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Summary We report the influence of horizontal vibrations on the time-evolution of the density of a very cohesive powder. For a wide range of vibration conditions, the kinetics of compaction presents a two time-scales behavior compared to model materials. A simple stochastic model, based on clusters of grains, has been developed to understand the compaction process, and a new empirical law is proposed to describe the evolution of the packing fraction $\phi$.

## INTRODUCTION

Numerous studies have focused on the time-evolution of the compaction of non-cohesive granular system (monodisperse glass beads, rice grains ...) submitted to vibrations or vertical tapping. Through experiments, two main empirical laws have been proposed to describe the time evolution of the volume fraction $\phi$ with the number of taps or vibration cycles $t$. The first one, based on a heuristics analysis, is an inverse logarithmic law [1, 2]:

$$\phi(t) = \phi_\infty - \frac{\phi_\infty - \phi_0}{1 + B\ln(t/\tau)} \tag{1}$$

with $\phi_0$ the initial packing fraction, $\phi_\infty$, the final packing fraction, $\tau$, a characteristic time, and $B$, a fitting parameter. The second one is a modified Heckel equation [3] which has been written as a stretched exponential function with an exponent $\beta$ and a characteristic time $\tau$ [4]:

$$\phi = \phi_\infty - (\phi_\infty - \phi_0)\mathrm{e}^{-(t/\tau)^\beta}. \tag{2}$$

While these expressions may fit well the experimental results obtained with model materials, many actual granular media used in industrial process are not made of monodisperse smooth spheres. As an exemple, in the nuclear industry, the shaping process of fuel pellets uses cohesive powders. A cohesive granular system is characterized by a very large angle of repose, difficulties for filling or emptying a silo, and a very small packing fraction due to the presence of macro-cavities, bulk holes and vaults. Through long time experiments under horizontal vibration, we investigate the kinetics of compaction of a very cohesive $UO_2$ powder mainly used in the nuclear industry. The $UO_2$ powder we use is a complex granular system constituted of sub-micron crystallites, aggregates around $0.6$ $\mu$m and agglomerates with a mean diameter $d = 30$ $\mu$m. The powder was held in a vertical plane-parallel tank of different sections ($15 \times 15$ mm$^2$, $25 \times 25$ mm$^2$, $40 \times 40$ mm$^2$ and $40 \times 70$ mm$^2$). The tank is vibrated horizontally with a permanent magnet shaker with a frequency range of 30 to 100 Hz, and with a normalized acceleration from $3g$ to $9g$.

In order to compare our results on the cohesive $UO_2$ powder with non-cohesive and weakly cohesive materials, we have also investigated the compaction of monodisperse glass beads with a mean diameter $d = 130$ $\mu$m, and an atomized alumina powder with a size-range $0.1 - 60$ $\mu$m.

## RESULTS

A typical experimental result of the compaction process under horizontal vibrations is shown on Figure 1. The time evolution of the $UO_2$ powder compactness presents two stages of compaction. During the first stage, the packing fraction increases rapidly and approaches a plateau value as with model non-cohesive materials. During the second stage, a second increase occurs, much more slowly: even after $10^7$ cycles, the final state does not seem to be reached. We have also observed, through different characterizations (SEM, laser diffraction particle size analyzer, and mercury porosimetry), that the vibration process do not modify the agglomerates. Our result on glass beads compaction showing only one compaction stage is similar to the results of the literature. For the alumina powder, we observe a weak second increase between 600 and $2 \times 10^4$ cycles. The two-stages compaction then seems intrinsic to cohesive granular materials with a strong effect for highly cohesive powders. The expressions (1) and (2) are then not able to fit the experimental results on $UO_2$ and alumina powder.

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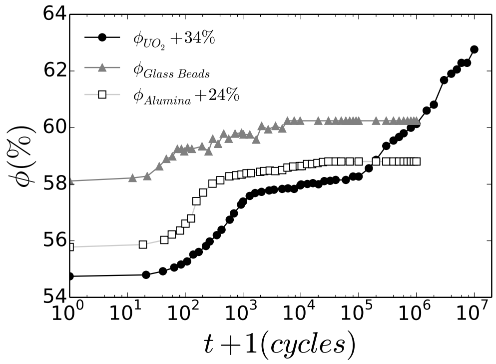


Figure 1: Examples of experimental results under horizontal vibrations at 100 $Hz$ and $7g$ acceleration. The tank was $15 \times 15$ mm$^2$.

The two-stages compaction process may be understood through a simple stochastic model. The model is a set of $N$ unit grains shared out between $N_c$ clusters of $n$ grains each. Clusters and grains inside each cluster are randomly placed with a linear fraction and without overlap. At each time step, the grains and the clusters may move according to probably laws $p_g$ and $p_c$ which are derived from normalized free volumes [6]. When a grain is allowed to move, it moves downward if the space below is free. When a cluster is allowed to move, it moves downward with a maximum falling distance of its size. The results obtained by this simulation show a two-stages evolution analog to the experimental results of the $UO_2$ powder. The first stage (short-time) is related to the compaction of clusters. It mimics the collapse of macro-cavities and large holes in a cohesive granular system. The time-scale of this first stage is proportional to the clusters number. The second stage (long-time) is related to the compaction of the individual grains, with a time scale proportional to the number of individual grains.

The experimental and numerical results are well fitted by an extension of the equation (2) with two stretched exponentials:

$$\phi = \phi_\infty - (\phi_\infty - \phi_p)\mathrm{e}^{-(t/\tau_2)^{\beta_2}} - (\phi_p - \phi_0)\mathrm{e}^{-(t/\tau_1)^{\beta_1}} \qquad (3)$$

with two characteristic times $\tau_1$ and $\tau_2$, two exponents $\beta_1$ and $\beta_2$, and a plateau packing fraction $\phi_p$. One of the main result of our study is that the characteristic times is proportional to the number of objects (clusters or grains). This result is also confirmed experimentally. Indeed, we observe that the characteristic times are related to the initial height in the tank. It seems also that the exponents $\beta_1$ and $\beta_2$ are linked to the probability laws and characterize the compaction rates of each stage. While a double exponential fit has already been proposed [7], we provide a very different interpretation of this expression, with a short-time scale associated to large-scale structures and a long-time scale associated to small-scales (but numerous) grains.

## CONCLUSION

Through experiments and a stochastic model, the compaction process of a cohesive powder is analyzed with a two-stages behavior. The time evolution of the volume fraction is very well fitted with a sum of two stretched exponential functions (3). While the physical origin of the exponents is still an open question, the characteristic time-scales are related to the number of moving structures (clusters or grains). The stochastic model may also be useful to describe the compaction of a non-cohesive granular material, and may be extended for multi-scales structures, leading to a multi-time-scales evolution of the packing fraction.

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