

Onset and Growth of Sand Ripples due to a Steady Viscous Flow in an Annular Channel

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A layer of glass beads of initially constant thickness confined in an annular channel was exposed to a viscous flow generated by the steady rotation of the upper annular plate. The critical velocity on the formation of ripples and the growth process were elucidated experimentally. Theoretical models were proposed to explain the initial stage of a ripple that reflects three-dimensional growth, the intermediate stage in which the growth of a ripple in the lateral direction is restricted by the side boundary, and the final stages of the ripples in which interaction of neighboring ripples maintain a stationary state.

Key words: Sand Ripple, Viscous Fluid, Critical Velocity, Fourier Mode, Growth Model

1. Introduction

Formation of sand ripples has attracted attention for a long time, not only from practical point of views, such as the need of vegetation in desert area (sand dunes in deserts, Wasson and Hyde, 1983; Nagashima, 1991; Walker, 1997), submarine ripples or the coastal engineering (Kennedy, 1969; Engelund and Fredsøe, 1982; Horikawa, 1982) and Martian ripples (Beatty *et al.*, 1982; Benson, 2003), but also from scientific point of view on the pattern formation in granular material (Bagnold, 1936, 1941; Kawamura, 1948). When the sand bed is of insufficient amount and is exposed to a wind with almost fixed direction, a peculiar type of dune called “barchan”, which has a crescent shape viewed from above and whose vertical cross-section are asymmetric, with smaller slope on the upstream side, is observed (Sauermann *et al.*, 2000; Elbelrhiti *et al.*, 2005). Laboratory experiments (Hersen *et al.*, 2002; Endo *et al.*, 2005; Katsuki *et al.*, 2005a), and numerical simulations such as phenomenological models (Nishimori and Ouchi, 1993; Nishimori *et al.*, 1998; Katsuki *et al.*, 2005b), fluid mechanical closure model (Van Boxel *et al.*, 1999), continuum saltation model (Sauermann *et al.*, 2001), and a large-eddy simulation (LES) (Zhang *et al.*, 2003, 2005) revealed the onset and the movement of them, as well as the interaction of barchans (Lima *et al.*, 2002; Schwämmle and Herrmann, 2003; Hersen *et al.*, 2004; Katsuki *et al.*, 2005b) which seem to agree satisfactorily with observations. On the other hand, when the sand bed is thickly spread as is met in the interior region of desert, the situation becomes more complicated. The surface patterns, such as *transverse dunes* with ridges perpendicular to the wind direction, *longitudinal dunes* with the ridges parallel to the wind direction, and *star dunes* (pyramidal sand mounds with slipfaces on three or more arms from the crest), are considered to be determined by the amount of available sand and the type of flow (Bagnold, 1936, 1941; Kawamura, 1948; Wasson and Hyde, 1983), but the details of the formation processes, pat-

tern sizes, dependence on the particle characteristics, etc are not fully understood. One of the difficulty in experiment is the finite size of the apparatus. Indeed, Endo *et al.* (2005) and Katsuki *et al.* (2005a) performed experiments on the ripple formation in a straight channel of 10 m long and 0.2 m width, and observed an initially localized flat belt of sand bed exposed to a unidirectional flow split into transverse dunes, followed by the formation of barchan dunes. Their experimental apparatus, however, had difficulty in sand supply, so that the long-term evolution of sand ripples could not be traced.

Recent studies on the onset and growth of sand ripples due to viscous flow have shed light on a new features of pattern formation in granular materials (Betat *et al.*, 1999, 2002; Yizhaq *et al.*, 2004; Andreotti *et al.*, 2006). Betat *et al.* (1999) made a quasi-one-dimensional experiment in a narrow annular channel between two concentric circular cylinders of finite height. The granular bed was exposed to a “shear flow” caused by the rotation of a disc at the upper boundary of the channel, and the ripples were observed as long as 60 hours. The exponential growth of certain Fourier modes of the wave amplitude was reported in a certain range of particle Reynolds numbers near the threshold value of the ripple formation, and the growth rates of the wavelength were compared with those obtained by the linear stability theory. In their succeeding paper (Betat *et al.*, 2002), they showed the saturation of mean amplitude, which was achieved via almost linear growth for about 24 hours, in contrast to an exponential growth of the mode amplitude (Betat *et al.*, 1999). Reynolds number and Shields parameter dependences of the stationary state amplitudes, wavelength and drift velocity of the ripples are also shown. However, their assumption of the linear profile in the channel is not guaranteed, as the authors admit, because of the side walls to impose a no-slip condition as well as the presence of granular bottom, which makes quantitative comparison with the linear stability theory and scaling in terms of

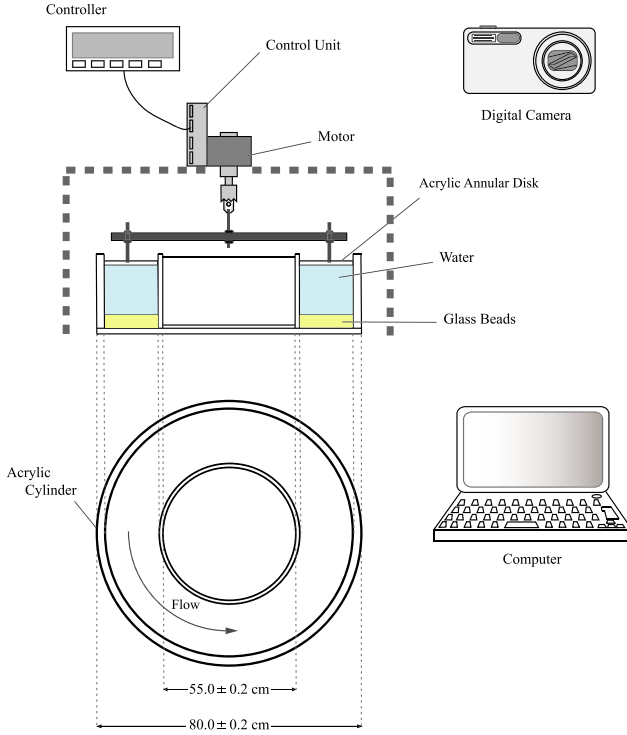


Fig. 1. Schematic diagram of the experimental apparatus.

“reduced shear stress excess” difficult. In the case of the aeolian sand ripple, Yizhaq *et al.* (2004) reported the initial power-law growth of the wavelength with exponent about 0.35 in a nonlinear continuum model, whereas Andreotti *et al.* (2006) did not show such behavior of the wavelength, although they suggested an exponential growth of the amplitude in the initial stage. Thus the formation process and the long time behavior of ripples are still disputable partly because of the difference in Bagnold number (i.e., air vs. water), partly because of the experimental difficulty of determining accurate time of the start of depression on the “flat” surface (i.e., smooth surface with respect to the grain size) of the granular layer, and partly because of the limited size of experimental apparatus.

A lot of works on the stability of erodible beds have been made, which are found in review articles and papers by Kennedy (1969), Engelund (1970), Fredsøe (1974), Richards (1980), Engelund and Fredsøe (1982), Sumer and Bakioglu (1984), Werner and Gillespie (1993), etc. These stability analyses, however, were concerned with the formation of dunes rather than ripples, the former being larger scale wave pattern on the granular bed. Betat *et al.* (1999) also compared their experimental results with stability criteria and discussed the growth of Fourier modes, but their Froude number $Fr \equiv V/\sqrt{gH}$ does not seem to be comparable with that of the theory. Recently an experiment on the dynamics of a bed of particles using similar experimental setup, i.e., an annular channel sheared by a viscous Couette flow, has been made by Charru *et al.* (2004). Their study, however, was focused to fundamental problems of the particle motion near the threshold flow velocity, in which ripples were not formed. In the succeeding papers (Charru and Hinch, 2006a, b) they concluded, on the basis of the

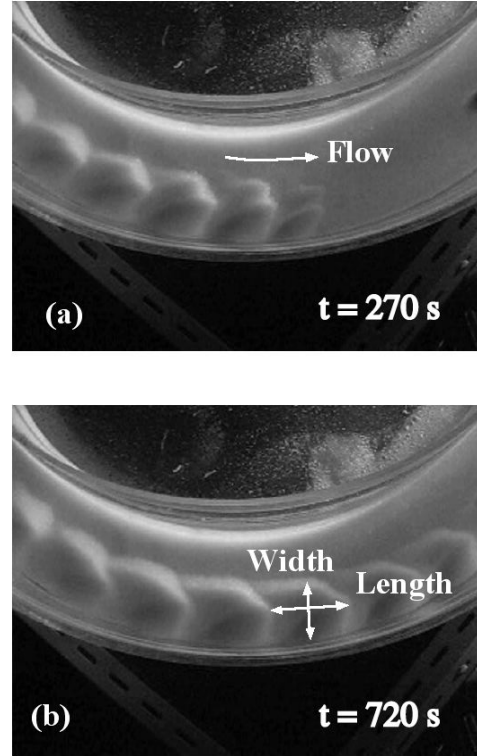


Fig. 2. Growth of sand ripples and the definition of width and length of the ripple.

erosion-deposition model, that increase of fluid viscosity suppresses the ripples under steady flow and that the only possibility of ripple formation remains for oscillatory flow. In our experiment, however, we observed the formation of ripples as long as three hours, so that the newly generated ripples took over to the previous ones in the annular channel. Although no steady state were achieved because of incommensurate sizes and wavelengths of the ripples that met the old ones, the surface undulations did not look suppressed by the main flow. This discrepancy may be attributed to their assumptions of higher viscosity of the fluid, long wave and small amplitude deformation, etc. which may not be satisfied because the Reynolds number is much higher in our case, and because the observed local flow field near the bottom is spatially and temporally varying.

In our previous paper (Hori *et al.*, 2007; Oshiro and Sano, 2007), we have reported the onset of barchans and growth of ripples due to a viscous flow in an annular region, as well as the interaction and self-adjustment of wavelength of the ripples. In this paper, we show our experimental results on the onset and growth of ripples, and propose models that describe the initial growth of the ripples as well as the effect of the container wall and the long time behavior of the interaction of ripples.

2. Experimental Apparatus

We show our experimental setup in Fig. 1. Our experimental apparatus is basically the same as the one reported in our previous papers (Hori *et al.*, 2007; Oshiro and Sano, 2007). It has two transparent acrylic resin cylinders of diameters 80.0 ± 0.2 cm and 55.0 ± 0.1 cm (average diameter

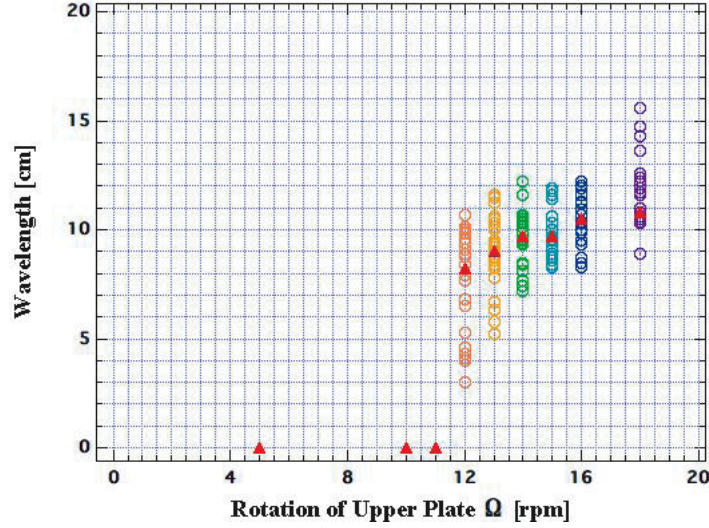


Fig. 3. Onset of sand ripples.

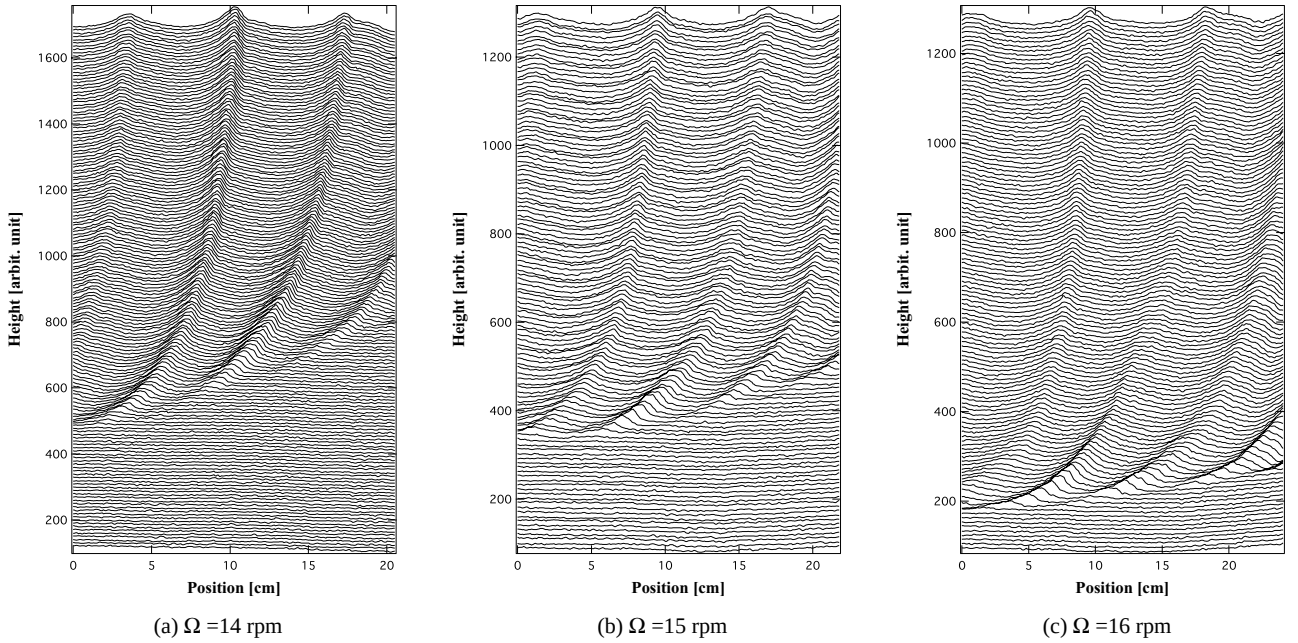
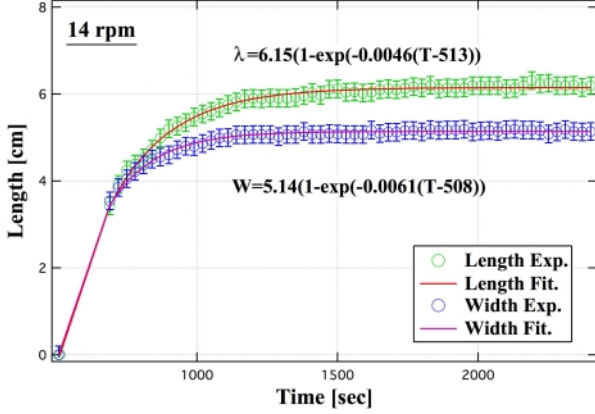
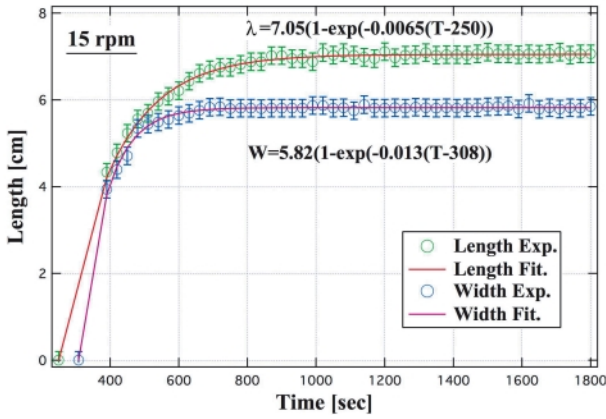
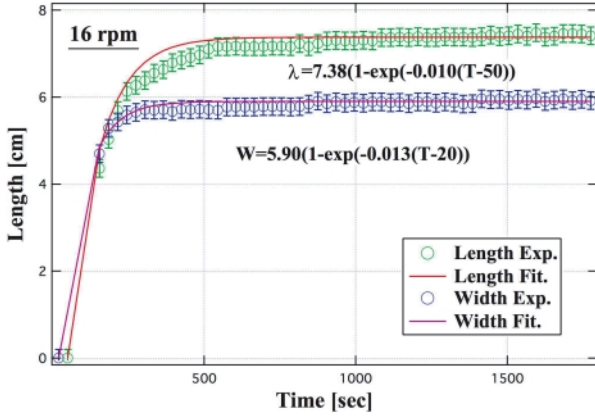


Fig. 4. Time sequence of sand ripple for (a) $\Omega = 14$ rpm, (b) $\Omega = 15$ rpm, and (c) $\Omega = 16$ rpm. In each figure, the abscissa is the position in the circumferential direction, whereas the ordinate is the height of the granular surface. The data are given at every 15 seconds, whose baselines are shifted by the amount proportional to the elapsed time.

$\bar{D} = 67.5$ cm) with 12 cm height, which are placed at a concentric position with their generators vertically. The upper surface of the annular region is covered by an annular acrylic resin plate, which can rotate at a prescribed angular velocity Ω . Thus our test section consists of outer and inner fixed side walls with separation distance $W = 11.0 \pm 0.3$ cm, a fixed bottom wall and a sliding upper wall whose vertical position H is chosen between 5 and 10 cm. Tap water at room temperature was used as a working fluid, and glass beads of mean diameter $d = 0.06$ cm were placed uniformly on the bottom of the annular region up to a specified height $h = 3.0$ cm. The fluid flow is generated by rotating the upper annular plate at an angular velocity $\Omega = 16$ rpm, which gives a typical velocity $V = 20$ cm/s at the

central position of the channel. The detailed velocity profiles are given in our previous paper (Hori *et al.*, 2007). As is reported, the vertical velocity distribution in the bulk is nearly constant, and only a very thin boundary layer of the order of a grain size is present near the granular surface. On the other hand, the horizontal velocity distribution shows almost linear increase toward outer boundary reflecting solid rotation of the annular plate, which imposes shear layers of the order of less than one tenth of channel width near the side boundaries. A digital camera equipped with an automatic recording system was set along the rotating axis at such a distance from the channel that the deformation of the surface of the granular material over the *entire* test section can be observed with sufficient resolution.

(a) $\Omega = 14$ rpm(b) $\Omega = 15$ rpm(c) $\Omega = 16$ rpmFig. 5. Wavelength and wave width for (a) $\Omega = 14$ rpm, (b) $\Omega = 15$ rpm and (c) $\Omega = 16$ rpm.

3. Experimental Results

Figures 2(a) and (b) are the example of granular ripples observed from above at 270 s and 720 s, respectively, after the initiation of the fluid flow. In Fig. 2(b) the definition of the length and width of the ripple is given. New sand ripples are generated successively at a position ahead of the preceding ripples, and the whole sand ripples drift slowly in

Table 1. Fitting parameters for wavelength λ .

Ω (rpm)	λ_0 (cm)	t_0 (s)	σ_λ (1/s)
14	6.15	513	0.0046
15	7.05	250	0.0065
16	7.38	50	0.010

Table 2. Fitting parameters for wave width W .

Ω (rpm)	W_0 (cm)	t_0 (s)	σ_W (1/s)
14	5.14	508	0.0061
15	5.82	308	0.013
16	5.90	20	0.013

the downstream direction. In this example, a newly created ripple overtook the oldest ripple, and the entire channel region was occupied by the ripples after about 30 min. By choosing an appropriate incident angle of the illuminating light, we obtain the image density profile of the granular surface, from which we can estimate the surface undulation. The accuracy of the horizontal position of the ripples is quite good, which was checked in our previous paper (Hori *et al.*, 2007) by comparing the intensity of the transmitted sheet-like light that was inserted below the granular layer. On the other hand, the measurement of the height of ripple in the present paper may have some error due to surface undulation, which can be corrected to a certain extent by comparing with similar data obtained in Hori *et al.* (2007).

Figure 3 shows the critical velocity of the onset of sand ripple. Measurements of the wavelength were made after the ripples had fully developed, so that the time of observation T_{meas} was 2400 min for $\Omega = 12$ rpm, 2000 min for $\Omega = 13$ rpm, 1300 min for $\Omega = 14$ rpm, 970 min for $\Omega = 15$ rpm, 800 min for $\Omega = 16$ rpm, and 180 min for $\Omega = 18$ rpm. The wavelength were varied around the mean value described by a solid triangle in Fig. 3 due to the interaction between the neighboring ripples (Oshiro and Sano, 2007). We can estimate the critical rotation Ω_c of the upper plate for the occurrence of the sand ripple be between 11 rpm and 12 rpm. This critical angular velocity was qualitatively supported by direct observation that no transport of sand grains was recognized below Ω_c . Once the ripples were generated, the wavelength λ increased gradually with Ω .

Figure 4 show the dependence of the initial growth of sand ripples on the rotation of annular plate. In each case, the first ripple was initiated by setting a small dimple (about 1 cm in diameter, and 0.5 cm in depth) at a prescribed position, which was exposed to the flow generated by the rotation of the annular plate at $\Omega = 14, 15$ and 16 rpm. In our preliminary experiment without a granular layer, we have found that the steady flow was achieved within an order of 1 min after starting rotation of the annular plate, so that we have chosen the origin of time $t = 0$ at the start of rotation in this paper. We have also checked the almost linear dependence of the characteristic flow V on the angular velocity Ω , so that the latter is used as a measure

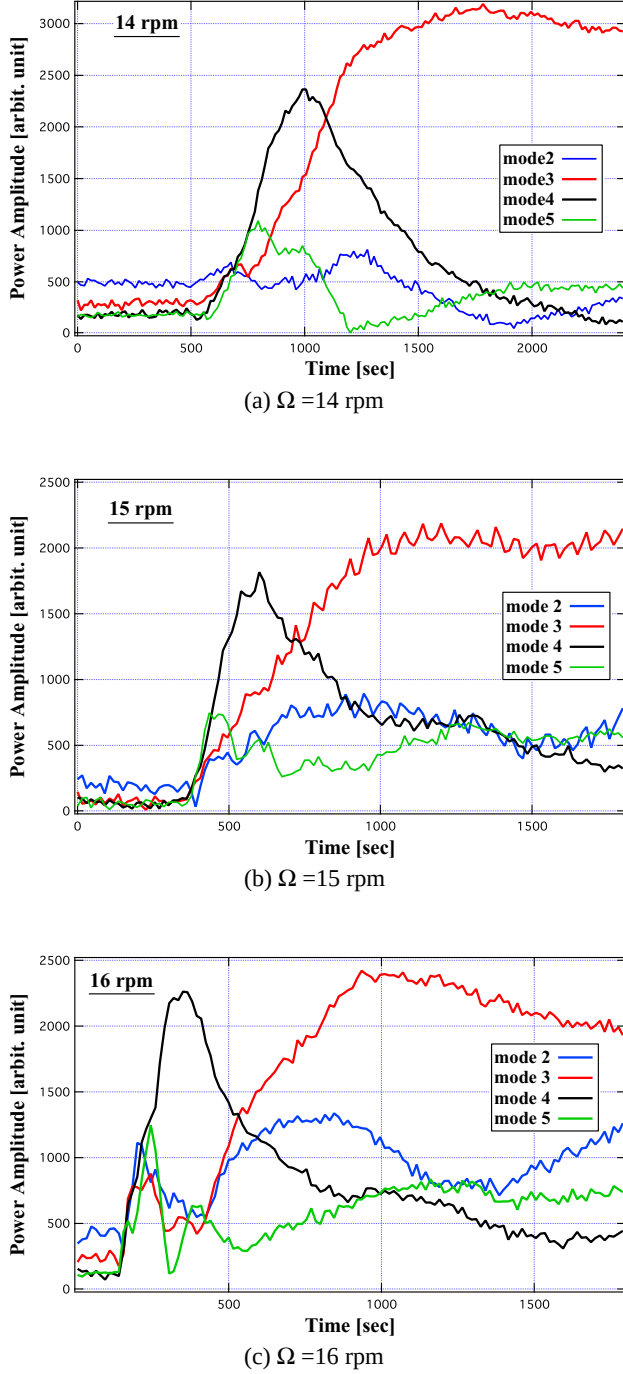


Fig. 6. Time sequence of the Fourier mode for (a) $\Omega = 14$ rpm, (b) $\Omega = 15$ rpm, and (c) $\Omega = 16$ rpm.

of the magnitude of the applied velocity. In each figure, the abscissa is the position in the circumferential direction, whereas the ordinate is the height of the granular surface. The data are given at every 15 seconds, whose baselines are shifted by the amount proportional to the elapsed time.

We see that

- (i) onset of the ripple is earlier for larger Ω ,
- (ii) the wavelength is larger for larger Ω ,
- (iii) the apparent wave height (i.e., without correction) is almost the same irrespective of Ω .

We show the typical time development of the wavelength (λ) and wave width (W) in Fig. 5. The empirical fits of these

data are given by

$$\lambda = \lambda_0 \{1 - \exp[-\sigma_\lambda(t - t_0)]\}, \quad (1)$$

$$W = W_0 \{1 - \exp[-\sigma_W(t - t_0)]\}, \quad (2)$$

where the fitting parameters are given in Tables 1 and 2. The fittings seem reasonably well except that of λ for $\Omega = 16$ rpm. As will be discussed in the last section, the deviation of λ from the above fitting in $\Omega = 16$ rpm case will be ascribed to the presence of linear growth stage, which reflects the influence of the boundary walls of the container.

Figures 6 shows the development of the Fourier modes for the ripples described by Figs. 4(a)–(c). In the tested cases $\Omega = 14$ rpm and 15 rpm, the mode 3 grows almost linearly and attains constant value (Fig. 7). Our data does not necessarily support exponential growth as has been reported by Betat *et al.* (1999). On the other hand, the growth in case $\Omega = 16$ rpm is complicated, probably because of the boundary effect and the stronger interaction between the neighboring ripples, which will be discussed in the last section.

4. Discussion

We can summarize our experimental data in the following three stages:

- (1) initial stage, characterized by 3D growth,
- (2) intermediate stage, characterized by 2D growth,
- (3) fully developed stage, or stationary states.

In the following, we shall consider the growth model for each stage.

4.1 Initial stage

Initially the ripple is sufficiently small, so that it can grow in the stream, side and vertical directions without experiencing the boundary effect. In this case the ripple can grow similarly in 3D, so that the volume of the ripple Q is proportional to the pattern size l , and that the increment of the volume is given by

$$dQ = 3kl^2 dl, \quad (3)$$

where k is a constant.

The tangential stress on the particle is given by

$$\tau = \mu \frac{\partial U_x}{\partial y}, \quad (4)$$

where μ is the viscosity of the fluid and we have taken the x, y coordinate system with the x axis in the direction of flow as is shown in Fig. 8 (U_x being the x component of fluid velocity). The work done by the force $F = \tau S$ during the time dt is

$$dW \sim FU_x dt, \quad (5)$$

where S is the area of the upstream-side slope of the ripple (see Fig. 8):

$$S \sim C_0 l^2 \quad (C_0 : \text{constant}). \quad (6)$$

Thus we can estimate the work done by the fluid:

$$dW \sim \mu \frac{\partial U_x}{\partial y} C_0 l^2 U_x dt. \quad (7)$$

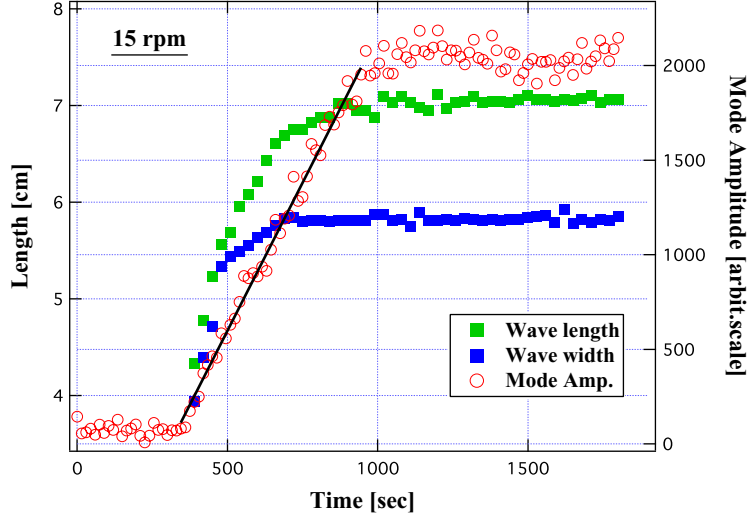


Fig. 7. Comparison of wavelength, wave width and amplitude of mode 3 for $\Omega = 15$ rpm.

On the other hand, the work w necessary to convect each particle by the distance l is given by

$$w = \mu' \Delta m g l, \quad (8)$$

where μ' is the dynamical friction coefficient and Δm is the mass of the particle in water. Total work is calculated by summing up dN particle, so that we have

$$dW = \mu' \Delta m g l dN = \mu' \Delta \rho g l dQ, \quad (9)$$

where we have taken account of the relation $\Delta m = (4/3)\pi a^3 \Delta \rho dN = \Delta \rho dQ$ (a being the radius of the sphere and $\Delta \rho$ being the density difference).

The initial stage growth will be governed by

$$\mu \frac{\partial U_x}{\partial y} C_0 l^2 U_x dt = \mu' \Delta \rho g l dQ (= \mu' \Delta \rho g l 3kl^2 dl),$$

or

$$\frac{dl}{dt} = \frac{\mu C_0 U_x}{3k\mu' \Delta \rho g l} \left(= \frac{C_1}{2l} \right), \quad (10)$$

where the constant C_1 is $C_1 = 2\mu C_0 U_x (\partial U_x / \partial y) / (3k\mu' \Delta \rho g)$. This equation is integrated to give

$$l = C_1 \sqrt{t - t_0}, \quad (11)$$

where t_0 is the time of the onset of the ripple.

4.2 Intermediate stage

When the increase in width is saturated to a certain size W_0 due to the limitation of the channel wall whereas further growth of ripple in other directions is allowed, then we have

$$dQ = 2klW_0 dl, \quad (12)$$

so that Eq. (9) becomes $\mu' \Delta \rho g l dQ = \mu' \Delta \rho g l 2klW_0 dl$. Then we have

$$\mu \frac{\partial U_x}{\partial y} C_0 l^2 U_x dt = \mu' \Delta \rho g l 2klW_0 dl, \quad (13)$$

from which we have an expression

$$l = C_2 t + l_0, \quad (14)$$

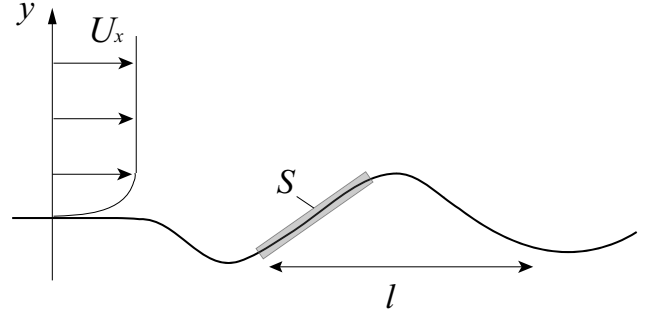


Fig. 8. Transport of sand and deformation of the surface.

where C_2 is a constant:

$$C_2 = \mu C_0 U_x \frac{\partial U_x}{\partial y} / (2k\mu' \Delta \rho g W_0).$$

4.3 Fully developed stage

When the size of the ripple becomes large enough, the growth of ripples is suppressed by the presence of neighboring ones as well as the boundary wall. Then the sand ripples achieve a stationary state either by surface creep or by saltation, where the net increment of sand volume in each ripple dQ is zero. As shown in Fig. 9, the particle convected along the surface (creep) will be released at the top of the hill y_0 into the fluid region. Then its motion will be described by

$$\begin{cases} \Delta m \frac{d^2 x}{dt^2} = 6\pi \mu a (U_x - u) \\ \Delta m \frac{d^2 y}{dt^2} = 6\pi \mu a (U_y - v) - \Delta m g. \end{cases} \quad (15)$$

Here u and v are, respectively, the x and y components of the particle velocity. In a steady stream, the streamwise acceleration of the particle will be negligible, so that $u \approx U_x$, and $x \approx U_x t$. On the other hand, $U_y \approx 0$, so that the terminal velocity in the y direction is $v = -\Delta m g / 6\pi \mu a$. Then the traveling distance x_0 of that particle during the fall

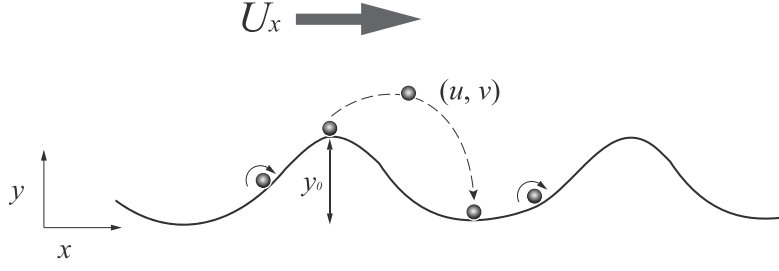


Fig. 9. Surface creep and saltation.

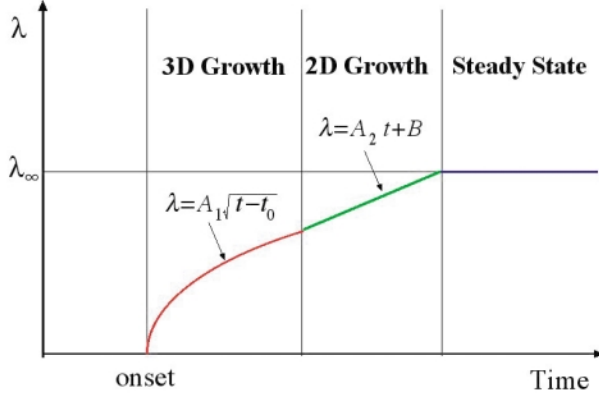


Fig. 10. Three regime growth model.

of height y_0 with the above terminal velocity is estimated to be

$$x_0 = \frac{6\pi\mu a y_0}{\Delta m g} U_x = \frac{9\mu y_0}{2a^2 \Delta \rho g} U_x, \quad (16)$$

from which we can estimate the wavelength $\lambda \approx 2x_0$.

Thus it is anticipated that the wavelength is

- 1) shorter for heavier particle,
- 2) shorter for larger particle,
- 3) longer in more viscous fluid,
- 4) longer for faster flow,
- 5) proportional to the wave height.

4.4 Comparison with experiment

Our models are schematically described in Fig. 10. The wavelength and wave width data shown in Figs. 5(a)–(c) are plotted in logarithmic scale in Fig. 11, which seem to agree with the square-root growth in the initial stage in spite of some scattering of the data. Apparently the side wall of the container restricts the dimension of horizontal spread. Closer look of the ripple formation, however, reveals that the boundary is not as clearly defined as the solid wall. Indeed, the inner side of the ripples are limited by the natural boundary of the undulation of the granular surface associated with the decrease of velocity due to the boundary layer (see e.g., Fig. 2), which is also the case near the outer cylindrical wall. Thus the side boundaries of the surface undulation are not directly limited by the solid walls, but rather by the velocity distribution. As has been reported (Hori *et al.*, 2007), horizontal velocity distribution in our annular channel is an almost linearly increasing function across the channel width accompanied by the boundary layer near the

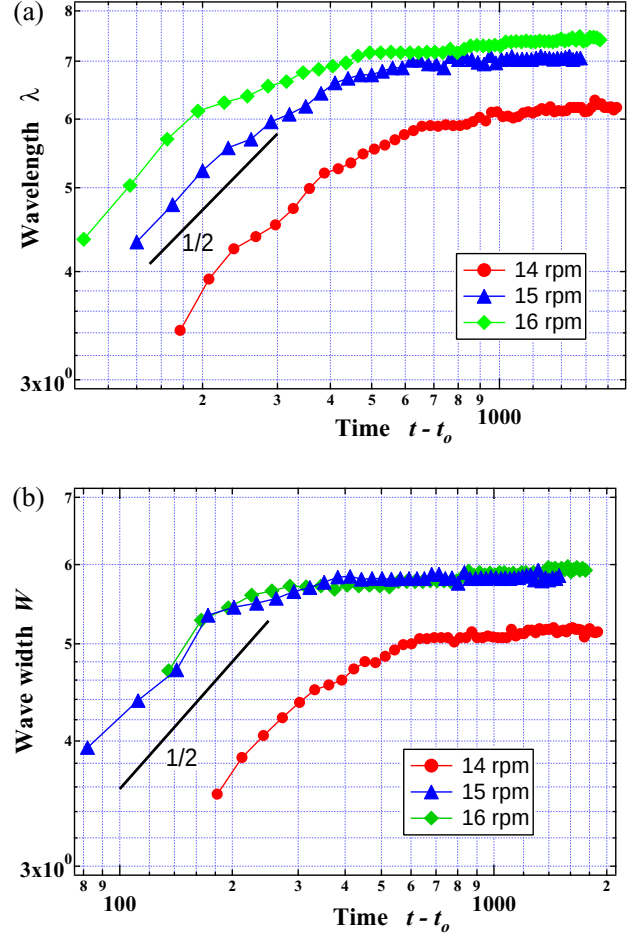


Fig. 11. Initial Growth of the wavelength (a) and wave width (b) in log-log plot.

walls. The latter distribution causes faster movement of the ripple in outer part of the ridges, which results in obliquely arranged ripples, and hence partially overlapped ripples in the circumferential direction (see Fig. 2(b)). This overlapping is enhanced in slower flow, which makes difficult to observe 2D growth range in Figs. 5(a) and (b). On the other hand, the intermediate region is recognized in Fig. 5(c), which duly results in poorer agreement in the exponential fitting curve of Fig. 5(c) and non-monotonic behavior of mode 3 in Fig. 6(c).

We have as yet no data to check the anticipation (1)–(3) of Subsec. 4.3, because all the data were obtained using glass beads of a single diameter in a particular fluid (water),

which will be ascertained in our future investigation. The dependence of the wavelength on the fluid flow, however, seems justified. In our model Subsec. 4.3, the wavelength is estimated by Eq. (16):

$$\lambda \approx 2x_0 \approx \frac{5.72\mu y_0}{a^2 \Delta \rho g} \Omega, \quad (17)$$

where we have inserted an empirical relation $U_x \approx 1.27\Omega$ (Hori *et al.*, 2007). If we choose, as a rough estimation, $\mu = 0.010$ g/s cm for water, $y_0 = 2.0$ cm, $\Delta \rho = 1.5$ g/cm³, $a = 0.030$ cm, and $g = 980$ cm/s², we have $\lambda \approx 0.17\Omega$. On the other hand, the wavelength in Fig. 3 is well approximated by $\lambda = 0.65\Omega$, if the data in the Ω range less than 11 are omitted. Although the proportional coefficient differs by a factor of 4, these relations agree qualitatively with our anticipation (4). As for our anticipation (5), we have not yet obtained sufficiently reliable data for the measurement of wave height. In our previous paper (Hori *et al.*, 2007), we have obtained the thickness of the layer by measuring intensity of the illuminated sheet of light that was placed below the granular layer. The latter technique, however, is applicable to relatively thin layer (less than about 2 cm in glass beads of a diameter 0.06 cm), so that a new technique using a light with much more intensity will be required, which is also left for our future investigation.

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