CHAPTER 138

The Criterion of Ripple Formation by Wave Action

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Abstract

In this paper, we emphasize that there must exist a common mechanism governing ripple formation in the case of both waves where the acceleration effect exists, and unidirectional flow, where the acceleration effect is usually ignored. Using a light sediment with an immersed specific gravity of about 0.8, which is nearly one-half that of natural sand, a series of ripple formation experiments were performed in order to determine the formation criterion. Using the experimental data, along with data collected by other researchers the ripple-formation criterion was investigated in terms of the ratio of water particle orbital diameter to sediment grain diameter as an acceleration parameter, on the so-called Shields diagram. Emphasis is placed on the importance of this ratio in the criterion of ripple formation in relation to that by unidirectional flow.

1. INTRODUCTION

Sand transport due to wave action or by combined wave & current action is one of the transport phenomena which takes place as prescribed by the laws governing sediment and fluid interation. Many investigations on such a phenomenon have been actively carried out. One of the most salient futures pertaining to sediment transport by waves and by flowing water is the threshold of sediment movement. All the experimental data for the threshold of sediment movement can be plotted on a Shields diagram, but there exists an acceleration effect in wave motion. In relation to sediment transport, the relevant phenomena by waves and by flowing water must be identified and qualified in the mechanics of sediment transport.

The seabed sediment ripple is of great interest not only in understanding the formation phenomena, but also in establishing the mechanics of sediment transport by wave action. Many physical model experiments of beach change have been performed, but none have introduced seabed forms in their comparisons between model and prototype phenomena, as well as in their similitude. Physical model experiments should be carried by placing major emphasis on bed form similitude, which in turn results in a similitude of the governing physical phenomenon.

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When no bed form considerations are made severe scale effects may result in thc comparison between model and prototype. It is therefore noted that, in physical model experiments scabed forms and their formation criteria are required in order to determine what seabed forms occur in the prototype.

Thus far, many attempts have been made to classify seabed forms, by Bagnold(1946), Manohar(1955), Komar & Miller(1975), Kaneko(1980) and Horikawa & Shibayama(1982), in terms of Shields number and other parameters such as sediment Reynolds number and the ratio of water particle orbital diameter to sediment grain diameter. As previously mentioned, the classification of bed forms by waves should be made in relation to that by unidirectional flow. It is however further mentioned that a common formation mechanism must exist between the sea and river beds, even though additional parameters may exist which specify a specific phenomenon. In 1975 Komar and Miller examined the seabed forms and their formation criteria in relation to those by unidirectional flow. In the criterion, experimcntal data of the sea bed forms were plotted on a Shields diagram where the sediment Reynolds number is defined using maximum water particle velocity. An empirical formula of the criterion from ripple to sheet flow condition was then proposed, however, no considerations were made on the acceleration effect due to wave motion on the criterion of ripple formation. Kaneko proposed a criterion of seabed forms in terms of the sediment mobility parameter and the ratio of boundary layer thickness to sediment grain diameter. In the criterion, seabcd forms are classified into five such as no ripple, two-dimensional ripple, brick pattern, irregular ripple and sheet flow. Sunamura introduced the asymmetry of wave motion into the criterion of seabed forms and proposed a dimensionless sediment-wave parameter which was given from the threshold condition by Komar and Miller. Horikawa and Shibayama, on the other hand, proposed a criterion of sediment transport types using the Shields number and the ratio of sediment fall velocity to maximum water particle velocity, but not shear velocity. This criterion is not for seabed classification and its formation criterion, but the dimensionless parameters used are worthy of being considered in relation to the parameters employed by the other researchers.

In this paper, using a light sediment with an immersed specific gravity of about 0.8 which is nearly one-half that of natural sand, a series of ripple formation experiments were carried out in order to determine the formation criterion in the case of small sediment Reynolds number. Using the experimental data, along with data collected by other researchers the ripple formation criterion is investigated based on the ratio of water particle orbital diameter to sediment grain diameter on the so-called Shields diagram. This ratio expresses the effect of wave acceleration on sediment transport. Emphasis is placed on the importance of the ratio in the criteria of ripple formation in relation to that by unidirectional flow.

2. SAND TRANSPORT TYPES AND BED FORMS

In general, there are usually two states of sand transport which are only for convenience in their investigation. Recently, Shibayama and Horikawa(1982) proposed a classification of sand transport types in relation to the ripple formation. Four states are used to classify sediment transport, they are bed load, transition from bed load to suspended load, suspended load and sheet flow. Their classification is shown in Figure 1 where τ^* is the Shields number and u_0/w_0 the ratio of maximum water particle

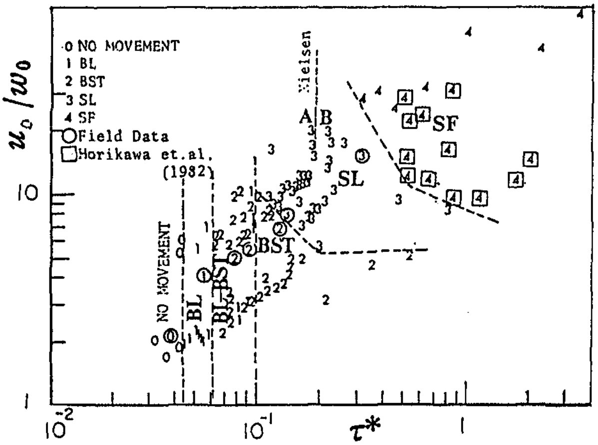


Figure 1. Classification of sand transport types by Shibayama & Horikawa

velocity at the sea bottom to fall velocity of the sand. These transport states are identified according to the resulting bed forms. In the case of no movement, sand does not apparently move by the wave action, but at the threshold condition a critical state is reached such that sediment movement is initiated. The transport state identified as flat bed describes a condition where sediment movement and transport exist yet the bed remains flat. In the state, sand moves mainly as bed load. At a certain state when the shearing stress acting on the sand bed becomes large, ripples appear. In this state, sand moves in suspension around the ripples, and this corresponds to suspended load in the classification of sand transport types by Shibayama and Horikawa. As the shearing stress becomes larger, a flate bed again results, and it is usually identified as sheet flow, first named by Bagnold(1946). The flat bed states occurring under conditions just after the movement threshold is reached and after ripple formation correspond to the lower and upper regimes of flow in the case of river bed mechanics.

3. THE CRITERIA FOR SEABED FORMS

The most important factors governing seabed formation are first considered by referring to both the previous investigations of seabed forms, their formation criteria and the threshold of sand movement. Secondly, using the main factors selected the criteria of seabed forms are proposed.

3.1 Classifications of Seabed Forms and Their Main Factors

As already mentioned, Komar & Miller(1975) classified seabed forms into three groups, no movement, ripple and sheet flow as shown in Figure 2 where u_0D/ν is the sand grain Reynolds number relative to the maximum water particle velocity at the bottom, not to the shear velolcity. The sand transsnport phenomenon is well governed by the shearing stresses acting on the seabed, it is questionable as to why the sand grain Reynolds number u_0D/ν is used instead of u^*D/ν where u^* is the shear velocity.

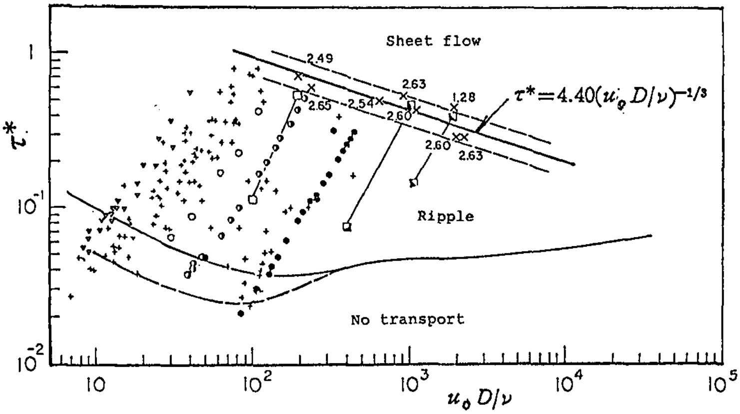


Figure 2. Classification of ripple formation by Komar & Miller(1975)

In Figure 2, it is clearly shown that the criterion for separation between no-movemnt and ripple is not well established, however, in the upper regime where sheet flow initiates, the criterion operates well, and results in an empirical formula in the form

$$\tau^* = 4.40(u_0D/\nu)^{-1/3} \tag{1}$$

In addition to the ripple to sheet flow classification scheme employed by Komar & Miller, Manohar(1955) considered the sand grain size effect in addition to the Shields number. Carsterns, Neilson & Altinbilek(1969) introduced the ratio of the water particle orbital diameter to the sand grain diameter into the criterion, however no graphical presentation was presented. In 1976, Dingler and Inman proposed an emprical criterion in the form

$$u_0^2/(\sigma/\rho-1)gD = 240 \tag{2}$$

In 1979, Nielsen proposed an empirical criterion in the form

$$\tau^* = 0.83 \tag{3}$$

And more recently Shibayama and Horikawa(1982) proposed the critial Shields number as 0.5 to 0.6., and 0.4 in the experiment by Shibayama(1984). The criteria proposed by Nielsen and Shibayama & Horikawa are independent of the sand grain Reynolds number. It is generally difficult to qualify the resistance law in the sheet flow. As stated by Komar and Miller(1975), the constitutive equation for two-phase flow by Bagnold(1956) is given by

$$\tau^* = C \tan\varphi \tag{4}$$

where C is the static volume concentration being about 0.6 to 0.7 for natural sands and $\tan\varphi$ is the coefficient of solid friction which varied from 0.375 to 0.75 in Bagnold's experiment. The critical Shields number therefore varies from 0.23 to 0.53. These values of the critical Shields number are close to those previously mentioned by Nielsen and Shibayama & Horikawa.

More recently, Kaneko(1980) classified seabed forms using two parameters, the sediment mobility paprameter and the ratio of the sand grain diameter to the boundary layer thickness in Figure 3.

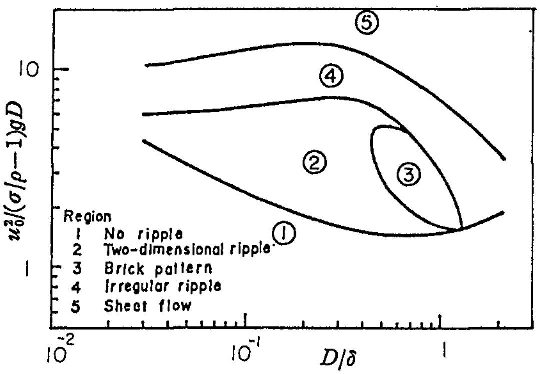


Figure 3. Classification of seabed forms by Kaneko(1980)

In this figure, the ratio is rewritten as

$$D/\delta = \sqrt{\pi D^2/\nu T} \tag{5}$$

where T is the wave period and ν the kinematic viscosity of water. The ratio, which is in the form of a Reynolds number, considers the effect of boundary shearing stress acting on the seabed. He classified seabed froms into the following five stages, 1) no ripple, 2) two-dimensional ripplc, 3) brick pattern, 4) irregular ripple and 5) sheet flow. The classification shows that a brick pattern forms under limited conditions defined by the two parameters, furthermore, the region over which the brick pattern forms is small relative to the regions occupied by the other four bed form classifications. In this classification, however, no consideration is made of the threshold of sand movement and the flat bed in the lower regime.

Furthermore, Sunamura(1981) introduced the asymmetry effect of the wave field on the bed forms using the Ursell parameter $U_r = HL^2/h^3$, where H is the wave height, L the wave length and h the water depth and a new parameter F, where

$$F = \frac{u_0^2}{(\sigma/\rho-1)gD^{1/2}d_0^{1/2}} \tag{6}$$

where d_0 is the water particle orbital diameter. This parameter was introduced by Komar and Miller(1975) as a relation describing the threshold of sand movement. His classification is expressed as an empirical formula in the form

$$F = KU_r^{1/4} \tag{7}$$

where the coefficient K specifies seabed forms in the following five stages: 1) no movement, 2) flat bed, 3) ripple bed, 4) flattened-ripple bed and 5) sheet flow. The asymmetry of the wave field was shown to influence seabed formation, however, this effect will not be considered any further.

From the above considerations of seabed forms and their formation criteria, the expressions for the criteria from flat bed to ripple bed and ripple bed to sheet flow are not so clear, however, the dimensionless parameters for specifying the formation criteria are useful. River bed forms and their formation criteria are considered, and in this criteria the ratio of water depth to sand grain diameter is assumed to be very large, while ignored in the criterion for seabed forms. In the theory of the threshold of sand movement by Tsuchiya, Ueda and Oshimo(1984), as shown in Figure 4, the theoretical curves of the sand movement threshold are expressed by three parameters, the Shields number, sand grain Reynolds number or sediment-fluid number and the ratio of water particle orbital diameter to sand grain diameter. And in this paper, specified are four stages; they are no sand movement, flat bed, ripple and sheet flow, flat bed in the upper regime. Based on these considerations, the formationcriterion of seabed can be expressed by

$$F_1(\tau^*,\ u^*D/\nu \text{ or } D_\nu^*,\ d_0/D) = 0 \tag{8}$$

where the ratio does not remarkably influence the threshold of sand movement as shown in Figure 4, but as already mentioned by Tsuchiya (1987), the ratio effect is remarkable in the geometry of ripples when the ratio becomes greater than about 1000. Therefore an influence of the ratio on the criteria from flat bed to ripple and ripple bed to sheet

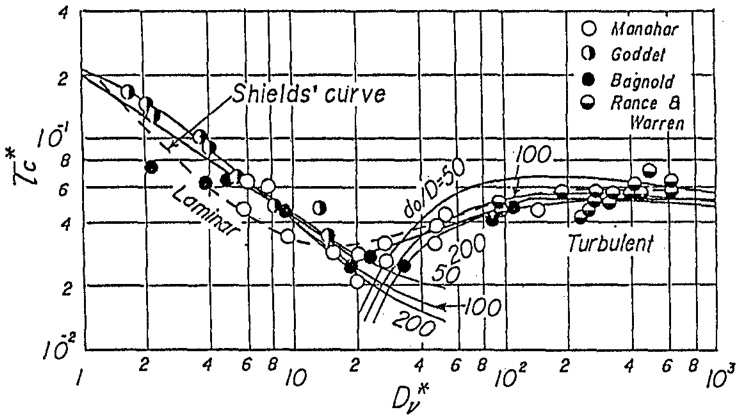


Figure 4. Criterion for the threshold of sand movement

flow may be expected to exist. It is well-known that the ratio expresses the acceleration effect in the wave motion. Physically, the seabed formation when the ratio becomes infinity may correspnds to that by unidirectional flow having an infinite value of the ratio of water depth to sand grain diameter. From this fact the flat beds in the lower and upper regimes may be defined as lower-flat bed and upper-flat bed, respectively.

The upper-flat bed corresponds to the so-called sheet flow. In these regimes, however, the essential difference between sea and river bed formation is the free surface effect which is described by the Froude number, and exists only in the river bed formation.

Additionally, dimensional analysis is used to describe the seabed forms and their formation criteria by Yalin(1964), Mogridge & Kamphuis(1973), Dingler & Inman(1976), and more recently Kaneko 1980) in the form

$$F_2\{u_0^2/(\sigma/\rho-1)gD,\ D^2/\nu T,\ d_0/D\} = 0 \tag{9}$$

Using expression (9) Kaneko derived Figure 3. Both expressions (8) and (9) are physically related to the shear velocity.

3.2 Experimental Data and Their Arrangement

Using a double-deck wave tank 38m long, 0.7m wide and 0.7m deep and a light sediment with an immersed specific gravity of about 0.8 and a diameter of 0.085cm, several experiments were carried out to determine seabed forms and their formation criteria in the region of small sediment Reynolds number. Experimental data from this and other experiments arc shown in Table 1 for the immersed specific gravities and diameters of the sediment used.

Table 1. The experimental data used

Researchers (Year published)	Immersed specific gravity $(\sigma/\rho-1)$	Grain diameter D in cm
Manohar(1955)	1.60	0.101
	1.65	0.028
Lofquist(1968)	1.65	0.055
	1.65	0.021
		0.018
Carstens, Neilson & Altinbilek(1969)	1.47	0.030
	1.62	0.059
	1.66	0.019
Horikawa & Watanabe (1967)	1.65	0.020
Sunamura(1981)	1.65	0.020
	1.65	0.070
	1.65	0.156
Tsuchiya & Banno (1988)	0.80	0.085

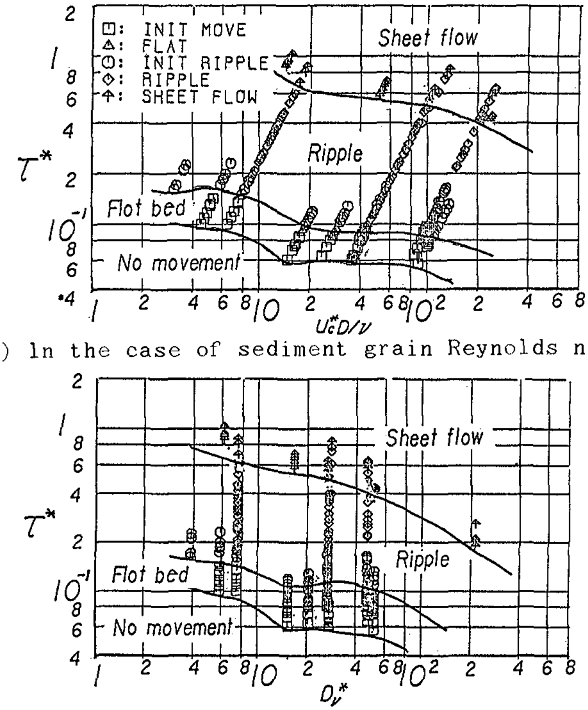
In the expression of the formation criterion by (8), the shear velocity, which results from the interaction between waves and sediment, should be carefully estimated. In this paper, formulas for the friction factor by Jonsson(1966) and Madsen & Grant(1980) were used. Practically, the friction factor can be expressed by Nielsen(1981) as

$$f_w = \exp\{5.12(5D/d_0)^{0.194}-5.98\} \tag{10}$$

Using the experimental conditions of waves and the sediment properties shown in Table 1, the friction factor was calculated by (10) and Madsen & Grant' formula and then the shear veloctiy was obtained in relation to the maximum water particle velocity at the sea bed. Finally, all the dimensionless parameters in (8) were calculated.

Figure 5 shows an example of the changing stages of bed forms in relation to the Shields number and sediment grain Reynolds number or sediment-fluid number. In the figures, based on the bed forms specified by the researchers bed forms are shown with symbols which are initial movement, flat, initiation of ripple, ripple and sheet flow. All the experimental data were arranged in the sediment conditions as shown in the figure. From these figures, criteria for the four stages in seabed forms can be obtained. The criterion from no-movement to flat-bed in the lower regime is greatly due to the findings of observers, and as stated by Sleath (1984), the experimental data are very scattered.

However, the experimental data for the other criteria are not so scattered because observational findings of the criteria are generally obvious.



(a) In the case of sediment grain Reynolds number

(b) In the case of sediment-fluid number

Figure 5. Determination of the criteria from experimental data (1)

3.3 The Formation Criterion of Seabed Forms (1)

The formation criterion for seabed forms by (8) is shown in Figure 6 where only the Shields curve is shown for the threshold of sand movement. In the figure, the criteria from lower-flat bed to ripple bed and ripple bed to upper-flat bed, sheet flow are shown with the ratio of water particle orbital diameter to sand grain diameter. Using (10) Komar & Miller' empirical formula (1) can be transformed to

$$\tau^* = 3.22 f_w^{1/7} D_\nu^{*-3/7} \tag{11}$$

where in the estimation of the friction factor the value of d_0/D in (10) was evaluated as 3,400 by Carstens, Neilson & Altinbilek(1969) and 16,000 by Kennedy & Falcon(1965) for the criterion from ripple to sheet flow.

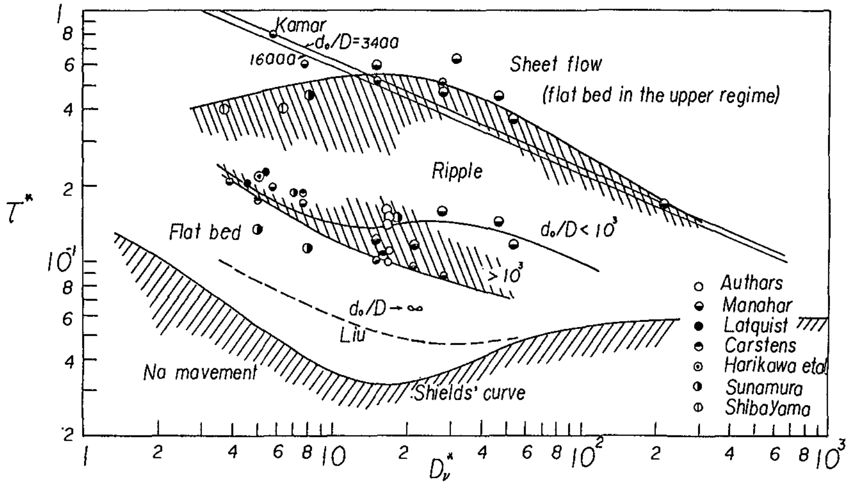


Figure 6. The formation criterion of seabed forms by (8)

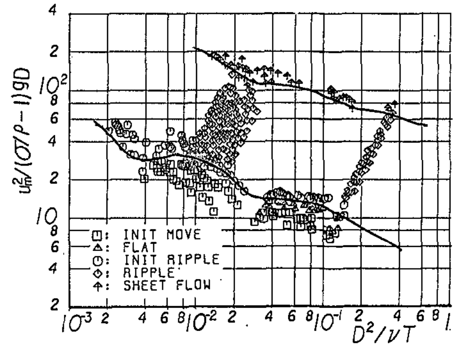
In the formation criteria shown in Figure 6, no experimental data for the threshold of sand movemnt are shown due to the high degree of scatter. In Figure 1, the general trend of the experimental data are shown to be similar to the curves by Tsuchiya & Banno. It is noted that the criteria from lower-flat bed to ripple and from ripple to upper-flat bed can be described by the Shields number, the sediment grain Reynolds number or sediment-fluid number and the ratio of water particle orbital diameter. The experimental data is not enough to definitely specify the criteria, so that further experiments are needed especially for the regions where the sedimnt-fluid number are very small or greater than about 100, and for the case when light sediment is used in the wide range of d_0/D. However, it is noted from the figure that in the criterion from lower-flat bed to ripple the effect of the ratio of water particle orbital diameter to sand grain diameter clearly exists, that is, the values of the critical Shields number in the case of d_0/D values larger than 1,000 are plotted lower than those in the case of values smaller than 1,000. This tendency increases with the increase in the sediment-fluid number. And, the criterion changes with the sediment-fluid number. In the figure Liu's curve for the criterion from lower-flat bed to ripple by unidirectional flow is also shown. In this case, the value of d_0/D may be considered as infinity in relation to the criterion of ripple formation by waves. These tendencies show that the the critical Shields number for larger sediment is smaller than that smaller sediment, that is, ripples formed in course sediment are generated by a smaller Shields number than that in fine sediment. Comparing Liu's curve for unidirectional flow with the curves for the criterion from lower-flat bed to ripple, the curve for the d_0/D values larger than 1,000 which are not so comparable to infinity may tend to approach Liu's curve.The range of lower-flat bed becomes narrow with the increase of sediment-fluid number and may then vanish when the value becomes about 100, this tendency may be further supported by Liu's curve. In the region of samller sediment-fluid number, the effect of the ratio d_0/D is not obvious and may disappear.

In the criterion from ripple to upper-flat bed, Komar & Miller's empirical formula (11) is shown in Figure 6. The average value of the critical Shields number may be very close to the values used by Shibayama & Horikawa(1982), but the Shields number changes with the sediment-fluid number. The curve shown in the figure by a solid line is very similar to Komar & Miller's, except for the region of small sediment-fluid number. In this criterion, the effect of the ratio of water particle orbital diameter to sand grain diameter disappears in the whole range of sediment-fluid number. The formation of sheet flow in the upper flat-bed is of course caused by high shear flow both in sediment transport by waves and unidirectional flow, however, it is recognized that in the upper-flat bed no interaction between the free surface and seabed forms by wave action exists, but pronounced interaction between the free water surface and river bed forms exists where the ratio of water depth to sediment grain diameter is most predominant. Therefore, the formation criterion of sheet flow by wave action can not be directly compared with that by unidirectional free surface flow.

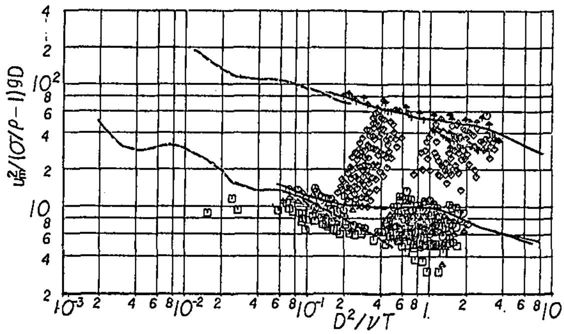
3.4 The Formation Criterion of Seabed Forms (2)

By use of (9) the formation criterion of seabed forms is considered. As already described, Kaneko(1980) proposed the criteria of seabed forms classifying them into his own five stages, as shown in Figure 3. Using the experimental data shown in Table 1 with the same dimensionless parameters as those by Kaneko, but classifying only four stages of seabed forms as used in the previous criterion, the formation criterion was examined.

Using Manohar's data shown in Table 1, all the dimensionless parameters in (9) were calculated and the results are shown in Figure 7 where (a) and (b) represent values of d_0/D smaller than 1,000 and larger than 1,000, respectively. It is obvious that the formation criterion of seabed forms can be made, but the effect of the ratio of water particle orbital diameter to sediment grain diameter is not so remarkable. In the region of large Reynolds number $D^2/\nu T$ in (a) and around the transition from lower-flat bed to ripple, larger values of d_0/D may result in larger values of the sediment mobility parameter. In the criterion from ripple to sheet flow, however, the influence of the ratio is hardly found. This may be supported by the result obtained by Figure 6.



(a) In the case where d_0/D<1,000



(b) In the case where d_0/D>1,000

Figure 7. Determination of the criteria from experimental data (2)

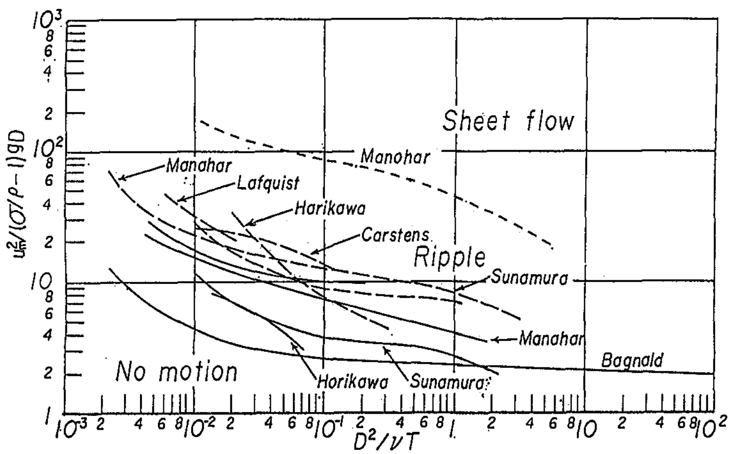


Figure 8. The formation criterion of seabed forms by (9)

In the figure, neglecting the effect of the ratio of water particle orbital diameter to sand grain diameter, the criteria are obtained separately by researchers in terms of the sedimcnt mobility parameter $u_0^2/(\sigma/\rho-1)gD$ and the sediment Reynolds number $D^2/\nu T$. Figure 8 shows the criteria from no movement to flat bed, flat bed to ripple and ripple to upper-flat bed, respectively. On the threshold of sand movement, as already pointed out by Komar and Miller(1975), an effect of the ratio exists. And, by this expression the criteria from flat bed to ripple have a similar tendency in relation to the sediment Reynolds number, however, there is a large variation due to experimental conditions. This variation may be mainly due to the expression of the formation criteria, as well as experimental conditions.

It is recongnized from this fact that the previous expression of the formation criterion of seabed forms is better than the latter one taking into account the mutual relation in the formation prosseses of bed forms by waves and unidirectional flows.

4. CONCLUSIONS

In the criterion of sebed forms, many investigations have been carried out in terms of the so-called Shields diagram and other dimensionless expressions derived by dimensional analysis. In this paper, using a light sediment some experiments were conducted, and using the experimental data, along with data collected by other researchers, the ripple formation criterion was studied as the formation criterion of seabed forms in relation to that by unidirectional flows. Further experiments are needed, but from the formation criteria of seabed forms the main conclusions are:

1) As shown in Figure 6, the formation criterion of seabed forms can be made on the Shields diagram by introducing the ratio of water particle orbital diamter to sand grain diameter which acts as an acceleration effect in the wave motion. When the ratio becomes infinity the critical Shields number for the criterion tends to the unidirectional one.

2) The criterion of sheet flow, upper-flat bed can be expressed both by the Shields number and sediment-fluid number. In this criterion, the ratio has little influence on the formation criterion.

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