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The perpetual fragility of creeping hillslopes

Nakul S. Deshpande[1], David J. Furbish[2,3], Paulo E. Arratia[4], and Douglas J. Jerolmack[1,4]

[1] *Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
[2] *Departments of Earth and Environmental Sciences Vanderbilt University, Nashville, Tennessee, USA*
[3] *Civil and Environmental Engineering, Vanderbilt University, Nashville, Tennessee, USA*
[4] *Department of Mechanical Engineering & Applied Mechanics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*

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Abstract

Soil-mantled hillslopes owe their smooth, convex shape to creep[1,2]; the slow and persistent, gravity-driven motion of grains on slopes below the angle of repose. Existing models presume that soil creep occurs via mechanical displacement of grains by (bio)physical disturbances[3,4]. Recent simulations[5], however, suggest that soil can creep without these disturbances, due to internal relaxation dynamics characteristic of disordered and fragile solids such as glass. Here we report experimental observations of creeping motion in an undisturbed sandpile, at micron resolution over timescales of $10^0 - 10^6$ s, for a variety of natural and synthetic granular materials. We observe two behaviors typically associated with creeping glass: strain occurs as localized and spatially-heterogeneous grain motions[6] ; and creep rates decay as a power-law function of time[7]. Further, creep can be accelerated or suppressed by thermal cycles and shaking, respectively. Averaged strain profiles decay exponentially with depth, in agreement with field observations of creeping hillslope soils[8–10]. Our findings demonstrate that soil is fragile in terms of sensitivity to disturbances, but that creep dynamics are robust across grains and glasses. Mapping soil creep to the more generic glass problem provides a new framework for modeling hillslope sediment transport, and new insights on the nature of yield and failure.

Keywords— geomorphology, granular physics, glassy dynamics, relaxation and rejuvenation, aging

Introduction

The shapes of hills encode a signature of tectonics, climate and life, through the influence of these processes on sediment transport[4,11–13]. Soil fails by landslides on the steepest slopes, leaving telltale scars on the landscape. Below the angle of repose, however, soil-mantled hillslopes are characteristically smooth and convex[4,13]. Although this soil is considered a solid, it appears to flow over geologic time in a process called soil creep[14,15]. What is the mechanism for granular motion below the angle of repose? This has been speculated on for over 100 years[1,2]. Modern treatments trace their origin to Culling[3], who envisioned that the net effect of environmental disturbances (biological, hydrological and physical) acting on and within soil was to inject porosity, which facilitates particle motion. He also recognized that porosity, and the associated particle activity, must diminish with depth. In the continuum limit Culling proposed a diffusion-like relation between sediment flux and topographic gradient, that has been elaborated on by many authors and implemented in virtually all landscape evolution models[4,13,15–18]. Remarkably, the hypothesized grain motions in Culling's model have never been experimentally examined. More broadly, Culling's mathematical formulation corresponds to a physical picture of soil as a peculiar kind of "granular gas" (Supplementary Materials Section S1) that is inconsistent with known granular mechanics. Researchers have begun to recognize the need to understand grain-scale dynamics, in order to derive physically-informed models of soil mixing and transport on hillslopes[19,20]. While tracers have been used for over 60 years to measure coarse profiles of soil displacement on hillslopes[14], the slow and erratic nature of creep has prevented direct observation of grain motions in the field. The canonical hillslope laboratory experiment of Roering and colleagues[21] showed how acoustic noise can induce grain motion below the angle of repose; however, our reanalysis indicates that grains were actually fluidized into inertial flows, rather than sub-critical creep (Fig. S1).

Creep has also been recognized in the context of dense granular flows. These flows have been modeled with a local '$\mu(I)$ rheology' where the effective friction (μ) is a function of a dimensionless shear rate called the inertial number, $I \equiv \dot{\epsilon}d/\sqrt{P/\rho}$, where $\dot{\epsilon}$ is shear rate, d is grain size, P is confining pressure and ρ is density[22]. Inertial flows transition at depth to a slow creep regime, characterized by intermittent and apparently random particle motions[23,24] and exponential velocity profiles[25,26]. Recent experiments and simulations suggest the transition to creep occurs below $I \sim 10^{-5}$ (refs.[5,26,27]). The local $\mu(I)$ rheology predicts that grains should be static below yield, and therefore cannot describe the creep regime[26]. To account for creep, nonlocal models have been proposed in which fluidized motions from the inertial regime diffuse downward into the bulk[28]. However, recent experiments have revealed creep in the absence of a flowing layer[29,30]. Observations in a progressively tilted sandbox showed that, on approach to the angle of repose, sporadic and localized grain motions became more frequent and eventually linked up to affect yield[29]. Granular simulations have reproduced these behaviors without any imposed disturbances[5]. The addition of low-amplitude ($\ll d$), random perturbations accelerated simulated creep rates, but did not qualitatively change the dynamics[5,31]; however, the spectrum of disturbances explored in these models is quite limited.

Creep in amorphous solids, such as glass, is associated with sub-yield plastic deformation in response to an applied stress[6]. A unifying characteristic of amorphous solids is that they are fragile: any particle configuration is metastable, and very small perturbations can lead to structural rearrangements[27,32]. These creep motions are manifest as spatially heterogeneous, mesocopic (length $\gg d$) zones of strain[6]. In glasses, relaxation by plastic rearrangements leads to aging; rigidity increases with time, leading to a slow down in creep rates. This decline in plasticity can be reversed by rejuvenation, typically by changing temperature[33]. There is emerging evidence that granular creep shares deep similarities with glasses[5,27], and theorists have proposed that mechanical noise in granular systems may modulate creep in an analogous manner to thermal fluctuations in glasses[7,34]. No experiments, however, have been conducted to test these ideas. In this study we examine creep dynamics of an undisturbed sub-critical sandpile, probing grain motions through time using an optical technique that allows us to observe exceedingly slow strain rates. Creep behavior in the sandpile exhibits all of the hallmarks of relaxation in glassy materials. We also explore how disturbances can enhance or reverse aging, completing the picture of soil creep as relaxation and rejuvenation of a fragile solid and illustrating that in the natural environment, hillslopes are made perpetually fragile by environmental perturbations. Comparisons of experimental creep profiles with data from natural hillslopes indicate that laboratory observations are generalizable.

Undisturbed creep results

Our first objective is to demonstrate the existence of creep in a minimally-disturbed model hillslope. Based on previous work[5,23,25,26,29], we expect creep rates to be exceedingly slow ($\leq 10^{-6} m/s$) which makes typical particle tracking methods impractical. Instead, we measure grain motions via spatially-resolved Diffusing Wave Spectroscopy (DWS)[35], which determines strain associated with changes in the granular structure that occur on the order of the optical wavelength (10^{-6}m) (see Methods). Our experimental system consists of a granular heap initially prepared (time $t = 0$) just below the angle of repose, that is confined in an acrylic cell (Fig. 1) sitting on a vibration-isolating optical table (see Methods, Fig. S2). Most experiments used glass beads with ideal optical properties; however, natural sand, and a mixture of equal parts sand and kaolinite powder, were also tested (Fig. S3).

The first important result is that creep occurred for all experiments and granular materials, and it persisted over all observed timescales ($10^0 - 10^6$ s M1-4). Initial creep velocities ($t = 0$) were on the order of nm/s (cm/year) i.e., comparable to measured rates of hillslope soil creep in the field (see below) – and we confirmed that inertial numbers for undisturbed creep were all below yield ($I < 10^{-5}$) (Figs. S4, S5). All experiments exhibited glass-like 'spatially-heterogeneous dynamics'[6], manifest as discrete, mesoscopic ($\gg d$) zones of strain that occurred throughout the system (Fig. 1c). At early times, these deformation zones were relatively larger and more concentrated near the sandpile surface. At later times these zones became smaller and occur less frequently, with lower spatial density. Cumulative strain ϵ resulting from this deformation diminished with depth beneath the surface because of increasing confining pressure, which restricts dilation that is often associated with grain rearrangement[23,29] (Fig.4b). We also observed sensitivity to the preparation protocol, a ubiquitous phenomenon in fragile solids[36]. For example: the region of intense and persistent deformation seen near the pile apex (Figs. 1; 3 M1) always occurred at the location where avalanches had formed when the sand was first poured.

Information on the time-dependent dynamics of creeping motion in the pile is encoded in the correlation function G of the speckle patterns (see Methods). In the experiments reported here, G decayed monotonically with lag time τ; this decay was most rapid at early times t indicating fast grain motions, and slowed through time (Fig. 2). Normalizing the lag time of each correlation by the e-folding time, we find that the curves $G(\tau/\tau_e)$ collapse onto a single exponential master curve (Fig. 2) consistent with previous observations of granular creep[23] and molecular dynamics simulations of glass[37]. The growth of the relaxation timescale τ_e increased as a power-law function of time (Fig. 2). Such power-law 'aging' is a classical behavior of creeping glass and other amorphous solids[7]. Our interpretation is that the initially loose sandpile has many 'soft spots'[32] associated with low packing density and/or frictional contacts, and that strain relaxes these soft spots, redistributing stress within the system, leading to an overall slowing down of creep with time[7].

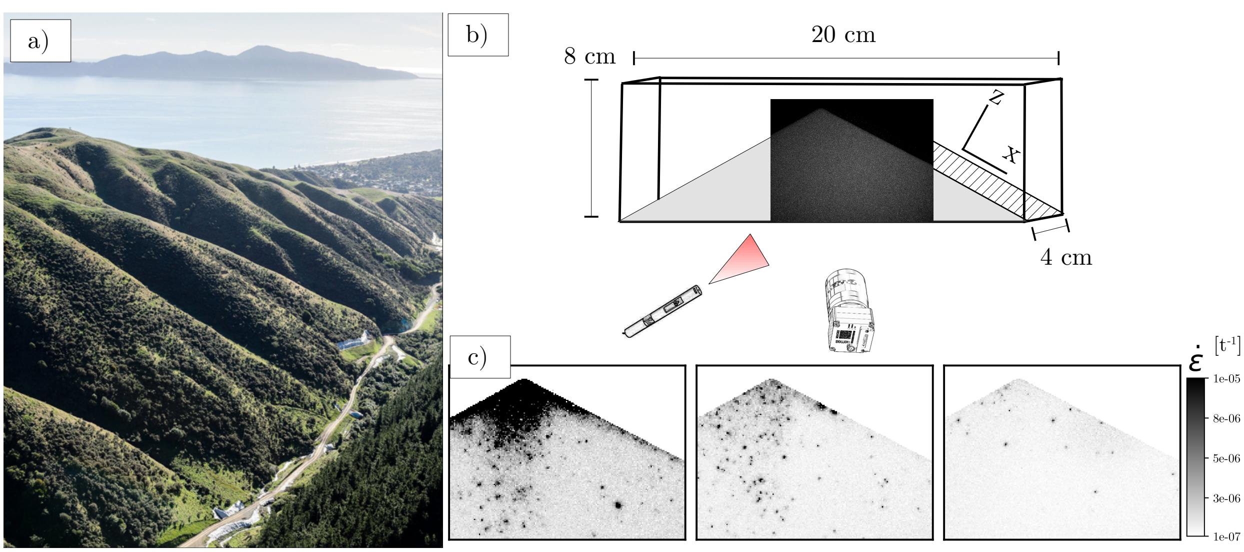

Figure 1: Experimental setup and phenomenology. a) Soil-mantled hillslope in the Te Puka Valley, New Zealand (PC: Waka Tokahi, NZ Transport Agency). b) Experimental DWS setup. c) Spatially-resolved maps of creep rates at three times ($t = 1, t = 16$ and $t = 1024$ s) since building the pile.

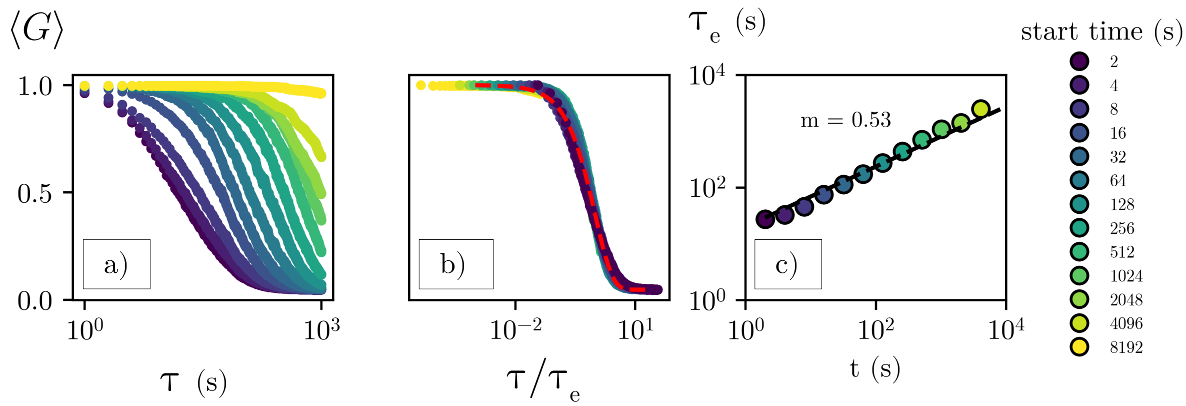

Figure 2: Glassy relaxation in an undisturbed granular heap. a) Spatially-averaged correlation function for 13 start times. b) Data are reasonably collapsed by τ_e; red dotted line indicates exponential decay. c) Growth of the relaxation timescale; slope determined from least-squares regression of $t = t_0 \tau_e^m$, where $m = 0.53$.

The role of mechanical disturbances

In the above description, granular creep progressively slows down. In this picture of relaxation, creep rates should tend asymptotically toward zero with time. Not all of our experiments, however, exhibited this behavior. Humidity fluctuations occurred for some runs, producing a complex response in terms of creep dynamics – notably at late start times (Fig. S8). Data indicate that some reversible (elastic) strain occurred in these runs — perhaps due to nanoscale capillary bridges or other tribological effects[38,39]. Similar behavior has been seen for weakly heated granular materials[35,40], suggesting that some kinds of disturbance may reverse relaxation and reactivate creep.

Natural hillslopes appear to creep indefinitely, and they are perpetually disturbed: bombarded by seismic waves, thermal cycles, wetting and drying, and bioturbation[8–10,16,41,42]. We posit that the same relaxation processes observed in our experiments also play out in natural soils, but that some environmental disturbances rejuvenate soil creep. Inspired by previous work[35,40] we examine heating as a method for creep rejuvenation in our experiments (see Methods). Thermal loading may be considered a proxy for shrink-swell and freeze-thaw cycles that occur in natural soils[8–10,42] (see Methods). The sandpile was first allowed to relax for 10^4 s before applying disturbances. At the instant heat was turned on, an increase in strain rate $\dot{\epsilon}$ was observed as most of the pile began to creep faster (Fig. 3). This was likely due to thermo-mechanical stresses created by volumetric expansion of the grains[40], though expansion of the apparatus walls may have also played a role. Interestingly, the spatially-averaged strain rate $\langle\dot{\epsilon}\rangle$ (see Methods) increased by more than ten times, reaching the same value observed at $t = 0$; i.e., just after preparation of the sandpile. Correlation functions also appeared similar to those observed at $t = 0$ (Fig. S10). This demonstrates that a few seconds of heating was able to reverse 10^4 s of aging. Once heat was switched off, $\langle\dot{\epsilon}\rangle$ dropped immediately, then slowly decayed toward the pre-heating value (Fig. 3a). Repeated cycles of heating and cooling produced concurrent cycles of rejuvenation and relaxation, respectively; the overall effect was to sustain an approximately constant average creep rate, that did not decay with time (Fig. S11). The ability of thermal cycling to sustain enhanced creep rates has intriguing implications for natural hillslope soils.

Tapping of grains may induce surface flows on heaps, but also leads to compaction of the bulk[43,44]. Tapping may mimic some effects of seismic shaking of hillslopes[41]. We allowed an initial pile to relax for 10^4 s, then tapped the pile with a metronome at 1 Hz (see Methods). Taps initially excited grains throughout the pile. As time progressed, however, a thin and fast-moving surface layer developed a sharp boundary at its base, below which the bulk grain motions slowed dramatically and became very intermittent (Fig. 3). The development of these two regimes is similar to the creep-flow transition observed in experiments[23] and simulations[5] of heap flows above the angle of repose (Fig. S12). There was an overall trend of decreasing $\langle\dot{\epsilon}\rangle$ with increasing number of taps (Fig. 3). We conclude that vibrations fluidized surface grains but drove compaction in the bulk[44], leading to more rapid relaxation (compared to the undisturbed case) as the pile evolved toward a denser, lower-energy state (Fig. S13). We interpret the boundary between fast and slow regions as a yield surface[29]. These findings may have relevance for landslide development from earthquakes. In particular, while vibrations in our experiments excited surficial flow, the underlying bulk became more rigid and less susceptible to future fluidization.

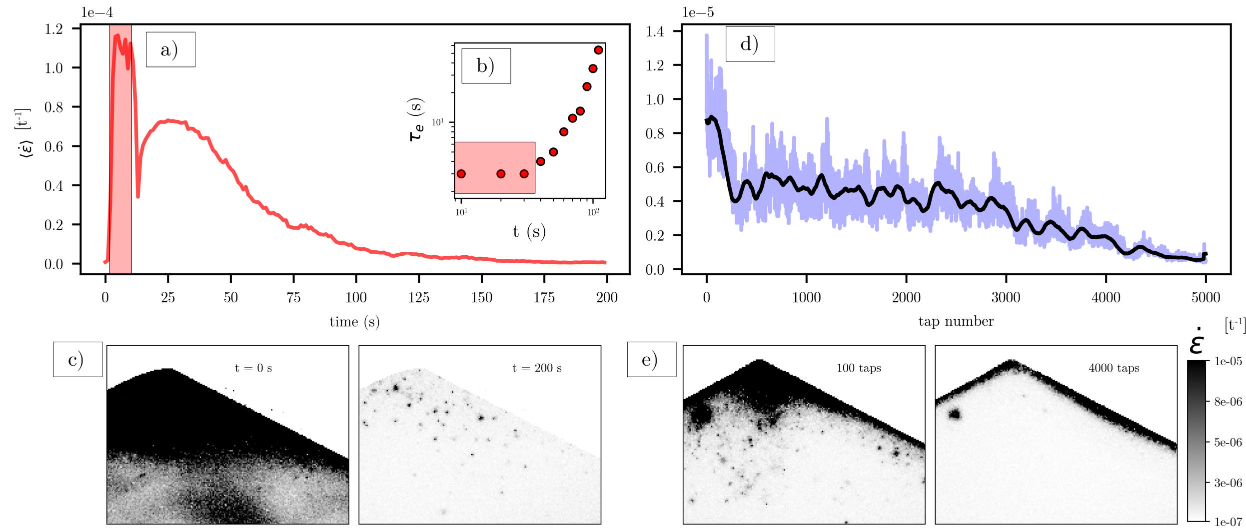

Figure 3: Mechanical perturbations drive rejuvenation and aging. a) Spatially-averaged strain rate including 10 s of heating applied (red rectangle) and relaxation after removal of the heat source. b) Relaxation timescale τ_e during and following heat response (Fig. S10). c) Spatial maps of strain rate during and following heat pulse. d) Time series of spatially-averaged strain rate (blue line). Black line indicates moving-window average (100 taps). e) Spatial maps of strain rate determined over one tap cycle (tap number indicated in figure). Note that after many taps, creep is mostly confined to a thin, localized layer at surface.

Comparison with field observations

Field measurements of soil creep on hillslopes are quite coarse compared to our experiments. Nonetheless, profiles of displacement, measured over decades by buried tracers in so-called 'Young pits' (Fig. 4a), provide a long-time average of soil motion at discrete depths z. Horizontal velocity profiles ($u(z)$) measured from a variety of environments are typically exponential-like[14,45,46], though quantitative comparisons among field sites have not been made. Here we examine previously published field data from Young pits at four sites around the world, where creep was reportedly driven by different forcings[8–10,42]. We confirm that all field data have $I \ll 10^{-5}$, i.e., they are in the granular creep regime. All velocity profiles are reasonably well described by an exponential function $u/u_0 = e^{-z/\lambda}$, where u_0 is the surface velocity and λ is a decay length determined from data fitting (Figs. 4c, S6). The latter two parameters must be related to site-specific soil characteristics and environmental disturbance regimes, but exploring this is beyond the scope of this paper. For these hillslopes $u_0 \sim 10^{-9}$ m/s (Figs. 4c, S6), comparable to our measured experimental creep rates for the initially loose and heated grains.

We compare our undisturbed creep experiments to field data, by first generating depth (z) profiles of downslope (x)-averaged cumulative strain through time from the surface to 1-cm below (Fig. 4b). Our experiments permit determination of strain rate rather than velocity (see Supplementary Materials Section S5); however, the normalized strain rate profile $\dot{\epsilon}/\dot{\epsilon}_0 = e^{-z/\lambda}$ is essentially equivalent to a normalized velocity profile. We see that our experimental data fall on top of the field profiles (see Fig. S3 for experiments with other materials). It is important to note, however, that while exponential profiles have been reported for granular creep in many experiments[23,25,26], an exponential profile is not diagnostic of creep. Inertial flows may also exhibit exponential velocity profiles[22,28]. Also, creep in highly heterogeneous soils, or soils with macro-scale disturbances such as tree throw[47], can exhibit erratic velocity profiles that are not well fit by an exponential.

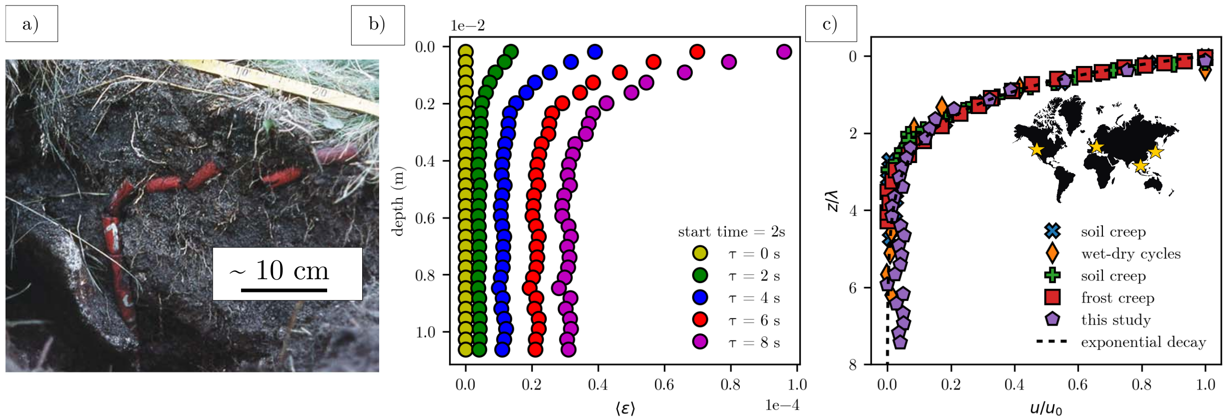

Figure 4: Depth-averaged strain profiles from the lab and field. a) Excavated Young Pit indicating the displacement of tracer pegs over a 17-year interval (PC Alfred Jahn). b) Depth and horizontally-averaged cumulative strain profiles at three lag times, measured in an undisturbed creep experiment. Profiles start at 2048 s after deposition. c) Compilation of soil deformation data from four studies and field environments - originally compiled by Roering[46]. Freeze-thaw cycles near Strasbourg, France[8], wet-dry cycles in Kuala Lumpur, Malaysia[42], freeze-thaw cycles in the Japanese Alps[9], wet-dry cycle in Stanford, California[10]. Data are fit by an exponential decay, the parameters of which are then used to reasonably collapse the data (Fig. S6)
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Discussion and outlook

By probing a seemingly static sandpile with speckle imaging, our experiments have revealed a seething and ceaseless creeping motion — even in the near absence of mechanical disturbances. These motions are strikingly similar to recent observations of creep in a heap of Brownian (micron-scale) particles[48], even though our sand grains are non-Brownian. Further, we have shown how granular creep rates can be tuned by imposing external disturbances that are geophysically relevant. Our experiments reveal deep similarities in how grains and glasses creep, and provide compelling evidence that mechanical disturbances in granular systems play a role akin to thermal fluctuations in glasses[7,27,34].

Intriguingly, even though the mechanics of grain motion are fundamentally different from Culling's model, our final result provides a kind of confirmation of his physical intuition[3]. In particular: heterogeneity in granular structure leads to seemingly random grain motions that decrease with depth; and mechanical disturbances can introduce new stresses and/or porosity that facilitate motion. Creep motions are consistent with granular self diffusion[49]; however, this does not imply that there is any Culling-like diffusion relation between flux and slope. Moreover, Culling and subsequent hillslope researchers did not anticipate persistent creep even in the (near) absence of disturbance. How do we understand the similarity in creep rates and profiles between our undisturbed and initially loose sandpile, and natural (disturbed) hillslope soils? Our new view separates creep into a generic relaxation process whose rate depends on granular friction/cohesion and structure, and diverse rejuvenation processes associated with environmental disturbances. We speculate that the primary role of biophysical disturbance in natural hillslopes is to maintain soil in a loose and fragile state, where relaxation rates are high. Other types of disturbance, however, can have the opposite effect; shaking can lead to compaction and enhanced aging, depressing bulk creep rates even as surface motions are enhanced.

Although soil is sensitive to disturbances, geologic history, and boundary effects[5,27], qualitative creep dynamics are robust across materials and environments. Future granular simulations could be used to reveal how disturbances influence the contact forces and/or structure that ultimately drive creep. Experiments could examine the consequences of cohesion/adhesion, surface charge, moisture, bioturbation and other effects on creep dynamics. Resolving these factors will allow derivation of a coarse-grained creep rheology model, whose kinematics and scales are determined by physically-meaningful parameters. Our results indicate that elastoplastic models developed to describe the rheology of amorphous solids[7] — that can explicitly incorporate mesoscopic scales of grain rearrangements, and rejuvenation by mechanical noise — may be good candidates. An improved model of soil creep is not only useful for predicting hillslope sediment transport; it will also help us to better understand how creeping soil accelerates to the yield point, which leads to catastrophic landslides[5].

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Methods and protocols

Measuring grain motion

The principle of DWS is that highly coherent light illuminates our granular heap, where photons scatter and interfere, which produces a random 'speckle pattern' that is collected with a CCD camera (Fig. 1, Supplementary Material S3). As grains slowly creep past one another, they change the photon trajectories and render new speckle patterns. We achieve spatially-resolved measurements by partitioning images into a grid with cells (metapixels) of size l*, the mean free path of photons within the material. This quantity is around $l* \approx 3d$ for the granular materials used (see Methods). Fluctuations in the speckle pattern between a start time t and a lag time τ within each metapixel are quantified via the normalized correlation function, $G(t, \tau)$ (Fig. 2)[35]. Global dynamics across the whole sandpile are measured by averaging G for each metapixel, signified as $\langle G \rangle$. This allows determination of the first important quantity for assessing glassy dynamics: the relaxation time τ_e, determined as the time at which $\langle G \rangle = 1/e$ (Fig. 2). For most experiments we used monodisperse glass beads (Cerroglass), of diameter $d_s = 100\mu m$ and density $\rho =$ 2.6 g/cc, to build the sandpile. This material was chosen because its scattering properties are well understood and it is standard in DWS experiments. From the correlation function G, we can apply optical theory[35] to determine the second important quantity for examining glassy dynamics: ϵ, the strain that occurs within a volume set by l* (see Supplemental Materials Section S3). Whereas DWS can still be used to examine relative grain motions for the sand and clay mixtures we used, use of more complex materials precludes us from calculating l* and hence from determining absolute strain ϵ (Supplementary Material S5).

Experimental procedures

Our experimental system is not meant to be a scaled model of a hillslope, either in a geometric or dynamic sense. Rather, it is designed to optimize the direct observation of grain motions, in order to understand the granular physics of creep that are relevant for soil motion at the pedon scale in nature. Reported experiments were conducted in relatively constant ambient temperature (21C +/- 0.2) and relative humidity (23.8% + 0.3) conditions (Fig. S7). The heap was prepared by allowing a fixed volume/flow rate of granular material (well within the continuous-flow regime[22]) to flow out of a funnel, at a fixed height 8 cm above the center of the cell bottom. Results are reported for glass beads, unless otherwise stated. Our 'undisturbed' experiments consisted of allowing the initial pile to relax under gravity, with no imposed external disturbances. We note, however, that small-scale ambient fluctuations in temperature and relative humidity did occur (Fig. S7). We conducted a 'short' duration experiment at a frame rate of $f = 1Hz$ for 10^4 seconds (2.8 hours) immediately following preparation, and a 'long' duration experiment with $f = 0.2Hz$ for 10^6 seconds (11 days). Image collection began at the start of emptying the funnel, while analysis of creep dynamics reported here started as the last grain entered the system and avalanching ceased ($t = 0$) — making the initial condition a sandpile prepared just below the angle of repose (Fig. 1). We computed both the instantaneous strain rate determined from successive image pairs through time, $\dot{\epsilon}(\tau = 1s) = \epsilon(t)f$ (e.g., Fig. 1), and the temporal evolution of the relaxation timescale τ_e sampled from different start times t, for each metapixel in an image. From these we generated ensemble-average values for each image, $\langle \dot{\epsilon} \rangle$ and $\langle \tau_e \rangle$, that characterized the spatially-averaged dynamics of the sandpile through time (Figs. 1, 2, 3). From instantaneous strain values we also computed surface-normal (z) profiles of downslope (x)-averaged strain (Figs. S4, S5); this allowed us to generate depth profiles of cumulative strain through time, for comparison to field data (Fig. 4).

Disturbance protocols

For experiments with disturbance, a pile prepared following the protocol above was allowed to relax for 10^4 s before disturbances began. Heating of glass beads produces a small but measurable volume expansion[40] (coefficient of thermal expansion $\sim 10^{-6} K^{-1}$) that is reversed as grains cool. At $t = 0$ heat was applied to the side of the cell for 10 s by a heat gun, producing a measured sidewall temperature of 50C (Fig. S9). After 10 s the heating element was removed, while the creep response was documented for another 200 s (Fig. 3). For tapping experiments, discrete taps were delivered to the pile using a metronome (double pendulum) that rests on a platform attached to the cell (Fig. S9). At $t = 0$ we initiated a series of 5000 taps delivered at a rate of 1 Hz, and recorded images at the same rate — but phase-lagged from the taps — for the 5000-s duration (Figs. 3, S9).

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Additional information: Extended data figures and methods are included in Supplementary Materials.

Data availability statement: Data will be deposited in the publicly shared repository figshare, and all code used to analyze these data will be publicly available on github.