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# Memory of the Unjamming Transition during Cyclic Tiltings of a Granular Pile

Deboeuf S.<sup>1</sup>, Dauchot O.<sup>2</sup>, Staron L.<sup>3</sup>, Vilotte J.-P.<sup>1</sup>, Mangeney A.<sup>1</sup>

<sup>1</sup>*Institut de Physique du Globe de Paris, Paris, FR*

<sup>2</sup>*Service de Physique de l'État Condensé, CEA, Saclay, FR*

<sup>3</sup>*Department of Applied Mathematics and Theoretical Physics, Cambridge, UK*

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Discrete numerical simulations are performed to study the evolution of the micro-structure of a granular packing during successive load-unload cycles, consisting of quasi-static rotations in the gravity field between opposite inclination angles. We show that both dynamic and structural quantities exhibit hysteresis during these cycles due to the exploration of different metastable states. Interestingly, the hysteretic behaviour of the pile strongly depends on the maximal inclination of the cycles, giving evidence of the irreversible modifications of the pile state occurring close to the unjamming transition. More specifically, we show that for cycles with maximal inclination larger than the repose angle, the weak contact network carries the memory of the unjamming transition. These results demonstrate the relevance of a two-phases description -strong and weak contact networks- for a granular system, as soon as it has approached the unjamming transition.

## I. INTRODUCTION

The discrete nature of granular materials makes their evolutions very complex. In response to an external driving force, the macroscopic behaviour of a granular system is determined by the intimate interplay between the evolving disordered micro-structure, *i.e.*, the arrangement of the grains and the geometry of their contact network, and the frictional interactions at the contacts, that allow for non trivial force transmissions [1, 2, 3]. Even though significant advances have been made in the last decade [4, 5, 6, 7], the underlying question of a physically-based identification of the relevant internal variables and of their evolution laws remains open [8, 9].

A particular issue of recent works on granular media concerns the transition from/to a rigid solid-like state to/from a flowing fluid-like state, due to its broad interest in geological and industrial processes and in particular to its challenge for condensed matter physics. This transition, *e.g.*, the signature of the development of a yield stress or flow threshold in a disordered granular system, or of an infinite relaxation time compared to the actual experimental time-scale, has recently generated a flurry of activity [10, 11, 12, 13]. Even though dense granular materials are athermal, it has recently been proposed that the transition could be seen as a “unjamming/jamming transition” at zero temperature [11, 14, 15], motivated by remarkable analogies between granular and glassy systems at both macroscopic and microscopic scales [16, 17, 18, 19].

In this picture, the granular system is driven out of equilibrium under quasi-static external driving force, introducing fluctuations, as the system explores different packing configurations or metastable states, that could be related to an “effective temperature” [20, 21]. Important non equilibrium effects of structurally disordered granular systems, beside the slow relaxation to equilibrium [12, 22, 23], are: bistability and hysteresis [24, 25, 26] as the result of a memory effect due to the internal history dependence of systems out of equilibrium

and the lack of an unique metastable state [2]; and a jerky response to the external driving force with impulse-like events (local rearrangements of grains or avalanches), as the result of the exploration of local minimal energy configurations, *i.e.*, metastable states [27, 28]. A related important question is whether a diverging length-scale exists on the jammed side of the transition [29].

The well known observation of different characteristic angles of the stability of granular systems results from such memory effects. When dense granular piles are inclined in the gravity field, there exists a maximal angle of stability, or avalanche angle  $\theta_a$  at which the pile starts inevitably to flow, and an angle of repose  $\theta_r < \theta_a$ , defined as the slope angle at which the system comes back to rest. In the range  $[\theta_r, \theta_a]$ , the system exhibits a bistable behaviour where it can be in a jammed -rigid- or an unjammed -flowing- state. In that region, the jammed state of the granular pile is conditionally stable, *e.g.*, an avalanche can be triggered by perturbations of finite amplitude [30, 31]. Under rotation in the gravity field, the pile undergoes therefore a subcritical transition.

In [27, 32, 33], the unjamming transition of a 2D cohesionless granular bed slowly tilted towards the avalanche angle  $\theta_a$  was numerically investigated. This transition is characterized by a jerky response to the smooth rotation of the principal stress direction with respect to the packing, as attested by the occurrence of local rearrangements of grains. An analysis of the local stresses reveals the existence of a significant population of overloaded grains, carrying a shear stress ratio larger than the critical threshold of the packing at the unjamming transition. This allows to define a coarse-graining length scale, or “correlation length”, which increases with the rotation up to an angle identified to  $\theta_r$ , where it jumps to a length-scale comparable with the thickness of the granular bed. This jump can be mapped onto a percolation transition of the overloaded grains, and coincides with the onset of a packing dilation, indicating coherent shearing prior to the unjamming transition. Further insights in the domain  $[\theta_r, \theta_a]$  were achieved when analysing the highly

frictional contacts, *e.g.*, the critical contacts where the friction is fully mobilized. Indeed the critical contacts are at incipient slip and likely give rise to local rearrangements of grains. A “correlation length”, based on the multi-scale analysis of the critical contacts, exhibits a power-law type divergence with an onset that coincides with  $\theta_r$ . These highly frictional contacts tend to be associated with the weak contact network, as defined in [34], suggesting a two-phases system and a second-order phase transition. The emergence of long “correlation lengths” within the range  $[\theta_r, \theta_a]$ , both in the stress and the friction states, is consistent with experimental measurements of both the amplitude of the local perturbation required to trigger an avalanche and the increasing scale of the response to a local perturbation, close to the unjamming transition [22, 31]. This suggests that a peculiar regime exists before the unjamming transition, namely in the range  $[\theta_r, \theta_a]$ , where the accumulation of friction forces and resulting local rearrangements of grains leads to a coherent shearing and enhances the structural disorder in the packing [35].

Such modifications of the micro-structure of granular systems within the range  $[\theta_r, \theta_a]$  at the unjamming transition should have a signature on non equilibrium effects, such as the system hysteresis during cyclic solicitations. In contrast to cyclic shear solicitations [17, 23, 36, 37], we focus here - in the continuation of [27, 32, 33] - on quasi-static cyclic rotations of dense cohesionless granular systems under gravity. Depending on the amplitude of the cyclic solicitations, the granular system can approach the unjamming transition. The internal history dependence or hysteresis can therefore be investigated depending on how far from equilibrium the system has been driven, *i.e.*, on the distance from the unjamming transition. We report here results of numerical experiments, based on the contact dynamics method, of quasi-static cyclic solicitations applied to a 2D cohesionless granular bed. These results show that the hysteresis does depend on the amplitude of the cycles, and exhibit specific memory effects when the system approaches the unjamming transition, as a result of the structural evolution. In particular the hysteresis is analysed in terms of both strong and weak contact network contributions to the global response. It is found that the weak contact network carries most of the signature of the memory effects, confirming the relevance of a two-phases description for the unjamming transition, and extending it to the quasi-static rheology, as soon as the granular system has approached the transition.

The paper is organized as follows. The numerical procedure and details of the numerical experiments are presented in section II. The section III focuses on critical contacts: after discussing previous results during monotonic external loading, we investigate the evolution of the critical contacts during relaxation and cyclic solicitations. In section IV the hysteresis of the granular system is analysed with respect to the amplitude of the cycles. Then the respective contributions of the weak and strong

contact networks to the hysteresis of the packing are investigated in section V. The paper ends with a discussion of the results in section VI.

## II. NUMERICAL PROCEDURES

Discrete simulations of granular media take into account the individual existence of each grain constituting the system. The behaviour of the collection of grains is entirely driven by the usual equations of motion and the contact laws ruling the interactions between the grains. The contact dynamics method, applied for this work, deals directly with infinitely stiff contact laws, assuming that grains interact through hard-core repulsion and non-smooth Coulomb friction only [38]. This implies that the contact force between two grains is non-zero only if the latter are touching. Once a contact is created between two grains, the latter cannot get closer, so that any normal relative motion is only repulsive: the grains are perfectly rigid and cohesionless. The Coulomb friction law consists of an inequality between the tangential and normal forces at contact, referred to as  $T$  and  $N$  respectively:  $\mp\mu N \leq T \leq \pm\mu N$ , where  $\mu$  is the microscopic coefficient of friction, and sets a threshold for a contact to slip. Accordingly, this controls the friction dissipation at the contact scale in the case  $T = \pm\mu N$  when tangential slip motion is possible according to the immediate environment of the contact, by contrast with the case  $\mp\mu N < T < \pm\mu N$  and no slip motion is allowed. In the present work, we are interested in the quasi-static evolution of the packing and concentrate on micro-plastic rearrangements only, therefore we consider purely dissipative collisions, and set the coefficient of restitution to zero.

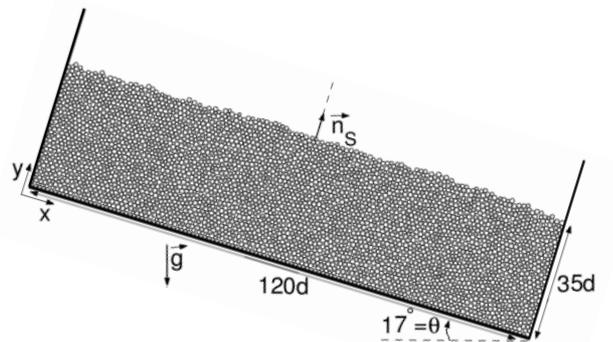


FIG. 1: A typical simulated granular pile of 4000 disks whose diameters are polydispersed at 40%, inclined at an angle  $\theta = 17^\circ$  in the gravity field  $\vec{g}$  with the  $xy$ -frame linked to the bottom of the box and the unity vector normal to the free surface  $\vec{n}_s$ .

The performed simulations are bi-dimensional. We consider packings of 4000 circular grains randomly de-

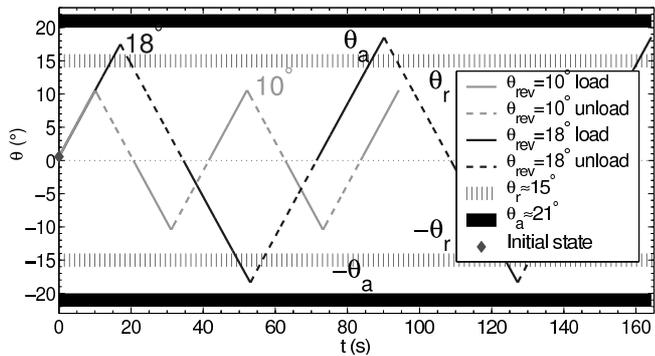


FIG. 2: Temporal plot of the surface slope  $\theta(t)$  of the granular pile during the load-unload solicitations for  $\theta_{rev} = 10^\circ$  (in gray) and  $\theta_{rev} = 18^\circ$  (in black). The horizontal lines, with a thickness equal to the size of the fluctuations among 50 realizations, correspond to the repose and avalanche angles  $\theta_r$  and  $\theta_a$ . The initial state of the pile just before the cycles start is represented by a diamond.

posited in a rectangular box. The grains diameters are uniformly distributed in the interval  $[d_{min}; d_{max}]$  with  $d_{max}/d_{min} = 1.5$ . The polydispersity, measured as  $(d_{max} - d_{min})/d \approx 40\%$  with  $d$  the mean disk diameter, prevents long-range crystal-like ordering in the packing by enhancing structural disorder. Each granular bed shows a nearly flat surface parallel to the bottom of the box, with a slope  $\theta$  with respect to the horizontal direction; its thickness is  $\approx 35d$ , and its length is  $\approx 120d$ . The granular packings have an initial solid fraction  $\rho_S \simeq 0.785$  and an initial coordination number  $Z \simeq 3.46$ . Figure 1 shows a typical granular pile inclined in the gravity field  $\vec{g}$  at an angle  $\theta = 17^\circ$ , with the  $xy$ -frame linked to the bottom of the box and the unity vector normal to the free surface  $\vec{n}_S$ . The microscopic coefficient of friction ( $\mu = 0.5$ ) is the same between all the grains and between the grains and the walls of the box.

The cyclic solicitations consist of rotations at a constant rate ( $\pm 0.001^\circ$  per time step) in the gravity field, the rotation being positive when clockwise. A positive rotation is first applied to newly generated granular piles so that the slope of the free surface increases from  $\theta = 0^\circ$  to a maximal inclination angle  $\theta_{rev}$  set by the experimentalist, corresponding to a load stage. After the inclination  $\theta_{rev}$  is reached, the direction of rotation is reversed, and the slope decreases back to  $0^\circ$ , corresponding to an unload stage. Rotation is maintained so that the slope of the pile evolves from 0 towards the opposite maximal inclination angle  $-\theta_{rev}$ . The direction of rotation is again reversed, and the cyclic solicitation is resumed. Two successive cycles are performed. This solicitation was applied on 50 granular piles differing in the initial disordered micro-structure, *i.e.*, the grains arrangement and the contact network geometry, and showing characteristic angles  $\theta_r \simeq 15^\circ$  and  $\theta_a \simeq 21^\circ$ . In the following when not specified, averages are taken over all 50 simulations. The granular beds, and the data describing the

first positive rotation, are the actual data of Staron *et al.* [32].

We study the influence of the load cycle amplitude and of the distance from the unjamming transition on the evolution of the pile state by considering two values of the maximal inclination angle  $\theta_{rev}$ , namely by applying small and large cycles. The smallest value of  $\theta_{rev}$  is chosen so that the small cycle keeps the pile out of the coherent shear regime identified prior to the unjamming transition:  $\theta_{rev} = 10^\circ < \theta_r$ . On the contrary, the largest value of  $\theta_{rev}$  is chosen in the range of slopes  $[\theta_r; \theta_a]$ , but below the minimal avalanche angle observed among the 50 realizations to prevent the pile from avalanching:  $\theta_{rev} = 18^\circ \in [\theta_r; \theta_a]$ . These two kinds of cycles are represented in Figure 2, where the slope of the pile  $\theta$  is plotted against the time  $t$  for both small (in gray) and large (in black) cycles. Continuous lines represent load stages, and dashed lines represent unload ones. The horizontal lines indicate the repose and avalanche angles  $\theta_r$  and  $\theta_a$ , with a thickness equal to the size of the fluctuations. A diamond indicates the initial state of the granular pile just before the cycles start, that will be reported on all the next figures.

### III. CRITICAL CONTACTS CLUSTERING

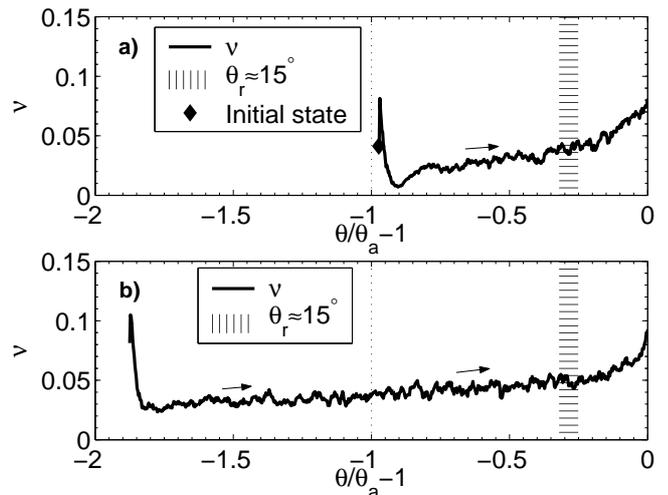


FIG. 3: Density of critical contacts  $\nu$  averaged over 50 simulations (a) during the first load starting from  $\theta \simeq 0^\circ$  and (b) during one large cycle, starting from a pile inclined at  $-\theta_{rev} = -18^\circ$ , when varying the slope inclination towards the avalanche angle.

As discussed in the case of slow monotonic external loading of a granular slope in [27, 32, 33], the coherent shear regime identified prior to the unjamming transition corresponds to the structuration in the packing of highly frictional contacts, *e.g.*, contacts where forces have reached the Coulomb friction threshold, *i.e.*,  $T = \pm\mu N$ , referred to as critical contacts. An interest-

ing issue would be the evolution of the critical contacts during cyclic solicitations.

We discuss first the robustness of previous results on critical contacts [27, 33] against the pile preparation. Figure 3 displays the evolution of the density of critical contacts  $\nu$ , defined as the proportion of critical contacts to the total number of contacts in a granular packing, averaged over 50 piles, when varying the pile inclination  $\theta$  towards  $\theta_a$ , from  $0^\circ$  (a) and from  $-\theta_{rev} = -18^\circ$  (b). At the beginning of the solicitation, both evolutions of  $\nu$  show a sudden drop to a minimum value indicating the instantaneous loss of critical contacts. After this first stage and in spite of the different initial conditions, the behaviour of the critical contacts when approaching the unjamming transition is approximately the same:  $\nu$  increases up to a maximal value  $\nu_c \approx 8\%$ .

The loss of critical contacts occurring at the transition from load to unload in Figure 3b) [39], indicates that the frictional state of the packing related to past solicitations is immediately modified. This could be related to the end of coherent shearing [23].

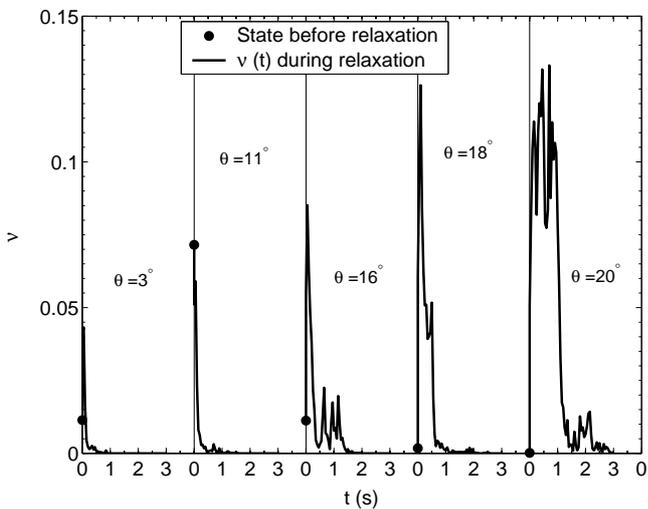


FIG. 4: Relaxation of the density of critical contacts  $\nu$  as a function of time in 5 granular piles inclined at different angles ( $\theta = 3^\circ, 11^\circ, 16^\circ, 18^\circ, 20^\circ$ ) after the rotation was stopped at  $t = 0$ . The state of the pile just before the relaxation starts is represented by a circle.

We now observe the relaxation to a static packing in terms of critical contacts by suddenly stopping the rotation. Figure 4 shows the evolution of  $\nu$  as a function of time after the rotation was stopped at  $t = 0$  in 5 granular piles inclined at different angles ( $\theta = 3^\circ, 11^\circ, 16^\circ, 18^\circ, 20^\circ$ ). The state of the piles before the relaxation starts is represented by a circle. Whatever the density of critical contacts and the inclination when the packing starts to relax,  $\nu$  vanishes after a complex transient dynamics. The time needed for critical contacts to relax is larger for slopes close to  $\theta_a$ : this confirms the complex relaxation towards equilibrium of a granular packing [12, 22, 23], and this is consistent with observa-

tions of long-range correlations close to the unjamming transition [22, 27, 30, 31, 32]. The relaxation of the critical contacts for rigorous static conditions implies that  $\nu$  is expected to vanish asymptotically when the rotation rate tends to zero. In this sense, the density of critical contacts is not an internal variable, but a dynamic response function.

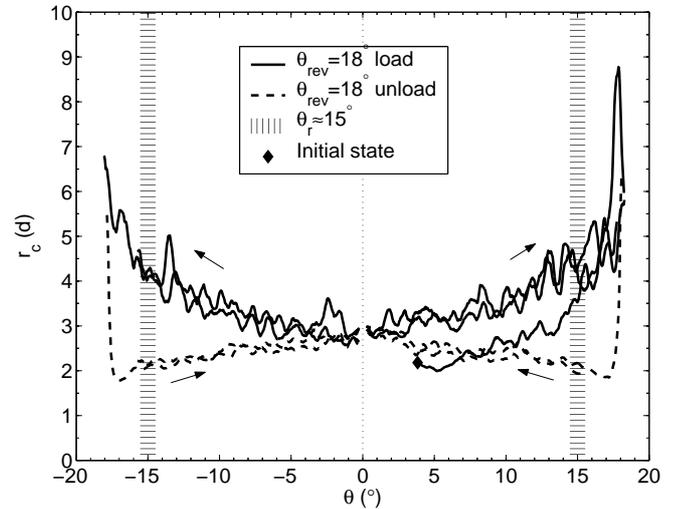


FIG. 5: Size of the correlated clusters of critical contacts  $r_c$ , slide-averaged over  $1^\circ$ -intervals as a function of the slope angle  $\theta$  during the successive cyclic solicitations for  $\theta_{rev} = 18^\circ$ .

Signature of the loss of critical contacts at the transition from load to unload is also visible in the evolution of the “correlation length”  $r_c$ , defined as the mean size of clusters such that locally  $\nu = \nu_c$ . Figure 5 displays the evolution of  $r_c$  as a function of the pile slope during load and unload process for  $\theta_{rev} = 18^\circ$ . During each load stage,  $r_c$  increases sharply above  $\theta_r$  and is expected to reach the size of the pile at the unjamming transition, as shown in the case of monotonic external loading [27]. Upon reversal of the solicitation, *i.e.*, for  $\theta = \pm\theta_{rev} = \pm 18^\circ$ ,  $r_c$  immediately reduces to a few grain diameters. There is no more evidence of correlation within the granular pile in terms of critical contacts, when the rotation sense is reversed, indicating the end of coherent shearing. Note that after the first load,  $r_c$  shows the same cyclic evolution, indicating the same behaviour of critical contacts during the two successive cycles, especially when approaching the unjamming transition. The reduction of frictional mobilization at the transition from load to unload, induces a strong hysteresis in both the evolution of  $\nu$  and  $r_c$  during load and unload cycles. Is this hysteresis apparent on other global characteristics of the granular pile?

The critical contacts play a significant role when approaching the unjamming transition. Accordingly one may wonder whether the response of the pile is altered by the hysteretic evolution of critical contacts observed in the range of slopes  $[\theta_r; \theta_a]$ . Also one would like to know whether the possible effect of the observed hysteresis is

localized in the domain  $[\theta_r; \theta_a]$  or conditions the response of the pile along the full cycle of solicitation. In the following, we investigate the hysteretic response of the pile to cyclic solicitations and the effect on this response of having approached the unjamming transition. To do so, we consider two different amplitudes of load-unload cycles, namely two values of the reversal angle  $\theta_{rev}$ , and we compare the response of the granular pile in terms of stress, strain and evolution of the contact network for  $\theta_{rev} = 10^\circ$  and  $\theta_{rev} = 18^\circ$ .

#### IV. HYSTERETIC PHENOMENA DURING LOAD AND UNLOAD SOLICITATIONS

While the granular pile is cyclically tilted in the gravity field, the induced stresses as well as the resulting deformations are investigated. We start with the comparison of the global stress state during load and unload stages.

##### A. Stress state of the granular pile

During the cycles of both amplitudes, the maximal value of the shear to confinement ratio, as defined in [13]:  $I_{max} \approx 10^{-5}$ , shows that the evolution of the packing is actually quasi-static. As a result, static stresses transmitted via contacts are much larger than kinematic ones due to momentum transport during collisions, so that the stress tensor of the granular pile  $\sigma$  in the  $xy$ -frame is evaluated as follows from [40]:

$$\sigma_{ij} = \frac{1}{n^c} \sum_{\alpha=1}^{n^c} f_i^\alpha l_j^\alpha, \quad (1)$$

where  $i$  and  $j$  denote the space dimensions and  $\alpha$  the contact.  $\vec{f}$  is the contact force,  $\vec{l}$  is the vector normal to the contact surface, and  $n^c$  is the total number of contacts. The tangential and the normal stresses  $\sigma_T$  and  $\sigma_N$  along the direction of the free surface are calculated:

$$\sigma_N = \| (\sigma \vec{n}_S) \vec{n}_S \|, \quad (2)$$

$$\sigma_T = \| \sigma \vec{n}_S - \sigma_N \vec{n}_S \|, \quad (3)$$

where  $\vec{n}_S$  is the unity vector normal to the free surface, from which the shear stress ratio  $\sigma_T/\sigma_N$  is evaluated. The direction of the eigenvector of  $\sigma$  corresponding to the largest eigenvalue is the principal stress direction, whose angle with the direction normal to the free surface is  $\Psi$ . The principal stress direction corresponds to the direction where stress is purely compressive.

Figure 6 a) displays the shear stress ratio  $\sigma_T/\sigma_N$  and Figure 6 b) the evolution of the principal stress direction  $\Psi$  during small ( $\theta_{rev} = 10^\circ$ ) and large ( $\theta_{rev} = 18^\circ$ ) load-unload cycles. Both  $\sigma_T/\sigma_N$  and  $\Psi$  exhibit hysteretic evolutions related to irreversible modifications of the force transmissions at contacts, but the hysteresis loops are of rather small amplitude and independent of  $\theta_{rev}$ .

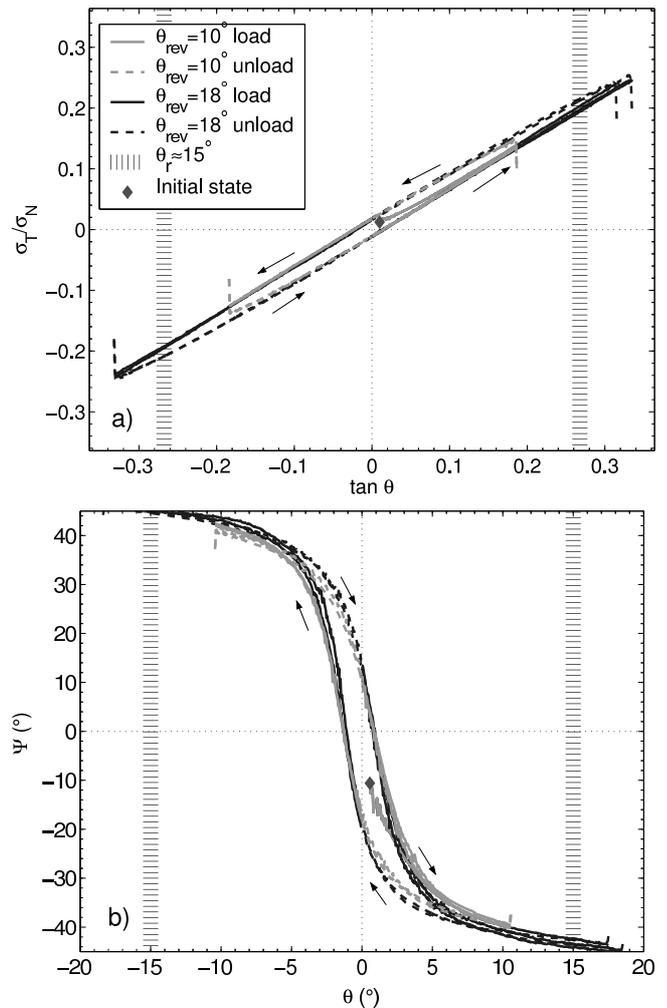


FIG. 6: (a): Shear stress ratio  $\sigma_T/\sigma_N$  and (b): principal stress direction  $\Psi$  as a function of the pile slope  $\theta$  during cyclic rotations for small ( $\theta_{rev} = 10^\circ$ ) and large ( $\theta_{rev} = 18^\circ$ ) amplitudes. The vertical lines correspond to the value of  $-\theta_r$  and  $\theta_r$ . The initial state is represented by a diamond.

During the first load,  $\sigma_T/\sigma_N \simeq a \tan(\theta)$  in agreement with the predictions of continuous media mechanics for an infinite slope inclined in the gravity field at static equilibrium, except that  $a$  is not exactly equal to one:  $a = 0.8$ . It can be shown that this difference is to be attributed to finite size and walls effects [32]. During the following cycles,  $\sigma_T/\sigma_N \simeq a \tan(\theta) + \epsilon(\sigma_T/\sigma_N)_{res}$ , where  $\epsilon = -1$  (resp.  $\epsilon = +1$ ) during load (resp. unload) and  $a = 0.8$ . A residual stress ratio  $(\sigma_T/\sigma_N)_{res}$  of the order of 5% of the typical shear stress ratio is recorded for  $\theta \simeq 0^\circ$ . The principal stress direction  $\Psi$  tends to  $\pm 45^\circ$  for large inclinations, exhibiting a rather smooth evolution. Note that for hydrostatic equilibrium, *i.e.*, equal normal stresses:  $\sigma_{xx} = \sigma_{yy}$ , it is expected that  $\Psi = -45^\circ$  (resp.  $\Psi = +45^\circ$ ) for  $\theta > 0$  (resp.  $\theta < 0$ ).

The stress state evolution of the granular pile is plotted on the above figures for the two successive cycles: the plots perfectly collapse after the first load. In the

following, the two successive cycles are reported on all the figures.

Altogether both the shear stress ratio  $\sigma_T/\sigma_N$  and the principal stress direction  $\Psi$  depend only on the sense of rotation as evidenced by the weak hysteresis, but not on the solicitations path or the history of past cycles.

### B. Deformation of the granular pile

The exploration of different metastable configurations results in the apparition of critical contacts in the packing, that induces local rearrangements of grains. The effect of these rearrangements is apparent when plotting the variations of the volumic strain  $\epsilon_V = (V - V_0)/V_0$ , where  $V$  is the volume of the pile and  $V_0$  its initial volume, as a function of the slope of the pile during successive small and large cycles (Figure 7).

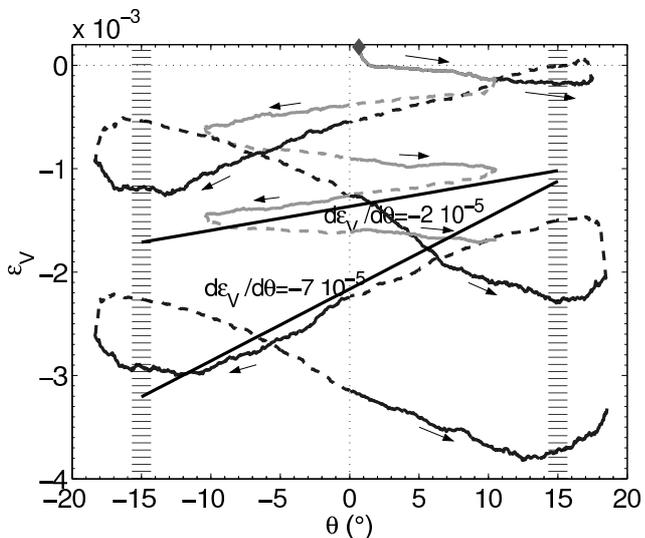


FIG. 7: Volumic strain  $\epsilon_V$  as a function of the pile slope during small and large cycles (same symbols as figure 6). The two lines are indications of the compaction rate  $d\epsilon_V/d\theta$  for  $\theta_{rev} = 10^\circ$  and  $\theta_{rev} = 18^\circ$ .

Irrespective of the value of  $\theta_{rev}$ , cycles produce an overall densification of the pile of the order of  $10^{-3}$ , corresponding to a slight increase of the solid fraction  $\rho_S$  from 0.785 to 0.79. Obviously, the small number of cycles experienced in the present work does not allow to observe a saturation of the volume and eventually a critical state [9, 41]. It is known that in similar cyclic solicitations [39], as well as in other experimental set-ups [10, 42], even after a large number of cycles ( $10^4$  cycles), the volume still slowly decreases.

For slopes  $\theta \lesssim \theta_r$ , the granular pile is contracting:  $\epsilon_V$  decreases. On the contrary, for slopes in the range  $[\theta_r; \theta_a]$ , the rearrangements cause the granular pile to become dilatant:  $\epsilon_V$  increases both during load and unload. As a result, for small cycles ( $\theta_{rev} = 10^\circ$ ) the granular pile remains contractant, whereas for large cycles

( $\theta_{rev} = 18^\circ$ ), the granular pile exhibits compaction and dilation stages. This latter behaviour is typical when shearing dense granular media because deformation is possible only if grains mistrap, confirming the onset of a coherent shearing above  $\theta_r$ .

Interestingly, the dilation stage, occurring when  $\theta \in [\theta_r; \theta_a]$ , changes the overall behaviour of the pile, and this over the complete solicitation. The compaction is twice more efficient for large cycles than for small ones, showing that densification depends on the solicitation path [43]. This leads us to speculate that grains are much more allowed to rearrange when the pile has previously evolved in the coherent shear regime identified prior to the unjamming transition.

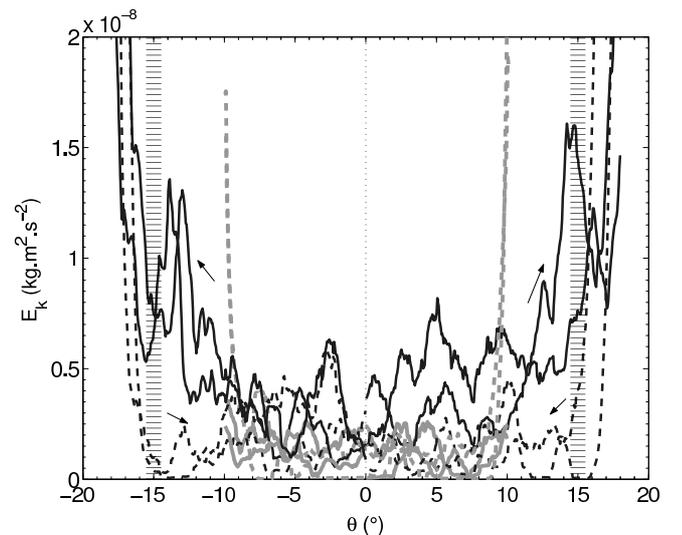


FIG. 8: Kinetic energy  $E_k$  averaged over all the grains and slide-averaged over  $1^\circ$ -intervals as a function of the inclination angle  $\theta$  for  $\theta_{rev} = 10^\circ$  and  $\theta_{rev} = 18^\circ$  (same symbols as figure 6).

This largest susceptibility for grains to rearrange in the case of large cycles ( $\theta_{rev} = 18^\circ$ ), when the pile has approached the unjamming transition, is also apparent on the amplitude of the local rearrangements. When recording the kinetic energy  $E_k$  averaged over all the grains and slide-averaged over  $1^\circ$ -intervals as a function of the pile slope (Figure 8), one sees that large cycles allow stronger rearrangements both during load and unload. Even for small inclinations  $\theta$ , the kinetic energy involved in the local rearrangements is three times higher when the granular pile has been loaded up above  $\theta_r$ . It is likely related to coherent shearing occurring prior to the unjamming transition.

Exploring the domain  $[\theta_r; \theta_a]$ , allows for stronger rearrangements and larger volumic strains during the full solicitation despite no apparent signature on  $\sigma_T/\sigma_N$ , leading to a more efficient compaction. As a result, the volumic deformation of the granular pile shows a strong dependence on the amplitude of the cycles.

### C. Evolution of the contact network

We now investigate the effect of the deformations on the evolution of the micro-structure, *i.e.*, the geometry of the contact network.

#### 1. Coordinancy of the grains

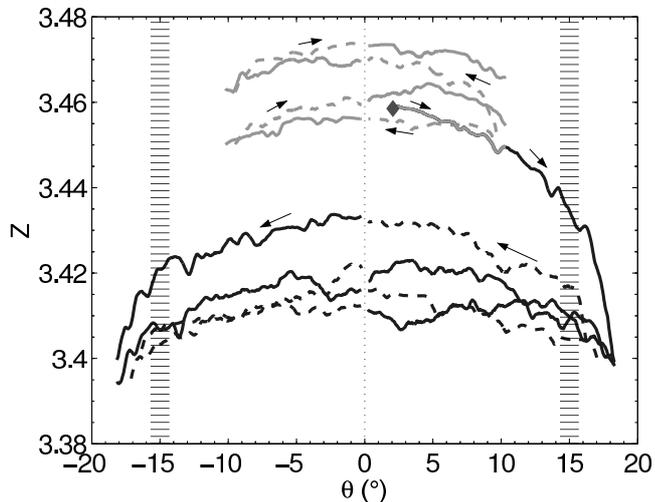


FIG. 9: Coordinancy of the grains  $Z$  slide-averaged over  $1^\circ$ -intervals as a function of the slope of the pile for successive small and large cycles (same symbols as figure 6).

The coordinancy  $Z$ , *i.e.*, the mean number of contacts per grain, slide-averaged over  $1^\circ$ -intervals is plotted in Figure 9 as a function of the pile slope during the cyclic solicitations. For both values of the amplitude  $\theta_{rev}$ , the coordinancy  $Z$  varies less than 1%. Nevertheless, it exhibits a weak hysteresis according to the sense of rotation:  $Z$  tends to decrease during load, but to increase during unload.

Small and large cycles are identified by two different states: the value of the coordinancy depends on  $\theta_{rev}$ . During small cycles ( $\theta_{rev} = 10^\circ$ ),  $Z$  remains approximately at its initial value, by contrast with large cycles ( $\theta_{rev} = 18^\circ$ ), for which a variation of the coordinancy occurs during the first exploration of the domain  $[\theta_r; \theta_a]$ .

Smallest coordinancy observed for  $\theta_{rev} = 18^\circ$  corresponds to densest granular piles, contrary to intuitive observations [44]. Such an anti-correlation between the evolutions of the coordinancy and the volume under an external driving field could be related to the dependence of the packing stability on its number of contacts. An “isostatic” packing has the minimal number of contacts required to remain at metastable equilibrium, by contrast with a “hyperstatic” one, that could loose some contacts and not its stability. In the latter packing, a significant cooperation of contacts is needed for a grain to rearrange. On the contrary, in the former packing, a slight change

in the force transmission at contacts will cause a local rearrangement of grains. In the case of large cycles, the significant decrease of  $Z$  observed during the first load makes the packing become less hyperstatic: grains rearrangements occur easily, enhancing the compaction of the pile. When a packing has approached the unjamming transition, the micro-structure is less frustrated and evolves towards denser or more stable configurations.

#### 2. Fabric of the pile

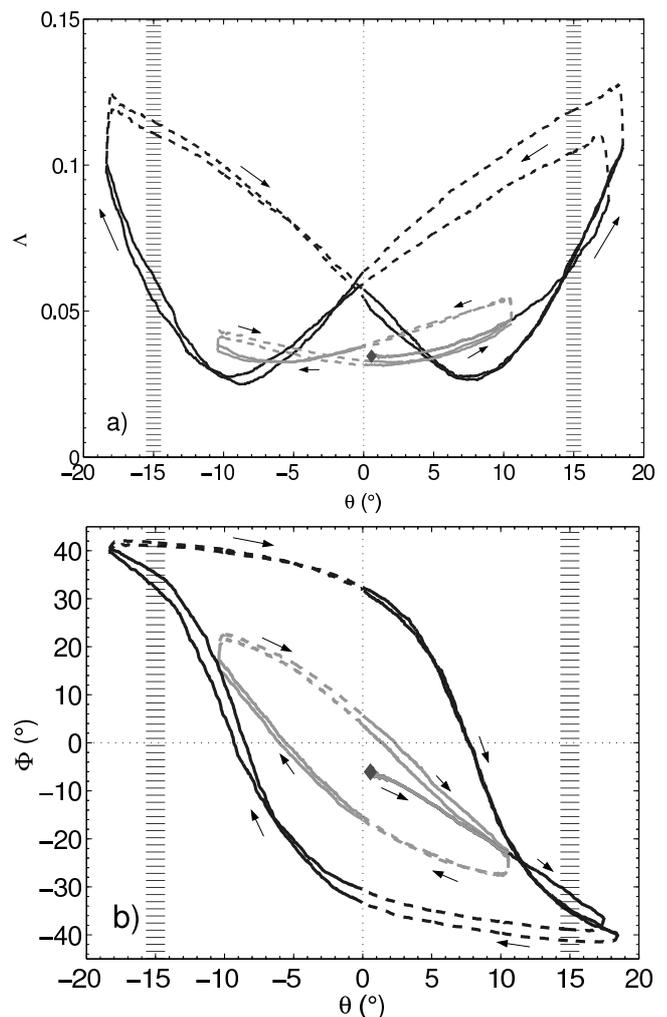


FIG. 10: Anisotropic intensity  $\Lambda$  (a) and anisotropic direction  $\Phi$  of the contact network (b) as a function of the pile slope during the successive cyclic rotations for  $\theta_{rev} = 10^\circ$  and  $\theta_{rev} = 18^\circ$  (same symbols as figure 6).

To further analyse the evolution of the micro-structure of the pile, we now consider the statistics of the orientation of contacts. To do so, the fabric tensor  $\mathbf{t}$  is computed

using the following definition as defined in [45]:

$$t_{ij} = \frac{1}{n^c} \sum_{\alpha=1}^{n^c} n_i^\alpha n_j^\alpha, \quad (4)$$

where  $i$  and  $j$  denote the space dimensions and  $\alpha$  the contact,  $\vec{n}$  is the unity vector normal to the contact surface, and  $n^c$  is the total number of contacts. The fabric allows to investigate the evolution of the geometry of the contact network, especially if contacts are created, opened or modified such that their alignment tends towards a privileged direction. In particular, the anisotropic intensity  $\Lambda$  is calculated as:

$$\Lambda = 2 \times (t_1 - t_2), \quad (5)$$

where  $t_1$  and  $t_2$  are respectively the larger and smaller eigenvalues of  $\mathbf{t}$ . In the case of an isotropic contact network, *e.g.*, spatially periodic, the anisotropic intensity  $\Lambda = 0$ . The direction of the eigenvector of  $\mathbf{t}$  corresponding to the largest eigenvalue is the anisotropic direction, whose angle with the direction normal to the free surface is  $\Phi$ .

Figure 10 a) displays the evolution of the anisotropic intensity  $\Lambda$  as a function of the pile slope during the cyclic solicitations for  $\theta_{rev} = 10^\circ$  and  $\theta_{rev} = 18^\circ$ . During small cycles, a rather isotropic state is observed, and only small variations of  $\Lambda$  with  $\theta$  are observed ( $\Lambda \simeq 0.05$ ): the geometry of the contact network is only weakly affected by the solicitation and remains close to the initial one. On the contrary, for large cycles, the anisotropic intensity evolves significantly showing variations up to the maximum value  $\Lambda \simeq 0.12$ . Approaching the unjamming transition obviously strongly modifies the geometry of the contact network, *e.g.*, by introducing structural anisotropy.

Figure 10 b) displays the evolution of the anisotropic direction  $\Phi$  as a function of the pile slope during the cyclic solicitations for  $\theta_{rev} = 10^\circ$  and  $\theta_{rev} = 18^\circ$ . Irrespective of the value of  $\theta_{rev}$ ,  $\Phi$  evolves during the solicitations and rotates in the sense opposite to the driving rotation:  $\Phi$  decreases (resp. increases) when  $\theta$  increases (resp. decreases). Following this evolution, the anisotropic direction tends to approach that of the free surface and for large inclinations,  $\Phi$  tends towards the principal stress direction  $\Psi = \pm 45^\circ$ . This behaviour corresponds to the mechanisms of creation of contacts in the direction of compressive stress, and the loss of contacts in the direction of extension.

Besides these general observations, the contact network evolution exhibits more complex features. Both for small and large cycles, the fabric exhibits a strongly marked hysteresis, probing the irreversible modifications of the disordered micro-structure. The hysteresis loops of  $\Lambda$  and  $\Phi$  are very smooth. Furthermore when the granular pile approaches the unjamming transition, namely for large cycles ( $\theta_{rev} = 18^\circ$ ), the shape of the hysteresis is dramatically changed, and the loop amplified. This

points out the peculiar effect of coherent shearing occurring prior to the unjamming transition on the granular packing evolution. More particularly, the fabric evolves less rapidly during unload than during load for large cycles ( $\theta_{rev} = 18^\circ$ ). In other words, the packing seems to be less able to reorganize its geometry during unload than during load when having approached the unjamming transition. The same remark applies both to the evolution of the anisotropic intensity  $\Lambda$  and to the anisotropic direction  $\Phi$ . This is rather unexpected given that the efficiency of rearrangements are increased in the case of large cycles, and this during the complete solicitation.

Note that for large amplitudes ( $\theta_{rev} = 18^\circ$ ), the hysteretic cycles of  $\Lambda$  and  $\Phi$  are symmetric, by contrast with small amplitudes ( $\theta_{rev} = 10^\circ$ ), for which an asymmetry related to the initial fabric anisotropy remains. Exploring the range of slopes  $[\theta_r; \theta_a]$  when approaching the unjamming transition allows a profound modification of the contact network according to its initial state, by increasing structural disorder.

Altogether the fabric of the pile (see  $Z$ ,  $\Lambda$  and  $\Phi$ ) at an angle  $\theta$  strongly depends on the solicitation path.

## V. RESPECTIVE ROLE OF STRONG AND WEAK CONTACTS

Dense quasi-static granular media exhibit two contact networks, strong and weak, depending on the intensity of the force transmitted at contacts [34]. In the present work, since a vertical gradient of the contact forces is related to the gravity field, a contact at a depth  $h$  is defined as strong (resp. weak) if it transmits a normal force larger (resp. smaller) than the averaged normal forces at depth  $h$ .

It was shown that during the slow tilting under gravity of a granular pile, critical contacts and more generally high frictional contacts were mainly weak contacts [33]. Other studies have also shown that the strong and weak contacts have different and specific roles in the behaviour of a granular pile depending on the solicitation [32, 34]. This suggests to investigate the respective contributions of these two populations of contacts towards the hysteretic behaviour of the pile. In order to do so, the computation of the stress and fabric tensors are now restricted to strong or to weak contacts using respectively equation (1) or (4).

### A. Strong contact network

Figure 11 displays the principal stress direction in the strong contact network  $\Psi^s$  as a function of the surface slope during small ( $\theta_{rev} = 10^\circ$ ) and large ( $\theta_{rev} = 18^\circ$ ) cycles, that exhibits weak hysteresis as a function of the pile slope. The hysteresis is approximately the same irrespective of the amplitude of the solicitation, as observed

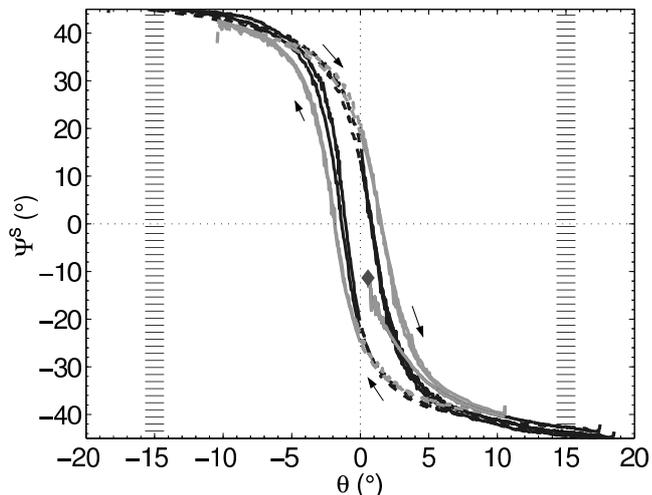


FIG. 11: Principal stress direction in the strong contact network  $\Psi^s$  as a function of the pile slope during the successive load-unload cycles for small and large amplitudes (same symbols as figure 6).

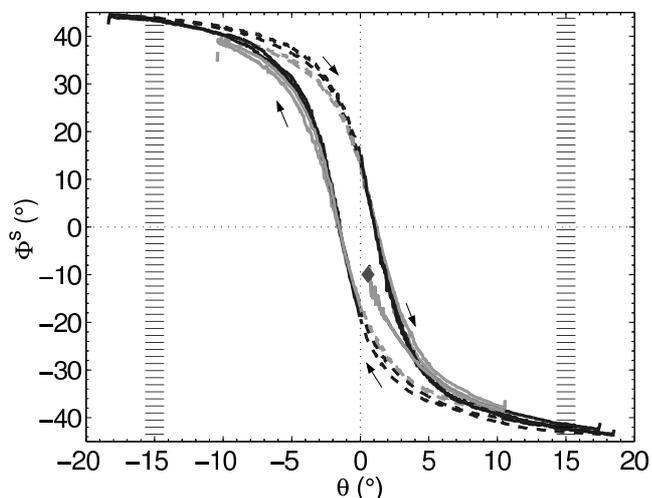


FIG. 12: Anisotropic direction of the strong contact network  $\Phi^s$  as a function of the pile slope during successive load-unload cycles for small and large amplitudes (same symbols as figure 6).

previously for the total contact network (Fig. 6 *b*)). The strong contact network represents by far the largest contribution to the global stress [34]. Accordingly  $\Psi^s$  and  $\Psi$  exhibit very similar behaviours.

The anisotropic direction of the strong contact network  $\Phi^s$  is displayed as a function of the pile slope during the cyclic solicitations in Figure 12. The evolution of  $\Phi^s$  exhibits hysteresis during the cycles of both amplitudes. However, unlike the previous observations on the fabric of the total contact network (Fig. 10 *b*)), the size of the hysteresis loops is small for small ( $\theta_{rev} = 10^\circ$ ) and large ( $\theta_{rev} = 18^\circ$ ) cycles. Note that the evolution of  $\Phi^s$  is very much correlated with the evolution of  $\Psi^s$ , and the shape of the hysteresis loops of both  $\Psi^s$  and  $\Phi^s$  are smooth.

During cyclic solicitations, neither the stress nor the fabric of the strong contact network is sensitive to the amplitude of the cycles.

## B. Weak contact network

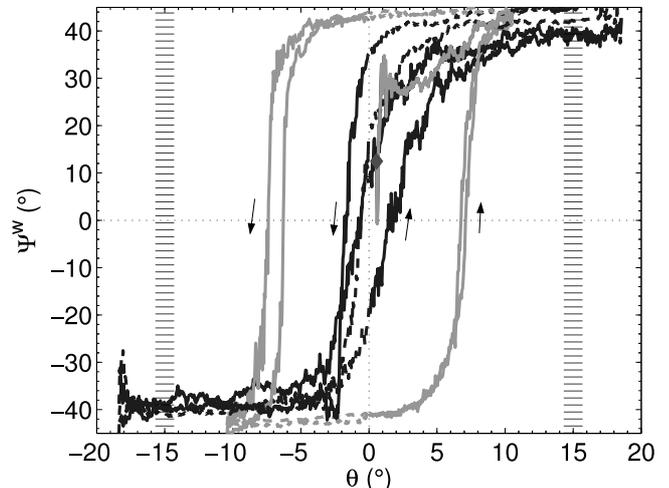


FIG. 13: Principal stress direction in the weak contact network  $\Psi^w$  as a function of the pile slope during the cycles for small and large amplitudes (same symbols as figure 6).

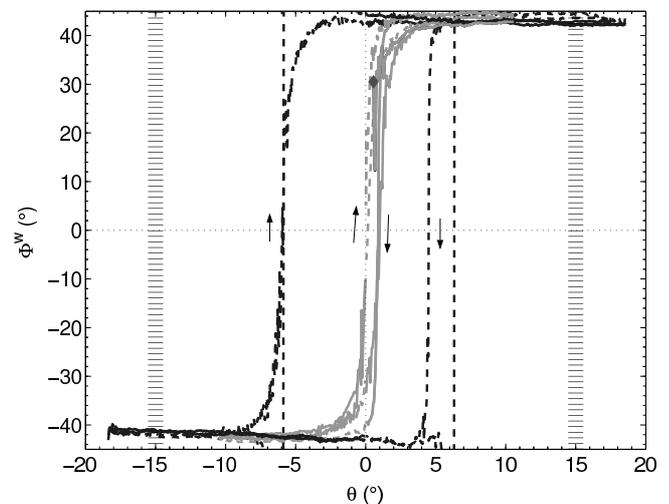


FIG. 14: Anisotropic direction of the weak contact network  $\Phi^w$  as a function of the pile slope  $\theta$  during small and large cycles (same symbols as figure 6).

Figure 13 displays the principal stress direction in the weak contact network  $\Psi^w$  as a function of the surface slope during small ( $\theta_{rev} = 10^\circ$ ) and large ( $\theta_{rev} = 18^\circ$ ) cycles. The evolution of  $\Psi^w$  is strongly influenced by the amplitude of the solicitations. This qualitative change is not reflected by the total contact network response

(Fig. 6 b)) due to the dominant contribution of the strong contact network to the global stress [34].

Figure 14 displays the evolution of the anisotropic direction of the weak contact network  $\Phi^w$  as a function of the pile slope for small ( $\theta_{rev} = 10^\circ$ ) and large ( $\theta_{rev} = 18^\circ$ ) cycles. The response of the weak contact network is again strongly dependent on the cycles amplitude  $\theta_{rev}$ , by contrast with the response of the strong contact network (Fig. 12). For small cycles ( $\theta_{rev} = 10^\circ$ ),  $\Phi^w$  exhibits nearly no hysteresis, and remains approximately always normal to  $\Phi^s$ , as observed in the case of continuous loading [33]. On the contrary, for large cycles ( $\theta_{rev} = 18^\circ$ ), a strong hysteretic behaviour is observed, which consists of a premature rotation of  $\Phi^w$  upon reversal. This effect leads to a remarkable orientation of the fabric of the two contact networks:  $\Phi^w$  and  $\Phi^s$  are equal during a part of the cycle, attesting the temporary alignment of the two contact networks. The particularly early evolution of the weak contact network geometry when the pile has approached the unjamming transition, is actually responsible for the delay observed in the reorganization of the total contact network. As a consequence, upon reversal, the packing keeps the memory of the previous orientation of the total contact network during a large part of the cycle (Fig. 10 b)).

Contrary to the smooth shape of the hysteresis loops in the strong contact network (Fig. 12) and in the total contact network (Fig. 10 b)), the hysteresis loops in the weak contact network (Fig. 14) exhibit an abrupt macroscopic jump. It should also be mentioned that the weak contact network response exhibits large fluctuations from one realization to another one. These fluctuations are strongly enhanced close to the unjamming transition. Evidences of these fluctuations are for instance the noisy signal for  $\Psi^w$  (Fig. 13) and the absence of superposition of the hysteretic loops for  $\Phi^w$  (Fig. 14).

Altogether, in the weak contact network by contrast with the strong one, both stress and fabric are very sensitive to the amplitude of the cyclic solicitations. Two conclusions can be drawn from these observations:

- In the limit of small solicitations, *e.g.*, for cycles with  $\theta_{rev} = 10^\circ$ , the hysteretic behaviour of the granular pile when looking at both stress and fabric state is dominated by the strong contact network contribution;
- For large cycles, namely when the pile approaches the unjamming transition, the weak contact network becomes strongly affected, and the hysteretic behaviour of the pile is strongly modified despite the lack of modification of the response of the strong contact network.

Accordingly the hysteretic behaviour of the pile is the result of a complex interplay between the strong and weak contact networks, whose relative contributions strongly depend on the amplitude of the cycles.

## VI. DISCUSSION AND CONCLUSION

The successive tiltings of the granular pile from different initial conditions up towards the avalanche angle allow to demonstrate that the density and the correlation length of the critical contacts are relevant dynamic response functions to describe the metastable evolution of the packing towards the unjamming transition.

The response of the granular packing to the quasi-static cyclic solicitations reveals that the evolution of the critical contacts is hysteretic when the pile has approached the unjamming transition. At the transition from load to unload, the frictional state of the packing is immediately removed, attesting the end of coherent shearing, as observed in the case of experiments of shear reversal [23, 36].

When looking for such memory effects on other features of the pile, namely on stress, strain and fabric, they exhibit different responses. The stress state exhibits weak hysteretic evolutions as a function of the slope, and the hysteresis reveals to be independent of the amplitude of the cycles. On the contrary, the strain and the fabric evolutions of the pile, related to structural disorder only, are very sensitive to the amplitude of the cycles. These observations will hardly be explained by a simple constitutive law relating stress and fabric of the granular pile: such a relation should be not so trivial, since one could observe two piles characterized by two different granular fabrics, but with the same stress state. This would suggest that forces transmission in a granular pile may evolve even with a weak cooperation of the contact network, and whatever the level of structural disorder.

Further analyses of the strong and weak contacts contributions to the macroscopic behaviour allow to clarify these intriguing observations. In the strong contact network, neither the stress nor the fabric depends on the solicitation amplitude. In the weak contact network, both the stress and the fabric are sensitive to the cycle amplitude. The apparent mismatch between stress and fabric at the scale of the total contact network does not survive when separating weak and strong contact networks contributions. It simply comes from the strong contact network weight in the overall stress. Accordingly, the above analyses stress the relevance of a constitutive law which specifies the two-phases -weak and strong- nature of granular media. In the strong contact network, stress and fabric are very much synchronized, and a rather simple relation between them eventually governs the dynamics. The behaviour of the weak contact network is much more complex. A strong memory of the unjamming transition changes the response of the weak contact network during the full solicitation, probably due to high sensibility of weak contacts to coherent shearing occurring prior the unjamming transition. Finally the observed fluctuations in the weak contact network are presumably related to long-range correlations. These correlations within the pile allow a local rearrangement of grains to further propagate and to affect essentially the weak contacts, due to

their highest friction mobilization, as recently shown in [33]. This high sensibility of the weak contacts to local perturbations enables them to evolve collectively and to change the micro-structure of the packing. A signature of the localization of the correlations in the weak contact network could be seen in the particular shape of the hysteresis loops. Whereas they are very smooth in the total and strong contact networks, the hysteresis loops in the weak contact network exhibit abrupt macroscopic jumps. These delay and instantaneous responses could be related to the relative contribution of structural disorder and finite-size interactions or correlations, as suggested in [46, 47]. In this picture, the hysteresis with a jump in the weak contact network would suggest that the size of correlations is larger than the typical length-scale of the structural disorder in this phase, contrary to the predominant role of disorder in the micro-structure of the packing.

To conclude, the behaviour of the pile is strongly modified close to the unjamming transition, as experimentally

observed [22, 28, 31], and coinciding with important irreversible modifications of the micro-structure. These modifications result from a specific solicitation of weak contacts: these latter play a considerable role in the behaviour of the pile despite their marginal contribution to the stress state. The present paper demonstrates the relevance of a two-phases description, not only for the destabilization process, but also for the quasi-static rheology, as soon as the granular sample has approached the unjamming transition in its past history. Further study will have to investigate the complex behaviour of the weak phase in order to extract a constitutive relation for this phase and how it couples to the rest of the pile.

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