CHAPTER 129

Sand Ripple Geometry and Sand Transport Mechanism Due to Irregular Oscillatory Flows

Shinji Sato*

Kiyoshi Horikawa** F. ASCE

ABSTRACT

This paper describes characteristics of sand ripples and sand transport mechanism in regular and irregular oscillatory flows on the basis of detailed laboratory measurements. A set of empirical relations were proposed to evaluate the sand ripple geometry as well as the onset of the sheet flow transport. The applicability of the proposed relationships to the irregular wave conditions with prototype scales was confirmed with existing field data.

1. INTRODUCTION

In order to understand sediment transport due to waves, it is of great significance to elucidate the geometry of bed forms as well as the mechanism of sand movement. Although a number of laboratory investigations have been performed on the sand transport due to waves, most of them have been carried out only for the condition of monochromatic oscillatory flows. Laboratory experiments for the condition of irregular oscillatory flows are necessary for better understanding of sand movement under realistic conditions encountered on natural beaches.

The sand transport mechanism and bed form geometry under irregular waves were investigated through field measurements by Inman (1957), Dingler (1974) and Nielsen (1984). Detailed laboratory measurements of the net sand transport rate under irregular waves were recently carried out by Mimura et al. (1986) and Sato and Horikawa (1986). However, the influence of wave irregularity on sand movement mechanism should be further investigated since reliable data under well-controlled irregular waves are still insufficient.

The sand transport under sheet flow condition is frequently observed on

* Research Associate, Yokohama National University, 156 Tokiwadai, Hodogaya-ku, Yokohama 240, JAPAN
** Professor, Saitama University; Professor Emeritus, University of Tokyo

natural beaches where wave-induced velocities at the bottom exceed a critical value. The evaluation of the sand transport rate under sheet flow condition is of significance since the sand transport rate becomes extremely large. Since the reproduction of the sheet flow condition is difficult in laboratory wave flumes, most of the experimental investigations on sheet flow transport have been carried out by using oscillating beds or oscillatory flow tunnels. Manohar (1955) described characteristics of bed forms as well as the disappearance of ripples on the basis of experiments by using an oscillating bed. Komar and Miller (1975) expressed the condition for the ripple disappearance in terms of the Shields parameter and the Reynolds number of oscillatory flows. Horikawa et al.(1982) evaluated sand transport rates under sheet flow condition on the basis of the measurements of the velocity and the concentration of sand particles by using an oscillatory flow tunnel. Horikawa et al.(1982) also confirmed the applicability of the criteria for the onset of the sheet flow proposed by Manohar (1957) and Komar and Miller (1975). Further investigations on the sheet flow transport were conducted by Staub et al.(1984), Bakker and van Kesteren (1986) and Sawamoto and Yamashita (1987).

The objectives of the present study are to evaluate the geometry of sand ripples in irregular oscillatory flows and to discuss the effect of wave irregularity on sand transport mechanism. Characteristics of bed forms under irregular oscillatory flows are described for a wide range of conditions corresponding to the sand ripple regime and the sheet flow regime. Empirical relationships for the sand ripple geometry as well as the critical condition for the onset of the sheet flow are proposed which are applicable to the conditions with prototype scales.

2. FACILITIES AND PROCEDURES OF EXPERIMENTS

Experiments were performed in an oscillatory flow tunnel as shown in Fig. 1. The tunnel was equipped with a hydraulically-driven piston

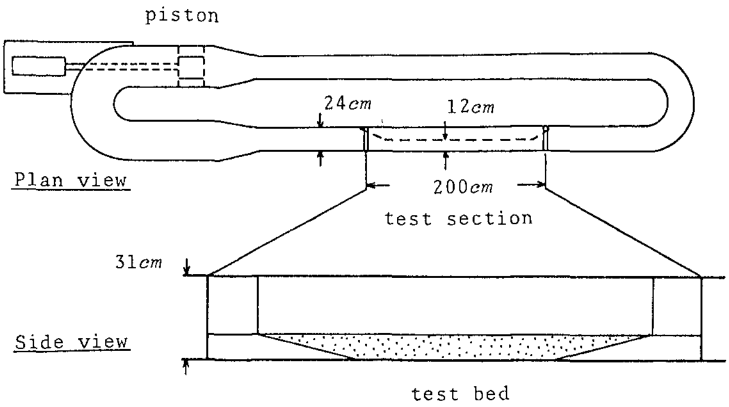

Fig. 1 Experimental facilities

controlled through an electric servo-system. The motion of the piston was controlled so as to reproduce the near-bottom water particle motion under regular and irregular waves based on the linear wave theory. Irregular oscillatory flows were simulated by assuming that the power spectrum of the irregular surface elevation was given by the Bretschneider-Mitsuyasu spectrum [Mitsuyasu (1970)]. The significant wave period was set to be in a range between 1s and 7s. Three kinds of irregular velocity histories were calculated for each wave period by assuming three different conditions for the depth to wavelength ratio h/L as illustrated in Fig. 2, in which the power spectrum density and the frequency are respectively nondimensionalized by the corresponding values at the peak of the power spectrum. Effects of the wave nonlinearity and the superimposed currents are not taken into consideration in the present study.

Two kinds of well-sorted sand were used as bed materials. The median diameters of the sands were 0.18mm and 0.56mm. The sand was filled in the test section to make initially flat test bed which was 160cm in length as shown in Fig. 3. A series of experiments (58 runs in total) were performed for the conditions of regular and irregular oscillatory flows. The width of the test section was reduced by half in some experimental runs in order to reproduce large-amplitude oscillatory

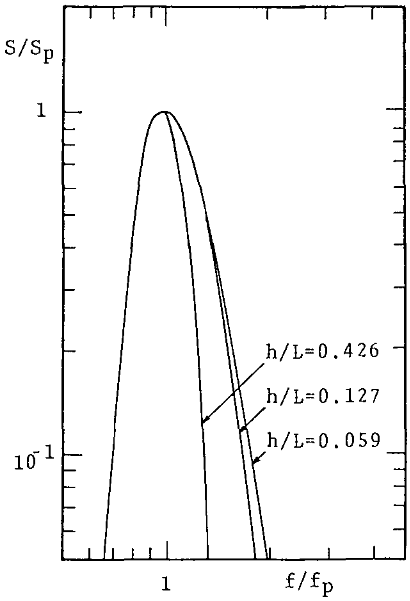

Fig. 2 Power spectra of velocity histories of irregular oscillatory flows

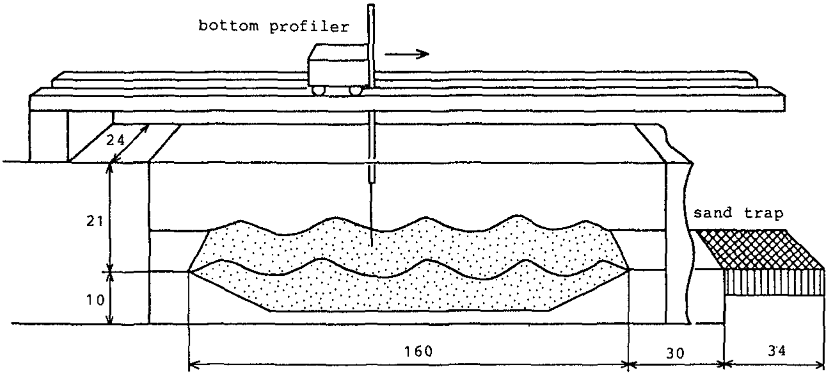

Fig. 3 Experimental set-up

flows.

Sand ripples were developed in 43 runs of the present experiments. Bottom profiles of the test bed were measured in detail by using a bottom profiler installed on the top of the tunnel. The wavelength and the wave height of the ripples were evaluated from the bottom profile measurements. In several runs of irregular oscillations, the ripple wave height were observed to vary in a range of 10% during the action of the oscillations. In such runs, ripple profiles were measured several times during the course of an experimental run. The ripple geometry was then determined as an average of these measurements. The development of bed forms and the type of sand movement for each run of the experiments were photographed through the side wall of the tunnel.

3. SAND RIPPLE GEOMETRY IN IRREGULAR OSCILLATORY FLOWS

In the analysis of several field investigations performed so far, the amplitudes of near-bottom velocity histories were calculated on the basis of the linear wave theory by using the significant wave height and period determined from the measured surface elevation. However, such evaluations sometimes induce considerable errors when the shape of the power spectrum density of near-bottom velocities is considerably different from that of the surface elevation. The great scatter of the published data in field investigations is considered to be partly attributed to the error in the evaluation of near-bottom velocities.

In order to understand the difference in the evaluation of near-bottom velocities, correlations were examined between the sand ripple geometry and hydraulic parameters evaluated in the following two methods. Figures 4 (a) and (b) show the relationship between λ/D and do/D for the condition of irregular oscillatory flows, in which λ is the ripple wavelength, do the diameter of the water particle displacement and D the sand grain diameter. The solid line indicates a regression relation for the ripple wavelength in regular oscillatory flows. The quantity do was

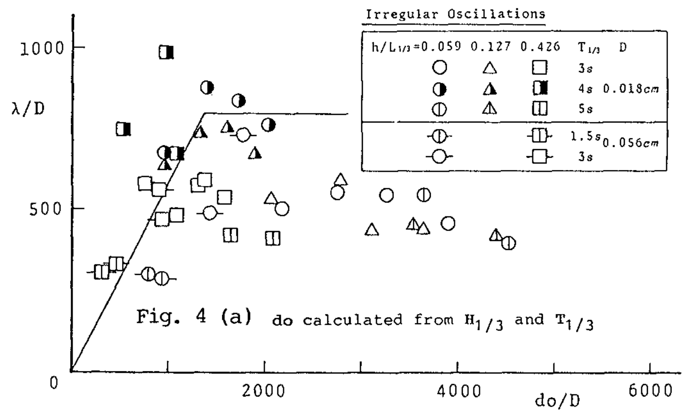

Fig. 4 (a) do calculated from $H_{1/3}$ and $T_{1/3}$

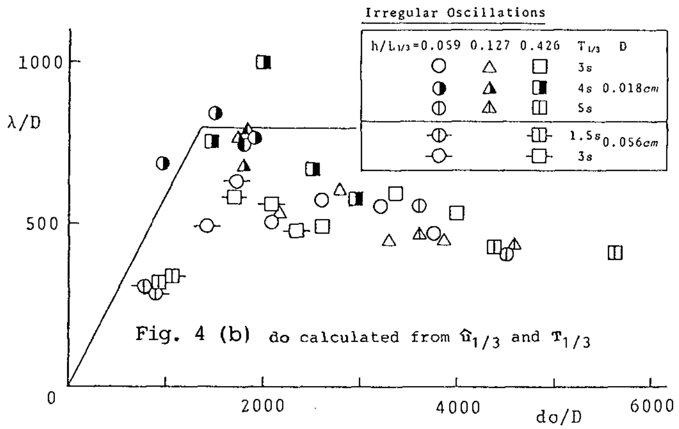

Fig. 4 (b) do calculated from $\hat{u}_{1/3}$ and $T_{1/3}$

Fig. 4 Ripple wavelength in irregular oscillatory flows

evaluated in Fig. 4(a) on the basis of the linear theory by

$$do = \frac{H_{1/3}}{\sinh kh} \tag{1}$$

where k denotes the wave number calculated by using the significant wave period. The evaluation of do was based on the following equation in Fig. 4(b):

$$do = \frac{\hat{u}_{1/3}T_{1/3}}{\pi} \tag{2}$$

in which $\hat{u}_{1/3}$ was the significant amplitude of velocity histories evaluated by means of wave-by-wave analysis of the velocity history and $T_{1/3}$ was the corresponding significant wave period. The scatter of data in Fig. 4(b) appears smaller than that in Fig. 4(a). The above fact indicates that hydraulic parameters evaluated directly from near-bottom velocity histories are correlated better to the sand ripple geometry. It was also confirmed that the relationship between the ripple steepness and the Shields parameter Ψ was also correlated better when the Shields parameter was evaluated by using the significant amplitude of velocity histories. The hydraulic parameters for irregular oscillatory flows were therefore evaluated in the present study by using the significant amplitude of velocity histories.

The geometry of sand ripples was analyzed for a wide range of conditions by Brebner (1980), Nielsen (1981) and Sato et al.(1987). Sato et al. (1987) found that the sand ripple geometry was described for a wide range of conditions in terms of two hydraulic parameters, do/D and the following Shields parameter Ψ:

$$\Psi = \frac{1}{2} fw \frac{\rho \hat{u}^2}{(\rho_s - \rho)\, gD} \tag{3}$$

where fw is the friction factor, $\hat{u}$ the velocity amplitude, ρ_s and ρ densities of sand and water and g the gravity acceleration.

Figures 5 and 6 respectively show the relationship between λ/do and $do/D\Psi^{1/2}$ and the relationship between η/λ and Ψ for the ripples observed

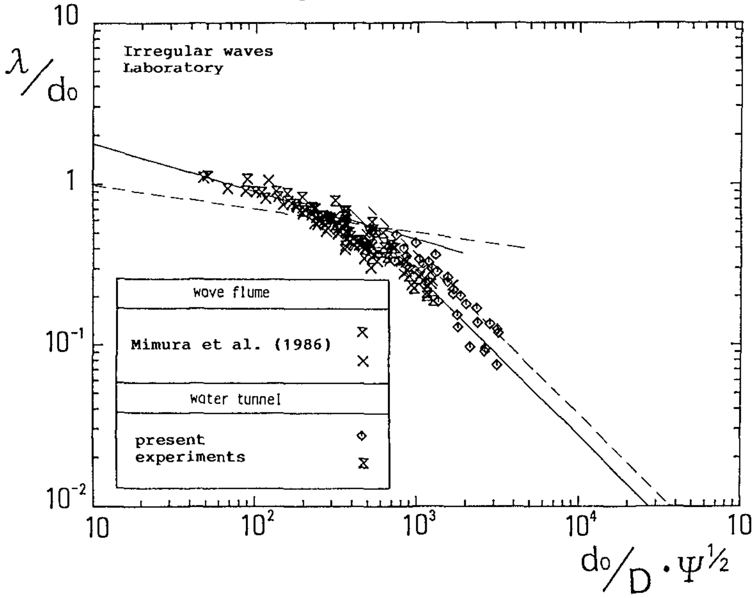

Fig. 5 Relationship between λ/do and $do/D\Psi^{1/2}$ for ripples in irregular oscillatory flows

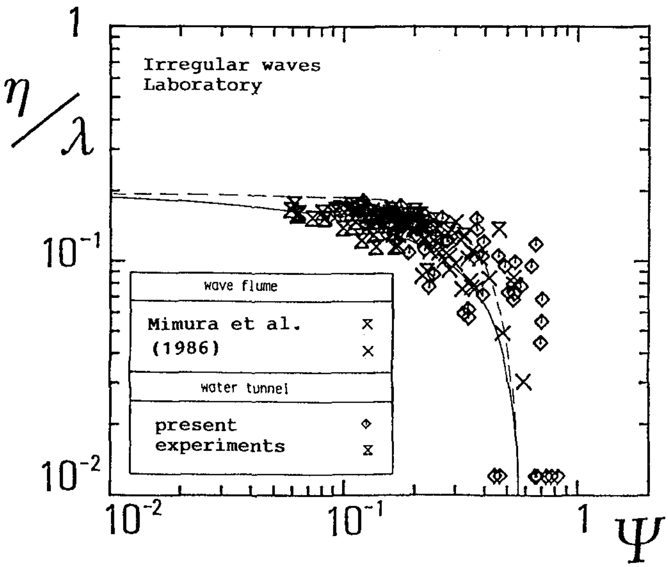

Fig. 6 Relationship between η/λ and Ψ for ripples in irregular oscillatory flows

in the present experiments, in which the solid lines represent the regression relations expressed by

$$\lambda/do = 3.55\ (\ do/D\ \Psi^{1/2}\ )^{-0.292} \quad \text{for } do/D\ \Psi^{1/2} < 480 \qquad (4)$$

$$\lambda/do = 280\ (\ do/D\ \Psi^{1/2}\ )^{-1} \quad \text{for } do/D\ \Psi^{1/2} > 480 \qquad (5)$$

$$\eta/\lambda = 0.191\ (\ 1 - \Psi/0.6\ ) \qquad (6)$$

and the broken lines represent the relations for the ripple geometry in regular oscillatory flows proposed by Sato et al.(1987). The wavelength of ripples in irregular oscillatory flows tends to become longer than that in regular oscillatory flows for the condition of small-amplitude oscillations, while ripples with shorter wavelength frequently developed in irregular oscillatory flows with large amplitude. The ripple steepness in irregular oscillatory flows tended to decrease considerably compared with that in regular oscillatory flows. The scatter of the data in the region of large Ψ seems to imply the need of further analysis on bed form characteristics in large-amplitude irregular oscillatory flows.

Figures 7 and 8 show the relationships for ripples on natural beaches. Although the scatter of the data is large compared with that of the data in laboratory measurements, it is verified that Eqs.(4), (5) and (6) also give good predictions of the geometry of sand ripples on natural beaches.

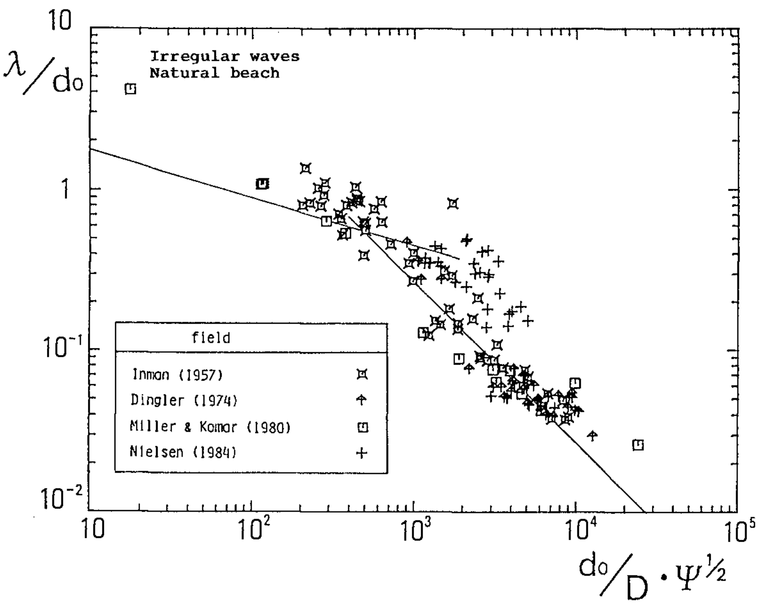

Fig. 7 Relationship between λ/do and $do/D\Psi^{1/2}$ for ripples on natural beaches

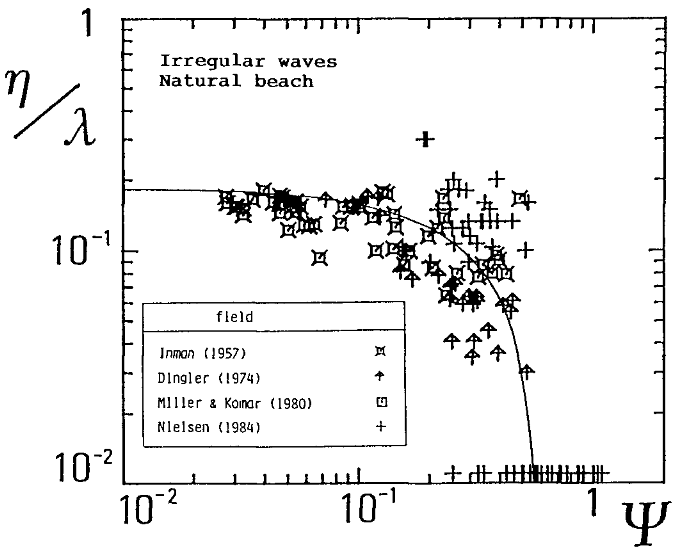

Fig. 8 Relationship between η/λ and Ψ for ripples on natural beaches

4. DISAPPEARANCE OF SAND RIPPLES

When the amplitude of oscillatory flows became large, sand ripples generally tended to disappear and sand particles began to be transported in the sheet flow. In regular oscillatory flows with large amplitudes, large-scale undulations, which were called dunes hereafter, were frequently generated as shown in Photo 1. The wavelength of the dunes was of the order of 1m. Flat bed then tended to develop with the further increase of the amplitude. The development of such dunes in regular oscillatory flows was also reported by Bosman (1981) and Sakakiyama et al. (1985). Characteristics of the dune geometry will not be further discussed in the present study since the length of the test bed in the present experiments was not considered to be enough to reproduce undisturbed dunes.

Photo 2 illustrates bed forms developed in a large-amplitude irregular oscillatory flow. Dunes were rarely generated under irregular oscillatory flows. On the other hand, small-scale two-dimensional ripples were generally observed in the transition region between the ripple and the non-ripple regime. The mechanism of the formation of these small-scale ripples was similar to the initial stage of ripple formation on a flat bed, that is, the geometry of these small two-dimensional ripples in large-amplitude irregular oscillatory flows were

Photo 1 Bed forms developed in a large-amplitude regular oscillatory flow

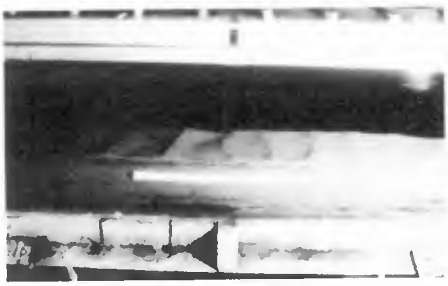

Photo 2 Bed forms developed in a large-amplitude irregular oscillatory flow

considered to be maintained by the iteration of conflicting actions of the ripple elimination due to large waves and the ripple formation due to relatively small waves.

Figure 9 shows the classification of bed forms under regular oscillatory flows. Open symbols indicate the presence of sand ripples and solid symbols indicate the disappearance of sand ripples. Data obtained by Bosman (1981) and Horikawa et al. (1982) were also plotted in the figure. Data were classified in the non-ripple regime when the ripple steepness was less than 0.05. Dunes were also classified in the non-ripple regime in the present study since sand particles on the duned bed were observed to be transported in sheet flow over the whole domain. The broken line in Fig. 9 represents the criterion for the onset of the sheet flow proposed by Komar and Miller (1975), in which ν is the kinematic viscosity of water. The relation proposed by Manohar (1955) was also examined for both regular and irregular oscillatory flows, which revealed that experimental data were not well classified by these criteria. The onset of sheet flow was therefore reanalyzed in the present study by using two parameters, *do/D* and Ψ, which were found to be essential parameters in describing the sand ripple geometry.

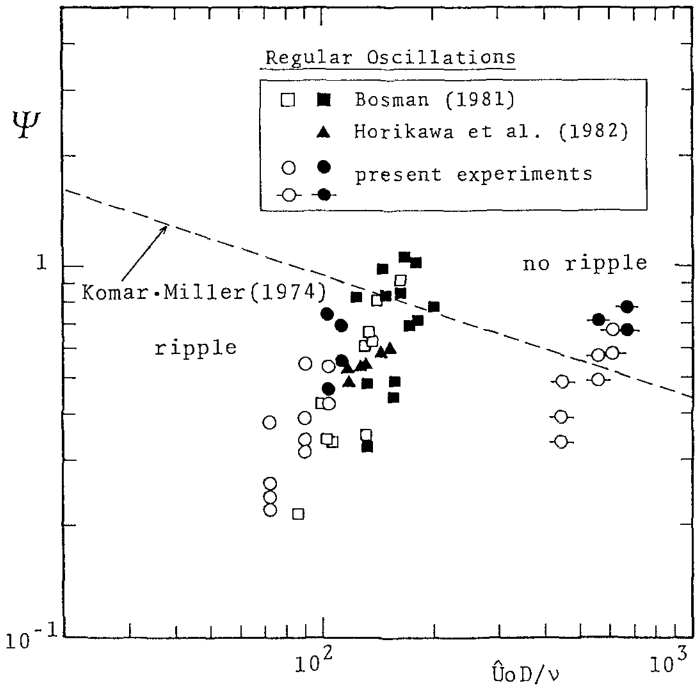

Fig. 9 Disappearance of ripples in regular oscillatory flows

Figure 10 shows the classification of bed forms under regular oscillatory flows in terms of *do/D* and Ψ. It is noticed that the disappearance of ripples was well described by the broken line in the figure which was expressed by

$$\Psi = 7.8\ (\ do/D\ )^{-1/3} \qquad (7)$$

Figure 11 shows the classification of bed forms under irregular oscillatory flows. Although the number of data was not sufficient, the critical condition for the disappearance of ripples in irregular oscillatory flows appeared to be described by Eq. (7).

Figure 12 shows the classification of bed forms on natural beaches. Values of *do* and Ψ were calculated on the basis of the linear theory by using the significant wave height and period of measured surface elevations. Although the scatter of the data is large, Eq. (7) appears to give an appropriate boundary between the ripple and the non-ripple regimes.

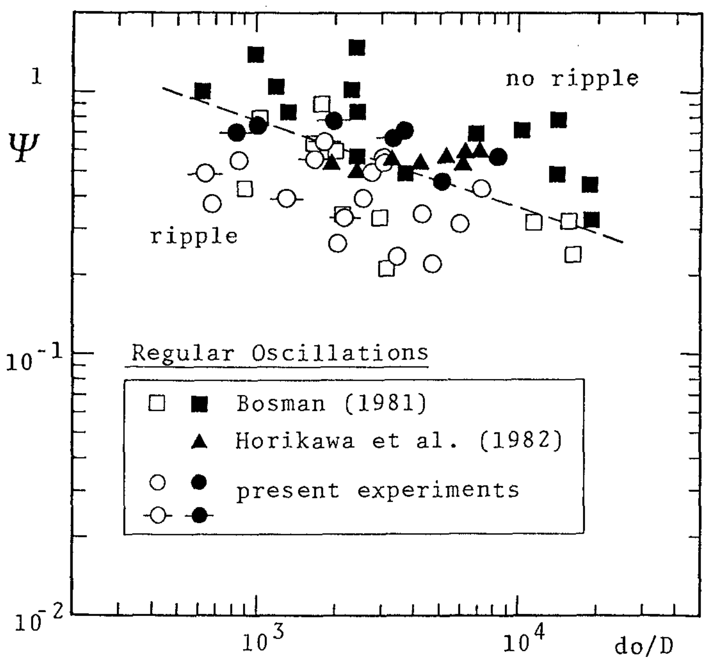

Fig. 10 Disappearance of ripples in regular oscillatory flows

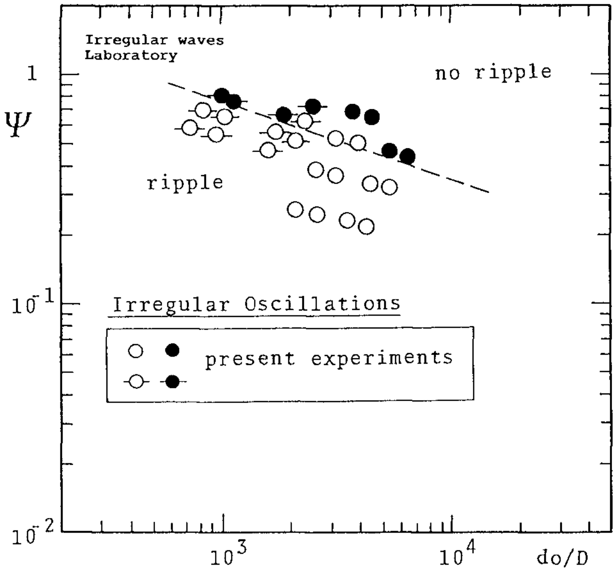

Fig. 11 Disappearance of ripples in irregular oscillatory flows

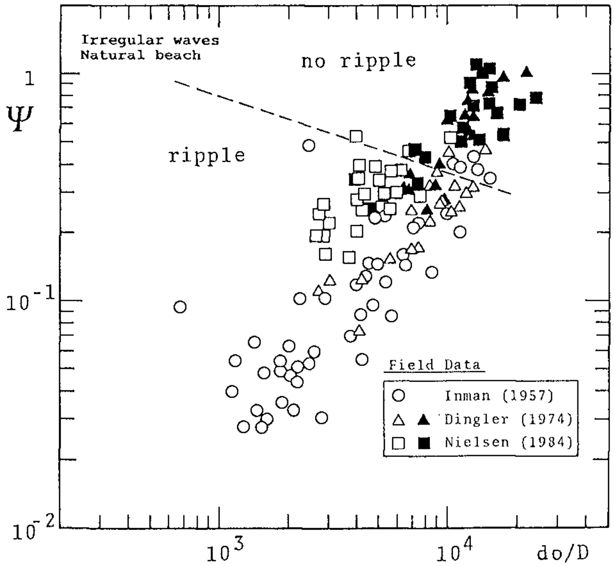

Fig. 12 Disappearance of ripples on natural beaches

Since the critical condition for the ripple disappearance was fairly described by Eq. (7), it is expected that the ripple steepness in large-amplitude oscillatory flows might be correlated better with a parameter $\Psi(do/D)^{1/3}$. Figure 13 shows the relationship between η/λ and $\Psi(do/D)^{1/3}$ for ripples in irregular oscillatory flows. The solid line represents a regression relation expressed by

$$\eta/\lambda = 0.170\ (\ 1 - (\ \Psi\ (\ do/D\ )^{1/3}/7.8\ )^2\ ) \qquad (8)$$

Figure 14 shows the steepness of ripples on natural beaches. The correlation of data in Figs. 13 and 14 in the region of large Ψ is considerably improved compared with that in Figs. 6 and 8.

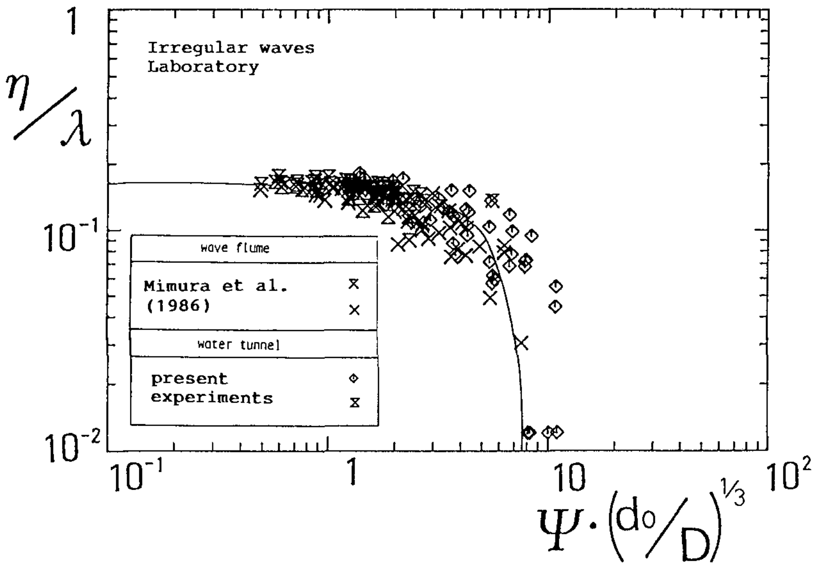

Fig. 13 Relationship between η/λ and $\Psi(do/D)^{1/3}$ for ripples in irregular oscillatory flows

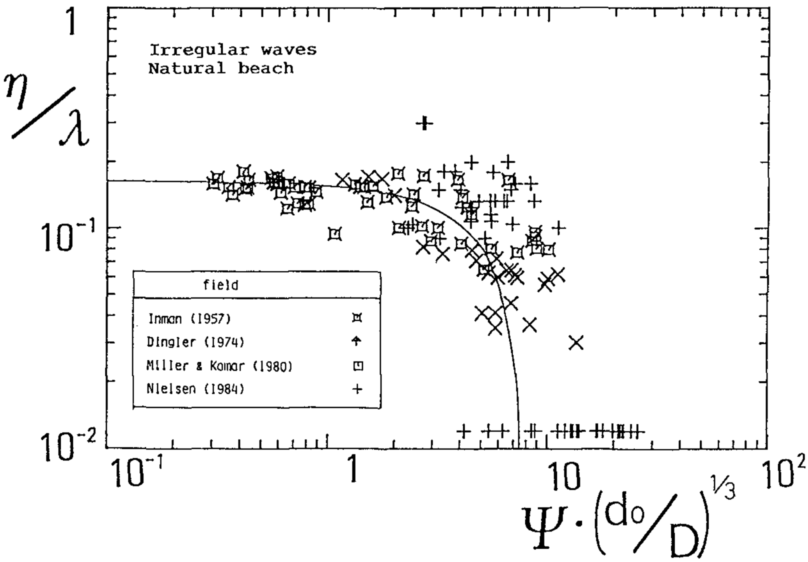

Fig. 14 Relationship between η/λ and $\Psi(do/D)^{1/3}$ for ripples on natural beaches

5. CONCLUDING REMARKS

Characteristics of the sand ripple geometry as well as the mechanism of sand movement in irregular oscillatory flows were investigated through a series of laboratory measurements. The sand ripple geometry and the critical condition for the disappearance of ripples were consistently expressed in terms of do/D and Ψ for both regular and irregular oscillatory flows. The applicability of the proposed relations to the condition with prototype scales was also confirmed with data on natural beaches.

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