Ripples with secondary crests as a possible indicator of palæo-wave direction: a laboratory experiment

Tomohiro Sekiguchi*

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*Center for Marine Environmental Studies, Ehime University, Bunkyo-cho 2-5, Matsuyama 790-8577, Japan

Abstract

The geometry of ripples having single or double secondary crests in each trough was examined through a wave flume experiment. The results showed that ripples with a secondary crest(s) exhibit asymmetrical profiles. In the case of ripples with a single secondary crest, the crest appears on the onshore side of each trough. In the case of double secondary crests, the distance from an onshore main ripple crest to one secondary crest on the offshore-dipping slope is larger than the corresponding distance between the other secondary crest and an offshore-adjacent main crest, and also the former secondary crest is located higher than the latter. Such geometric asymmetry becomes significant depending on the degree of velocity asymmetry, which is inherent in wave-induced oscillatory flow. The present experiment suggests that the geometrical characteristics of this type of ripples in the geological record enable us to infer the direction of ancient wave propagation.

Key words: wave ripples, secondary crest, geometric asymmetry, flow asymmetry, wave propagation

Introduction

Wave-generated ripple marks, which have single or double small crests in each trough, have been occasionally observed in geological records (e.g., Allen, 1982; Fritsch and Moore, 1988). Such small crests are called as “secondary crests” (Evans, 1943). Ripples with a secondary crest(s) in each trough have been reported from field investigations of the recent natural environment (e.g., Evans, 1943; Allen, 1982; Makino, 1994; Traykovski et al., 1999) and from laboratory experiments (Shulyak, 1963; Lofquist, 1978; Hansen et al., 2001a, b; Sekiguchi and Sunamura, 2004b).

This type of ripples develop as an ephemeral feature during deformation of existing original ripples into those with smaller length (e.g., Shulyak, 1963; Lofquist, 1978; Traykovski et al., 1999; Hansen et al., 2001a; Sekiguchi and Sunamura, 2004b). Such ripple deformation takes place responding to reduction in the ratio of the near-bottom orbital diameter (= the total amplitude of oscillatory flow) to the length of original ripples (Lofquist, 1978; Hansen et al., 2001b; Sekiguchi and Sunamura, 2004b), and is in connection with waning of wave power (e.g., Evans, 1943). Thus, the presence of secondary crests in the geological record suggests an intermediate stage of ripple deformation process. Sekiguchi and Sunamura (2004b) found that ripples with double secondary crests develop with a smaller ratio of orbital diameter to the original ripple length in comparison with those with a single secondary crest.

Ripple deformation due to the reduction in the ratio of the orbital diameter to the original ripple length much depends on the velocity asymmetry in wave-induced oscillatory flow (Sekiguchi and Sunamura, 2004b). The oscillatory flow on the bottom has a larger onshore velocity with shorter duration and a smaller offshore velocity with longer duration (e.g., Komar, 1998). Such velocity asymmetry is expected to affect the geometry of ripples with secondary crests and their development: this type of ripples in ancient rocks may provide new information of palæo hydraulic conditions. However, no studies have been conducted from this point of view. Based on these backgrounds, the present wave-flume study attempts to examine the geometry of ripples with secondary crests and their evolution considering velocity asymmetry in wave-induced oscillatory flow.

Laboratory Experiments

The present experiment was carried out using a wave flume with 14 m long, 25 cm wide, and 50 cm deep (Sekiguchi and Sunamura, 2004a). A piston-type wave generator is equipped at one end of the flume. A fixed
slope of 1/20, covered with a layer of cobbles, was installed at the other end to reduce energy of reflected waves that direct offshore. A sand bed (3 m long, 25 cm wide, and 3 cm deep) was placed in a horizontal portion of the flume using well-sorted sand with a median diameter of 0.20 mm.

The experimental condition was determined so as to fulfill the criterion for the secondary-crest formation (Sekiguchi and Sunamura, 2004b). The original ripples, which have a symmetrical shape with an almost equivalent spacing were firstly prepared on the sand bed; the length of original ripples, \( \lambda \), ranged from 4.1 cm to 10 cm. Then, the waves that satisfied the above condition were allowed to act on the original ripples: 15 cm \( \leq h \leq 30 \) cm, 0.9 sec \( \leq T \leq 1.5 \) sec, and 4.7 cm \( \leq H \leq 8.6 \) cm, where \( h \) is the water depth over the sand bed, \( T \) is the wave period, and \( H \) is the wave height measured over the sand bed. Sixteen experimental runs were carried out, and the development process of secondary crests was observed.

Wave reflection coefficients were measured during each experiment, and calculated according to Wiegel (1964, p. 53). The result indicated that they were less than 7 %, suggesting that an influence of reflected waves on ripple deformation was small. Therefore, the influence will be ignored in the present study.

**Results and Analysis**

Secondary crests appear only at the early stage of ripple deformation process. Single or double secondary crests initiate in each trough as the original ripple crests become smaller and sharper (Figs. 1.a, 1.b, 2.a, 2.b). The original and secondary crests vary their position with time; however, the original ripple length does not significantly change at the initial stage of the secondary-crest development (Figs. 1.b, 1.c, 2.b, 2.d). Some secondary crests develop larger and become new ripples (the thin arrows in Figs. 1, 2), while the others merge partially or completely into the neighboring ripples (the thick arrows). The symbols \( D, \lambda, h, T, H \), and \( U \) respectively indicate sediment grain diameter, original ripple length, water depth, wave period, wave height, and Ursell number (see detail in the text).
Ursell number (Ursell, 1953) was employed in the present study as a surrogate for representing the degree of flow asymmetry: as Ursell number increases, the flow augments its asymmetry. Sunamura (1980, 1981), Montzouris (1990) and Sekiguchi and Sunamura (2004a) have adopted this parameter in their ripple studies. Ursell number, $U$, is calculated using $h$, $H$, and the wavelength, $L$, through the relation:

$$U = \frac{HL^2}{h^3}$$

According to linear wave theory (e.g., Dean and Dalrymple, 1992; Komar, 1998), $L$ is given as:

$$L = \left(\frac{gT^2}{8\pi}\right) \tanh \left(\frac{2\pi h}{L}\right)$$

where $g$ is the gravitational acceleration.

Fig. 3 shows the temporal change in the position of a single secondary crest; the parameter on the y-axis, $p_a/p_b$, indicates how a secondary crest deviates from the center of the ripple trough, where $p$ is the horizontal length from a secondary crest to the adjacent onshore crest of original ripples and $p$ is the horizontal distance to the adjacent offshore crest (see the inset in Fig. 3), and the x-axis denotes the time normalized by wave period, $t/T$. It is found that all data are plotted in the area of $p_a/p_b < 1$ irrespective of the value of $U$, indicating that development of a secondary crest deviates onshore, although a secondary crest created by waves with $U > 10$ tends to develop more onshore, especially at the initial stage.
Fig. 1. Relationship between \( q_a/q_b \) and \( U/T \) for \( U \geq 10 \) (a), and between \( d_b/d_a \) and \( t/T \) for \( U < 10 \) (b). The regression curves for data with \( U < 10 \) (dashed lines) and \( U > 10 \) (dash-dotted lines) are also plotted. Refer to Fig. 1 for the symbols \( D, \lambda, b, T, H, U \), and for \( A \) and \( t \).

Figs. 4.a and 4.b illustrate the temporal variation in the location and the relative height of double secondary crests, respectively. The y-axis in Fig. 4.a indicates \( q_a/q_b \), where \( q_a \) is the horizontal distance from an onshore secondary crest to the adjacent ripple crest and \( q_b \) is the similar quantity with respect of an offshore secondary crest (see the inset), while the y-axis in Fig. 4.b denotes \( d_b/d_a \), where \( d_b \) is the vertical distance from the ripple trough to an onshore secondary crest and \( d_a \) is the similar quantity concerning an offshore secondary crest (see the inset). Fig. 4.a illustrates that all data but one are plotted in the region of \( q_a/q_b > 1 \). This indicates that double secondary crests are asymmetrically located with the offshore crest being closer to the offshore main ripple crest. Although data for \( U > 10 \) are insufficient in number, they show that \( q_a/q_b \) tends to increase with time. Data for \( U < 10 \) indicate that \( q_a/q_b \) is independent of time. Fig. 4.b shows that all data are in the area of \( d_b/d_a < 1 \), indicating that the onshore secondary crest is higher than the offshore crest. It is found that the relative height between the two is larger under more asymmetrical flow field (\( U > 10 \)).

**Discussion and Conclusions**

The present test showed that under oscillatory flow by waves, ripples with a secondary crest(\( s \)) have asymmetrical profiles: \( p_a/p_b < 1 \) for the case of a single secondary crest, and \( q_a/q_b > 1 \) and \( d_b/d_a < 1 \) for double secondary crests. The geometric asymmetry tends to be marked with larger \( U \)-values. Photographs presented by Lofquist (1978) and Hansen et al. (2001a) illustrate that ripples with a secondary crest (\( s \)), formed under purely oscillatory flow, have symmetrical profiles. In the oscillatory-bed experiment of Hansen et al. (2001a), a single secondary crest occurs at the center of each trough, \( i.e., \) \( p_a/p_b = 1 \) (the solid star symbol in Fig. 3). The test of Lofquist (1978) by use of an oscillatory water tunnel showed that the development of double secondary crests in each trough, having similar location and height to each other, \( i.e., \) \( q_a/q_b \approx 1 \) and \( d_b/d_a = 1 \) (The open star symbols in Fig. 4). Thus, the asymmetrical profile of ripples with a secondary crest(\( s \)) in the present test can be attributed to velocity asymmetry in wave oscillatory flow.

The present experiment indicates that ripples with a secondary crest(\( s \)) exhibit asymmetrical profiles, which suggests that such geometrical characteristics enable us to infer the direction of waves acted during ripple deformation, onshore or offshore. In the case of ripples with a single secondary crest, the crest appears on the onshore side of each trough. In the case of double secondary crests, the distance from an onshore main ripple crest to one secondary crest on the offshore-dipping slope is larger than the corresponding distance between the other secondary crest and an offshore-adjacent main crest, and also the former secondary crest is located higher than the latter. With knowledge of these, it is possible to determine which side of ripples is onshore or offshore (Fig. 5). Ripples with a single secondary crest observed in the shallow-water region in the field (Makino, 1994, Figs. 3, 4.c;
Traykovski et al., 1999, Image 10 in Fig. 6) show asymmetrical profiles with $p_s/p_c < 1$. The field evidence strongly suggests that the criterion in Fig. 5 is applicable to the field environment. It is concluded that the shape of ripples with a secondary crest(s) in geological records serves as a possible indicator of the direction of ancient wave propagation.

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