Granular flows triggered by vibration below the avalanche angle are ubiquitous in nature. However, the mechanism of triggering and the nature of the resulting flow are not fully understood. Here we investigate the triggering of the shear instability of granular layers by nanometer-amplitude ultrasound close to the static threshold. We find that such small-amplitude and high-frequency sound waves provoke unjamming, resulting in a self-accelerated inertial flow or a creep-like regime which stops flowing after the removal of ultrasound. We show that these effects are due to the reduction of interparticle friction at grain contacts by the shear acoustic lubrication. Our observations are consistent with the bistability inherent to velocity-weakening friction models [e.g., Jaeger et al., *Europhys. Lett.* **11**, 619 (1990)]. This work should help to understand the local and remote triggering of landslides and earthquakes by seismic waves.

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I. INTRODUCTION

Laboratory studies of the frictional instability in sheared granular media have emerged as a powerful tool for investigating dynamics of seismic faults, landslides, and avalanches [Figs. 1(a) and 1(b)] [1,2]. An important and challenging issue in seismic hazard is to understand the remote dynamics triggering of earthquake by impinging seismic (elastic) waves at microstrain amplitude [3]. Moreover, recent observations showed that perturbations from local foreshocks activities are probably a part of the earthquake nucleation process [2,4] and that large rockfall events and avalanches can be triggered by volcanic seismicity [5]. Indeed, dynamic stress from seismic waves can perturb fault systems that are close to the yield stress, e.g., due to tectonic stresses $\tau \lesssim \tau_t$ [Fig. 1(c)], and force failure earlier in time relative to an unperturbed fault or cliff. Understanding the mechanics of local and remote triggering of landslides will go a long way in quantifying seismic hazard.

Advances in granular physics and acoustics have paved the way for understanding how and under what conditions impinging seismic waves may trigger a fault slip. A granular medium is an assembly of discrete macroscopic solid grains that interact with each other by dissipative contact forces. Unlike ordinary solids and liquids, static and dynamic properties of dense granular media are determined by inhomogeneous contact force networks, exhibiting multiple metastable configurations. Sound waves propagating from grain to grain provide not only a unique probe of such networks (often opaque) [6–9] but also a controlled perturbation via elastic softening and frictional dissipation [10–14]. Granular media undergo a transition from a jammed solid state to a flowing liquid state when the external shear exceeds the static yield stress [15].

Theoretical and experimental studies suggest that this transition is a subcritical bifurcation [16–19] [sketched in Fig. 1(d)], with dynamics similar to solid friction at multicontact interfaces [20] [insets of Figs. 1(a) and 1(b)] well-described by the rate and state constitutive law by Dieterich, Rice, and Ruina [1,2]. Burridge and Knopoff have also used this kind of velocity-weakening friction in their spring-block model to describe the earthquake stick-slip dynamics [21,22]. Here, we define $\mu = \tau / \sigma_n = F_c / F_s$ the shear stress (force) normalized by the normal stress (force) from which the static and dynamic coefficients of friction $\mu_{s,d} = \tau_{s,d} / \sigma_{n,s,d} F_{s,d} / F_n$ follow. Here $\tau_r$ and $F_r$ are the static friction stress and force at yield while $\tau_d$ and $F_d$ are the dynamic friction stress and force. In the inclined plane geometry of angle $\theta$ such as in the present study [Fig 1(b)], we have $\mu = \tan \theta$ and $\mu_s = \tan \theta_m$, with $\theta_m$ the (maximum) angle of avalanche. The angle of repose $\theta_r$ being a few percent lower than $\theta_m$ [23–26] corresponds to the dynamic friction $\mu_d = \tan \theta_d$ at the minimum shear load [Fig. 1(d)].

Previous works [20,27–29] showed that for shear forces far below the threshold $\mu \ll \mu_s$, both granular layers and rough solid interfaces [Figs. 1(a), 1(b), and insets] respond elastically as shown in Fig. 1(c), via the reversible deformation of contacting grains or/and asperities, in the jammed state (region I). For $\mu \lesssim \mu_s$, nonlinear response occurs with creep-like irreversible sliding. For $\mu \gtrsim \mu_s$, the system yields and starts to slide over a transient characteristic distance $D_s$ (slip weakening) [1,2,20] before reaching the steady-flow region II/III at a velocity $V$ or shear rate $\dot{\gamma}$ imposed by the load (to be described in the following). In the representation $\mu = \mu(V)$ or $\mu(\dot{\gamma})$ plotted in Fig. 1(d), the velocity weakening region ($\dot{\gamma} < \dot{\gamma}_0$), referred to as “II,” is unstable and can lead to intermittent
flow behavior (e.g., stick-slip). Such frictional instability results from an aging-rejuvenation competition acting within the micrometer-sized contacting asperities [20], which can also be modeled by the micro- or nanoblocks coupled elastically by springs [30]. For high flow rates ($\dot{\gamma} > \dot{\gamma}_0$), the slope of $\mu(\dot{\gamma})$ is positive and ensures the stability of the steady flow as in region III.

The possible failure of a granular medium, such as the sandpile, caused by external vibrations, has been known for a long time in engineering and geophysical applications, however a unified physical description still lacks. The vibrations considered are most of the time of large-amplitude $U_0 \gg d$ with $d$ the grain size and low-frequency $f < f_0$, where $f_0$ is a characteristic frequency determined by the stiffness of Hertzian contacts [20,28]. The amount of shaking is usually estimated by the reduced peak acceleration of the grain $\Gamma = a/g = (2\pi f^2 U_0/g$ with $g$ the gravity. When $\Gamma > 1$, vertical vibrations cancel almost normal forces exerting on the grain (confined under gravity) and modify consequently the spatial arrangement of grains, resulting in phenomena such as compaction, convection, shear banding, to mention a few [31–33]. This is similar to the oscillation effect on the normal stress facilitating sliding [34,35] and also to the scenario of the acoustic fluidization in a confined continuous medium. In this scenario, the acoustic pressure $p_a = (\rho c^2)\nu_a$, with $c$ the sound speed and $\nu_a$ the vibration velocity, is expected to temporarily relieve the pressure of the overburden, thereby decreasing the yield stress [36]. For horizontal vibrations, whenever $\Gamma > \mu$, the grains in the top layers of free surface slide against each other [37–39] akin to the slider on an inclined frictional plane [28,29]. Other studies claim that shaking should be parametrized by the vibration velocity $\nu_a = (2\pi f) U_0$ squared, because the vibrations interact with the medium in terms of a granular temperature $T_g$ proportional to the kinetic energy of the grain $T_g \sim (1/2) m \nu_a^2$ with $m$ the grain mass [33]. More recent works suggest rather a collisionlike pressure term, $p_c \sim (1/2) \rho v_a^2$ with $\rho$ the granular mass density [40,41].

However, the above scenarios, involving large-amplitude vibrations, cannot explain the dynamic earthquake triggering by seismic waves at micro- and nanostrain amplitude [2,3], nor the laboratory experiments using nanometer-amplitude ultrasound to soften the material modulus by 30% via nonlinear dynamics [10,12]. Also, some modifications of the stick-slip cycle by ultrasound remain unexplained [11]. In these situations, the oscillation frequency of ultrasound $f \geq 40$ kHz is high compared to the characteristic frequency $f_0 \sim 5$ kHz in millimeter-thick granular layers [20,28] so that grains cannot have normal motion, due to inertia, in order to suppress the weight of the overburden. On the other hand, for a nanometer ultrasonic vibration, the collisionlike pressure estimated as $p_c \sim 10^{-4}$ Pa $\ll \sigma_0$ ($\sim 10$ Pa) is too small to be considered.

In this work, we focus on the triggering of granular instabilities by small-amplitude and high-frequency sound waves. In such conditions, we have already evidenced another mechanism in which the local threshold friction force at one grain contact can be reduced by a shear acoustic lubrication.
lowering the effective interparticle friction coefficient [42]. However, the question is whether such local effects could give rise to collective motion since small-amplitude ultrasound does not induce grain displacement per se at the relevant length-scale (i.e., grain diameter \(d\)) during avalanches. We will show that depending on the interplay between the ultrasound amplitude and the driving force, granular layers can be found in different states: jammed solid, slow creep flow, and fast inertial liquid. Our experimental results are analyzed on the basis of velocity-weakening friction models.

II. EXPERIMENTS

The experimental setup is shown in Fig. 1(b). A given mass of glass beads (of diameter \(d\)) is deposited on the surface of an ultrasonic transducer by pluviation, building a flat and homogeneous granular layer of controlled thickness \(h\) and packing density (solid volume fraction \(\phi \sim 0.6\)). After a waiting time of 10 min to overcome aging effects [10,12] and ensure a controlled initial state, the avalanche angle \(\theta = \theta_0\) is measured as a reference state by inclining the plane until the flows of the grains are computed with a tracking procedure [44]. The resolution of grain motions is limited by the pixel size of images that is about 5 \(\mu m\). The Probability Distribution Function (PDF) of grain velocities is then obtained as shown in Fig. 2 where we plot both the transverse (a) and longitudinal (along the slope) components (b). The central part of the PDF is fitted with a Gaussian curve. From these PDFs, we deduce the average flow velocity \(V_{flow}\) and the standard deviation \(\delta V\). For the transverse component, the PDF are symmetrically distributed around \(V_1 = 0\) as there is no preferential path in that direction. Along the longitudinal direction, the PDF are asymmetric around \(V_1 = 0\) with a nonzero average flow velocity. All distributions have large tails, due to both the heterogeneous nature of the granular flow [45] and some boundary effects due to the geometry of the transducers.

III. RESULTS

A. Dynamics of triggered granular flows

Figure 3(a) depicts the normalized friction \(\mu/\mu_s = \tan \theta/\tan \theta_0\) vs the dimensionless flow velocity \(\tilde{V} = V_{flow}/(gd)^{1/2}\) on the intermediate roughness surface. Depending on the distance to yielding, we observed different regimes of flow triggered by ultrasound. For \(\mu/\mu_s < 1\) and too small amplitudes of ultrasound, the system is in the jammed state I, defined by the vertical (plain) line \(\tilde{V} = 0\) as in Fig. 1(d). In region II close to region I, flow occurs at a very small averaged velocity \(\tilde{V} \sim 10^{-2}\). Closer to yielding, for \(\mu/\mu_s \sim 0.9\), we find a rather abrupt dynamic transition where the system jumps, around a characteristic \(\tilde{V}^* \sim 3 \times 10^{-3}\) (dotted line) from an intermittent creep flow to a much faster, continuous inertial flow (dashed line). As shown in Fig. 3(b), \(\tilde{V}^*\) corresponds to a marked peak in the evolution of the transverse relative velocity fluctuations \(\delta V/V_{flow}\), indicating the boundary of a phase transition to the stable flow state. Above the transition, the granular layer flows with a typical \(\tilde{V} > 10^{-1}\), close to the order of magnitude of the flow velocity of a natural avalanche, which is used here arbitrarily to define region III for the onset of stable flow.

The observed ultrasound-induced granular flow may be characterized by different states as provided by the order of magnitude of the typical average velocity. This is shown in Fig. 3(c) where \(\mu/\mu_s\) is replotted from Fig. 3(a) but as a function of the ultrasound amplitude \(U_\theta\). Such a phase diagram shows that transition between the jammed state, the creep flow state, and stable flow state shall occur via arbitrary paths in the \((\mu, U_\theta)\) plane. Below, we shall suggest a local friction model to describe the line schematically delimiting jammed state I and flowing state II/II.

Moreover, inspection of Fig. 3(a) suggests that in the dynamic transition zone between regions II and III, the flow velocity is an increasing function of the amplitude at imposed shear \(\mu\). For example, for \(\mu/\mu_s \approx 0.85\), when the ultrasound amplitude \(U_\theta\) is increased from 15 to 45 nm, the flow velocity is increased by \(\Delta V_{flow} \approx 3\) mm/s, which gives an increasing factor about \(\Delta V_{flow}/\Delta U_\theta \approx 10^3\) s\(^{-1}\). We confirm this trend with more precision by showing additional measurements of \(\tilde{V}\) from experiments achieved with a fine increase of the

| TABLE I. Dependence of the avalanche angle on surface roughness and layer thickness. |
|-------------------------------|-----------------|-----------------|-----------------|
| Roughness                     | Smooth          | Intermediate    | Rough           |
| Thickness \(h/d\)             | 3               | 3               | 11.6            | 3               |
| \(\theta_0\) \((d \approx 0.5\,\text{mm})\) | 16.5° ± 1°     | 20.2 ± 1°      | 16.5° ± 1°     | 36° ± 1°       |
| \(\theta_2\) \((d \approx 0.1\,\text{mm})\) |                  | 22.5°          |                 |                 |

FIGURE 3. (a) The normalized friction \(\mu/\mu_s\) vs the dimensionless flow velocity \(\tilde{V} = V_{flow}/(gd)^{1/2}\) for different granular layers and surface roughnesses. For \(\mu/\mu_s > 1\) and too small amplitudes of ultrasound, the system is in the jammed state I. For \(\mu/\mu_s \sim 1\), a rather abrupt dynamic transition to a fast, continuous inertial flow is observed. (b) The evolution of the transverse relative velocity fluctuations \(\delta V/V_{flow}\) as a function of the ultrasound amplitude \(U_\theta\). (c) The observed ultrasound-induced granular flow may be characterized by different states as provided by the order of magnitude of the typical average velocity. This is shown in Fig. 3(c) where \(\mu/\mu_s\) is replotted from Fig. 3(a) but as a function of the ultrasound amplitude \(U_\theta\). Such a phase diagram shows that transition between the jammed state, the creep flow state, and stable flow state shall occur via arbitrary paths in the \((\mu, U_\theta)\) plane. Below, we shall suggest a local friction model to describe the line schematically delimiting jammed state I and flowing state II/II.
ultrasound amplitude at constant inclination in a layer of large beads \(d = 500 \mu m\) as shown by Fig. 3(d). At \(\mu/\mu_s = 0.73\), the flow velocity increases continuously with amplitude \(U_0 > 25\) nm, such that \(\Delta V_{\text{flow}}/\Delta U_0 = 1.1 \times 10^5 \text{s}^{-1}\), a value consistent with the preceding measurement. In this region (II) where the flow velocity is controlled by ultrasound, the granular layer stops flowing when the ultrasound is removed (see video 2 in the Supplemental Material [43]). By contrast, as shown in Fig. 3(a), when the inclination increased close to the threshold at \(\mu/\mu_s \leq 1\), the dynamics of

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FIG. 2. PDF of grain velocities driven by ultrasound \((U_0 = 15\) nm\) in a layer of thickness \(h/d = 11.6\) \((d = 100, \mu m)\) deposited on the surface of intermediate roughness. The angle of inclination \(\theta\) varies from 19.5° to 21° \((\theta_m \approx 22.5°)\). (a) PDF of the transverse velocity, symmetric around \(V_\perp = 0\). (b) PDF of the longitudinal velocity \(V_\parallel\) along the slope, from which the average flow velocity \(V_{\text{flow}}\) is computed.

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FIG. 3. (a) Normalized friction coefficient \(\mu/\mu_s\) vs normalized flow velocity \(\bar{V} (= V_{\text{flow}}/(gd)^{1/2})\) for a layer thickness \(h/d = 11.6\) \((d = 100 \mu m)\) and \(f = 40\) kHz on the intermediate roughness surface \((\theta_m = 22.5°)\). The flow is driven by ultrasound amplitudes \(U_0 = 15, 23,\) or \(45\) nm (respectively, black circles, red triangles, and blue squares) and the symbol star corresponds to the occurrence of avalanche without ultrasound at the maximum angle \(\theta_m\). The continuous line corresponds to the model from Ref. [17] (see text). (b) Relative transverse velocity fluctuations vs \(\bar{V}\). Inset illustrates the necessary initial condition \(\bar{V} > \bar{V}^*\) for the grain to escape from a geometric trap formed by its neighbors (see text). (c) Phase diagram constructed by replotting \(\mu/\mu_s\) from (a) as a function of \(U_0\) illustrating different states of the system. (d) Variation of \(\bar{V}\) vs ultrasound amplitude \(U_0\) \((f = 40\) kHz\) at various imposed \(\mu/\mu_s\) for a layer thickness \(h_1/d = 3\) \((d = 500 \mu m)\) on the intermediate rough surface \((\theta_m = 20.2°)\). The open triangles points correspond to a short-burst excitation with 1-s duration.
flow converges toward the reference state (marked by the star symbols), i.e., the onset of avalanche without ultrasound, in region III [Fig. 3(d)]. There, the inertial flow at a typical velocity $\tilde{V} \gtrsim 1.5 \times 10^{-1}$, used to define region III (dashed line), is mostly insensitive to ultrasound, being only a function of the imposed shear $\mu$ as confirmed, e.g., for $\mu/\mu_s = 0.83$. We found additionally that in region III, applying the ultrasound either by a short burst (of 1-s duration) or by a continuous wave results in the same flow velocity. All our experiments show that close to $\mu_s$, ultrasound vibrations only affect the threshold but not the flow dynamics.

B. Unjamming by ultrasound

In Fig. 4, we investigate in more details the unjamming by ultrasound of static layers of large beads ($d = 500 \mu \text{m}$) at $\mu_s^*(U_0) < \mu_s$ from the jammed state (I). This threshold $\mu_s^*$ decreases linearly with increasing $U_0$ in a systematic manner as for the I-II/III line in Fig. 3(c), which confirms that perturbations by ultrasound excitation and static shear stress play complementary roles in the triggering process. Figures 4(a) and 4(b) show that the unjamming starts at smaller amplitude for low frequency of vibration, low roughness of the transducer, and small thickness of the granular layer. When the unjamming occurs, large flow velocities were found for $\mu$ close to $\mu_s$, as those observed in Fig. 3(d).

IV. DISCUSSION

A. Bifurcation between creep-like flow and self-accelerated inertial flow (macroscopic-scale analysis)

To understand qualitatively the different regimes of flow triggered by ultrasound (Fig. 3), we use as a guide the heuristic friction model developed by Jaeger et al. [16]:

$$\mu = \mu_s/(1 + \alpha \tilde{\gamma}^2) + \beta \tilde{\gamma}^2. \quad (1)$$

Here, $\mu(\tilde{\gamma})$ is the normalized shear defined above, $\tilde{\gamma} = \sqrt{\gamma d/g_\perp}$ ($d$ is the grain size) is the dimensionless flow (shear) rate with $g_\perp = g \cos \theta$ and $\gamma$ would scale with $V_{\text{flow}}/h$ ($h$ is related to the sample thickness). $\mu_s$ is the granular static friction coefficient, which depends on the grain-grain friction coefficient, the depth of the trapping by neighboring grains, and the energy loss during collisions, which involves the coefficient of restitution. Figure 5(a) shows a typical plot of $\mu(\tilde{\gamma})$...
Thus lowering the avalanche angle or yield stress from the application of ultrasound reduces the interparticle friction coefficient, bifurcates between a stable inertial flow for imposed shear (points) as explained in the text. (b) Evolution of the flow rate as a curve) to (b) Evolution of the flow rate as a curve) to

\[
\dot{\gamma} = \frac{\dot{V}}{h},
\]

where \( \dot{V} \) is the flow rate. We may also investigate this bifurcation phenomenon from the given initial condition to the stable states as a function of time [28,46]. To do so, we consider the motion of a single mass (“slider”) on an inclined plane [inset of Fig. 1(b)] within the framework of a mean-field approximation. It is submitted to a shear force by gravity and a friction by the phenomenological friction law in Eq. (1). The mean acceleration approximately written as

\[
\frac{dV}{dt} = F_s - \mu_s \frac{\dot{V}}{h}
\]

is lowered to the pink one [42], which depicts the velocity-weakening behavior for minimum value in the blue curve) to \( \mu_s \) (minimum value in the blue curve) the granular system stops to flow in the absence of ultrasound and goes back to the initial solution at \( \gamma = 0 \), i.e., the stable jammed state (I). Moreover, in the latter case, the velocity of triggered flow increases with increasing ultrasound amplitude by lowering further \( \mu_s \) [42], as for the experimental observation in Fig. 3(d) with \( \mu_s = 0.73 \).

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\frac{dV}{dt} = \mu_s \frac{\dot{V}}{h}
\]
flow rates $\dot{\gamma}$ corresponding to the triggered flows under two imposed shears [red circles in Fig. 5(a)], $\mu_1 = \tan \theta_1$ with $\dot{\gamma}_s = 1.2$ and $\mu_2 = \tan \theta_2$ with $\dot{\gamma}_s = 1$, respectively. For the inclined plane at $\theta_1$, the system reaches a steady inertial flow at long time whereas for the lower inclination $\theta_2$, the flow slows down and arrests quickly, being consistent with the above analysis via Fig. 5(a). Qualitatively, such a bifurcation agrees well with our experiments on triggered granular flows [Figs. 3(c) and 3(d)]. It is worth noting that in yield stress fluids such as foams, emulsions, and polymers the thixotropic effect resulting from the competition between structuration and destruction by shear can also lead to a viscosity bifurcation as a function of time [46].

**B. From creep to inertial granular flows (local-scale analysis)**

Simulations and experiments [47] showed that in the quasi-static regime at a very low imposed flow velocity, external driving induces large velocity fluctuations of grains when the system is far below the yield stress, associated with the complex dynamics of a grain confined by high local static threshold. However, at high flow velocity, the relative velocity fluctuations decrease with the flow velocity [48]. Here, Fig. 3(b) shows that all data collapse on the same curve when plotting the relative transverse velocity fluctuations $\delta V/V_{flow}$ versus flow velocity, independent of the ultrasound amplitude and of the inclination.

Around a threshold flowing velocity $V^* \sim 0.03$, the relative velocity fluctuations $\delta V/V_{flow}$ abruptly becomes a decreasing function of $V_{flow}$ (or $V$) similar to previous studies [47,48]. Above $V^*$, the observed small relative velocity fluctuations are characteristic of the large failure event dominated by the inertial number: the granular layer is in the inertial flow state (region III), corresponding to highly uncorrelated grain motion [49]. There, the dynamics arising from the naturally occurring avalanche at $\mu_2$ and the triggered flows are indistinguishable [Fig. 3(b)], which is consistent with the observation in Fig. 3(a) where the effect of ultrasound is negligible during the fast continuous flow. This is also in line with the results in Fig. 3(d) close to $\mu_1$ where triggered avalanches flow at the same velocity with or without prolonged ultrasound.

Below $V^*$, for $\mu/\mu_s \ll 1$, perturbations such as shear and vibration can induce some grain motion but the momentum transfer is insufficient for a global flow (avalanche), given the low static load. In the intermittent regime for an imposed shear load near the metastable zone, the averaged creep flow state (region III), corresponding to highly uncorrelated grain motion, as shown in Fig. 3(d) for $\mu/\mu_s = 0.73$. This is probably due to the decrease of the interparticle friction coefficient $\mu_p$ induced by the acoustic lubrication which ensures a decreased frictional loss during local slipping events.

The robust superposition of the relative velocity fluctuations in Fig. 3(b) suggests that the order of magnitude of the threshold velocity $V^*$ is given by the intrinsic dynamics of the granular system. The intensity of the threshold velocity results from the kinetic energy acquired by the grains during the ultrasound-induced rearrangement events, and should be large enough for the grains not to remain trapped after collisions. Then, one needs $(1/2)mv^2 = E(\theta) = mgd f(\theta)$ if the shocks are elastic [see inset of Fig. 3(b)] with $f(\theta) \sim (1 - \cos(\theta - \theta_0)) \sim (\theta - \theta_0)^2/2$, corresponding to a geometric parameter [17]. This gives a minimum velocity $V(\mu) \geq V^* = (\mu_2 - \mu)(gd)^{1/2}$ for escaping the potential energy trap near the threshold. As shown Fig. 3(a) this order of magnitude for the threshold velocity $V^* \sim \mu_2 - \mu \sim 0.04$ (with $\mu_2 = \tan \theta_0, \mu_1 \approx 0.41$) corresponds consistently to the location of the velocity jump $V^*(\sim 0.03)$ observed in the curves $\mu(V)$ at imposed shear around $\mu_1/\mu_s \sim 0.9$ and define a transitional boundary separating conveniently region II, where the flow velocity depends on the amplitude, from the inertial flow region III. We may also estimate the characteristic velocity for the system with larger beads in Fig. 3(d) at $\mu/\mu_s = 0.73$ (region II), $V^* \sim 10^{-1}$ (with $\mu_s \approx 0.37$). Again, the separation between the different dynamic behaviors II/III matches the experiment. The results are summarized schematically in Fig. 5(a) where $\tilde{\gamma}(\sim 0.3)$ is obtained from the intersection $\mu_1$ with the curve $\mu(\gamma)$ in the unstable region.

**C. Rearrangement of grains unjammed by ultrasound**

As mentioned above, in a confined granular material, ultrasound can weaken the shear contact stiffness via microslip at grain contacts, inducing the frictional dissipation and reducing the material rigidity [12,13,50]. For a single grain under gravity [42], such shear ultrasound-induced decrease of the stiction area of a (hertzian) contact results in sliding the static threshold. We surmise that a similar mechanism is at work here for the granular layer on the macroscopic scale.

As indicated above in Eq. (1), the static friction coefficient $\mu_1 = \mu_p + \mu_s (= \tan \theta_0)$ includes both the interparticle friction $\mu_p$ and the geometric trapping $\mu_s$ (dilatancy effect). Because of the small amplitude of ultrasound, the sound matter interaction only modifies $\mu_p$ but not $\mu_s$, hence $\mu_1\sim \mu_p + \mu_s$. From the Mindlin friction model, we have shown that decreases of both the shear contact stiffness $\Delta k_1/k_1$ [12] and the interparticle friction coefficient $\Delta \mu_p/\mu_p$ [42] are approximately proportional to $\sim f_s/(\mu_p W)$, where $f_s$ is the oscillating tangential force and $W$ the static normal force at a single contact. Such a scaling of vibration-induced softening $\sim -F_{ext}/(\mu_p W)$ can also be generalized to the effective shear contact stiffness at a multi-contact interface between solids [51] and to the shear modulus [13] and the yield stress [52] in a vibrated granular medium where polydisperse contact asperities are replaced by grain contacts and inertial effects are negligible. Here $F_{ext}$ is the imposed macroscopic oscillating shear force, $W$ the normal load, and $\mu$ the (averaged) effective interparticle friction coefficient. Accordingly, we adopt here this scaling formula for the granular layer to describe the reduction of $\Delta \mu_p/\mu_p \sim -F_{ext}/(\mu_p W)$, which implies that $\mu_{*p}/\mu_{s} \sim 1 - F_{ext}/(\mu_p W)$.

For the granular layer considered here [Fig. 1(b)], we may write the above shear oscillating force by $F_{ext} = k \dot{\gamma}$ with $k$ the effective stiffness of the granular layer and $\dot{\gamma}$ the averaged displacement amplitude of shear vibration over the thickness $h (= 1.5 \text{~mm})$. To evaluate $\dot{\gamma}$, we assume the ultrasound amplitude at a distance $z$ from the transducer to be given by $U(z) \sim U_0 \exp(-z/\delta)$ with $U_0$ the source amplitude and $\delta (\sim \lambda = c/\nu)$ the attenuation length dominated by wave scattering [7]. Thus we have $\dot{\gamma} \equiv (1/\hbar) f_s U_0 \exp(-z/\delta) dz = (\delta/\nu U_0)(1 - \exp(-\delta/\hbar))$. With a wave speed $c \sim 10 \text{~m/s}$
Subsequently, avalanches triggered by ultrasound via the decrease of the interparticle friction coefficient, leading to remarkable alteration of the effective temperature in the unjamming diagram. The analysis shows that the static threshold of granular layers is lowered by ultrasound. The ultrasonic transducer surface shall pin a small fraction of the grains in the vicinity of the solid surface and increase roughness of the transducer surface. The wavelength of the ultrasonic transducer, the phenomenon observed here is similar to shaking experiments, grain motions do not correspond to geometrical rearrangements such as jumps forced by the oscillations, but rather to jiggles or agitations in traps formed by neighbors thanks to the small potential energy released from the decrease of interparticle friction $\mu_p$ by the shear acoustic lubrication at grain contacts. This sound-matter interaction depends on ultrasound frequency and layer thickness due to wave attenuation, as well as on the transducer surface roughness which pins the grains by the dilatancy effect.

Close below the angle of repose, we observe the triggered flow with a larger averaged velocity increasing with the ultrasound amplitude, owing to the reduction of the granular threshold $\mu_s$ via the decrease of interparticle friction $\mu_p$. This creep-like flow can be sustained only by a prolonged excitation and arrests when ultrasound is turned off. At higher inclination, close to $\theta_s$, triggered avalanches are fast and continuous with a flow velocity independent of the applied ultrasound; it is dominated by the inertial self-generated dynamics of the granular system. These experimental observations agree with the predictions of any velocity-weakening friction model, consistent with the picture of the unjamming transition.

We believe that this work provides a unified picture of the behavior of vibrated granular matter. The multiscale analysis will be useful to better understand the local and remote dynamic triggering of landslides and earthquakes by seismic waves, including aftershocks.

V. CONCLUSION

In summary, we have investigated the flow of granular layers triggered by nanometer-amplitude ultrasound below the threshold. When the angle of inclination is far below the angle of repose $\theta_s$, the ultrasound induces highly fluctuating grain motions with a small average flow velocity. As opposed to shaking experiments, grain motions do not correspond to geometrical rearrangements such as jumps forced by the oscillations, but rather to jiggles or agitations in traps formed by neighbors thanks to the small potential energy released from the decrease of interparticle friction $\mu_p$ by the shear acoustic lubrication at grain contacts. This sound-matter interaction depends on ultrasound frequency and layer thickness due to wave attenuation, as well as on the transducer surface roughness which pins the grains by the dilatancy effect.

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