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Scale Effects and Geometry of Sand Ripples under Wave Effects
海底砂漣의 形狀特性과 縮尺效果

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Abstract□Sand ripple, the smallest bottom configuration, is one of the most important factors in the mechanism of sand transport. This paper deals with characteristics of ripple geometry generated by regular and irregular waves. Especially, rearrangement of ripple spacing caused by increasing or decreasing waves is investigated through movable bed experiments. Nondimensional length of rearranged ripples becomes very close to that of measured ripples in the field. Furthermore, stochastic characteristics and occurrence limits of three dimensional ripples are investigated through the wave number spectrum calculated from the measured bottom topography.

要 旨: 海底最小 Scale의 地形인 砂漣은 Scale은 작지만, 漂砂移動을 유발시키는 중요한 要素중의 하나이다. 本 硏究는 이러한 海底砂漣의 形狀特性을 면밀히 檢討하고, 종래 檢討되지 않았던 3次元 砂漣의 統計的 形狀特性을 分析하였다. 또한 來襲波가 變化할 경우, 이미 形成되어져 있는 砂漣이 새롭게 形成되는 砂漣에 미치는 影響(現地에서 砂漣의 履歷效果)에 대해서 檢討하였다. 그 結果, 파고가 증가하거나 감소하는 履歷效果의 影響을 입은 砂漣의 無次元波長은 지금까지의 Flat bed에서 직접 形成된 砂漣의 無次元波長보다 그 값이 크고, 現地砂漣의 無次元波長에 보다 근접한 값을 나타냈다. 따라서, 現地와 實驗室의 Scale의 差異(縮尺效果)는 이와같은 砂漣의 履歷效果가 하나의 要因으로 作用하고 있는 것이 확인되었다.

1. INTRODUCTION

When we want to reproduce the field transport sediment in a laboratory, we have to establish a similitude law. A similitude law is necessary when the sediment transport in a field is reproduced in a laboratory. When we apply our knowledge of sediment transport obtained in the laboratory to the prediction of sediment transport in the field, we can apply Froudian law to a fluid motion that becomes agitation agency and transporting capability of sediments. However, we can not apply Froudian law to sediment movement. When we scale down the size of sediment for the laboratory situation, it becomes too small to be cohesionless sediment. Many researchers have already carried out studies regarding similitude law of bed material. However, universal similitude law has not been established yet.

The difference of ripple scales in the field and in the laboratory is one of the most important problems to establish similitude law of sediment transport, because ripple plays an important role in the suspension of sediment. The difference of ripple scale may cause the scale effects in suspended sediment and occurrence of sheet flow.

The followings are conceivable causes that bring about these scale effects.

(1) Ripples in the field are generated by irregular waves, but ripples in the laboratory are usually reproduced by regular waves.

(2) The difference between grain Reynolds number and a KC number is large.

(3) Ripples are generated as a result of ever-changing waves in the field. That is, the existing ripples

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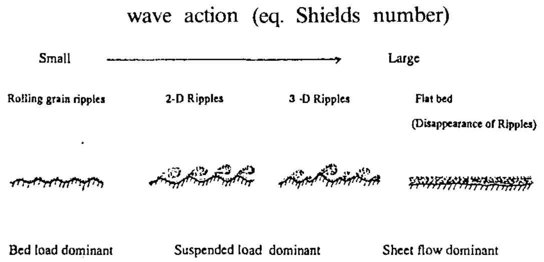


Fig. 1. Bottom topography and mode of sediment movement.

in the field received effects of time history of incident waves. But ripples in laboratories are usually generated directly from a flat bed by incident waves of unique characteristics.

The points at issue listed in (1) and (2) have already been examined by many investigators through experiments. However, the effect of time history of incident waves on ripple geometry is not yet fully studied.

A transformation of bed configuration according to the increase of wave action is shown in Fig. 1. Generally, modes of sediment movement are related to the above mentioned microscopic bottom topography and be classified into bed load, suspended load and sheet flow as illustrated in Fig. 1. Although the initiation of 2-D ripples has been studied by many investigators, only a few studies have been carried out about the occurrence and characteristics of 3-D ripples.

In this resarch we examined the effect of time history of incident waves on ripple geometry by using regular waves and irregular waves. The occurrence limits of 3-D ripples are also investigated.

2. FACILITIES AND PROCEDURES OF LABORATORY EXPERIMENTS

Laboratory experiments were carried out in two dimensional wave flumes using regular waves and irregular waves of Bretschneider-Mitsuyasu type spectrum. Five series of regular wave experiments and two series of irregular wave experiments were carried out. In each series, we increased wave height of incident waves at a fixed frequency and then decreased them to investigate the characteristics of rearrangement of ripple geometry to varying waves. The details of these experimental conditions are shown in Table 1. Each set of waves was generated for two hours. Two kinds of well-sorted sand of mean grain size, 0.12 mm and 0.45 mm, were used to construct movable bed on the horizontal fixed bed. The length of movable bed was 6 m in each flume. In the experiment, we measured bottom profiles along two measuring lines in the direction of wave propagation by a resistance type bottom profiler. To reduce the influence of reflected waves in the flume, we used a wave absorber with vertical slits at the opposite end of the wave maker. The maximum reflection coefficient was less than 6% in all experiments. The height and length of ripples were defined by a wave-by-wave analysis of measured bottom topography after passing through numerical (high-pass) filter. Wave number spectra of bottom topography were also calculated. Furthermore, we examined deformation process of sand ripples in detail by video analysis.

3. RIPPLE GEOMETRY AND EFFECT OF TIME HISTORY OF INCIDENT WAVES

3.1 Nondimensional Length of Ripple

Many studies on generations and characteristics of ripples have been carried out. In these studies, ripple length λ is normalized by the water particle excursion (d_0) defined by using a water particle velocity at the bottom U_b and an angular frequency as follows;

$$d_0 = U_b/\sigma = H/8\ (1/\sinh\ kh) \tag{1}$$

Homma *et al.* (1964) and Sakakiyama *et al.* (1984) analyzed the nondimensional ripple length λ/d_0 with respect to Reynolds number(R_D) and mobility number(M_n) defined as follows:

$$R_D = U_b d_0/\nu \tag{2}$$

$$M_n = U_b^2/\sigma_s\ gD \tag{3}$$

Nielsen (1981) investigated the nondimensional length (λ/d_0) in the laboratory and in the field by using mobility number proposed by Brebner (1979). He reported that the significant difference in ripple geometry existed between in the laboratory and in

Table 1. Case of movable bed experiments for Sand Ripple

Case	Wave Height(cm)	Wave Period(sec)	Water Depth(cm)	Current Velocity(cm/s)	Initial Bed	Wave Condition
1	6.0	1.25	25	0	Falt	Irregular
2	7.9	1.25	〃	〃	〃	〃
3	8.7	1.25	〃	〃	〃	〃
4	6.5	1.5	〃	〃	〃	〃
5	8.7	1.5	〃	〃	〃	〃
6	10.3	1.5	〃	〃	〃	〃
7	7.8	1.25	〃	〃	Relict	〃
8	8.9	1.25	〃	〃	〃	〃
9	8.6	1.5	〃	〃	〃	〃
10	10.9	1.5	〃	〃	〃	〃
11	12.3	2.0	50	〃	Flat	Regular
12	14.5	2.0	〃	〃	〃	〃
13	22.5	2.0	〃	〃	〃	〃
14	11.3	2.5	〃	〃	〃	〃
15	13.2	2.5	〃	〃	〃	〃
16	21.5	2.5	〃	〃	〃	〃
17	11.5	1.5	〃	〃	〃	〃
18	14.2	1.5	〃	〃	〃	〃
19	19.0	1.5	〃	〃	〃	〃
20	5.0	1.25	25	〃	〃	〃
21	4.5	1.5	〃	〃	〃	〃
22	14.7	2.0	50	0	Relict	Regular
23	17.0	〃	〃	〃	〃	〃
24	22.8	〃	〃	〃	〃	〃
25	16.8	〃	〃	〃	〃	〃
26	14.5	〃	〃	〃	〃	〃
27	12.1	〃	〃	〃	〃	〃
28	13.4	2.5	〃	〃	〃	〃
29	16.0	〃	〃	〃	〃	〃
30	21.5	〃	〃	〃	〃	〃
31	15.9	〃	〃	〃	〃	〃
32	13.5	〃	〃	〃	〃	〃
33	11.1	〃	〃	〃	〃	〃
34	14.3	1.5	〃	〃	〃	〃
35	16.9	〃	〃	〃	〃	〃
36	19.1	〃	〃	〃	〃	〃
37	17.0	〃	〃	〃	〃	〃
38	14.2	〃	〃	〃	〃	〃
39	11.2	〃	〃	〃	〃	〃
40	8.2	1.25	25	〃	〃	〃
41	14.8	〃	〃	〃	〃	〃
42	8.2	1.5	〃	〃	〃	〃

the field, and proposed a formula of the difference.

Kaneko (1980) analyzed ripple geometry by using the relative diameter of bed material to the water particle excursion d_0/D instead of M_n. The difference of λ/d_0 between laboratories was reduced a little. However nondimensional length (λ/d_0) of the field ripples in the region of $d_0/D<3\times10^3$ is fairly larger than those of laboratories.

Sato *et al.* (1987) investigated λ/d_0 with respect to a parameter $\psi=\phi_D^{1/2}d_0/D$ that is a combination of Shields number and λ/d_0. They showed that the resulting, difference of λ/d_0 between the field and

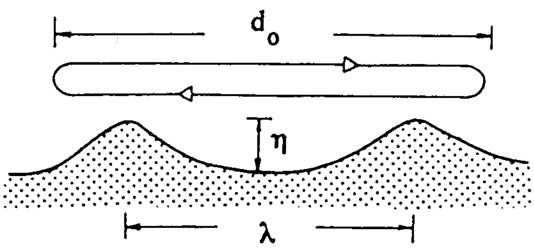


Fig. 2. Definition sketch of ripples.

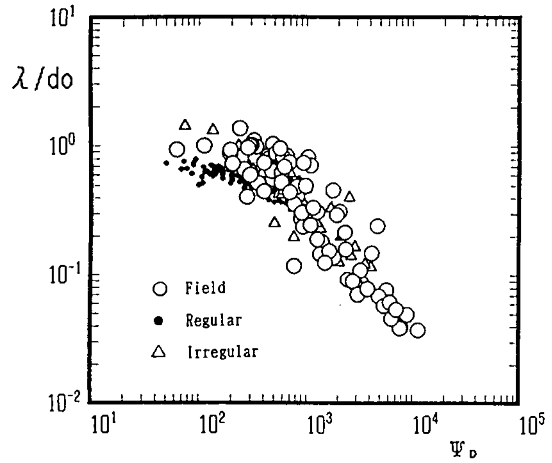


Fig. 3. Relationship between λ/d_0 and ψ_D for ripples in laboratory and field (I).

the laboratory became small.

Fig. 3 illustrates the relationship between nondimensional ripple length λ/d_0 and parameter $\psi(=\phi_D^{1/2}d_0/D)$ proposed by Sato *et al.* Table 2 is the raw data of ripple geometry obtained in these experiments. The Shields number ϕ_D used in the parameter ψ is calculated by using the formula as follows:

$$\phi_D = 1/2(f_w U_b^2)\sigma_s\ gD \quad (4)$$

$$f_w = \exp(5.21(d_0/k_s)^{0.19} - 0.125) \quad (5)$$

$$k_s = 2.50D \quad (6)$$

Again nondimensional ripple length in the field is larger than that in the laboratory in the range of ψ smaller than 10^3.

Generally, water particle motion near the bottom receives a great influence of ripple geometry. Wave-generated ripples influence sediment transport in two ways. First, flow contraction near the crests

Table 2. Data of ripples geometry used in the analysis

Inman (1957) Miller & Komar (1980) Nielsen (1984) Nielsen and Gordon (1984)	Field Data
Nakato *et al.* (1977) Lofquist (1978) Hashimoto et al (1983) Sato et al (1985)	Wave Tunnel
Matsunashi (1964) Hosoi & Kida (1973) Nielson (1979) Sawamoto *et al.* (1982) Hayagawa *et al.* (1985) Maeda (1987) Sawaragi *et al.* (1991) This study (1992)	Wave Flume

leads to vastly increased local shear stresses and higher sediment concentration. Secondly, ripples increase the bed roughness, which leads to larger vertical length scales of the sediment concentration profiles. Therefore, the sand ripple geometry should be taken into account when we evaluate the roughness in the expression of the bottom shear stress.

Eq. (6) is proposed by Kamphuis (1974) based on the measurements of shear stress on a movable bed but with no ripples. Some researchers have carried out experimental studies on the roughness of movable bed with bottom configurations. The representative expressions are shown below,

Grant & Madsen(1982) $k_s = 27.7\eta/\lambda(\eta)$ (7)

Vitale(1979) $k_s = 2D_{90} + 0.01\eta$ (8)

Nielsen(1983) $k_s = 8\eta/\lambda(\eta) + 190D(\phi_D - 0.05)^{1/2}$ (9)

It is reported that the bottom stress calculated by using Eq. (7) overestimates wave attenuation on ripple bed (Nielson, 1983).

Eq. (8) can be applied only to rippled bed, whose height η is smaller than 6.9 cm. Therefore, in this study the expression of Nielsen is used for the evaluation of roughness and we estimate ripple-height Shields number ϕ_η. Fig. 4 shows the relation between λ/d_0 and ψ_η evaluated using ϕ_η instead of ϕ_D. We can see from Fig. 4 that there still remains difference between the values of λ/d_0 in the field and

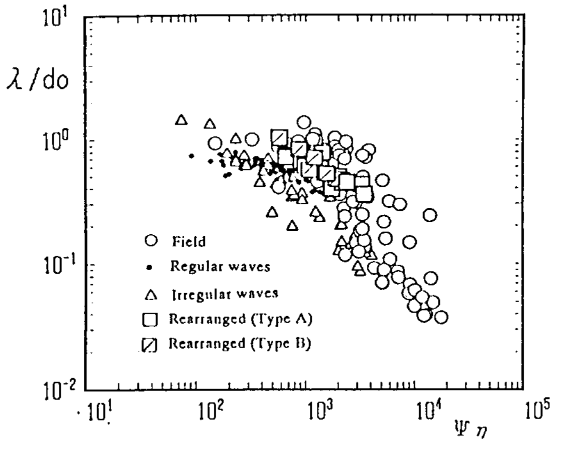


Fig. 4. Relationship between λ/d_0 and ψ_η for ripples in laboratory and field (II).

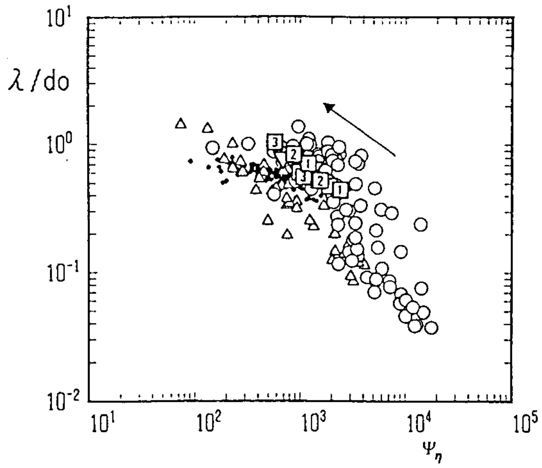


Fig. 5. Result of the case of gradually decreasing wave height (Type-A).

in the laboratory.

3.2. Effect of Variation of Incident Wave Height on Ripple

The results obtained from experiments where incident wave heights were changed are shown in Fig. 5, i.e. the results of series 1-7 of this experiment. Type-A is a result of the case of gradually decreasing wave-height and Type-B is a result of gradually increasing wave-height. These results are shown by different symbols in the figure.

Values of λ/d_0 of the cases of Type-A are generally larger than those of ripples generated by one wave train. This tendency agrees with the measured result in the field (Davies, 1983). He reported that some length of ripples that were generated by large waves and rearranged by the following small waves became larger. As a result, nondimensional lengths of ripples of the laboratory in the process of increasing wave height become close to the nondimensional lengths of ripples in the field.

The difference of nondimensional ripple in laboratories and in fields in the range of ψ_η of this experiments can be explained by considering the time history of incident waves. However, we could not generate large waves in the range of $\psi_\eta > 6\times10^3$ due to the capacity of the wave generater. Therefore, we could not investigate the effect of waves on the disappearance limit of ripple form. According to the video analysis, the rearrangements of ripple spacing in the process of increasing and decreasing wave height take place in the following manner. In the process of decreasing wave height, one new ripple was generated between wave crests at interval of a few ripples without any significant influence on surrounding ripples. In the process of increasing wave height, one ripple or a few successive ripples disappeared out.

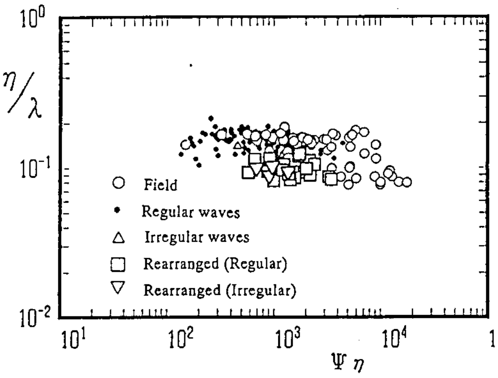


Fig. 6. Ripple steepness versus ψ_η for ripples in laboratory and field.

3.3. Ripple Steepness

As for the estimation of the wave height of ripples, good correlation were obtained with the relationship between the ripple steepness (η/λ) and the Shields parameter. Fig. 6 shows the relation between ripple steepness and Shields number. We can see from Fig. 6 that there is no significant difference in steepness between the ripples generated by regular and irregular waves in the laboratory. The difference of steepness between the field ripples and that of the laboratory is also small. The steepness of field ripples shows large scattering. The steepnesses of measured ripples in the processes of decreasing and increasing wave height correspond to the lower limit of the scattering of the field data. Again, we could not investigate the influence of waves in the range of $\psi_\eta > 6\times10^3$ on the steepness of ripples.

4. 2-D RIPPLES AND 3-D RIPPLES

It is very important from the engineering point of view to distinguish 2-D and 3-D ripples, because the characteristic of suspended sediment from the bottom deeply depends on the ripple geometry. When the incident wave is small (ψ_η is small), evenly-spacing long-crested ripples are generated. We define these irregular(short created) ripples as "3-D ripple." A so-called 'Brick Pattern' that appeared in the experiments of Bagnold (1946) and Kaneko (1980) did not take place in our experiments. They used an oscillatory flow tunnel instead of the wave tunnel. The 3-D ripples have the wave number both in the direction of wave propagation and in the perpendicular direction of wave propagation. Therefore, we can easily distinguish 2-D and 3-D ripples by comparing bottom topvograpies of the right angle direction. However, there is not a quantitative index to distinguish 2-D and 3-D ripples. Here, we examine the procedure to judge whether the ripple is 2-D and 3-D by using a wave number spectrum calculated from the bottom profile of only one measuring line. The wave number spectrum was calculated from the measured bottom topography at the interval of 0.5 cm and a number of data used in the calculation was 1024. Geometric characteristics of a ripple of each range was checked by the spectrum band width parameter defined by Eq. (10).

$$\varepsilon=(1-m_2^2/(m_0m_4))^{1/2}$$

$$m_n=\int_0^\infty f_n S(k)dk \tag{10}$$

Fig. 7 illustrates the occurrence range of 3-D ripples with the relation to ε and Shields number ϕ_η

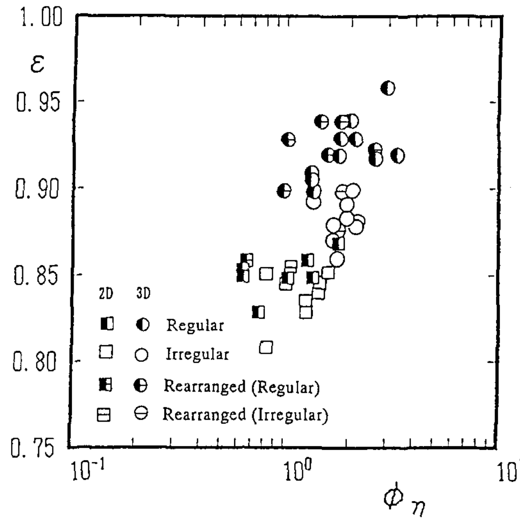


Fig. 7. Stochastic characteristics of geometry of regular and irregular wave generated ripples.

From the figure, it is found that 3-D ripples appear in the ranges of $\varepsilon>0.87$ in both regular and irregular wave experiments.

There is not a significant difference in the value of ε of the occurrence region of 3-D ripples generated by single wave from flat bed and varying waves where ripples received the effect of relict ripples formed by former incident waves.

Kaneko (1980) used two parameters $U_b/(\sigma_s gD)^{1/2}$ and D/σ, to express the occurrence limit of 3-D ripples, where $\sigma=(2\nu/\omega)^{1/2}$ and ω are the frequency. Sato *et al.* (1985) investigated the effect of ϕ_D and d_0/D on the limit. Here we examine the occurrence limit of 3-D ripples by using the ratio of water particle orbital excursion to sand grain diameter d_0/D and Shields number ϕ_η where the effect of the ripple is included. The result is shown in Fig. 8. As can be seen from the figure, the occurrence region of 2-D and 3-D ripples can be estimated by ϕ_η and d_0/D with small transition zone.

In this study, we used quantities related to the significant wave to evaluate various parameters in the cases of irregular wave tests. As for the occurrence limit of 3-D ripples, there is no significant difference between occurrence limit in regular wave and irregular wave tests.

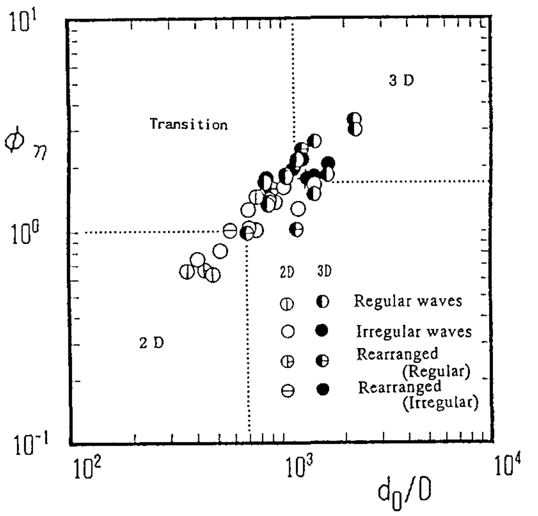


Fig. 8. Transition of ripples in regular and irregular waves.

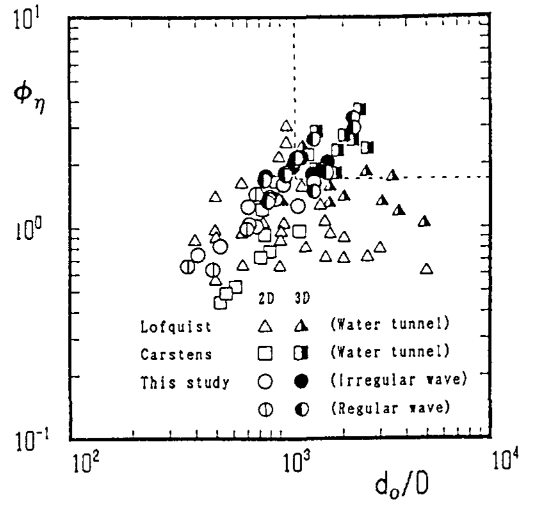
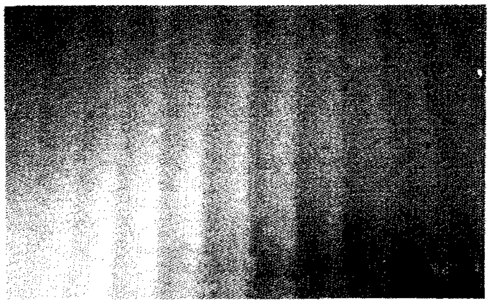
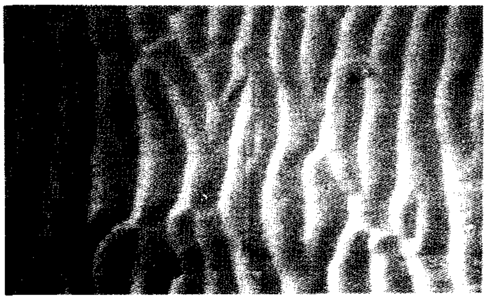


Fig. 9. Occurrence limits of 2-D and 3-D ripples.



(a) Two dimensional ripple.



(b) Transition condition.

(c) Three-dimensional ripple.

Fig. 10. Typical geometry of two and three-dimensional ripples.

5. CONCLUSIONS

The main conclusions obtained in this sutdy are summarized as follows:

1. Nondimensional length λ/d_0 of ripples generated in the decreasing process of incident waves became larger than that formed from a flat bed by one wave train. Especially nondimensional ripple length in a decaying process of wave height became very close to the field ripples. Therefore, the effect of initial condition of ripple generation is one cause of a scale effect between the field and the laboratory.

2. The characteristics in the geometry of 3-D and 2-D ripples are able to be expressed very well by a spectrum band parameter.

3. The occurrence region of 3-D ripples is predicted very well by Shields parameter where the effect of a ripple geometry together with the grain size are taken into account in the evaluation of shear velocity.

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