

Strain hardening by sediment transport

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The critical fluid-shear stress for the onset of sediment transport, θ_c , varies with the history of applied shear. This effect has been primarily attributed to compaction; the role of shear jamming is less explored. We examine the response of a granular bed to fluid-shear stress cycles of varying magnitude and direction, and determine isotropic and anisotropic contributions. Creep and bed-load transport result in direction-dependent strain hardening for $\theta/\theta_c < 4$. Dilation-induced weakening, and memory loss, occur for larger stresses that fluidize the bed. Our findings provide a granular explanation for the formation and breakup of hard-packed riverbed “armor.”

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The entrainment of granular materials by fluid shear acts to shape diverse landscapes on Earth and other planets [1]. While decades of research mostly examined the influence of fluid-flow structures and turbulence, a recent focus on granular rheology and structure has spurred progress in determining the roles of collisions and viscous dissipation in sediment transport dynamics and rates [2–8]. A central challenge that emerges is understanding the nature of the threshold of motion itself. In liquid-driven flows such as rivers, “bed-load” transport is often envisioned as a thin layer of surface grains moving over a static or “jammed” sediment bed [9,10]. In this context, the onset of bed-load transport is typically defined by the dimensionless critical Shields stress, θ_c , which is a threshold value of the Shields number, $\theta \equiv \tau/[(\rho_s - \rho)gD]$, where τ , ρ_s , ρ , g , and D are the fluid-shear stress, particle density, fluid density, gravity, and grain size. Clark *et al.* [11] offered a new interpretation of θ_c as the stress at which moving grains

can no longer find a stable (static) configuration; this opens the possibility of relating the susceptibility of fluid entrainment to granular confinement. On the other hand, Houssais *et al.* [4] observed that grains beneath the threshold for bed-load motion were not static, but rather exhibited a slow and erratic creeping motion with caged dynamics. In their laminar flow experiments, θ_c coincided with a transition from creep to a dense-granular flow on the surface.

Temporal variation in the entrainment threshold is commonly observed in natural rivers; θ_c changes as a function of the history of fluid stress [12–14], causing hysteresis in observed sediment transport rates through a flood [14–16]. Experiments indicate that these transient dynamics arise due to the formation and breakup of riverbed “armor” [17,18]. Armoring has been proposed to arise from vertical grain-size segregation in polydisperse riverbeds [19–21], and by formation of a hard-packed “pavement” surface [10,17,22–24]. In this study we consider the latter, in which the increased resistance of riverbed sediments to fluid entrainment may be considered a form of strain hardening. Charru *et al.* [10] observed a steady decline in bed-load transport rate—over several days—under constant θ , which they attributed to an increase in effective θ_c by compaction of the near-bed region. Even subcritical ($\theta < \theta_c$) flows cause armoring due to granular creep [17,25], which can only be broken up by flows far exceeding critical ($\theta \gg \theta_c$). Using an experimental setup similar to ours, Allen and Kudrolli [25] focused on the transient response of a sediment bed to subcritical fluid shear. They observed that that creep rates diminished over

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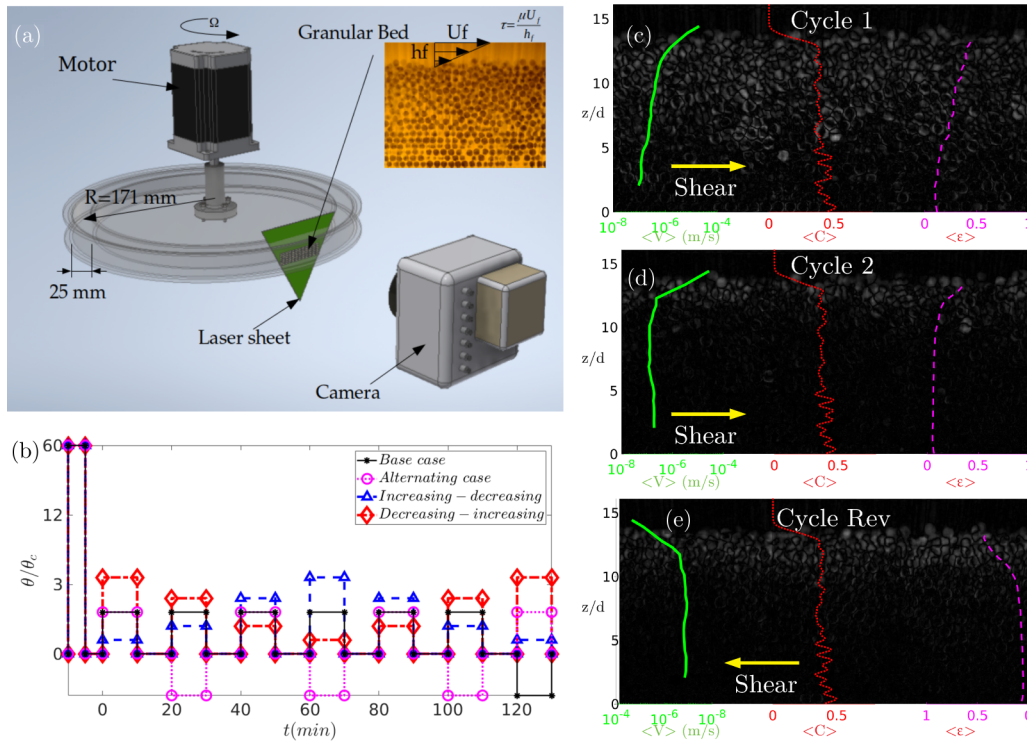


FIG. 1. (a) Schematic of the experimental setup. (b) Protocols used in the experiments. (c)–(e) Strain (background in gray scale, where the light spots correspond to higher strain values), longitudinal and time-averaged particle velocities ($\langle V \rangle$; green line) and concentrations ($\langle C \rangle$; red dotted lines), and longitudinal-averaged strains (magenta dashed lines) for indicated cycles in the “base case” experiment.

time, while the granular packing fraction ϕ of the sediment bed increased toward the volume fraction associated with the glass transition, $\phi_{RCP} \simeq 0.64$. Moreover, they showed that the value θ_c needed to initiate bed load systematically increased with ϕ .

The findings above are consistent with the general picture that the rigidity of granular materials is primarily controlled by packing fraction or, more specifically, the distance from the jamming/glass transition characterized by $\phi_{RCP} - \phi$ [1,26–28]. It is now known, however, that strain hardening may also occur without any change in volume. This “shear jamming” arises from the development of a granular fabric that is oriented to resist an applied, directional boundary shear [29–32]. Like compaction, the resulting strain hardening produces a history-dependent memory in the mechanical stability of the granular pack [33]. But unlike compaction, this memory is stored in anisotropic structures that are fragile when subject to changes in shear direction [31]. Shear jamming and compaction may operate in tandem; it is well known that shearing or shaking in multiple directions allows more compaction than one direction alone (see, e.g., [34])—presumably because the suppression/destruction of anisotropic structures allows the bed to access a higher ϕ configuration.

We expect that fluid-sheared granular beds experience both isotropic (compaction) and anisotropic (shear jamming) strain hardening, due to the free-surface condition and directionality of applied shear. Indeed, recent studies have shown that the onset of sediment transport is controlled, in part, by the development of anisotropic grain fabrics [35,36]. However, the contributions of creep (subcritical) vs bed-load (supercritical) transport to strain hardening have not been isolated, and the

conditions that lead to armor breakup and erasure of memory have not been characterized. In this Letter we address these issues with laminar sediment transport experiments, in which a sedimented bed of grains was subject to fluid shear-stress cycles of 10-min duration, with varying magnitude and direction. The device and materials are completely described in previous work [4]. Briefly, a bed (20–22 mm thick) of monodisperse acrylic beads (diameter, $d = 1.5$ mm; density, $\rho_s = 1190$ kg/m³) was submerged in a refractive-index matched oil (kinematic viscosity, $\mu = 7.2 \times 10^{-2}$ Pa s; density, $\rho = 1050$ kg/m³) inside an annular flume [Fig. 1(a)]. A rotating lid was used to achieve fluid shear rates of $2.9 \text{ s}^{-1} \leq \dot{\gamma} \leq 14.5 \text{ s}^{-1}$, which corresponds to Shields numbers of $0.1 \leq \theta \leq 0.5$, where $\tau = \mu \dot{\gamma}$. Channel and grain scale Reynolds numbers, $\text{Re} = \rho U_f h_f / \mu$ and $\text{Re}_s = \rho \dot{\gamma} d^2 / \mu$, respectively, were within $0.7 \leq \text{Re} \leq 3.5$ and $0.077 \leq \text{Re}_s \leq 0.384$, where U_f is the lid velocity at the channel centerline and h_f is the gap distance between the lid and bed surface. The preparation protocol involved almost complete suspension of the granular bed by preshearing for 5 min at $\theta = 6$, followed by 5 minutes of quiescence to allow settling. From our previous work we choose a reference critical Shields stress of $\theta_c = 0.1$ [2]. Images captured at 60 Hz in the illuminated midchannel cross section [Fig. 1(b)] allowed determination of vertical profiles of granular velocity, strain rate, and concentration, averaged over each 600-s stress cycle and horizontally in the x direction. Average velocity ($\langle V \rangle$) was determined from standard particle image velocimetry (PIV) techniques, and average concentration ($\langle C \rangle$) was estimated from image filtering and thresholding [37]. Strain was determined in the following manner: from one image to the next, a mobility

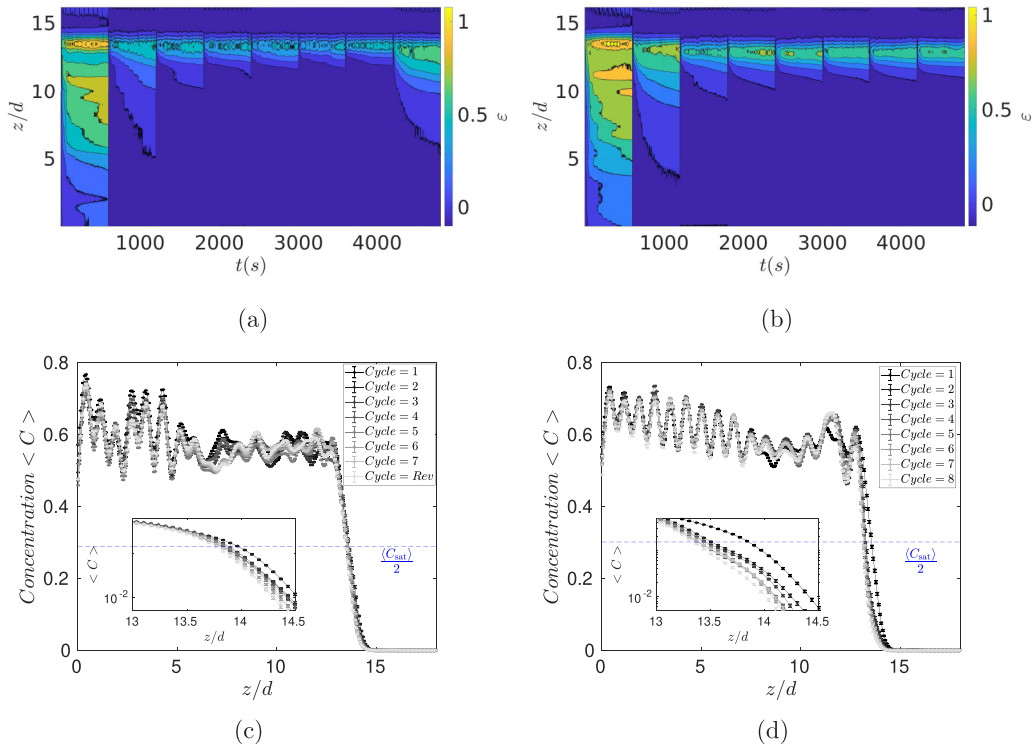


FIG. 2. M matrix representing local particles' mobility intensity for (a) the “base case” with reversal at the last cycle, and (b) “alternating case” where stress is reversed for each cycle, and variation from blue (darker shades in gray scale) to yellow (brighter shades in gray scale) corresponds to increasing in mobility. Time-averaged vertical concentration $\langle C(z) \rangle$ at each cycle for (c) the “base case” with reversal at the last cycle, and (d) “alternating case” where stress is reversed for each cycle. $\theta = 2\theta_c$ for all cycles, with gray levels scaling with time.

matrix $M(x, z)$ was measured as the intensity difference at each pixel and its dimensionless equivalent, averaged in time and the x direction, $m^*(z)$ (see Fig. 1, and the Supplemental Material [37]); an effective strain was estimated at each elevation as $\epsilon(z) = \langle C_{\text{sat}} \rangle / \langle C \rangle(z) \int_z^{z+\Delta z} m^* dy$.

We first describe the phenomenology associated with unidirectional cyclic shear, followed by a direction reversal, in a typical run that we call the “base case” (Fig. 1). At time $t = 0$ s a constant fluid shear stress of $\theta = 2\theta_c$ (i.e., $\theta = 0.2$) was applied in a clockwise direction. An unjamming front, initiated at the surface, propagated downward at progressively slower speed through time [Figs. 1(c) and 2(a)]. At $t = 10$ min the shear was turned off, and the time-integrated parameters were computed for the first cycle. Depth (z) profiles of average particle velocity and concentration followed the bipartite patterns reported previously [2,4]; $\langle V \rangle$ decreased rapidly with depth while $\langle C \rangle$ increased to a constant value in the bed-load layer, and below this layer $\langle V \rangle$ diminished more slowly (Fig. 1). The granular bed compacted by roughly 2% over the first stress cycle, as determined from a decrease in the bed-surface elevation (defined as the location at which $C/C_{\text{max}} = 0.5$ [4]). Repeated identical stress cycles showed progressive compaction and strain hardening of the granular bed—as evidenced by reduced mobility of particles at all depths (Figs. 2 and 3)—though the effect of each subsequent cycle was diminished. Interestingly, the boundary between the upper bed-load layer and the lower creeping layer became sharper as the bed hardened, as indicated by the developing kink in the velocity profile. Using this kink to delineate the two regimes (cf. [2,37]), we can quantify changes in mobility

in the creeping and bed-load layers separately (Fig. 3). Strain rates for creep diminished more rapidly and significantly than bed load. Reversing the shear direction after seven cycles resulted in a (roughly) doubling of the strain rates for creep and bed load (Fig. 3). Notably, this increased mobility was accompanied by a jump in compaction (Fig. 3). This behavior is consistent with observations of shear jamming and fragile states in granular systems [31]. In particular, while bed compaction and particle mobility appeared to saturate under a unidirectional stress, their abrupt increase on reversal indicates that the bed was conditioned to one direction but fragile to other directions. These results suggest that direction-dependent (anisotropic) strain hardening was smaller than, but of similar order to, (isotropic) compaction (Fig. 3), and that memory of the former was erased by changing the shear direction.

Repeating the base case experiment at higher θ values shows qualitatively similar behavior, but quantitative differences. As θ increases, the magnitude of strain hardening increases for creep but decreases for bed load (Fig. 3). We attribute this to volume change and memory in the bed. Creep is generally associated with compaction, and the finding that increasing θ results in enhanced creep rates and faster strain hardening is in agreement with Allen and Kudrolli [25]. Intense bed-load transport, however, is associated with dilation and yielding, which erase memory [33]. The response to shear direction reversal supports this interpretation; mobility is greatly enhanced for the creep regime for all θ , but the jump in mobility for bed load diminishes as θ increases.

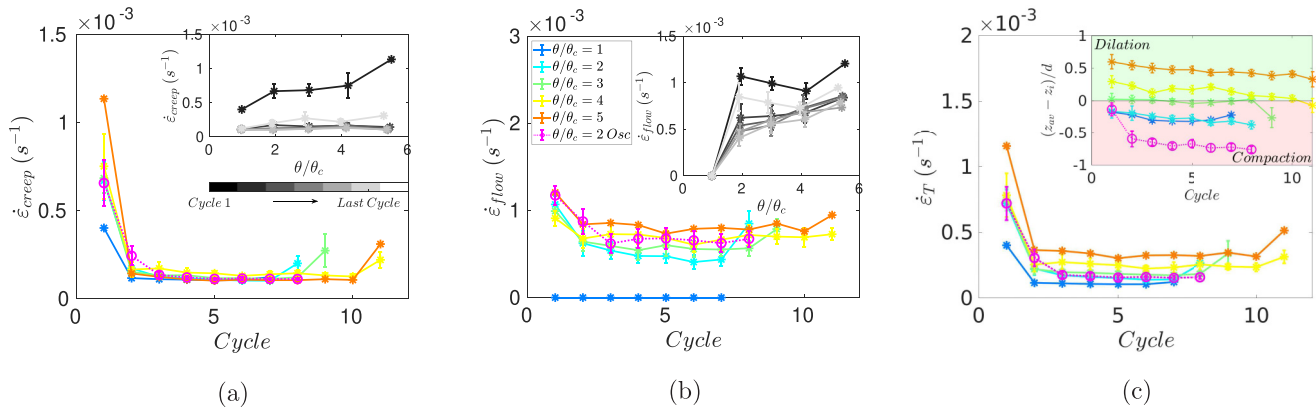


FIG. 3. Base and alternating cases. Strain rate measured in (a) the creeping part, (b) the flowing part, and (c) the total part of the sediment bed, as a function of time, or stress cycle, each cycle taking place over $\Delta t = 600$ s. Insets: Strain rate measured in (a) the creeping part and (b) the flowing part as a function of θ/θ_c , and (c) relative change of the bed surface elevation as a function of θ/θ_c . Gray levels scale with time where the last cycle corresponds to the directional reverse; blue to orange colors represent low to high stresses. Curves of lightest level of gray correspond to the final cycle of base cases, when fluid shear is reverse. Pink curves correspond to the oscillatory scenario [also shown in Figs. 2(b) and 2(d)].

To further probe anisotropic effects, we compare a second “alternating case” experiment with $\theta/\theta_c = 2$ in which the only change from the base case is that shear direction was reversed for each cycle (Fig. 1). An important first observation is that bed compaction under alternating shear direction is much larger than all unidirectional experiments (Fig. 3), consistent with previous work [34]. If volume fraction were the only control on particle mobility, we would expect strain rates for the alternating case to be much lower than all unidirectional experiments. Particle mobility, however, remained elevated compared to the base case (Fig. 3). We deduce that the alternating shear limited the development of a persistent granular fabric. Although shear reversal allowed the bed to find a more dense configuration, this did not make the bed stiffer compared to the unidirectional case. On the other hand, particle mobility in the alternating case was significantly lower than when shear was reversed at the end of the base case (Fig. 3). We infer that the bed developed some kind of resisting fabric under bidirectional flow, similar to memory formation observed in oscillatory shear experiments [33], but that this fabric was not as strong as structures trained under unidirectional shear.

The above results reveal isotropic and anisotropic contributions to strain hardening, and that the latter may be erased by reversing flow. For unidirectional flows such as rivers, where shear reversal does not occur, these findings would lead us to expect only armored riverbeds. Clearly this is not the case; sufficiently large floods are known to break up armor and enhance sediment mobility [38]. It has been suggested that shear-induced dilation breaks up granular structures and weakens the bed [10,25], but this idea needs more systematic study. We performed two experiments to examine the effects of changing shear-stress magnitude under constant direction. Both experiments began with the same preparation protocol as above (i.e., an initially loose bed), and imposed stress sweeps with 13 cycles of 10 min each over a range $(0.6\text{--}5)\theta_c$ (Fig. 1). In the first sweep ($S \uparrow \downarrow$) stress was increased then decreased, and in the second sweep ($S \downarrow \uparrow$) stress was decreased and then increased. For both experiments we observed net compaction

of the bed for $\theta < 4\theta_c$, and net dilation for larger stresses (Fig. 4). We also confirmed that particle mobility decreased with compaction, and increased with dilation (Fig. 4). We conclude, to first order, that dilation results from vigorous bed-load transport and acts to break up armoring, and compaction occurs under creep and weak bed load and forms armor.

The two stress sweeps, however, reveal a second-order history dependence. For $S \uparrow \downarrow$, the first stress cycle at $0.6\theta_c$ initiated transient bed-load transport at the surface, that quickly died away. Small but measurable compaction occurred for subcritical stress cycles as a consequence of creep, in agreement with [25]. Persistent bed-load transport began at the surface for $\theta = \theta_c$, and compaction increased with increasing stress up to $2\theta_c$. Beyond this value, relative dilation occurred with increasing stress as the bed-load layer grew to consume more of the pack [Fig. 4(a)]. On the downward stress sweep, significant hysteresis was observed for $\theta < 2\theta_c$ because the strain-hardened and compacted bed could not return to its presheared condition. These patterns were reversed for the $S \downarrow \uparrow$ sweep [Fig. 4(b)]. Starting from the highest stress the bed was more dilated relative to $S \uparrow \downarrow$, presumably because creep-induced compaction had not occurred. Relative compaction and declining mobility commenced with decreasing stress. Strong hysteresis was observed on the return (upward) stress sweep for $\theta > 2\theta_c$, where the strain-hardened and compacted bed suppressed dilation relative to the initial condition. These tests indicate that some memory of shear, in terms of strain hardening, exists even when applied stresses are $5\theta_c$. This memory is retained at depths that remain beneath the bed-load layer, and thus do not experience dilation; this implies that exceptionally large stresses capable of fluidizing the entire bed would be needed to erase all history of shear.

Compaction has long been known to cause stiffening of granular beds, due to increasing volume fraction that drives the system toward the jammed state [39]. The more recent recognition that materials may be driven toward jamming by shear, without any change in volume, has revealed the importance of anisotropic grain fabric [29,31,32]. Both of these

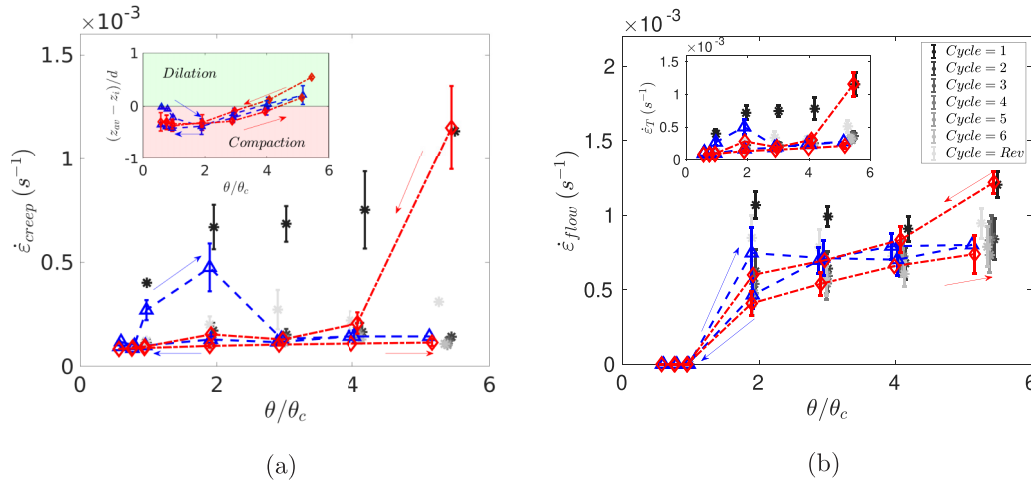


FIG. 4. Hysteresis cases. (a) Strain in the creeping part of the bed. Inset: Relative change of the bed surface elevation as a function of θ/θ_c . (b) Strain in the flowing part of the sediment bed, as a function of the dimensionless shear stress. Inset: Total strain as a function of θ/θ_c . Gray levels scale with time, blue curves correspond to the increase-then-decrease stress scenario, and red curves correspond to the decrease-then-increase stress scenario.

factors are relevant in sediment transport, and our experiments found that they contribute comparably to strain hardening of the bed. Our findings add to recent experimental evidence [25,40] that creep is a primary driver of strain hardening and aging in granular beds. Creep may occur far below the entrainment threshold, and far beneath the bed-load layer. Interestingly, the separation between bed load and creep for an initially loose bed was not well defined (Fig. 1); the interface sharpened through time as a consequence of strain hardening. The emergence of a (more) mobile surface layer is reminiscent of granular heaps subject to tapping [40], and also of the “active layer” description of mobile bed materials in natural rivers [41]. Due to the self-organization of river channels to a near-threshold state, fluid stresses rarely exceed $2\theta_c$ [42–44]. We thus expect that most flows strain-harden the bed, while only exceptional floods break up surface armoring. This is in qualitative agreement with river observations that document changes in the threshold of motion as a function of flood history [12,13,38]. We urge caution, however, in

extrapolating our findings to natural settings. We expect that the shape and size dispersion of natural grains will influence the rate, but not the style, of creep and bed load [21,45,46]. Perhaps more significant is that the entrainment threshold θ_c for bed-load transport in turbulent flows may be different in nature from viscous flows, due to inertial effects of particle motion [5,8,47]. Exploring the consequences of more “realistic” particle and flow conditions, while maintaining the ability to observe particle dynamics within the granular bed, is an important challenge.

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