“Barchan” Dunes in the Lab

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We demonstrate the feasibility of studying dunes in a laboratory experiment. It is shown that an initial sand pile, under a wind flow carrying sand, flattens and gets a shape recalling barchan dunes. An evolution law is proposed for the profile and the summit of the dune. The dune dynamics is shown to be shape invariant. The invariant shape, the “dune function” is isolated.

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Dunes dynamics has strong impact on the ecology and the economy of sandy areas, but remains far from being understood. Since the single major work on sand dunes formation, written by R. A. Bagnold in 1941 [1], a world wide inventory of deserts has been developed in the fields by Sharp (1966) [2] and McKee (1979) [3], in application of aerial photography by Smith (1968) [4] and via Landsat imagery by Fryberger et al. (1979) [7] and Breed et al. (1979) [6], among others. Five basic types of dunes have been recorded: crescentic, linear, star, dome and parabolic. The most common dune is the crescentic, also called barchan. This type of dune forms under mono-directional winds. In that sense, barchans are also the most "simple" dunes. They are characterized by a crescentic crest normal to the wind direction, with downwind arms. The stronger the wind, the less open is the crescent. The windward (resp. leeward) face is concave (resp. convex). The barchans move over desert surfaces, while maintaining nearly constant shape. Various models [8, 9, 10, 11] have been proposed, from cellular automata to two-phase (static and moving sand) models. However, if they qualitatively capture most of the fields observations, they call for more experimental data. On the one hand, field measurements are difficult to perform and often incomplete. On the other hand, it is believed that dunes have a minimal size of the order of the meter, not reducible to smaller laboratory scales.

In this Note, we show experimentally that an initial sand pile, under a wind flow carrying sand, flattens and gets a shape recalling barchan dune. After a short description of our experimental setup and protocol, we present first quantitative results about the observed dune patterns. We finally discuss why it is actually possible to observe dunes in the lab.

Fields observations indicate a very generic behavior of dunes essentially controlled by the wind direction and force, with little dependence on the details of the wind structure. Accordingly a very simple design has been chosen for the wind tunnel. It consists namely of two sections (figure 1(a)): the first one (100 mm wide, 100 mm high, 730 mm long) is devoted to establish a regular wind; the second one (230 mm wide, 175 mm high, 650 mm long) is open at its end and its floor is covered with 500 µm roughness sand-paper. The wind speed is constant and set below the "fluid threshold" and above the "impact threshold". These thresholds are defined as follows. For wind speeds above the "fluid threshold", grains are picked up from the surface and given a forward momentum, before being brought back to the surface under their own weight, after a typical "saltation length". If the surface is covered with sand, the grains loose most of their energy at the impact, but eject more than one grain on average. Once the saltation is initiated, it is self-sustained as long as the wind speed remains superior to the "impact threshold". For the considered sand, made up of monodisperse 250 µm diameter glass beads, the fluid threshold \( u^*_f \approx 25 \text{ cm/s} \) and the impact threshold \( u^*_c \approx 20 \text{ cm/s} \) [1], where \( u^* \) is the friction velocity as defined for a turbulent boundary layer [12].

FIG. 1: set up and measurement technique (a) Schematic drawing of the wind tunnel, with sand injection and measurement set up: (1), (2) first and second wind tunnel sections; (3) ventilator; (4) honeycomb; (5) sand injection; (6) CCD camera; (7) parallel lighting; (8) light intensity modulating grid; (b) A typical top view of a dune with the modulated lighting. The local streamwise phase gradient is directly proportional to the local slope.
The initial condition is a sand pile of volume $V_s$, centered in the wind tunnel. The wind is then set up and it is checked that no sand motion occurs until a sand flux $q_s$ is added to the wind at the top of the entrance of the second channel section; (in the following $q_s$ is the vertically integrated sand flow rate per spanwise length unit). In the present study, we report on three experiments $E_{1,2,3}$ with respectively $q_{s1} = 1.25 \pm 0.25$ gs$^{-1}$m$^{-1}$ and $V_{s1} = 30$ cm$^3$, $q_{s2} = q_{s1}$ and $V_{s2} = 20$ cm$^3$, $q_{s3} = 5 \pm 0.25$ gs$^{-1}$m$^{-1}$ and $V_{s3} = V_{s1}$. The quantitative sand pile evolution, is obtained by profilometry : A sinusoidal light intensity is projected onto the experimental field and a CCD camera records the field images from the top at regular time interval. The local streamwise phase gradient of the light intensity is directly proportional to the local slope (figure 1(b)). The recorded images are processed in order to obtain the topography $h(x, y)$.

After a transient of the order of 5 minutes, the typical crescent shape of the dune (figure 2), with arms downwind and a slip-face on the leeward side appears. A slight disturbance of this face actually induces avalanching. The crescent crest is rather open as expected in low wind conditions. Under the present experimental conditions, the dune is eroded until full removal of the initial amount of sand. Figure 3 displays the evolution of the streamwise profile $h^+(x, t)$ going through the dune summit. The sand pile first rapidly decreases in size to evolve towards a characteristic shape with a concave upwind side and a convex downwind side. Figure 3(b) displays more frequent time steps after the transient regime, scaled by the summit abscissa $x_s$ and height $h_s$. Once the dune profile is reached, its shape remains the same up to rescaling. Figure 4 displays the evolution of $x_s$ and $h_s$. The time has been scaled by $t^* = \frac{x_s^2}{\rho_s h_s(0)^2}$, where $\rho_s = 1.57$ g/cm$^3$ is the sand bulk density, $q_s$ the injected sand flux rate, and $h_s(0)$ the maximum height at the initial condition.

This time scale $t^*$, here suggested by a dimensional analysis, is naturally recovered in the resolution of the mass balance equation (see later). The dunes obtained in the three experiments exhibit the same evolution, with identical scaled lifetimes. After the initial transient, the dunes propagate at constant velocity and their height decay like a square root of time, as shown in inset of figure 4(b). Altogether, the dune profile follows an evolution given by:

$$h^+(x, t) = h_s(t) D \left( \frac{x-x_s}{h_s} \right),$$

with $\frac{h_s(t)}{h_s(0)} = 1 - \alpha \sqrt{\frac{t}{t^*}}$,

and $\frac{x_s(t) - x_s(0)}{x_s(t) - x_s(0)} = \frac{1}{t^*}$;

where $\alpha$ is a dimensionless constant $D$, and the "dune function", is the invariant shape of the dune profile.

These evolution laws can easily be recovered by considering mass transport and losses of the sand pile. Let
us consider an infinitesimal streamwise layer of the dune with profile $h^+(x,t)$. We assume the airflow carrying sand to be confined to a layer of constant height $H$. We also assume the sand flux to be uniform in height, so that the sand flux per height unit is $\frac{\rho q_s}{H}$. The expected proportionality between the sand transport $\rho_s h_s q_s$ due to the dune motion at velocity $v_s$ through a cross section at the abscissa of the maximum height, and the sand flux through a section of height $h_s$ outside the dune gives $\rho_s h_s q_s \propto \frac{\rho q_s}{H^2} h_s$, thus the observed constant velocity. Considering now the mass per spanwise length unit $M = A h_s^2$, where $A$ is the dimensionless area under $D$, we compute its decay rate. On one hand the balance of erosion and deposition rates must be proportional to the sand flux per height unit times the dune cross section. On the other hand, if the wind charged in sand is confined in a layer of height $H$, when passing over the dune it is accelerated by a factor of $H/(H-h_s)$ which may enforce the erosion, so that:

\[
\frac{dM}{dt} = 2A \rho_s \frac{dh}{dt} h_s \propto \frac{\rho q_s}{H} h_s,
\]

thus \(\frac{dh}{dt}(\tilde{H} - \tilde{h}_s) \propto -\frac{q_s}{\rho h_s^2(0)},\)

where $\tilde{h}_s = h_s/h_s(0)$; $\tilde{H} = H/h_s(0)$. Integrating with the initial condition $\tilde{h}_s(0) = 1$, one has the relation:

\[
\tilde{h}_s^2 - 2\tilde{H}\tilde{h}_s + 2\tilde{H} - 1 = \alpha^2 \frac{t}{t^*},
\]

with $\alpha^2$ a positive proportionality constant. The decreasing solution with time is:

\[
\frac{h_s(t)}{h_s(0)} = \tilde{H} - \sqrt{\alpha^2 \frac{t}{t^*} + (\tilde{H} - 1)^2}.
\]

The simpler expression obtained experimentally is recovered when $\tilde{H} = 1$, in agreement with the visual observation that the injected sand flux extends on a height of the same order of the initial sand pile. This specific feature may be different in nature.

How is it that we could observe dunes at a much smaller scale than in nature with the same kind of sand? In deserts, dunes have to grow from flat initial conditions. As already pointed out by R. A. Bagnold [1], the self accumulation process responsible for dunes building is efficient if the wind speed is high enough to charge the wind in sand prior to the dunes field. For a typical wind speed of 25 km/h, at one meter above ground, the friction velocity is $u^* \simeq 1$ m/s and the saltation length is $l_s \simeq 10$ cm [1]. A typical dune streamwise extension is of the order of a hundred to a thousand times the saltation length. Such ratios are clearly out of reach of the lab experiment. Yet the above results clearly demonstrate the feasibility of dune investigation in a lab, at least during a long transient. Moreover, the downwind motion of the dune reveals a transport mechanism similar to the one observed in nature, in which the windward face is eroded, while the leeward face accumulates sand until avalanches set up. Having dealt with low wind, artificially charged in sand, we have lowered the saltation length down to $l_s \simeq 1$ cm. This is more than one tenth of the sand pile streamwise extension, but it is small enough to let saltation occurs on the windward face of the dune and accordingly to let the basic dynamics mechanisms take place. Since there must actually be not just a single saltation length but a distribution of them around an average, the main difference between nature and our experiment is that, in nature saltation jumps an order of magnitude larger than the averaged value still transport sand on the dune, whereas in our experiment, the grains are lost for the dune. This difference may explain why our experimental dunes erode so fast.

Altogether, we believe that the initial sand pile evolves according to the same elementary erosion and deposition
mechanisms as those involved in a stationary dune dynamics in nature. Together with the robustness of the
dune shape underlined by Werner’s elementary model, it leads us to conclude to the relevance of the dune function obtained here. Whether the laboratory dunes are exactly barchan dunes, in a sense which should be
precised, needs further investigation of both field and experimental data. Beyond the above quantitative results, the
present work has proved the feasibility of investigating small dunes convenient for lab investigations. It calls for
further studies under various wind conditions, with different sand types and opens a new kind of investigations in
desert studies.

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