Granular flows : fluidization and anisotropy

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Granular Flows: Fluidization and Anisotropy

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If we stand on the shore and look at the sea,
we see the water, the waves breaking, the foam,
the sound, the air, the winds and the clouds,
the sun and the blue sky, and light.
There is sand and there are rocks.
There are animals and seaweed,
hunger and disease,
and the observer on the beach.

Any other spot in nature has a similar variety of things.
It is always as complicated as that, no matter where it is.
Curiosity demands that we ask questions,
that we try to understand this multitude of aspects as resulting from
the action of a relatively small number of elemental things,
and forces acting in an infinite variety of combinations.

Is the sand other than the rocks?
Is the moon a great rock?
Is the sand perhaps nothing but a great number of very tiny stones?

– Richard P. Feynman
The Feynman Lectures on Physics, p2-1

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CHAPTER 1

INTRODUCTION TO GRANULAR MATTER

1.1 Granular Materials

Granular materials are present all around us. Common examples include sand, rice, powder, coal, cement, seeds, pills, rock avalanches, and on a much larger scale a collection of icebergs, and the particles that form the rings of Saturn. Because of this omnipresence, research on granular materials is relevant for everyday applications, but it also presents intriguing fundamental challenges [1–4].

The two most basic characteristics of a granular material are that its constituents must be large enough to not be significantly influenced by thermal fluctuations, and that the interactions between particles are dissipative. In practice, the lower limit size for the grains is about 1 µm. For a typical sand grain raised in height by its own radius (0.5 mm), the difference between the potential and the thermal energy is a startling factor 10^{13} [1].

Like water, that, depending on temperature and pressure, can be solid (ice), liquid (water) or gas (vapor), a granular material can also show behavior that corresponds to different phases of matter. When you walk on the beach, the sand behaves like a solid and carries your weight. When you sit down and take off your shoes, the sand flows out of these as if it were a liquid. When shaken vigorously, sand behaves like a gas.

A pile of sand behaves like a solid because it is jammed due to the gravity-induced pressure. The friction between the grains plays an additional strengthening role. The stresses in a granular solid are not distributed uniformly, but are conducted away along so-called force chains [5–8], which are networks of grains with relatively strong contacts.

For making sand show liquid or gas-like properties, it has to be forced externally to drive it away from its equilibrium state. This can be done for example by tilting or vibrating the system. Surprisingly, a very small displacement of a particle can significantly alter the force chains and weaken the packing [6].

Despite some similarities between the behavior of granular solids, liquids, and gasses to their molecular counterparts, the granular phases exhibit a range of unique properties [1–4].

An example of a specific property of granular solids is that they dilate under external shear. This is caused by the shear deformation which disrupts the close-packed arrangement of the grains, forcing them into less dense arrangements. This mechanism explains the white rings around footprints made by someone walking on wet sand. The shear flow induced by a foot widens the voids between the grains. As a result, the water can drain away, which in turn makes the sand drier and whiter.

Another specific property of granular phases is found in granular liquids. Sand in an hourglass always flows at the same rate, irrespective of the amount of sand that is left in the upper vessel. In an hourglass filled with water, the flow slows down as the water level in the upper vessel (and hence the hydrostatic pressure) decreases. Sand hardly builds up a hydrostatic pressure in such a container, because the gravitational force is re-directed towards the sides of the hourglass via the force chains in the packing [9].

A very counterintuitive property of a granular gas is its tendency to cluster. An ordinary gas will spread over the entire available space, but a granular gas does the opposite: it forms clusters [10, 11]. The reason for this lays in the inelastic collisions between the grains. Once a region is denser because of a fluctuation, the particles in that region will collide more, lose more energy and form a dense cluster.

Granular materials are part of a bigger class of materials that exhibit the *jamming transition*. This transition, which separates a disordered solid-like state and a liquid-like phase, is also used to describe colloidal suspensions, emulsions, foams and even elastic networks [12–14].

Early granular research was performed by pioneers such as Coulomb (who investigated the stability of a granular heap from the point of friction [15]), Faraday (who studied heaping of the surface of a vibrated powder [16]), Hagen and Janssen (who described saturation of pressure with depth in silos [9, 17]), Reynolds (who introduced the notion of dilatancy [18]), and traveler and World War I & II veteran Bagnold, who studied sand and desert dunes [19], as well as the flow of dense suspensions and granular materials.

Knowledge about the behavior of grains is very relevant for industrial applications, as many industries rely on the mining, milling, mixing, transporting, and storing of granular materials. It has been estimated that more than 50% of sales in the world involve products produced using granular materials at some stage [2, 3]. Major sectors that work with granular materials include civil engineering, the chemical (fuels and catalysts are often used in the form of grains to maximize the surface area), mining, pharmaceutical (powders are used to make pills), food, and glass industry. Estimates say that there are energy losses up to 40% in industrial processes that involve granular media, which are caused by a lack of knowledge on how to handle them [20]. Another major domain of applications of granular materials is earth science (geophysics), as our soil is mostly composed of grains. Examples of granular physics at play are avalanches, landslides, dune formation, erosion, and earthquakes.

In the 1980's, physicists got interested in granular media. Fundamentally, an important consequence of the fact that a granular system is athermal and dissipative, is that the system cannot explore phase space, and therefore is strongly non-equilibrium. In the absence of external forcing, each metastable configuration of the material will last indefinitely, and no thermal averaging over nearby configurations occurs. Because each configuration is unique and has its own precise properties, a granular experiment can never be precisely reproduced and results have to be defined in terms of ensemble averages. Because k_BT is effectively zero, traditional thermodynamic methods are not applicable to granular materials. Moreover, when driven, a wealth of counterintuitive phenomena arises. For example: vibrations make particles of different sizes separate to different regions of the system rather than mix them [21]. Since there are no attractive forces between the particles, this separation appears to violate the principle that entropy is always maximized, which normally favors mixing. In a granular material, the influence of (thermodynamic) entropy is small compared to dominant dynamical effects.

Granular systems offer a relatively simple possibility to study dissipative systems far from equilibrium. Noble Prize winner De Gennes originally used sandpile avalanches as a macroscopic picture for the motion of flux lines in a type-II superconductor [22]. Slow relaxations that are found in vibrated sandpiles show behavior that is similar to the slow relaxation found in glasses, spin glasses and flux lattices [1]. Nonlinear dynamical phenomena are observed, which are useful to understand the breakdown phenomena in semiconductors, stick-slip friction on a microscopic, and earth-quake dynamics on a macroscopic scale [1].

1.2 Examples

In this section I will describe some examples of granular research that focuses on every day applications.

1.2.1 Grain Silo

A very concrete and relevant example of granular physics at work is the grain silo. The silo illustrates clearly what can go wrong if - because of a lack of understanding of granular physics - a granular material is handled as if it were a regular solid or liquid. When building a silo, the forces that will work on the bottom and side walls of the silo have to be estimated to determine how strong the walls need to be.

Naively, you could expect most of the weight of the particles to be carried by the bottom of the silo, so the sidewalls can be made thin. As explained in the previous section, in a granular system, a significant part of the forces is carried to the side walls [9, 17]. So in fact, a thin wall will not suffice. This effect is even enhanced by the fact that these forces are not distributed homogenously over the entire side wall. At the points where the force chains of particles that carry most of the weight hit the wall, the force that the wall has to sustain is significantly higher than the force that corresponds to a homogenous estimate. Unfortunately, many silos are still built with walls that are too thin – they will rupture and cause the entire silo to collapse [4].

Another significant complication that occurs in silos is clogging of the grains. Two important questions are how to minimize the probability of clogging, and how to make the grains unjam in case it clogs nonetheless. Going into the silo to unclog the grains by hand is extremely dangerous; no less than 25 deaths a year in grain silos are reported in the United States alone [23]. This clearly shows the relevance of understanding how to deal with granular materials.

1.2.2 Brazil Nut Effect

A granular effect that is widely known is the Brazil Nut Effect (or: Muesli Effect). This effect describes the phenomenon that in a jar of muesli or nuts, the biggest nuts always raise to the surface. The origin of this effect is not trivial to describe, as there are three physical mechanisms that cause the segregation of the big and the small particles [24]. The simplest mechanism is that when the system is agitated, the small particles can fill small voids at the bottom of the system while bigger particles cannot. As a result, small particles migrate downwards and big ones upwards. Surprisingly, the air pressure also plays a role, as the rearrangement of nuts requires air flow. The practical implications of this effect on transporting and storing granular materials are immense.

Another manifestation of this effect is the observation that in a bag of potato chips, the biggest chips are at the top of the bag. A good method to get the chips out uniformly mixed is by opening the package on the bottom [25].

1.2.3 Quicksand

A question that often arises when discussing granular materials is "can one drown in quicksand?" The *simple* answer to this question is "no"; the density of quicksand is twice as high as the density of a human, so according to Archimedes' law, a person in quicksand will only sink up to their waist [26].

The *complex* answer to the question is: "that depends on the definition of quicksand". Actual quicksand is a relatively dense mixture of clay, sand, and water, in which a person cannot drown. On the contrary, research has been done on so-called dry quicksand [27], which consists of a lose packing of 40 µm grains and air. By blowing air through the packing, a packing fraction of 41% can be reached. Taking a material density of sand (quartz) of 2.65 kg/l, this results in a density of 1.09 kg/l. This is remarkably close to the density of the human body, which is around 1.06 kg/l. This leads to the conclusion that it would be possible to drown in this system. In the desert, similar packings may evolve from the sedimentation of very fine sand after it has been blown into the air by the wind.

1.2.4 Soft Robotic Gripper

A recent and very nice application of granular physics is the soft robotic gripper [28, 29]. A bag, filled with grains (*e.g.* coffee powder), is gently placed on an object. As air is pumped out off the bag, the grains jam, become rigid, and the bag will grab on to the object. A soft robotic gripper has been produced which can grab almost any object without breaking it; examples include an egg, a drinking glass, or a pen. By pumping air back into the bag, the gripper releases the object. By creating an overpressure, the object can be ejected. Via this mechanism the robotic gripper is able to play darts [30]. The gripper is simple, cheap, firm, and able to work with fragile objects. Because of its simplicity and reliability, the gripper could be very suitable for use in outer space [31].

In order to jam and unjam the packing with as little air as possible, the coffee powder can be replaced by 3D printed particles whose shape has been optimized using evolutionary algorithms [32].

1.2.5 Shear Thinning and Thickening

Physicists in general often describe a fluid or viscous material in terms of viscosity. Granular materials, similar to materials such as ketchup and blood, become less viscous when they are sheared. This kind of material behavior is called *shear thinning*. An everyday example of such a material is modern paint. When modern paints are applied, the shear created by the brush or roller will allow them to thin and wet out the surface evenly. Once applied, the paint regains its higher viscosity which avoids drips and runs.

Water belongs to a different class of materials called *Newtonian fluids*. For these types of matter, the viscosity is independent of the flow rate.

A third and perhaps most intriguing class are the *shear thickening* materials which become stiffer when sheared. The best known example is cornstarch. When gently stirred, it behaves like a liquid, but if smacked on with a hammer, it becomes rock hard [33]. Similarly, one can run over a big bath of cornstarch, but when walking gently, one sinks in. Two possible applications of shear thickening materials are a speed bump that is soft when you drive slowly, but hard when you drive too fast [34], and a bulletproof vest that is comfortable to wear because it only becomes stiff when hit by a fast bullet [35].

1.3 Shear and Vibration

An unperturbed granular material is rigid because of friction and gravity-induced pressure. To make the material yield and flow, it has to be forced externally [1, 2, 36–43]. The best known scenario that leads to granular flow is exerting a shear stress that is large enough to overcome the friction. This can for instance be done by simply tilting a layer of sand [1, 2].

Another possibility to let a granular material yield, is to first make it lose its rigidity using mechanical agitations. These agitations itself do not have to induce flow [38, 44–49]. To actually make the system flow, an additional stress is exerted, and the resulting flow rate then depends on both the amount of agitation and the stress [38, 44, 47, 50]. The idea that both the stress and the amount of agitations determine the flow rate, lies at the basis of numerous models for slowly flowing disordered materials [51–54].

A well-known method to agitate a granular system is by using vibrations. Experiments where the role of vibrations were studied include: *(i)* an experiment where the maximum angle of a stable granular slope was found to decrease with the amount of vibrations [41, 55], *(ii)* an experiment where granular flow on an inclined plane was induced using vibrations [39, 40], and *(iii)* a study that reported how grains flow out of a silo more easily when vibrated [56].

In many experiments it is found that even a tiny amount of agitations significantly weakens the system. This is caused by the fact that the force chains in the packing can already be disturbed by a small displacement of a particle [6]. This was for instance shown in experiments where piezo crystals are used to induce tiny rearrangements in the material [43, 57, 58]. Similarly, a system can also be weakened using tiny shear-induced agitations [59].

Once a system is flowing, it is agitated by the flow itself, even *far away* from the flowing region [38, 44, 60–63]. Agitations therefore play a crucial role in non-local granular rheology models [37, 64–67]. They may even, among other things, explain the large extension of shear bands in split-bottom granular flows [68–70].

Chapter 2-5 of this thesis will be devoted to experiments where we shear a weakly vibrated granular packing. Even though we use a low peak acceleration for the vibrations, and always stay below 1 g, we find that the vibrations significantly influence the flow properties of the system.

1.4 This Thesis

This thesis starts with an introduction to the flow of weakly vibrated granular media in chapter 2, which describes the results found in prior work using the same experimental setup [13, 71]. In chapter 3, we study to which extent the frictional description of granular materials is still valid in the case of weak vibrations. We do this by altering the pressure, which affects the frictional contacts. When the acceleration approaches 1 g, we find that the system loses its pressure dependence and behaves more like a liquid. In chapter 4, we focus on the transition between slow flows - which are enabled by the vibrations - and fast inertial flows. For a certain amount of vibrations, the regimes of slow and fast flow start to merge. We investigate the resemblance between this point and a second-order critical point, and investigate the scaling of several flow properties with the distance to the potential granular critical point. In chapter 5, we show the presence and importance of anisotropy, which is built into the system when it is sheared in a certain direction. We find that the anisotropy varies with flow rate and vibration intensity, where the anisotropy is directly related to the required shear stress.

In chapter 6, we change focus and look at the flow of rod-shaped anisotropic particles (without vibrations). We find that the fact that the particles now have an orientation, causes a strong convection, which results in a heap of particles that arises from the surface of the packing.