Vibration induced dynamical weakening of pyroclastic flows: Insights from rotating drum experiments

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Abstract

Pyroclastic flows are characterized by their high mobility, which is often attributed to gas-fluidization of the usually fine and/or low density particles. However, the physical mechanism that might drive sustained fluidization of pyroclastic flows over extraordinarily long runout distances is elusive. In this letter it is proposed that a powerful mechanism to weaken the frictional resistance of pyroclastic flows would arise from the prolonged and intense mechanical vibrations that commonly accompany these dense gravitational fluid-particle flows. The behavior of fine powders in a slowly rotating drum subjected to vibrations suggests that fluid-particle relative oscillations in granular beds can effectively promote the pore gas pressure at reduced shear rates. Dynamical weakening, as caused by the enhancement of pore fluid pressure, may be a powerful mechanism in any geophysical process that involves vibrations of granular beds in a viscous fluid. This is particularly relevant for granular flows involving large amounts of fine and/or light particles such as pyroclastic density currents.

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I. INTRODUCTION

Understanding the dynamics of pyroclastic flows (PF) triggered by the collapse of lava domes and explosive eruptions is crucial for hazard mitigation in populated areas around volcanoes. A main characteristic of PF is their high mobility leading to astonishingly long runout distances even on subhorizontal slopes [3, 8, 12, 33, 34, 36]. PF commonly contain large amounts of fine ash (particle size $d_p \sim$ 1-100 μm and density $\rho_p \sim 2500$ kg/m^3) [28] and light pumice rock fragments ($\rho_p = 500$ kg/m^3, $d_p \sim 10$ mm) [6] whose dynamics is essentially influenced by the gas-solid hydrodynamic interaction [9, 28, 32–34, 36]. Thus, an excess of pore gas pressure above atmospheric pressure may easily lead to a fluidization state in which the drag force exerted by the interstitial gas on the particles counterbalances their weight and frictional forces become negligible. In the fluidization regime, the granular flow acquires the behavior of a low viscosity fluid lacking any resistance to shear. Fluidization has long been considered a key process to explain the enhanced mobility of PF [33, 36]. Lab-scale observations on fluidized granular flows in horizontal flumes, where a high pore gas pressure is artificially imposed by continuously injecting gas through the substrate, demonstrate that a state of sustained fluidization leads to essentially infinite runouts [34]. Fluidized PF would propagate as low viscosity fluids over most of their emplacement [33]. Accordingly, ignimbrite deposits from prehistoric PF show the signatures of negligible friction and suppressed turbulence at the depositional boundary layer, which is indicative of a fluidization governed dynamics [8].

Several mechanisms have been proposed as responsible for the enhancement of pore gas pressure leading to fluidization such as the hindered settling of fine particles from the initially fluidized bed, exsolution of gas from juvenile clasts, engulfing of air at the avalanche front, released gas from rough substrates and high shear rates [3, 12, 34, 36]. Yet, it is uncertain whether the mechanisms considered so far would be intense enough to sustain fluidization of PF over runout distances up to 100 km and across topographic obstacles as inferred from some PF deposits [8]. Once the pore gas pressure within a finely grained mixture (with typically low hydraulic permeability and high porosity compressibility) is increased by any mechanism it could be maintained for long durations due to retarded pore pressure diffusion, which could explain the considerable runout distances of PF [28, 32]. The key question is then what mechanism plays the major role on rising the pore gas pressure.

A further important characteristic of PF is the generation of intense mechanical vibrations usually by collisions of pyroclasts onto the mountain slope or other obstacles [15, 40]. Seismic signals associated with PF are generally distinguished by significantly long durations and large amplitudes proportional to the volume of PF. Remarkably, seismic signals of similar features are generated by snow avalanches, which also exhibit long runout distances [37]. In this letter we explore the possibility that mechanical vibrations excited by the propagation of PF promote their mobility by enhancing the pore gas pressure. To this end, we have observed the behavior of two types of powders in a rotating drum subjected to mechanical vibrations. The rotating drum setup has been already used in previous studies within the context of PF to assess the role of particle size and density on fluidization [4] and the generation of ash by abrasion of volcanic rock fragments [21]. Here, we use the rotating drum setup to shed light on the effect of mechanical vibrations on the dynamical behavior of PF.

II. MATERIALS AND METHODS

Two diverse types of granular materials have been tested in our work. On one hand, we have observed the behavior of cornstarch (particle size $d_p \simeq 15$ μm and density $\rho_p \simeq 1550$ kg/m^3) as representative of an easily fluidizable fine powder. Cohesiveness of the cornstarch powder is reduced by mixing it with 0.5% by weight of flow control additive (Aerosil® from Evonik) [13]. When subjected to a gas flow, a bed of this fine powder reaches a highly expanded fluidized state characterized by a nonbubbling and liquid-like frictionless behavior [41]. On the other hand, we have tested the behavior of glass beads (particle size $d_p \simeq 100$ μm and density $\rho_p \simeq 2500$ kg/m^3). Fluidization of these glass beads is characterized by the development of large gas bubbles just beyond the onset of fluidization, which hampers bed expansion. This is the characteristic behavior of Geldart B granular materials [18, 41].

Figure 1 illustrates a schematic representation of the experimental setup. In our work we have used a cylindrical Plexiglas drum (4.5 cm internal radius and 2cm depth), which is driven by a motor that allows a maximum angular velocity of 100 revolutions per minute (rpm) around its horizontal axis. The drum is rotated by a shaft supported on the base of an electromagnetic vibration exciter through a pair of bearings. The vibrator is driven by a signal generator that provides sinusoidal, vertical vibrations of controlled amplitude ξ_1, and frequency f (in the range 25-200 Hz). The shaft is fitted at the other end to the motor axis by means of an elastic cardan. Peak vibration velocity $u_1 = \xi_1 2\pi f$ is monitored using a piezoelectric accelerometer. A CCD camera interfaced to a computer for image processing records the profile of the powder as affected by rotation and vibration.

When a bed of a cohesive powder is tilted the avalanche angle depends generally on the length of the slope since cohesion leads to a coherence length of size not negligible as compared to the system size for small scale systems [30, 45]. The smaller the length of the slope is, the larger is the angle it can sustain. In the case of the glass beads used in our study cohesion is negligible and therefore effects on the avalanche angle related to the finite size of the drum are not expected. On the other hand, cohesion of the fine powder used in our work has been artificially reduced, which serves to minimize the dependence of the maximum slope angle on its length. As reported in previous studies [45] for a powder similar to the one used in the present work, the avalanche angle of a tilted bed becomes roughly independent of the length of the slope for lengths above $\simeq$8 cm. Since the diameter of the drum used here is 9 cm, it may be expected that effects on the avalanching behavior due to the finite size of the drum are neither relevant for this material.

III. RESULTS AND DISCUSSION

As reported in a previous study [9], the two types of materials used in the present work display also contrasting behaviors with increasing drum rotating velocity (see Fig. 2). The fine powder is progressively fluidized by the air that becomes engulfed in the powder by each avalanche. The extent of fluidization increases with the rotation velocity and the whole bed becomes fluidized at a rotation velocity $\Omega \simeq 90$ rpm (Fig. 2(a2)). At this point the granular bed looses any frictional resistance to shear. As may be seen in Fig. 2(a2), the gas-solid mixture acquires an expanded state with a nearly horizontal slope. Particle volume fraction is decreased from $\phi \simeq 0.4$ in the settled (solid) state to $\phi \simeq 0.2$ in the fully expanded (fluidized) state. Using $L \sim 1$ cm for the characteristic size of avalanches, the shear rate is estimated to vary between $\dot{\gamma} \sim \Omega R/L \sim 1$ s^{-1} at the lowest rotation velocity ($\Omega \simeq 4.8$ rpm) and $\dot{\gamma} \sim 40$ s^{-1} in the full fluidization state ($\Omega \simeq 90$ rpm). According to field observations, the thickness of natural PF is usually on the order of tens to several hundred meters whereas PF velocities are in the range $\sim$10 ms^{-1}-300 ms^{-1} [8, 20]. Thus, the maximum expected values of shear rate in gas-fluidized PF would be $\dot{\gamma} \sim 10$s^{-1} as in the recent Merapi eruption where fine ash PF around 10 m thick propagated at velocities of about 125 m/s [20]. Bearing in mind that comparing the observations of small-scale experimental flows and large-scale natural phenomena presents both temporal and spatial scaling problems [8], our results suggest that shear rates in PF are not high enough to cause full fluidization of fine powders.

The behavior of fluidizable fine powders in a rotating drum has been analyzed in detail in

[10]. Experimental results for several materials and using drums of different diameters show that the interstitial velocity of the air that continuously escapes from the fluidized powder while the drum is rotating scales on average proportionally to the tangential velocity of the drum $u_i \sim \alpha\Omega R$, where $\alpha \sim 0.01$. At the smallest rotation velocity used in the experiments described in the present paper ($\Omega = 4.8$ rpm), $u_i \sim 0.02$ cm/s, which is not large enough as to fluidize the powder. Thus, the material displays a plastic behavior. Fluidization starts to occur when the rotation velocity is further increased leading to interstitial gas velocities similar to the minimum fluidization velocity, which is $u_{mf} \sim 0.1$ cm/s for the powder analyzed in this work [13]. Figure 2(a3) shows that the addition of vibration to the slowly rotating drum ($\Omega = 4.8$ rpm) has a relevant effect on the dynamical behavior of the fine powder. As seen when full fluidization occurs at large rotation velocities (Fig. 2(a2)), the slowly rotated bed looses progressively its frictional strength as the intensity of vibrations is increased. For sufficiently strong vibrations, the angle of the slope drops to zero (Fig. 2(a3)) even at the relatively small shear rates ($\dot{\gamma} \sim 1$ s^{-1}) corresponding to the lowest rotation velocity. Note however that powder expansion is not observed as in the case of full fluidization in the rapidly rotating drum (Fig. 2(a2)).

In contrast to the fine powder behavior in the rotating drum, the avalanching dynamics of the glass beads is determined by inertial stresses [9]. In this case, the average angle of the slope is increased with the rotation velocity as the centrifugal acceleration builds up (Fig. 2(b2)). However, vibration is seen to weaken the frictional resistance of the glass beads in the slowly rotating drum too (see Fig. 2(b3)). The minimum vibration intensity to reduce the angle of the slope to zero depends on the vibration frequency and the material. Thus, it is $u = 4.2$ mm/s at $f = 50$ Hz for the fine powder (Fig. 2(a3)) whereas, by extrapolating the experimental results (shown below), it may be estimated that a vibration velocity of about $u \simeq 10$ mm/s would be needed to completely nullify the frictional resistance of the avalanching glass beads.

If a powder bed is sheared it yields plastically when the shear stress reaches a critical value τ_c (yield strength) usually related to the normal stress σ by means of the Coulomb friction law $\tau_c = \mu_s\sigma$, where $\mu_s = \tan\theta_s$ is the static friction coefficient and cohesion is neglected [2]. After failure, the granular bed acquires a state of higher porosity and continues to deform at a slightly decreased shear stress $\tau_d < \tau_c$. The coefficient of dynamic friction $\mu_d = \frac{\tau_d}{\sigma}$ is thus somewhat smaller than the static friction coefficient. Assuming that μ_d is a constant which depends only on the material, its value may be estimated from the average angle of the slope. In the slowly rotated drum and in the absence of vibrations we obtain $\mu_d \simeq \tan\theta_d \simeq 0.48$ for the fine powder and

$\mu_d \simeq 0.54$ for the glass beads . Data on the relative variation of the dynamic friction coefficient $\frac{\Delta\mu_d}{\mu_d}$ (estimated from the average angle of the slope) are plotted in Fig. 3a as a function of the relative increase of velocity $\frac{\Delta u}{u_0}$, being u either the tangential rotation velocity (in the absence of vibrations) or the peak vibration velocity in the slowly rotating drum ($\Omega = 4.8$ rpm fixed). Remarkably, the data from both type of experiments for the fine powder conform to a common linear trend, which suggests that the effect of vibration obeys also to the enhancement of the gas-solid hydrodynamic interaction. On the other hand, vibration and rapid rotation yield contrasting effects for the glass beads. Inertial stresses prevail in the rapidly rotating drum for the glass beads, which leads to dynamical strengthening as the centrifugal acceleration increases. Contrarily, the vibrated rotating bed looses progressively frictional resistance as the intensity of vibrations is increased. Thus, one might wonder whether gas-solid hydrodynamic interactions might play also a role on the dynamical weakening of vibrated granular beds of relatively large inertia particles, which would otherwise reach a bubbling fluidization regime only when subjected to large gas-solid relative velocities ($u \gtrsim 0.5$ m/s) [9].

The question on the role of gas effects on vibrated granular beds of large inertia grains is longstanding. The interested reader may find a recent review on this subject in [42]. It dates back to Faraday [17] who already observed the onset of convective currents within the bulk of thick layers of large inertia sand grains subjected to vertical vibrations. A strong indication of the relevant role of gas effects was that convection disappeared when air was pumped out and appeared again as the air was readmitted as more recently confirmed by other works [24, 29, 42]. Convective currents in a vibrated granular bed give rise to the formation of a surface heap along which particles avalanches down to be subducted into the bed at its lowest point. In close analogy with our observations, the angle of this slope is smaller than the dynamic friction angle of the material (in the absence of vibrations) and decreases further as the intensity of vibrations is increased. Moreover, chemical engineering studies have long reported that the gas-solid drag can be notably promoted by oscillations even with no net fluid flow [16, 22, 39]. For example, the settling of large inertia beads is substantially slowed down by vertical oscillations of the surrounding fluid and eventually stopped [16, 39]. The oscillating surrounding fluid generates an additional drag that retards settling of the beads and the observed retardation was much greater than that expected from the fluid-solid drag under steady conditions. Thus, it seems likely that an enhancement of the fluid-particle hydrodynamic interaction due to oscillations in dense gravitational flows could lead to dynamical weakening.

Our observations demonstrate that dynamical weakening occurs as the rotating velocity is increased due to fluidization in the case of the fine powder [10]. Fluidization is caused by the increase of pore gas pressure over atmospheric pressure Δp , which leads to a a reduction of the effective friction coefficient μ_{ef} with the rotation velocity. The rise of the pore gas pressure acts by decreasing the effective normal stress $\sigma_{ef} = \sigma - \Delta p$, where $\sigma = \rho_p \phi g L$ is the powder weight per unit area, ϕ is the particle volume fraction and L is the typical thickness of the bed. Thus, the bed would exhibit an effective dynamic friction coefficient given by $\mu_{ef}\sigma = \mu_d(\sigma - \Delta p)$. The relative decrease of μ_d can be thus obtained from the pressure drop per unit length: $\frac{\Delta \mu_d}{\mu_d} = -\frac{\Delta p}{\sigma} = \frac{1}{\rho_p \phi g}\frac{\Delta p}{L}$.

When a fluid flows steadily across a granular bed at low Reynolds numbers, the Carman-Kozeny equation [7, 31] applies:

$$\frac{\Delta p}{L} = E\frac{\phi^2}{(1-\phi)^3}\frac{\eta}{d_p^2}u_s = \Lambda n_0 F_S \tag{1}$$

where u_s is the superficial gas velocity defined as the gas flow rate per unit area. E is an empirical constant ($E \simeq 180$ for spheres), $d_p = 2R$ is particle size, $n_0 = \frac{3\phi}{4\pi R^3}$ is the number of particles per unit volume, $F_S = 6\pi\eta R u_s$ is the Stokes drag force, η is the fluid's dynamic viscosity and $\Lambda \simeq \frac{10\phi}{(1-\phi)^3}$ is the factor that takes into account the hydrodynamic interactions within the bed [42]. In the case of a vibrated bed, gas-particle relative oscillations (oscillatory flow) would be established instead of a steady flow. The drag force on a sphere of radius R undergoing oscillations in a viscous fluid can be calculated in the limit of either small oscillations amplitude ($\frac{\xi_1}{R} < 1$) or small Reynolds number ($Re_1 = \frac{u_1 \rho R}{\eta} = \frac{\xi_1}{R}\left(\frac{R}{\delta}\right)^2 < 1$) as

$$F_1(t) = 6\pi\eta R\left(1+\frac{R}{\delta}\right)u_1(t) + 3\pi R^2\sqrt{\frac{2\eta\rho}{\omega}}\left(1+\frac{2R}{9\delta}\right)\frac{du_1}{dt} \tag{2}$$

where $u_1(t)$ is the instantaneous oscillation velocity, $u_1 = \xi_1 2\pi f$ is the peak oscillation velocity, ρ is the fluid density, and $\delta = \sqrt{\frac{\eta}{\rho\omega}}$ is the thickness of the Stokes boundary layer surrounding the sphere across which the fluid flow becomes irrotational [23]. If the interaction between the Stokes boundary layers developed around neighbor spheres is neglected, the Carman-Kozeny equation can be adapted to oscillatory flows through granular beds [44], which leads to a root mean square (rms) pressure drop per unit length

$$\frac{\Delta p_1'}{L} = \Lambda \Upsilon n_0 F_S' \tag{3}$$

where $F_S' = 6\pi\eta R u_1'$, u_1' is the rms oscillation velocity ($u_1' = \frac{u_1}{\sqrt{2}}$) and

$$\Upsilon = \left[\left(1 + \frac{R}{\delta}\right)^2 + \left(\frac{R}{\delta}\right)^2 \left(1 + \frac{2R}{9\delta}\right)^2 \right]^{1/2} \tag{4}$$

Thus, we can write

$$\frac{\Delta\mu_d}{\mu_d} = -\beta \Upsilon u_1' \tag{5}$$

where $\beta = \frac{6\pi\eta R\Lambda n_0}{\rho_p \phi g}$.

For a randomly packed bed ($\phi \simeq 0.6$) of the noncohesive glass beads used in our tests $\beta \simeq 120$. On the other hand, the analysis of the fine powder is more subtle. Fine cohesive particles are usually agglomerated due to the prevalence of the attractive force between the particles as compared to their weight [11]. By considering agglomerates as effective spheres, the volume fraction filled by the agglomerates ϕ^* is simply related to the particle volume fraction ϕ by $\phi^* = \phi \frac{k^3}{N}$, where N is the average number of particles per agglomerate and $k = \frac{d^*}{d_p}$ is the ratio of the agglomerates size to the size of the individual particles. Fluidized agglomerates screen the external flow field and can be treated as effective particles of density $\rho^* = \rho_p \frac{N}{k^3}$ [46]. Settling tests reported elsewhere [43] yield $N \simeq 9.1$, $k \simeq 2.44$ for the powder used in the present work. Thus we may use $d^* \simeq 37$ μm and $\rho^* \simeq 990$ kg/m^3 for the size and density of the agglomerates as effective particles, respectively. The packing density measured for this powder under flow conditions [43] is in the range $\phi \simeq 0.2-0.3$, which yields $\phi^* \simeq 0.3-0.5$. Using these numbers, we would predict $\beta \simeq 200-800$.

Experimental data of $\frac{\Delta\mu_d}{\mu_d}$ versus $\Upsilon u_1'$ for the slowly rotating drum with added vibrations of increasing intensity are plotted in Fig. 3b. The best linear fits yield $\beta \simeq 116$ for the glass beads and $\beta \simeq 285$ for the fine powder, which are close to the theoretically expected values as caused by an increase of the rms pore air pressure. Data obtained for the fluidizable fine powder in the non-vibrated drum with increasing rotation velocity are plotted also in Fig. 3b. In this case $\Upsilon = 1$ and u_1' is replaced by the superficial gas velocity u_s, which is related to the interstitial gas velocity u_i by $u_s = (1-\phi^*)u_i$. Remarkably, the data fits to the same trend of the vibrated drum data for $u_s = 0.0065\,\Omega R$, which is consistent with the scaling of the interstitial gas velocity with the tangential rotation velocity of the drum reported elsewhere ($u_i \sim 0.01\,\Omega R$) [10].

As a general comment, it must be noticed that the diameter of the drum used in our experiments is small. Ideally, only drums of very large size would allow dismissing any effect of boundary curvature on powder flow [4]. However, the application of vibrations to heavy drums would be technically difficult using our setup. Nevertheless, the experiments carried out in our work serve to capture the essential effect of vibrations on dense granular flows, which can be explained from a simple physical model where boundary effects are neglected. Additional experimental work should be pursued in future studies to address the possible role of surface flow curvature. A key issue in the interpretation of our results is that high pore gas pressure was generated within the granular media by vibrations, which leads to a reduction of the dynamic friction angle. It should be remarked however that pore gas pressure was not measured in our experiments and this would be a further interesting subject for future work. On the other hand, recent experimental results do show that the pore gas pressure in a granular bed subjected to a gas flow is enhanced when high intensity sound vibrations are applied [47]. As a result, the minimum gas fluidization velocity is decreased in a similar way that fluidization is observed in our rotating drum experiment at reduced rotation velocities when mechanical vibration is applied. Application of either mechanical or sound vibrations would equivalently promote the pore gas pressure due to the enhancement of drag by gas-solid relative oscillations. Finally, it must be stressed that vibration induced dynamical weakening could be promoted by other physical mechanisms that might prevail in some particular situations as proposed elsewhere [1, 24, 26, 27]. For example, according to the *acoustic fluidization* mechanism proposed by Melosh [26, 27], high-amplitude and high-frequency vibrations would be also capable of generating transient mechanical stresses intense enough as to facilitate failure under a reduced shear stress in geophysical granular flows (regardless of the presence of interstitial fluids) although the consistency of this theory was later questioned [35].

IV. CONCLUSIONS

Our observations suggest that vibrations may promote fluidization of dense granular flows by enhancing the pore fluid pressure. Thus, the intense and prolonged mechanical vibrations that can arise in nature as dense granular flows propagate on terrains with irregular surfaces [48] could contribute to the sustained fluidization of these flows over long runout distances. Vibration enhanced fluidization would be a main mechanism specially in the case of pyroclastic flows mostly consisting of a matrix of easily fluidizable fine ash and light pumice particles. In particular, if the ratio $\frac{R}{\delta}$ is very large, vibrations would lead to a notable enhancement of the rms pore gas pressure at small shear rates (by a factor $\Upsilon \simeq \frac{2}{9}\left(\frac{R}{\delta}\right)^2 \gg 1$). This can be the case of large and light pumice rock fragments found in ignimbrite deposits of pyroclastic flows with very large runout distances, which are easily fluidizable due to their very low density [8] (using $R = 2$ cm, it is $\Upsilon \sim 100$ for an oscillation frequency of 10 Hz). Dynamical weakening would be further promoted for high vibration frequencies that may be produced by the scattering of waves in heterogeneities as it is believed to occur in fault gouges [27].

The enhancement of pore gas pressure by oscillatory flows could be also a potentially relevant mechanism on the dynamical weakening of granular materials observed in other geological processes such as seismic faulting [5], landslides [25], detachment faulting [19] and impact crater formation [26], although pore pressure generation in gas-particle systems by oscillatory flows is likely to be efficient only for small and/or light particles. Dynamical weakening by oscillatory flows would be more pronounced if the interstitial fluid is a liquid as might occur in dense gravitational liquid-particle flows (lahars) usually triggered by heavy rains on unconsolidated materials such as ash, sand, or gravel, which are accompanied by mechanical vibrations of very long duration and high frequencies [48].

In the present study it has been assumed that pore gas compressibility can be ignored, which is justifiable for small scale systems at ambient temperature [28]. However, gas compressibility cannot be neglected in the case of large scale gas-particle mixtures such as pyroclastic flows and snow avalanches, where it would arguably have a relevant effect on the pore pressure diffusion process [28]. In addition, a temperature gradient across a porous solid may lead to a great amplification of acoustic oscillations as gas parcels within the bed are compressed and expanded by the oscillating pressure. Likewise, intense pore gas oscillations may create a significant temperature gradient across the material. This is the so-called thermoacoustic effect, which is at the basis of thermoacoustic engines and refrigerators [38]. An open issue that would deserve further study is whether temperature gradients commonly expected in pyroclastic flows [14] could favor sustained fluidization by enhancing acoustic oscillations of the pore fluid.

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