Granular community goes to the desert

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The physics of granular media is an ancient science. It is present in practically all fields of applied physical sciences. At a fundamental level, models of hard spheres or disks have been used from the early times of classical Greece to nowadays investigations to characterize the microscopic states of organisation of matter. Conversely, in the last two decades, a large community of physicists has made use of what had been acquired in the microscopic physics world to try to enrich our understanding of the science of "real grains". In the eighties, as we were testing percolation ideas by mixing conducting and insulating otherwise identical grains in various concentrations [1], we realized then that the way the packings were built had a strong influence on the result of the experiments. Replacing a single conducting grain by an insulating one tells one in particular how many good electrical contacts this grain had, and this varies with filling conditions and packing pressure. The question led us to be acquainted with the British school which since Bernal [2] had studied arrangements of packings in connection with the structure of the liquid state. But probably the most spectacular finding for us was that of a photoelastic experiment by P. Dantu [3] on compressed arrays of parallel aligned photoelastic cylinders which clearly showed that the stresses propagated along continuous chains of cylinders leaving a lot of them practically free of stress due to arching (similar work had been done independently by Josselin de Jong in Holland). This result was not well recognized at this time partly because of a prevalent dogma in mechanics based on homogenization procedures which use phenomenological local constitutive laws to evaluate global properties of heterogeneous - generally periodic - structures. Clearly this can not apply in the granular case of a granular assembly; because of the very large distribution of local forces a global geometrical description is needed [4]. Percolation ideas have been applied to the problem taking into account the asymmetry between presence or absence of inter-grain forces when the grains are either pressed together or pulled apart, like a network of fuses or of diodes and unlike a mechanical spring lattice. Such models can account for the fact that the value of the exponent x of the force F - deformation D law, $F = D^x$, is much larger than that of an individual contact (given by Hertz law $f = d^{3/2}$) due to the increase of active mechanical contacts where forces increase. More recent results have been obtained to describe propagation laws of forces from a point force applied at the top surface of a packing of grains. They were stimulated by the observation that, in some cases, the load exerted at the bottom of a conical heap of grain has a minimum below the tip [5]. Another very active subject is how to obtain an optimal compact disordered system as well as its long time evolution (which is not to far from aging in glasses) [6].

The rediscovery of the heaps, which had been first observed by Faraday when vibrating vertically a thin horizontal bed of grains, has initiated the modern research activity on grains in motion. Regular periodic patterns can be produced as well as soliton structures [7]. The main mechanism is the appearance of circulation flows, where the grains are lifted upwards in the core of conical heaps during the downward plate motion, and of avalanches which descend along the surface of the cones. This convective motion grossly evokes that of the fluid within a Bénard cell, and dynamic structure concepts have been applied to this problem.

The dynamics of avalanches is of practical and environmental interest. The results obtained over the last 10 years are important and have contributed to the recent interest in sand dunes. We know from C. A. Coulomb's work, who was at the time of his finding a civil engineer working on fortifications, that there is a maximum angle of stability of a cone given by $tg\,\theta_M = \mu$, where μ is a friction parameter depending on the nature of grains and of their interaction. When an avalanche starts, it will usually stop at a slightly smaller angle of repose θ_m; the difference between these two values comes from the fact that, in order to flow, a dense packing of grains has to expand a little, a classical phenomenon in granular physics known as Reynold's dilatancy. The self-organized criticality concept promoted by Per Bak neglected this hysteretic effect: this permitted him to associate with the existence of the Coulomb critical angle a particular class of critical effects where fluctuations (here avalanches) of all sizes would maintain the cone angle at this fixed value when the size of the cone varies. In fact, between θ_M and θ_m local avalanches can be triggered artificially. Their structure is a well defined function of the angle and the layer thickness [8]. Several theoretical treatments have been proposed in the recent years [9] to describe the flow of sand in avalanches. They use a two-phase description with an upper thin layer flowing and exchanging matter with the lower fixed phase and are tested experimentally in many groups.

A new partner in the problem is wind which transports sand, shapes and causes the dunes to move. We consider one-directional

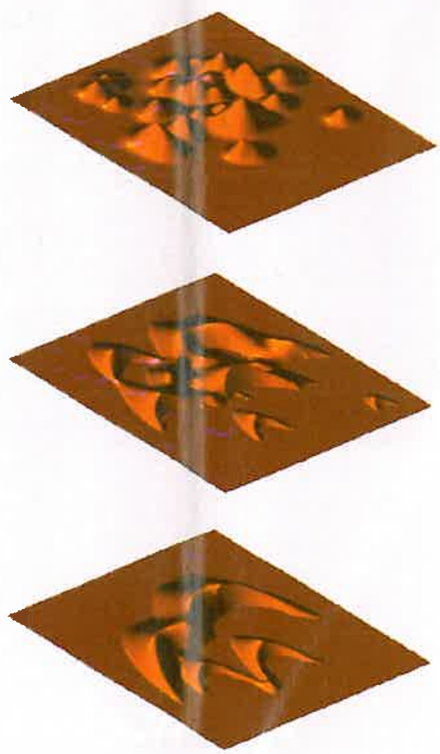

Fig. 1: Computer simulation of the evolution of a granular surface starting from an artificial random configuration at t = 0, t = 180 days and t = 470 days.

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wind, such as provided by the NW-SE wind due to the trade winds in West Sahara, which gives rise to so called "Barchans" dunes that have crescent-like shape. However, in conditions of seasonal winds having two main possible directions at an angle, elongated - "longitudinal" - dunes will form along the bisector of this angle.

Depending on their size, the grains carried by the wind will roll along the surface (reptation), will be lifted in the air by hydrodynamic forces (saltation), or be suspended for the smallest ones. The saltation process is dominant for dune formation and will act within a limited range of grain sizes (typically between 100 μm and 300 μm), as larger grains will not have enough momentum to get them off the ground. The grains are accelerated by the wind along their trajectories; when they hit again the granular bed, they eject new grains due to the impact. This chain reaction increases the surface flux until it saturates because the air cannot carry more particles. The exponential increase in the flux and its subsequent saturation can be described by the logistic equation coupled to the shear stress of the wind on the ground. The latter one can be obtained by integrating over the logarithmic turbulent velocity profile of the wind; it depends, of course, on the topography which itself is modified by the surface flux thus closing the iterative scheme: topography → wind field → surface flux. Recently, software doing exactly this has been developed and applied mostly to Barchan fields [10]. In the figure, we see a computer simulation of the temporal evolution of a set of Gaussian hills into a Barchan field as it is typically observed in nature.

Among the most recent results obtained, we should mention the quantitative description of the shape of a Barchan dune and the understanding of its stability and shape invariance. Today, we have a clear criterion for the minimum size of such a dune and for the formation of its crest. But Barchans are only a very specific type of dunes and there is still much work to be done to understand the other ones, over one hundred observed dune morphologies! In the future, it should also be possible to study numerically techniques to destroy dunes in particular using appropriate obstacles.

Concerning the flow of air and grains which experience mid air collisions and the turbulent flow profile being modified by the grain dynamics, much work remains to be done on this subject, after the theoretical contributions of Sørensen [11] and Jenkins [12], both in field experiments and air tunnels. In particular, it seems of importance to get beyond the statistically averaged description of turbulence and to introduce fluctuations and eddies of different size.

Another important issue is water. Dunes are a potential reservoir of water at a certain depth where water does not evaporate. This is clear from the growth of very long rooted plants (up to 30 meters deep) on dunes. This is also a crucial parameter for keeping the dunes fixed. How we can keep and use the water stored in sand is another vital issue for millions of peole.

Collaboration with those concerned mostly with the problems of moving dunes seems very important at this stage. Our studies on sand dunes have shown us the multiplicity of required competences: physicists, fluid mechanicians, geomorphologists and geologists, naturalists, but also social scientists which deal with anthropic parameters, are the first partners in coping with the increasing risk of dune formation in a mushroom city like Nouakchott (Mauritania) whose population grew by a factor of nearly 1000 in less than half a century! We held there a one-week meeting last March with the support of the EPS and with a large participation of scientists and engineers of the country. Several important and urgent issues were addressed, one of which dealing with the "route de l'espoir" between Nouakchott and Bamako, the capital of Mali. This east-west road being constantly covered by sand moving from north to south has become a test ground for dune-breaking and sand flux controlling techniques. But the new harbor of Nouakchott raises also vital problems for the city due to underwater uncontrolled sand transport induced by the large dike whose construction twenty years ago had not been correctly planned, leading to the sanding of the harbor and as well as creating a serious threat of submerging the city built below sea level

The Nouakchott meeting was part of an international program that we have initiated and has had the support of the EPS from its beginning, three years ago. It involves European physicists (mostly from France, Germany, Denmark) as well as from concerned countries (at the present time, Tunisia, Mauritania, Morocco and Algeria) and with the appreciated contribution of the U. S. A. (the support of NASA was justified by the dunes observed on Mars!). The progress from the first meeting two years ago in Tunisia to the recent one in Nouakchott is spectacular and shows much common interest in this typical "physics for development" project such as the EPS wishes it to develop. On the aspect of education and technical formation, we are establishing, in partnership with the Ministry of Education of Mauritania and, hopefully, other countries, original programs for doctorate studies which combine disciplines much broader than our classical curricula, with combined studies followed in Europe and Africa.

The research project is going to be pursued on a regional scale with a next meeting in Agadir (Morocco), planned in two years where we expect to maintain a participation of the EPS. Meanwhile we will strengthen the exchange in coupled experimental work, numerical and theoretical models and studies in the field, using it as an observation site as well as a large scale wind tunnel! This empirical activity must be accompanied by a deeper understanding of grain transport and of the coupling between changing winds and changing topography with the hope to better control the motion of dunes and, more generally, the progress of desertification.

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