SEDIMENT TRANSPORT UNDER SHEET FLOW CONDITION

by

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ABSTRACT

A series of laboratory experiments in an oscillatory tank was carried out to investigate the sheet flow of sediment. Objectives of the study were to determine the criterion for inception of sheet flow, and to evaluate the sediment transport rate under the sheet flow condition. In order to proceed with the investigation, it was necessary to develop devices appropriate for tracing the sediment particle movement, and for measuring the extremely dense sediment concentration in the moving layer of sheet flow. The chief results are: 1) the criteria for the inception of sheet flow given by Manohar (1955) and by Komar and Miller (1974) are both applicable to materials composed of spheroidal particles, and 2) the average rate of sediment transport for sheet flow is well described by an empirical relationship given by Madsen and Grant (1976) for the bed load transport rate on a plane bed in oscillatory flow.

INTRODUCTION

The prediction of beach profile change is, at present, one of the most important subjects in the field of coastal engineering. In order to proceed with the prediction of beach evolution, appropriate formulae must be developed for evaluating the sediment transport rate in the surf zone as well as in the offshore zone. The characteristics of waves, currents, and movement of sediment particles in these regions are evidently completely different depending upon the location. For example, Dingler and Inman (1976) presented diagrams of various types of bed configurations appearing in the shallow water region. These are the relict, rippled, transition, and sheet flow regimes. The rippled bed gives way to the sheet flow regime in the surf zone, in particular under storm conditions. Although studies on sediment transport in the sheet flow condition are necessary to understand beach profile change in the surf zone, very few investigations have been reported on this particular phenomenon.

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The authors therefore initiated a series of laboratory investigations using an oscillatory flow tank to isolate the fundamental aspects of sheet flow. In this paper, the main results on the items listed below will be discussed. These are:

1) Criterion for inception of sheet flow,

2) Sediment concentration in the layer moving as sheet flow,

3) Advection speed of sand particles in the moving layer, and

4) Sediment transport rate under the sheet flow condition evaluated on the basis of items 2) and 3).

EXPERIMENT LAYOUT

The experiments were performed in an oscillatory flow tank. There are two reasons for using such an apparatus. First, sheet flow occurs in the surf zone where the environmental conditions are difficult to control, and where the fluid flow is complicated. Secondly, in order to produce sheet flow on a horizontal bed while at the same time avoiding the complication of wave breaking, a very large flume would be necessary. Therefore, it is convenient to use a tank such as ours in which the amplitude (max. 75 cm) and period (1 to 10 s) of the oscillatory flow can be varied over a wide range covering the scale of the prototype.

Figure 1 shows a schematic diagram of the oscillatory flow tank and the various measuring apparatus used. The oscillatory flow is produced by a piston. The flow section is 25 cm wide, 25 cm high and 200 cm long. Sediment materials were placed along the bottom plane of the test section as described in the next paragraph. The period, amplitude, and mean velocity of the oscillatory flow in the test section were evaluated from readings of a wave gage at the vertical riser of the oscillatory tank, as shown in Fig. 1. A motor-driven 35 mm camera was used to record the particle concentration in the upper layer of the flow, and to determine the particle advection speed throughout the flow. An electro-resistance sediment concentration detector was used to measure the concentration in the lower layer of the sheet flow. The instruments and techniques are discussed in detail as they appear below.

Figure 2 shows two types of setups in the test section. A vinyl chloride plate was introduced to reduce end effects. For the heavier materials, the test section was narrowed to obtain a higher flow velocity. Six kinds of bed material were used to study the inception criterion; three consisted of natural sands, and three of plastic particles. The characteristics of the test materials are given in Table 1. For studying the transport rate, only sand (1) in Table 1 was used (Toyo-ura standard sand, median grain size 0.2 mm).

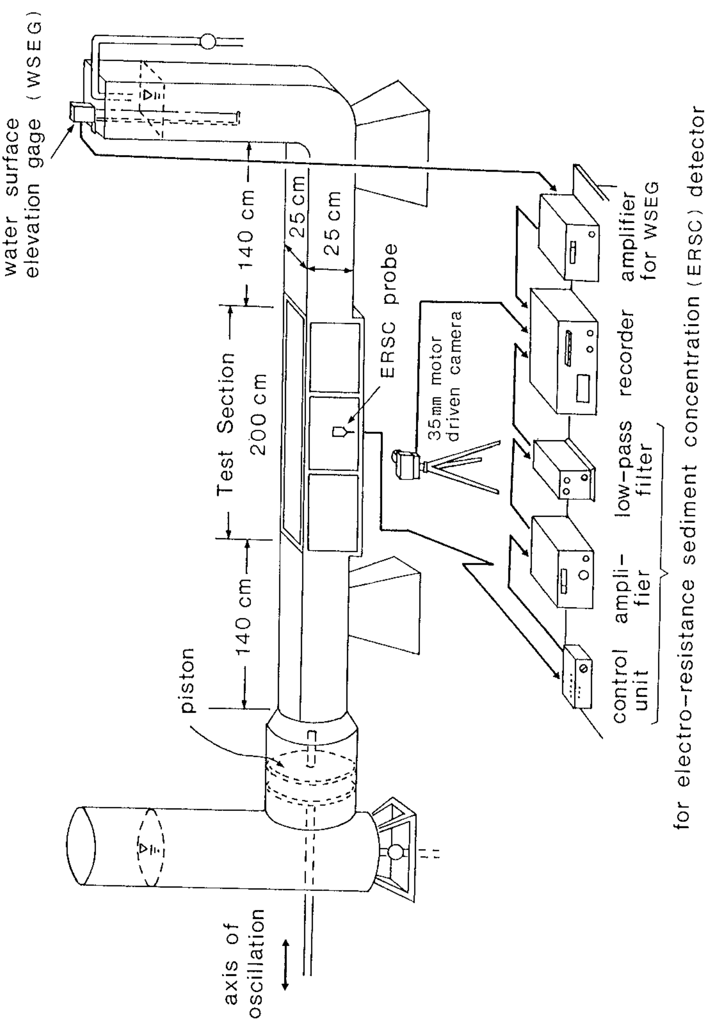

Fig. 1 Oscillatory flow tank and measuring apparatus.

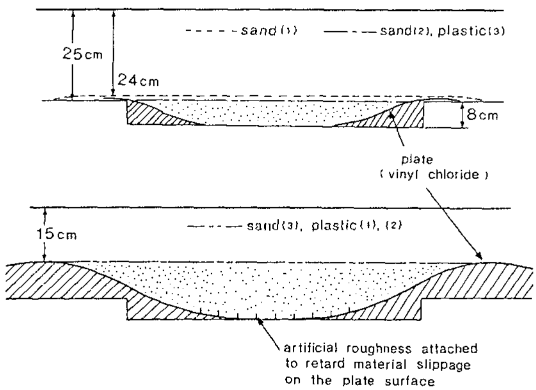

Fig. 2 Setting conditions of material.

TABLE 1 Characteristics of material used.

Material	d (cm)	ρ_s / ρ	α_1 (deg)	α_2 (deg)	w (cm/s)
Sand (1)	0.02	2.66	37.0	24.4	2.6
Sand (2)	0.05	2.66	35.9	26.2	6.5
Sand (3)	0.07	2.66	34.4	27.8	9.8
Plastic (1)*	0.2	1.42	36.9	24.4	11.8
Plastic (2)*	0.4	1.18	36.2	20.8	9.4
Plastic (3)	0.03	1.56	22.4	13.9	1.8

d : grain diameter, ρ_s / ρ : specific gravity
α_1 : angle of repose underwater (bed tilted from horizontal)
α_2 : angle of repose underwater (settlng naturally)
w : fall velocity

* cylindrically shaped

CRITERION FOR INCEPTION OF SHEET FLOW

A series of runs was carried out under various flow conditions to determine the inception of sheet flow. The inception criterion was visually defined as the initiation of the plane-bed mode by two procedures. The first was to increase stepwise the amplitude of the flow velocity by reducing the period of oscillation while holding the horizontal amplitude of the piston constant. In this process, the generation, development, and disappearance of bed ripples were visually observed. The second procedure was to decrease the amplitude of the flow velocity from the already existing condition of sheet flow. During the latter process, the regeneration of bed ripples was observed. Figure 3 shows sample results. The horizontal and vertical axes in this diagram are the near-bottom orbital amplitude, and the period of oscillatory flow, respectively. It is seen that the two procedures give essentially the same inception criteria, and that, therefore, sheet flow can be detected fairly precisely.

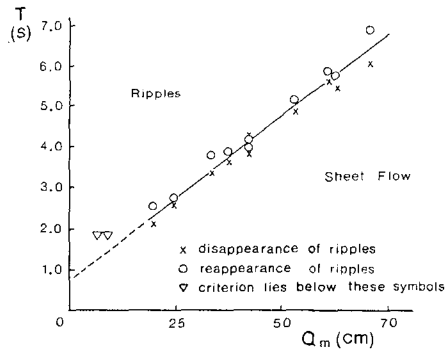

Fig. 3 Experimental results for criterion of sheet flow (sand (1)).

As far as the authors can determine, three criteria for the inception of sheet flow have been reported (Manohar, 1955; Komar and Miller 1974; Dingler and Inman, 1976). These are summarized in Table 2, for which the expression given for Manohar's criterion was derived by the authors on the basis of the original form. In Table 2, $\hat{U}$ is the maximum orbital velocity, $s = (\rho_s - \rho)/\rho$, ρ_s and ρ are the densities of the sand and fluid respectively, d is the grain diameter, is the kinematic viscosity of the fluid, g is the gravitational acceleration, and f_w is the wave friction coefficient of Jonsson (1966).

TABLE 2 Criteria for inception of sheet flow.

Manohar (1955)

$$\Theta \equiv \frac{\hat{U}^2}{sdg} = \frac{2\times 10^3}{\sqrt{\hat{U}d/\nu}}$$

Komar · Miller (1974)

$$\Psi \equiv \frac{f_w \hat{U}^2}{2sdg} = \frac{4 \cdot 4}{(\hat{U}d/\nu)^{1/3}}$$

Dingler · Inman (1976)

$$\Theta = 240$$

Figure 4 gives a comparison of the criteria of Manohar (1955) and of Dingler and Inman (1976) with the present data and with Manohar's data obtained using an oscillatory plate. The vertical and horizontal axes are the non-dimensional parameters, Θ , and the Reynolds number based on the grain size, Re, respectively. From this figure it is seen that Dingler and Inman's criterion is likely to give a rough estimate of the criterion for inception of sheet flow. Manohar's criterion is seen to describe the data well except for those data pertaining to the cylindrically-shaped plastic particles (open triangles at upper right of Fig. 4; plastic (1) and (2), Table 1).

Figure 5 gives a comparison of Komar and Millers' (1974) criterion with the laboratory data, where the vertical and horizontal axes are, respectively, the Shields parameter Ψ and the Reynolds number based on the grain size, Re. In this diagram, Manohar's (1955) data were plotted together with the present data for reference. In general, Komar and Miller's criterion is seen to fairly well describe the trend of the experimental results. The data for sand (1) indicates a tendency for the inception criteria to level off at the lower Reynolds numbers, which is not reproduced by the expression of Komar and Miller. Although it appears from the present experimental results that the criterion of Manohar (1955) is somewhat superior to that of Komar and Miller, we must reserve judgement until more data are available.

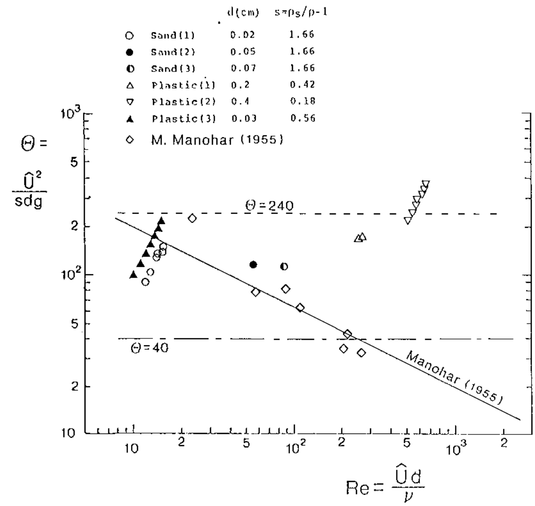

Fig. 4 Criterion for inception of sheet flow (Θ ~ Re).

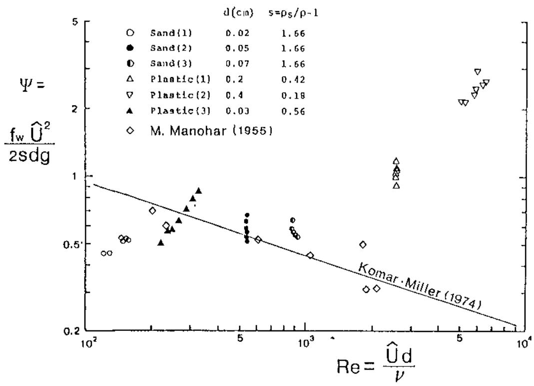

Fig. 5 Criterion for inception of sheet flow (Ψ ~ Re).

The main reason for the apparently anomalous results with the cylindrical plastic particles is that these particles did not move as easily as the other (spheroidal) particles. It can be concluded that the criterion for the inception of sheet flow is closely related to the shape of the sediment particles. More data are needed to determine an appropriate criterion for inception of sheet flow for odd-shaped particles.

SEDIMENT CONCENTRATION IN SHEET FLOW

Sediment Concentration Measuring Techniques

In order to measure the concentration of suspended sediment produced by wave action, photoelectric concentration meters are usually employed. However, this type of meter can not be applied to measure the sediment concentration in the sheet flow moving layer, because 1) the sediment concentration is too high to be measured by conventional apparatus, and 2) the meter itself disturbs the flow. Therefore, measurements were made employing a photographic technique and a newly developed electro-resistance type sediment concentration meter.

A photographic technique was used to measure the suspended sediment concentration in the upper layer. As shown in Fig. 6, a copper plate (0.1 mm thick, 1 cm wide and 20 cm long; painted black) was placed vertically and parallel to the flow direction, at a distance of 1 cm from the inside of the glass wall of the oscillatory tank. Successive pictures of sand particle movement during oscillatory flow were taken at certain intervals for 15 to 20 frames over the flow period using a motor-driven camera and a stroboscopic lamp. The sand particles passing through the 1 cm-wide section between the copper plate and glass wall were counted on the pictures.

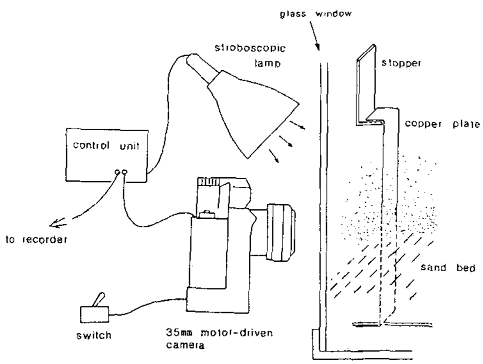

Fig. 6 Experimental arrangement for measuring grain movement in upper layer.

In the vicinity of, or inside the moving layer of sheet flow, the sediment concentration is extremely high and therefore a special measuring device was developed for the present investigations. The measurement principle is based on the fact that the electrical resistance of a water/sand mixture is a function of the concentration of sediment particles. A schematic of the measurement device is given in Fig. 7. In order to calibrate the instrument, a cylindrical tank (diagrammatically shown in Fig. 8) was used. This calibration tank is suitable for generating a uniform and constant suspended sediment concentration. The concentration can be varied over a wide range.

A typical calibration curve of the instrument is given in Fig. 9, where the horizontal axis C' is the relative volumetric concentration defined as C' = 0 for water only, and C' = 1.0 for sediment settled in still water. The vertical axis is the ratio between the output voltage V for a certain value of C', and the voltage V_0 for C' = 1. The linearity of the calibration curve is adequate to measure the sediment concentration over a wide range of concentration. Another advantage of the device is the small size of the sensor, which minimizes disturbance of the flow field.

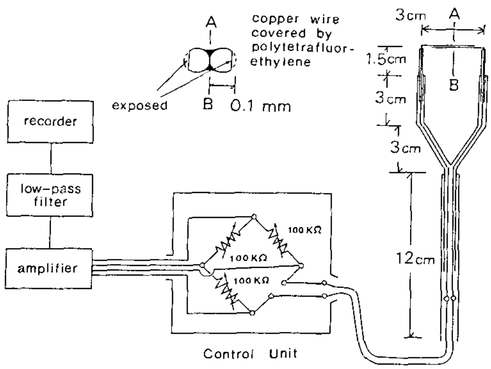

Fig. 7 Electro-resistance type sediment concentration meter.

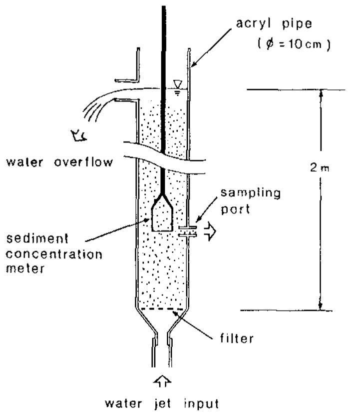

Fig. 8 Calibration apparatus for sediment concentration meter.

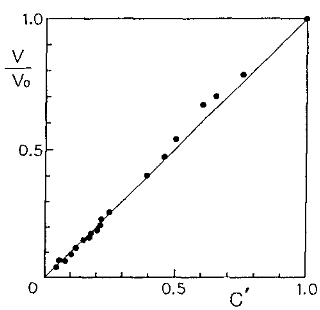

Fig. 9 Calibration curve for electro-resistance type sediment concentration meter.

Measured Concentration

Table 3 indicates the eight oscillatory flow conditions tested which produced the sheet flow regime in the bed material. The data obtained using the photographic technique will first be presented. This concerns the sediment concentration in the upper layer. Figures 10(a) and 10(b) exhibit some vertical distributions of sediment concentration under constant orbital amplitude and constant velocity amplitude, respectively. The vertical axis, y, is the elevation above the surface of the initial bed. The horizontal axis, $\bar{C}_N$, is the number of sand particles contained in a rectangular body of water with a horizontal cross section of 1cm by 1cm and a vertical length of 1 mm, averaged over one oscillatory cycle. Here the value $\bar{C}_N$ = 1.0 corresponds to a mass concentration of 167 mg/liter.

From Fig. 10(a), it is seen that the suspended sediment concentration increases with increase in the velocity amplitude (that is, an increase of bottom shear stress) under the condition of constant orbital amplitude. Figure 10(b) indicates that the elevation which the sediment particle reaches above the bed decreases with a decrease in the oscillation period under the condition of constant velocity amplitude. This result is believed due to the fact that for shorter periods, the flow reverses direction before turbulence is fully generated along the bottom. The vertical distribution of the concentration of the sediment located higher than 7 mm above the bed is expressed well by an exponential function of distance from the bed.

TABLE 3 Experimental conditions.

Case	Half-excursion length, a_m (cm)	Period, T (s)	Maximum orbital velocity, $\hat{U}$ (cm/s)
1-1	72	3.6	127
1-2		4.2	108
1-3		4.8	95
1-4		5.4	87
1-5		6.0	76
2-2	58	3.4	108
3-2	44	2.6	
4-2	34	2.0	

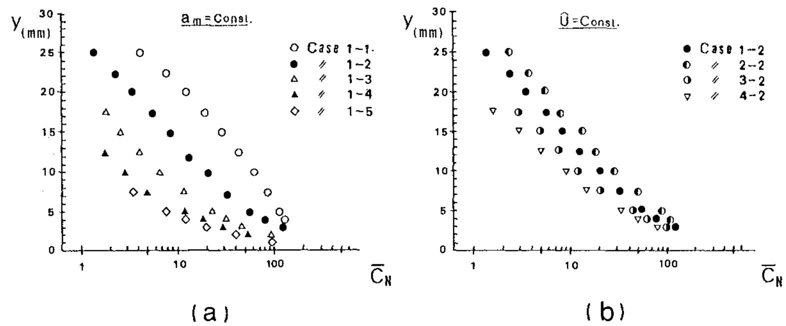

Fig. 10 Distribution of average concentration in upper layer.

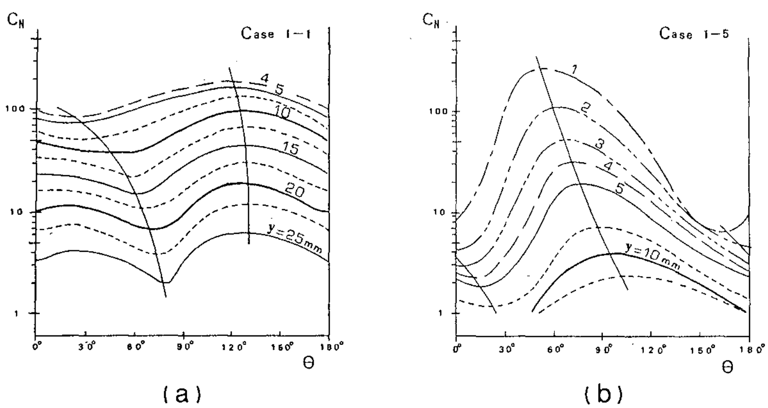

Fig. 11 Variation of concentration with phase angle.

Time variations of sediment concentration at selected elevations for two particular cases are shown in Figs. 11(a) and (b). Here the vertical axis, C_N, is the number of sediment particles in a certain volume of water, and the horizontal axis, θ, is the phase of oscillatory flow. The phase $\theta = 0^{o}$ corresponds to the time when the velocity changes direction, and $\theta = 90^{o}$ corresponds to the time when the velocity reaches a maximum. Figure 11(a) is a typical result, while Fig. 11(b) is atypical. The trends of the phases of maximum and minimum concentration are indicated by solid lines. On the basis of the data of all eight cases shown in Table 3, it can be concluded that the phase of the sediment concentration in the vicinity of the bed is almost equal to that of the oscillatory flow velocity, although the phase of concentration tends to move ahead as the flow period increases. The phase difference between the sediment concentration and the oscillatory flow velocity increases with increase in elevation.

Now, the sediment concentration in the moving layer of sheet flow will be considered. Figure 12(a) shows the vertical distributions of sediment concentration at various phases for Case 1-1, measured by the electro-resistance concentration meter. According to these plots, the sediment concentration changes considerably in the layer spanning 3 to 5 mm above and below the location of the initial bed surface. The minimum sediment concentration above the initial bed surface occurs a little after the phase of $\theta = 0^{o}$ (minimum flow velocity); the maximum concentration occurs at approximately $\theta = 90^{o}$ (maximum velocity).

The curves of sediment concentration at the phases of 90^{o} and 120^{o} have an inflection point in the layer just below the initial bed level. This phenomenon is presumably caused by strong vortices appearing near the bed. It can be observed from Fig. 12(a) that sand particles lifted up at the phase of high velocity fell to the bottom during the stages of velocity deceleration.

ADVECTION SPEED OF SAND PARTICLES

The advection speed of the sand particles was measured under the same conditions as those of the sediment concentration measurements. A number of pictures were taken at certain constant intervals with various shutter speeds by using a motor-driven 35mm camera. The advection speed of the moving particles was determined by tracing individual particles on successive frames.

In the upper layer, the camera was focused on interior particles to eliminate the influence of the glass wall. In the lower layer, because of the extremely high concentration, the advection velocity could not be obtained by direct observation of individual particles.

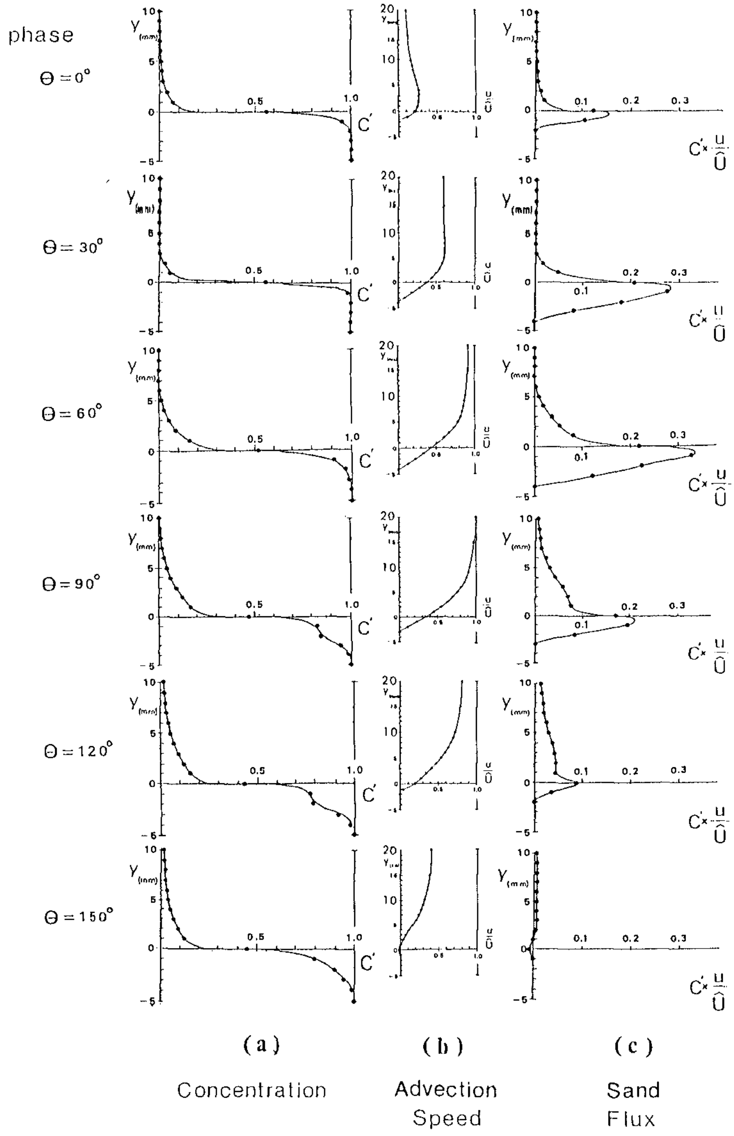

Fig. 12 Vertical distribution of concentration, advection speed, and sand flux.

Therefore, an extrapolation procedure was used as follows: 1) Amplitudes of motion down to an elevation of 2 mm from the initial bed were obtained by means of the normal camera technique. The depth at which the amplitude became zero was determined by measuring the position of the electro-resistance probe at maximum concentration (no sand dilation) for given flow conditions. The vertical distribution of amplitude in the lower layer not amenable to direct measurement was then estimated by curve fitting. 2) The phase of the motion during the time which the sand was assumed to move was determined by using the same photographic technique as described above, but using more readily visible plastic particles. 3) The advection velocity in the lower layer was then calculated using the amplitudes and phases derived by the above separate procedures.

Figure 12(b) shows curves of the vertical distribution of advection speed u normalized by the amplitude of the main flow velocity $\hat{U}$, at various phases in a half cycle of the oscillatory flow. It is seen that the vertical distributions of advection speed of sediment particles are quite similar to those of water particle velocity inside the oscillatory boundary layer flow: the sand advection speed in the upper layer ($y \gtrsim 20$ mm) is almost always equal to the main flow velocity, whereas it decreases in amplitude and advances in phase with decrease in elevation. The gain in phase approaches about 45^o at the lowest elevation of the moving layer, corresponding to that of the laminar boundary layer flow velocity. However, the advection speed in the lower layer does not vary sinusoidally in time, but changes intermittently, having significant magnitude only over a limited time duration at certain phases of the oscillatory cycle. This is due to the intense frictional forces between sediment particles.

SEDIMENT TRANSPORT RATE

The flux of sediment concentration is defined as the product of the concentration C' and the advection speed u at each elevation and each phase. Figure 12(c) gives the vertical distributions of the concentration flux (divided by the amplitude of main flow velocity, $\hat{U}$) thus obtained at the various phases for the present case. It is realized from this figure that the moving layer in the vicinity of the initial bed surface with a thickness of the order of 10 mm contributes significantly to the sediment transport rate.

The instantaneous sediment transport rate through a vertical cross-section was evaluated from the verical integration of concentration flux at each phase. Taking the average of the instantaneous transport rate over a half cycle of oscillatory flow yields the mean transport rate for each experimental case. In this way, a total of six data points for the mean sediment transport rate under the sheet flow condition were obtained.

Madsen and Grant (1976) treated bed load movement induced by oscillatory flow and proposed a formulae to relate the nondimensional transport rate Φ to the Shields parameter Ψ , based on a Brown-type formulae of bed load transport rate in a uni-directional flow. The relation is given by

$$\Phi = \frac{\bar{q}_s}{wd} = 12.5\ \Psi^3 \tag{1}$$

where $\bar{q}_s$ is the sediment transport rate averaged over a half wave cycle, w is the fall velocity of the sediment particles, and d is the grain size. The definition of the Shields parameter Ψ is given in Table 2. This relation was found to agree well the experimental data of Kalkanis (1964) and Abou-Seida (1965), obtained using an oscillatory plate moving horizontally in a sinusoidal manner in a still water basin.

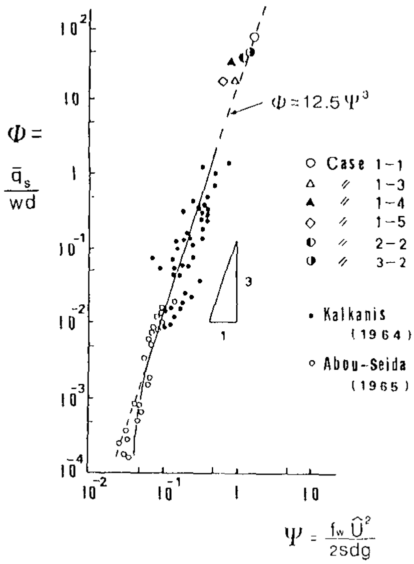

Fig. 13 Relation between non-dimensional transport rate and Shields parameter.

In Fig. 13, the present results, obtained under the sheet flow conditions, are plotted on a figure given by Madsen and Grant (1976). It is seen that the formula proposed by Madsen and Grant fits the present data quite well. However, since the amount of data obtained under the condition of high Shields parameter is scarce, further effort is needed to accumulate more data on the sediment transport rate of sheet flow.

It should be emphasized that the beach configuration is transformed due to the net rate of sediment transport, i.e., the difference between onshore and offshore transport rates. It is clear from Fig. 12 that the magnitudes of the instantaneous sediment flux are significantly different even for the same main flow velocity, depending on whether the flow is at the stage of acceleration or deceleration (compare $\theta = 30^\circ$ and 150°, or $\theta = 60^\circ$ and 120°). This implies that a more detailed examination of the sediment movement is required in order to establish a transport formula which can estimate the instantaneous or net rate of sediment transport under the asymmetrical variation of flow velocity such as occurs in the surf zone.

CONCLUSIONS

In order to elucidate the fundamental aspects of the sediment transport phenomena under the sheet flow condition, a series of laboratory experiments was performed in an oscillatory flow tank utilizing specially developed measuring devices and techniques. In particular, the electro-resistance type concentration detector was found capable of measuring exceptionally high concentrations which can not be measured by conventional photoelectric concentration meters.

From the experimental results, the following conclusions were obtained:

1) The criteria for the inception of sheet flow given by Manohar (1955), and by Komar and Miller (1974) agree favorably with the laboratory data (for spheroidal particles) in general. However, the shape of the sediment particles seems to exert significant influence on the criterion, as expected.

2) In the range of experimental conditions reported, the thickness of the moving layer of the sheet flow is of the order of 10 mm.

3) The data for the mean rates of sediment transport under the sheet flow condition agree with a bed load relation given by Madsen and Grant (1976). The upper limit of validity of this expression was thus extended.

4) Since the instantaneous transport rate differs between accelerating and decelerating phases of motion, further study is necessary to establish a formula for the net transport rate.

ACKNOWLEDGEMENTS

The authors appreciate the assistance of Dr. N. C. Kraus of the Nearshore Environment Research Center in the preparation of the manuscript. This work was partially supported by a grant in aid for scientific research by the Ministry of Education, Science and Culture, the Japanese Government.

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