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Particle trajectories and size sorting above a rippled bed under standing water waves

T. D. Chu,^{1,*} A. Jarno-Druaux,¹ F. Marin,¹ and A. B. Ezersky²

¹Laboratoire Ondes et Milieux Complexes, UMR CNRS 6294 Université du Havre, 25 rue Philippe Lebon, B.P. 540, F-76058 Le Havre Cedex, France

²Laboratoire Morphodynamique Continentale et Côtière, UMR CNRS 6143 Université de Caen, 2-4 rue des Tilleuls, F-14000 Caen, France

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Particle trajectories and size sorting above an artificial rippled bed under standing surface waves are experimentally and theoretically studied. It is observed that fine particles may be trapped in a very thin region near the ripple crests. When the surface waves damp, fine particles concentrate on the top of ripple crests forming narrow strips, while coarse particles settle more uniformly along the rippled bed. Measurements of particle concentrations before their deposition confirm this size segregation. The present experimental results are explained with a theoretical approach.

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I. INTRODUCTION

Periodic patterns with typical wavelengths of ≈ 10 cm often cover seabeds in coastal zones. These structures, generally called ripples, result from complex interactions between the flow of water and the granular bottom. Since the pioneering works of Ayrton [1] and Bagnold [2], the formation of vortex ripples induced by oscillatory motion has been intensively studied. Many experimental and theoretical works have been conducted on the morphology of these structures, which significantly affect sediment transport, wave damping, and boundary layer structure. The wavelength of ripples is roughly proportional to the amplitude of the water motion [3], and the flow in their vicinity is dominated by the generation and ejection of lee-side coherent vortices [4–6]. Detailed visualizations of vortex dynamics have been carried out [7–9].

A majority of the literature devoted to ripple patterns considers the case of homogeneously sized grains [10–12]; however, sediments in coastal zones are usually heterogeneous in size. It should be noted that pattern formation in granular materials containing different particles is widely investigated now [13]. However, the studies of grain segregation for ripples under waves are scarce. A surface sorting is reported: coarse sediments are observed to accumulate mostly along the ripple crests, while fine grains mostly accumulate in the troughs [14–16]. The presence of fine particles forming very narrow strips on the top of crests is mentioned in [16]. In the case of standing waves, sand bar formation is observed with bar crests composed of coarse sand and flat plateaus of fine sand [17]. The density segregation under decaying highly nonlinear waves, solitons, is considered in Ref. [18]. Light grains concentrate in a narrow region close to the ripple crests when the waves are damped. The sorting process was not analyzed in detail in Ref. [18]. The aim of the present work is to study the segregation process above a rippled bed under a simple oscillating flow, standing waves, from a detailed analysis of the motion of individual particles of different sizes. Grain trajectories under standing waves and decaying standing waves are experimentally obtained, and concentrations of sinking particles are measured before their deposition on the

bed. There is only a restricted number of experimental studies on granular material dynamics dealing with trajectories of individual particles [19]. Present measurements improve the theoretical model for the flow above ripple crests proposed in Ref. [18]. Finally, a model for the flow above ripple troughs is suggested to complete the explanation of the experimental results.

This paper is organized as follows. In Sec. II, a short description of the experimental setup is given. The experimental results are presented in Sec. III. Sec. IV is devoted to the $f_r = 0.31$ theoretical approach. The theoretical results are compared with the experimental findings. The paper ends with conclusions in Sec. V.

II. EXPERIMENTAL SETUP AND PROCEDURE

The experiments were conducted in a 5.4-m-long, 0.3-m-wide wave flume. Surface waves are generated by an oscillating paddle at one end of the flume; a near-perfect reflection takes place at the other end. The frequency of the oscillating paddle is chosen close to the resonant frequency Hz of the mode whose wavelength is equal to the effective flume length ($L_w = 5$ m). The water depth at rest h is 0.26 m. The height and the period of the wave are measured with two resistive probes. For the present tests, the maximum wave height at the antinode H is 0.04 m. Ripples were generated beneath standing waves from an initially flat bed, which consisted in a 4-cm layer of polyvinyl chloride (PVC) grains of density $\rho_p = 1350$ kg.m⁻³ and median diameter $d_p = 0.20$ mm. Ripples formed rapidly along the flume once the wave maker was switched on. Their size and shape change from one end of the flume to the other end, depending on their position in relation to the position of the nodes and antinodes of the standing wave. The regions under the antinodes are essentially flat, whereas the regions under the nodes where the bed shear stress is maximum are covered by the greatest ripples. When the equilibrium state is reached, we switch off the oscillating paddle and empty slowly the wave flume in order to maintain the natural form of the bed. The rippled bed is then covered by a thin powdering of cement. When this powdering is dry, the wave flume is refilled with the same water level at rest as previously (0.26 m). PVC particles are then carefully injected through the free surface above

*tien-dat.chu@univ-lehavre.fr.

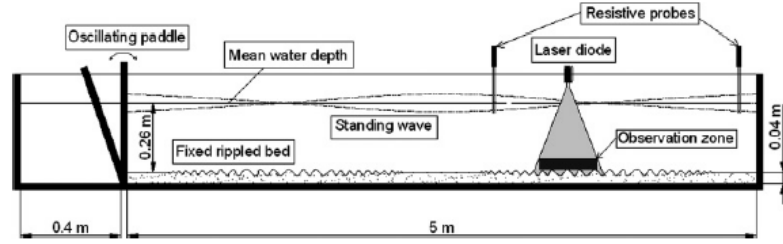


FIG. 1. Side view of the flume.

the fixed rippled bed, and their trajectories are registered. The flow conditions change along the wave flume and the Reynolds number, $Re = U_\infty a / \nu$, varies in the range $0 < Re < 5700$, where $U_\infty = a\omega = \pi H / [T \times \sinh(kh)]$ is the velocity of fluid particles at the edge of the bed boundary layer, a is the orbital amplitude of fluid particles at the same place, ω is the wave pulsation, T is the wave period, ν is the water kinematic viscosity, and k is the wave number. The edge of the bottom boundary layer may be estimated at the height k_s above the level midway between crest and trough of the ripples [20], where k_s is the Nikuradse roughness length, which may be estimated for a ripple bed by $k_s = 25H_r^2/L_r$ [21]. The studied zone for the particle trajectories and the sediment sorting is chosen close to the node located in the vicinity of the wall reflecting the surface waves (Fig. 1). In this zone, ripples are mostly regular and bidimensional; their wavelength L_r and their height H_r are, respectively, 5.5 and 1.5 cm, and we have $Re \approx 4500$. The mobility number (Ψ), the Stokes sedimentation velocity (U_0), and the Stokes number (St) are calculated as follows: $\Psi = (a\omega)^2/d_p g(s-1)$, $U_0 = d_p^2(\rho_p - \rho_w)g/18\nu\rho_w$, and $St = d_p^2\rho_p\omega/18\nu\rho_w$, where g is the acceleration due to gravity, s is the relative density of grain, and ρ_w is the fluid density. The Shields number θ may be estimated with $\theta = 0.5f_w\Psi$, where f_w is the friction factor. Following Davies [22], the flow regime depends on the values of Re and a/k_s ; this regime is rough turbulent in the considered zone. Five different kinds of PVC particles have been used, as specified in Table I showing the experimental conditions; the hydrodynamic forcing is the same for all of the tests. Tests 1 to 5 were carried out with well size-sorted particles (P_1 to P_5), while Test 6 involved a mixture of 50 % (in weight) very fine particles (P_1) and 50 % medium particles (P_3) and Test 7 involved a mixture of 50 % very fine particles (P_1) and 50 % coarse particles (P_5).

Grain trajectories were obtained performing particle tracking velocimetry (PTV). The principle of PTV is to individually follow each introduced particle in successive images. A high-resolution camera Dalsa Falcon PT-41-4M60 (resolution 2352×1728 pixels), 62 frames per second, is used in combination with a laser diode, which generates a thick vertical light sheet. The thickness of the light sheet is fixed to two centimeters so that particles stay long enough in the illuminated area to enable the capture of grain trajectories over several wave periods [23,24]. Particle trajectories are obtained using a program presented in Ref. [25] and adapted to the present experiments. For present tests, two phases of the flow were considered: during the excitation of standing waves [phase (1)] and during

the decay of surface waves [phase (2)], after the stopping of the oscillating paddle. The dimensions of the observation window of the video camera are fixed to one ripple wavelength in the vertical direction, one ripple wavelength in the horizontal direction for the phase 1 and four ripple wavelengths for the phase 2. The large horizontal area for phase 2 allows accurate study of the sediment sorting and the settling zones for decaying waves, when the horizontal zoom in on one ripple length for phase 1 provides very precise information on particle trajectories close to the ripple crests, as shown in the next section.

III. EXPERIMENTAL RESULTS

A. Particle motion in the vicinity of ripple crests during the excitation of standing waves

Organized vortices are formed on the lee side of ripples and shed above ripple crests each half-cycle [20,26]. Figure 2(a) depicts a typical trajectory above the rippled bed under the effect of vortices showing the complex motion of particles. Let us focus on the area close to ripple crests. The oscillating movement of particles in a zone confined just above the top of the ripple crests can be observed, as shown in Fig. 2(b). In this confinement zone, particles can be “captured” [Figs. 2(b) and 2(c)] and ejected in the flow several periods later [Fig. 2(d)]. Form and dimensions of the confined zone are determined by the extreme positions of grains that oscillate in it. Its lower limit is the ripple crest and its height varies from zero at its

TABLE I. Experimental conditions.

Particle	s	d_p (mm)	U_0 (mm/s)	U_∞/U_0	St	Ψ
P_1	1.35	0.11	2.1	51.4	1.6×10^{-3}	29.9
P_2	1.35	0.19	5.8	18.5	4.5×10^{-3}	17.9
P_3	1.35	0.28	13.2	8.2	10.2×10^{-3}	11.9
P_4	1.35	0.45	33.4	3.2	25.8×10^{-3}	7.5
P_5	1.12	0.57	18.1	5.9	33.7×10^{-3}	17.3
Test number	Particle					
1	P_1					
2	P_2					
3	P_3					
4	P_4					
5	P_5					
6	50 % P_1 - 50 % P_3					
7	50 % P_1 - 50 % P_5					

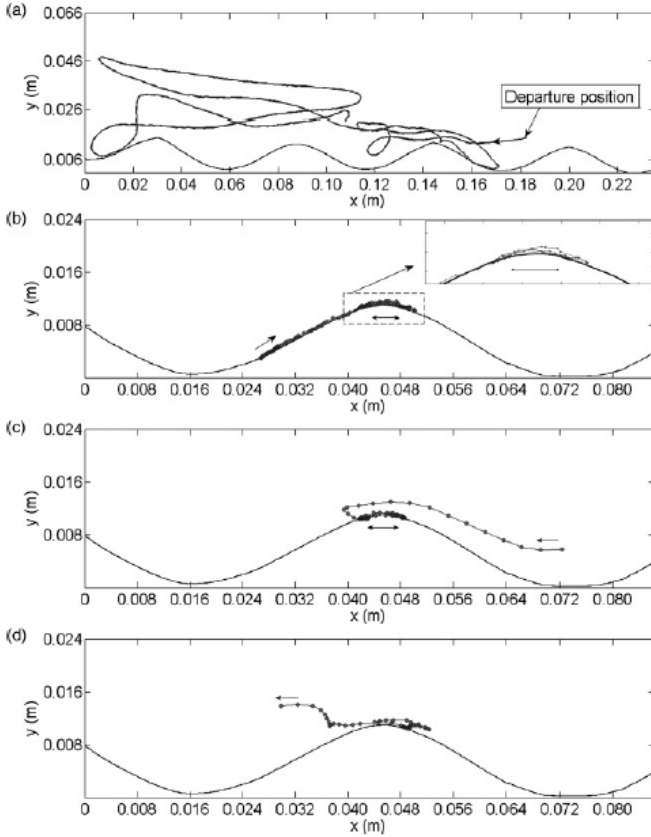


FIG. 2. Typical particle trajectories. (a) Particle trajectory under the action of vortices, Test 1; (b) Rolling of a particle along ripple side and “capture” in the confinement zone, Test 2; (c) “Capture” of a suspended particle, Test 2; (d) “Ejection” of a particle from the confinement zone, Test 4.

168 extremities to $H_{cz} = 0.9$ mm at the top of the ripple crest; this height is comparable with the Stokes layer thickness, $\delta = \sqrt{2\nu/\omega} \approx 1$ mm, and is greater than the grain size. The length
 169 L_{cz} of the confinement zone may be estimated at 10.9 mm, which corresponds approximately to one-fifth of the ripple
 170 wavelength in the tested zone. Present tests show that the ejected particles are the ones for which the diameter d_p
 171 is greater than approximately 0.28 mm. These particles are more exposed to the vortices than finer ones. We measured the mean
 172 resident time of particles in the confinement zone according to the sediment size. This time varies from one-half to two
 173 or three times the wave period for coarse particles. It is much longer for very fine and fine particles, ranging from three times
 174 the wave period to the total duration of the experiment. The grains capture and ejection at ripple crests may be considered
 175 as a sediment sorting process. The existence of a confinement zone is taken into account in the theoretical approach which is
 176 presented in Sec. IV.

186 **B. Particle trajectories during the decay of surface waves**

187 When the oscillating paddle is stopped, suspended particles start to settle under the action of gravity. Let us consider that
 188 the time $t = 0$ is the instant corresponding to the stopping
 189

of the oscillating paddle. The settling velocity of the coarse particles ($d_p = 0.45$ mm, Test 4) is about 15 times larger than
 190 the one for the very fine particles ($d_p = 0.11$ mm, Test 1). As shown in Fig. 3(a), the amplitude of motion of coarse
 191 particles before they reach the bed is large, since these particles begin to settle rapidly after a few wave periods ($t \approx 2-3$
 192 T) when the hydrodynamic forcing is still intense. Coarse particles generally reach the bed after a trajectory composed of
 193 four lateral excursions in the observation window. On the other hand, finer particles, which are lighter [Figs. 3(b)–3(d)], reach
 194 the bed later when the amplitude of fluid motion is weaker; the number of lateral excursions increases when particle size
 195 decreases. The maximum number of lateral excursions is equal to 10 for very fine particles ($d_p = 0.11$ mm). The ratio of the
 196 amplitude of the lateral extension of particle excursion a_p on the amplitude of the fluid motion a outside the boundary layer
 197 in the dynamical phase [phase (1)] used as a reference fluid amplitude is estimated. Typical values of a_p/a are 0.45 and 0.1
 198 for coarse (Test 4) and very fine particles (Test 1), respectively, when they arrive in the observation window. These values
 199 decrease as particles approach the bed. About 100 trajectories of sinking particles have been measured. Initial positions of
 200 these particles at the upper limit of the observation window are
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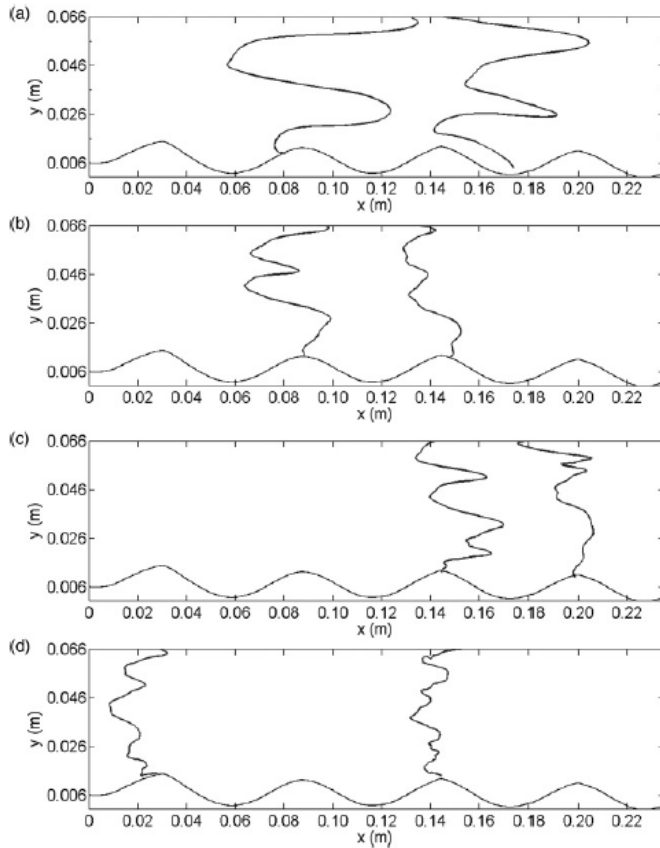


FIG. 3. Typical particle trajectories during the waves damping. (a) Test 4; (b) Test 3; (c) Test 2; (d) Test 1.

213 uniformly distributed above ripples. Places where the grains
 214 settle along the rippled bed are analyzed according to their
 215 size. The histogram of repartition of particles deposition zone
 216 over the three regions delimiting the crest, trough, and both
 217 sides is shown in Fig. 4. The length of the region defining the
 218 vicinity of ripple crest is fixed to 10 mm (18 % of the ripple
 219 wavelength in the considered zone) divided equally on both
 220 sides of the top of the ripple. The length of the trough region
 221 is estimated at 16 mm; both sides occupy 29 mm. The results
 222 show that 61 % of the very fine and medium particles (Tests 1
 223 to 3) settle in the vicinity of the ripple crests, whereas 39 % of
 224 these particles settle elsewhere. In the case of coarse particles
 225 (Tests 4 and 5), only 29 % of grains settle in the vicinity
 226 of the crests. Furthermore, for the range of coarse particles
 227 considered herein, no privileged deposition place is noted. Let
 228 us consider the temporal evolution of particle concentrations
 229 just above the rippled bed when the surface waves damp.

230 C. Suspension sorting during the decay of surface waves

231 Figure 5 depicts the area in which particle concentrations
 232 have been obtained; this area is a 1-cm-high horizontal strip.
 233 Its lowest level is 2.9 mm above the highest point of the bed.
 234 Zones delimiting regions above ripple crests (10 mm long) and

235 above ripple troughs (16 mm long) are defined in the legend of
 236 Fig. 5. Particle concentrations per unit area have been obtained
 237 in the following way: the number of particles crossing the strip
 238 is counted during their settling when the water waves damp.

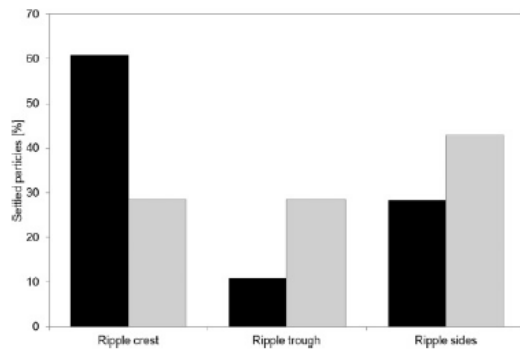


FIG. 4. Distribution of settled particles along the rippled bed surface. Black column: medium, fine, and very fine particles (Tests 1, 2, and 3, respectively); gray column: coarse particles (Tests 4 and 5).

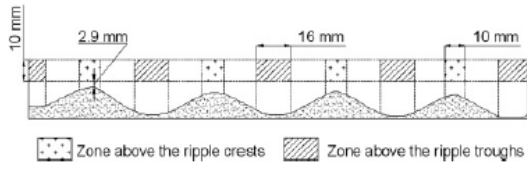


FIG. 5. Area above the rippled bed where particle concentrations have been measured.

239 The strip is in a vertical plane illuminated by a laser diode
240 (Fig. 1). The particles concentration C is estimated along the
241 strip as $C = n/S$, where n is the number of detected particles
242 in the considered zone and S is the surface of this zone.

243 The temporal evolution of relative concentration C/C_{\max} is
244 shown in Fig. 6, where C_{\max} is the maximum concentration
245 measured over all the experiments during the settling process.
246 The relative error of concentration measurement is related to
247 the particle detection process in the horizontal strip performed
248 in the Matlab program. It is estimated at 5 % and depicted
249 in Fig. 6 with error bars. The origin of temporal axis $t = 0$
250 corresponds to the time where the oscillating paddle is stopped.
251 This figure exhibits an exponential decrease of C/C_{\max} with
252 t/T . Using a best-fit procedure, the temporal variation of
253 particle concentration may be estimated with the following
254 equations:

$$C/C_{\max} = 1.49e^{(-0.268t/T)}, \quad (1)$$

0.45 $\leq d_p \leq$ 0.57 mm, ripple crest and trough,

$$C/C_{\max} = 1.16e^{(-0.032t/T)}, \quad (2)$$

0.11 $\leq d_p \leq$ 0.28 mm, ripple crest,

$$C/C_{\max} = 1.11e^{(-0.039t/T)}, \quad (3)$$

0.11 $\leq d_p \leq$ 0.28 mm, ripple trough.

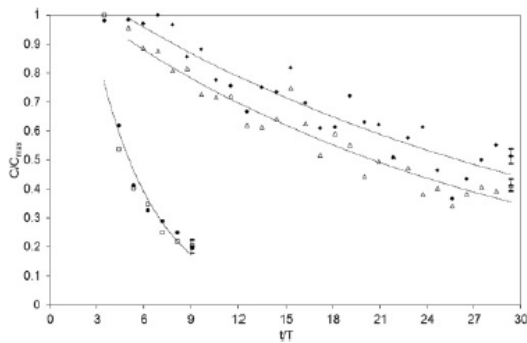


FIG. 6. Temporal evolution of particle concentrations close to the bed when the surface waves damp. \blacklozenge Above ripple crest: $0.11 \leq d_p \leq 0.28$ mm (Tests 1, 2, and 3). \blacktriangle Above ripple trough: $0.11 \leq d_p \leq 0.28$ mm (Tests 1, 2, and 3). \bullet Above ripple crest: $0.45 \leq d_p \leq 0.57$ mm (Tests 4 and 5). \square Above ripple trough: $0.45 \leq d_p \leq 0.57$ mm (Tests 4 and 5). The curves represent the trendlines obtained using a best-fit procedure.

255 The particles in the size range $0.45 \leq d_p \leq 0.57$ mm settle
256 rapidly and regularly without significant difference between
257 the concentrations above the ripple crests and troughs. As far
258 as the particles in the size range $0.11 \leq d_p \leq 0.28$ mm are
259 concerned, the two plotted curves exhibit similar variations
260 and a trend to higher concentration above the crests that
261 can be interpreted as a size sorting above the rippled bed
262 during the particle settling when the surface waves damp. The
263 concentration distributions show temporal fluctuations in the
264 size range $0.11 \leq d_p \leq 0.28$ mm when these distributions are
265 more regular for coarser grains. These are the result of the high
266 sensitivity of the light particles to the fluid movement until the
267 water becomes totally still.

D. Particle sorting after the decay of surface waves

268 In this section, we consider the final state for Tests 6 and 7,
269 when the water waves are damped. Figure 7(a) shows the grain
270 sorting at the end of Test 6 involving a mixture with 50 % of
271 very fine particles ($d_p = 0.11$ mm) and 50 % of medium par-
272 ticles ($d_p = 0.28$ mm). Based on the observation of Fig. 7(a),
273 one ripple wavelength is split in five regions defined on this
274 figure: (i) designates the region on the top of the crest; (ii) is
275 the region nearby (i) directed toward the fixed end of the wave
276 flume; (iii), (iv), and (v) are, respectively, the ripple side toward
277 the fixed end of the flume (right ripple side), the ripple trough,
278 and the ripple side toward the oscillating paddle (left ripple
279 side). A calculation to estimate the proportions of covering for
280 each type of grain has been carried out. This process consists
281 in affecting ranges of color levels to very fine and medium
282 particles and in counting the number of pixels associated to the
283 two categories of grains in each region. The pixels uncovered
284 by particles are also counted. The results are reported in
285 Fig. 7(b) as percentages. Average values are calculated in each
286 zone. The top of the crest (i) is almost saturated in very fine
287 particles covering 82 % of this region, while the nearby region
288 (ii) is covered essentially by medium grains (70 %). For the
289 three other regions, very fine and medium particles are present
290 composing a mixture. For standing waves above a flat bed,
291 the steady drift takes the form of closed recirculating cells
292 with boundaries at a spacing of one-quarter the wavelength of
293 the surface waves [27,28]. Very close to the bed that is inside
294 the Stokes boundary layer thickness, the fluid particle drift
295 is oriented toward the node of the water surface profile and
296 away from the antinodes. However, the drift is in the opposite
297 direction further in the outer flow. Present tests are carried
298 out above a rippled bed, and vortices are generated leading
299 to suspended load transport. As shown in Fig. 1 (Sec. II),
300 the particle trajectories are recorded between the antinode of
301 the surface wave in the central part of the flume and the node
302 close to the fixed end of the channel, where the drift is oriented
303 toward the wave paddle, outside the Stokes layer. A possible
304 reason for the settling of medium particles on the right ripple
305 sides forming strips close to the ripple crests is the effect of drift
306 velocity leading to vortices formed more vigorously during one
307 half-cycle than during the other. The vortices generated above
308 the left ripples sides are stronger than the ones formed above
309 the right sides; at flow reversal, these vortices move toward the
310 right sides carrying particles. The medium particles settle on
311 the bottom when the vortices intensity is still high. The very
312

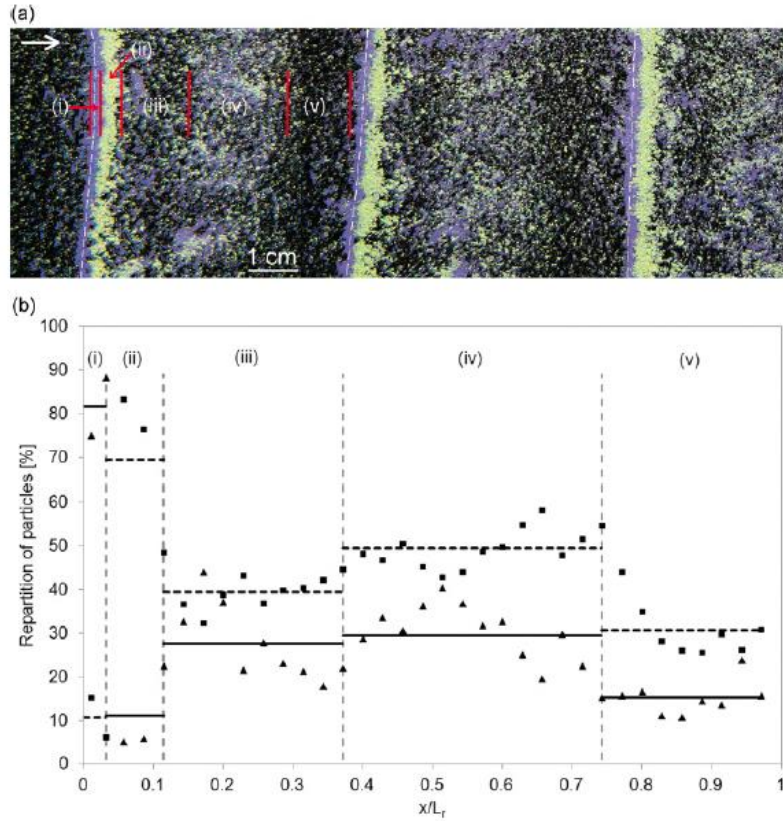


FIG. 7. (Color online) (a) Sediment sorting on the bed at the end of Test 6. The dashed lines represent the ripple crests positions. The arrow depicts the direction from the wave paddle to the fixed vertical end of the flume. Ripple crests are covered by very fine particles [violet (gray) grains]; a strip of medium particles [light beige (white) grains] is located nearby each crest. Very fine and medium particles are observed on the ripple troughs and sides. (i)–(v) Designate the five regions along one ripple wavelength used to evaluate the particle covering. (b) Repartition of particles over one ripple wavelength at the end of Test 6. Limits between different regions (vertical dashed lines); averaged values of medium particles distribution (horizontal dashed lines); averaged values of fine particles distribution (horizontal solid lines). (▲) Very fine particles; (■) medium particles.

313 fine particles fall later, when the vortices intensity is weaker
 314 and the asymmetry becomes negligible.
 315 For Test 7, which was carried out with a mixture with 50
 316 % of very fine particles ($d_p = 0.11$ mm) and 50 % of coarse
 317 particles ($d_p = 0.57$ mm), approximately the same particle
 318 segregation was qualitatively observed as for Test 6, the coarse
 319 particles taking the role of the medium particles used for Test
 320 6. We can just note that the relative narrow strips of medium
 321 particles, which were observed in region (ii) for Test 6, were
 322 wider for the coarse particles of Test 7. These observations are
 323 explained in the next section with a theoretical approach.

324 IV. THEORETICAL APPROACH

325 We present in this section an improvement of the theoretical
 326 model proposed in Ref. [18] for the flow above ripple crests and
 327 a simple model for the flow above ripple troughs, to explain

328 the present experimental results on the sorting of particles
 329 under damping waves. The model presented in Ref. [18]
 330 was not based on a detailed analysis of particle trajectories
 331 above a rippled bed; the process of grain segregation was
 332 not considered in detail. Present experimental results for
 333 particle trajectories show us in particular that close to ripple
 334 crests, particles oscillate. The model previously developed in
 335 Ref. [18], which had as specificity a fixed hyperbolic point
 336 at ripple crest, had to be improved to take into account the
 337 oscillating movement of particles in a small zone just above
 338 the ripple crest (confinement zone). This consideration affects
 339 the particle trajectories and the settling zones.

340 A. Improvement of the theoretical model proposed in Ref. [18] 341 for the flow above ripple crests

342 A very simple model in a narrow region near ripple crests
 343 was considered in Ref. [18], taking into account only the Stokes

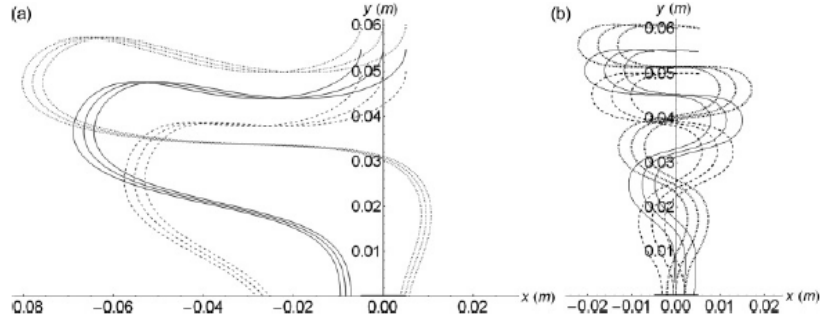


FIG. 8. Theoretical trajectories starting from nine different initial points above the ripple crest. (a) $d_p = 0.45$ mm; (b) $d_p = 0.28$ mm. The solid bold line on the x axis depicts the area near the ripple crest.

344 force, and assuming in the first approximation that the bottom
 345 is flat. The flow was modeled in the vicinity of each crest
 346 by the stream function, $\psi = -a(\alpha x + y)y$, where x and y
 347 are the horizontal and vertical coordinates. The point $x =$
 348 0 , $y = 0$ corresponds to ripple crests. The coefficient $\alpha =$
 349 $\alpha_0 \sin(\omega t)$ is the parameter that controls the slope of the line
 350 separating the forward and return flows. The value of α_0 may
 351 be estimated from present tests from flow visualization: $\alpha_0 \approx$
 352 1 rad. The coefficient $a = a_0 \sin(\omega t)$ is related to the vorticity
 353 $\bar{\Omega} = 2a\bar{z}$, where \bar{z} is a unit vector perpendicular to the flow
 354 plane. A slip condition is assumed on the bed surface $y = 0$,
 355 and the influence of viscosity was neglected outside the Stokes
 356 layer. It was supposed that this thickness is much less than
 357 the other characteristic scales of motion in the vicinity of the
 358 ripple crest. A particularity of the flow was the presence of
 359 a hyperbolic point with a stationary position at $x = 0, y = 0$.
 360 Present experimental results show (Sec. III A) that close to
 361 ripple crests, particles oscillate in a confinement zone. An
 362 improvement of the model presented in Ref. [18] consists in
 363 introducing an oscillating movement of the hyperbolic point.
 364 We suggest modeling the flow in the vicinity of ripple crests
 365 by the following stream function: $\psi = -a[\alpha(x + x_0)y + y^2]$,
 366 where $x_0 = X_0 \sin(\omega t)$. X_0 is the amplitude of the movement
 367 of hyperbolic point and is considered to correspond to half
 368 of the length of the confinement zone. The horizontal (U_x)
 369 and vertical (U_y) components of the flow velocity vector are
 370 obtained from the stream function:

$$U_x = \frac{\partial \psi}{\partial y} = -a[\alpha(x + x_0) + 2y], \quad (4)$$

$$U_y = -\frac{\partial \psi}{\partial x} = a\alpha y. \quad (5)$$

371 The particle velocity \vec{V} does not coincide with the flow
 372 velocity \vec{U} . For our experimental conditions, the Stokes
 373 number is a small parameter ($St \sim 10^{-3}, 10^{-2}$) that we use
 374 as an expansion parameter. The particle velocity is written as

$$\vec{V} = \vec{V}^{(0)} + St\vec{V}^{(1)} + St^2\vec{V}^{(2)} + \dots \quad (6)$$

375 Neglecting all terms proportional to St^2 in Eq. (6), the
 376 particle velocity field may be written as follows [18]:

$$V_x = U_x - \frac{St}{\omega}\sigma \frac{dU_x}{dt}, \quad (7)$$

$$V_y = U_y - U_0 - \frac{St}{\omega}\sigma \frac{dU_y}{dt}, \quad (8)$$

377 where V_x and V_y are the projections of the particle velocity
 378 vector onto the horizontal and vertical directions, and $\sigma = 1 -$
 379 ρ_w/ρ_p . After the substitution of Eqs. (4) and (5) into Eqs. (7)
 380 and (8), we obtain the following expressions for the particle
 381 velocities close to the ripple crests:

$$V_x = -a[\alpha(x + x_0) + 2y] + \frac{St}{\omega}\sigma[(\dot{\alpha}\alpha + a\dot{\alpha})(x + x_0) + 2\dot{a}y - a^2\alpha^2(x + x_0) + a\alpha\dot{x}_0], \quad (9)$$

$$V_y = a\alpha y - U_0 - \frac{St}{\omega}\sigma[(\dot{\alpha}\alpha + a\dot{\alpha})y + a^2\alpha^2y]. \quad (10)$$

382 It is supposed that after the oscillating paddle is stopped, the
 383 turbulence decays much more rapidly than the waves. During
 384 the wave damping, it is reasonable to consider that the vorticity
 385 and the length of the confinement zone decay in the same way
 386 as the amplitude of the surface waves. We suppose that the
 387 change of the amplitude of particles velocity during a wave
 388 period is small compared with the particles velocity amplitude.
 389 The particles velocity temporally averaged over a wave period
 390 $T = 2\pi/\omega$ is easily obtained from Eqs. (9) and (10):

$$\langle V_x \rangle = -a_0\alpha_0 e^{-2\gamma t} \left[\frac{1}{2} + \frac{St}{\omega}\sigma \left(\gamma + \frac{3}{8}a_0\alpha_0 e^{-2\gamma t} \right) \right] x, \quad (11)$$

$$\langle V_y \rangle = a_0\alpha_0 e^{-2\gamma t} \left[\frac{1}{2} + \frac{St}{\omega}\sigma \left(\gamma - \frac{3}{8}a_0\alpha_0 e^{-2\gamma t} \right) \right] y - U_0, \quad (12)$$

391 where γ is the rate of exponential decay of surface waves.

392 The horizontal component $\langle V_x \rangle$ is negative for $x > 0$
 393 and positive for $x < 0$, and particles tend to move toward
 394 the ripple crest ($x = 0$) when the surface waves damp. The
 395 rate of exponential decay for the present surface waves is
 396 estimated at $\gamma = 0.021 \text{ s}^{-1}$ from measurements of the temporal
 397 evolution of surface waves using resistive probes. Figure 8
 398 shows typical particle trajectories for different initial positions
 399 and two median diameters: $d_p = 0.45$ mm and $d_p = 0.28$ mm.
 400 The vertical coordinates of these initial positions are chosen
 401 close to the upper bound of the observation window considered
 402 in Secs. II and III (one ripple length high). The fine particles

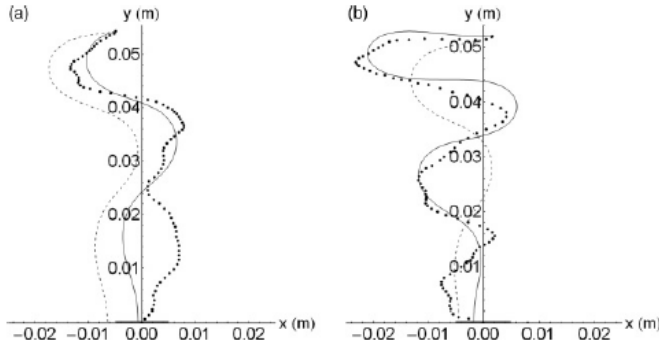


FIG. 9. Comparison of theoretical and experimental particle trajectories. (a) $d_p = 0.28$ mm; (b) $d_p = 0.19$ mm. Present measurements (dotted line); Ezersky and Marin's (2008) model (dashed line); present model (solid line). The solid bold line on the x axis depicts the area near the ripple crest.

403 ($0.11 \leq d_p \leq 0.28$ mm) are found to settle close to ripple crests
 404 when the coarser ones may fall everywhere on the bed. These
 405 particles settle on the bottom after only a few wave periods;
 406 Fig. 6 exhibits that most of them reach the area very close to
 407 the bottom approximately for $4 \leq t/T \leq 9$, when the damping
 408 time of surface waves is much greater ($1/\gamma \approx 48$ s $\approx 15 T$).
 409 For $d_p \leq 0.28$ mm, the time for particles to reach the bottom is
 410 greater; Fig. 6 shows that when $t/T = 30$, particles are not all
 411 deposited on the bed. The settling area near the ripple crests is
 412 well predicted by the present theoretical model. Experimental
 413 and theoretical particle trajectories are depicted in Fig. 9; this
 414 figure shows that the present adjustment of the model proposed
 415 in Ref. [18] significantly improves the prediction of particle
 416 trajectories and deposition areas.

417 B. Model of flow above ripple troughs

418 The vorticity field above an artificial rippled bed under
 419 waves was considered in Ref. [20]. It was shown that the
 420 values of the vorticity are much weaker above ripple troughs
 421 than close to ripple crests (except very close to the bed). A
 422 sketch of the rippled bed is depicted in Fig. 10. It can be seen
 423 that the "angles of ripple troughs" slightly vary along the bed;
 424 the averaged value is 135° .

425 Let us consider the classical model of potential flow for a
 426 135° angle:

$$427 f(z) = \beta(z e^{-i\pi/8})^{4/3}, \quad (13)$$

428 where z is a complex variable, $z = x_1 + iy_1$, $i^2 = -1$, and
 429 $\beta = \beta_a \cos(\omega t)$ for an oscillating flow; the point $x_1 = 0$, $y_1 = 0$
 430 corresponds to ripple troughs. Using this model, which takes
 431 into consideration the curvature of the streamlines in the ripple
 troughs, we are able to understand qualitatively why particles

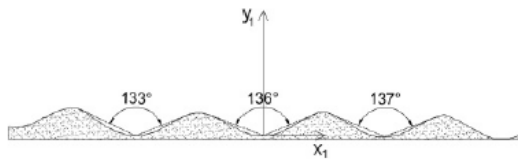


FIG. 10. Sketch of the rippled bed.

432 settle in the ripple troughs. The complex function of the flow
 433 may be written in the following way:

$$434 f(z) = \varphi + i\psi = \beta(r e^{i\theta} e^{-i\pi/8})^{4/3} \\
 = \beta r^{4/3} \left(\cos \frac{4}{3} \left(\theta - \frac{\pi}{8} \right) + i \sin \frac{4}{3} \left(\theta - \frac{\pi}{8} \right) \right), \quad (14)$$

435 where φ and ψ are the potential and stream functions,
 436 respectively, $r = \sqrt{x_1^2 + y_1^2}$, and θ is the polar angle. Using
 437 the Cartesian coordinates U_{x1} and U_{y1} for the flow velocity
 components, we get

$$438 U_{x1} = U_r \cos \theta - U_\theta \sin \theta = \frac{4}{3} \beta r^{1/3} \cos \left(\frac{\theta}{3} - \frac{\pi}{6} \right), \quad (15)$$

$$439 U_{y1} = U_r \sin \theta + U_\theta \cos \theta = -\frac{4}{3} \beta r^{1/3} \sin \left(\frac{\theta}{3} - \frac{\pi}{6} \right), \quad (16)$$

440 where U_r and U_θ are the radial and orthonormal coordinates of
 441 the flow velocity vector, respectively.

442 Substituting Eqs. (15) and (16) into Eqs. (7) and (8), we
 443 get the instantaneous particle velocities after some transfor-
 444 mations:

$$445 V_{x1} = \frac{4}{3} \beta (x_1^2 + y_1^2)^{1/6} \cos \left[\frac{\arctan(y_1/x_1)}{3} - \frac{\pi}{6} \right] \\
 - \frac{St}{\omega} \sigma \left\{ \frac{4}{3} \beta (x_1^2 + y_1^2)^{1/6} \cos \left[\frac{\arctan(y_1/x_1)}{3} - \frac{\pi}{6} \right] \right. \\
 \left. + \frac{16}{27} \beta^2 (x_1^2 + y_1^2)^{-2/3} x_1 \right\}, \quad (17)$$

$$446 V_{y1} = -\frac{4}{3} \beta (x_1^2 + y_1^2)^{1/6} \sin \left[\frac{\arctan(y_1/x_1)}{3} - \frac{\pi}{6} \right] - U_0 \\
 - \frac{St}{\omega} \sigma \left\{ -\frac{4}{3} \beta (x_1^2 + y_1^2)^{1/6} \sin \left[\frac{\arctan(y_1/x_1)}{3} - \frac{\pi}{6} \right] \right. \\
 \left. + \frac{16}{27} \beta^2 (x_1^2 + y_1^2)^{-2/3} y_1 \right\}. \quad (18)$$

447 Figure 11 shows typical comparisons between theoretical
 448 and experimental trajectories above ripple trough. The initial
 449 vertical coordinate of theoretical trajectories is chosen close
 450 to the ripple height H_r . The parameters of flow and particle
 451 are the ones that were used in the model above the ripple
 452 crest; β is estimated using the model of flow velocity at the
 453 upper edge of the bottom boundary layer. Although the
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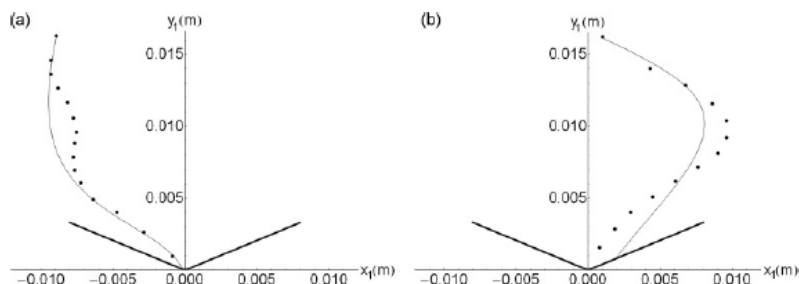


FIG. 11. Comparison between theoretical [Eqs. (17) and (18)] and experimental particle trajectories. Bold lines forming an angle represent the ripple trough region; present model (solid lines); present measurements (dotted lines). (a) $d_p = 0.45$ mm; (b) $d_p = 0.28$ mm.

450 theoretical trajectories are simpler than the experimental ones,
451 a qualitative agreement is obtained.

452 Assuming an exponential decay of the flow, $\beta =$
453 $\beta_a \cos(\omega t) e^{-\gamma t}$, it is easy to obtain the particles velocity field
454 temporally averaged over one wave period:

$$(V_{x_1}) = -\frac{8}{27} \frac{St}{\omega} \sigma \beta_a^2 e^{-2\gamma t} (x_1^2 + y_1^2)^{-2/3} x_1, \quad (19)$$

$$(V_{y_1}) = -U_0 - \frac{8}{27} \frac{St}{\omega} \sigma \beta_a^2 e^{-2\gamma t} (x_1^2 + y_1^2)^{-2/3} y_1. \quad (20)$$

455 It should be noted that our model cannot be applied
456 for coordinates corresponding to positions very close to
457 the bed, because the influence of viscosity must be taken
458 into consideration for these positions. The averaged vertical
459 velocity of particles induced by the oscillating flow is directed
460 toward the ripple trough, due to centrifugal forces acting on
461 particles moving in a flow near a concave wall. The averaged
462 horizontal velocity of particles is negative for $x_1 > 0$ and
463 positive for $x_1 < 0$, and particles tend to converge toward
464 the ripple trough according to Eqs. (19) and (20). Using
465 Eqs. (11), (12), (19), and (20), it can be emphasized that
466 the ratio between the vertical and horizontal components of
467 particle velocities is much smaller near the ripple crest than in
468 the ripple trough. It means that a particle in the vicinity of a
469 ripple crest will converge more strongly toward this crest than
470 a particle with the same diameter above a ripple trough will
471 converge toward the trough. Comparing Eq. (12) with Eq. (20)
472 for the averaged vertical velocity of particles, it is possible
473 to conclude that the particles settling time is greater near the
474 ripple crest than near the ripple trough. The centrifugal effect
475 near the concave wall leads to an averaged velocity in the same
476 direction as the gravity force. In other words, coarse particles
477 settle rapidly on the bed before the damping of surface waves,
478 and fine particles with smaller settling velocities are more
479 affected by the mean horizontal velocities toward the ripple
480 crest than coarser particles. Then, an accumulation of fine
481 particles appears at ripple crests when the surface waves are

482 completely damped, as observed in the present experiments
483 (Sec. III).

V. CONCLUSIONS

484
485 This paper presents an experimental and theoretical study
486 of particle size sorting above an artificial rippled bed under
487 standing water waves. Present tests were carried out in a 5.4-
488 m-long wave flume with lightweight grains; two phases were
489 considered: during the excitation of standing waves [phase (1)]
490 and during the decay of surface waves [phase (2)]. Particle
491 trajectories were obtained for the two phases with a high-
492 resolution camera. In the first phase, fine and medium particles
493 ($0.11 \leq d_p \leq 0.28$ mm) are trapped in a thin confinement zone,
494 approximately one Stokes boundary layer thickness high, close
495 to ripple crests. In the second phase, trajectories and deposition
496 zones of particles on the rippled bed strongly depend on their
497 size. Most of fine and medium particles fall in the vicinity of
498 ripple crests when coarser particles ($0.45 \leq d_p \leq 0.57$ mm)
499 settle more uniformly along the rippled bed, with nevertheless
500 an asymmetry in the deposition zones due to the mean flow
501 induced by standing waves near the bottom. Measurements
502 of particles concentration close to the bottom show a size
503 segregation during the wave damping, when particles are still
504 in suspension: the concentrations of the finest tested particles
505 is higher above the ripple crest than above ripple trough, when
506 no significant difference can be noted for coarser particles.
507 An improvement of the model proposed in Ref. [18] for the
508 flow above ripple crests and a simple model for the flow above
509 ripple troughs explain the present experimental results. Further
510 research is needed to consider particle size segregation with
511 active beds.

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512
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