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Ambivalent role of fine particles on the stability of a humid granular pile in a rotating drum

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ABSTRACT

We have studied the influence of fine particles on the stability of a granular medium in a rotating drum. The stability diagram of this system was established as a function of the drum rotation speed, fine particle content and relative humidity. Four regimes were observed. At low fine content, an avalanching regime is encountered at low rotation rate, and a continuous flow regime at high rotation rate. At high fine content, a stick–slip regime at the drum wall is seen at low rotation rate and a continuous sliding regime at high rotation rate. The influence of fines is ambivalent. At low fine content, they fluidize the pile and decrease its stability, by granular lubrication. At high fine content, they solidify the pile and increase its stability, by jamming the grain assembly. The enhancement of humidity increases the stability for high fine content, but has no effect for low fine content.

1. Introduction

Granular matter is one of the most complicated materials, as it can present either gaseous, liquid and solid behaviors. Its mechanical properties have been studied by various methods: inclined plane, tilted box, rotating drum, etc. Among these configurations, the rotating drum is commonly used in laboratory experiments and also in the industry for processing granular matter [1]. Indeed, in the simple configuration of a rotating cylinder, several processes can be performed: mixing, drying, segregation or chemical reactions.

The stability of a dry or humid granular pile in a rotating drum has been extensively studied, revealing the richness of the granular motion inside the cylinder. By varying the rotation velocity, different regimes of the bed behavior are observed: slipping, slumping, rolling, cascading, cataracting and centrifuging. Among them, slumping and rolling are usually used in industry for material mixing [2]. At low rotation velocity, the granular pile is lifted as a solid body pursuing the rotating drum, the surface angle θ of the pile increases until a maximum angle of stability, the "upper repose angle", named θ_m, is reached, then the granular pile destabilizes at its surface and particles on top start to roll downhill as an avalanche. When the slope of the pile reaches a minimum angle of stability, the "lower repose angle", called θ_r, the avalanche stops, and so on until another avalanche occurs. This regime is defined as the slumping or discrete avalanche regime. The subsequent rolling regime occurs when the rotation velocity is increased. In this case, the cycle duration is shorter than the avalanche duration. Thereby the grains at the surface continuously roll, keeping the surface angle constant.

A lot of researches have studied the granular bed behavior in the slumping and rolling regimes. However most of these studies are performed with a monodisperse granular matter, while in industrial processes the granular material is usually bidisperse or even polydisperse. Moreover even a so-called monodisperse granular medium can contain a certain quantity of small particles due to the wear of the grains, especially in the grinding process [3]. The presence of such "dust" particles of very small sizes is one of the origins of the phenomenon of re-agglomeration and caking of particles [4,5]. Up to now, it has hardly been studied in experimental researches.

By adding a small quantity of fine particles to a monodisperse granular pile and measuring the maximum stability angle of this pile in a rotating drum with a controlled relative humidity, we have shown recently that the influence of the fines on the pile stability is ambivalent [6]. We detail here the experiments leading to this result and show how, at low fine content, the small particles play the role of granular lubricant and make the heap more unstable, and at higher content, they block the inner motions inside the heap and solidify it. These results enable to make a link between independent and inconsistent observations, that had not been compared until now, showing that fine particles in one well-defined system may either play a fluidizing or a jamming role, depending on their percentage.

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2. Experiments

2.1. Experimental setup

The experimental setup is illustrated in Fig. 1, based on a device used in previous studies [4]. The granular material is introduced in a stainless steel drum of 10 cm radius and width, rotating around its horizontal axis at a fixed speed controlled by a synchronous electric motor (AKM23D AN CNAA, Kollmorgen). The rotation speed of the cylinder can be varied from 0.0001 to 500 rpm. In this study only slow rotation speeds were used. The cylinder is enclosed by two glass windows with a hole at their center for air exchange with the outside atmosphere. The drum is partially filled with a fixed quantity of 200 g of glass beads, with a filling ratio of 30%. The glass beads used in this study are soda–lime glass beads (BV250) of diameter $(250 \pm 50)\mu$m (Sigmund Lindner). The surface of the glass beads has been observed by atomic force microscopy (AFM) and scanning electron microscopy (SEM), showing a small roughness of the surface, typically 500 nm (Fig. 2). Fine glass beads (BF10) of diameter $(5 \pm 4)\mu$m of the same material are added in the granular pile as fine particles. The density of the soda–lime glass is 2.50 kg/L and the bulk density of the bed of large particles is 1.46 kg/L (manufacturer data).

Usual bidisperse granular mixtures are known to segregate. Therefore we have sampled the mixture at the top and bottom of the heap at the end of some experiments and we have observed by optical microscopy that the fine particles' content was uniform. This absence of segregation finds an explanation in the characteristic distribution of the fine particles among the large ones (see Section 4.1 and Fig. 13).

The experimental setup is placed in a sealed poly(methyl methacrylate) box. Both relative humidity and temperature are controlled in the experiments. The temperature in the box is controlled with a heating resistor regulated by a temperature controller, and is fixed at 29.0 °C. A large flat beaker of saturated aqueous inorganic salt solution is placed in the box to maintain a constant value of relative humidity during the experiments. Four different salts are used in our experiments. Table 1 shows the theoretical value of the relative humidity in the atmosphere in the presence of the saline solutions at 25 °C. The relative humidity H is measured by a hygrometer with an accuracy of 1.5%. As the experiments are carried out at 29 °C, and a slight discrepancy may exist between the expected and real values of the relative humidity, only measured values are used thereafter. A fan is placed inside the box to ensure homogeneous temperature and humidity.

The granular pile is illuminated from the front through the glass windows to improve the surface detection (Fig. 3). A digital video camera placed in front of the drum is used to continuously record the behavior of the granular medium. The angle of the surface of the pile with the horizontal is automatically calculated from the captured images. The uncertainty in the angle measurements is typically $\pm$ 0.5°.

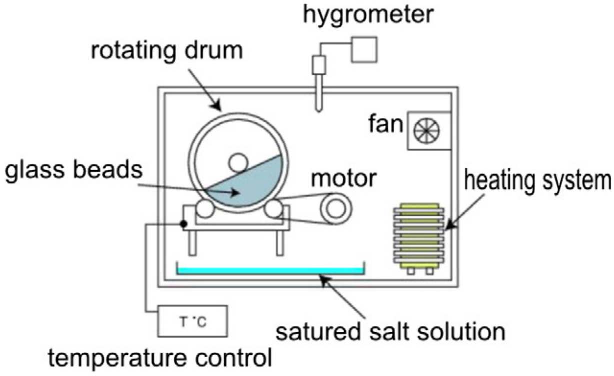

Fig. 1. Experimental setup.

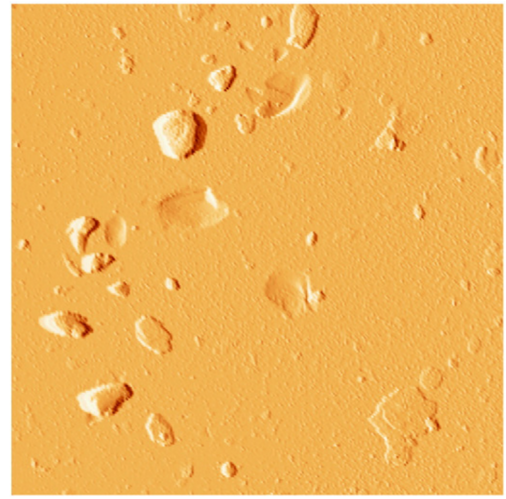

Fig. 2. AFM observation of the large glass bead surface (error signal). The picture size is $15 \times 15 \mu m^2$.

2.2. Procedure

1. A 200 g mixture of coarse and small beads is mixed in a vessel by hand.
2. The mixture is introduced in the drum in rotation at relatively low speed (1 rpm) for 24 h in the desired environment to homogenize the atmosphere throughout the granular pile.
3. Rotation at 5 rpm during 30 s provides an initial reference state of the pile.
4. Rotation at the desired speed n during a few cycles is used as “pre-measurement”. It permits to determine the flowing regime of the granular medium. If the regime is avalanching or stick–slip (see below), it gives an indication of the maximum and minimum angles of stability θ_m and θ_r of the granular pile. Fig. 4 shows an example of pre-measurement in the avalanche regime. If the regime is continuous flowing or sliding (see below), it gives an indication of the dynamic repose angle. The reference angle θ_{ref} is determined as the angle 0.5° smaller than the maximum angle or dynamic repose angle.
5. The drum rotates at the same rotation speed n, and the evolution of the surface angle of the granular pile θ is recorded versus time. For each turn, a 3 s stop, which corresponds to the waiting time t_w, is effected at $\theta = \theta_{ref}$. Then the rotation continues in the same direction at the same speed until an avalanche occurs. The avalanche angle θ_m and repose angle θ_r are recorded (Fig. 4).
6. The last step is repeated 100 times and the values of the avalanche angle θ_m and repose angle θ_r are determined from the average value of the 100 measurements performed by automatic image analysis.

The most important experimental quantities in this procedure are the waiting angle θ_{ref} and waiting time t_w. Indeed previous studies have shown that the stability of the heap firmly depends on these two values. This influence is a consequence of the fact that the cohesion of the heap partly stems from the slow condensation of capillary bridges between the beads [4]. So the maximum stability angle is observed to

Table 1
Relative humidity provided by saturated salt solutions at fixed temperature.

Salt	Theoretical relative humidity at 25 °C
Lithium bromide (LiBr)	6%
Potassium acetate (KCH3CO2)	23%
Potassium carbonate (K2CO3)	43%
Sodium bromide (NaBr)	58%