Three-dimensional antidunes coexisting with alternate bars

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ABSTRACT: Antidunes are fluvial bedforms that form in rivers with supercritical flows. The water surface over antidunes is strongly in phase with the bed surface, and the water surface is amplified to produce large surface waves. Many experimental studies have addressed antidunes; however, the shapes of three-dimensional antidunes in a wide channel with alternate bars have not yet been appropriately understood. In this study, we experimentally investigated the streamwise and transverse length scales of antidunes under conditions with a large width–depth ratio. Our experimental results provide evidence for the coevolution of antidunes and free alternate bars, and show for the first time that the development of free bars greatly alters the three-dimensional shape of water surface waves over antidunes. In the absence of free bars in a wide channel, multiple longitudinal wave trains form, and the number of wave trains counted in the transverse direction increases with increases in the width–depth ratio. However, the presence of free bars affects the local flow characteristics, resulting in a decrease of the number of wave trains in the transverse direction. Therefore, we propose a simple model for predicting the reduction in the number of wave trains by combining two previous theories for antidunes and free bars. Results obtained by the model were found to largely agree with experimental observations. © 2020 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd

KEYWORDS: 3D antidune; alternate bar; standing wave; bedform; supercritical flow

Introduction

The river bedform is a critical element for defining local flow structures and sediment transport processes. Bedforms are characterized in terms of streamwise length scale of deformations, with ripples having the shortest length, dunes and antidunes having an intermediate length, and bars having the longest length (e.g. Colombini and Stocchino, 2012; Charru et al., 2013; Bradley and Venditti, 2017; Bohorquez et al., 2019). Step-pools and cyclic steps have a longer wavelength than dunes and antidunes, but a shorter wavelength than bars (e.g. Parker and Izumi, 2000; Weichert et al., 2008; Cartigny et al., 2014; Sloatman and Cartigny, 2019). It is well known that the formation of dunes and antidunes changes the hydraulic resistance of alluvial streams and thus modifies the flow velocity and depth (e.g. Engelund, 1966). A dune with an asymmetrical triangular profile is produced under subcritical flow, where the boundary layer flow separates at the dune crest to form lee vortices, increasing the hydraulic resistance (e.g. Smith and McLean, 1977; Nelson and Smith, 1989; Lyn, 1993). An antidune is typically observed in supercritical flows and shows little asymmetry. Because the water surface above an antidune is synchronized in phase with the bedform, the water surface is amplified to produce large surface waves – so-called ‘rooster tails’ – that are often observed during a flood (e.g. Kennedy, 1961; Guy et al., 1966; Núñez-González and Martín-Vide, 2010; Yokokawa et al., 2010) (Figure 1). An antidune causes an updraft, which impairs the stability of the blocks installed to protect river banks and levees (Iwasaki et al., 2018). In addition, antidunes found in the rock record are used for the estimation of Paleo-hydraulic conditions (e.g. Carling and Shvidchenko, 2002; Burr et al., 2009; Kostic et al., 2010; Yokokawa et al., 2010; Carling, 2013).

The dynamics of both dunes and antidunes have been investigated experimentally (e.g. Fukuoka et al., 1982; Carling and Shvidchenko, 2002; Recking et al., 2009; Núñez-González and Martín-Vide, 2011; Cartigny et al., 2014; Bohorquez et al., 2019), analytically (e.g. Kennedy, 1961, 1963; Engelund, 1970; Hayashi, 1970; Parker, 1976; Colombini, 2004; Andreotti et al., 2017; Charru et al., 2013), and computationally (e.g. Giri and Shimizu, 2006; Bohorquez and Ancey, 2016; Doré et al., 2016; Olsen, 2017), commonly assuming two-dimensional bedforms. However, it is known that two-dimensional (2D) dunes and antidunes with uniform transverse crests evolve into three-dimensional (3D) forms. Best (2005), in a review of dunes, showed that the flow over 3D dunes (e.g. Maddux et al., 2003a; Venditti et al., 2005; Venditti, 2007) is very different from that over 2D dunes (e.g. Smith and McLean, 1977; Nelson and Smith, 1989; Lyn, 1993; Ojha and Mazumder, 2008; Mazumder et al., 2009). For instance, 3D bedforms cause secondary flow circulations (Maddux et al., 2003a,b), and the
level of turbulence increases or decreases depending on the shape of the crests of 3D dunes (Venditti, 2007). Based on these experimental studies, the motion of 3D dunes has been computationally modelled by coupling large eddy simulation (LES) and the sediment continuity equation (Nabi et al., 2013; Khosronejad et al., 2015; Shimizu et al., 2019).

There is less research on 3D antidunes compared to 2D/3D dunes and 2D antidunes. Kennedy (1961, 1963) analytically showed for the first time that 3D antidunes occur at high Froude numbers, but multiple wave trains cannot be predicted because the assumed transverse wavelength is equal to the channel width. Yokokawa et al. (2010) explained the formation conditions of 3D antidunes by applying the model for 3D step-pools proposed by Hasegawa and Kanbayashi (1996). In their model, the transversal wavelength of 3D antidunes is defined by diagonal cross-waves, which could theoretically result in multiple wave trains in the transverse direction. Yokokawa et al. (2010) validated the model through an experiment with a single antidune train, but not with multiple antidune trains. Recently, Colombini and Stocchino (2012) proposed a linear stability analysis for 3D antidunes and found the possible conditions for co-existence of 3D antidunes with free alternate bars. However, the effects of bar formation on the length scale of 3D antidunes have hardly been studied experimentally.

The gaps in the above models can be inferred from the water surface waves caused by antidunes observed in the Toyohira River, Japan, during the 1981 flood (Figure 1). The streamwise wavelength of the waves was roughly 18 m, the wave height was roughly 2–3 m, and the number of wave trains was 1 or 2 in the transverse direction (Inoue et al., 2011). As reported by the Hokkaido Regional Development Bureau, during the 1981 flood, the channel width, flow depth, grain diameter, and Froude number were roughly 70 m, 3 m, 1.22, respectively. The Chézy coefficient and the ratio of Shields number to critical Shields number, back-calculated from the equations shown in Colombini and Stocchino (2012), were 11.3 and 3.2, respectively. The number of trains estimated using Yokokawa et al.’s (2010) model is 4 to 5 under the above-mentioned conditions. This overprediction may have been caused due to the formation of alternate bars not included in the model, a phenomenon likely to occur when the width–depth ratio becomes larger than 20 (e.g. Kuroki and Kishi, 1984; Colombini et al., 1987). Bar formation alters the local flow field and may change the shape of the 3D antidunes. The transverse wave number with the highest growth rate is zero under the conditions (Figure 3a in Colombini and Stocchino, 2012), i.e. the 2D antidunes are the most prevailing bedforms. It is possible that the 2D antidunes lead to the formation of transversely uniform water surface waves, unlike the 3D surface waves observed in the Toyohira River. This suggests that Colombini and Stocchino’s (2012) model may not be efficiently applied to nonlinear cases with well-developed free bars. Because free bars often form in gravel-bed rivers, adding the influence of well-developed bars into Yokokawa et al.’s (2010) model will lead to a better understanding of Paleo-hydraulic conditions and flood defences.

In this study, we performed open-channel experiments to investigate the transverse number of water surface waves over a mobile bed with 3D antidunes and free bars. The experimental results are discussed with respect to the previous model (Yokokawa et al., 2010). Also, a novel method for estimating the transverse number of antidunes over alternate bars is proposed.

This paper is organized into seven sections. First, we introduce the analytical background of the formation of water wave trains and 3D antidunes in supercritical open channel flows. Then, we explain the experimental setup for measuring planar surface elevations. Next, the experimental results of the temporal evolution of the wave field and the transverse number of wave trains, respectively, are discussed. Then, the proposed analytical model describing the planar wave field that forms over antidunes superimposed on bars is validated. The limitations of the proposed model are discussed, and finally our findings and conclusions are summarized.

Theoretical Wavelength and Transverse Wavenumber of 3D Antidunes

First, we explain the wave–current interactions in supercritical flows in a straight channel with a flat bed, as proposed by Yokokawa et al. (2010) and Hasegawa and Kanbayashi (1996). These interactions may be observed at the initial state before the onset of bar deformation.

Figure 1. A train of water surface waves on the Toyohira River in Japan observed during a flood in 1981 (image courtesy of Atsushi Yoshii, Sapporo River Work Office, Hokkaido Regional Development Bureau). [Colour figure can be viewed at wileyonlinelibrary.com]
The Doppler shift equation (Peregrine, 1976) gives the relation between the wave frequency in the frame of reference, \( \omega \), and the frequency \( \sigma \) of a wave, propagating with velocity \( \mathbf{U} \):

\[
\omega = \sigma + \mathbf{U} \cdot \mathbf{K}
\]

(1)

where the wavenumber vector \( \mathbf{K} = (k_x, k_y) = k(\cos \alpha, \sin \alpha) \), and \( \alpha \) is the angle between \( \mathbf{U} = (U, 0) \) and \( \mathbf{K} \) (see Figure 2). The dispersion relation between \( \sigma \) and \( k \) in the case of small-amplitude waves is commonly expressed as follows:

\[
\sigma^2 = gk \tan khh
\]

(2)

where \( g \) is the gravitational acceleration and \( h \) is the water depth. Similar to previous studies (e.g. Chawla and Kirby, 2002; Chatterjee et al., 2019), by substituting the Doppler relation of Equation 1 into Equation 2, Equation (2) can be rewritten as follows:

\[
(\omega - \mathbf{U} \cdot \mathbf{K})^2 = gk \tan khh
\]

(3)

Thus, the wave speed \( c = \omega/k \) in a current with velocity \( \mathbf{U} \) has the relation

\[
c - U \cos \alpha = \pm \sqrt{\frac{g}{k}} \tanh khh
\]

(4)

No wave is able to propagate upstream parallel to a supercritical flow (\( \alpha = \pi \)) because \( c = -U + \sqrt{\frac{g}{k}} \tanh khh = -Fr \sqrt{gh} + \sqrt{\frac{g}{k}} \tanh khh \approx (1 - Fr) \sqrt{gh} \) is always negative, with Froude number \( Fr = U/\sqrt{gh} \). However, if \( \alpha \) takes a critical value to fulfill \( U \cos \alpha = -\sqrt{\frac{g}{k}} \tanh khh \), i.e. \( c = 0 \), the waves are held stationary against the opposing supercritical flow with respect to the wave direction. The stationary wave condition is thus written in terms of Froude number as follows:

\[
Fr = \frac{1}{\cos \alpha} \sqrt{\frac{\tanh khh}{kh}}
\]

(5)

It should be noted that, in addition to the wave angle \(-\alpha\) fulfilling Equation 5, it simultaneously fulfills the stationary condition; thus, we get two stationary waves with wavenumbers \( k(\cos \alpha, \sin \alpha) \) and \( k \) (\( \cos \alpha, -\sin \alpha \)).

Hasegawa and Kanabayashi (1996) and Yokokawa et al. (2010) used these two stationary wave components in supercritical flows over bedforms with uniform spanwise crests to explain the formation of 3D bedforms. The wave rays intersect each other in the channel; thus, the waves are superposed at the crossing locations, resulting in wave amplification with a streamwise wavelength of \( \lambda_x = 2\pi/k_x = 2\pi/k \cos \alpha \) along the channel. The locally amplified waves, which are also called diagonal cross-waves and feature uneven forms in the spanwise direction, may be further superimposed on waves induced over antidunes that form with wavelength \( \lambda_a \). In cases where \( \lambda_a \) coincides with \( \lambda_x \), the maximum wave height can be achieved by wave amplification, and the 2D undulations of the antidunes gradually become 3D.

Kennedy (1963) derived the critical Froude number for distinguishing upstream and downstream-migrating 2D antidunes:

\[
Fr = \sqrt{\frac{A}{k_x^2 \tanh khh}}
\]

(6)

where \( k_x \) is the streamwise wavenumber of antidunes (\( 2\pi/\lambda_a \)).

Figure 2. Conceptual diagram for stationary crossing waves.

Yokokawa et al. (2010) advocated that rather than the migration direction of antidunes, Equation 6 roughly represents the wavelength of downstream-migrating antidunes, as shown in Figure 2 of Bohorquez et al. (2019) and our experimental results. The Taylor approximation of Equation 6 gives us

\[
Fr = \sqrt{\frac{1}{(k_xh)^2} + \frac{1}{3}}
\]

(7)

When diagonal cross-waves form in a channel, Equation 5 can be written as

\[
Fr = \frac{k \tanh khh}{(k_x h)^2}
\]

(8)

where \( k = \sqrt{k_x^2 + k_y^2} \). Yokokawa et al. (2010) and Hasegawa and Kanabayashi (1996) defined the transverse wavenumber \( k_y = 2\pi n/B \) using the transverse wavenumber mode \( n \) (i.e. the number of wave trains counted in the transverse direction; we refer to \( n \) as the transverse number in this paper) and the channel width \( B \). In other words, \( n \) is the ratio of the channel width \( B \) to the lateral wavelength \( \lambda_x \) in their model.

Yokokawa et al. (2010) assumed that resonance occurs between diagonal cross-waves and antidunes when the streamwise wavenumbers are mutually identical (i.e. \( k_x = k_y \)). The transverse number is derived from Equations 7 and 8 (see Appendix A):

\[
n = \frac{\sqrt{Fr^4 - A^2(Fr^2 - 1/3)B}}{2\pi A(Fr^2 - 1/3)h}
\]

(9)

where \( A = \tanh khh \). While \( n \) should be an integer when the water surface waves are perfectly in phase with the antidunes, we may interpret the real-valued \( n \) given by Equation 9 as indicating a mode in which water surface waves are partially in phase with antidunes (\( \lambda_x \approx \lambda_a \)), which is used in the current analysis.
A combination of 2D Exner equation and some 2D/3D water flow model should generally be applied for calculating the water surface elevation; however, in this study we deploy a simple model proposed by Yokokawa et al. (2010) to explain the formation of 3D waves over antidunes, thereby eliminating the need for fully physics-based flow–sediment transport–morphodynamic models. In order to explain Yokokawa et al.’s (2010) model, we assume that water and bed surfaces can be represented by the cosine, similar to Kennedy (1961, 1963). The waveforms of two stationary cross-waves are expressed by $A_a \cos(k_x x + k_y y)$, where $A_a$ is the water wave amplitude and $k_x$ and $k_y$ are the wavenumbers in the $x$ and $y$ directions, respectively. The waveform of an antidune is expressed by $A_a \cos(k x)$, where $A_a$ and $k$ are the amplitude and wavenumber of antidune, respectively. In this paper, we simply superpose the two stationary cross-waves with the antidunes and visualize the deformation of water surface shape $\Delta H$:

$$\Delta H = A_a \cos(k x + k_y y) + A_a \cos(k x - k_y y) + A_a \cos(k x)$$

(10)

In Equation 10, the magnitude of the amplitude depends on the specified parameters (i.e. $A_a$ and $A_w$), but the streamwise and transverse length scales are calculated by the above theoretical equations [i.e. Equations 7 and 8]. The calculation method of $\Delta H$ is as follows. First, we input the Froude number $F_r$ and water depth $h$ in Equation 7 to obtain $k_x$. Then, we substitute $k_x$ into $k_y$ in Equation 8 to obtain $k_y$. Finally, $\Delta H$ can be calculated by substituting the obtained $k_x$, $k_y$, and $k$ into Equation 10. For example, the single wave trains shown in Figure 3a are drawn under the conditions of $F_r = 1.3$, $h = 0.09$ m, and $B = 0.5$ m, and the two wave trains shown in Figure 3b are drawn under the conditions of $F_r = 1.3$, $h = 0.045$ m, and $B = 0.5$ m. Figure 3 shows that the transverse number $n$ is strongly dependent on the water depth. In addition, substituting $F_r$, $h$, and $B$ mentioned above into Equation 9 yields $n = 1$ and 2, respectively. Therefore, Equation 10 visually represents the transverse number of wave trains estimated by Equation (9).

While Yokokawa et al. (2010) used a simplified version of Equation 9 to predict the formation of 3D antidunes with the lowest number ($n = 1$), that equation provides no validation for higher numbers (i.e. $n \geq 2$). In this study, we discuss the formation mechanism of 3D surface waves and antidunes through comparisons with experimental results over multiple transverse numbers using Equation 9.

**Experimental Setup**

Laboratory experiments were conducted in a 25 m-long sloping channel of 1.0 m width at the Civil Engineering Research Institute for Cold Regions (CERI) (Figure 4). Table 1 summarizes the experimental conditions of flow discharge, bed slope, and channel width to define the width–depth ratio $B/h$ and Froude number $F_r$ for all 29 runs. We used two sorted sediments with mean diameters of 1.42 and 5.00 mm. All the experimental runs started with a flat bed with an alluvial thickness of 10 cm. Sediment was steadily supplied near the upstream end to maintain the sediment layer at a constant thickness throughout the experiments. The Toyohira River shown in Figure 1, with a width–depth ratio of about 23 and a depth–grain ratio of 23, serves as a typical example of a gravel-bed river. Our study covers a wide range of cases with varying width–depth ratios and depth–grain size ratios. We conducted 12 runs of the experiments with a width–depth ratio of 15 or more and a depth–grain size ratio equal to or less than 50.

Detailed time-series measurements of the water surface on antidunes have rarely been performed. In this study, we used a yttrium aluminium garnet (YAG) laser sheet and laser-induced fluorescence (LIF), often used for wave measurement (Duncan et al., 1999; Buckley and Veron, 2016), for measuring the cross-sectional deformation of the water surface in the channel. A YAG laser sheet (wavelength 532 nm) was created over the channel width at a distance of 12.5 m from the channel’s...
upstream end (Figure 4). With the water dyed with sodium fluorescein being excited by the laser to emit fluorescence with a peak wavelength of 580 nm (Figure 5), the cross-sectional distribution of the fluorescence over the laser sheet was recorded by a digital video camera (with a resolution of 1024×768) from the downstream side (Camera 1 in Figure 4). A high-pass optical filter was installed on the camera lens to prevent the laser light reflected on the free surface from being recorded, since disordered reflections on disturbed free-surface forms would otherwise have caused erroneous detection of the surface location. Continuous video measurements were performed for 242 min from the start of the experiments. Image coordinates were transformed to real coordinates using a linear image transformation in order to provide quantitative measurements of the water surface. The free surface was defined to be the location where the vertical gradient of image intensity was the

![Figure 4](image-url) The experimental setup. Water and bedload were constantly supplied from the upstream end. Two digital cameras were used to take photos for measuring the wavelength, wave height, and number of water surface waves in the transverse direction. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1. Experimental conditions

| Run | Channel width B (m) | Grain size d (mm) | Bed slope S | Flow discharge Q (l/s) | Water depth h (m) | Froude number Fr | Width-depth ratio B/h | Depth-grain size ratio h/d | Shields numbera τ* |
|-----|---------------------|-------------------|-------------|------------------------|------------------|------------------|----------------------|------------------------|------------------|
| Run 1 | 0.5 | 1.42 | 0.0080 | 15.2 | 0.045 | 12.1 | 1.02 | 15.1 | 0.154 |
| Run 2 | 0.5 | 1.42 | 0.0080 | 36.8 | 0.079 | 6.3 | 1.04 | 55.6 | 0.273 |
| Run 3 | 0.5 | 1.42 | 0.0145 | 8.1 | 0.025 | 20.0 | 1.30 | 17.6 | 0.155 |
| Run 4 | 0.5 | 1.42 | 0.0145 | 1.8 | 0.010 | 50.0 | 1.16 | 7.0 | 0.062 |
| Run 5 | 0.5 | 5.00 | 0.0180 | 19.5 | 0.045 | 11.1 | 1.31 | 9.0 | 0.098 |
| Run 6 | 0.5 | 5.00 | 0.0180 | 26.7 | 0.055 | 9.1 | 1.32 | 11.0 | 0.120 |
| Run 7 | 0.5 | 5.00 | 0.0180 | 42.9 | 0.075 | 6.7 | 1.34 | 15.0 | 0.164 |
| Run 8 | 0.5 | 5.00 | 0.0320 | 10.3 | 0.025 | 20.0 | 1.66 | 5.0 | 0.097 |
| Run 9 | 0.5 | 5.00 | 0.0320 | 21.7 | 0.040 | 12.5 | 1.73 | 8.0 | 0.155 |
| Run 10 | 0.5 | 5.00 | 0.0320 | 30.7 | 0.050 | 10.0 | 1.76 | 10.0 | 0.194 |
| Run 11 | 1.0 | 5.00 | 0.0150 | 44.6 | 0.050 | 10.0 | 1.27 | 10.0 | 0.091 |
| Run 12 | 1.0 | 5.00 | 0.0150 | 113.3 | 0.090 | 18.0 | 1.34 | 16.0 | 0.164 |
| Run 13 | 1.0 | 5.00 | 0.0150 | 67.8 | 0.065 | 15.4 | 1.31 | 13.0 | 0.118 |
| Run 14 | 1.0 | 5.00 | 0.0250 | 57.5 | 0.050 | 20.0 | 1.64 | 10.0 | 0.152 |
| Run 15 | 1.0 | 1.42 | 0.0110 | 44.5 | 0.050 | 20.0 | 1.27 | 35.2 | 0.235 |
| Run 16 | 1.0 | 1.42 | 0.0110 | 76.2 | 0.070 | 14.3 | 1.31 | 49.3 | 0.329 |
| Run 17 | 1.0 | 1.42 | 0.0250 | 15.1 | 0.020 | 50.0 | 1.71 | 14.1 | 0.213 |
| Run 18 | 0.5 | 1.42 | 0.0303 | 12.4 | 0.026 | 19.2 | 1.89 | 18.3 | 0.336 |
| Run 19 | 0.5 | 1.42 | 0.0303 | 9.5 | 0.022 | 22.7 | 1.86 | 15.5 | 0.285 |
| Run 20 | 0.5 | 1.42 | 0.0250 | 11.3 | 0.026 | 19.2 | 1.72 | 18.3 | 0.277 |
| Run 21 | 0.5 | 1.42 | 0.0080 | 8.0 | 0.030 | 16.6 | 0.98 | 21.1 | 0.102 |
| Run 22 | 0.5 | 1.42 | 0.0080 | 23.8 | 0.060 | 8.3 | 1.03 | 42.3 | 0.205 |
| Run 23 | 0.5 | 1.42 | 0.0080 | 12.6 | 0.040 | 12.5 | 1.01 | 28.2 | 0.137 |
| Run 24 | 0.5 | 1.42 | 0.0040 | 16.8 | 0.060 | 3.7 | 1.32 | 43.2 | 0.102 |
| Run 25 | 0.5 | 1.42 | 0.0040 | 31.0 | 0.090 | 5.6 | 0.73 | 63.4 | 0.154 |
| Run 26 | 0.5 | 1.42 | 0.0040 | 47.4 | 0.120 | 4.17 | 0.73 | 84.5 | 0.205 |
| Run 27 | 0.5 | 1.42 | 0.0040 | 71.5 | 0.160 | 3.13 | 0.71 | 112.7 | 0.273 |
| Run 28 | 0.5 | 5.00 | 0.0050 | 23.8 | 0.070 | 7.14 | 0.82 | 14.0 | 0.149 |
| Run 29 | 0.5 | 5.00 | 0.0050 | 53.0 | 0.120 | 4.17 | 0.81 | 24.0 | 0.256 |

a \(\tau* = hSg/\rho_d\), where \(\rho_s\) is submerged specific gravity of sediment (1.65).
maximum, and this was detected on the cross-section over the channel width. Streamwise surface forms were recorded from the side of the channel by another video camera (Camera 2) so that the wavelengths of the wave trains could be estimated. After Run 3, we used 3D scanners for measuring the bed elevation in order to investigate the shapes of 3D antidunes and alternate free bars.

**Evolution of Wave Surfaces**

In our experiments, antidunes were observed in 14 of the 29 runs (Table 2 and Figure 6). 3D antidunes formed for \( Fr \) ranging between 1.0 and 1.7 (Runs 1, 2, 3, 7, 12, 14, 15, 16, 17, 21, 22, and 23), whereas 2D antidunes formed only when \( Fr \) was equal to 0.8 (Runs 28 and 29, Figure 7a). Previous experimental studies conducted by Núñez-González and Martín-Vide (2010) also showed that 3D antidunes form only when \( Fr > 0.95 \). Results obtained from mathematical models (Yokokawa et al., 2010; Colombini and Stocchino, 2012) also support this sensitivity between the Froude number and the mode of antidunes (i.e. 2D or 3D).

Although Bohorquez et al. (2019) showed that antidunes form when the Froude number is in the range 0.7–2.5, antidunes were not observed in our experiments for Froude number greater than 1.7 (Figures 6 and 7b). According to Engelund and Hansen (1967), antidunes do not form for

| Run | Bedform type                  | Wavelength (m) (average values) | Transverse number of wave trains |
|-----|-------------------------------|---------------------------------|----------------------------------|
|     |                               | \( t < 10\text{min} \) | \( t > 30\text{min} \) | \( t < 10\text{min} \) | \( t > 30\text{min} \) |
| Run 1 | 3D antidunes                  | 24.5                            | –                                | 1–2                        | 1–3                        |
| Run 2 | 3D antidunes                  | 42.5                            | 24.7                             | 3–4                        | 1–3                        |
| Run 3 | 3D antidunes on alternate bars | 19.3                            | –                                | 1–2                        | 1–2                        |
| Run 4 | 3D antidunes                  | 51.8                            | 45.5                             | 1–3                        | 1–2                        |
| Run 5 | 3D antidunes on alternate bars | 49.1                            | 54.9                             | 2–3                        | 1–2                        |
| Run 6 | 3D antidunes                  | 32.8                            | –                                | 3–5                        | 3–4                        |
| Run 7 | 3D antidunes                  | 44.3                            | –                                | 2–3                        | 2–3                        |
| Run 8 | 3D antidunes on alternate bars | 17.7                            | 22.3                             | 8–10                       | 1–4                        |
| Run 9 | 3D antidunes                  | 16.1                            | 21.2                             | 3–4                        | 1–2                        |
| Run 10 | 3D antidunes                  | 28.5                            | –                                | 1–2                        | 1–2                        |
| Run 11 | 3D antidunes                  | 25.4                            | –                                | 1–2                        | 1–2                        |
| Run 12 | 3D antidunes                  | 31.2                            | –                                | 0                           | 0                           |
| Run 13 | 3D antidunes                  | 47.2                            | –                                | 0                           | 0                           |

Note: In Runs 3, 14, 17, and 21, alternate bars gradually developed over time. The data of \( t < 10\text{min} \) and \( t > 30\text{min} \) indicate the wavelength and transverse number of 3D antidunes before and after bar formation.
Fr > 1.7 when $U/u_*$ is between 9 and 12, where $U$ is the depth-averaged flow velocity and $u_*$ is the shear velocity. Ohata et al. (2017, Figure 3c in their paper) show that it is easy to form an upper plane bed when the Shields number is low. These could also represent the reason for the absence of antidunes in our experiments presented here.

In all runs in which these wave trains were observed, antidunes formed on the riverbed in phase with the surface waves as shown in Figures 7a, f, and g. In Run 7 with a low width–depth ratio, a single train of steep waves formed along the centre line of the channel as shown in Figure 7c. In Run 3 with a high width–depth ratio, three wave trains were observed in the transverse direction at the early stage of the experiment as shown in Figure 7d. However, the transverse number of wave trains changed to unity after 30 min as shown in Figure 7e.

Figure 8 shows the time records of the measured transverse distribution of surface elevation in Run 7. Initially, two wave trains formed over the channel width and slowly propagated downstream following the downstream migration of the antidunes (Figures 8a and b); that is, surface elevations with two local maxima were achieved above the antidune crest, and the local minima above the antidune trough periodically varied with a wave period of about 28 s. The transverse number of wave trains gradually varied in the transition period (Figures 8c–e), finally resulting in one wave train ($n = 1$) in the quasi-steady state (Figures 8f and h). We find that the patterns of surface elevation at the first transverse number (i.e. Figure 8h) and the second transverse number (i.e. Figure 8b)
correlate with the analytical ones of stationary crossing waves over the antidune shown in Figure 3. Also, the transverse number \( n \) estimated by Equation 9 is 1.3 under the conditions of Run 7, which is also supported by the measured transitional mode from 2 to 1. These results indicate the validity of the assumption of Yokokawa et al. (2010) that the oblique cross-waves coupled with the antidunes to create the steep wave trains.

Transitions in wave steepness at transverse wavenumber \( n \geq 2 \) were observed in Run 3 (Figures 7d and 9). While three mildly steep wave trains initially formed in the transverse direction (Figure 9a), steep wave trains appeared near the channel wall on one side over time and changed location to the other side, in succession (Figures 9b–h). That is, the location of the highest wave train changed from near the left wall (\( y \approx 40 \text{ cm} \)) in Figure 9b to near the right wall (\( y \approx 10 \text{ cm} \)) in Figure 9c, and back to \( y \approx 40 \text{ cm} \) again in Figure 9d. While Equation 9 estimates \( n \approx 4 \) in this case, the observed transverse number \( n \) varies from 1 to 3, indicating overprediction by Equation (9). The velocity of the wave train’s downstream propagation, corresponding to the migration velocity of the antidune, decreased from 0.92 cm s\(^{-1}\) in Figure 9a to 0.70 cm s\(^{-1}\) in Figure 9d, suggesting long-term transition of the mean bed deformation.

We observed alternate bars with streamwise wavelengths of 4–6 m in addition to antidunes with streamwise wavelengths of 0.15–0.30 m in the channel in Run 3. Alternate bars started to form at the phase shown in Figure 9b, and they slowly grew and migrated downstream. Figure 10 shows the observed bed elevation changes after Run 3. The amplitudes of the alternate bars increased from the upstream section to the downstream section, as generally observed in the flume experiments of free alternate bars (e.g. Lanzoni, 2000). In the upstream section where alternate bars did not develop (i.e. \( x = 5–10 \text{ m} \)), two or three antidune trains formed. In the downstream section with well-developed alternate bars (i.e. \( x = 10–20 \text{ m} \)), single antidune trains formed over the alternate bars.
Transitions of Transverse Number of Wave Trains

Figure 11 shows the relationship between the width–depth ratio ($B/h$) and the observed transverse number of water surface waves, together with the prediction of Equation 9. The measured transverse number of wave trains is proportional to $B/h$ in the early stage ($t < 10$ min) as shown in Figure 11(a), which is well predicted by Equation 9 for the range of conditions under which 3D antidunes form (i.e. $1.0 \leq Fr \leq 1.7$). However, in the later stage ($t > 30$ min), the transverse number for $B/h > 15$ decreases (i.e. Runs 3, 14, 17, and 21 in Figure 11b) and takes values limited to the range of $1 \leq n \leq 3$, which significantly deviates from the prediction by Equation 9. In contrast, the transverse numbers for the cases of lower $B/h$ are unchanged over time. The cases for $B/h > 15$ (Runs 3, 14, 17, and 21) fall into the regime of alternate bar formation (e.g. Kuroki and Kishi, 1984; Colombini et al., 1987), and alternate bars were actually observed in these runs. As already discussed, the formation of alternate bars changes the wave field.

Figure 12 compares the observed wavelengths of surface waves with the wavelengths estimated from Equations 6 and 7. Equations 6 and 7 closely approximate the observed wavelengths of the wave trains for all runs, indicating that the streamwise wavelengths of the wave trains are identical to those of the antidunes, which supports the fundamental assumption of wave train formation coupled with downstream migrating antidunes as explained earlier. However, we find that the wavelengths of Runs 3, 14, 17, and 21 (after bar formation) are significantly larger than Equation 7, indicating that the formation of alternate bars increases the streamwise wavelengths of antidunes. Because the previous model used the streamwise wavelengths of antidunes without considering the effects of alternate bars, the model failed to predict the transverse number of wave trains as shown in Figure 11b.

Figure 9. Temporal variation of water surface height measured with the initial riverbed height as zero (Run 3). The relatively large water wave trains are surrounded by dashed ovals. In Run 3, alternate bars gradually formed over time and coexisted with antidunes. (a) Before bar formation, three wave trains formed near the centre of the channel. (b–f) After bar formation, one or two wave trains alternately formed near the left and right sidewalls. [Colour figure can be viewed at wileyonlinelibrary.com]
Modification of Antidune Wavelength on Alternate Bars

This section discusses the effects of the formation of alternate bars on the transverse number of wave trains. The formation of alternate bars reduces the effective channel width where antidunes can form. This is likely one of the factors behind water surface waves not forming near the centre of the channel (Figure 9). However, it is not possible to explain the increase in the streamwise wavelength shown in Figure 12 only by considering reduction of the channel width, because the streamwise wavelength strongly depends on the Froude number, not channel width [Equation 7]). Thus, we consider both the reduction in effective channel width and the change in local Froude number to estimate the transverse number of 3D antidunes after bar formation.

The bar’s topography causes the Froude number to change in the transverse direction: that number increases on the slope downstream from the tops of bars and decreases near the pool. We estimate the distribution of Froude numbers using empirical formulas for bar wavelength and wave height proposed by Ikeda (1984):

\[
\frac{2\lambda_b}{B} = 181 C_f \left( \frac{B}{h} \right)^{0.55}
\]

\[
\frac{Z_b}{h} = 1.51 C_f \left( \frac{B}{h} \right)^{1.45}
\]

where \( \lambda_b \) is the half-wavelength of alternate bars, \( Z_b \) is the wave height of alternate bars, \( C_f \) is the bed friction coefficient, \( h \) is the averaged water depth, and \( B \) is the channel width. The formation of alternate bars changes the local bed slopes near the banks; the local slopes increase on one side and decrease on the other side. In this model, the average bed slopes near the banks \( S^* \) are calculated using the ratio of bar height to half-wavelength \( (Z_b/\lambda_b) \):

\[
S^* = S \pm \gamma Z_b/\lambda_b
\]

where \( S \) is the initial bed slope and \( \gamma \) is a model parameter indicating the development of alternate bars (i.e. \( \gamma = 0 \) indicates a flat bed, and \( \gamma = 1 \) indicates well-developed alternate bars).

The local Froude numbers on both banks are expressed in terms of the Chézy formula:

\[
F_{r}^2 = \frac{C_c^2}{B} (S - S^*) = \frac{1}{C_f} - S^*
\]

where \( C_c \) is Chézy’s constant and \( C_c^2/B = 1/C_f \). The Froude number gradually changes in the transverse direction from the bar to the opposite pool. Here, we simply assume that the distribution of Froude numbers varies linearly between the two banks, so that

\[
F_r(y) = F_r^0 (1 - y/B) + F_r^0 (y/B)
\]

The change in Froude number changes both the antidune wavenumber \( k_a(y) \) and the angle of the diagonal cross-waves \( a(y) \). \( k_a(y) \) and \( a(y) \) are given by Equations 7 and 5, respectively:

\[
k_a(y) = \sqrt{\frac{1}{F_r(y)^2 h^2} + \frac{3}{2}}
\]

\[
\cos a(y) = \frac{1}{F_r(y)} \sqrt{\frac{\tanh kh}{kh}}
\]

For counting the number of wave trains in the transverse direction, we simply superpose the diagonal cross-waves and antidune waves, similar to Equation 10:

\[
\Delta H = A_w \cos(k_x y) x + k_y(y) y
\]

\[
+ A_w \cos(k_x y) x - k_y(y) y
\]

\[
+ A_w \cos(k_x y) x
\]

when \( 1.0 \leq F_r(y) \leq 1.7 \)

where \( k_x(y) = k \cos a(y) \) and \( k_y(y) = k \sin a(y) \). Equation 18 is the same as Equation 10, except that \( k_w, k_x, \) and \( k_y \) are changed to functions of \( y \). Although Engelund and Hansen (1967) showed that antidunes form for \( F_r \leq 1.7 \) when \( U/u_r = 9~12 \),
such conditions are not included in Equation 7 as shown in Figure 12. In addition, 3D antidunes did not form when \( F_r < 1.0 \) in our experiments, as well as in previous experiments (Núñez-González and Martín-Vide, 2010). Therefore, Equation 18 should be limited by the formation conditions, especially when spatially varying Froude numbers are used. This limitation represents the reduction of effective channel width where antidunes can form.

We explored the model sensitivity by varying the model parameter of bar development \( \gamma \) because the degree of bar development changes spatiotemporally as shown in Figures 9 and 10. Figure 13 shows \( \Delta H \) calculated under the conditions of Run 3. The number of wave trains decreases with increasing \( \gamma \) (i.e. as alternate bars develop). Wavelengths are greater at higher Froude numbers (\( y \approx 0.07 \)m in Figures 13b and c) than at lower Froude numbers (Figure 13a). This tendency is in agreement with the experimental results shown in Figure 9.

Figure 14 compares the transverse number of wave trains estimated from Equation 18 when \( \gamma = 1 \) to the measured transverse number of wave trains on the alternate bars. The results of the current model are found to be consistent with the experimental results, which ensures the validity of the model as well as the interpretation of the transverse number of wave trains on the antidunes on the alternate bars.

### Discussion

#### Model limitations

Since the water flow over alternate bars is sinuous in the plan view, wave trains have formed obliquely in Figures 9f–h. Although our model includes the reduction in the effective channel width due to bar formation, it does not take into account the direction of the sinuous flow. In addition, the amplitudes of surface waves are different: greater near the sidewall and smaller near the transverse centre. This suggests that the amplitudes of the diagonal cross-waves or the antidunes change depending on the sinuous flow field over alternate bars. To deal with the above-mentioned limitations, a morphodynamic model, which couples 2D Exner and 3D hydrodynamic models, is required (e.g. Colombini and Stocchino, 2012; Nabi et al., 2013; Khosronejad et al., 2015). However, the linear stability analysis proposed by Colombini and Stocchino (2012) cannot be applied to nonlinear cases of large bar heights. Although numerical models proposed by Nabi et al. (2013) and Khosronejad et al. (2015) can deal with nonlinear levels, to the best of our knowledge, there are no instances of simulations of antidunes on alternate bars. The computational complications involved in calculations of the sharp water surface waves on 3D antidunes may constitute a reason contributing to the lack of simulation
studies for antidunes on alternate bars (e.g. Nabi et al., 2013 used rigid-lid approximation for the boundary condition for the water surface). A multi-phase flow model such as the VOF method is required to simulate a water surface with breaking waves. Even though the model presented in this study has several limitations, it provides a simple and efficient way to calculate the streamwise and transverse length scales of water surface waves over 3D antidunes, especially when estimating Paleo-hydraulic conditions from sedimentary records that do not contain wave amplitude.

We have succeeded in measuring the water surface shape on 3D antidunes using a YAG laser sheet and LIF in detail. The measured water surface profile will be valuable verification data when constructing the above numerical analysis model. However, the flow over the 3D antidune has not been measured, and it has not been clarified what kind of vortex or turbulence is formed under the sharp water surface. In our experiments, antidunes coexisted with free bars in four runs, but all of the bars were alternate bars in the straight flume. The effects of the braid bars formed in the wider channel and the point bars formed in meandering channels on antidunes have not been investigated or modelled. In addition, breaking waves over antidunes can affect the shape of gravel bars because sandbars are formed not only by river flows but also by water surface waves near a shore (e.g. Yu and Mei, 2000). These will be exciting challenges for the future.

Possible model application

The model proposed here, based on the series of experiments and theoretical description of the waves, will contribute to better prediction of the wave characteristics induced by 3D antidunes in rivers, especially in the presence of alternate bars. The water surface waves formed in supercritical flow conditions result in highly energetic and destructive flows, causing high risk for river training works (e.g. Iwasaki et al., 2018). Our model will be able to predict the location and hydraulic conditions for the occurrence of such waves, contributing to better river management works.

Another implication of the present results may be possible estimation of the Paleo-hydraulic condition by applying our model to the bedform structures recorded in ancient and present sedimentary deposits. Not only for rivers, the model will provide new insights in this regard for submarine environments. In analogy to river bedforms, 3D, crescent-shaped antidunes have also been observed in submarine environments (e.g. Hughes Clarke, 2016); however, their origin and formative
conditions are difficult to ascertain because of large varieties in bedform characteristics and lack of in-situ measurements (e.g. Symons et al., 2016; Peakall et al., 2020). In submarine environments, bedforms are formed by turbidity current, which is driven by the density difference between the current and ambient water due to the suspended sediment in the flow. Although the physical mechanism of the flow and the resultant characteristics of bedforms between two environments are different (Cartigny and Postma, 2017), there may exist some similarities in terms of bedform regime (Sequeiros et al., 2010). A key non-dimensional parameter explaining the regime of turbidity current is the densimetric Froude number, which is defined as the ratio of current velocity to the internal wave propagation speed occurring at the interface between main flow and ambient water (e.g. Imran et al., 2017). It will be of value to apply the herein proposed framework to the turbidity current case by using the densimetric Froude number instead of the Froude number and dispersion relation of internal waves to understand 3D antidune dynamics in submarine environments. Although the internal flow and sediment structures (e.g. thin, dense basal driving layer) will also be an important factor for the current itself and the resulting bedform dynamics (Baas et al., 2009; Cartigny et al., 2013; Cartigny and Postma, 2017; Luchi et al., 2018; Dorrell et al., 2019), our model might be applicable to explain the antidune dynamics driven by some types of turbidity currents. The application of the proposed model to a series of submarine bedform experiments and detailed in-situ measurement data of flow and deposits (Clare et al., 2016; Kostaschuk et al., 2018; Hage et al., 2019) will be an important step forward for a unified understanding of bedform dynamics and interpreting the origin of deposits in deep-water environments.

**Conclusions**

Most of the previous experiments on antidunes have been conducted under conditions with a small width-depth ratio, meaning that we lack knowledge on antidune dynamics in rivers with wide alluvial beds (i.e. conditions in which free alternate bars are likely to form). We mainly focus on the influence of the formation of alternate bars on the streamwise and transverse length scales of 3D antidunes. Here we show the results of flume experiments conducted under conditions with a large width-depth ratio and the results of the model presented in this study, as follows.

The transverse number of water wave trains increases with increasing width-depth ratio, indicating that multiple trains of 3D antidunes can be developed in the transverse direction in a sufficiently wide channel without alternate bars.

3D antidunes coexist with alternate free bars. When alternate bars form, however, the transverse number of wave trains decreases until eventually one or two wave trains develop near the sidewall. In addition, the streamwise wavelength of 3D antidunes after bar formation is 1.1 to 1.3 times as great as that observed before alternate bar formation.

Previous theories for 3D antidunes (Yokokawa et al., 2010; Colombini and Stocchino, 2012) failed to predict the observed wavelength and the transverse number of wave trains at a nonlinear level after the development of alternate bars. Therefore, we have proposed a simple model for calculating 3D antidunes on bars by combining two previous theories dealing with antidunes and alternate bars. Our model allows predictions of the increase in streamwise wavelength and reduction in the number of transverse waves after free bars develop.

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**Data Availability Statement**

The experimental data used in this paper are available from http://river.ceri.go.jp/contents/archive/experimental%20data%2010antidune/research2717.html.

**Conflict of Interest**

The authors have no conflict of interest to declare.

**Appendix**

Equation 7 can be written as

\[ k_{3h} = \sqrt{\frac{1}{F_r^2 - 1/3}} \]  (A1)

Equation 8 can be written as

\[ kh = \frac{F_r^4 (k_x h)^2}{\tanh kh} \]  (A2)

Substituting the above equations in \( k_{x} = \sqrt{k^2 - k_{s}^2} \) as \( k_{s} \approx k_{x} \):

\[ k_{x} = \frac{1}{h} \sqrt{\frac{F_r^4 (k_x h)^4}{(\tanh kh)^3} - \frac{1}{F_r^2 - 1/3}} \]  (A3)

\[ = \frac{1}{h} \sqrt{\frac{F_r^4}{(\tanh kh)^2 (F_r^2 - 1/3)^3} - \frac{1}{F_r^2 - 1/3}} \]

\[ = \frac{1}{h} \frac{\sqrt{F_r^4 - (\tanh kh)^2 (F_r^2 - 1/3)}}{\tanh(F_r^2 - 1/3)} \]

Therefore

\[ n = \frac{k_{x} B}{2\pi} = \frac{\sqrt{F_r^4 - (\tanh kh)^2 (F_r^2 - 1/3)} B}{2\pi\tanh(F_r^2 - 1/3) h} \]  (A4)

**NOTATION**

- \( A \) : tanh(kh)
- \( A_a \) : antidune amplitude
- \( A_w \) : water wave amplitude
- \( B \) : channel width
- \( c \) : wave speed
- \( C_f \) : bed friction coefficient
- \( d \) : sediment grain diameter
- \( F_r \) : Froude number (=U/\sqrt{gh})
- \( g \) : gravitational acceleration
- \( h \) : water depth
- \( H \) : water surface elevation
$k$: magnitude of wave number of diagonal cross-waves
\[ -\sqrt{k_x^2 + k_y^2} \]
$K$: wave number vector
$k_x$: wave number of antidunes in longitudinal direction ($=2\pi/\lambda_x$)
$k_y$: wave number of diagonal cross-waves in longitudinal direction ($=2\pi/\lambda_x$)
$k_z$: wave number of diagonal cross-waves in transverse direction ($=2\pi n/B$)
$n$: transverse wavenumber mode of diagonal cross-waves (or 3D antidunes)
$S$: bed slope
$s_g$: submerged specific gravity of sediment (1.65)
$t$: time
$U$: depth-averaged flow velocity
$x$: longitudinal coordinate
$y$: transverse coordinate
$z$: vertical coordinate
$Z_b$: wave height of alternate bars
$\alpha$: angle between $U$ and $K$
$\gamma$: model parameter for bar development
$\lambda$: wavelength of antidunes in longitudinal direction
$\lambda_z$: half wavelength of transverse bars in longitudinal direction
$\lambda_x$: wavelength of diagonal cross-waves in longitudinal direction
$\sigma$: Shields number ($=U / \sqrt{g s_z}$)
$\varnothing$: frequency relative to the water moving with current $U$

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Movie S1. Supporting information