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Granular compaction by fluidization

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Abstract. How to arrange a packing of spheres is a scientific question that aroused many fundamental works since a long time from Kepler's conjecture to Edward's theory (S. F. Edwards and R.B.S Oakeshott. *Theory of powders.* Physica A, **157**: 1080-1090, 1989), where the role traditionally played by the energy in statistical problems is replaced by the volume for athermal grains. We present experimental results on the compaction of a granular pile immersed in a viscous fluid when submited to a continuous or bursting upward flow. An initial fluidized bed leads to a well reproduced initial loose packing by the settling of grains when the high enough continuous upward flow is turned off. When the upward flow is then turned on again, we record the dynamical evolution of the bed packing. For a low enough continuous upward flow, below the critical velocity of fluidization, a slow compaction dynamics is observed. Strikingly, a slow compaction can be also observed in the case of "fluidization taps" with bursts of fluid velocity higher than the critical fluidization velocity. The different compaction dynamics is discussed when varying the different control parameters of these "fluidization taps".

1 Introduction

Since Edwards' theory on piles of athermal spheres [1], several ways to compact a dry granular pile have been tried and studied using vibrations [2], taps [3–5], shear [4, 6] or heating cycles [7, 8]. Shearing appears the more efficient way to compact [6] with a global solid volume fraction $\phi \simeq 0.66$ reached after about 10^4 cycles which is significantly higher than the random close packing $\phi_{RCP} \simeq 0.64$. To obtain a similar high volume fraction by tapping, one needs a two-step process [3], with first hard taps allowing to reach irreversibly $\phi \simeq 0.63$ and then by decreasing tap intensity to achieve a pile that reach reversibly $\phi \simeq 0.655$. The common feature of all these solicitations is that they originate at wall boundaries and propagate into the bulk of the packing through the grain contacts. A more efficient way of compaction should be a global sollicitation. It is well known that applying an upward viscous flow to a granular pile will generate a global decompaction of the granular bed that ultimately leads to a fluidized bed. Schröter *et al.*[9] showed for instance that cycles of fluidization/sedimentation of a collection of non-Brownian spheres lead to a higher solid fraction of the granular bed at rest for lower fluidization velocities, extending the works of Onada and Liniger[10].

In the present study we extend the work of Schröter *et al.* [9] to short enough upward flow pulses to avoid the final expansion (fluidization) of the granular bed but also to low enough upward continuous flow, below the critical velocity for fluidization. In both cases, an efficient compaction is observed.

2 Experimental set-up and procedure

2.1 Apparatus

The experimental set-up is sketched in Fig. 1. The suspen-

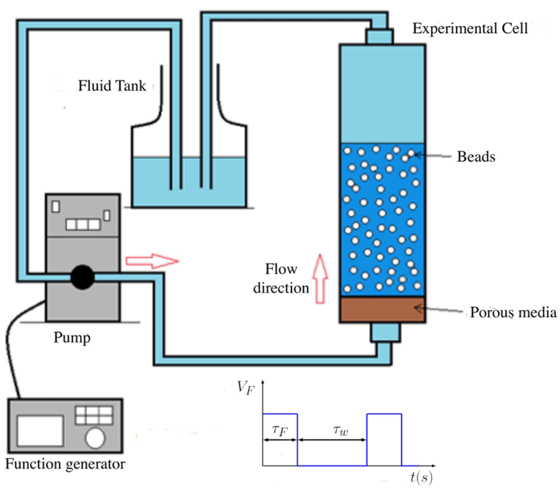

Figure 1. Sketch of the experimental set-up.

sion is contained in a vertical tank of 50 cm high and of rectangular cross-section $S = 8 \times 2\,\text{cm}^2$. The suspension consists in glass spheres of radius $a = 1$ mm and density $\rho_p = 2500\,\text{kg/m}^3$ dispersed in a water-glycerol mixture

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(90% in mass of glycerol) of density $\rho = 1235\,\mathrm{kg/m^3}$ and viscosity $\eta = 156 \cdot 10^{-3}$ Pa · s at 24 °C. In these conditions, the typical sedimentation velocity for an isolated sphere is the particle Stokes velocity $U_0 = 2(\rho_p - \rho)ga^2/9\eta = 16.4 \cdot 10^{-3}$ m/s corresponding to a particle Reynolds number $Re_p = \rho U_0 a/\eta \simeq 0.13$ smaller than 1. For the whole set of experiments, the mass M of particles has been kept constant with the value $M_b = 360$ g corresponding to $N = 69590$ particles. An upward volume flow rate Q injected at the bottom of the tank is fixed using a gear pump without any significant noise and without any significant dependance to pressure loss. However to prevent flow rate variation and achieve an uniform flow in the experimental cell, the fluid is injected through a 2 cm high porous media located at the bottom of the cell and which is fitted with the rectangular section of the cell. The porous media opening is $50\,\mu$m with a permeability that is one order of magnitude lower than the permeability of the granular bed and which thus controls the flow. The pump is controlled with a wave form generator which allows the generation of any flow sequence from continuous flow of upward velocity $U_F = Q/S$ to periodic flow bursts with a given upward velocity U_F during the time τ_F separated by the waiting time τ_w with thus the period $T = \tau_F + \tau_w$. In this bursting regime, the mean upward velocity $\overline{U}_F = U_F \tau_F/T$ is thus smaller than the burst velocity U_F and the fluid displacement $U_F \tau_F$ have to be compared to the grain size a. The experimental tank is lightened from behind and images of the cell are taken at a rate of 4 images per second, thanks to a camera located 1 meter from the cell and with its axis perpendicular to the largest cell plates. The solid volume fraction ϕ of the granular bed is measured from the bed height H as $\phi = M_p/\rho_p S H$ through image analysis : From a sequence of individual images, a spatio-temporal diagram of the time evolution of the bed is built which leads to $H(t)$ and $\phi(t)$. The relative precision in the ϕ measurement corresponds to the relative precision in the H measurement which is about 10^{-4} for $H \simeq 30$ cm here.

In a fluidized bed the solid fraction ϕ is imposed by the upward flow of average velocity U_F according to the Richardson-Zaki (RZ) law[11] which reads here $\phi = 1 - (U_F/U_s)^{1/n}$[12]. In our experiments, the evolution of ϕ as a function of U_F/U_s is shown in Figure 2. Our experimental data follows fairly well the RZ law with the exponent value $n = 4.3$ and an experimental Stokes velocity $U_s = 16 \cdot 10^{-3}$ m/s very close to the value expected for a perfectly monodisperse suspension of spheres.

2.2 Procedure

Each granular pile is prepared following the same procedure. A fluidized suspension of solid fraction $\phi = 0.22$ is first obtained by imposing a constant upward velocity $U_F/U_S = 0.359$. This initial upward flow is then switched off so that the suspension settles and achieve a very reproducible granular bed of solid fraction $\phi_0 = 0.605 \pm 0.005$. Note that this ϕ_0 value may depend on some parameters such as the Stokes and particles Reynolds numbers as well as the friction coefficient of the spheres[10, 13]. We define the critical velocity for fluidization U_c as the one that would lead from the RZ law to the initial bed solid fraction ϕ_0 so that $U_c/U_s = (1 - 0.605)^{4.3} \simeq 0.018$. For $U_F > U_c$, the granular bed packing expands to form a fluidized suspension. It has worth noting that the RZ law is for a suspension only granular pile, and thus cannot be extrapolated below the minimum of fluidization. The corresponding curve part of the RZ law are thus shown not in continuous line but in dashed line in Fig. 2. The experimental results present in the following have been obtained with continuous flows of upward velocity $U_F < U_c$ and with burst flows of velocity $U_F < U_c$ and $U_F > U_c$ but $\overline{U}_F < U_c$.

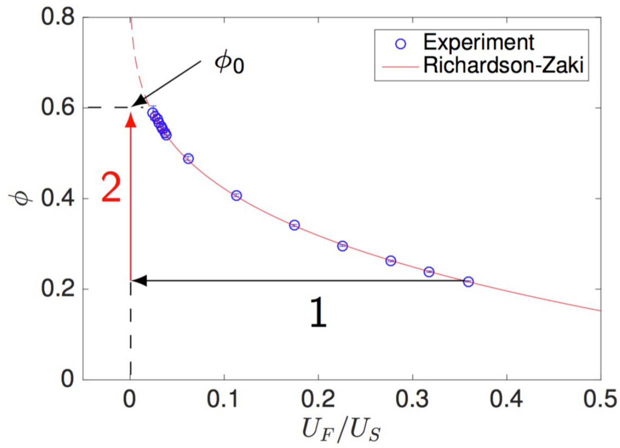

Figure 2. Solid volume fraction ϕ of fluidized bed as a function of the normalized upward flow velocity U_F/U_s. (○) Experimental data and (—) fit of equation $\phi = 1-(U_F/U_s)^{1/n}$ with $n = 4.3$ from RZ law.

3 Results and Discussion

3.1 Continuous flow

Starting from the granular bed packing of initial volume fraction $\phi_0 = 0.605$, an upward flow of velocity $U_F < U_c$ is now applied and the image processing allows to follow the time evolution of the solid fraction of the packing $\phi(t)$ as reported in Figure 3a for $U_F/U_s = 0.014$. We observe a significant increase of $\phi(t)$ that arises from successive local rearrangements. This increase is first fast at short time from $\phi_0 = 0.605$ to typically $\phi \simeq 0.62$ within about the first 10 s, and then slower as 3 days are required for a subsequent increase up to $\phi \simeq 0.625$. This behavior has to be compared with the one observed by [9] in which the pile reaches a stationary volume fraction after the first flow pulse for $U_F/U_S \approx 0.014$ and after 80 minutes for pulses of lower flow velocity $U_F/U_S \approx 0.0125$. As ϕ_0 depends on the detailed experimental conditions and considering the time evolution observed in Fig. 3a, $\phi - \phi_0$ is now reported in the log-lin plot of Fig. 3b as a function the time t/τ_s normalized with the Stokes time $\tau_S = a/U_s = 0.06$ s which corresponds to the time that would be necessary for an isolated grain to settle along its own radius a. For $\ln(t/\tau_S) \gtrsim 5$, which corresponds to $t \gtrsim 10$ s the data are rather well fitted by the logarithmic

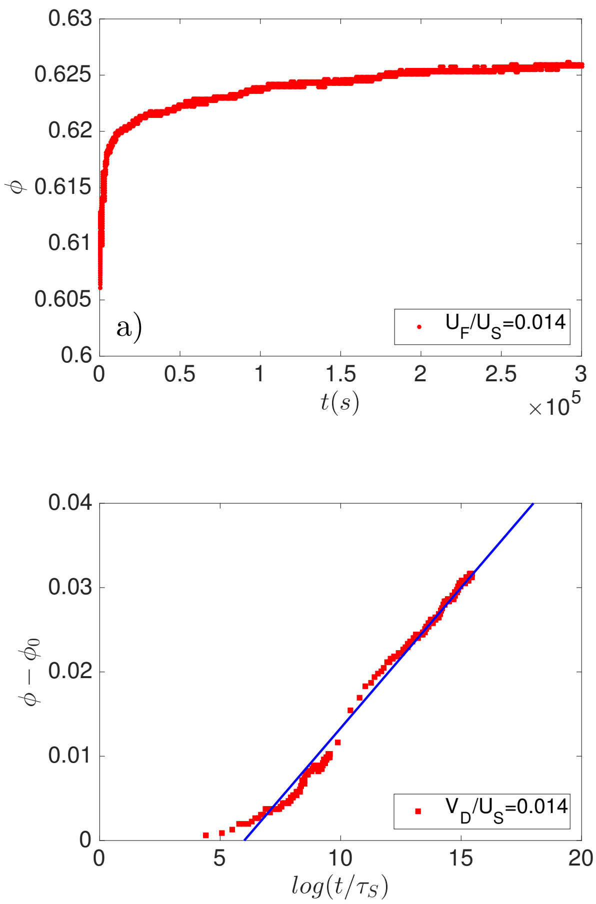

Figure 3. (a) Solid fraction ϕ of the granular bed as a function of time t for $U_F/U_S = 0.014$. (b) Solid fraction deviation from the initial value $\phi - \phi_0$ as a function of the normalized time t/τ_s. ( ) Experimental data and (—) fit of equation $\phi - \phi_0 = \alpha \log(1 + t/\tau)$ with $\tau/\tau_s \simeq 240$ and $\alpha \simeq 0.0022$.

evolution $\phi - \phi_0 = \alpha \ln(1 + t/\tau)$ with the characteristic time $\tau \simeq 15\,s$ and $\alpha \simeq 0.0022$.
By performing experiments at other U_F values, we observed that the characteristic time τ decreases for increasing flow velocity U_F as reported in Fig. 4. Note that it was not possible to perform experiments for $U_F/U_S \lesssim 0.008$ as the pump does not deliver a continuous flow anymore at such low flow rates. The data of Fig. 4 may be fitted by a linear decrease of equity that lead to $\tau = 0$ for $U_F/U_s = 0.0175$. As expected, this value corresponds very well to the critical fluidization velocity $U_c/U_s \simeq 0.018$ defined previously. Note that very close to U_c, we observe an intermittent regime, with successive phases of compaction and decompaction, as already reported in other situations such as in segregation/mixing of bidisperse fluidized suspension [14] or in the avalanche granular flows [15].

3.2 Flow taps

The effect of flow bursts on the solid fraction ϕ of the packing has been studied by varying the burst velocity U_F and

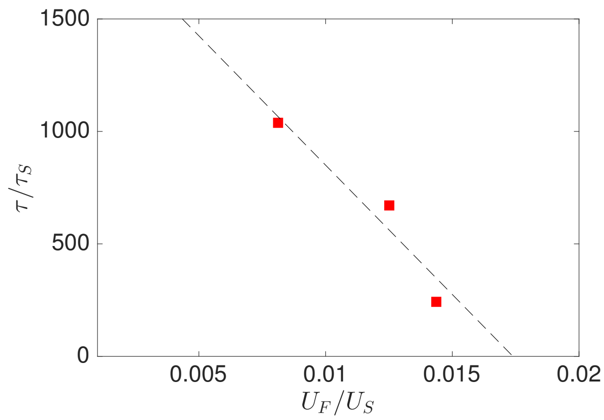

Figure 4. Normalized haracteristic time of compaction τ/τ_s as a function of the normalized upward flow velocity U_F/U_S in the continuous case.

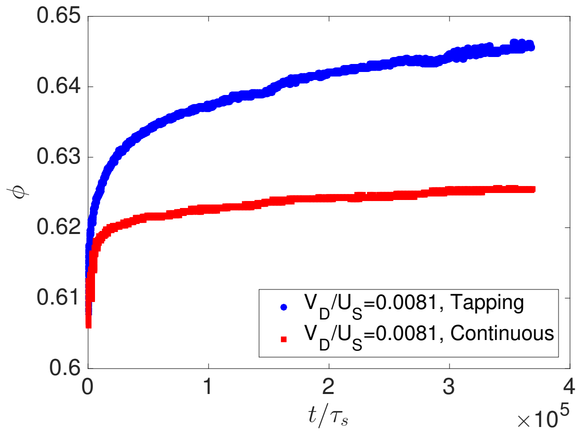

Figure 5. Time evolution of the solid fraction ϕ of the packing for the upward flow velocity $U_F/U_s = 0.0081$ in the (—) burst case and (—) continuous case.

the burst time τ_F but keeping constant the fluid displacement $U_F\tau_F = 0.54$ mm of the order of half the bead radius. The waiting time τ_w between two successive bursts has been kept constant at the value $\tau_w = 12\,s \gg \tau_s$ high enough to allow the subsequent completed sedimentation of the grains that may have been displaced during the burst flow.

Figure 5 displays the evolution of the solid fraction ϕ of the packing as a function of the normalized time t/τ_S for burst flow together with the continuous flow at the same flow velocity $U_F/U_s = 0.0081$ smaller than the critical fluidization U_c. One observe that such a burst flow lead also to a compaction and that the process is surprisingly more efficient than the continuous flow. For instance, at $t/\tau_S \simeq 1.3\,10^5$, $\phi \simeq 0.64$ corresponding to ϕ_{RCP} for the burst flow whereas $\phi \simeq 0.62$ in the continuous flow. Note that the solid fraction of the packing may be larger than the

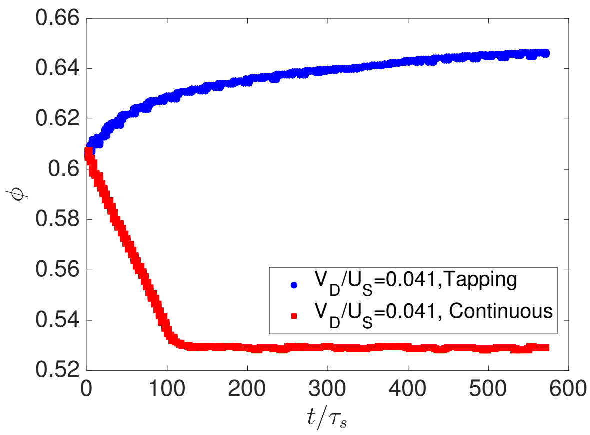

Figure 6. Time evolution of the solid fraction ϕ of the packing for the upward flow $U_F/U_s = 0.041$ in the (—) burst case and (—) continuous case.

RCP value flow and we observe due some crystallization initiates at the lateral walls before going further in the bulk. Figure 6 displays now $\phi(t)$ for burst flow together with the continuous flow at the same flow velocity $U_F/U_s = 0.041$ now larger smaller than the critical fluidization U_c. In such a case, $\phi(t)$ decreases linearly in the continuous flow before reaching the lower constant value $\phi \simeq 0.53$ as expected from the fluidization process and the corresponding RZ law. But the burst flow still leads to a surprising compaction, which we observed faster for increasing burst flow velocity U_f. Indeed ϕ_{RCP} is reached at $t/\tau_s \simeq 1.3\times10^5$ for $U_F/U_s = 0.008$ but only $t/\tau_s \simeq 2.5\times10^2$ are necessary for $U_F/U_s = 0.041$.

4 Conclusion

We have studied the compaction dynamics of a granular pile when submitted to weak upward viscous flow of velocity U_F. In the case of a continuous flow, the solid fraction ϕ is observed to increase when the flow velocity is below the critical velocity for fluidization U_c, with a logarithmic time evolution controlled by a characteristic time τ decreasing for increasing U_F. In the case of flow bursts, compaction is surprisingly more efficient than in the continuous flow and is also strikingly observed even when the burst flow velocity is larger than the critical velocity ($U_F > U_c$).

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