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Stripes in granular avalanches: how segregation couples with vortices

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Pearse *et al.* (*J. Fluid Mech.* vol. 1032, 2026, A4) reveal that a novel segregation pattern emerges when mixtures of large and small particles flow rapidly down a slope. Regular longitudinal stripes of large particles are observed, arising from the coupling between longitudinal vortices and vertical segregation processes. Pearse *et al.* derive a simple yet insightful model capturing the segregation dynamics.

Key words: avalanches, geophysical and geological flows

1. A new segregation pattern in rapid granular avalanches

The phenomenon of granular segregation is a striking effect observable in mixtures of particles of varying sizes. Popularised by the 'Brazil nut effect' (Rosato *et al.* 1987), where larger nuts migrate upward in vibrating cereal packages, segregation is also a feature of granular flows in diverse contexts, including rotating drums, inclined planes and silos (Ottino & Khakhar 2000; Gray 2018). The universal tendency of larger grains to separate from smaller ones poses significant industrial challenges, particularly when uniform mixing is required. This phenomenon also plays a critical role in shaping natural landscapes and geophysical deposits resulting from avalanches, landslides and debris flows.

Despite extensive research, the physical origin of segregation at the grain scale remains incompletely understood, with ongoing research on how forces are distributed among the different type of grains (van der Vaart *et al.* 2015; Guillard, Forterre & Pouliquen 2016; Duan *et al.* 2025). While many questions persist, substantial progress has been made in developing continuum models that successfully describe segregation across a wide range of configurations (Gray 2018). Given the extensive body of research on granular

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segregation, one might have assume that all possible patterns had already been observed. However, Pearse, Johnson & Gray (2026) managed to surprise us in their study by revealing a novel phenomenon. They evidence and analyse a novel segregation pattern that emerges during rapid flows of bidisperse granular materials on steep inclined planes. Their experiments show that regular longitudinal bands form within the flowing mixture, which persist in the deposit. This observation stands in contrast to the classical understanding of segregation for flow down inclined planes, where larger particles typically rise to the surface, forming a fast-moving layer that accumulates at the flow front and often triggers instabilities (Pouliquen, Delour & Savage 1997; Woodhouse *et al.* 2012). However, the pattern described by Pearse *et al.* (2026) is neither front-controlled nor driven by density differences between particles as reported by d'Ortona & Thomas (2020).

At the core of this phenomenon lies a secondary instability in rapid granular flows on inclined planes, which generates longitudinal vortices. Previous research has shown that, at high inclinations, homogeneous granular flows can destabilise, forming transverse vortices (Forterre & Pouliquen 2001; Börzsönyi, Ecke & McElwaine 2009). The origin of these vortices remains debated, as multiple physical mechanisms may contribute to their formation. One hypothesis attributes their emergence to the agitation of strongly sheared grains near the base, which creates a less dense layer beneath a denser upper layer, thereby inducing a Rayleigh–Taylor-like instability (Forterre & Pouliquen 2002). Another potential explanation involves normal stress differences, with recent continuum models incorporating normal stresses demonstrating their ability to induce secondary transverse flows (Gadal, Johnson & Gray 2026).

Rather than discriminating between these mechanisms, Pearse *et al.* take an elegant and pragmatic approach. They demonstrate that the presence of longitudinal vortices, when coupled with a simple model of upward granular segregation, can explain the formation of the longitudinal bands of large particles.

2. How segregation models capture the observation

The authors begin their study by presenting experimental evidence of the novel segregation pattern through two distinct configurations. In the first set-up, a mixture of large green (225 μm) and small white (105 μm) particles is released onto a steep curved slope (figure 1*a*). The granular mass accelerates downhill, then decelerates and eventually comes to rest, forming a deposit that preserves the internal flow structure. The striking observation is the emergence of longitudinal stripes extending beyond the flow front. The segregation pattern spans the entire depth of the layer, as confirmed by cross-sectional cuts of the deposit (figure 1*b*). The second configuration examines flow on an inclined plane at a constant angle. While this set-up does not permit direct observation of the internal structure, it demonstrates that a steady-state regime with longitudinal stripes can be achieved, which is closely linked to the formation of longitudinal vortices.

To explain these observations, the authors develop a kinematic model that qualitatively captures the segregation pattern and identifies the key control parameters. They assume a fixed flow structure characterised by a three-dimensional velocity field representing longitudinal vortices, as sketched in figure 1(*c*). This structure is assumed to remain constant and decoupled from the evolution of the particle repartition. For a layer of thickness H, the velocity field (u, v, w) is assumed to be uniform in x and described by the following equations:

$$u = u^* \left(1 - (1 - z/H)^{3/2}\right), \tag{2.1}$$

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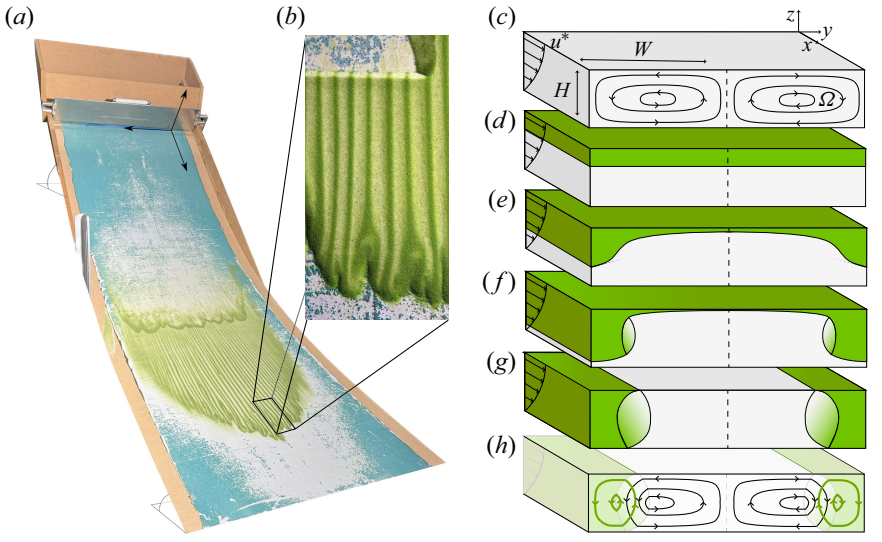


Figure 1. (*a*) Experimental set-up used by Pearse *et al.* (2026) illustrating the stripes pattern observed when a mixture of large green grains (225 μm) and small white grains (105 μm) is released at the top of the slope. (*b*) Close-up of the deposit, with a cross-sectional cut revealing the internal structure of the stripes. (*c-h*) Sketches of the segregation process: (*c*) velocity field used to model the longitudinal vortices; (*d–g*) time evolution of the distribution of large (green) and small (white) particles, starting from two segregated layers; (*h*) transverse streamlines of the large (in green) and small (in black) particles at steady state (figures inspired by the original figures of Pearse *et al.* 2026).

$$v = \Omega \sin\left(\frac{\pi y}{W}\right)(2z - H), \tag{2.2}$$

$$w = -\left(\frac{\Omega \pi}{W}\right)\cos\left(\frac{\pi y}{W}\right) z(z - H), \tag{2.3}$$

where u^* represents the free-surface downslope velocity, W is the width of the longitudinal vortices and Ω is the rotational velocity. The resulting velocity field, illustrated in figure 1(*c*), depicts counter-rotating vortices aligned with the primary flow direction. The authors then use this velocity field in an advection-segregation equation to predict the evolution of the relative concentration ϕ^s of small particles. Based on experimental observations indicating that the stripe pattern remains quasi-uniform along the flow direction, they simplify the problem by assuming that ϕ^s is independent of the downslope coodinate x. The governing equation for the concentration of small particles is

$$\frac{\partial \phi^s}{\partial t} + \frac{\partial}{\partial y}(\phi^s v) + \frac{\partial}{\partial z}(\phi^s w) - \frac{\partial}{\partial z}\left[q\phi^s(1 - \phi^s)\right] = 0. \tag{2.4}$$

This equation describes how the concentration of small particles evolves through two competing mechanisms: advection by the transverse vortex velocities (v, w) and modification by a segregation flux represented by the final term in (2.4) and characterised by the segregation velocity q. The segregation flux is assumed to act along z perpendicular to the slope, a reasonable assumption given that the strongest shear occurs parallel to the slope. While the segregation velocity q is known to depend on local shear rates, stress gradients and other parameters, the authors simplify the model by treating q as a constant parameter. By introducing dimensionless variables, the authors demonstrate that

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the system's behaviour is governed by two key dimensionless parameters: the aspect ratio H/W and the ratio of segregation velocity to vortex velocity $\Lambda = q/(\Omega H)$.

Figure 1(*d–g*) illustrates the formation of stripes from an initially fully vertically segregated layer, the configuration expected in the absence of longitudinal vortices. The transverse velocity induced by the vortices stretches the coarse particle layer at the centre of the vortex cell, while pushing it downward at the sides (figure 1*e*). As large particles become overtaken by small ones (figure 1*f*), they segregate back towards the free surface, creating a recirculation zone that ultimately leads to the formation of longitudinal stripes (figure 1*g*). The steady-state dynamics of large and small particles are summarised in figure 1(*h*), where green lines represent the streamlines for large particles and black lines represent those for small particles. The size of the recirculation zone, where the two particle types interpenetrate, is governed by the dimensionless parameter Λ. Higher segregation velocities relative to the vortex velocity result in a thinner recirculation zone. Using this approach, the authors solve the system of equations to analytically predict the steady-state flow pattern, including shock structures and what they term a 'breaking wave', a mixed region with sharp interfaces separating pure large and pure small particle regions.

3. Implication and perspectives

The analysis presented by Pearse *et al.* convincingly demonstrates that for rapid granular flows down steep slopes, the coupling between longitudinal vortices and segregation dynamics leads to the formation of longitudinal stripes of large particles, a pattern that had never been observed before. The elegance of their model lies in its simplicity, which clearly elucidates the underlying physical mechanisms. As the authors acknowledge, the origin of longitudinal vortices remains an open question. As acknowledged by the authors, several key questions remain to be addressed for the development of more complete and predictive models. First, the origin of longitudinal vortices is still an open question. A complete model would need to integrate the mechanisms governing vortex formation, and recent rheological models proposed by some of the same authors, particularly those accounting for normal stress differences (Gadal *et al.* 2026), could serve as a promising starting point. Second, the assumption of a constant vertical segregation velocity represents a simplification that could be relaxed in light of recent advances in understanding the origin of segregation fluxes (Gray 2018; Duan *et al.* 2025). Finally, the authors mention the potential role of diffusion processes, which have been shown to influence particle mixing in other granular flow configurations.

Beyond its fundamental contributions to granular physics, this work has important implications for geophysical applications. Field observations of natural deposits, such as those from large, rapid landslides, often reveal longitudinal stripe patterns accompanied by particle size sorting (Shreve 1966; Magnarini *et al.* 2024). While previous studies suggested that longitudinal vortices might explain the corrugated morphology of these deposits (Magnarini *et al.* 2019), Pearse *et al.*'s findings provide a mechanistic explanation for the observed size repartition. This study thus bridges the gap between controlled laboratory experiments and large-scale natural events, demonstrating how simple experiments can shed light on the dynamics of massive geophysical phenomena.

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