CHAPTER 102

LABORATORY STUDY ON TWO-DIMENSIONAL BEACH TRANSFORMATION DUE TO IRREGULAR WAVES

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ABSTRACT

In the present study, effects of irregular waves on two-dimensional beach transformation and related phenomena were investigated through a series of laboratory experiments. Attempts were made to determine a representative wave of irregular wave trains which controlled individual phenomenon related to the two-dimensional beach profile change. It was found that the representative wave is different for each phenomenon. For the macroscopic beach profile change, it is the mean wave which represents whole incident waves. On the other hand, some of microscopic phenomena, such as initiation of sand movement and sand ripple formation, are controlled by larger waves in the wave train selectively, of which representative wave is the significant wave.

1. INTRODUCTION

There have been many studies on two-dimensional beach transformation and cross-shore sediment transport in and out of the surf zone. While a number of laboratory studies were performed on this subject, phenomena in real beaches could not be necessarily reproduced in wave flumes. The difference of phenomena in real beaches and laboratories is caused by several factors such as scale effect of physical model, three-dimensional effect of real topographic change, irregularity of real waves, etc. Among them, the effects of wave irregularity on the beach profile change have scarecely examined, since most of laboratory experiments were carried out by regular waves. While there are a few attempts to investigate bar formation and sediment transport rate under irregular waves such as by Tsuchiya and Inada(1974), and Wang and Liang(1975), complete understanding of this subject is beyond us. In order to connect the knowledge accumulated by historical laboratory studies with real phenomena, it is fundamentally important to determine the effects of wave irregularity on two-dimensional beach transformation.

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In the present study, a series of laboratory experiments were performed under the action of irregular waves. Beach profiles were measured at several time steps of wave action in an experiment. On the basis of these measurements of beach profiles, macroscopic profile change, threshold of sand movement, characteristics of sand ripples and net rate of cross-shore sediment transport were investigated. In order to examine the effects of irregular waves on these phenomena, results of the present study were compared with those from previous investigations of regular waves. While there are several ways to express the characteristics of irregular waves, the concept of representative wave was employed. As the representative wave, significant wave and mean wave were taken. It is a main objective to determine the representative wave for each phenomenon, which plays an almost same role as a train of irregular waves in generating the target phenomenon.

2. EXPERIMENTAL PROCEDURE

Laboratory experiments were performed in a wave flume, 19m long, 1m deep, and 0.8m wide, as shown in Fig. 1. A sandy beach was placed at one end of the flume. Two kinds of well-sorted quartz sand were used as bed materials: one is fine sand (Toyoura sand) with mean diameter, d_{50}, of 0.18mm, and the other coarse sand with d_{50} of 0.75mm. The wave flume was devided into two parts so that two tests with different bed materials could be carried out simultaneously. In order to make it easy to compare the results of the present experiments with those of regular wave studies, tests were limited to a uniform initial beach slopes of 1/10 or 1/20.

The wave generator used can produce irregular waves with any spectrum. In the present study, the Bretschneider-Mitsuyasu spectrum (Bretschneider 1968, Mitsuyasu 1970) was employed for incident waves. The general form of this spectrum, S, is

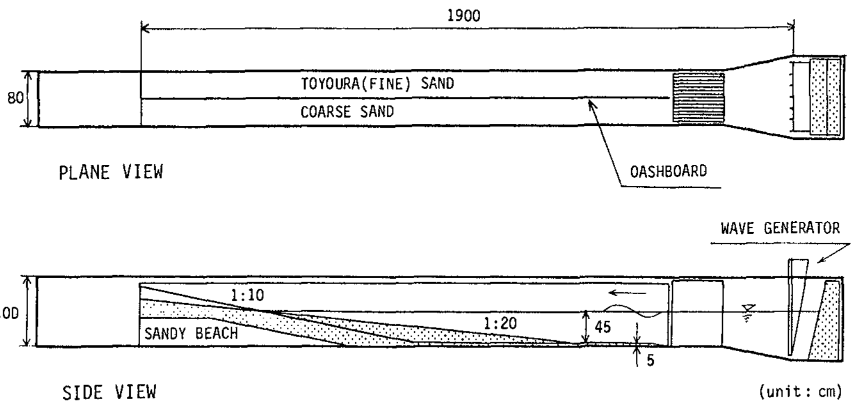


Fig. 1 Wave flume

Table 1 Experimental conditions

Ser. A (TOYOURA SAND, d_{50}=0.18mm)						Ser. B (COARSE SAND, d_{50}=0.75mm)					
Case	Initial Slope	Significant Wave		Mean Wave		Case	Initial Slope	Significant Wave		Mean Wave	
		$(H_{1/3})_o$ (cm)	$T_{1/3}$ (s)	$(H_m)_o$ (cm)	T_m (s)			$(H_{1/3})_o$ (cm)	$T_{1/3}$ (s)	$(H_m)_o$ (cm)	T_m (s)
A-1	1/20	5.3	1.9	3.5	1.5	B-1	1/20	5.4	1.8	3.5	1.6
2		6.2	1.3	4.0	1.1	2		6.1	1.4	4.0	1.2
3		3.4	0.9	2.2	0.8	3		3.4	0.9	2.2	0.8
4		8.7	1.3	5.3	1.1	4		8.7	1.3	5.3	1.1
5		11.9	1.4	7.7	1.2	5		11.9	1.4	7.8	1.2
6		9.5	1.8	6.5	1.7	6		9.5	1.8	6.5	1.7
7	1/10	6.0	1.9	4.1	1.6	7	1/10	5.9	1.9	4.0	1.6
8		6.2	1.4	4.0	1.2	8		6.2	1.4	4.0	1.2
9		3.5	0.9	2.3	0.8	9		3.5	0.9	2.3	0.8
10		9.7	1.3	6.0	1.2	10		9.7	1.3	5.9	1.2
11		9.3	1.8	6.3	1.6	11		9.2	1.9	6.3	1.6
12		11.0	1.4	7.3	1.3	12		10.9	1.4	7.2	1.2

Subscript o indicates the deep water wave.

$$S(f) = 0.257H_{1/3}^{2}\ T_{1/3}^{-4}\ f^{-5}\exp(-1.03(T_{1/3}f^{-4})) \qquad (1)$$

where f is frequency, and $H_{1/3}$ and $T_{1/3}$ are significant wave height and period. Keeping the spectrum of incident waves same, significant wave height and period were changed for each experiment. Consequently, twenty four experimental cases were chosen with combinations of two grain sizes, two initial slopes, and several ranges of representative wave height and period. Experimental conditions are summerized in Table 1.

In the course of each experiment, wave motion, sand movement, and beach profile were measured systematically. In order to measure beach profiles continuously and accurately, bottom profilers of electromagnetic type were used. The region coverd by this measurement is from a sufficient high point on the backshore where wave uprush could not reach to the offshore end of the sandy beach. Beach profiles were measured three times in a case, namely just before the start of wave action (0 hour), 3 and 9 hours after it. Net rate of cross-shore sediment transport was calculated from the data of beach profiles in a similar way developed by Watanabe et al.(1980). In the middle of wave action, wave profiles and near-bottom velocities were measured with intervals of 25 or 50 cm along the beach as well as an offshore point. Moreover, states of wave breaking and sediment motion were observed and recorded by using a video-tape recorder.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Macroscopic Beach Profile Change

As the first topic of experimental results, macroscopic beach profile change will be discussed. Figures 2 (a) to (d) show the beach profiles and distributions of the net rate of cross-shore sediment transport for all the cases listed in Table 1. Beach profiles were obtained after 9 hour wave action and the net rate of sediment transport rate was evaluated from the difference of two successive beach profiles measured at 0 and 3 hours after wave action. Positive values of sediment transport rate indicates onshore transport and negative values are for offshore transport. In Figs. 2 (a) to (d), results are ranged as a parameter C increases, which was suggested by Sunamura and Horikawa(1974) for the classification of beach profiles. As the parameter C is closely correlated with the wave steepness, it can be said that the order of the results corresponds to that of wave steepness.

For the regular wave experiments, it has been reported that sandy beach transforms systematically into some equilibrium profile according to the conditions of incident waves. From Figs. 2, it is seen that beach profile shows a systematic change even under the conditions of irregular waves.

In cases of fine sand (Ser.A), beach profiles vary from accreting type to eroding type. Under the conditions of smaller C, therefore smaller wave steepness, berm forms on the foreshore for both cases with

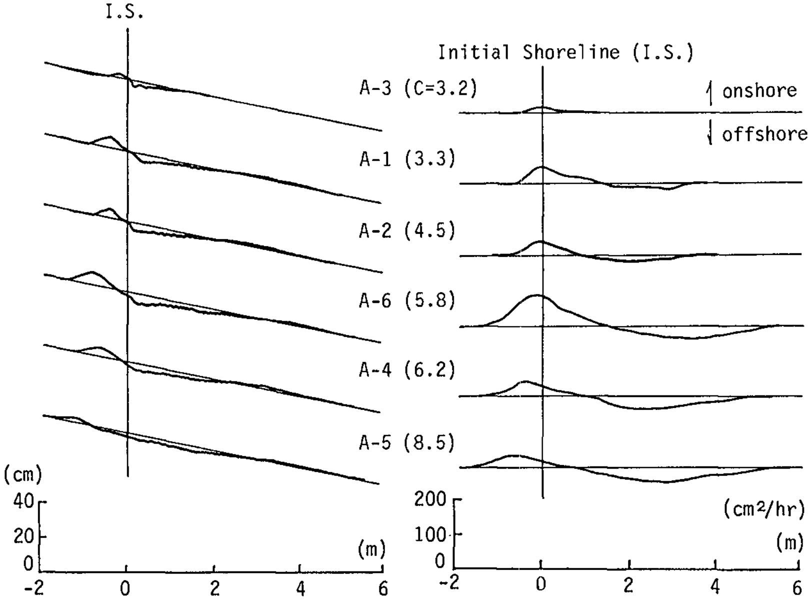


Fig.2 (a) Beach profiles and cross-shore sediment transport rate (initial slope=1/20, d_{50}=0.18mm)

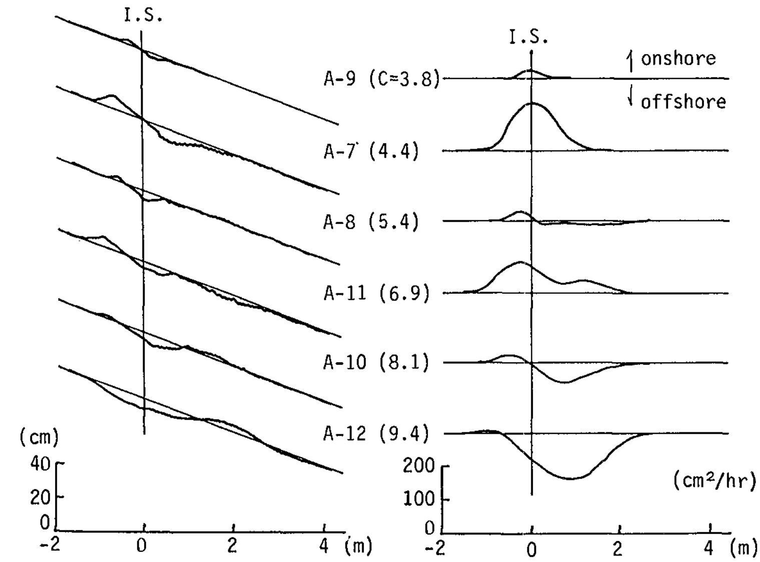


Fig.2 (b) Beach profiles and cross-shore sediment transport rate (initial slope=1/10, d_{50}=0.18mm)

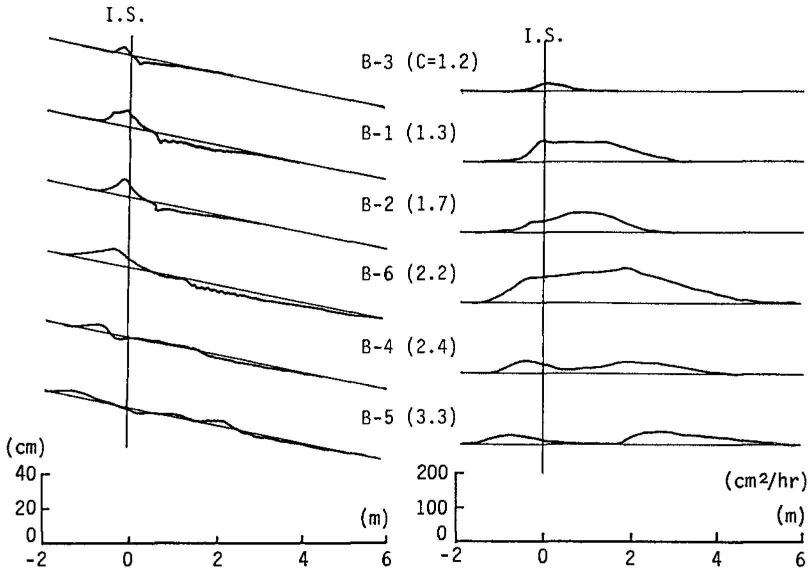


Fig.2 (c) Beach profiles and cross-shore sediment transport rate (initial slope=1/20, d_{50}=0.75mm)

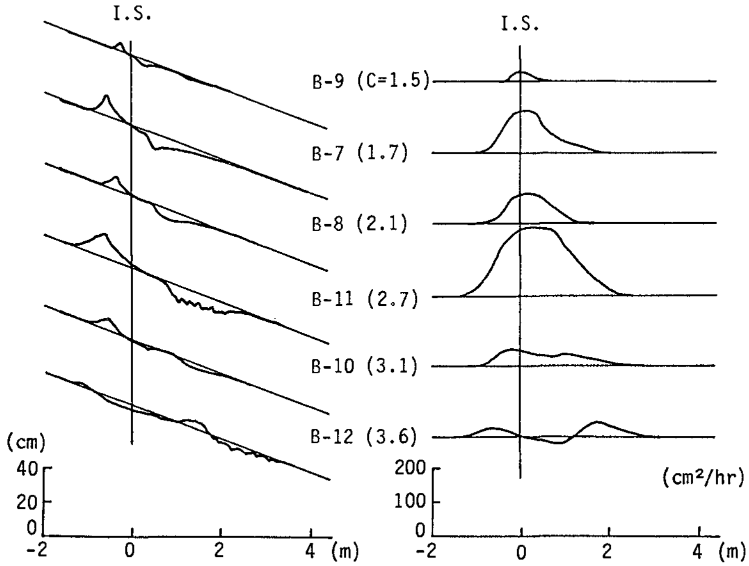


Fig.2 (d) Beach profiles and cross-shore sediment transport rate (initial slope=1/10, d_{50}=0.75mm) initial slope of 1/10 and 1/20, and the direction of sediment transport is onshore in the whole region. As the value of C increases (wave steepness also increases), erosion of the foreshore begins and a bar becomes noticable. The sediment transport turns offshore. A complete eroding beach formed in Case A-12, of which incident waves were severest among the cases with initial slope of 1/10. In cases of coarse sand (Ser. B), eroding type of beaches did not appear because of the limitation of wave height and steepness. However, it can be seen that beach profiles and distributions of sediment transport rate vary in a systematic manner depending on the value of C.

It was observed that the progress of beach transformation was considerably slow in the present experiments comparing with regular wave cases. This tendency seems to be caused by wave irregularity. Namely, under the incidence of irregular waves, some waves may erode the beach, while other may act toward accretion. Coexistence of waves with conflicting actions yields the slow transformation of beaches. On the other hand, all waves have the same action under the regular wave conditions. Therefore, it should be noted that the beach transformation are accelerated in regular wave experiments.

3.2 Classification of Beach Profiles

It is well known that there are two typical types of natural beaches, that is bar (eroding) and step (accreting) type beaches. Many investigations have been performed to determine parameters classifying beach profiles, such as by Johnson (1949), Iwagaki and Noda (1962),

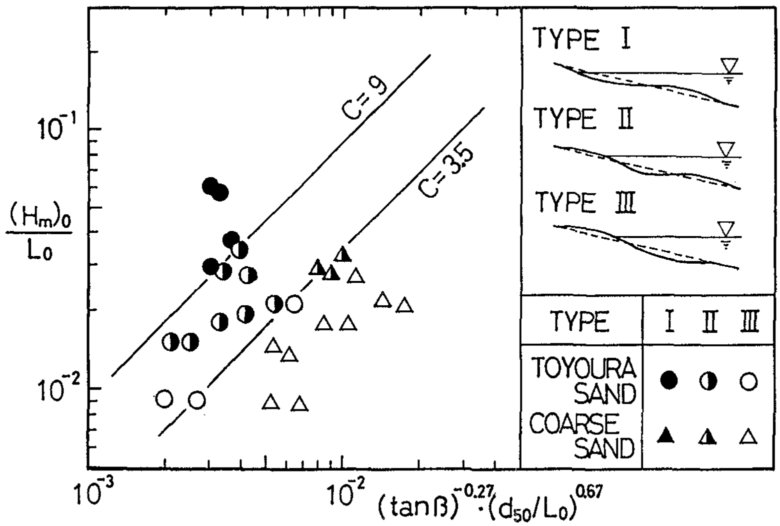


Fig. 3 Classification of beach profiles

Nayak (1970), Dean (1973), Sunamura and Horikawa (1974), and Hattori and Kawamata (1980). In the present study, adaptability of the classification of beach profile suggested by Sunamura and Horikawa is examined.

They classified beach profiles into three types based on the displacement of topography from the initial beach slope: Type 1 = a shoreline retrogresses and sand accumulates in offshore zone (eroding type), Type II = a shoreline advances and sand piles up offshore (intermediate type), and Type I1I = a shoreline progresses and no sand deposition takes place offshore (accreting type).

These three types are distinguished by a nondimensional parameter,

$$C = (H_0/L_0)\ (\tan\beta)^{0.27}\ (d/L_0)^{-0.67} \tag{2}$$

where H_0 and L_0 are deep water wave height and length, $\tan\beta$ is initial beach slope, and d is grain diameter. Horikawa et al.(1975) determined the range of C parameter for each type on the basis of experimental results of regular waves as follows.

Type I: $10 < C$, Type II: $3 < C < 10$, Type 1I1: $C < 3$.

Figure 3 shows the result of application of this classification to the present data given in Figs. 2. Figure 3 also includes the data of additional experiments performed in the same wave flume (Irie et al. 1985). For this application, mean waves were taken as the representative incident wave, that is, the values of ordinate and abcissa of Fig. 3 were calculated based on the wave height and length of the mean wave. It can be seen that this classification is effective for irregular wave cases, and that the mean wave gives considerably close criteria of classification as those for regular waves.

When the significant wave was used as the representative wave, the critical values of C moved from 3.5 to 5 and from 9 to 15 respectively. Therefore, it is concluded that the representative wave for the macroscopic beach profile change is the mean wave. This means that the macroscopic beach profile change is not controlled by a paticular group of waves, but by the whole incident waves.

3.3 Threshold of Sand Movement

As the threshold of sand movement, critical water depth was examined. 1t was determined based on a measured beach profile for each case, by judging the initiation point for the topographic change of the offshore region. Therefore, the critical water depth in the present study is for the general movement of sand particles, not for the initial movement.

The reference material were taken from the previous study by Horikawa and Watanabe (1967). Their method is certified to correspond with the results of laboratory experiments of regular waves.

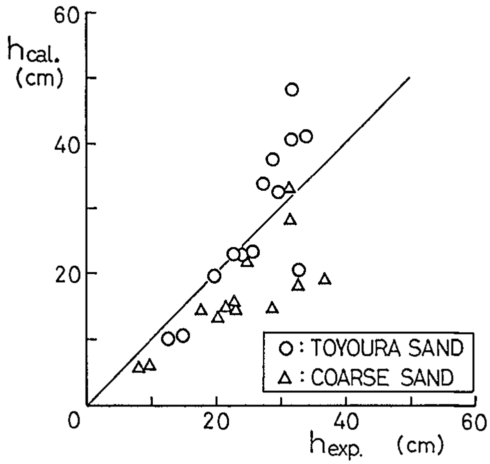


Fig. 4

Comparison of critical water depth between experiments and calculations

Figure 4 shows a comparison of the critical water depths obtained in the present experiments ($h_{exp.}$) and those of calculation by Horikawa and Watanabe's method ($h_{cal.}$). For this calculation, the quantities of significant wave were used. The agreement is considerably good in the region of small water depth, though the measured values tend to scatter as the water depth increases.

On the other hand, the mean wave gave forty percent smaller values of calculated critical depths, resulting in large disagreement with the measured values. Therefore, it is concluded that the representative wave for the threshold of sand movement is the significant wave. This conclusion seems to be as a matter of course, because sand grains cannot feel the influence of small waves in a deep area.

3.4 Characteristics of Sand Ripples

It has been certified that sand ripples play an important role in transporting sediment mainly through regular wave experiments. In the present experiments of irregular waves, sand ripples were observed in all cases of fine sand and a few cases of coarse sand. The most distinguishing feature is that the position and shape of sand ripples were considerably stable in spite that various waves passed over them one after another. Cloud of suspended sediment were often generated above the sand ripples, as seen in the regular wave experiments. It is recognized, therefore, that sand ripples are important for sediment transport also under the action of irregular waves.

In the present study, the initiation of formation and scales of sand ripples are investigated quantitatively. Among many studies on these subjects, the reference materials of regular wave experiments were taken from the study by Riho et al.(1981).

In the regular wave study, Riho et al. determined the critical conditions of the ripple formation on the basis of two physical quantities: one is the ratio of orbital diameter of water particle at the bottom (d_0) to the median diameter of sand particles (d_{50}),and the other the Shields parameter. The orbital diameter, d_0, was evaluated from the wave profile based on the small ampritude theory. Moreover, in order to take the asymmetry of wave profile into account, they introduced a corrected orbital diameter, d_0', as:

$$d_0' = 4\alpha(1-\alpha)d_0, \qquad \alpha = \eta_c/H \tag{3}$$

where η_c is amplitude of wave crest and H is wave height. The magnitude of Shields parameter, was calculated from the maximum velocity of water particle at the bottom.

Figure 5 shows the critical conditions of ripple formation. The left-hand side figure is for the significant wave and right-hand side figure is for the mean wave. In these figures, real lines indicate boundaries of ripple formation obtained in the present experiments and dashed lines are those given by Riho et al. for the regular wave experiments. It is seen that the significant wave gives closer values of both boundaries to those for the regular waves.

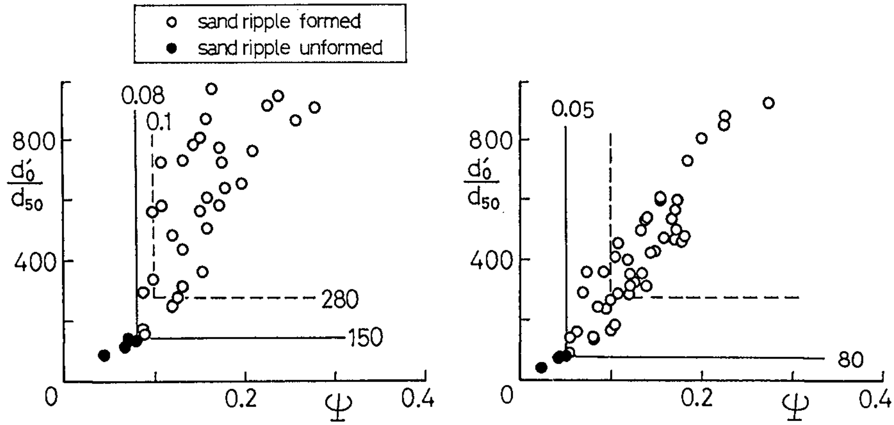
Figure 6 shows the relationship between the wave length of ripple (λ) and the orbital diameter of water particle (d_0') given by Fig. (3). Again, the left-hand side and right-hand side figures are for irregular wave and regular wave experiments respectively. In these figures, empirical relationships of λ with d_0' are shown: real lines are for irregular waves, and dashed lines are for regular waves. Refering to these figures, it is found that the orbital diameter calculated from the quantities of significant wave gives a considerably close relationship to that for regular waves. On the other hand, the agreement becomes bad, when the mean wave is used for the calculation of d_0'. Consequently, it can be concluded that the representative wave which controls the characteristics of sand ripples is the significant wave.

3.5 Cross-shore Sediment Transport Rate

Watanabe (1981) has proposed a formula for cross-shore sediment transport based on the concept of so-called power model.

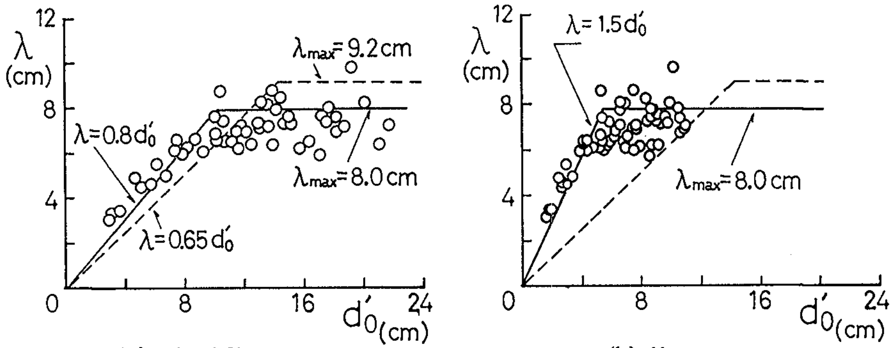
$$\Phi = A(\Psi - \Psi_c)\Psi^{\frac{1}{2}} \tag{4}$$

where $\Phi = q/w_0 d$ is dimensionless transport rate, q is net rate of cross-shore sediment transport, w_0 is the settling velocity of sand particle, d is the grain diameter, $\Psi_c$is the critical Shields number for general movement of sands, and A is constant. This formula is based on an assumption that the amount of sand set in motion are considered to be propotional to the excess of Ψ over its critical value, Ψ_c. It was certified that Eq. (4) gives good agreement with the data of regular wave experiments with Toyoura sand, when A is 7 and Ψ_c is 0.11.



(a) Significant wave (b) Mean wave

Fig. 5 Critical conditions for sand ripple formation



(a) Significant wave (b) Mean wave

Fig. 6 Relationship between wave length of sand ripples and orbital diameter of water particle

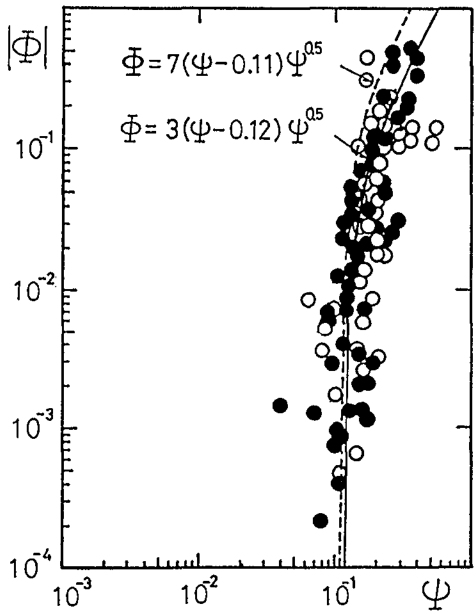


Fig. 7

Net rate of cross-shore sediment transport (Toyoura sand, d_{50} = 0.18mm)

Figure 7 shows the relationship between the non-dimensional sediment transport rate and the Shields parameter for the cases of fine (Toyoura) sand in the present experiments. In the figure, open and closed symbols indicate onshore and offshore transport respectively.

Experimental data do not so scatter, showing the same tendency as seen for regular wave experiments: namely, the value of Φ increases rapidly with the Ψ value while the latter is small, but its increase rate gradually diminishes as Ψ increases. It is very interesting that the Shields parameter is effective in expressing the sediment transport rate even under the irregular wave conditions. Eq. (4) again gives a good expression for the experimental data. However, the magnitude of the coefficient A seems to be somewhat smaller for irregular wave cases than for regular wave ones. This may indicate that the efficiency of wave power to set sand grains in motion reduces under the irregular wave conditions. This tendency corresponds to the slow speed of the beach transformation as mentioned before.

As for the representative wave, two of them gave very similar results. Therefore, the representative wave could not be specified for the sediment transport rate.

4. CONCLUSIONS

Through the present study, the effects of irregular waves on two-dimensional beach transformation were investigated. The examined subjects are macroscopic beach profile change and its classification, threshold of sand movement, characteristics of sand ripples and cross-shore sediment transport rate. The representative wave for each phenomenon were determined by comparing the results of the present experiments of irregular waves with those from regular wave studies. It is very interesting that there are two kinds of phenomena related to the two-dimensional beach transformation, which are controlled by whole incident waves or a group of large waves in a irregular wave train. These understandings are the important step to obtain a general view of beach transformation in real coasts.

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