CHAPTER 109

LABORATORY STUDY ON SAND TRANSPORT OVER RIPPLES DUE TO ASYMMETRIC OSCILLATORY FLOWS

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ABSTRACT

Mechanism of sand movement due to asymmetric oscillatory flows was investigated through experiments. Measurements of bed forms, suspended sand concentration and net sand transport rate were carried out by using an oscillatory flow tunnel. The process of entrainment and suspension of sand above asymmetric ripples was quantitatively described. The geometry of ripples and the net sand transport rate in regular and irregular flows were expressed in terms of hydraulic parameters characterizing the oscillatory flow. Two-dimensionality of ripples was found to be an important factor in the estimation of the net sand transport rate.

1. INTRODUCTION

In order to predict sediment transport and wave attenuation over a sand bottom, it is of great importance to understand the geometry of bed forms and the mechanism of sand suspension. Sand ripples are frequently observed to be asymmetric in shallow water region where velocity histories near bottom become asymmetric owing to the nonlinearity of surface waves and superimposed currents. The asymmetry of flows and ripples is considered to exert crucial influences on the direction and the net rate of sand transport in the on-offshore direction. Although several models have been proposed for the sand transport rate over ripples on the basis of experimental results [e.g. Sunamura(1980)], the validity of these models is not fully verified owing to the lack of reliable data of the sand transport rate.

The present study attempts to investigate the sand movement over ripples due to asymmetric oscillatory flows. A series of experiments are conducted under the conditions of regular and irregular asymmetric oscillations by using an oscillatory flow tunnel. Detailed measurements of bed forms are carried out for each run of the experiments to elucidate characteristics of the sand ripple geometry and the net sand transport rate. The influences of the asymmetry and the irregularity of velocity histories on the shape of ripples as well as the resultant net sand transport rate are discussed for a wide range of conditions. The process of sand suspension under asymmetric oscillations is also described through the measurements of the suspended sand concentration.

2. EXPERIMENTAL PROCEDURES

2.1. FACILITIES AND CONDITIONS OF EXPERIMENTS

Experiments were performed in an oscillatory flow tunnel which consisted of a loop of closed conduits and a hydraulically-driven piston whose motion was arbitrarily controlled by input voltage signals. A section of the tunnel was covered with glass side walls and removable acrylic ceilings. The beds in this section were composed of wooden plates as

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Fig. 1 Experimental set-up.

illustrated in Fig. 1. The central region of the beds was lowered with mild slopes at both ends, in which well-sorted sand with median diameter 0.18 mm was filled to make initially flat test bed. Sand traps were installed at both ends in order to trap the sand that would otherwise move out of the test section.

Experiments were carried out for regular and irregular oscillations. The input signals were simulated by using a digital computer, in which time histories of the displacement of water particles under waves were calculated on the basis of linear and nonlinear wave theories. Velocity histories of regular oscillations were simulated on the basis of the fifth-order Stokes or the third-order cnoidal wave theory. Six signals involving various degrees of nonlinearity were created, in which three signals were simulated by using the Stokes wave theory and the other three signals were simulated by the cnoidal wave theory. Figure 2 shows a typical velocity history calculated by the cnoidal wave theory, in which u_c is the maximum onshore velocity, \hat{u} is the total amplitude of the velocity variation and ω is the angular frequency of the oscillation.

It is also of importance to understand the sand movement under irregular oscillations. However, it is not easy to calculate the velocity variations due to nonlinear irregular waves. In order to incorporate the effect of the nonlinearity in a simple manner, wave-by-wave approach was attempted in the present study. Since each wave crest propagates like an independent wave in the very shallow water region, velocity variations can approximately be calculated by applying the regular wave theory to each wave. On assuming the Bretschneider-Mitsuyasu spectrum, variations of the surface elevation were numerically simulated. Each wave was defined by means of zero-up-crossing method and a series of couples of wave heights and periods were obtained. Velocity histories of each wave were then calculated by using the Stokes or the cnoidal wave theory on the assumption that each wave was an independent regular wave. Velocities of each wave were connected at zero-upcrossing points to produce a continuous velocity history as shown in Fig. 3.



Fig. 2 Velocity history of regular asymmetric oscillations.



Experimental conditions are listed in Table 1, in which T is the mean period of the oscillatory flows and d_0 is the mean total displacement of the oscillations. The total number of experimental cases is 50 cases for regular oscillations and 25 cases for irregular oscillations.

2.2. NET SAND TRANSPORT RATE

Measurements of bed forms and the net sand transport rate are of practical importance in connection with the calculation of beach profile change. In order to estimate the net sand transport rate over large-scale steady-state ripples in a high accuracy, the following procedures were developed in the present study by combining sand traps and detailed measurements of the bed topography.

- (1) Initially flat test bed is exposed to the action of oscillatory flows until steady-state bed forms develop.
- (2) Bottom profiles of the test bed are measured in detail and sand transported out of the test bed is removed.
- (3) The action of the oscillatory flow is continued for an additional duration Δt .
- (4) Bottom profiles are measured again and the sand transported out of the test bed is collected, which is dried for 24 hours in a drying kiln.

The difference of sand surface level $\Delta h(x,y)$ (positive accretion) and the dry mass of sand collected at onshore and offshore ends, m_{on} and m_{off} , are evaluated through the procedures described in the above. Mass conservation of sand leads to

$$(1-\lambda_{\nu})\int_{0}^{B}\int_{0}^{L}\Delta h dx dy + (m_{on} + m_{off})/\rho_{s} = 0$$
⁽¹⁾

where (x,y) indicate the coordinates as in Fig. 1, B and L are the width and the length of the test bed respectively, $\lambda_{\nu}(=0.4)$ is the porosity of the sand and ρ_s (=2.64g/cm³) is the density of sand. The net sand transport rate q_x at x (positive onshore) is evaluated by

$$q_x(x) = \left(\int_0^x \int_0^x (1-\lambda_v) \Delta h dx dy + m_{on}/\rho_s\right) / (B\Delta t)$$
⁽²⁾

Table 1 Experimental conditions.

	u _c /û	T(s)	d _o (cm)	
RL	0.5	1 - 7	5 - 65	sinusoidal oscillations
S1	0.555	3 - 5	17 - 51	simulated by the Stokes wave theory
S 2	0.570			
S 3	0.626			
C1	0.639			simulated by the cnoidal wave theory
C2	0.722			
C3	0.831			

Regular oscillations

Irregular oscillations

	u _c /û	T(s)	d _o (cm)	
IL	0.5	3.90	16 - 51	symmetric oscillations
11	0.52			
12	0.60	3.68	27 - 51	asymmetric oscillations
I3	0.68			

The net sand transport rate free from the disturbances created at the both ends of the test bed was estimated by means of these procedures. In order to make accurate evaluation of sand volume change, bottom profiles were measured in detail along ten measuring lines with a bottom profiler installed on a self-moving carriage. It was found that the ratio of the residue of Eq. (1) to the evaluated net sand transport rate was about 10 % even for a case in which three-dimensional ripples were developed. The error of the evaluation of the net sand transport rate in the present experiments was therefore considered to be less than 10 %, which was excellent compared with other methods attempted in the previous studies.

2.3. CONCENTRATION OF SUSPENDED SAND

In order to understand the process of sand suspension, the concentration of suspended sand was measured for a case in which typical two-dimensional ripples were developed. The measurements were carried out under asymmetric oscillation of signal C2 with the period and the total displacement of the oscillation being $3 \ s$ and $24.1 \ cm$ respectively. Variations of sand concentration were measured at about 100 points above an asymmetric ripple with a light-absorption-type probe whose diameter was $0.3 \ cm$ at the end of the sensor. Measuring points were arranged in a grid whose spacings were $1 \ cm$ in x direction and $0.5 \ to 2 \ cm$ in z direction. The measuring points closest to the bed were set at $0.5 \ cm$ above the bed, which was found critical in order not to cause the local scour. Variations of the concentration and the displacement of the piston were simultaneously recorded for $40 \ s$ and were then converted to digital values with an interval of $0.04 \ s$.

3. THE GEOMETRY OF RIPPLES

Sand ripples developed in asymmetric oscillatory flows are generally asymmetric as illustrated in Fig. 4; the flank of a ripple facing onshore being steeper than the other. Since the formation of sand ripples plays an essential role in the sand transport, it is firstly of significance to understand characteristics of sand ripples.

Small scale ripples were developed at the beginning of the ripple formation from initially flat bed. It required 5 to 40 minutes under regular oscillations and 15 to 90 minutes under irregular oscillations until steady-state ripples were developed. The irregularity of waves thus tended to delay the formation of steady-state ripples. This is because the action of each wave is not always effective for the formation of the resultant ripple geometry since the size and the intensity of lee vortices were not uniform under irregular waves.

Two-dimensional ripples as shown in Fig. 4 were developed in 45 cases. Threedimensional ripples were observed in the other 30 cases in the flow with large Reynolds numbers. Since mechanics of sand movement changes drastically over two- and threedimensional ripples, it is firstly of importance to understand the condition for the occurrence of two- and three-dimensional ripples.



Fig. 4 Schematic diagram of an asymmetric ripple.

et al. (1969), in which the range of two-dimensional ripples was found to be

$$d_0/D < 1550$$
 (3)

where D is the sand diameter. Lofquist(1978) undertook further experiments using an oscillatory flow tunnel and suggested that the two-dimensionality of ripples was dependent on two parameters, d_0/D and $U_0^2/[(\rho_s/\rho-1)gD]$, in which U_0 was the amplitude of velocity histories, ρ was the density of water, and g was the gravity acceleration. Kaneko(1981) classified characteristics of ripples by using $U_0^2/[(\rho_s/\rho-1)gD]$ and D/δ , in which δ was the thickness of the Stokes layer. Transition from two- to three-dimensional ripples was also discussed by Vongvisessomjai(1984), in which relationships for the geometry of ripples in oscillatory flows were proposed in terms of a parameter $U_0/\sqrt{(\rho_s/\rho-1)gD} \cdot d_0/(2D)$.

Relationships between characteristics of ripples and various hydraulic parameters were examined, including new data obtained under the conditions of asymmetric and irregular oscillations [Sato(1986)]. It was found that the most essential parameters to describe characteristics of ripples were d_0/D and the Shields parameter Ψ defined by,

$$\Psi = \frac{1}{2} f_{w} \frac{U_0^2}{(\rho_{s}/\rho - 1)gD}$$
(4)

in which f_{ψ} was the friction factor proposed by Jonsson(1966) which was evaluated on the assumption that the bottom roughness was equal to the sand grain diameter.

Figure 5 shows the classification of ripples developed in sinusoidal oscillations in terms of d_0/D and Ψ . Three-dimensional ripples are developed under conditions with large values of d_0/D and Ψ . The boundaries between two- and three-dimensional ripples are well described by the broken lines.

The classification of ripples in asymmetric flows is also made by using d_0/D and Ψ . Figure 6 shows the classification of ripples in asymmetric flows, in which the Shields parameter is evaluated by the following equation:

$$\Psi_{rms} = \frac{1}{2} f_w \frac{(\sqrt{2}u_{rms})^2}{(\rho_s/\rho - 1)gD}$$
(5)

where u_{rms} indicates the root mean square value of the velocity history.

The wavelength and the wave height of ripples are also formulated in terms of d_0/D and Ψ . Sato(1986) analysed data of ripples obtained in wave flumes, in oscillatory flow tunnels and on natural beaches, in which functional relationships between the ripple geometry and hydraulic parameters were derived as

$$\lambda/d_0 = 1.4(d_0/D \cdot \Psi^{1/2})^{-0.146} \tag{6}$$

$$\eta/\lambda = 0.191(1 - (\Psi/0.6)^2) \tag{7}$$

for two-dimensional ripples in regular oscillations and

$$\lambda/d_0 = 350(d_0/D \cdot \Psi^{1/2})^{-1} \tag{8}$$

$$\eta/\lambda = 0.158(1 - (\Psi/0.6)^2) \tag{9}$$

for three-dimensional ripples in regular oscillations. Relationships for the conditions of irregular oscillatory flows were expressed by

$$\lambda/d_0 = 3.55 (d_0/D \cdot \Psi^{1/2})^{-0.292} \tag{10}$$

for $d_0/D \cdot \Psi^{1/2} < 650$ and Eq. (8) for $d_0/D \cdot \Psi^{1/2} > 650$, and

$$\eta/\lambda = 0.191(1 - \Psi/0.6) \tag{11}$$

where values of d_0 and Ψ were evaluated using significant waves.



Fig. 5 Occurrence of two- and three-dimensional ripples in sinusoidal flows.



Fig. 6 Occurrence of two- and three-dimensional ripples in regular asymmetric flows.

Figure 7 shows the relationship between λ/d_0 and $d_0/D \cdot \Psi_{rms}^{1/2}$ for the data obtained in the present experiments by using sinusoidal and regular asymmetric oscillations together with existing data in sinusoidal oscillatory flows with sand whose diameter was about 0.2 mm. Values of λ/d_0 for two- and three-dimensional ripples are well expressed by Eqs. (6) to (9) with no significant deviations between data in sinusoidal flows and data in asymmetric oscillations.

Figure 8 shows the relationship between the ripple steepness η/λ and the Shields parameter. Values of η/λ are almost constant for both sinusoidal and asymmetric oscillations



Fig. 7 Relationships between λ/d_0 and $d_0/D \cdot \Psi^{1/2}$ for ripples in regular oscillations.



Fig. 8 Relationships between η/λ and Ψ for ripples in regular oscillations.

except in the transition region to the sheet flow. It is confirmed that the ripple steepness in asymmetric oscillatory flows can be consistently predicted by using the Shields parameter.

Figures 9 and 10 show the geometry of ripples in irregular oscillations. It is noticed that the geometry of ripples in irregular flows are also analysed consistently by using two parameters d_0/D and Ψ when these parameters are evaluated by using significant waves. It is found that the wavelength of ripples developed in irregular oscillations is almost the same with that in regular oscillations but the ripple steepness reduces considerably in irregular oscillations, which is consistent with the analysis made by Nielsen(1981).



Fig. 9 Relationships between λ/d_0 and $d_0/D \cdot \Psi^{1/2}$ for ripples in irregular oscillations.



Fig. 10 Relationships between η/λ and Ψ for ripples in irregular oscillations.

The asymmetry of ripples is also of great importance since it exerts strong influences on the formation of lee vortices and in turn on the amount of the net sand transport. Figure 11 shows the relationship between the asymmetry of ripples and that of velocity histories. Data of ripples obtained in the previous experiments by using the same facilities are plotted together. The asymmetry of ripples increases linearly with the asymmetry of velocity histories until it reaches a critical value. On the assumption that the curve of the onshorefacing flank of a ripple is a sinusoidal curve whose maximum slope angle is equal to the repose angle of the sediment ϕ_r , the maximum of the ripple asymmetry is expressed by

$$\left(\frac{\lambda_c}{\lambda}\right)_{\max} = 1 - \frac{\pi}{2} \frac{\eta/\lambda}{\tan\phi_r}$$
(12)

If values of η/λ and ϕ_r are approximated by the mean values of data in the present experiments, 0.16 and 33 ° respectively, the maximum asymmetry of ripples is estimated as

$$\left(\frac{\lambda_c}{\lambda}\right)_{\max} = 0.61 \tag{13}$$

The above relation appears to explain the trend of the experimental data in strongly asymmetric oscillatory flows.

4. DISTRIBUTION OF SUSPENDED SAND CONCENTRATION

It was observed in the experiments that suspended sand clouds of high concentration were formed above two-dimensional ripples and that the sand transport in suspension appeared to contribute as the essential portion of sand movement. In order to predict the sand transport rate over ripples, it is of great concern to estimate the magnitude and the distribution of suspended sand concentration.



Fig. 11 Relationships between the asymmetry of ripples and the asymmetry of velocity histories.

Distributions of the equi-phase mean concentration were evaluated in order to understand the spatial and temporal variations of suspended sand concentration. Figure 12 illustrates distributions of the equi-phase mean concentration during one period. A suspended sand cloud is formed above the steeper flank of a ripple ($\omega t = \pi/5$) when the direction of the flow is onshore. The cloud is then thrown up over the ripple crest after the flow direction changes ($\omega t = 3\pi/5$) and transported offshore. The formation of a sand cloud is not appreciable during the period when the direction of the flow is oscillatory flows. It is concluded that the essential portion of sand suspension occurs during the period when the flow direction is onshore. Sand suspension by the strong onshore flow is therefore considered to be of importance in the estimation of the net sand transport rate under asymmetric oscillations.



Fig. 12 Distributions of equi-phase mean concentration of suspended sand.

5. NET SAND TRANSPORT RATE

Figure 13 illustrates measured profiles of steady-state ripples developed in a case in which the oscillation was produced by a signal C2. The figure on the bottom indicates the spatial variation of the net sand transport rate q_x evaluated by Eq. (2). The arrows at both ends, x=0 cm and x=110 cm, represent the volume of trapped sand. Values of q_x are regarded to be almost constant in the central region of the test bed, in which the net sand transport rate free from the disturbance produced at both ends can be estimated. The periodic variations in q_x are considered to be due to the movement of sand ripples. The net sand transport rate Q was therefore evaluated as a mean value of q_x over a region of one wavelength of a ripple at the center of the test bed.



Fig. 13 Measured profiles of bed forms and the net sand transport rate.

Figure 14 shows the variation of the net sand transport rate at various stages in the development of ripples from initially flat bed. Measurements of bottom profiles and collections of trapped sand were conducted at t/T=150, 450, 750 and 1050. The net sand transport rate Q was small but positive at the initial stage of ripple formation in which the sand was observed to move dominantly as bed load. The direction of the net sand transport gradually tended to be in the offshore direction with the increase of sand suspension enhanced by the development of ripples until it reached a steady state at t/T=600. Since the time required for the development of steady-state ripples is generally considered to be small compared with the duration of steady-state waves on natural beaches, it is practically of significance to elucidate the net sand transport rate over steady-state ripples.



Fig. 14 Variations of the ripple geometry and the net sand transport rate with the development of ripples.

The net sand transport rate over steady-state ripples was in the offshore direction for all the cases in the present experiments. Since sand suspension occurred dominantly above the steeper flank of ripples when the flow direction was onshore, the resultant net sand transport rate was considered to be strongly dependent on the maximum onshore velocity u_c . Figure 15 shows the relationship between the following dimensionless net sand transport rate Φ and the Shields parameter Ψ_{an} evaluated by using u_c :

$$\Phi = \frac{Q}{w_s D} \tag{14}$$

$$\Psi_{on} = \frac{1}{2} f_w \frac{u_c^2}{(\rho_s/\rho - 1)gD}$$
(15)

The solid line represents the following empirical relation proposed by Watanabe(1982) on the basis of laboratory experiments of two-dimensional beach deformation

 $|\Phi| = 7(\Psi - \Psi_c)\Psi^{1/2} \tag{16}$

where $\Psi_c(=0.11)$ represents the threshold of the Shields parameter for the general movement of sand particles. The relation proposed by Madsen and Grant(1976) for the sand transport rate during a half period is also depicted by the broken line,

$$|\Phi| = 12.5\Psi^3 \tag{17}$$



Fig. 15 Relationships between the net sand transport rate and the Shields parameter.

It is found that measured transport rates are expressed well by Eq. (16) for a wide range of conditions. The differences due to the degree of the asymmetry of velocity histories are not recognized but two-dimensionality of ripples appears to be an important factor.

Figure 16 is a comparison between measured net sand transport rates $|\Phi_m|$ and transport rates $|\Phi_c|$ calculated by Eq. (16). The transport rate over two-dimensional ripples exceeds the calculation a little, while the transport rate is found to decrease considerably over three-dimensional ripples. This is considered to be consistent with the observation that sand suspension by coherent vortices is not significant when three-dimensional ripples are developed.

The net sand transport rate under irregular oscillations can be estimated by considering the contributions of each wave in a similar manner with that for the cases of regular oscillations. The net sand transport rate is calculated by

$$\Phi = (\sum \Phi_i T_i) / (\sum T_i)$$
⁽¹⁸⁾

where T_i represents the period of each wave and Φ_i is the calculated transport rate for each wave calculated by Eq. (16). Figure 17 shows the comparison of measured net sand transport rate $|\Phi_m|$ and the transport rate $|\Phi_c|$ calculated by Eq. (18). Calculated values agree fairly well with measured values for the cases in which two-dimensional ripples were developed. Transport rate decreases considerably under the conditions of three-dimensional ripples.



Fig. 16 Comparison of the measured and the calculated net sand transport rate (regular oscillations).



Fig. 17 Comparison of the measured and the calculated net sand transport rate (irregular oscillations).

6. CONCLUSIONS

The mechanism of sand movement due to asymmetric oscillatory flows was investigated on the basis of laboratory measurements. Characteristics of the ripple geometry and the net sand transport rate were discussed in terms of hydraulic parameters characterizing the oscillatory flow. The geometry of ripples in asymmetric oscillations was described by two parameters d_0/D and Ψ for both regular and irregular oscillations. The asymmetry of ripples was found to be dependent on the asymmetry of velocity histories and the repose angle of the sand. The measurements of suspended sand concentration revealed that the asymmetry of flows and ripples exerted strong influences on the formation of sand clouds and that the entrainment of sand by the strong onshore flow was important in the estimation of the sand transport. The net sand transport rate over steady-state ripples was expressed by the Shields parameter based on the maximum onshore velocity. It was found that the net sand transport rate decreased considerably over three-dimensional ripples. Further studies are expected on the measurements under the conditions of much larger bottom shear stresses and the simulation of the nonlinear velocity variation under irregular waves.

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