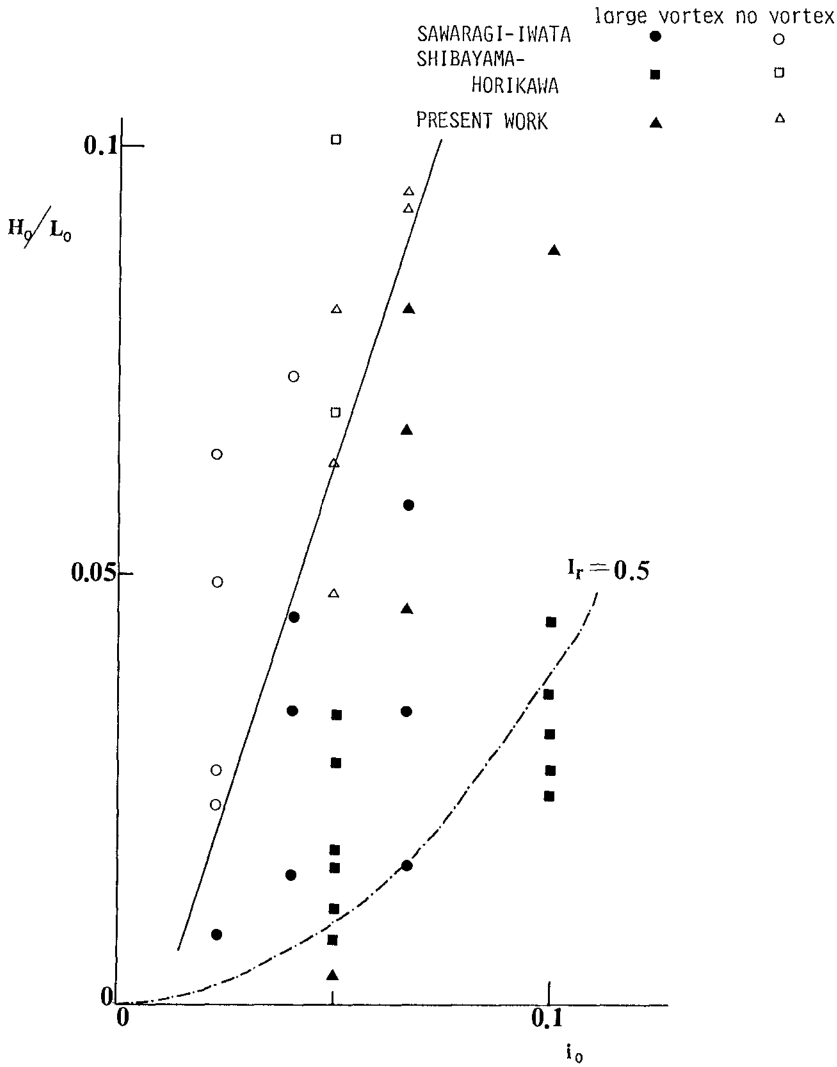

Figure 2: Conditions for Creation of Large Vortex.

From the figure, the necessary wave condition for producing sand suspension due to the mechanism described in the present paper can be determined. This condition is necessary but not sufficient to produce suspended sand. For sand suspension, another condition is required: sand particles must be small, or light enough to be moved or suspended by the velocity field created by the large vortex. However, this condition has not yet been described in a quantitative manner.

3. SAND MOVEMENT AND CONCENTRATION DISTRIBUTION

In experiment B-1, a 35-mm camera utilizing a shutter speed of 1/30 s was used and sand particle pathlines were obtained by tracing the film. The reason why we chose this condition was to minimize the effect of air bubbles. If the wave period is long, air bubbles created by wave plunging go up to the surface in early wave phase, and therefore we can measure sand concentration without the effect of air bubbles thereafter. Figures 3 (a-1) to (a-6) show the experimental results. In this figure, the formation process of the suspended sand cloud can be seen. The arrows indicate the velocity vector of the sand particle movement, the dotted region denotes the cross-sectional area of sand cloud, with one dot representing one sand particles in the photographs.

The sand movement process can be described as follows: (a) Immediately after the wave crest passes the inspection section in the flume, the large vortex created by wave plunging touches bottom. Sand particles on the bottom start into suspension due to the arrival of the vortex (Phase a-1); (b) The suspended sand cloud increases in size and a high concentration area is formed (Phase a-2); (c) Suspended sand particles diverge and some of them are deposited on the bottom (Phase a-3); (d) Suspended sand grains move offshore and some particles are deposited on the bottom (Phases a-4 and a-5); and (e) The next wave crest arrives and a portion of the previously suspended sand particles move onshore (Phase a-6). Figure 3 — (A) shows the time history of water surface elevation measured at Point x (observation point indicated in Fig. 3, a-1). The numbers in Fig. (A) indicate the wave phase at the time of each measurement.

Figure 3(b-1) to (b-6) shows the time series of the sand concentration distribution for the the same experimental run. The sand concentration was measured with a Iowa type concentration meter (Nakato et al., 1977), which optically measures the concentration. The probe consists of a 6 mm diameter emitter and detector, separated by a distance of 10 mm. The concentration was obtained at 71 points in the wave breaking area and the equi-phase-mean value over 15 waves were obtained. The equi-phase-mean value should be used because the suspension process fluctuates somewhat from one wave period to the next. In order to calculate equi-phase-mean value of the concentration, each

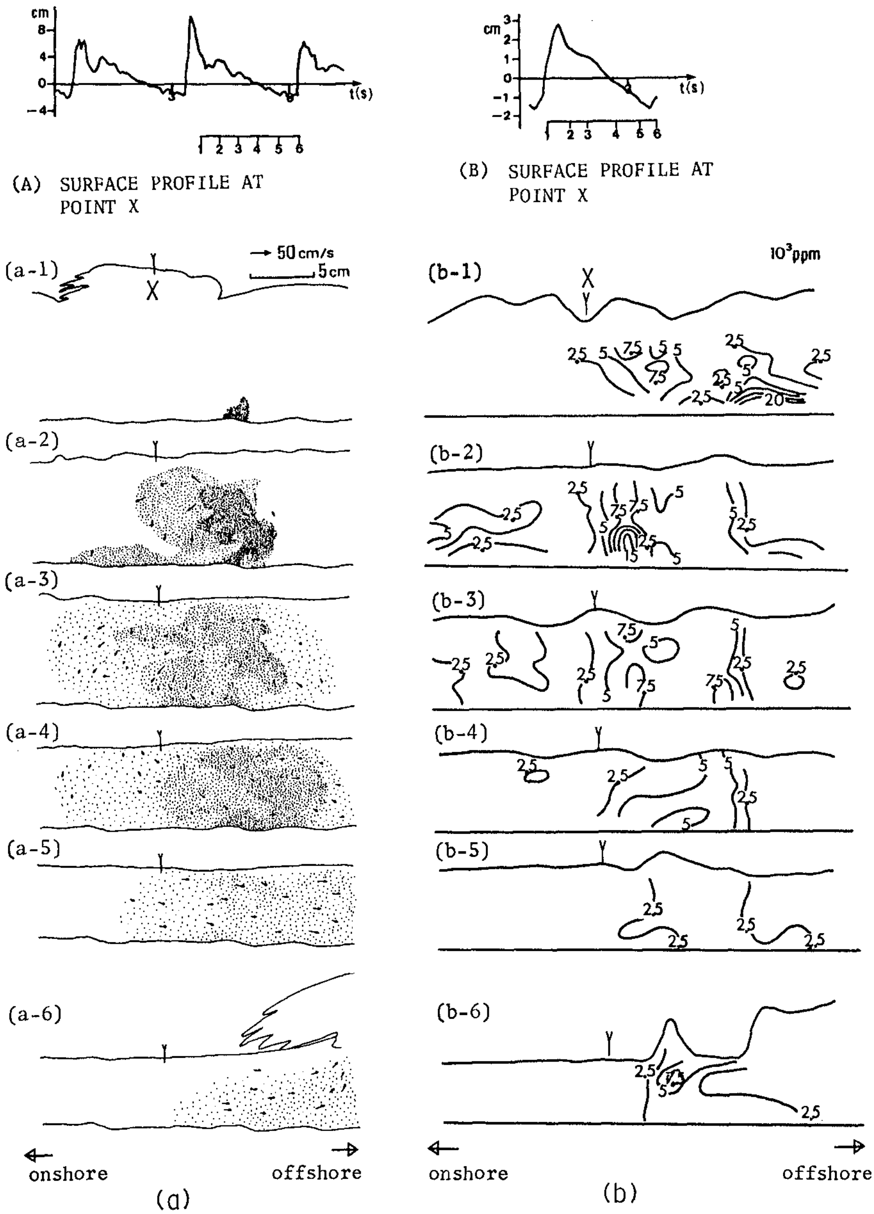

Figure 3: Suspended Sand Movement and Corresponding Sand Concentration.

wave period was divided into 90 intervals. The equi-phase-mean values was obtained by averaging the concentration over 15 waves for each phase. For the wave phase i,

$$\bar{c}(\theta_i) = \frac{1}{N}\sum_{n=1}^{N} c_n\ (\theta_i) \qquad (1)$$

where $\bar{c}$:equi-phase-mean concentration, i:wave phase, $\theta_i=2\pi i/90$, $i=1,\cdots 90$, n:number of the wave, $n=1,\cdots 15$. From this figure, we can see a high concentration area which corresponds to the location of the suspended sand cloud. The equi-phase-mean value of the water surface are also displayed.

It should be mentioned that the laboratory results discussed here are limited to the case of regular waves traveling onto a beach of initial constant slope. Although the experiment was started with a constant sloping beach, a bottom trough formed due to the action of the plunging waves and the water depth at the wave plunging point became greater as time went on. The result was that the agitation of the bottom material due to wave breaking diminished as time went on. For the present experiments, the initial beach profile was set to form a uniformly sloping beach. Each experiment was allowed to proceed until the bottom becomes somewhat deformed, i.e., less than 100 waves for the present case, then the experiment was stopped and the bottom was smoothed to a uniform slope again. Thus the interaction between the profile change and wave transformation is believed to be negligibly small.

The gradient of wave pressure in the horizontal direction (cross-shore distance) in the breaking area might be considered to play a role in sand movement. Madsen (1974) analyzed this effect and concluded that the pressure gradient alone may affect bed stability but is not great enough to remove sand particles from the bed. Therefore, the pressure gradient appears to be only a secondary factor to control the amount of sand set in motion during the sand suspension process.

4. A SIMULATION MODEL

In order to formulate a simulation model of the sand movement, the following two processes should be evaluated. The first one is the sand suspension process due to a large vortex and the second one is the process of sand transport in turbulent motion. We first consider suspension rate due to a large vortex.

(1) A model for sand suspension rate

The total amount of suspended sand in the sand cloud can be calculated for each phase by integrating the concentration for the area of the sand cloud. Figure 4 shows the result indicating sand mass per one centi-meter width for the same experimental run with Figure 3. In the figure, surface profile history is also indicated. From the figure, we can observe that the total amount of suspended sand rapidly increases after passage of the wave crest and subsequently decreases gradually as part of the sand cloud is deposited on the bottom. If we neglect the rate of sand falling to bed in the sand suspension process, we can estimate the rate of sand suspension from the gradient of sand mass curve. Then a pick up rate is modeled as

$$f(t) = A \sin(2\omega t + \varphi) \tag{2}$$

where A is the constant, ω is angular frequency and φ is the phase shift. And we will consider the range $f(t) > 0$ and $0 < \omega t + \varphi/2) < \pi$ only. Here the empirical constant A was determined by the previously described sand mass curve of Figure 4 as the gradient of the curve for the first suspension period.

(2) A model for sand movement and velocity measurement in wave breaking region

Next we will consider suspended sand movement in the turbulent field. Here, sand velocity was modeled as the sum of water particle velocity including turbulence and the sediment particle fall velocity. This assumption was called "zero order solution" by Nielsen (1984) and he discussed the validity of the assumption. Then sand movement was simulated by means of the Monte Carlo method. The motions of sand particles were calculated by integrating the velocity of sand particles.

In order to evaluate sand movement, the information of velocity field is required in the wave breaking area. In general, the velocity can be divided into the following three components (Okayasu et al., 1986), which are (1) steady flow, (2) periodic motion (which include wave motion and large vortex), and (3)turbulence. A laboratory experiment was performed by using a wave flume which was 23 m long, 0.8 m wide and a step type beach profile was used. The profile consisted of a 1/10 slope and a flat bed. The reason why we chose this type of beach topography was to fix the breaking point of each wave. Figure 5 shows the beach profile used and the arrangement of measuring points. The measuring area was from 0.5 cm to 14.5 cm above the bottom and 80 cm long in an on-offshore directed vertical plane. The measuring points were arranged to make 2 cm grids. In total, 328 measuring points were set in the test section.

A hot film velocimeter with a split type probe was used to measure

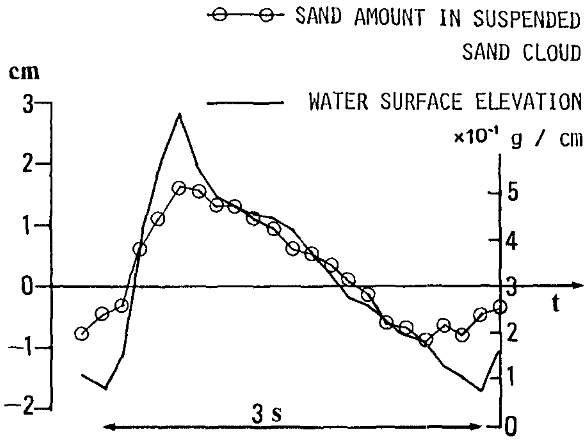

Figure 4: Phase Change of Sand Amount in Suspended Sand Cloud.

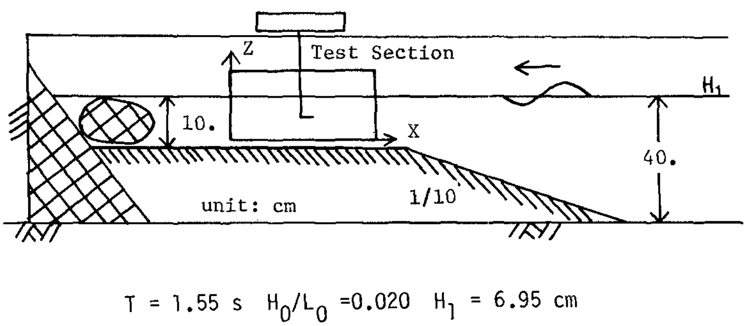

Figure 5: Experimental Set-Up and Condition for Velocity Measurement.

the time history of two-dimensional velocity vector. By using the velocimeter, we can obtain two components of velocity data, which are one component of velocity histories with plus or minus sign and an absolute value of the other component. Therefore we cannot get full information about the signs of two components. In the present case, the sign of the on-offshore component velocity was not determined. It was reversed once in every wave period according to the surface profile. The velocity data were sampled every 10 ms and were converted into digital data. The equi-phase-mean values of velocity over 30 periods were calculated. Each wave period was divided into 150 intervals and the equi-phase-mean value was obtained as an average of the velocity value at the same phase of every wave. The turbulence component was determined as the deviation from the equi-phase-mean value.

Figure 6 shows the resultant measured velocity field, which are steady flow, periodic component and turbulent intensity of vertical velocity component at the phase immediately after the wave plunging. The turbulent intensity of horizontal velocity component was also obtained but not illustrated in the figure. From the figure, we can obviously observe a large scale vortex by velocity vectors. The high turbulent region is in good agreement with the vortex region indicated by velocity vectors.

(3) Simulation results

Figure 7 shows an example of simulation result of sand particle distributions. First, sands were suspended from the initial suspension area which is shown in the figure, according to the time history of pick-up function. The initial suspension area was supposed to locate 4 cm above the bottom for the present case. Sands diverged according to velocity field which include turbulence. Here, the velocity characteristics such as the steady flow, the equi-phase-mean velocity and the turbulent intensities between the grid points were determined by means of linear interpolation between the grid points. Sands formed suspended sand cloud and moved to offshore. Sands which fell down to the level of 2.5 cm above the bottom were considered to fall on the bed and they are not indicated in the figure. Figure 8 shows example of sand particle pathlines. Here also we can identify the location of suspended sand cloud area. The sand particle pathlines exhibit the same tendency to the laboratory phenomena which is the formation and the movement of suspended sand cloud under the function of the organized motion in turbulence.

The present model is elementary one and was done as the first trial. It can be concluded that the present model is promising for the future development. For further improvements, precise modeling of pick up rate and velocity field is required.

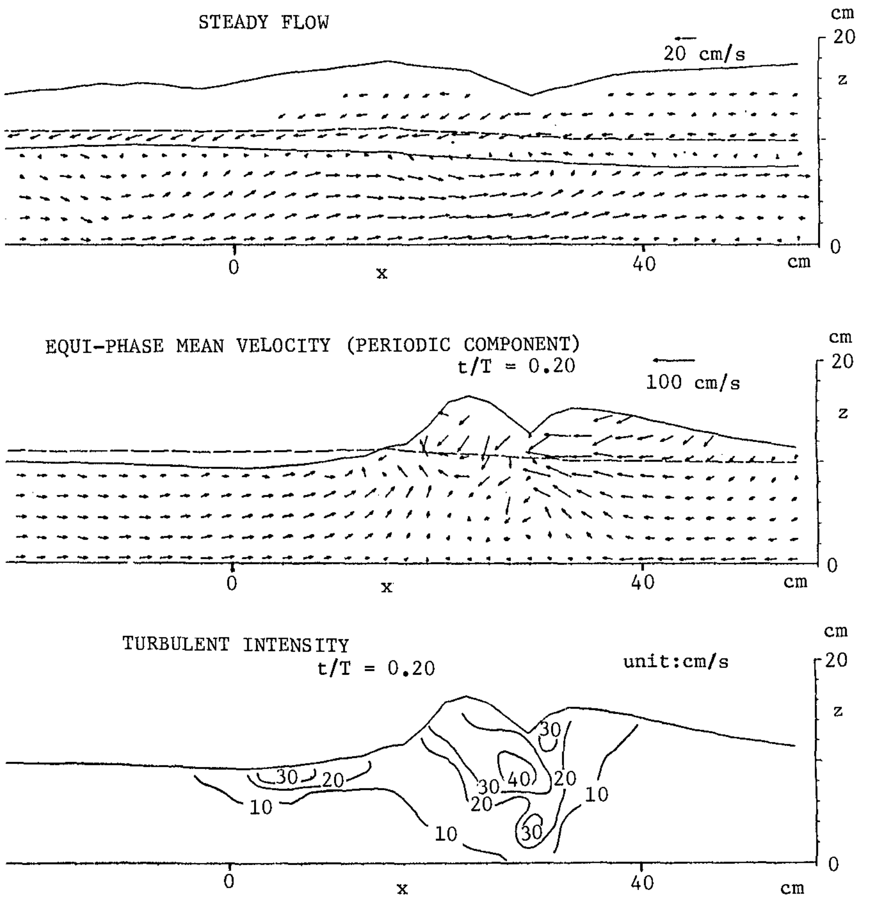

Figure 6: Measured Velocity Field.

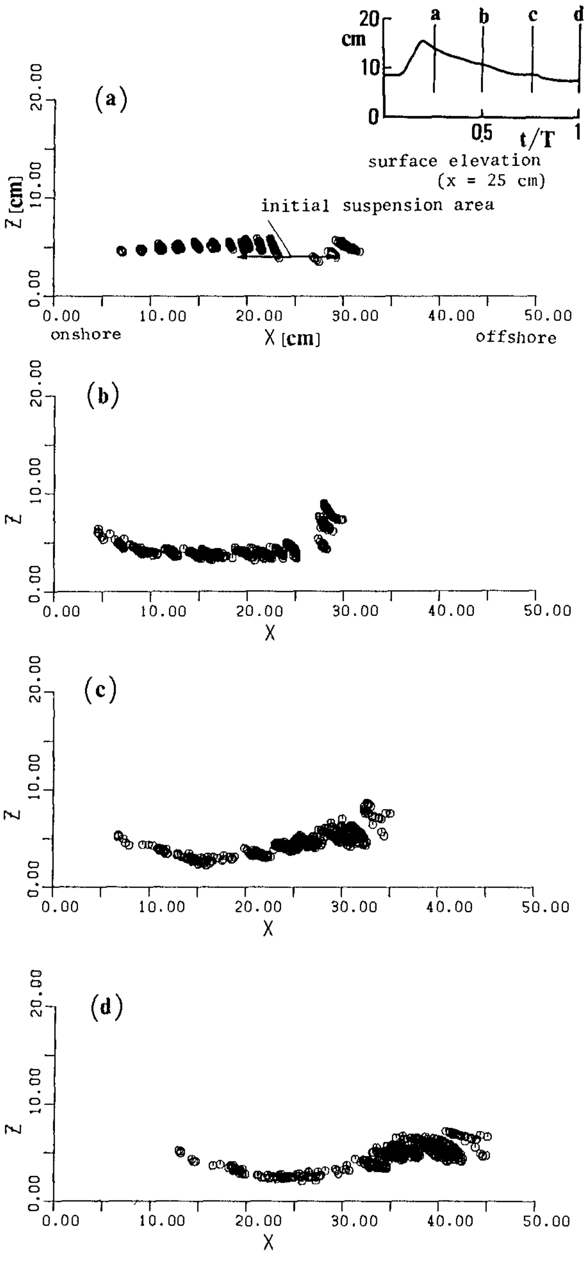

Figure 7: Examples of Sand Particle Distribution.

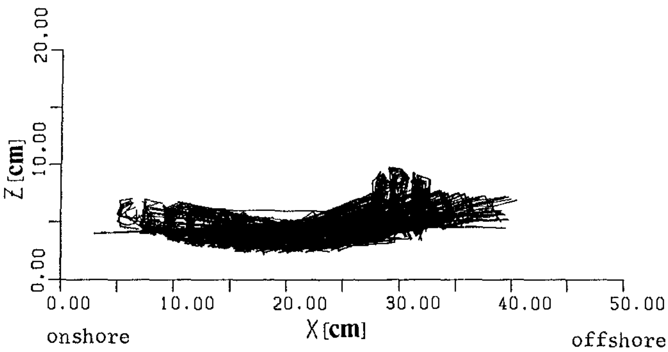

Figure 8: Examples of Sand Particle Pathlines.

The air bubbles have possibility to give an important effect to formation of suspended sand cloud (personal communication with Dr. P. Nielsen). The air bubbles which are created by wave plunging produce upward flow in wave breaking area when they go up to the water surface after the large scale vortex disappears. The upward flow produced by the bubbles transports sand particles upward and therefore diverges sands to upward directions. This effect should be examined more precisely by laboratory experiments as a next step.

5. CONCLUSIONS

The formation of a large vortex induced by plunging waves was found to be one of the necessary conditions for sand suspension caused by breaking waves. The condition for the vortex formation is determined by deep water wave steepness and bottom slope. The movement of suspended sand was divided into two processes; (1) suspension due to the large vortex and (2) sand transport in the turbulent flow. An appropriate modeling of the two processes was performed and simulation results were obtained. The results are not satisfactory but judged to be promising for the further improvement.

ACKNOWLEDGMENTS

The authors thank to Dr. N. Mimura of Ibaraki University, and Mr. A. Okayasu of the University of Tokyo for their co-operations in performing the experiment of Section 4-(2). This study was financially supported by a grant in aid for scientific research, No. 59750405, Ministry of Education, Science and Culture, Japanese Government, which is granted for the first author.

REFERENCES

1. Battjes, J.A., "Surf Similarity," Proc. 14th Coastal Eng. Conf., pp.466-480, 1974.

2. Dean, R.G., "Heuristic Model of Sand Transport in the Surf Zone," Proc. Conf. on Engineering Dynamics in the Surf Zone, pp.208-214, 1973.

3. Madsen, O.S., "Stability of a sand bed under breaking waves," Proc. 14th Coastal Eng. Conf., pp.776-794, 1974.

4. Nakato, T., Locher, F.A., Glover, J.R. and Kennedy, J.F., "Wave Entrainment of Sediment from Rippled Beds," Proc. of ASCE, vol. 103, no. WW1, pp.82-99, 1977.

5. Nielsen, P., "On the Motion of Suspended Sand Particles," J.G.R., vol. 89, no. C1, pp.616-626, 1984.

6. Okayasu, A., Shibayama, T. and Mimura, N., "Velocity Field under Plunging Waves," Proc. 20th Coastal Eng. Conf., 1986.

7. Sawaragi, T. and Iwata, K., "On Wave Deformation after Breaking," Proc. 14th Coastal Eng. Conf., pp.481-499, 1974.

8. Shibayama, T. and Horikawa, K. "Sediment Suspension due to Breaking Waves," Coastal Eng. in Japan, vol. 23, pp. 183-176, 1982.