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Precursors and triggering mechanisms of granular avalanches

Précurseurs et mécanismes de déclenchement d'avalanches granulaires

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A B S T R A C T

The dynamics of inclined granular packings driven towards their stability limits are studied experimentally using imaging techniques as well as acoustic methods. The former allow one to study grain rearrangements during the tilting. The implementation of both passive and active acoustic methods for probing the granular packings, with capabilities for time-resolved measurements, provides information on various elastic properties of the layers along the destabilization process, including the transient precursors. Systematic experiments of granular layer destabilization for various granular media and external conditions are compared and allow one to better understand the mechanisms responsible for the appearance, periodicity, and intensity of precursors.

R É S U M É

La dynamique des empilements granulaires inclinés jusqu'à leur limite de stabilité peut être étudiée à l'aide d'expériences utilisant des techniques d'imagerie ou des méthodes acoustiques. Les premières permettent l'étude des réarrangements de grains pendant l'inclinaison. L'implémentation de méthodes acoustiques passives et actives pour le sondage d'empilements granulaires en temps réel permet d'estimer la variation des propriétés élastiques au cours du processus de déstabilisation, incluant le régime des précurseurs. Des expériences systématiques de déstabilisation de couches granulaires pour divers milieux granulaires et conditions extérieures sont comparées et permettent une meilleure compréhension des mécanismes responsables de l'apparition, de la périodicité et de l'intensité des précurseurs.

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1. Introduction

The existence of the unjamming transition plays a large part in the interest in granular materials. The latter are jammed at rest and can sustain some load, but if a threshold shear stress is exceeded, part of the material starts to flow. In response to some change in external applied forces, the macroscopic activity of a granular system is related to the evolving geometry of its contact network and to the nature of the contacts. It leads to complex behaviors of great interest for industrial and natural processes. In nature, geological processes like landslides or rock avalanches involve an unjamming transition of granular media. Other natural events like earthquakes are often seen as interacting elements that discharge collectively when they reach a trigger threshold [1,2]. The corresponding models are closely related to avalanches models.

For free surface flows of granular systems under the action of gravity, the unjamming transition above a critical shear stress is evidenced by the existence of an angle of maximum stability of a pile: θ_M. It is the angle at which the flow starts; the angle of the pile relaxes then towards the smaller angle of repose. Many studies have been devoted to these angles, but most of them focus on the succession of avalanches in a rotating drum [3–5], or on a continuously fed pile [6–8]. In both cases, the heap is built by successive avalanches, giving a specific contact network geometry to the bulk. An alternative method for investigating avalanche dynamics is to incline gently an undisturbed granular bed in the gravity field.

The exploration of the dynamical response of an inclined granular packing before the avalanche starts is of the greatest interest, as it allows a study of the dynamical transition from a static packing to a flowing one and brings information that may be helpful for the prediction of the occurrence of the avalanche. Obviously, the capability of predicting the probability of occurrence is an important motivation for this area of research.

2. Avalanche precursors

Freshly prepared piles filling a box were used to study the rearrangements at the surface before the first avalanche [9–11]. First, small rearrangements implying only a few grains are detected. The size and the rate of these rearrangements increase with the inclination angle. At some stage, large-amplitude and quasi-periodical events are observed (Fig. 3b). These events, called precursors, consist of collective motions of grains. A correlation between the pseudo-period of the precursors and the number of layers gives some clues that these precursors are not only superficial events.

More recent results [12] confirmed that the precursors are bulk phenomena and allowed to interpret these events as reorganizations of the weak-contact sub-network occurring in the packing. This is in agreement with computer simulations of inclined 2D packings [13,14] that revealed the occurrence of intermittent rearrangements of grain contacts in the bulk. However, beyond the observation of experimental and numerical evidence of the existence of precursors to avalanches, these regular events have never been explained theoretically.

This oscillating behavior is reminiscent of stick-slips originating from the difference between static and dynamic frictions in frictional system submitted to an increasing load at a small rate. By the way, seismic processes are sometimes modeled by arrays of sliders connected by springs (Burridge–Knopoff model [15]). Moreover, granular assemblies sheared between planes also exhibit a stick-slip behavior [16] and have been used to model fault gouges. Regular precursors are observed before the onset of frictional motion, and in the mechanical response of amorphous media as metallic glasses and granular materials, before the rupture (see [17] and references herein). More generally, physical systems responding through abrupt events to slowly increasing stresses are rather abundant; earthquakes have already been held up; plastic bursts in crystals are another example [18]. They often can be seen as the depinning of an interface under an external field. Within the waiting intervals between the fast, abrupt events, a slow restructuring of the pinning field can occur; stresses may be relaxed through competing processes, such smooth responses can have effects on the abrupt events properties. These slow processes may be important for intermittency. As proposed in [18], whenever avalanches compete with slow coexisting processes to minimize the local internal stress, the dynamics give rise to a self-organized avalanche oscillator.

3. Investigating the behavior of granular avalanche precursors

Beside the numerical simulations of 2D and 3D [19] inclined granular packings, various experimental methods have been used to expose the secrets of these strange happenings: direct observation of the surface or the side of the box with a camera [20,21,10], X-ray imaging technique [22], interferometric technique based on diffusive wave spectroscopy [17], and acoustic methods.

Optical measurements give access to grain motion and allow one to measure the precursor pseudo-period. Many parameters influence those quantities [21,17,19,23]: the material characteristics of the grains themselves (shape, surface features, size distribution...), environmental parameters (humidity, vibrations, triggering...), length, width, and height of the packing. Most of these parameters affect the contacts between grains, their capacity to influence the precursors is not surprising. In the same way, the preparation of the packing plays an important role [22,24,20], sometimes neglected by authors who get results seemingly paradoxical. It should never be forgotten that it is the force network which is submitted to strong modifications during the loading. Those modifications are the substance of the precursors, the preludes of the destabilization of the system. In such a context, the acoustic methods of detection, which are directly sensitive to force network restructuring, provide a particularly adapted tool of study.