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# Robust experimental study of avalanche precursory events based on reproducible cycles of grain packing destabilizations

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**Abstract.** Displacements of collective grains at the free surface of a tilted grain packing constitute precursory events preceding a granular avalanche. Laboratory experiments commonly performed by slowly tilting sphere packings from  $0^\circ$  to the avalanche angle ( $\theta_A$ ) are difficult to reproduce and the number of events is too small to assess robust statistical analyses of the precursor activity. To go beyond this limitation, we have developed a specific experimental setup which allows continuously tilting the packing with successive oscillation cycles between  $\theta_C < \theta_A$  and  $-\theta_C$ . We use a high resolution optical camera and process the images of the packing free surface to identify precursory events during many consecutive cycles of a single packing. The analysis deals with the mean angle of the first event ( $\theta_F$ ) and the mean angle between two consecutive events ( $\theta_I$ ). We show a good reproducibility in the event occurrence associated to a large number of events. We analyze the effect of the  $\theta_C$  parameter. The approach is very promising to highlight the effects of external parameters, including humidity, packing container geometry.

## 1 Introduction

Understanding the triggering and mechanism of granular flows is a great subject of interest in many domains. For instance, in pharmaceutical and agricultural domains, grains can be stored, piled or displaced; in natural domains, snow avalanches or giant landslides require prediction and prevention to prevent from dramatic events. At smaller scales, laboratory experiments on glass beads piles are performed to study gravity destabilization of the packing based on measuring the weight at the outlet of the packing container [1] or the fluctuations of the superficial beads by optical [2–4] or acoustical [3, 5, 6] methods. The avalanche triggering of a sphere packing depends on many parameters, including humidity [7] and container dimensions [6, 8, 9], assuming a quasi-static behavior. The quasi-static regime is satisfied if the inclination process allows the non displacement of the grains except when local shear forces have reached a critical value linked to the Coulomb’s friction law.

Displacements of collective grains at the free surface of a tilted grain packing constitute precursory events preceding the granular avalanche. In order to predict such abrupt critical events, a better understanding of the precursor activity is commonly assessed by slowly tilting sphere packings from the horizontal to the maximum stability angle associated to the avalanche  $\theta_A$ . But the destabilization activity also depends on the packing fabrication which make the experiment not perfectly reproducible.

By the use of an optical camera and a digital imaging technique, Bretz et al. [10] were the first to reproduce and observe the destabilization of the pile, characterized by rearrangements of the grains located at the surface: they put in evidence that the rearrangement distribution follows a power law as a function of the bead diameter. They have highlighted two kinds of events located before the avalanche: (i) small rearrangements that occur at low tilt angles with a power law size distribution followed by (ii) the so-called precursors that appear quasi periodically, for glass beads packings, when  $\theta \gtrsim 15^\circ$  with a non power law size distribution.

Nerone et al. [8, 11] have shown that the size of the rearrangements increases with the tilt angle for freshly prepared piles filling a box and that quasi-periodical large events can be observed few degrees before the first maximum stability angle. Indeed, the processes of pile stability are controlled by several physical factors, as described previously such as the size of the system (height [12], length [3] width [13–16]), the density or volume compaction of the packing [3, 12, 17–19] and the tilting regime [9, 20, 21].

All these first previous experiments [2, 8, 12, 18] and more recent studies [3, 4, 6, 22] dedicated to the identification of the precursors have been performed in simple environmental conditions of temperature, humidity and container dimensions and by direct tilting experiments up to the maximal stability angle.

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## 2 Description of the reproducible cycle experiments

### 2.1 Sphere packing fabrication

Kiesgen de Richter et al. [23] have stated that the packing and the activity of the packing depend strongly on the history of the system. Information on that past history, and in particular the packing fabrication, is stored in the initial network of physical contacts between the grains. If the packing container is randomly filled with a large number of spheres, identical packings are very unlikely. In order to reduce their differences and achieve the so-called "same history" of a packing fabrication [24], we define a four-steps protocol of the packing fabrication and prepare each sphere packing accordingly.

In the first step, a grid with a square mesh of 1 cm is positioned at the bottom of a rectangular container which the height is  $H_b=185$  mm. The dimensions of the box are adjustable by considering different lengths ( $L_b=240, 440, 640$  or  $1000$  mm) and widths ( $W_b=150, 200$  or  $300$  mm). In the present study, the dimensions are fixed to  $L_b=440$  mm and  $W_b=200$  mm.

In the second step, we fill the container with monodisperse glass beads with a diameter  $D = 2$  mm. In this case, the number of grain layers is about 90 which is high enough to avoid any influence on the maximal stability angle of the packing, the well-known wall effect in granular packings [25]. Note that this number is much larger than the limit of 10 layers observed by Aguirre et al. [18] and 40 according to Oger et al. [26].

In the third step of the sphere packing fabrication, we slowly pull out the grid, an operation which results in a nearly loose packing and reduces packing fraction fluctuations inside the packing. The packing fraction, defined as the ratio between the volume of sphere material with the volume of the whole packing, ranges between 0.55 (loose packing) and 0.64 (random close packing) and characterizes the sphere packing fabrication.

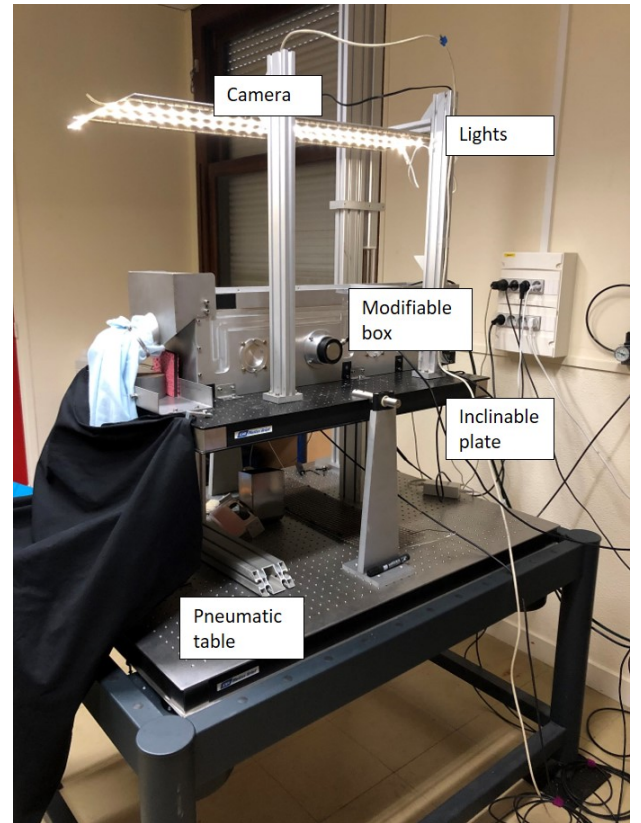
In the fourth step, we flatten the free granular surface of the packing by pushing horizontally a rigid metallic bar along the  $L_b$  direction. This operation, commonly used in similar experiments [23], may compact the superficial layer of grains and result in a "scrapped surface" of the packing.

### 2.2 Successive tilting cycles principles

Preliminary developments of an automatic tilting experimental setup have been designed to introduce original results in characterizing precursory events and avalanches of granular piles [6, 9, 27]. For the present work, this experimental setup has been significantly improved to reduce artifacts, including mechanical vibrations and electrostatic effects between the glass beads, to consider different sizes of the packing container, to synchronize several physical measurements not discussed here, and to perform cycling inclinations of the packing (Fig. 1).

The packing container is an aluminum rectangular box, which rotation is ensured by two horizontal axes made of

Teflon, perpendicular to the  $W_b$  direction and located at the center of the  $L_b$  length of the box. Filled with glass beads, the sphere packing is balanced and can be tilted by the use of a linear actuator to a maximum angle of  $30^\circ$  at a speed  $V_i$  in the range  $1.7 - 14^\circ/mn$  controlled by a LabVIEW™ program. In the present work, the experiments have been performed at the minimum inclination speed. The tilt angle is recorded by the acquisition program through an analogical/digital USB card. The sphere packing is positioned on an optical table, managed by four pneumatic attenuators and mounted on damping pads in order to reduce external vibrations that may modify the dynamics of the packing.



**Figure 1.** Photography of the full setup showing the adjustable metallic box sitting on the inclinable plate managed on two horizontal axis fixed on a pneumatic table. Camera is positioned between the LED bands and are sitting both on top of an horizontal plate coupled with the inclinable plate supporting the container.

The experimental setup allows performing a complete cycle  $c$  composed of four angle ranges: from  $0^\circ$  to  $\theta_C$  (first quarter-cycle  $Q_c^1$ ), from  $\theta_C$  to  $0^\circ$  (second quarter-cycle  $Q_c^2$ , reverse of  $Q_c^1$ ), from  $0^\circ$  to  $-\theta_C$  (third quarter-cycle  $Q_c^3$ ) and from  $-\theta_C$  to  $0^\circ$  (fourth quarter-cycle  $Q_c^4$ , reverse of  $Q_c^3$ ). The first quarter-cycle of the first cycle, noted  $Q_S$ , corresponds to the angle range considered in many classical avalanche experiments. A multi-cycle experiment is defined by a number  $N$  of successive cycles and a maximum tilt angle  $\theta_C$  lower than the avalanche angle  $\theta_A$ . The first cycle starts with  $Q_c^1=Q_S$  and the last cycle ends with  $Q_N^4=Q_E$  where the angle increases from  $0^\circ$  up to  $\theta_A$ .

### 3 Measurement of the precursor activity

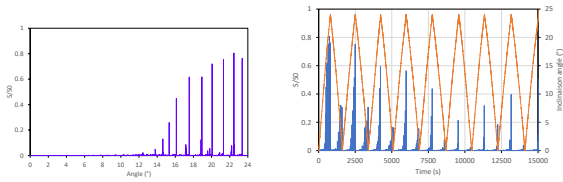
#### 3.1 Optical detection of the precursory events

During the experiment, an optical camera takes one image of the free granular surface per second with a resolution of  $2448 \times 2050 \text{ pixels}$  on 8 bits gray level. This total surface is defined as  $S_0$ . Positioned  $1 \text{ m}$  above the sphere packing with an aperture speed of  $1/15000 \text{ s}$ , the camera allows imaging a surface  $S_0 = 230 \text{ mm} \times 230 \text{ mm}$  of the center of the granular surface and a sphere covers about 20 pixels. The LabVIEW™ program used to control the multi-cycles is also used for the image acquisition which is thus synchronized with the tilt angle measurements as a function of the recording time.

Four stripes of LEDs illuminate the packing free surface in order to produce sphere shadows. Changes in the shadows surface between two consecutive images is used to detect the sphere displacements: an ImageJ [28] script, initially developed by Kiesgen et al. [3], consists in comparing two consecutive images by subtracting, thresholding to remove the noise and then quantifying the surface  $S$  of the displaced sphere shadows as a function of the tilt angle. Based on the ratio  $S/S_0$ , the detection of a precursory event is similar to the approach used in previous studies [3, 6–8] and corresponds to an activity  $S/S_0$  close to unity, which means that a precursor is a sudden displacement of nearly all the superficial spheres of the packing.

#### 3.2 First quarter-cycle precursor activity: $0^\circ$ to $\theta_C$

Most of the published works on sphere packing precursory events consists in slowly tilting the packing from the horizontal to the avalanche angle  $\theta_A > \theta_C$ . Similarly, we have performed a first quarter-cycle experiment from  $0^\circ$  to  $\theta_C = 20^\circ$  on a glass bead packing prepared according to the protocol detailed in Section 2.1. The image processing allows detecting 5 main peaks of activity with  $S/S_0 \approx 1$  associated to precursory events during the first quarter-cycle  $Q_S$  (Fig. 2, left).



**Figure 2.** (left) First quarter-cycle ( $Q_S$ ) precursor activity,  $S/S_0$ , measured by slowly tilting a 2 mm glass bead packing from  $0^\circ$  to  $24^\circ$ . (right) 9 half cycles made with  $Q_c^1$  and  $Q_c^2$  with  $\theta_C$  equals also to  $24^\circ$

In Oger et al. [7], we have characterized the dynamic of the precursor activity with the number  $N_C$  of precursory events related to the cycle angle  $\theta_C$ , the angle of the first event  $\theta_F$  and the step angle  $\Delta\theta$  between two consecutive events. Note that, due to the noise in the image processing, the definition of the first event may be unclear,

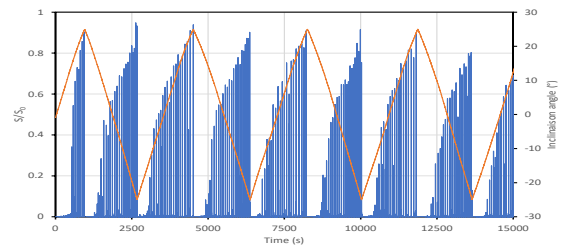
associated to uncertainties in  $N_C$  and  $\theta_F$ . In the present case study, the precursory activity of the sphere packing is characterized by  $N_C = 5$  during the first quarter-cycle,  $\theta_F \approx 13^\circ$  and  $\Delta\theta \approx 2^\circ$ . But these parameters fluctuate when the experiment is performed with other sphere packings and many experiments are required for statistic analyses in order to increase the total number  $N_t$  of detected precursory events and to get more representative statistical results. This approach has strong limitations when aiming at using the parameters to quantify the effects of external conditions (humidity, temperature, inclination speed, maximum angle  $\theta_C$ , etc.) on the precursor activity by considering different initial sphere packings because changes in the precursor activity may also be attributed to the initial state of the sphere packing.

To avoid this uncertainty, the sphere packing should not be changed and, aiming at increasing the total number  $N_t$  of precursors, the first quarter-cycle has to be reproduced. Using our improved experimental setup, we are able to perform such an experiment which consists in series of 9 successive  $Q_c^1$  and  $Q_c^2$  quarter-cycles in the positive angle range measured as a function of the acquisition time (Fig. 2, right). The first inclination  $Q_c^1$  corresponds to  $Q_S$  (see details in Fig. 2, left): the reverse inclination  $Q_c^2$  shows that, in this quarter-cycle, the internal packing structure is not reorganized enough to allow some local then global force chains redistribution. When we repeat the measurements (half cycles), the precursory activity clearly decreases with the cycle number and as a result, the number of precursory events remains limited.

### 4 Robust statistics based on multi-cycle precursor activity

#### 4.1 Reproducibility of the precursor activity

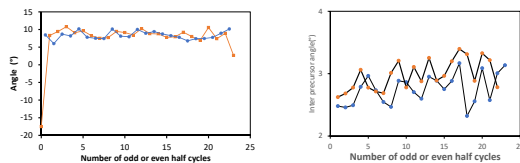
Our experimental setup allows titling the sphere packing not only from  $0^\circ$  to  $\theta_C$  and reverse ( $Q_c^1$  and  $Q_c^2$  quarter-cycles, respectively) but also to the negative angles  $-\theta_C$  ( $Q_c^3$  and  $Q_c^4$  quarter-cycles). Thus, we are able to perform series of full cycles, a multi-cycle experiment with  $N = 4$  full cycles and a maximum angle  $\theta_C = 25^\circ$  in Fig. 3.



**Figure 3.** Multi-cycle precursor activity  $S/S_0$  in blue lines and the red line represents the inclination angle  $\theta$  measured by slowly tilting a 2 mm glass bead packing in the range  $\pm\theta_C = 24^\circ$  identical as in Fig. 2.

The precursor activity of the first quarter-cycles  $Q_C^1$  and  $Q_C^2$  are similar to the previous experiment (Fig. 2) but, in the case of a multi-cycle experiment, it remains stable during the cycles and can start at an angle much before the  $\theta_F$  first event angle: as a result, the total number  $N_t$  of precursory events can very high. Interestingly, the results show a good reproducibility of the precursor activity after the quarter-cycle  $Q_S$ : one full-cycle is required to get a representative sphere packing behavior.

## 4.2 Statistical analyses



**Figure 4.** Evolution of the first events  $\theta_F$  (left) and the precursor intervals (right) versus the number of the cycles up to 23 oscillations.

Figure 4 demonstrates that, after the first full cycle, we can observe a good reproducibility of the precursor measurements such as  $\theta_F$  and  $\Delta\theta$ . This crucial conclusion will allow us to make good statistics and also reproducible experiments even with more uncertainly initial packing fabrication.

## 5 Discussion and conclusion

As concluded previously, we have now a perfect tool to measure the small perturbations which can occur when we are changing some mechanical parameters such as humidity rate, friction coefficient or other classical parameters of grain packings.

## References

- [1] M.A. Aguirre, N. Nerone, I. Ippolito, A. Calvo, D. Bideau, *Granular Matter* **3**, 75 (2001)
- [2] N. Nerone, M. Aguirre, A. Calvo, D. Bideau, I. Ippolito, *Phys. Rev. E* **67**, 011302 (2003)
- [3] S. Kiesgen de Richter, G. Le Caër, R. Delannay, *Journal of Statistical Mechanics: Theory and Experiment* **2012**, p04013 (2012)
- [4] M. Duranteau, Ph.D. thesis, Université Rennes 1 (2013)
- [5] V.Y. Zaitsev, P. Richard, R. Delannay, V. Tournat, V.E. Gusev, *EPL (Europhysics Letters)* **83**, 64003 (2008)
- [6] M. Duranteau, V. Tournat, V. Zaitsev, R. Delannay, P. Richard, *Identification of avalanche precursors by acoustic probing in the bulk of tilted granular layers*, in *Powders and Grains 2013: Proceedings of the 7th International Conference on Micromechanics of Granular Media* (AIP, 2013), Vol. 1542, pp. 650–653
- [7] L. Oger, C. El Tannoury, R. Delannay, Y. Le Gonidec, I. Ippolito, Y.L. Roht, I. Gómez-Arriaran, *Physical Review E* **101**, 022902 (2020)
- [8] N. Nerone, M. Aguirre, A. Calvo, I. Ippolito, D. Bideau, *Physica A* **283**, 218 (2000)
- [9] R. Delannay, M. Duranteau, V. Tournat, *Comptes Rendus Physique* **16**, 45 (2015)
- [10] M. Bretz, J.B. Cunningham, P.L. Kurczynski, F. Nori, *Physical Review Letters* **69**, 2431 (1992)
- [11] N. Nerone, S. Gabbanelli, *Granular Matter* **3**, 117 (2001)
- [12] M. Aguirre, N. Nerone, A. Calvo, I. Ippolito, D. Bideau, *Granular Matter* **3**, 75 (2001)
- [13] P. Boltenhagen, *The European Physical Journal B* **12**, 75 (1999)
- [14] S.C. du Pont, P. Gondret, . Perrin, M. Rabaud, *Europhysics Letters (EPL)* **61**, 492 (2003)
- [15] W. Bi, R. Delannay, P. Richard, N. Taberlet, A. Valance, *Journal of Physics: Condensed Matter* **17**, S2457 (2005)
- [16] J. Métayer, Ph.D. thesis, Université de Rennes I (2008)
- [17] P. Evesque, D. Fargeix, P. Habib, M.P. Luong, P. Porion, *J. Phys. I France* **2**, 1271 (1992)
- [18] M.A. Aguirre, N. Nerone, A. Calvo, I. Ippolito, D. Bideau, *Physical Review E* **62**, 738 (2000)
- [19] N. Gravish, D.I. Goldman, *Physical Review E* **90**, 032202 (2014)
- [20] A. Kabla, G. Debrégeas, J.M. di Meglio, T.J. Senden, *Europhysics Letters (EPL)* **71**, 932 (2005)
- [21] A. Jarray, V. Magnanimo, S. Luding, *Powder Technology* **341**, 126 (2019)
- [22] V. Gibiat, E. Plaza, P. De Guibert, *The journal of the Acoustical Society of America* **123**, 3142 (2008)
- [23] S. Kiesgen de Richter, V.Y. Zaitsev, P. Richard, R. Delannay, G. Le Caër, V. Tournat, *Journal of Statistical Mechanics: Theory and Experiment* **2010**, P11023 (2010)
- [24] D. Bideau, E. Guyon, L. Oger, in *Disorder and Fracture*, edited by J.C. Charmet, S. Roux, E. Guyon (Springer US, 1990), Vol. 204, pp. 255–268, nato asi series (series b: physics) edn., ISBN 13:978-0-306-43576-8
- [25] L. Oger, J.P. Troadec, D. Bideau, J.A. Dodds, M.J. Powell, *Powder Technol.* **46**, 121 (1986)
- [26] O. L., D. R, Y. Le Gonidec, p. to be submitted (2020)
- [27] S. Kiesgen de Richter, phdthesis, Université de Rennes1 (2009), thèse de doctorat dirigée par Delannay, R. et Le Caer, G., Physique Rennes 1 2009, <http://www.theses.fr/2009REN1S070>
- [28] W. Rasband, *Imagej*, U. S. National Institutes of Health, Bethesda, Maryland, USA, <http://imagej.nih.gov>, 1997-2018, <http://imagej.nih.gov>