The surface of our planet is covered by a disordered granular layer. When tilted under gravity, the majority of the time it creeps: particles slowly move downward, despite being under the critical angle (or critical stress) for avalanching. This study contributes to the fundamental understanding of granular creep, investigating how a particular mechanism—a gentle porous flow—enhances sediment creep under gravitational stress. In a quasi-2D microfluidic apparatus, sediment layer creep experiments were performed under sub-yielding angle and porous flow conditions. Logarithmic decay rates of the deformation are observed, with the rate increasing with both the tilt angle and porous flow rate. We identify a new dimensionless parameter, $P^*$, that accounts multiplicatively for the porous flow and sediment layer slope effects on particle motion; this allows a rescaling of all the widely dispersed creep deformation results on a single curve. This curve presents two very distinct creep regimes whose natures are not fully understood. However, observations of the void size distributions during the creep experiments also show a systematic change of the microstructure between the two regimes.

Significance Statement

Amorphous particulate materials, under small forces far from generating steady deformation are known to exhibit slow rearrangements and aging, often call "creep". Granular creep stays hardly understood, although it happens all the time and shapes hillslopes smooth. We show experimentally that a sediment bed traversed by a gentle porous flow slowly deforms—and creeps downward—due to the perturbations of small porous flow stresses on grains. That deformation rate correlates with both the mean system slope and fluid flow intensity acting together on the grains. Interestingly, those results are partly consistent with the sub-yield dynamics observed when temperature perturb grain piles. Our findings help predicting how landscapes change both slowly and rapidly due to precipitations; how they creep over hundreds years or landslide in few minutes.

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Fig. 2. (a) Sketch of the experimental apparatus, (top) from the camera point of view and (bottom) from the side. (b) Example of image analysis results, where the blue crosses is the detected bed surface elevation, and the green and magenta crosses are the detected particle centers and voids centers respectively. (c) Example of a analyzed image region, where the whole detected surface is represented (blue crosses), during an experiment at $\theta_{ap} = 9^\circ$ and $Q_f = 280$ µL/min. (d) Results of downward creep (over time, for experiments performed at (top) $\theta_{ap} = 6^\circ$, (middle) $15^\circ$ and (bottom) $21^\circ$. The gray scale is fixed and represent the range flow discharge intensity over which bed surface deformation was measurable; the darker the higher the flow discharge intensity.

slow compaction of fine particles generates vertical porous flows.

As temperature and stress conditions effects on amorphous material elasto-plasticity are intensely studied, it is perhaps not surprising that the effects of rain and hydrogeology on soil deformation remain puzzling. An important point is that the best empirical estimation (based on field observations) of the risk of onset for a landslide incorporates both rain intensity and duration, with the form of the risk function varying with the field site (9). Interestingly, two distinct types of dynamics have been monitored in the field: on one hand, water saturation of soils can, after some time, trigger sudden fast big avalanches (landslides); on the other hand, it can lead to a continuous increase in the creep rate observed in slow landslides (10). The first of these effects of water saturation recalls how vibrations trigger avalanching (11, 12), while the latter may be seen as similar to observations of creep in faults saturated by precipitation (13). At a much smaller scale, the latter also has similar features to the recent observation of the to influence of slight Brownian agitation on downward creep of suspensions of particles in the gravity-sensing mechanism of plant cells (14, 15).

Our goal is to decipher the effects of the local fluid flow on slow plastic rearrangements of particles. We investigate the phenomenon experimentally by a novel approach. For simplicity, we apply a gentle vertical porous flow to a settled bed of athermal spheres, which form a loose arrangement supported in part by frictional contacts, specifically considering the combined influence of tilt angle and flow strength. This study builds on previous work in the same setting, where we studied the dynamics of a horizontal (zero tilt) quasi-2D sediment layer subjected to a vertical porous flow at a range of intensities crossing the threshold for internal erosion, or channelization (16). This work systematically measured particle rearrangements for porous flows under the first channel criterion, showing the emergence of both a net particle lateral position fluctuation and compaction. In a gravitationally settled bed under weak flow, particles exhibit – individually or collectively – small rearrangements that allow further settling (a dynamics also recently observed in a 3D system (17)).

In this study, the influence of slope is central, as we explore sediment down-slope creep under the control of porous flow intensity. We consider the influence of the porous flow, at angles below the angle of repose and for porous flow strengths under the criterion of channelization. Interestingly, our results can be compared with recent experiments of Berut et al. (14), showing that piles of hard silica particles can creep downward due to slight Brownian agitation, with the creep rate found to be dependent only on the ratio of gravitational to thermal energy. Unlike those experiments, the definition of a new parameter, combining external gravity stress and internal fluid stress, is necessary to reconcile our observations, and when the creep rates are reduced using this parameter, two distinct regimes are observed.

**Experimental setup and protocol**

In a PDMS microfluidic cell of dimensions $L \times H \times \delta = 67 \text{ mm} \times 25 \text{ mm} \times 0.5 \text{ mm}$, filled completely with water (viscosity $\eta = 0.001 \text{ Pa s}$), a quasi-2D layer of polystyrene particles of mean diameter $d = 0.4 \text{ mm}$ is allowed to settle (see figure 2a). The gap is assured to be constant over the channel by using pre-manufactured sheets for molding. When the apparatus is tilted at an angle $\theta_{ap}$ from the horizontal, the mean stress resulting from an individual particle weight is $P_0 = \Delta p gd/3 \times \cos \theta_{ap}$, with the gravitational acceleration, $g$,
and the density difference $\Delta \rho = \rho_{\text{particle}} - \rho_{\text{water}} = 50 \text{kg.m}^{-3}$.

The layer of particles rests on a grid which forms a part of the microfluidic channel, made up of 0.5 mm diameter pylons separated by 0.3 mm. The side walls in the long dimension of the channel are roughened, using a pattern of half pylons to mimic the grid surface roughness. The front and back walls are transparent and smooth, and their surface is treated to be hydrophilic (details in Material and Methods). The quasi-2D configuration results essentially in a monolayer, such that particles are only able to be offset slightly in the depth (z) direction (see figure 2b), with the experimental advantage that all voids are visible. The sediment bed height is always about 40 $d$, and its width is 168 $d$. To avoid significant lateral wall effects, particle dynamics were observed at the center of the image center, over a region of 50$d \times 100$d, as shown on figure 2c.

For each experiment, the same protocol was followed. First the sediment layer was prepared (details in Material and Methods section), and thereafter, the camera (EOS rebel t3i) and syringe pump (Harvard PHD2000) were simultaneously started, taking photos and injecting a constant fluid discharge $Q_f$ through the bed. At the same time, the apparatus tilt was set from 0 to the angle $\theta_{\text{ap}} > 0$. The hydrostatic pressure inside the system was maintained constant over all the experiments by a water tower whose water surface level is kept at a fixed distance from the center of the channel. The range of flow discharge explored is $70 < Q_f < 285 \mu \text{L/min}$.

Photos were taken every four seconds for the first five minutes of the experiments, and then every 28 seconds for the next hours. Experiment durations were limited by the syringe pump (Harvard PHD2000) and the image resolution is on average 855 pixel per particle cross section area, and is sufficient that all voids can be detected. On each image, the bed surface, particle centers and thereafter voids sizes are detected (more details in Material and Methods). An example of typical results is given in figure 2b and 2c. The detected bed surface is fit by a line to measure the bed surface angle over time $\theta(t)$.

A separate set of experiments without porous flow was performed to assess the critical angle – after taking the bed above its critical stress – at which pure particles avalanching stops in the experimental setup. This angle was determined to $\theta_{\text{stop}} = 32 \pm 0.5^\circ$ (see Supporting Information text and figure S1).

**Experimental creep results**

We performed six series of experiments at different apparatus angles $\theta_{\text{ap}} = 27, 21, 15, 9, 6$ and 3$, all significantly lower than the critical angle $\theta_{\text{stop}}$. For each of those series, the imposed flow discharge $Q_f$ is varied, and each set of control parameters ($\theta_{\text{ap}}, Q_f$) was repeated three times.

For each experimental series, a similar phenomenology is observed: as the porous flow traverses the bed, the resulting drag causes some particles to rearrange, and, depending on the control parameters, particles eventually start to move down the slope collectively. For larger slope and flow rate, the collective rearrangements and plastic events are also larger and more rapid. Conversely, at very low angle and flow discharge collective, rearrangements – if any occur – are less frequent and smaller, although the entire settled layer often demonstrates continuous compaction, as previously observed for experiments on horizontal beds (16). In these slow-regime experiments, the bed surface topography we record from image analysis is partially deformed while plastic events slowly propagate downward. Consequently, at given frequency of measurement and system size, the measurement of bed surface slope with time becomes intrinsically more uncertain. In another extreme regime, at high porous flow rate $Q_f$, the system exhibits the channelization instability, and the bed surface is very deformed (16): tracking of the surface angle is then neither possible nor relevant. Data presented in the following represent the dynamics between those two extreme cases, as do the movies 1 and 2 in the Supporting Information.

Figure 2d shows a subset of the data of bed surface slope evolution with time, at three different apparatus tilt angles, namely $\theta_{\text{ap}} = 6, 15,$ and 21$. These data are presented over the range of flow discharges for which we were able to detect deformation. The gray scale is fixed to represent the intensity of the flow discharge $Q_f$. Beyond a certain flow discharge, for each $\theta_{\text{ap}}$, most experiments exhibited a bed surface angle decay with time. The most rapid period of decay typically exhibited a logarithmic trend $\theta \propto \log(t)$, with faster decay at higher discharge rate.

When the fastest decay persisted over more than an order of magnitude of time, the trend of $d\theta/d(\log(t^*))$ over that time range was obtained by fitting the data with a linear function $\theta = \alpha \log(t^*) + \beta$. $t^*$ is the dimensionless time $t^* = t/\tau(P_{\text{drag}}/P_0)$, where the characteristic time scale $\tau = L^2 \eta/(\Delta \rho g d^3)$, comes from derivation of the sediment volume conservation and the surface angle change, and assuming particles velocity is the settling velocity (14). For all our experiments $\tau$ is constant and equal to 143 seconds. Time is also normalized by the dimensionless parameter defined in the vertical direction:

$$
\frac{P_{\text{drag}}}{P_0} = \frac{9 \eta U_{\text{bed}} \cos \theta_{\text{ap}}}{\Delta \rho g d^2} \propto \frac{F_{\text{drag,y}}}{P_0},
$$

with $P_0$ the weight stress of a particle, and the initial mean flow velocity inside the bed $U_{\text{bed}} = Q_f/[(1 - (\Phi_0))/6W]$, using $(\Phi_0) = 0.68$, the initial packing fraction value found (from image analysis) from averaging over all experiments (see values distributions in Supplementary Informations). The normalization of time by $P_{\text{drag}}/P_0$ takes into account the net effect of the flow mean stress pushing the particles, although it remains far below the criterion to lift a particle for all our experiments ($0 \leq P_{\text{drag}}/P_0 < 6\%$). The range of mean flow velocity $U_{\text{bed}}$ explored was $[0.1, 0.45]$ mm.s$^{-1}$.

Figure 3a presents the values of $\alpha$ as a function of the initial bed surface angle from the time region used for the data fit $\theta_{\text{tot}}$ (see figure 2d), while figure 3b presents the same data as a function of $P_{\text{drag}}/P_0$. First and importantly, due to the porous flow, measurable deformations are found until far under the yield criterion ($\theta_{\text{tot}} \geq \theta_{\text{stop}}$); even for angles lower than 8$, the angle of repose for frictionless particles. Second, the rate of logarithmic deformation with time is found to increase both with the bed surface angle, and the porous flow intensity, although the influence of the flow remains very weak relative to the particle weight.

These observations are generally consistent with our previous experiments made at $\theta_{\text{ap}} = 0$. In those experiments, the channelization instability was observed at $P_{\text{drag}}/P_0 = 0.064 \pm 0.02$, and below that level of forcing by the flow, particle rearrangements leading to net compaction were detectable.
Logarithmic decay rate $\alpha$ with time, as a function of the angle at the beginning of the time period over which the curve fitting was performed, $\theta_{\text{init}}$. (b) $\alpha$ reported as a function of the normalized averaged porous flow stress on particles, $P_{\text{drag}}/P_0$. Colors represent different experiment series, with blue, magenta, cyan, green, yellow and red squares (or light to dark gray squares) respectively representing series performed with $\theta_{\text{ap}} = 3, 6, 9, 15, 21$ and 27°. Black squares represent data for the four pure avalanching experiments (two fits per experiment, using artificially $P_{\text{drag}}/P_0 = 0.01$ for time normalization. See all data in dimensional form on figure S12).

for $P_{\text{drag}}/P_0 > 0.04$ (16). This range of drag due to the porous flow overlaps with the region of net downward deformation observed at the smaller angle $\theta_{\text{ap}} = 3^\circ$. As $\theta_{\text{ap}}$ increases, deformation is observed at weaker porous flow rates.

We propose here a new parameter combining multiplicatively the observed effects of porous flow intensity and the distance to the critical angle on the creep rate: 

$$P^* = \frac{P_{\text{drag}}}{P_0} \times (\tan \theta_{\text{stop}} - \tan \theta_{\text{init}})^{-n},$$  \[1\] 

with $n$ a positive number. On figure 4 the data of logarithmic decay $\alpha$ are reported as a function of $P^*$ using $n = 3/4$, which successfully provides a collapse of all the data of deformation logarithmic rates. The collapse remains satisfying in the range $2/3 \leq n \leq 1$ (see results for different values of $n$ in Supporting Information). While it is expected that the dynamics should have an essential dependence on the gravitational driving force represented by the difference between $\theta_{\text{stop}}$ and $\theta_{\text{init}}$, we do not have a physical explanation for the specific form in (1).

Remarkably, two very distinct trends are followed by the logarithmic decay rate presented as a function of $P^*$. These are seen on figure 4, for $0 < P^* \lesssim 0.1$ and $P^* \gtrsim 0.1$. To aid in seeing these trends, we present on the figure two functions which visually capture the two regimes, an exponential form $\alpha = 130 \exp(P^* - 0.095)$ for $P^* \lesssim 0.1$ and $\alpha = 12P^*$ for $P^* > 0.1$.

Data exhibit some dispersion around the trends, but remain quite satisfactory given that they all come from experiments performed in the creep domain ($\theta_{\text{ap}} < \theta_{\text{stop}}$) and near a free surface, both conditions that make reproducibility delicate.

Finally, figure 5a presents measurements of void size distribution, from the final image of all the experiments; these are representative of the distribution at any time, although some slight time evolution can be observed. Void sizes are normalized by the surface of an average particle $S_p = \pi (d/2)^2$ (: 855pxl on our images), which allows for comparison with three theoretical values of pores for a perfectly 2D layer: 1) the void size between three cylinders in contact $(2/\pi - 1/2)S_p \simeq 0.137S_p$, 2) the void size between four cylinders in contact $2(2/\pi - 1/2)S_p \simeq 0.27S_p$, and 3) the voids size between five cylinders in contact and forming a regular pentagon for which the void size is $\simeq 0.68S_p$.

All experiments present a peak at $S_v/S_p \simeq 0.11$, which represents voids made by three contacting particles. We interpret the fact that it is smaller than the value of case 1 in the prior paragraph as being due to slight three-dimensional organization. All experiments show a dip in the void distribution near $S_v/S_p \simeq 0.16$, followed by a second peak. The second peak is centered on the value from four contacting particles or case 2 above, and is substantially wider than the first peak owing to the deformation possible for this structure.

Although on first approximation all void distribution curves fall on top of each other, one can observe some systematic difference of the void sizes distribution as $P^*$ increases; in particular, there is a slight shift to larger void size in the
second peak, and a slight decay of the height of the first peak. These two signatures of microscopic arrangement change are consistent with an overall increase of the mean void size (computed over the fitting time windows used to compute $\alpha$) with $P^*$, as presented in figure 5b. Remarkably, the transition at $P^* \simeq 0.1$ observed on figure 4 is also marked in term of particles structure, as it corresponds to where the mean void size crosses the characteristic value of the voids made by four particles in contact in 2D: $S_v \simeq 0.27S_p$.

Discussion

Those new experimental results demonstrate that weak porous flow is (1) able to trigger downward sediment creep far under the criteria for either internal erosion (channelization) or pure avalanching, and (2) that the porous flow intensity also governs the creep deformation rate. This has implications for industrial processes using fluid for fluidizing and manipulating a mixture (18, 19). It also has important potential for improving modeling of the inception of erosion or avalanching in nature, as well as the duration of these events. These events occur on land where porous flow dynamics and its connection to sediment transport are active research areas (20–22), and our work is perhaps even more directly relevant for such events under the sea, where vertical porous flow due to sediment bed compaction is argued to be an important phenomenon (23, 24).

Prior studies have shown that there is a porous flow effect on the plastic dynamics of disordered particulate material, but they leave open the question of the fundamental nature of this effect. Indeed previous studies have investigated how temperature, a given level of stress annealing, or vibration could change the plastic behavior of glassy materials at a given external stress. It is reasonable to interpret our results as implying that porous flow-induced stresses may have different primary effects on the plastic behavior of amorphous particle assemblies depending on their intensity and the system susceptibility to particle rearrangements. In a similar vein, Cao et al. (4) concluded with regard to the molecular dynamics they observed during metallic glass creep: “At low stress and high temperature, the dominant mechanism is observed to be thermally activated particle flow, while at high stress, the mechanism is a more complex process of stress-induced enhanced local shear deformation and atomic diffusion.”

In our study, the linear dependence of the decay rate on $P^*$ for $P^* \geq 0.1$ interestingly echoes recent experimental results by Bérut et al. (14) of downward creep of piles made of buoyant hard particles, small enough to exhibit weak Brownian motion. Bérut et al. report the increase of the logarithmic decay with dimensionless time, $\alpha$, with $Pe^{-1}$ where $Pe$ is the Péclet number, the ratio of the thermal agitation force to the gravity acting on one grain. They also show analytically that this trend should be linear for small bed surface angle and small $Pe^{-1}$, considering motion by particle hopping over one another (an assumption the authors themselves present as simplistic). If we assume that fluid flow causes varying local forces that can have a similar perturbing effect on particles, it is plausible that $P_{\text{drag}}/P_0$ also drives a linear increase of $\alpha$. For this reason, we report the trend observed by Bérut et al. on figure 3b; this shows that the effect of porous flow – and perhaps also temperature agitation – is generally more complicated, and that subsurface dynamics is likely to be relevant. Indeed, our results seem to present such linear behavior with $P_{\text{drag}}/P_0$ for the series the closest to the critical angle of avalanche ($\theta_{\text{ap}} = 37^\circ$). For $P^* < 0.1$, and $\alpha < 1$, creep takes place, but the rate of logarithmic deformation $\alpha$ falls rapidly for smaller $P^*$.

We do not have a clear explanation now for the change of creep regime seen in figure 4, but the systematic change of mean void size through the transition at $P^* \simeq 0.1$ provides some support for physical reasonings. First, the mean void size increase with $P_{\text{drag}}/P_0$ can be understood as the result of a fraction of the particle weight in the bed being supported by flow stress, and not only by particle-particle contacts. Second, as $\theta$ becomes closer to $\theta_{\text{stop}}$, the potential energy in the system is higher, which increases the likelihood of, and resulting size of, collective rearrangements (25, 26). As these motions occur in the presence of a free surface, they can break old and create new voids, which can be bigger than average, given that they have not aged yet. Consequently, the general increase of mean void size with $P^*$ can be rationalized; the saturation to a
certain value of the mean size seems to imply that larger void creation stops increasing. The foregoing assumes the system remains far from the channelization criterion. The smaller void sizes in the exponential regime ($P^* \leq 0.1$) may result from different factors: as the rate of deformation becomes very slow and the potential energy is low (as the angle is lower), the particle bed is able to creep while staying compacted, via sliding rather than rolling particle displacements. This last scenario is consistent with our previous results of fluidization in the same apparatus (at $\theta_{\text{ap}} = 0$, where net bed compaction is observed at small $P_{\text{drag}}/P_b$). This reading of our results would associate the change of regimes as $P^*$ increases with a transition from a frictional-sliding dominated flow regime to a rolling-dominated one (27).

Our results are generally consistent with recent experiments by Gaudel et al. (28), which showed how vibrations suppress the critical angle $\theta_{\text{stop}}$, defined as the angle at which the system stops avalanching no matter how thick the stopping layer is. As vibration frequency and amplitude are increased, the granular layer keeps flowing at smaller and smaller thicknesses and angles. Interestingly, these authors observe two different effects of vibrations, for cases where $\theta_{\text{ap}} > \theta_{\text{stop}}$ and $\theta_{\text{ap}} \leq \theta_{\text{stop}}$. For those experiments, angle appears to be another control parameter (of the stopping thickness) for flows above critical, but not for sub-critical ones. However, creep experiments by Pons et al.(5) find a continuous effect of stress fluctuations on steady creep rate, but different for each mean imposed stress. This was also generally observed recently in long DEM simulations of dry systems by Ferdowski et al. (27). These important differences of behavior with mean stress seem to suggest that porous flow effects on creep rate are more related to the influence of stress fluctuations than vibrations.

Finally, the theoretical approach of considering statistics of the distances to the critical stress distribution, or stress annealing level in amorphous materials, appears the most relevant for further elucidating the coupled dynamics of porous flow and granular plastic deformation. Recent studies of the kind have made notable progress in understanding amorphous system dynamics near yielding (5, 7, 8). We believe that future efforts on coupling such models with the dynamics of porous flow could provide substantial insight.

Conclusion
We report here novel experimental observations of sub-yield granular deformation under gravity and weak porous flow stress. The tilted layer of grains exhibits a logarithmic decay of its slope with time, a classical creep mechanical behavior. The decay rate appears to scale with both the intensity of the mean gravity stress on particle-particle contacts (the system slope), and the intensity of mean porous flow stress on particles. We reconcile all our observations by proposing a new parameter, $P^*$ (see Eqn. 1) combining multiplicatively the porous flow stress and the distance to the critical gravity stress (or critical avalanching slope). The results open a new perspectives on modeling the long-time dynamics and failure of wet granular systems, and soils and sea beds in particular.

**Materials and Methods**

Readers will be able to access the data in the paper on ...

**Microfluidic channel making.** The channel was made of two PDMS slices, with one side etched with the channel geometry using photolithography techniques. To have very good flatness and constant depth of the channel, the mold master was made using SU8 pre-made 500 μm sheets of 96 mm diameter (from DJ MicroLami-nates, Inc). The sheet was thereafter laminated onto a wafer, using heat- and speed-controlled Sky 335R6 Laminator. To assemble the two PDMS slices, their faces were first treated with a plasma cleaner, and they were baked after assembled. Finally, before being filled, the channel interior surfaces were oxidized and silanized with polyethylene glycol (PEG), in order to make them hydrophilic. Finally, due to the fact that the channel is large by microfluidic standards, and experiments were relatively long and performed vertically, special care was taken to prevent channel deformation over time. In particular extra sealing PDMS joints were made along the PDMS slices contact corners, and the use of fluids (such as silicon oils) which penetrate PDMS over long time was avoided.

**Sediment layer preparation.** Before each experiment, the sediment layer was prepared following the steps: 1) At setup angle $\theta = 0^\circ$, water flow was injected from below, at a rate sufficient to re-suspend all of the particles. 2) While the particles were in suspension, the angle was changed to $+15^\circ$, so that particles settled down toward one end of the channel. 3) The angle was changed to $-15^\circ$, and an upward flow discharge of 215 mL/min was imposed, in order to trigger a slow particle flow down the slope, flattening the bed and making the bed surface parallel to the grid after 2 to 5 min. 4) The setup angle was then returned to $\theta = 0^\circ$, and the bed was weakly re-suspended again by a short manual injection, which displaced the particles just a few millimeters above the grid. The goal of this step is to remove structural anisotropy that may have developed in the preceding steps, thus enhancing the randomness of the porous media and contact network. 5) Immediately after particle settling in step 4, a suspended mass (of 300 g) was used to tap the channel, just once on the side, in order to make the layer compact. 6) The system was let age for 5 min. before beginning the experiment.

**Image analysis.** Images are analyzed to extract statistical information on the voids at each sampling instant. Using Python module OpenCV each image is first binarized using local thresholding, with particle centers identified as bright objects of circular shape within a size range using TrackPy Python module (29). Subsequent treatment makes the bright particle centers dark, in order to only have the voids left bright. From this modified version of the images, the bed surface topography is extracted as the top part of the largest object contour in the system, and voids are detected below the bed surface.

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