We study the compaction and mobility properties of a dense granular material under weak random vibration. By putting in direct contact millimetric glass beads with piezoelectric transducers we manage to inject energy to the system in a disordered manner with accelerations much smaller than gravity, resulting in a slow compaction dynamics and no convection. We characterize the mobility inside the medium by pulling through it an intruder grain at constant velocity. We present an extensive study of the relation between drag force and velocity for different vibration conditions and sizes of the intruder.

1 INTRODUCTION

Dynamics near jamming (glassy phase, aging, memory, intermittency) shows amazing analogies among a variety of very different systems (colloids, dense suspensions, foams, granular materials). Recently, several proposals have emerged with the aim of describing in a general and unified way this common behavior (Liu & Nagel 1998). With the idea of testing experimentally these, several studies have concentrated on granular materials under vibration. It was proposed that dense granular assemblies could be interesting models where a new kind of fluctuation-dissipation relations is likely to extend the classical notion of thermal temperature (Makse & Kurchan 2002). It was also suggested that a "structural temperature" could be a relevant concept that governs the granular reorganization dynamics around a local steady state in the jammed regime (Metha & Edwards 1989; Fierro et al. 2002). Experimentally, the dynamics of granular assemblies have been studied under different modes of excitation either under sinusoidal vibration or under sequences of taps. For granular assemblies under tap, density was shown to exhibit slow compaction regime and striking memory effects that resemble the phenomenology of spin glasses or ferro electric glasses (Nowak et al. 1998). Experimental determination of fluctuation-dissipation relation was also proposed, but it is not clear then, that in the weak agitation limit, the perturbing action of the probe can be decoupled from the intrinsic dynamics of the medium (D’anna et al. 2003). Moreover, in a regime where agitation is of the order or much larger than the acceleration of gravity, a granular assembly experiences two strongly distinct phases: an impact phase where grains reorganize and a launch phase where the average confining pressure is almost zero (free fall). In this last phase the resistance to external drag is almost inexistent and thus governs the mobility of an externally driven intruder (O. Zik & Rabin 1992). Furthermore, in all these situations, several studies have shown that boundaries generate convection effects that may couple strongly to the reorganization dynamics (Caballero et al. 2004; Philippe & Bideau 2003).

In this work, we propose a new mode of energy injection (sound waves) at high frequencies and low acceleration that produces a random agitation of the grains and suppress the convection effects. We present experiments on the mobility dynamics of an intruder driven in this weakly agitated medium.

2 EXPERIMENTAL SET-UP

Figure 1 schematically shows the experimental setup. A rectangular glass container is closed at its bottom by seven piezoelectric transducers, each one glued by its extremes to a plastic base in a way that the ceramic membrane is free to vibrate, being directly in contact with the grains only (figure 1 lateral view). The plastic bases of the transducers as well as the glass container are all fixed to a main plastic support. The container is filled with a bidisperse mixture of glass beads of 1 and 1.5mm and each piezoelectric is excited by...
Figure 1. Experimental setup. A glass container is closed at its bottom by seven piezoelectric transducers. The container is filled with a bidisperse mixture of glass beads of 1 and 1.5 mm that are in direct contact with the transducers. Each piezoelectric is excited by a 400 Hz square signal that is out of phase by $\pi$ compared to that of its neighbors. With this setup, the agitation created in the bulk is quite disordered and weak compared to typical experiments of vibrated granular materials (E.R. Nowak & Nagel 1998; Philippe & Bideau 2003; Kabla & Debregeas 2004) where all the container is shaken with accelerations of the order of or greater than gravity. The effective acceleration induced in the bulk is measured as a function of the input voltage with an accelerometer buried in the bulk. We found an homogeneous vibration level in the cell and a linear relation between driving voltage and effective acceleration level where the maximum voltage of 10 Volt corresponds to an rms acceleration ($\gamma_{rms}$) of 0.4 m/s$^2$. With such a weak excitation, the main mode excited in the system is the rotation of grains and re-organization of granular contacts. By tracking tracers we have verified that there is neither diffusion nor convection, at least for times as long as 24 hours.

3 MOBILITY AT CONSTANT VELOCITY

Figure 2. An Attwood-like machine is used to measure the drag force that results of driving an intruder bead glued to a metallic thread through the granular medium.

Figure 3. Evolution with time of the packing fraction of the granular pile vibrated at the maximum intensity ($\gamma_{rms} = 0.4 m/s^2$). There are shown ten independent experiments. Inset: Same data but with the time in logarithmic scale.

The packing fraction of the piling is obtained by placing a metallic lid on the surface of the pile and two inductive position sensors that measured the lid-sensor separation with a resolution of the order of micrometers (figure 2). Figure 3 shows the packing fraction evolution with time for ten different experiments vibrated at the maximum intensity. After fourteen hours of vibration a stationary state is not reached. However, since the compaction is logarithmic, at that stage the packing fraction can be considered as almost constant during the mobility experiments. Noteworthy is the reproducibility of the compaction curves for independent experiments, which allows us to say that mobility measures presented below were made at equal conditions.

The mobility experiment protocol was the following: 265 g of glass beads of 1 and 1.5 mm were poured in the container trying to make the upper surface as horizontal as possible without tapping the container. Then, the thread with the intruder grain was made to pass through the grains 16 mm deep from the surface of the pile (the total height was around 40 mm). The metallic lid was gently placed on the surface of the pile and the piezoelectric transducers were turned on at their maximum intensity ($\gamma_{rms} = 0.4 m/s^2$). After 14 hours of vibration the intruder grain was driven at constant velocity along ten centimeters.
For these experiments an intruder bead was glued to a $100\mu m$ metallic thread and we use two bead sizes of diameters $d_1 = 9$ and $d_2 = 2\mu m$. We also monitor the drag of the metallic thread alone. In figure 4 we show two examples of drag force measurements as a function of distance $x$ at a constant driving velocity of $10\mu m/s$. Measurements were performed without vibration and under a $0.4m/s^2$ acceleration. We also display a control experiment where bead and thread are driven at $100\mu m/s$ through the same path but without grains in the container. It represents the reference line and the intrinsic noise level of the Attwood setup. The mean drag force $< F_d >_x$ is obtained from $< F_d >_x = g(< W_0(x) - W(x) >_x)$, where $g$ is the acceleration of gravity, $W(x)$ is the weight measured by the gauge at position $x$ while driving the intruder bead through the grains, $W_0(x)$ is the weight measured at $x$ in the control experiment and the average is taken for displacement $2 < x < 8\mu m$. We already observe that the injection of sound waves strongly modifies the penetration resistance in the granular assembly.

Figure 5 shows the drag force as a function of the vibration intensity or, equivalently, the rms acceleration of the grains in the pile. Driving velocity was of vibration intensity which is expressed in terms of the rms acceleration of the grains in the pile.

Figure 6 shows drag force measurements for the $9\mu m$ bead with and without vibration. For the maximum vibration ($\gamma_{rms} = 0.4m/s^2$) the drag force increases logarithmically with velocity on three decades: $F \simeq F_0 \left(1 + \beta \ln \frac{V}{V_0}\right)$, with $F_0 = 2.10^{-2}, V_0 = 10^{-7}$ and $\beta = 0.144$. For $\gamma_{rms} = 0.2m/s^2$ the relation seems to be also logarithmic, though there are not many points. It is difficult to say something for the no vibration case because the variation in the value of the drag force, if any, is small compared to the error bar. In similar experiments in non vibrated granular materials, Albert et al. (R. Albert & Schiffer 1999) find a drag force independent of driving velocity, though they work with higher velocities than ours. In contrast, for small velocities but in a two dimensional setup, J. Geng and R. Behringer propose that there is a relaxation time associated to the smoothness of the grains which explains the rate dependence of the drag force. In our experiment as well as in that
of Albert et al., the rigidity of glass beads implies that there is not such a relaxation time and the drag force becomes independent of drag velocity. Thus, the logarithmic relation for vibrated experiments in figure 6 suggest that vibration introduces a relaxation time to the system and, consequently, a dependence of the force on velocity.

5 CONCLUSIONS
The relation between drag force and velocity of an object moving through a granular system has been studied for velocities and vibration conditions different from any previous work (O. Zik & Rabin 1992, R. Albert & Schiffer 1999, J. Geng & Behringer 2004). Vibration by an array of piezoelectric transducers allowed a weak and disordered agitation where the main mode excited is the rotation of the grains and tiny local reorganizations of a grain environment (contact distribution). The packing fraction exhibits a slow logarithmic growth when the pile is vibrated at the maximum available intensity for fourteen hours without reaching a stationary state. We have not yet performed compaction experiments for longer times so we do not even know the order of magnitude of the time required for stationarity or the possible effect that this could have on our rheology measures. So far, the only thing that we know is that all mobility experiments are done under equivalent density conditions.

In spite of accelerations much lower than the acceleration of gravity it was shown that the drag force depends significantly on the vibration intensity. Here we evidence a regime where at a constant energy input, the drag force increases in a logarithmic way with velocity. This result suggests an activated dynamics in analogy with solid on solid friction models (Rice & Ruina 1983, F. Heslot & Caroli 1994) and/or with glassy transition on thermal systems (M.D. Ediger & Nagel 1996). In the friction scenario the relevant parameter is an effective friction coefficient while in the glass analogy it is the viscosity. Both parameters are related to the temperature of the system, which means that the correct determination of an effective viscosity or a friction coefficient in granular systems would allow the definition of an effective granular temperature. In the regime we probe, we do not evidence a linear force/velocity relation that could validate a fluctuation dissipation approach to describe the local dynamics.

Acknowledgments This project is part of ECOS M03P01 and GC is supported by CONACYT and DGEP.

REFERENCES
A. Fierro, M. N. & Coniglio, A. 2002. Equilibrium distribution of the inherent states and their dynamics in glassy systems and granular media. Europhys. Lett. 59: 642.
E.R. Nowak, J.B. Knight, E. B. N. H. J. & Nagel, S. 1998. Density fluctuations in vibrated granular materials. Phys. Rev. E 57: 1971.
F. Heslot, T. Baumberger, B. P. B. C. & Caroli, C. 1994. Creep, stick-slip, and dry-friction dynamics: Experiments and a heuristic model. Phys. Rev. E 49: 4973.
G. Caballero, A. Lindner, G. O. G. R. J. L. & Clement, E. 2004. Experiments in randomly agitated granular assemblies close to the jamming transition. In Unifying concepts in granular media and glasses.
G. D’Anna, P. Mayor, A. B. V. L. & Nagel, S. 1998. Jamming is not just cool anymore. Nature 424: 909.
J. Geng & Behringer, R. 2004. Slow drag in 2d granular media. cond-mat 0406327.
Kabl, A. & Debregeas, G. 2004. Contact dynamics in a gently vibrated granular pile. Phys. Rev. Lett. 92: 035501.
Liu, A. & Nagel, S. 1998. Slow drag in 2d granular media. Europhys. Lett. 59: 642.
Makse, H. & Kurchan, J. 2002. Testing the thermodynamic approach to granular matter with a numerical model of a decisive experiment. Nature 415: 614.
M.D. Ediger, C. A. & Nagel, S. 1996. Supercooled liquids and glasses. J. Phys. Chem. 100: 13200.
Metha, A. & Edwards, S. 1989. Statistical mechanics of powder mixtures. Physica A 157: 1091.
O. Zik, J. S. & Rabin, Y. 1992. Mobility of a sphere in vibrated granular media. Europhys. Lett. 17: 315.
Philippe, P. & Bideau, D. 2003. Granular medium under vertical tapping: Change of compaction and convection dynamics around the liftoff threshold. Phys. Rev. Lett. 91: 104302.
R. Albert, M.A. Pfeifer, A.-L. B. & Schiffer, P. 1999. Slow drag in a granular medium. Phys. Rev. Lett. 82: 205.
Rice, J. & Ruina, A. 1983. Stability of steady frictional slipping. J. Appl. Mech. 50: 343.