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Formation of giant ripples in a circular water flume

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Giant ripples are formed on a sand bed with a long spacing of over 1 m, a high steepness, and a highly symmetrical shape. A plane bed of medium sands (0.50 mm in diameter) or fine sands (0.21 mm) developed into giant ripples under oscillatory wave conditions with long wave periods and low oscillatory velocities in a circular water flume designed for generating long-term oscillatory flows. Allen and Hoffman (2005) reported the presence of giant ripples at homologous stratigraphic levels accumulating in the Precambrian age and assumed that these giant ripples were generated by long-term waves with wave periods of 21 to 30 seconds. The results of the present experiments support this assumption. The discovery of a giant-ripple-like structure in the Pleistocene Shimousa group, Japan, indicates the possible existence of generation sources affecting the local area.

Key Words : *Giant ripples, Flume experiment, Long-term waves, Wave ripples*

1. Introduction

Wave ripples, which have typically straight-crested symmetrical shapes, are a type of bedform generated by oscillatory flow conditions. Clifton and Dingler (1984) [1)] reported that the ripple spacing (λ) depends on the orbital diameter of the wave (d_o) and the grain size (D). The value of d_o can be calculated as U_oT/π, where U_o is the orbital velocity of the wave, and T is the wave period. When the value of the ratio between the orbital diameter and the grain size (d_o/D) is in the range from 100 to 3,000, the ripple spacings are proportional to the orbital diameter. However, once the value of d_o/D exceeds 3,000, the ripple spacings are no longer proportional to d_o. Thus, the ripple spacings have an upper limit that depends on the grain size. In other words, small particles, such as sand or mud, cannot form large ripples with meter-scaled ripple spacings.

Wave ripples that have long ripple spacings over 1 m and sand-sized grains were, however, discovered at a homologous stratigraphic level in the Precambrian age, and these "giant ripples", were generated by long-term waves with a wave period of 21-30 seconds caused by strong winds of 20 m/s or greater[2)]. According to the "Snowball Earth" hypothesis, the entire surface of the Earth was covered by ice during the Marinoan glaciation (which ended approximately 635 million years ago). After the Marinoan glaciation, extreme climatic conditions, including strong winds exceeding 20 m/s, might have appeared due to the rapid rise of sea levels and melting ice.

Few experimental studies have examined bedforms under long-term oscillatory flows because the climatic conditions are not observed in the natural environment and generating long-term waves in a laboratory is difficult due to limitations in flume size. Therefore, a special water flume is needed in order to conduct experimental studies.

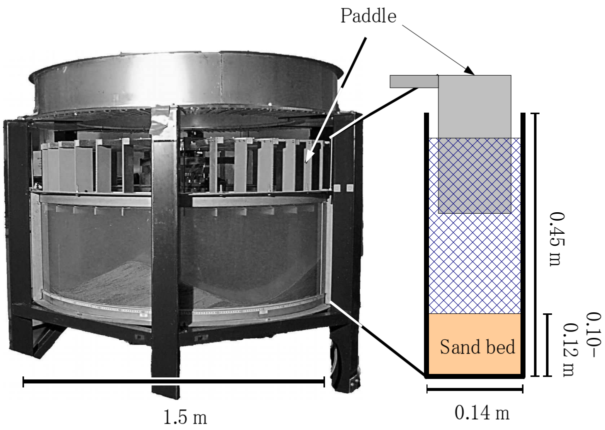

Fig.1 Photograph and diagram of the circular flume.

Southard et al. (1990)[3], carried out flume experiments on bedforms under long-term oscillatory flows with wave periods of approximately 15 seconds using a U-shaped tube and reported that wave ripples with large ripple spacings were formed.

The purpose of the present paper is to form “giant ripples” in the laboratory. We conducted flume experiments under long-term oscillatory flows using a circular flume. The circular flume can generate long-term waves because there is no limit imposed by the length of the channel.

2. Materials and Method

Experiments were performed in a circular water flume (Fig.1). The circular channel has an outer diameter of 1.5 m, a width of 0.14 m, and a depth of 0.45 m in the vertical cross section. The rotational motion generated by a series of paddles above the channel can produce various flow conditions. The flow velocities in the channel were measured by a Particle Image Velocimetry (PIV) technique in a series of preliminary experiments. In the present paper, we used the orbital velocities at 5 cm above the bottom calculated based on the results of preliminary experiments. The flow velocity depends on the distance between the paddles and the sand bed, the rotating speed of the paddles, and the water depth[4].

The experimental method was as follows. The initial condition was a flat bed of 10 - 12 cm in thickness. In the case of the Series A experiments, the sand bed consisted of medium sands (mean particle diameter: 0.50 mm). The Series B experiments were conducted using fine sands (mean particle diameter: 0.21 mm). The initial bed was exposed in various long-term wave conditions with various wave periods T (10 – 60 seconds), orbital velocities Uo (11 – 110 cm/s), and duration (5 – 14 hours). Table 1 lists the experimental conditions of all runs. The bedform near the outside wall of the circular channel was observed continuously throughout the entire experiment.

Table 1 Wave conditions in the Series A and Series B experiments

Series A (D = 0.50 mm)

Run No.	U_o [m/s]	T [s]	d_o [m]	duration [hour]
1	0.13	20	0.82	5
2	0.13	50	2.1	10
3	0.18	20	1.1	5
4	0.18	40	2.3	5
5	0.18	50	2.8	10
6	0.18	60	3.4	12
7	0.35	15	1.7	5
8	0.35	20	2.2	5
9	0.35	25	2.8	14
10	0.35	30	3.3	5
11	0.35	40	4.4	5
12	0.35	50	5.6	5
13	0.35	60	6.7	5
14	0.36	10	1.1	5
15	0.36	30	3.4	5
16	0.48	20	3.1	5
17	0.48	50	7.7	5
18	0.56	10	1.8	5
19	0.56	20	3.6	5
20	0.57	50	9.1	5
21	0.57	15	2.7	5
22	0.57	30	5.5	5
23	0.74	10	2.4	5
24	0.74	20	4.7	5
25	0.74	50	12	5
26	0.95	10	3.0	5
27	0.95	20	6.1	5
28	0.95	50	15	5
29	1.1	12	4.2	5

Series B (D = 0.21 mm)

Run No.	U_o [m/s]	T [s]	d_o [m]	duration [hour]
1	0.10	60	2.0	12
2	0.13	60	2.4	12
3	0.18	60	3.4	12
4	0.23	10	0.72	12
5	0.23	20	1.4	12
6	0.23	40	2.9	12
7	0.23	50	3.6	6
8	0.23	55	4.0	11
9	0.23	60	4.3	7
10	0.25	60	4.8	12
11	0.27	40	3.4	12
12	0.28	60	5.4	5
13	0.36	30	3.5	12
14	0.37	60	7.0	5
15	0.47	60	8.9	5

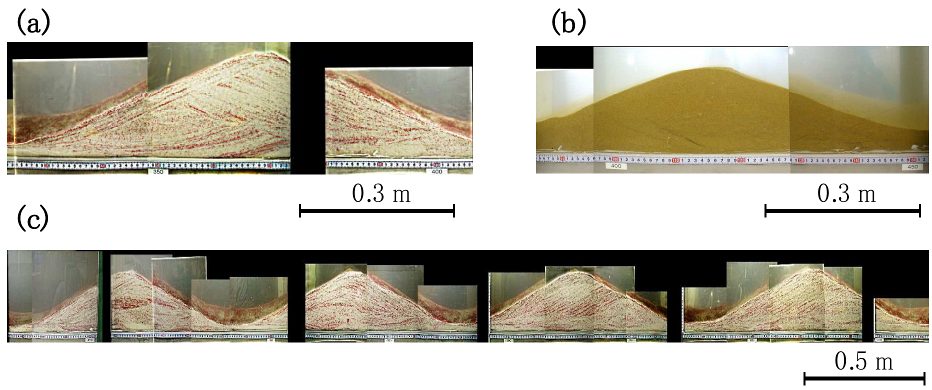

Fig.2 Giant ripples in the circular flume of the present study. (a) Largest ripple observed in the Series A experiments (λ = 1.01 m, η = 0.19 m, Run No. 6). (b) Largest ripple observed in the Series B experiments (λ = 0.89 cm, η = 0.11 cm, Run No. 12). (c) Series of giant ripples observed in the Series A experiments (Run No. 6).

3. Results and Discussion

Wave ripples that have long ripple spacings of approximately 1 m were formed. For the largest ripple in the Series A experiments, the ripple spacing λ was 1.01 m and the ripple height η was 0.19 m (Figs.2(a) and 2(c)). For the largest ripple in the Series B experiments, the ripple spacing λ was 0.89 m and the ripple height η was 0.11 m (Fig.2(b)). There were some sedimentary structures, such as chevron-type upbuilding and laminae dipping in a single direction.

Four types of deformations were observed in these experiments. In the "no ripples" case, there is no change from the initial flat bed. This situation occurred under weak waves with very small orbital diameters. Under stormy waves with very large orbital velocity, plane beds or ripples with a rounded crest were formed. Wave ripples with straight-crested symmetrical shapes were formed under the intermediate conditions between the no-ripples condition and plane beds or ripples with a rounded crest. The wave ripples could be divided into two groups: giant ripples and small ripples. The histograms of ripple spacing indicated bimodal distribution in both Series A (D = 0.50 mm) and Series B (D = 0.21 mm) (Fig.3). The border of two modes was not influenced by the channel length because the border of the ripple spacing normalized by grain size (λ/D) was the same for the Series A and Series B experiments. In the Series A experiments, a d_o of approximately 2.5 m was

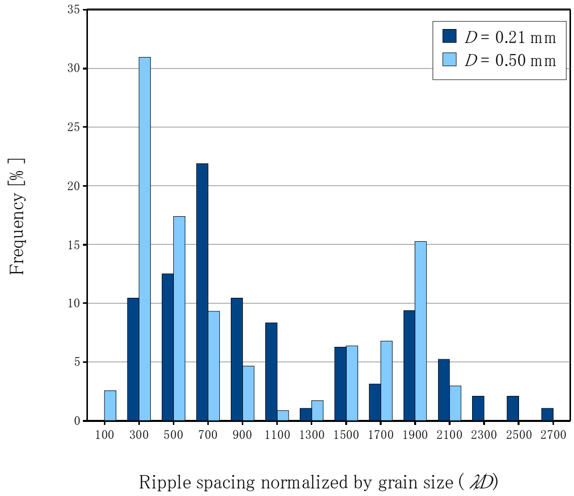

Fig.3 Histogram of ripple spacings normalized by particle diameter (λ/D). The number of measured ripples is 236 in Series A (D = 0.50 mm) and 96 in Series B (D = 0.21 mm).

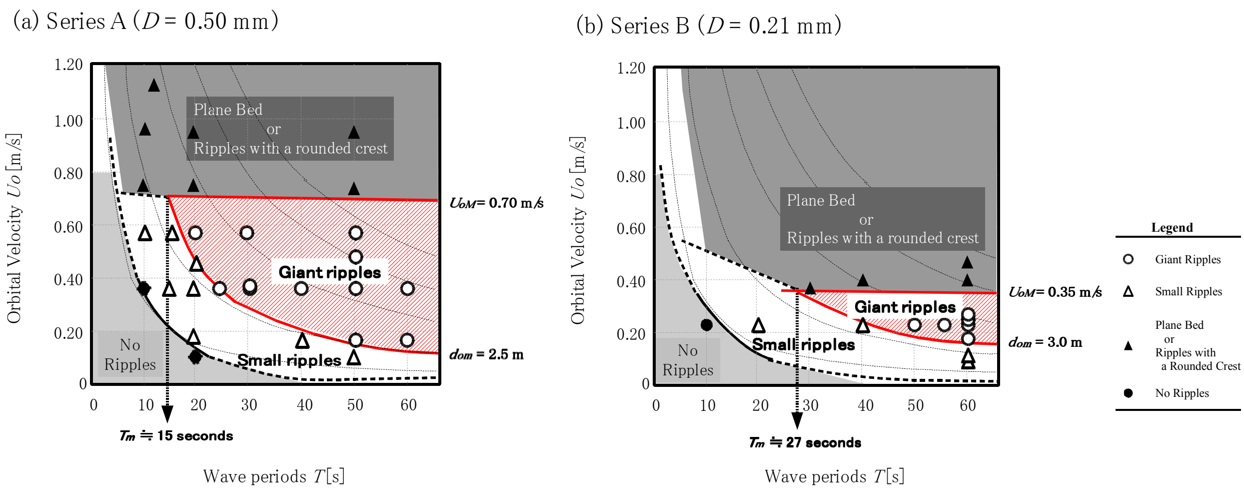

Fig.4 Phase diagrams of wave period T and orbital diameter d_o. (a) Based on the results of the Series A experiments. (b) Based on the values of U_{oM} and d_{om} as estimated based on the results of the Series B experiments.

required in order to exceed the border ripple spacing.

The formation conditions of giant ripples were dependent on the upper limit of the orbital velocity U_{oM} and the lower limit of the orbital diameter d_{om}. In the case of the Series A experiments (D = 0.50 mm), the value of U_{oM} was approximately 0.70 m/s, d_{om} was approximately 2.5 m, and T_m was approximately 15 seconds (Fig.4(a)). Thus, the minimum wave period T_m could be estimated based on the intersection point of U_{oM} and d_{om} in the phase diagram for U_o and T.

The particle diameter D had a significant influence on U_{oM} rather than d_{om}. In the Series B experiments, U_{oM}, which was approximately 0.35 m/s, was half that in the Series A experiments. On the other hand, d_{om} in the Series B experiments, which was approximately 3.0 m, was approximately the same as that in the Series A experiments. Moreover, T_m in the Series B experiments, which was estimated to be approximately 27 seconds, was larger than that in the Series A experiments due to the decrease of U_{oM} (Fig.4(b)).

These results showed that giant ripples could be formed under long-term waves, as reported by Allen and Hoffman (2005). They discovered numerous giant ripples at homologous stratigraphic levels accumulating in the Precambrian age and explained that the long-term waves were generated by the extreme climate condition caused by the severe changes in sea level following the Marinoan glaciation. Although the wide distribution of giant ripples in homologous stratigraphic levels appears to confirm their hypothesis, there may be another source of long-term waves that affects only localized areas and this source may be more common than the climate conditions following the Marinoan glaciation. This is indicated by a giant-ripple-like structure found in the Pleistocene Shimousa group, Japan (Fig.5).

Fig.5 Giant-ripple-like structure in the Pleistocene Shimousa group.

4. Conclusion

Giant ripples were formed under long-term wave conditions. The formation condition was an oscillatory flow with a large orbital diameter d_o and a small orbital velocity U_o. Since the upper limit of the orbital velocity U_{oM} changes with the grain size of the sand bed, the smaller the grain size of the sand bed, the larger the minimum wave period required to form giant ripples. These results were consistent with the findings of Allen and Hoffman (2005). Another source of long-term waves will be investigated in a future study.

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