3

Strange Phenomena in Cuban Sands

The greatest joy is the unexpected.

(Attributed to) Sophocles

3.1 Echoes of a Failed Class Demonstration: The Revolving Rivers

Excited by the elegant analogies one could establish between the critical state in type II superconductors and sandpiles, I rapidly decided to introduce them in class during a course on superconductivity I taught in 1994 at the Physics Faculty, University of Havana. Being an advocate of tabletop experimental demonstrations in class, I decided to show the students that a sandpile grows by avalanche dynamics—the paradigm of self-organized criticality (SOC) proposed by Per Bak and coworkers a few years before. Nothing could be simpler: by pouring sand on a table through a funnel, I expected to see the "classical" avalanche behavior, i.e., as the pile grew, sudden slides of sand unevenly distributed in space and time, should keep the angle of the pile around a pretty well defined value.

Flash anecdote

Most Cuban scientists belong to the *National Union of Workers of Education, Science and Sports*. The Union selects every year a number of *National Vanguards* among the most hard-working teachers, scientists, sports trainers, etc. Thanks to my scientific "merits", I was elected National Vanguard in the year 2001–there

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were a few dozen of them, I believe. In that occasion, the Union gave us our diplomas in a scenario that would have made *Stakhanov* very proud: we were invited to go to pick potatoes in the countryside. That was not unusual to a Cuban of my generation. But in this case, a truly unexpected scenario was waiting for us when we reached the working place: a battery of loudspeakers had been setup in the open, in such a way that, while picking potatoes in the furrows under the drilling tropical sunshine, we were systematically congratulated and cheered up by people from the Union. Moreover, the chiefs of our respective working brigades (democratically voted in situ) went to the improvised microphones—one after the other—to challenge the other brigades in a frantic competition to finish first picking up all the potatoes in their assigned areas. We were working hard—all of us were indeed hard workers by definition—but also laughing hard at the completely surrealistic situation we were trapped in.

So I decided to get a bunch of this incredibly fine and white sand I had seen by chance in a store room at the back of the Institute of Science and Technology of Materials (University of Havana), to be used for some unknown project. "Taking out a bit won't hurt anybody"—I justified to myself. Only months later I learned that the sand in question had been brought from a place called "Santa Teresa" in Pinar del Río province (some 200 km west from Havana) and was meant to feed a plant to produce silicon-based semiconductors. So, I took a couple of kilos of sand, and returned to my lab to polish up details for my class demonstration.[1]

So I clamped a funnel on a lab holder, and started pouring sand on a table. With a mix of fascination and preoccupation I realized that, instead of finding sudden, intermittent avalanches, a pile formed which had a thin river of sand on one side flowing from the apex of the pile to the edge of its base. The river rotated about the pile, depositing a new layer of sand with each revolution, thereby causing the pile to grow. For small piles the river was steady and the resulting pile was smooth. For larger piles, the river became intermittent and the surface of the pile became undulating. Years later, I would coin the serendipitous phenomenon "revolving rivers". But when I first saw it, I did not use elegant words to describe what was effectively a disaster for the demonstration I had planned for the next class.

[1] Over the years, I would return to the place to take further samples of "Santa Teresa" sand, and I noticed that the initial big pile was decreasing in size too fast. Then one gloomy afternoon I found myself standing with an empty bucket in the middle of a completely sandless room. It hadn't happened due to erosion or other natural causes, or to the fabrication of semiconductors, and definitely not to my periodic withdrawals: I suspect that my beloved sand had been used as a vulgar construction material, and lies somewhere in the walls of Havana, a crime that reminds me of Poe's "The Cask of Amontillado".

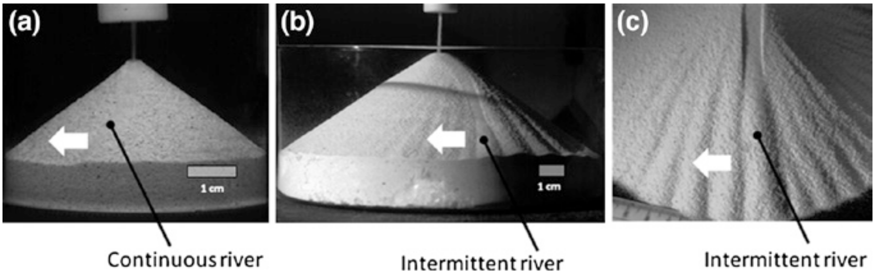


Fig. 3.1 Revolving rivers. When Santa Teresa sand is poured into a relatively small glass cylinder, a continuous revolving river appears, as shown in (**a**). If a wider cylinder is used, intermittent rivers appear, as shown in (**b**). In **c**, we show a top view of the intermittent rivers for a pile formed on a flat, open surface. The white arrows indicate the direction of rotation of the rivers, which can be clockwise or counterclockwise, depending on random fluctuations at the beginning of the experiment. In the continuous regime, sand just flows down the hill along the river, forming a stream that slowly moves laterally as a whole. In the intermittent regime, a sudden burst of sand first flows down, and then an uphill front travels from the lower edge of the pile up to a certain height, after which a further sudden burst of sand flows downhill, by the side of the previous event, which is seen as the river moving laterally around the pile

Anger was actually mixed with deep preoccupation, since I had before my very eyes what seemed a direct violation of the self-organized criticality paradigm that I was preparing to explain in class. So I momentarily skipped the demonstration, which was re-designed in later courses using a two-dimensional pile of beads… a much more "didactic" approach that I described in detail in the previous chapter. I had come across the revolving rivers phenomenon as soon as I picked up the first sand available, so I naturally assumed it was a very well known physical effect. So, the mysterious "Santa Teresa" sand was put to sleep in the darkness of a cupboard under a laboratory table—the same table upon which El Chicharotrón would soon be built. For six years the bag of Santa Teresa sand would feel the hypnotic vibrations of the avalanches produced by El Chicharotrón a few inches above it.[2] But the sleeping beauty would only be awoken years afterwards… thanks to a casual conversation with physicist Kevin Bassler (Fig. 3.1).

I met Kevin at the University of Houston, where I was doing a postdoc in the group of C.W. Chu—founder of the Texas Center for Superconductivity (TcSUH). My fascination with vortex avalanches made me follow my own

[2] She would also feel the scorpions (known in Cuba as *alacranes*) constantly chasing roaches in the darkness—a somewhat strange but rather typical feature of our lab's ecosystem.

way in Chu's lab, trying to detect them in superconducting niobium by using micro Hall probe arrangements. Although it was not one of Chu's lines of research, he was very patient with me—perhaps due to the many hours I dedicated to my passion for research, which seemed to resonate with his Spartan work ethic.[3] In parallel with the work in Chu's group, I was collaborating with Kevin, Maya Paczuski, and George Reiter at the Physics Department, University of Houston, which probably constituted one of the world's hardest core SOC groups. In fact, Per Bak himself (Maya Paczuski's husband) was seriously considering joining the department at the time. I had the opportunity to meet him personally. He even insisted on going to the lab to see my experiments on vortex avalanches first hand.

Flash anecdote

One of the young researchers of our group had a girlfriend that had been a little bit over-protected by her parents during her whole life. It happened in the mid 1990s, where food was scarce, and everybody moved around in heavy Chinese bikes. Our colleague was painfully pedaling up the hill of G-street, near the University of Havana, in the middle of a burning sunshine, with his fiancé sitting in the back of the bike. At some point, it seems that she felt too hot, and came up with a peculiar solution to the matter. She just told her soaking-wet boyfriend: "Honey, would you please speed up, so I get some breeze on my face? It's so hot, you know!"

Kevin and I were always engaging in scientific arguments on many physics topics, all of which he used to win. At some point, I told him that SOC in real sand should not be taken for granted, since sands showed this "revolving river" effect. He suddenly got very excited. "Ernesto, that is a very important thing; I just can't believe it". When I said to him that the effect would be found in any sand, he challenged me to make a practical demonstration for him. Absolutely certain of my success, I went to one of the parking lots outside, collected some sand into an envelope, got a funnel from the lab, and went back to Kevin's office. I cleared the papers on one table, and started to form a pile of sand using the funnel. I felt really embarrassed when no trace of revolving rivers showed up: just random avalanches, as expected by any sensible person using any sensible sand. I started to doubt my own recollections of the phenomenon, so I sent an email message to my then undergrad

[3] Shortly after my arrival at the Texas Center for Superconductivity, I had my first scientific meeting with C.W. Chu. He decided the time and place: Sunday August 8, 1999, at 11 AM, at a MacDonald's near TcSUH.

student Osvanny Ramos, who was in Cuba at the time. I described to him exactly where the Santa Teresa sand could be found, and the exact funnel I had used to see the revolving rivers—it would be easy for him, since the stuff was just under the table he was using to do the Chichartotrón experiments. In the afternoon I received the answer by email: "That sand you told me is so white, so fine… and, by the way, it does produce piles with these river-like flows of sand…" Upon my return from the States, the first thing I did was to take a video of the revolving rivers with my second hand *Magnavox* camera bought on e-bay while in Houston, and send Kevin the VHS cassette with somebody travelling back to the States. He was finally convinced! In the following months, I worked frantically doing experiments on the revolving rivers phenomenon, with the help of Osvanny Ramos, Etién Martínez—a first-year undergrad student at the time—and even my wife, Aramis. A couple of years later the resulting article would be published in collaboration with Kevin.

One of the many things we had to figure out was whether the sand from Santa Teresa was truly unique regarding the appearance of revolving rivers…. and serendipity helped us again. One day, Etién was watching the TV news, and they presented a report about a person whose hobby was to collect different kinds of sand from all over the world. He lived in a place called Santiago de las Vegas, some 20 km south-west of the university. After a couple of days, Etién showed up at his place equipped with a funnel, a metal holder, and a steely determination to check all the sands he could get his hands on. The sand collection enthusiast—whom I later identified as Eros Salinas, a geographer also teaching at the University of Havana—was indeed very kind: Etién was not only able to try more than 100 types of sand from all over the world, but he was invited to have lunch. The result was that 11 sands showed revolving rivers, around 10% of the statistical sample. However, nobody knew why: the revolving sands didn't look especially similar to each other… or especially different from the non-revolving ones!

However, it was possible to establish a quite good phenomenological characterization of the revolving rivers. For example, the "phase diagram" shown in Fig. 3.2 indicates for which flows and radial sizes the piles show continuous or intermittent rivers, and where the transitions between one and the other take place.

In addition, it was not difficult to reproduce some of the features in the behavior of the revolving rivers by simply using mass conservation—or, more

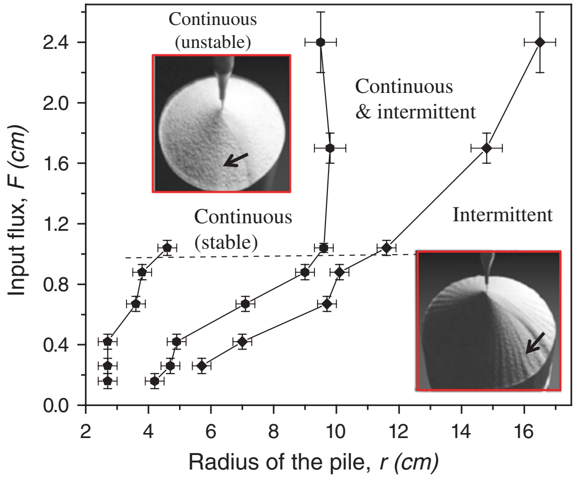


Fig. 3.2 "Phase diagram" of the revolving rivers for "Santa Teresa" sand. Along the horizontal and vertical axes we have the radius of the pile and the sand flow feeding the pile. Let us suppose that we move from left to right in the diagram along the dotted horizontal line. When the pile's radius is smaller than approximately 4 cm, continuous rivers appear and disappear: in fact, that happens in many granular materials. Continuous rivers stabilize—describing full revolutions around the pile with no interruptions—within the interval from 4 to 8 cm, approximately. Between 8 and 10 cm, the rivers are sometimes continuous, and sometimes intermittent. Intermittency stabilizes for piles of radius bigger than 10 cm, approximately. That behavior is true regardless of whether the piles are formed in cylinders of different radii, or just on a flat surface (in the first case, the radius is fixed for each glass size and, in the second case, it increases continually as more sand is added to the pile)

exactly, volume conservation.[4] The idea is to assume that the volume of sand deposited on each cycle due to a flow F is distributed as a uniform layer of material on the conical surface of the pile—the layer grows laterally on the surface, and its "growing front" is precisely the river. Figure 3.3a shows our simplified model for a conical pile growing on a horizontal open surface, which assumes that the thickness of the deposited layer is constant (implying a constant δr length at the base of the pile). The resulting formulas for the frequency of rotation of the river along the pile as a function of time and the pile radius are:

$$\omega = \frac{2}{(\tan\theta)^{1/3}} \left(\frac{\pi}{3}\right)^{2/3} F^{1/3} \frac{1}{\delta r} \frac{1}{t^{2/3}} \tag{3.1}$$

[4] Granular matter can either contract or expand under different circumstances, so the effective density of the medium is not necessarily constant during a given experiment. Then, establishing a simple proportionality between mass and volume in our case is just an approximation.

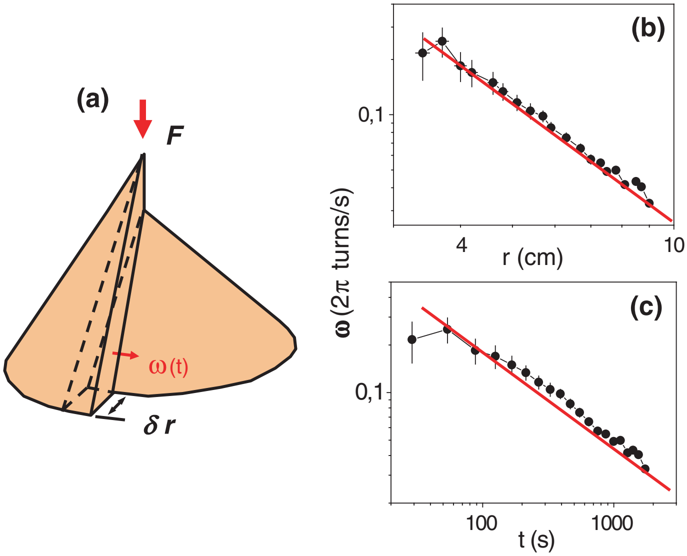


Fig. 3.3 Modeling Santa Teresa piles on a table. **a** A simple geometrical model for a growing sandpile on a horizontal open surface: the sand is added from top at a certain flow rate F (volume/time), and is deposited as a layer that exceeds the previous base radius by δr. The "river" revolves around the pile with an angular frequency ω. The points in graphs (**b**) and (**c**) show the experimental evolution of the revolving frequency versus radius and time, respectively, in log-log plots. The continuous lines correspond to formulas (3.1) and (3.2), where the following experimental parameters have been used: $F = 0.4$ cm^3, $\theta = 33°$, and δr $= 0.4$ cm^3

$$\omega = \frac{2F}{\tan\theta}\frac{1}{\delta r}\frac{1}{r^2} \tag{3.2}$$

where θ is the angle of the pile's slope relative to the horizontal. As can be seen in Fig. 3.3b and 3.3c, the expressions (3.1) and (3.2) quite closely reproduce the experimental evolution of the revolving frequency. Intuitively, it is clear why it decreases in time: the same amount of injected sand needs more and more time to cover the ever-growing surface of the conical pile. It is worth saying that the previous description is valid only for piles growing on a horizontal surface: if the pile is grown into a straight cylindrical container, its radius is constant, and so is the revolving frequency.

Our model is able to predict the behavior of the revolving frequency, but does not explain why the rivers appear in the first place, or why they rotate. We have just taken it for granted that they occur for some reason probably associated with the characteristics of the grains and their statistical size distribution.

3.2 An Open Problem in Three Steps

Beyond the simple prediction of the revolving frequencies, we can "dissect" the revolving rivers problem into three questions: (a) Why does a river form and stabilize on the pile surface? (b) Why does the river revolve around the pile either to the left or to the right? (c) Why is there a transition from the continuous to the intermittent regime in the rivers as the pile radius increases?

Let us discuss first questions (b) and (c), and then move on to (a).

Question (b) can be answered qualitatively with the help of Fig. 3.4, corresponding to a pile that grows on a horizontal open surface. The situation is easier to explain for the intermittent regime, but the idea can be extended to the continuous one: an avalanche occurs along a random radial direction, and, as it reaches the lower edge of the pile, the sand stops flowing downhill. As new sand enters the system, a front grows up from the base of the pile to the apex, following the "groove" carved by the downhill avalanche. This process results in an increase of the local slope of the pile. As the uphill front gets near the top of the pile, the river becomes unstable, and the next downhill avalanche occurs, say, to the left of the original one: that produces a slight deformation of the "surface topography" that "pushes" all future avalanches to the left of the previous ones. It is a memory effect. An analogous mechanism takes place in piles grown on cylindrical containers, like a whisky glass. However, if the pile grows on top of an upside-down whisky glass, as soon as the edge of the pile meets the edge of the cylinder, the river no longer revolves: all the sand entering from the top flows out of the system and no instability is produced to "push" the river sideways.[5]

Question (c) can be "isolated" experimentally in the following way. One can consider that once a river is established, the three-dimensional flow typical of "normal" sandpiles is restricted to a two-dimensional flow along the groove associated with the river. So, the revolving rivers can be taken as two-dimensional rivers revolving around the pile at an appropriate frequency. But we can "construct" an "independent" two-dimensional river by making sand flow between two vertical plates with a separation similar to the width of the rivers we see on the piles—a Hele–Shaw cell (see Fig. 3.5a). We did this and found that, as the two-dimensional pile grew, we did indeed first get continuous rivers, and then intermittent rivers, just like in the original piles.

[5] This particular experiment was inspired by physicist Hans Herrmann during a meeting in Brazil: he commented, as though it were the most natural thing in the world, that when *any* granular pile reaches the edge of a table, a stable river of flowing sand establishes, pouring sand off the table.

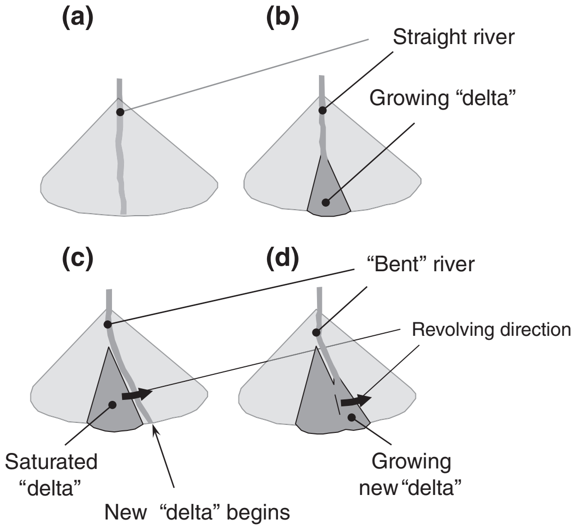
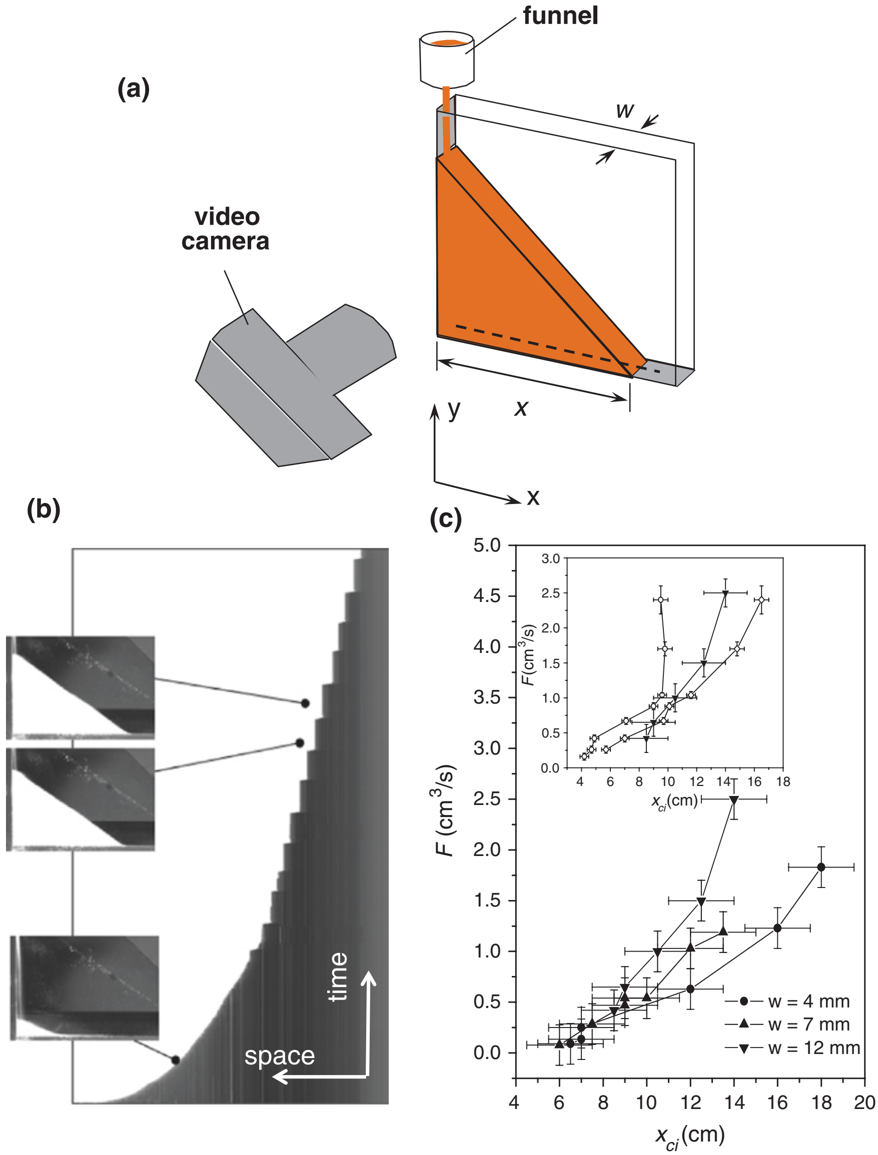


Fig. 3.4 Why rivers revolve around the pile. **a** At the beginning, a straight river is formed. **b** Once the initial avalanche associated with the river meets the base of the pile, an "up front" grows, producing a delta-like sub-pile that rests on the pile's surface. **c** As the up front is high enough to become unstable, the river deviates to one of the sides of the delta. **d** A new up front starts to grow, forming a new asymmetric delta that will "push" new deltas to the same side

This experiment had been made before, but curiously enough, researchers had concentrated on the description of the intermittent flow: the continuous regime and the transition between the two had received little attention.

Figure 3.5b shows clear experimental evidence of the transition for our experiments, using a spatial-temporal diagram whose construction is explained in the figure caption. The smooth part of the diagram shown there corresponds to the continuous regime, while the "step-like" section corresponds to the intermittent regime. In the latter, the almost horizontal sections correspond to sudden downhill avalanches that make the edge of the pile advance from left to right. The vertical parts, on the other side, are the intervals where the pile does not advance from left to right: the uphill front is just moving up, adding a new layer of sand to the pile, parallel to the previous free surface. The diagram clearly indicates that the transition from the continuous to the intermittent regime is quite sharp. Putting together a series of such diagrams based on videos taken for different input flows and separations between the glass sheets of the Hele–Shaw cell, one can construct the "phase diagram" shown in Fig. 3.5c, which can be compared to the "phase diagram" of the revolving rivers in 3D piles.



(a)
funnel
w
video
camera
y
x
x
(b)
time
space
(c)
F (cm³/s)
x_{ci} (cm)
w = 4 mm
w = 7 mm
w = 12 mm

Fig. 3.5 Continuous to intermittent transitions. **a** Sandpile formation on a Hele-Shaw cell: the size of the sandpile base, x, grows as sand is added from the upper left corner. At the beginning, the pile grows continually. After a certain "critical size", x_{ci}, the flow becomes intermittent (i.e., after a sudden avalanche down the hill, an up front grows to the top until a new avalanche takes place… and so on). **b** A spatial-temporal diagram based on a sequence of pictures of the evolution of the pile. The diagram has been constructed in the following way: one video of the pile formation is separated into a sequence of pictures. We then extract from each image the line of pixels indicated in (**a**) by the *dotted line*, and then organize one line of pixels on top of the other from bottom to top, as time goes by. In the resulting diagram shown in (**b**), *white* and *black* areas correspond to sand and background, respectively. Then, the horizontal growing velocity of the pile near its bottom is given by the inverse of the slope of the boundary between the white and black areas at any given moment. So, if the lower edge of the pile is not growing, the graph will show it as a vertical line. **c** Graph of the critical size where the transition occurs at different flows, measured for three different widths of the Hele-Shaw cell. It has been constructed from a series of spatial-temporal graphs like the one illustrated in (**b**). The inset shows a version of the graph in Fig. 3.2 for the revolving rivers. Notice the overall similarity between the curves (it is difficult to establish the width of the river in the pile, since it is not constant, but its average width is definitely between 4 and 12 mm for the case illustrated in the inset)

The existence of continuous and intermittent phases can be explained, at least for the case of a Hele–Shaw cell, by solving the so-called BCRE equations with the appropriate boundary conditions. The BCRE model was proposed by Bouchaud, Cates, Ravi-Prakash, and Edwards in 1994–1995 to explain the behavior of thick granular flows. They assumed that a granular flow on a pile is composed of two phases: a static one, and a rolling (or flowing) one on top of the first. The BCRE equations describe the evolution of the thicknesses of each of these layers, taking into account the fact that grains from the static layer can be eroded and become part of the flowing layer, while grains in the flowing layer can be advected and become part of the static phase. The BCRE equations were solved by Dorogotsev and Mendes in 1999 for the case of a pile in a Hele–Shaw cell. They found a continuous regime if the pile started to form in an empty cell, and an intermittent regime if it started to flow from a pile whose slope had reached an "angle of repose". However, the *transition* from the continuous to the intermittent behavior as the size of the pile increases was not predicted from the BCRE model.

Flash anecdote

During 2014, on several occasions I used my car to move the whole experimental setup for sand flows back and forth from the lab to an apartment Etién Martínez had borrowed. He convinced me using the argument that he could do experiments round the clock there. On one occasion, however, he made a curious request: "Ernesto, before going to my apartment to pick up the stuff,

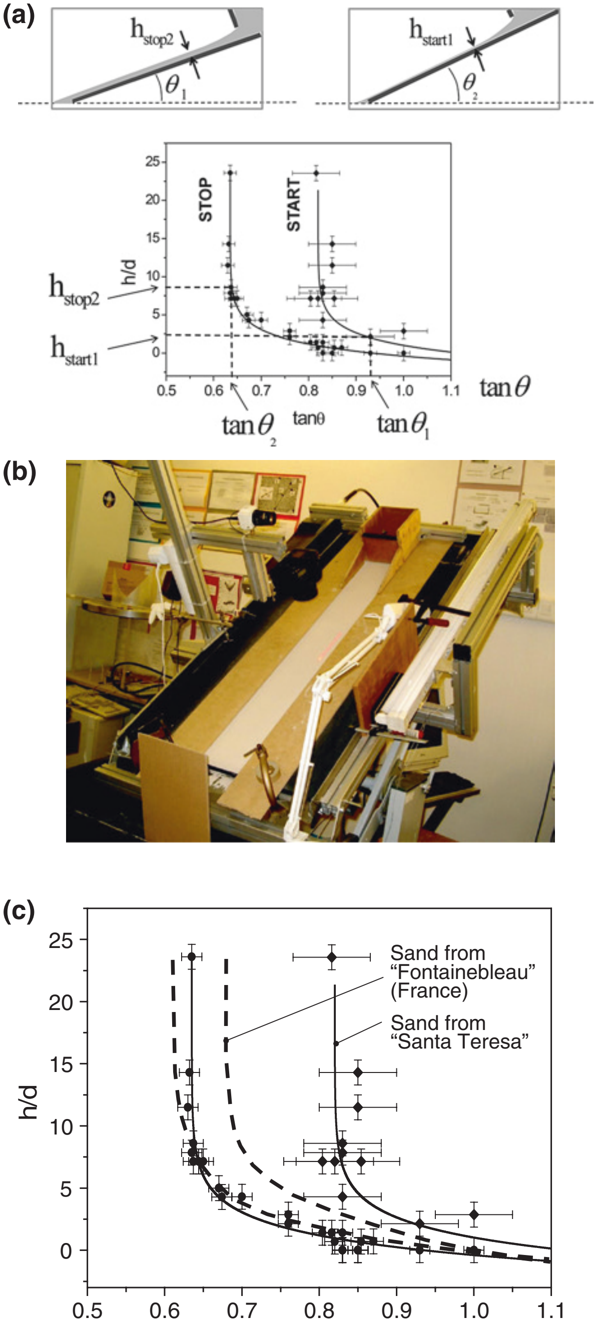

(a)
hstop2
θ1
hstart1
θ2
STOP
START
h/d
25
20
15
10
5
0
0.5
0.6
0.7
0.8
0.9
1.0
1.1
tanθ
tan θ2
tanθ
tan θ1
(b)
(c)
h/d
Sand from "Fontainebleau" (France)
Sand from "Santa Teresa"

Fig. 3.6 Avalanche instabilities on an incline. **a** A plane is first inclined at an angle θ_1, and sand is released from a horizontal slit at the top. As a result, a layer of sand of thickness h_{stop} is deposited on the surface. Then, the inclination is slowly increased until the sand becomes unstable at θ_2, which produces an avalanche. The final thickness of the layer is labeled $h_{start}(<h_{stop})$. The two pairs of values are plotted on the graph at the bottom (thicknesses are normalized to d, the average grain diameter). The rest of the graph is constructed on the basis of analogue experiments starting at different values of the inclination angle. The process results in a pair of curves START and STOP between which there is a region of metastability. Each curve can be described by the expression $\frac{h_{START,STOP}}{d} \sim \ln\left(\frac{\tan\theta - \mu_{START,STOP}}{\delta\mu}\right)$ where $\mu_{START}, \mu_{STOP}, \delta\mu$ are fitting constants. If the vertical sections of the START and STOP curves are widely separated horizontally (as in the case of the Santa Teresa sand), the values of μ_{START} and μ_{STOP} are quite different between them. **b** Real setup used to measure the avalanche diagram for Santa Teresa and other sands at the ESPCI (the sand is the very clear band along the center of the incline, bounded by two sheets of plywood). The thickness of the layer of sand is measured by shining a laser beam on the sand at a very small angle relative to its surface: the position of the laser spot on the sand surface is very sensitive to the thickness of the layer of sand. **c** Resulting avalanche diagrams for Santa Teresa sand (*continuous lines*) and for Fontainebleau sand (*dotted lines*). Notice that the first is much wider horizontally than the second

I need you to take me first to a glass workshop to cut this large piece of glass into 50 cm by 20 cm strips"—pointing to a big plate of glass I had meticulously stored in the lab for a long time. I did it, but not very enthusiastically, after being told about the cause of the detour: during a night of scientific desperation, my MSc student had cut up a glass cupboard of the borrowed apartment to construct new Hele–Shaw cells, and now he was rushing to replace it, since the owners were coming back from vacation!

Based on image analysis of sand flows in Hele–Shaw cells, Etién has recently found evidence indicating that sand tends to compact more in the intermittent than in the continuous regime. This observation may be relevant for the storage of granular matter in industry, or even for the interpretation of geological phenomena.

One curious thing about the continuous to intermittent transition *in Hele–Shaw cells* is the fact that *it happens for almost all sands*. It suggests that the real "personality" of the Santa Teresa sand is not to show the continuous to intermittent transition in a 2D scenario like a Hele Shaw cell, but its ability to produce stable rivers on the surface of a conical pile, transforming the 3D scenario into a "rotating" 2D scenario. That leads us back to question (a).

So, what can we say about question (a)? In 1999 Adrian Daerr and Stéphane Douady published a now classic experiment to study granular instabilities, producing different types of avalanches as explained in Fig. 3.6a. In 2006 Eric Clément, from the ESPCI (Paris, France) suggested

Fig. 3.7 Bike violence in Strasbourg. Renaud Toussaint trying to set his bike free from a lock whose key was lost. People in the car at the back do not seem to approve the scene. Photo taken in 2007

to me to carry out such experiment with the Santa Teresa sand, to identify any differences with other sands, and this I did.[6] Figure 3.6c indicates that sand from Santa Teresa produces wider stability diagrams than other "typical" sands… something that might be related to the fact that the grooves carved by the rivers on the pile's surface are more stable in Santa Teresa than in "common" sands. It might explain the robustness of the rivers. In fact, when one forms a conical pile using "common" sand, rivers do appear, but they only last for a very short time: the sand walls forming the groove are not stable enough, and are immediately destroyed.

In 2007 I carried Santa Teresa and a few more sands to the *Institut de Physique du Globe de Strasbourg* (France), where Renaud Toussaint (Fig. 3.7) helped to characterize the sands. After several tests, such as scanning electron microscopy, grain size distribution analysis using a laser technique, and the determination of the composition of the individual grains, we were unable to determine the distinctive "microstructural" features of the Santa Teresa sand that make it so special (Fig. 3.8).

[6]Besides being a scientific visionary, Eric is an irrepressible enthusiast. On that occasion his energy was so great and the lab so crowded that, as he showed me how to work with the experimental apparatus, his head bumped on several occasions against the sharp corners of the incline (see Fig. 3.6b). Each time he automatically shouted "merde"… with no effect at all on his enthusiasm.

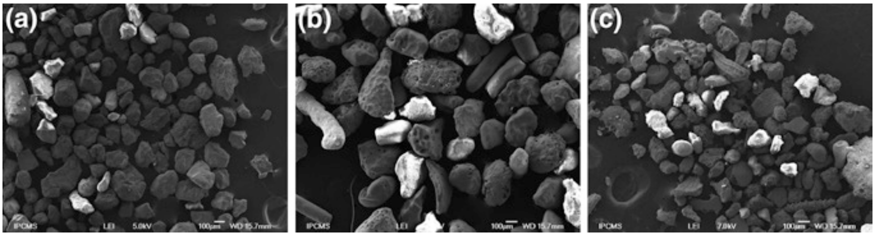


Fig. 3.8 Which sand produces rivers? Scanning electron microscope images of three different sands **a** Silicon-rich Santa Teresa sand. **b** Calcium carbonate-rich sand from famous "Varadero" beach in Matanzas province (200 km to the east of Havana). **c** Another silicon-rich sand of unknown origin. Only sand **a** shows revolving rivers. The width of each image in real life is approximately 3 mm

To make things even more puzzling, the Santa Teresa sand stopped showing revolving rivers after many experiments: some kind of aging process seemed to take place (which is quite stressful, since our local reserve of the "good sand" is finished). Stéphane Douady has seen the same in "singing sands" from the Ghord Lahmar region in Morocco. As those sands flow, the moving grains vibrate synchronously as they pass over each other, producing incredible organ-like sounds. As Stéphane puts it poetically, sands brought from Morocco to his laboratory in France stopped singing after some time, "because they felt homesick". What seems to happen is that, after many experiments, a smooth layer of silica gel on the grains' surface—apparently a key factor in the production of sound—goes away. Perhaps the same is true for Santa Teresa sand, but it remains an open question for the time being.

3.3 Uphill Bumps: Moving Against the Flow

Let us suppose that the Hele–Shaw cell described earlier is set on a table, in such a way that, when the pile grows enough to reach the end of the cell, the sand just falls across the edge of the table and hits the floor (Fig. 3.9a). In such a scenario, the flow inside the cell can only be continuous, since there is no horizontal surface at the end of the pile to "support" a new uphill front.

While performing the experiments to study the continuous to intermittent transition under the conditions just described, Etién Martínez eventually forgot to stop feeding the cell, and the sand actually reached its end, turning the lab floor into a perfect place for tap dancing. But in the process, Etién and Ovanny observed a curious phenomenon that had nothing to do with the original idea of the experiment: the random appearance of small

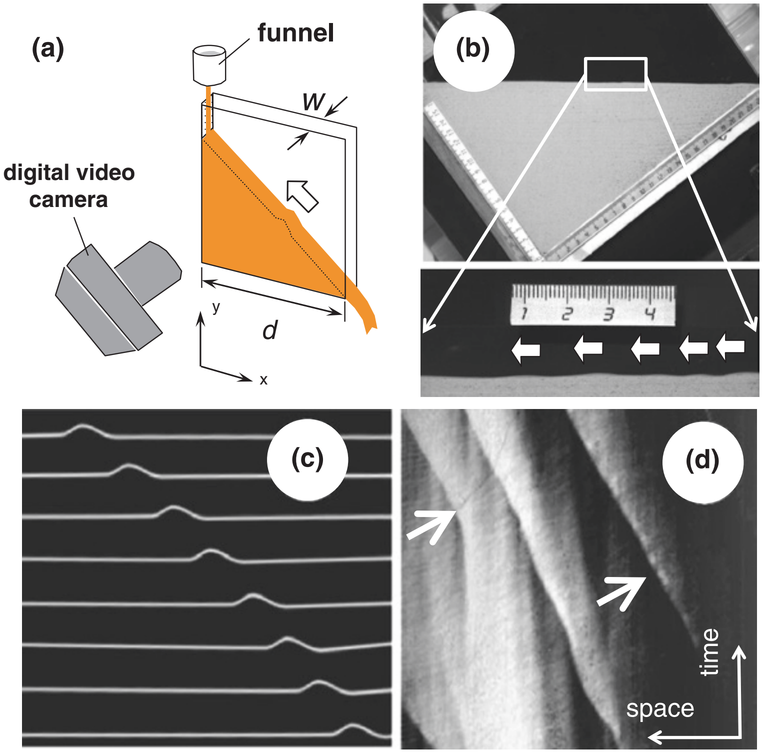


Fig. 3.9 Uphill bumps phenomenology based on a very simple setup. **a** Sketch of the experimental setup. **b** One picture taken by the camera in (**a**), with a zoom of one section of the surface where uphill bumps can be seen (the minimum division of the scale shown is 1 mm). *Thick arrows* in (**a**) and (**b**) indicate the direction of motion of the bumps. **c** A sequence of pictures of the surface of the pile (after digital treatment), where one bump moves from right to left as time increases from bottom to top. **d** A spatial-temporal diagram of the movement of a few bumps. The diagram has been constructed in the following way: one video of the uphill bumps is separated into a sequence of pictures. A horizontal line of pixels located slightly above the average surface of the pile is extracted from each picture, and then organized one on top of the other from bottom to top, as time goes by. Then, any moving feature in the video—like the front of one bump moving at approximately constant speed—is seen in the spatial-temporal diagram like a line (or band) whose slope is inversely proportional to the velocity of the bump. A feature moving at zero speed will show up as a vertical line

deformations on the free surface of the flowing sand, first near the lower end of the cell (like little hills of 1 cm length and around 1 mm height), then suddenly starting to move uphill against the flow for several centimeters, until they disappeared. Osvanny suggested to Etién to make further tests of the new observation, so they also set off in that direction. We later learned that the phenomenon had already been observed in other sands by Taberlet and co-workers in 2004, but the bumps had been described as forming "trains". In our case, we found some individual uphill bumps, standing alone, so we called them "solitary waves". In 2006, I had the opportunity to take nice fast-camera videos of the phenomenon while at Knut Jorgen Måløy's Lab (Physics Department, University of Oslo).

Figure 3.9d shows a spatial-temporal diagram where the uphill movement of a few bumps can be identified (the figure caption explains how the diagram was obtained). The inclined, straight feature indicated by the right arrow corresponds to a bump that passed across the field of vision at constant speed from right to left (a movement from left to right would have produced a line with a positive slope). Notice that any other bumps around are moving with the same speed and in the same direction. However, perhaps the cutest information from the diagram lies in the feature indicated by the left arrow: a bump was "born" at some moment, stayed in place for a short time (as revealed by the vertical segment), and then "awakened", i.e., it started to move in the same direction and with the same speed as its colleagues!

The uphill bump mechanism can be described "phenomenologically" using an idea proposed by Oscar Sotolongo, then head of the "Henri Poincaré" Cathedra for Complex Systems at the University of Havana (Fig. 3.10). A granular flow can be described by Saint-Venant equations (equivalent to mass and momentum conservation applied to a fluid flow), conveniently adapted to granular flows by the introduction of an effective friction force acting on the flowing layer of grains that depends on the depth of the layer.[7] Sotolongo found a specific depth dependence of the friction term that allows one to transform the modified Saint-Venant equations into the so-called Kortweg–de Vries equation (KdV), whose best known solutions are the *solitons*. A soliton is a single perturbation that travels long distances preserving its shape. However, we cannot say that ours are true solitons for two reasons: (a) after several centimeters of travel, the uphill bumps eventually disappear and (b) we have never seen two bumps collide and emerge from the collision without losing their individual identities—a second property of any feature deserving the name "soliton". So we cautiously called our bumps "solitary waves". Finally, it is worth mentioning that the depth dependence of the friction coefficient that converts the Saint-Venant equations into the KdV equation was chosen

[7] The BCRE model can be derived from the so-called Saint-Venant equations, after introducing a number of approximations.

Fig. 3.10 Oscar Sotolongo (*right*) and Etién Martínez (*left*) discussing at the whiteboard circa 2004

ad hoc, and has never been corroborated experimentally—a task extremely difficult to achieve.

But what is the detailed mechanism of bump formation and movement? They may be produced by a “stop-and-go” mechanism, suggested to me by Stéphane Douady when I met him briefly at the École Normale Supérieure de Paris in 2006. The stop-and-go mechanism is easily illustrated in the case of urban traffic. Assume you are driving on a congested street, and a policewoman (or policeman) standing at the curb captures your attention: you slow down for a while, but then she (or he) stares coldly at you, making you accelerate back to your original speed—“stop-and-go” dynamics. Interestingly, this maneuver forces the car right behind you to do the same, actually coming closer to you than normal, so a zone of “higher car density” has been created. Under certain circumstances, this “perturbation” moves backwards, while the cars actually move forwards.

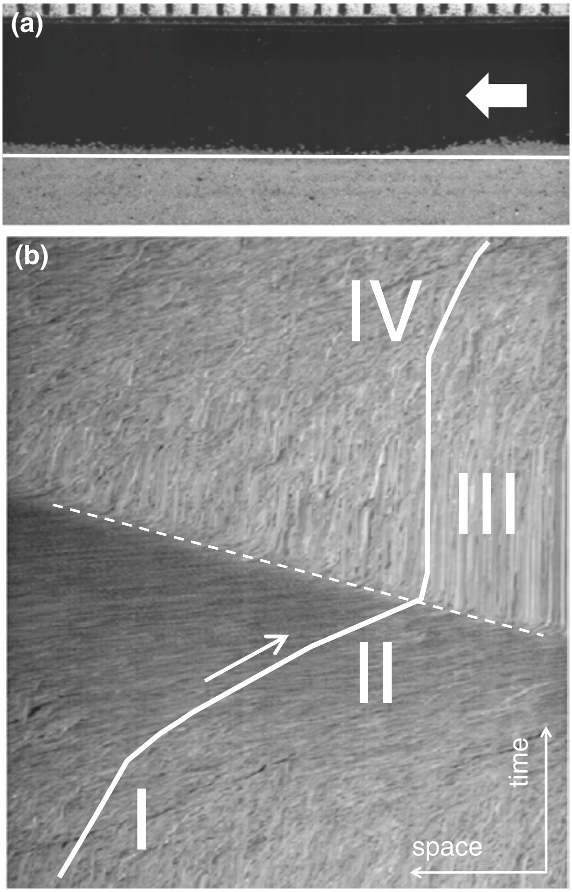


Fig. 3.11 Picturing the uphill bumps mechanism: a challenge that could not be met with cheap equipment. **a** A fotogram from a single bump extracted from a sequence of pictures taken at 6000 frames per second (the smallest division of the scale on top is 1 mm). **b** Spatial-temporal diagram taken along the horizontal line seen in (**a**), where "averaged" trajectories of particles can be identified (the line in (**a**) has been taken at a depth where many advection and erosion events take place). In *region* I, the particles move at a certain velocity from left to right. As the bump approaches from the right, particles suddenly increase their speeds, as seen in region II. In region III, particles have been stopped, and are at rest in the static layer, "waiting" for the bump to pass above them from right to left. When the bump has almost finished its passage, particles are eroded back to the flowing layer (*region* IV) and regain a left to right velocity that approaches the one they had in *region I*. Notice that the dotted line indicates the velocity of the bump front: as expected, it is smaller in magnitude than the particle speeds in regions I, II, and IV, and its direction is opposite to that of the particle velocities in those zones

The same dynamics seems to explain the counter-stream movement of bumps in granular flows: a local perturbation occurs in such a way that an abnormally large amount of grains originally belonging to the flowing layer get advected into the static layer, thus producing a hill-shaped "bump". As more and more grains are advected and stuck to the left part of the hill, the grains on the right-hand side are eroded, and re-incorporate back into the flowing layer. The result is a bump that moves from right to left, while the average flow of grains is actually from left to right. (In the explanation, "left" and "right" have the meaning illustrated, for example, in Fig. 3.9b and c.)

It would be nice to be able to track individual grains in a video and say "Aha! This specific grain was advected and then eroded as the bump passed by". But that is very difficult to do even in the case of high quality, high speed videos of fine sands like that from Santa Teresa. However, appropriate spatial-temporal diagrams from such videos strongly suggest that stop-and-go is the right mechanism, as illustrated in Fig. 3.11. Of course, I recognize that getting this piece of evidence was beyond the abilities of a cheap second-hand e-bay camera: it was obtained with a state-of-the-art high speed camera, at 6000 frames per second, using a nice microscope lens, and lots of watts of artificial illumination at Knut Jorgen's lab in Oslo.[8] Unfortunately, science sometimes requires more than a guerrilla-style approach.

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Wikipedia Links

https://en.wikipedia.org/wiki/Revolving_rivers

YouTube Links

Videos on revolving rivers using Santa Teresa sand http://www.youtube.com/watch?v=dATX3Vt0268

S. Douady showing singing sands in the Moroccan desert http://www.youtube.com/watch?v=t6Zt4XCHj3U