Ripples under partially standing waves for different reflection coefficients: a laboratory experiment

Naofumi Yamaguchi1* and Tomohiro Sekiguchi2

A series of wave-flume experiments was performed to examine ripple geometry, development, and migration under partially standing waves for five different intensities of wave reflection. The present experiments showed the cross-shore variation of the development and geometry of bedforms corresponding to the position of nodes and antinodes. The ripple field tended to initiate under nodes and spread from nodes to antinodes. The local-mean ripple spacings were the largest under nodes and the smallest under antinodes. The difference of the ripple development and the ripple spacing between nodes and antinodes became more pronounced with increasing the intensity of wave reflection. The local-mean ripple spacings in the present experiments correspond approximately with those predicted by Nielsen’s (1979, 1981) empirical formula. The trend of sediment transport predicted by ripple migration is consistent with the bed profiles at the end of each run. The geometry, development, and migration of ripples are a possible clue for understanding the cross-shore variation in local hydraulic conditions and mass sediment transport under partially standing waves.

Key words: laboratory experiment, oscillatory flow, partially standing wave, sediment transport, wave reflection, wave ripples

Introduction

Study of wave-formed ripple marks is fundamentally important for understanding sediment transport processes and morphodynamics in nearshore environments, because their bed roughness increases as the ripple marks develop, thus affecting the near-bed turbulence. Ripple geometry, i.e., ripple spacing and height, is closely related to near-bed hydraulic conditions and sediment properties; the quantitative relationship between ripple geometry and hydraulic conditions has been investigated in previous studies based on laboratory experiments (e.g., Bagnold, 1946; Manohar, 1955; Inman and Bowen, 1963; Carstens et al., 1969; Lofquist, 1978; Nielsen, 1979, 1981; Miller and Komar, 1980) and field observations (e.g., Inman, 1957; Dingler and Inman, 1976; Traykovski et al., 1999). In addition, ripple migration has been studied because it generally contributes to near-bed sediment transport (e.g., Hay and Bowen, 1993; Traykovski et al., 1999; Crawford and Hay, 2001; Masselink et al., 2007; Yamaguchi and Sekiguchi, 2011).

In the nearshore environment, where ripples develop well, partially standing waves are commonly generated by the interference between incident waves and the waves reflected from the coast. The intensity of wave reflection depends mainly on the beach slope and incident wave condition (Carter et al., 1973), and thus varies with coastal environments. Partially standing waves induce cross-shore variation in the near-bed oscillatory flow. Under partially standing waves, ripples are generally superimposed on larger-scaled undulations whose spacing is equal to half the wavelength of the incident waves (Carter et al., 1973; Lau and Travis, 1973; Heathershaw and Davies, 1985; O’Hare and Davies, 1990; Hancock et al., 2008). The geometry of those ripples shows a cyclic spatial variation; the ripples under the nodes of partially standing waves are larger than those under the antinodes (Kennedy and Falcon, 1965; Carter et al., 1973; Nielsen, 1979; O’Hare and Davies, 1993; Rey et al., 1995; Jan and Lin, 1998; Dulou et al., 2000;
Yamaguchi et al., 2007; Landry et al., 2009). However, to the best knowledge of the authors, there have been no studies that closely examined the variation in the ripple properties, in particular in the ripple development and migration, under partially standing waves for different intensities of wave reflection. The characteristics of ripple geometry, development, and migration may provide a clue for understanding the sedimentary process of the larger-scaled undulations, like rhythmic sandbars (e.g., Makino, 1994). In addition, it is necessary to understand the possible effect of partially standing waves on the spatial fluctuation of ripple characteristics. Therefore, the present experimental program was designed specifically to examine the cross-shore variation in ripple geometry and development of ripples under partially standing waves for different intensities of wave reflection.

**Physical Basis**

On the basis of the studies of Wiegel (1964) and Mei (1983), a partially standing wave, $\xi$, and the maximum near-bottom flow velocity, $u_b$, and the orbital diameter, $d_0$, under partially standing waves are represented as follows:

$$\xi = H_1 \left[ (1 + R_c) \cos kx \cos \frac{2 \pi t}{T} + (1 - R_c) \sin kx \sin \frac{2 \pi t}{T} \right]$$  \hspace{1cm} (1)

$$u_b = \frac{\pi H_1}{T \sinh kh} \sqrt{1 + R_c^2 - 2 R_c \cos 2kx}$$  \hspace{1cm} (2)

$$d_0 = \frac{u_b T}{\pi} \frac{H_1}{\sinh kh} \sqrt{1 + R_c^2 - 2 R_c \cos 2kx}$$  \hspace{1cm} (3)

Here, $h$ is the water depth; $H_1$, the height of the incident wave; $k$, the wave number ($=2\pi/L$; $L$ is the wavelength); $R_c$, the reflection coefficient; $T$, the wave period; and $x$, the horizontal axis taken in the direction of incident-wave propagation. According to the linear wave theory (e.g., Dean and Dalrymple, 1992; Komar, 1998), $L$ is given as follows:

$$L = \frac{g T^2}{2 \pi} \tanh kh$$  \hspace{1cm} (4)

where $g$ is the acceleration due to gravity. $R_c$ is given by the following relationship:

$$R_c = \frac{H_{\text{max}} - H_{\text{min}}}{H_{\text{max}} + H_{\text{min}}}$$  \hspace{1cm} (5)

where $H_{\text{max}} (=H_1 (1 + R_c))$ is the wave height at an antinode, e.g., $x=0$, $L/2$, etc., and $H_{\text{min}} (=H_1 (1 - R_c))$ is the wave height at a node, e.g., $x=L/4$, $3L/4$, etc. (Fig. 1). The reflection coefficient $R_c=0$ for pure incident waves that do not undergo reflection from the coast, and $R_c=1$ for pure standing waves that undergo perfect reflection. Under partially standing waves, i.e., $0<R_c<1$, the $u_b$ and $d_0$ values and the value of the mobility number, which is described below, reach their maximum at nodes and their minimum at antinodes. As $R_c$ increases to 1, the minimum values of $u_b$ and $d_0$ decrease to 0, and the difference between the maximum and minimum values of $u_b$ and $d_0$ becomes marked. The difference becomes negligible when the $R_c=\sim 0$.

In order to quantify the magnitude of the mobility of sediment particles, the mobility number $\phi$ has been widely employed in previous wave ripple studies (e.g., Carstens et al., 1969; Lofquist, 1978; Nielsen, 1979, 1981; Sekiguchi and Sunamura, 2004; Testik et al., 2005, 2006; Yamaguchi and Sekiguchi, 2010; Balasubramanian et al., 2011). The mobility number $\phi$ is given by

$$\phi = \frac{u_{\text{b}}^2}{(s-1)gD}$$  \hspace{1cm} (6)

where $s$ is the specific gravity of the sediment grains, and $D$ is the sediment grain diameter. The mobility of sediment grains increases with increasing $\phi$.

Many equations have been developed for predicting ripple geometry on the basis of near-bottom flow and sediment conditions. The present study employs the simplest linear-proportional relationship and Nielsen’s (1979, 1981) formulae for analyzing vortex ripple spacing. The linear-proportional relationship (e.g., Miller and Komar, 1980) is given as follows:

$$\lambda = 0.65d_0$$  \hspace{1cm} (7)

where $\lambda$ is vortex ripple spacing. Yamaguchi et al. (2007)
analysed ripples under partially standing waves using this relationship. Nielsen (1979, 1981) suggested the following empirical formula for ripples under regular waves:

$$\frac{\lambda}{d_0/2} = 2.2 - 0.345 \psi^{0.34}$$

(8)

This formula has been widely used in previous wave ripple studies (e.g., Traykovski et al., 1999; Faraci and Foti, 2002; Yamaguchi and Sekiguchi, 2010).

Sekiguchi and Sunamura’s (2005) criterion for a bed with perturbation was employed as a reference for the ripple threshold. The mobility number for the ripple threshold, \(\psi^*\), is given by

$$\psi^* = 2 + 5.7 \left( \frac{3.79}{kh + 0.65} - 1 \right) \exp \left( -8 \times 10^{-4} \frac{u_0 h_m}{\nu} \right)$$

(9)

where \(h_m\) is the height of perturbation (\(h_m = D\) for a flat bed), and \(\nu\) is the kinematic viscosity. In the present study, \(\nu = 0.01 \text{ cm}^2/\text{s}\). The equation shows that the \(\psi^*\) decreases with increasing \(kh\) and \(h_m\).

**Laboratory Experiments**

A series of wave-flume experiments were conducted to study ripple development under partially standing waves under the identical incident wave conditions but for different reflection coefficients. A wave flume 20-m long, 0.5-m wide, and 0.6-m deep (Fig. 2), at the Terrestrial Environment Research Center, University of Tsukuba, was used in the present experimental program. The flume was equipped with a piston-type wave generator at one end. This wave generator has a re-reflected wave control system that hinders the re-reflection of reflected waves at the wave generator; thus, the wave components in this flume consist only of the incident wave and the reflected wave. A wave energy absorber was fixed at the end opposite of the wave generator. The reflection coefficient was controlled by changing the volume of the wave energy absorber.

A sand bed (4.0-m long, 0.5-m wide, and 7-cm thick) was constructed on the horizontal portion of the flume. The bed material was well-sorted quartz sand with \(D = 0.20 \text{ mm}, s = 2.65\), and settling velocity \(w = 2.3 \text{ cm/s}\). In each run, the initial bed was flat.

Two capacity-type wave height meters (CHT6-30; KENEK Co., LTD., Japan) were installed in the flume for measuring the wave heights at a node and an antinode; an acoustic Doppler velocimeter (ADV; Nortek AS, Norway) was used for measuring velocity at a height of 2 cm above the initial bed. The velocities were measured before each run. The detailed conditions of ADV measurement were as follows: the sampling frequency was 25 Hz; the number of measurement points, \(\sim 60\) at 4-cm horizontal intervals; and the duration of each measurement, 60 seconds. These measured velocities were used for calculating the local orbital diameter \(d_0\) and the local mobility number \(\psi\) from Eqs. (3) and (6), respectively.

Two digital video cameras (HDV1080i, 30 frames/s) were placed beside the flume in order to record side and oblique top-view images of the bedform, developing in the central ~1.8-m-long region of the sand bed, and the water waves above it. The wave height at 37 points at 5-cm horizontal intervals was determined through video-image analysis. A digital still camera was installed above the flume to obtain top-view photographs of the ripples at the end of each run for measuring the ripple spacing.

The parameters of pure incident waves and induced near-bed flow in the present experimental series are given in Tables 1 and 2, respectively. The value of mobility number \(\psi\) under the pure incident wave (Table 1) was very close to the ripple threshold for a flat bed, i.e., \(\psi^* = 8.7\), calculated

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**Fig. 2** The wave flume used in the present study. The scale above the flume represents the horizontal position shown in Figs 3 and 4.
from Eq. 9, but it was significantly larger than the threshold for a bed with a perturbation, i.e., \( \psi^* = 2.9 \) for \( h_m = 1.5 \) cm. The reflection coefficients, \( R_c \), which were calculated from Eq. 5 using measured local wave height, \( H \) (Fig. 3), ranged from 0.03 to 0.52 (Table 2). These values agreed well with those calculated from Eq. 2 using \( H \) values (Fig. 3).

The value of \( u_{\text{max}}/w \), which indicates the direction of sediment transport under standing waves (Irie and Nadaoka, 1984; O’Donoghue, 2001), in the present experiments ranged from 8.1 to 11.9; thus, the present experiments were dominated by sediment transport from antinodes to nodes. As described above, the differences of the \( u_{\text{b}}, d_0, \) and \( \psi \) values between the nodes and antinodes became marked as \( R_c \) increased (Table 2, Fig. 3). The duration of each run was 60 minutes.

After the experiments, ripple spacing was measured along five cross-shore survey lines on the top-view photographs. Using the measured ripple spacings, the local-mean ripple spacing was calculated for a 5-cm moving average window. In the present study, these local-mean ripple spacing at the end of each run was regarded as the representative spacing at each site (Fig. 3).

### Results

Three types of cross-shore variations, which were dependent on \( R_c \), were observed in the development and geometry of the bedforms in the present study. When \( R_c \) was minimum, the near-bed hydraulic conditions were almost constant throughout the bed, and the \( \psi \) values were very close to the ripple threshold for a flat bed (Figs. 3a and 4a). Sediment grains moved and rolling-grain ripples (Bagnold, 1946) appeared in the initial 20 minutes of the experimental run. However, before the rolling-grain ripples developed into vortex ripples (Bagnold, 1946; the term ‘ripples’ indicates vortex ripples in this paper), they spread over the sand bed from both ends, where the bed perturbations were largest (Fig. 4a). The ripples attained a quasi-equivalent state less than 15 minutes after their initiation (Fig. 4a). In terms of ripple migration, there was no difference between nodes and antinodes. The local-mean ripple spacing at the end of the run was almost constant throughout the bed (Fig. 3a). The larger-scaled undulation did not form in this run.

For a moderate \( R_c \) value, \( \psi \) values around nodes were significantly higher than the \( \psi^* \) value for a flat bed, and those around antinodes were lower than the \( \psi^* \) value for a flat bed but higher than that for a bed with a perturbation (Fig. 3b–d). Rolling-grain ripples appeared initially and developed into vortex ripples preferentially under nodes (Figs. 4b–d and 5). The ripple field spread from nodes to antinodes, almost symmetrically onshore and offshore, and completely covered the bed (Figs. 4b–d and 5). Ripples tended to migrate from near antinodes to nodes, and they merged under nodes. Ripples directly under antinodes, however, did not migrate. Each ripple attained a quasi-equivalent state of its geometry less than 10 minutes. Even after the ripple field was sub-

<table>
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<th>Run ID</th>
<th>Wave characteristics</th>
<th>Flow condition</th>
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<tr>
<td></td>
<td>( R_c )</td>
<td>( H_{\text{max}} ) (cm)</td>
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<tr>
<td>RF.1</td>
<td>0.03</td>
<td>9.0</td>
</tr>
<tr>
<td>RF.2</td>
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<td>9.9</td>
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<td>RF.4</td>
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<tr>
<td>RF.5</td>
<td>0.52</td>
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Fig. 3  Cross-shore variation in hydraulic conditions and bed topography for (a) RF.1, (b) RF.2, (c) RF.3, (d) RF.4, and (e) RF.5. The parameters (top to bottom) water wave height $H$; measured maximum flow velocity (○), which also represents local orbital diameter, with orbital diameter estimated from Eq. 2 (dashed line); mobility number $ψ$ (△) with ripple threshold $ψ_*$ for a flat bed and a bed with perturbation ($h_m=1.5$) calculated from Eq. 9 (dashed grey line and alternate long and short dash line, respectively); elevation of bed topography at the end of each run (black line); and measured ripple spacing with local-mean ripple spacings (black line); and ripple spacings predicted by Eq. 7 (dashed grey line) and that predicted by Eq. 8 (grey line). The symbols ‘N’ and ‘A’ denote the positions of nodes and antinodes, respectively.
stantially developed, ripples were formed near antinodes and
developed while migrating toward nodes. Therefore, ripples
near antinodes were not always in a quasi-equivalent state,
even at the end of the test run. The local-mean ripple spac-
ing at the end of the run was the largest under nodes and
decreased toward antinodes (Fig. 3e). The crest of the
larger-scaled undulation occurred under nodes, while the
troughs developed under both the on- and offshore sides of
antinodes. Flat plateaus occurred directly under the anti-
nodes. The troughs under the onshore side of antinodes
were deeper than those under the offshore side.

As $R_c$ increased, i.e., as the $\psi$ value under nodes became
higher and that under antinodes lower (Fig. 3b–e), ripples
were formed more rapidly under nodes and more slowly
under antinodes, and the rate of ripple migration from anti-
nodes to nodes increased (Fig. 4b–e). The difference of the
local-mean ripple spacings between nodes and antinodes
became more pronounced with increasing
$R_c$ (Fig. 3). The spacings measured under antinodes are larger than those
predicted by Eq. 7, whereas the spacings under nodes are
nearly equal to or slightly smaller than those predicted (Figs.
3d and 3e).

Examination of the relationship between the local-mean
ripple spacing and the local hydraulic conditions near the
bed provides valuable information. In Fig. 3, the ripple
spacings predicted by the previous empirical formulae of the
linear-proportional relationship (Eq. 7) and Nielsen (1979,
1981) (Eq. 8) are also plotted for reference. The local-
mean ripple spacings measured in each run correspond
approximately with those predicted by Nielsen’s formula,
Eq. 8 (Fig. 3). In particular, the maximum and minimum
local-mean ripple spacings under nodes and antinodes in
each run were accurately predicted. In contrast, the linear-
proportional relationship of Eq. 7 poorly predicts the local-
mean ripple spacings measured under nodes and antinodes,
in particular in the case of high $R_c$ (Figs. 3d and 3e). The
spacings measured under antinodes are larger than those
predicted by Eq. 7, whereas the spacings under nodes are
nearly equal to or slightly smaller than those predicted (Figs.
3d and 3e).

Discussion

The trend in the sediment transport predicted by ripple
migration is consistent with the bed profiles at the end of
the tests. The present study showed that ripples migrated from
the on- and offshore sides of antinodes to nodes, and that the
ripple migration rate increased with increasing $R_c$ value (Fig.
4). Although the bed at the end of the tests might not be
equilibrium profiles because the duration of the present
experiments are not sufficiently long, these results suggest
that the near-bed sediment transport associated with ripple
migration contributes to the formation of an mound under
nodes, and that the sediment flux associated with ripple
migration during its formation becomes larger with in-
creasing $R_c$. The difference of the trough depths between
the on- and offshore sides of antinodes for the largest $R_c$
value was probably due to weak flow asymmetry, which
enhanced onshore ripple migration. The development
and migration of ripples may provide a clue for understanding
mass sediment transport, which induces larger-scaled cyclic
undulations and local seabed scouring under partially stand-
ing waves.

Although the bed under the on- and offshore sides of
antinodes was preferentially eroded, ripples directly under
antinodes did not migrate or only slightly migrated, and
thus, sediments were left undisturbed (Fig. 4). Similar relict
sediments directly under antinodes were reported by some
previous studies in which the $R_c$ value was nearly 1 (e.g., Irie
and Nadaoka, 1984; Landry et al., 2007). Thus, these relict
sediments directly under antinodes may arise when the flow
velocity under antinodes is not enough to transport sedi-
ments actively because the $R_c$ value is very large or the in-
cident wave is small. In contrast, when there is sufficient
flow velocity under antinodes, sediments directly under anti-
nodes are also transported to nodes, and thus, distinct larger-
scaled undulations with spacings of $L/2$ develop (e.g., Carter
et al., 1973; Lau and Travis, 1973; O’Hare and Davies,
1990, 1993; Rey et al., 1995; Jan and Lin, 1998; Dulou et al.,
The local-mean ripple spacings correspond approximately with those predicted by Nielsen’s formula, Eq. 8 (Fig. 3). Jan and Lin (1998) reported that, under the nodes and antinodes of three-dimensional (oblique) standing waves, Nielsen’s formula is applicable for predicting ripple geometry. The present results indicate that the formula for ripple spacings in Nielsen (1979, 1981) also holds for ripples under partially standing waves for varied reflection coefficients.

If the reflection coefficient can be estimated from variation of ripple spacing, it is useful to comprehend the spatial hydraulic condition. When the local-mean ripple spacing was proportional to the local orbital diameter $d_o$, the reflection coefficient $R_c$ could be specifically estimated from the maximum and minimum ripple spacings through Eqs. 3 and 7. Some previous studies indicated that the local ripple spacing and orbital diameter had the linear relationship (Yamaguchi et al., 2007; Landry et al., 2009). The present result, however, suggests that the local-mean ripple spacings are not always proportional to the local orbital diameter $d_o$.

Fig. 4  Ripple evolution from a flat bed for (a) RF.1, (b) RF.2, (c) RF.3, (d) RF.4, and (e) RF.5. The image is based on the temporal sequence of bed-surface profiles obtained from video camera images every 30 s. Black and white arrows denote the positions of nodes and antinodes, respectively.
especially in the case of large $R_c$ (Fig. 3), the measured ripple spacings under nodes and antinodes tend to be different from those predicted by the linear-proportional relationship (Eq. 7). Although it is not always possible to determine the specific value of the reflection coefficient $R_c$ from ripple spacings using the linear-proportional relationship (Eq. 7), the cross-shore variation in ripple spacings may help to make a rough estimate of the intensity of wave reflection.

**Conclusions**

The cross-shore variation in ripple geometry, the development and migration of ripples under partially standing waves was examined through wave-flume experiments for five different reflection coefficients. The results obtained may be summarized as follows:

1. Three types of cross-shore variations, which were dependent on $R_c$, were observed in the development and geometry of bedforms in the present study. When $R_c$ was minimum ($R_c=0.03$), ripples spread over the bed from both ends of the sand bed, and the local-mean ripple spacings at the end of the run were almost constant throughout the bed. For a moderate $R_c$ value ($R_c=0.13–0.35$), the ripple field spread from nodes to antinodes, almost symmetrically onshore and offshore. The local-mean ripple spacings at the end of the run showed a cyclic cross-shore variation; they were the largest under nodes and the smallest under antinodes. When $R_c$ was maximum ($R_c=0.52$), the ripple field initiated under nodes and spread from nodes to antinodes, but the ripple field did not reach the areas around the antinodes. These types depended on the cross-shore variation in the mobility number $\psi$ in relation to the ripple threshold $\psi^*$ for a flat bed and a bed with a perturbation.

2. The difference of the local-mean ripple spacing between nodes and antinodes became more pronounced with increasing $R_c$. The local-mean ripple spacings measured in each run correspond approximately with those predicted by Nielsen’s (1979, 1981) empirical formula. The present results indicate that Nielsen’s (1979, 1981) formula for ripple spacing also holds for ripples under partially standing waves with various reflection coefficients. In contrast, the local-mean ripple spacings did not always show a linear-proportional relationship with the local orbital diameter $d_0$. Although it is not always possible to determine the specific value of the reflection coefficient $R_c$ from ripple spacing using the linear-proportional relationship, the cross-shore variation in ripple spacings is indicative of the intensity of wave reflection.

3. The trend of sediment transport predicted from ripple migration is consistent with the bed profiles at the end of the test runs. These results suggest that near-bed sediment transport associated with ripple migration contributes to the formation of a larger-scaled undulation. The development and migration of ripples may provide a clue for understanding mass sediment transport, which induces larger-scaled cyclic undulations and local seabed scouring under partially standing waves.

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異なる反射率の部分重複波の下で形成されるリップル

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部分重複波の下で形成されるリップルの形態、発達過程、移動について、5段階の反射率を設定した造波水槽実験によって調べた。リップルの発達と形態は、節と腹の位置に対応した違いが見られた。リップルは節の下から発生し、節から腹に向かって広がる傾向があった。それぞれの実験におけるリップル平均波長は、節の下で最も大きく腹の下で最も小さかった。このような節と腹の下でのリップルの発達と波長の違いは、反射率の増加にともなって顕著になった。場所ごとの平均波長は Nielsen (1979, 1981) の経験式によって予測されるものと概ね一致した。また、リップルの移動から推定される堆積物輸送の傾向は、各実験終了時の地形と整合的である。こうしたリップルの地形、発達過程、移動は、部分重複波の下での局所的な水理条件や堆積物輸送を理解する手がかりとなりうる。