

Rough meets smooth: Unifying granular landslide speed and runout

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The flow of grains down an inclined plane is a paradigmatic system of granular physics. Even for this simple geometry, the flow behavior varies considerably depending on parameters such as inclination angle, injection flow rate, and substrate conditions. In the parameter space that yields steady-state conditions, there are generally distinct regimes for flow over smooth, rough, and erodible substrates. Here, using systematic experiments on rough and smooth surfaces at large inclination angles and with an injection that does not produce steady-state conditions, we find that the smooth and rough flow behaviors reunite. We also demonstrate that the travel distance following the steep incline depends on the roughness through the dynamic sliding friction with the substrate.

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Introduction. Movement relative to a surface is generally slower if the surface becomes rougher. This holds for barnacled ships [1], pipelines [2], and, of specific interest here, inclined granular flow. Surface roughness is presumably an important feature of natural large mass movements such as landslides and debris flows [3–5], but it has secured an even larger role in laboratory experiments where the treatment of flows over smooth, rough, and erodible substrates has effectively diverged [6,7]. A notable difference is that roughness can establish a no-slip boundary condition, which is used in many well-known models of granular flow, such as those based on depth-averaged equations [8–10].

The no-slip condition provides a robust basis for establishing a steady state for a range of parameters such as the inclination angle, while for smooth substrates the steady state is only accessible at a critical angle [6], in the presence of side walls [11–13] or with nonspherical beads [14]. The pursuit of a steady state is a common motif in work on inclined granular flow, since this should make the system more amenable to analysis. Thus, significant progress has been made from both an experimental and a theoretical perspective in understanding many diverse granular systems that employ a rough surface that engenders both a steady state and a no-slip boundary condition [15–19], including the development of the steady state itself [20,21], although the relevance of these laboratory insights to the natural flows that inspired them is still debated [22–26].

In the present work, we simulate granular landslides using systematic laboratory experiments for which we vary the grain and roughness element size to probe the relationship between flows over surfaces with widely varying surface roughness and wall slip properties. In our experiments, the angle of inclination is large ($\gtrsim 30^\circ$), and the injection is not continuous but momentary. For these laboratory experiments, a previous study using spherical glass beads and smooth glass surfaces [27,28] found that the runout distance scales with the volume of the landslide to the power $1/6$. Surprisingly, this scaling also applies to natural landslides where the substrate can be rough, raising the question of the role of roughness in determining the runout distance. Here, our results for the runout distance conform to the common wisdom that roughness tends to increase resistance. We find that such landslides over smooth and rough substrates follow a common, roughness-dependent scaling for the runout. Despite the large difference in surface roughness and wall slip properties between the different surfaces used, a common behavior emerges spanning a wide range of roughness, from a few nanometers, as for the smooth glass substrates for which wall slip is important, up to a fraction of a millimeter for surfaces overlaid with rough sandpaper and for which little if any wall slip is observed.

Experimental methods. In our laboratory experiments, we systematically vary the fall height H , the total volume V , the grain size D , and the roughness element size r . The experimental setup consists of a slope, a flat section, grains, and a container to house the grains before releasing them by rapidly raising a sliding metal gate. Our inclinations are relatively steep, $\theta \gtrsim 30^\circ$, and the dynamics of the granular flows are controlled by the finite mass of the released granular heap. After release through a gate, the granular mass starts its motion and accelerates, while its shape and thickness evolve continuously as it slides on the incline and reaches the horizontal plane where it stops. Thus, by almost any metric,

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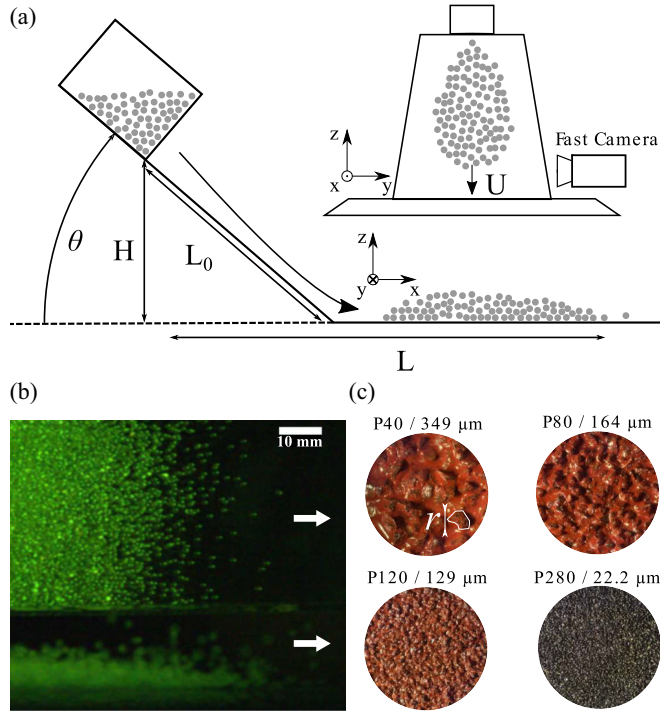


FIG. 1. (a) Side-view schematic (x - z plane) of the experimental setup. The grains are housed in a rectangular container and the surface is level. A sliding gate is removed to release them. The granular mass slides on the plane surface (65 cm wide, $\gtrsim 50$ cm long) with typical inclination $\theta \gtrsim 30^\circ$, reaches the horizontal plane, and eventually comes to rest. The grain motion is observed using a fast camera on the side of the flow (see inset, in the x - y plane) to measure the front speed U and the thickness h . (b) Typical images recorded by the side-view camera for μm grains. The upper frame is a top view of the flow, and the bottom frame a side view. (c) Example microscope images of the sandpaper with a typical asperity of size r indicated. The average roughness (r) is given for each sandpaper grit above the image.

the flow must be characterized as transient. See Fig. 1 for a schematic of the experimental setup and the Supplemental Material [29] for examples of the full transient dynamics of the landslide.

Our grains are nearly spherical glass beads that have been roughly sorted according to diameter D , ranging from $\sim 45 \mu\text{m}$ to $\sim 1.5 \text{ mm}$. We characterize each collection of grains by measuring their size distributions using an imaging technique [27]. We incorporate the grain size through the mean diameter of the mass-weighted distribution $\langle D \rangle$. While the smooth substrate used is made of glass with a surface roughness of a few nanometers (see the Supplemental Material [29] for a characterization of the surface roughness), we make the substrate surface rough by covering it with standard sandpaper (SiC sandpaper, 40–7000 grit). We define the roughness r of a given sandpaper as the mean size of surface asperities observed under the microscope, which follows the relation $r \propto 1/\text{sandpaper grit}$. See Fig. 1 for example microscope images of the grains and the Supplemental Material [29] for more information about characterizing the roughness.

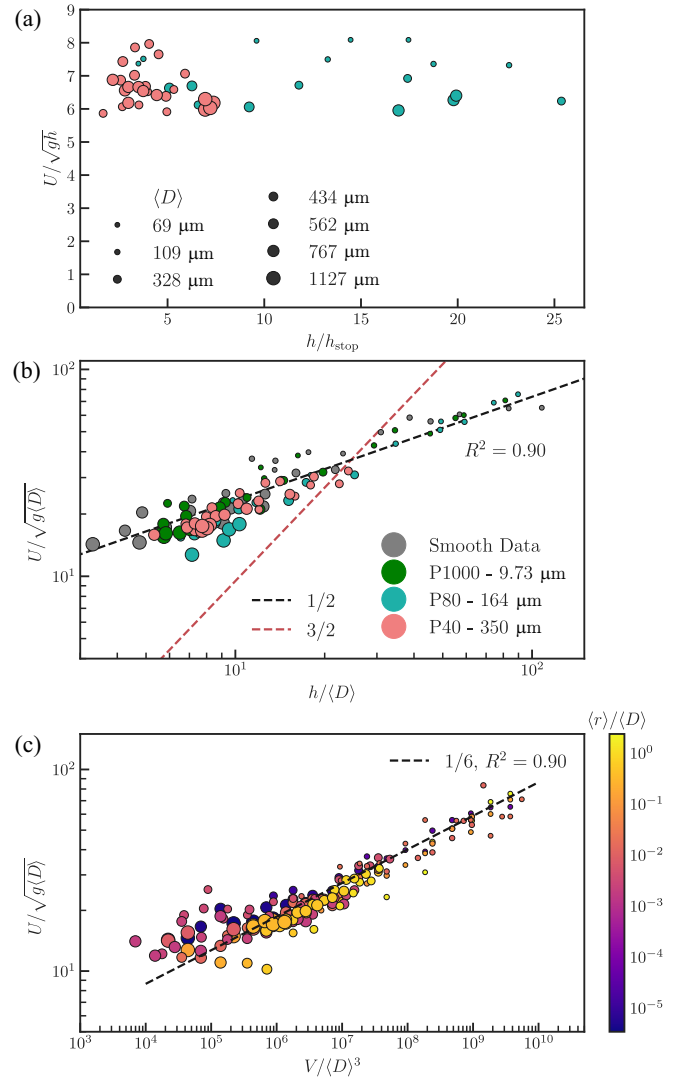


FIG. 2. (a) Plot of front speed U normalized with h and h_{stop} according to Pouliquen [6]. Our unsteady data on a rough substrate (P80-grit sandpaper, $\langle r \rangle \sim 164 \mu\text{m}$) do not show the same scaling or magnitude as previous work. (b) Plot of front speed U normalized with h and the grain size. The scaling is more consistent with the previous predictions for steady flow on a smooth substrate [11] than for a rough substrate [6]. Note that most data for $D \gg r$ (such as on the smooth substrate) have $h_{\text{stop}} = 0$ and thus cannot be displayed in panel (a). (c) A plot of the front speed U for several $\langle r \rangle$ plotted versus V where both are normalized by the grain size distribution. Each symbol represents a particular grain size (D), ranging from 67 to $1127 \mu\text{m}$. The data follow a power law of exponent $1/6$ (dashed line) [27] and show no discernible dependence on r .

The main observables are the landslide front speed U and the runout distance L . We determine V (in the container), H , and L using a standard measuring tape with millimeter precision. For each experiment, we measure the total mass M with a simple scale and gently sprinkle the grains into the rectangular container so that the surface is level. We identify the final front position as the frontmost position where a layer of grains is still in contact with the main mass [27]. The motion of the mass is recorded using a fast camera (Phantom v641) at a frame rate between 100 and 300 Hz. The front speed U of the

flowing mass is measured by tracking the front position of the flowing mass near the end of the inclined plane, using the time taken to travel the final 5 cm. To make contact with existing frameworks, we also measure the landslide thickness h with the same fast camera either directly from a side view of the flow or by measuring the deviation of an inclined laser sheet [6,39,40]. We conducted all the experiments at a humidity level between 40% and 70% and did not observe substantial influence of electrostatic effects or humidity.

Effect of roughness on flow speed. Previous work on steady flows with smooth and rough substrates, using a continuous injection of grains, has focused on the relationship between speed U and thickness h as an important flow diagnostic. For conditions where the minimum thickness h_{stop} of the immobile layer of grains is nonzero, it was demonstrated that determining this quantity for a given inclination, grain size, and roughness, (nearly) all data collapsed onto a single curve given by $U/\sqrt{gh} = \alpha + \beta h/h_{\text{stop}}$, where the parameters α and β depend on material and substrate properties [6,18,41]. Since h_{stop} is independent of h , this suggests that $U \propto h^{3/2}$. In contrast, for smooth (frictional) substrates, for which wall slip is important and for which $h_{\text{stop}} = 0$, a different scaling, $U \propto h^{1/2}$, was predicted and confirmed [11,42]. In Fig. 2(a), we show that our data for a nonzero h_{stop} are distinct from previous results [6,19] with no discernible dependence on h/h_{stop} and significantly higher Froude numbers ($U/\sqrt{gh}$) [6,19]. On the other hand, a plot of $U/\sqrt{g\langle D \rangle}$ versus $h/\langle D \rangle$ shown in Fig. 2(b) shows consistency with the scaling predicted and confirmed by Louge and Keast [11] for continuously fed granular flow on shallow, smooth inclines, despite the absence of continuous injection of grains in our flow.

This collapse can be expressed in another way, which does not require the difficult measurement of h and makes easier

contact with natural flows. When we plot the front speed U for different grain sizes and roughnesses versus the injected volume of grains V in Fig. 2(c), both normalized by grain size, we find, surprisingly, that the scaling of U conforms to the same $U \propto V^{1/6}$ behavior as with ping-pong balls and our own grains on a smooth substrate [27,43]. Once again, there is no apparent dependence on r within the resolution of our experiments.

Effect of roughness on runout. The runout behavior on the flat section, however, reveals a clear roughness dependence. The runout distance L is a simple diagnostic of the granular flow, even if its prediction is difficult. For smooth substrates the runout depends on V and H as $H/L \propto [(V/H^3)]^{-1/6}$ [27] when the landslide is big enough [28]. In Fig. 3(a), we combine the measured runout for smooth and rough substrates, which shows a clear dependence on r . However, the shape of the curves is still similar, offering hope of a relatively simple dependence on roughness. The conformity of all data to the power $-1/6$ [dashed line in Fig. 3(a)] highlights their common connection with the scaling of the front speed $U \propto V^{1/6}$ first observed in the motion of ping-pong balls [43], which we now explore further.

The runout distance and front speed can be connected by a heuristic estimate of the runout given by $L \simeq UT$, where T is the total time of the landslide event [27]. Since in log scale U shows no clear dependence on the roughness, the runout distance should be influenced primarily via the deceleration time. Determining the exact dependence of T and thus H/L on particle-particle or particle-substrate interactions is challenging. In work on granular slumping on rough substrates, Lube *et al.* [44] proposed a characteristic runout time given by $T \propto K\sqrt{H/g}$, where g is the gravitational acceleration and K is a friction coefficient. Here, we make the strong assumption

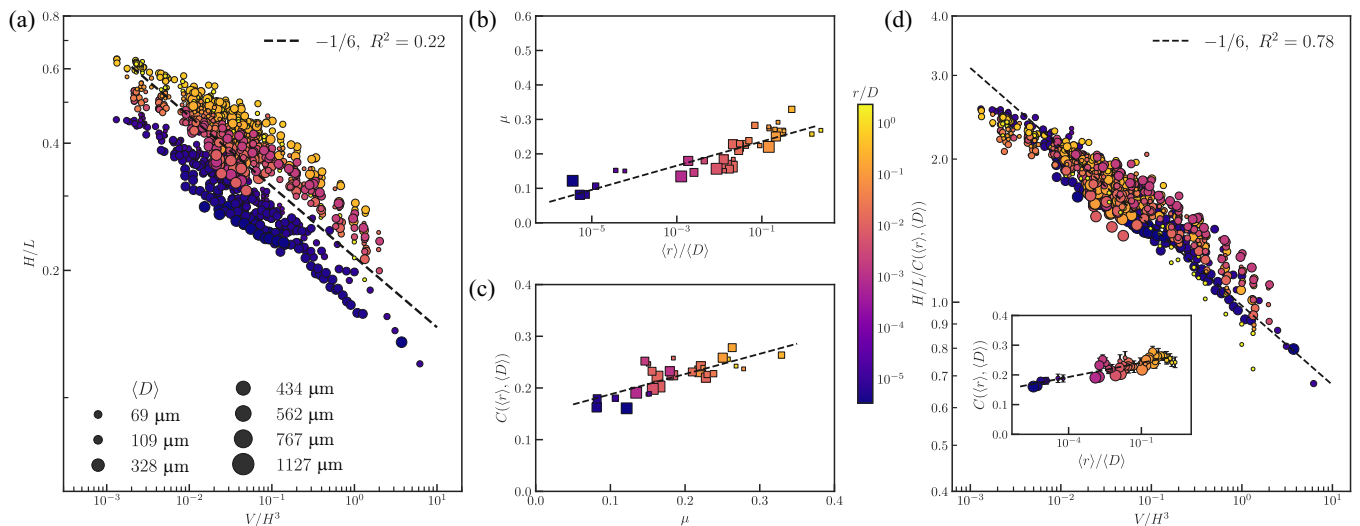


FIG. 3. (a) Plots of runout from the laboratory experiments. All tested grain sizes and roughnesses are shown on the same plot (H/L) vs (V/H^3). The substrate roughness is represented by a color code and bigger symbols represent larger grain size. There is an overall negative trend for the effective friction with the landslide size that follows a power law of slope $-1/6$ [27]. The dependence of the runout on substrate roughness shifts the colored curves vertically. (b) Plot of dynamic friction coefficients measured for our system by pulling a slider on a bed of free grains [29]. (c) These coefficients are compared with $C(\langle r \rangle / \langle D \rangle)$. (d) Runout data rescaled using the coefficient $C(\langle r \rangle / \langle D \rangle)$. Inset: The coefficient $C(\langle r \rangle / \langle D \rangle)$ for each set of experimental conditions ($\langle r \rangle$, $\langle D \rangle$); the dashed line is the fitting function used to normalize the runout data: $y = 0.007 \log(\langle r \rangle / \langle D \rangle) + 0.26$.

that $K \propto 1/\mu$ [45], where μ is the dynamic sliding friction coefficient, since an increase in friction will result in a decrease in runout time (faster deceleration). To test this assumption, we go on to measure μ for different values of $\langle r \rangle$ and $\langle D \rangle$ in ancillary experiments using several different methods (see the Supplemental Material [29]). We show in Fig. 3(b) that μ varies across a typical range of values and depends weakly on the ratio $\langle r \rangle / \langle D \rangle$ as $\mu \simeq A + B \log(\langle r \rangle / \langle D \rangle)$.

We next test whether this $\mu(\langle r \rangle / \langle D \rangle)$ can explain the runout dependence by fitting the relation $H/L \propto (V/H^3)^{-1/6}$ for different values of $\langle r \rangle / \langle D \rangle$ and determining a proportionality constant $C(\langle r \rangle / \langle D \rangle)$ for each fit. In Fig. 3(d), we confirm a similar logarithmic behavior of $C(\langle r \rangle / \langle D \rangle) = A' + B' \log(\langle r \rangle / \langle D \rangle)$, with different coefficients. The logarithmic dependence of both μ and $C(\langle r \rangle / \langle D \rangle)$ on $\langle r \rangle / \langle D \rangle$, as well as the significant correlation between these two quantities [Fig. 3(c)], suggests a common, likely geometric [46], origin. We visually verify that the empirically determined $C(\langle r \rangle / \langle D \rangle)$ captures the influence of roughness on the runout by normalizing the curves in Fig. 3(a) with $C(\langle r \rangle / \langle D \rangle)$, which yields the collapsed curves in Fig. 3(d). Thus, the full dependence of the runout can be expressed as

$$\frac{H}{L} \simeq f\left(\mu\left(\frac{\langle r \rangle}{\langle D \rangle}\right)\right) \left[\frac{V}{H^3}\right]^{-1/6}, \quad (1)$$

where $f(\mu(\langle r \rangle / \langle D \rangle))$ is a function that we determine experimentally and which remains to be fully investigated.

In summary, using systematic experiments of inclined granular landslides with various grain sizes on substrates with different roughness values, we have shown that such flows show a common roughness-dependent behavior independently of the wall slip properties of the surfaces. In particular, we find that the front speed U appears to be insensitive to the roughness on the steep incline, and the runout distance decreases with increasing roughness in a systematic manner. We relate this decrease with the ratio of roughness to grain size via an independently measured dynamic sliding friction coefficient. Since natural landslides have also been shown to conform to the scaling law in Eq. (1) [27], we submit that these large mass movements also belong to the same regime occupied by our experiments. We have found that the increased complexity of landslide physics resulting from many parameters [22] is not as intractable as it first seems. Although characterizing the roughness for natural landslides is challenging [47], our laboratory experiments provide a foundation for understanding and predicting even complex landslide runout scenarios.

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Data availability. The data supporting this study's findings are available within the Letter.

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