Submission code: 8Q0NX7Y9Q6

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Packing-Controlled Shear Bands in Dense Dry Granular Media

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SBGf Conference
18-20 NOV | Rio'25

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Abstract Summary

Granular materials confined under load can remain in metastable states until the deviatoric stress surpasses a density-dependent threshold, whereupon failure localises in well-defined shear bands. We investigate this localisation in a granular assembly on quasi-planar geometry penetrated at constant speed by a semicylindrical intruder. Particle-image velocimetry shows that the flow collapses into paired logarithmic-spiral shear bands that nucleate, rotate and extinguish intermittently, synchronised with saw-tooth oscillations of the penetration force. The sequence is a nucleation–relaxation loop: elastic loading raises the force until a modified Mohr–Coulomb criterion is met, after which a new band forms and the force drops abruptly. The internal friction coefficient is not constant but rises sharply with packing fraction, $\mu = \mu(\phi)$. Below a critical density $\phi_c \approx 0.59$, deformation is diffuse and force evolves smoothly; above ϕ_c the measured band geometry and force-drop amplitude are reproduced quantitatively by integrating the Coulomb yield locus with $\mu(\phi)$. The results link packing-controlled friction, quasi-static rheology and the morphology of shear bands in dry granular media.

Introduction

Granular failures such as landslides, debris avalanches, and embankment collapses catastrophically in sudden episodic events that typically originate deep inside the material, where *in-situ* observation is a very difficult task. The mobility of a granular assembly is governed by the interplay between inter-particle contact forces and external boundary conditions (Majmudar and Behringer, 2005; Nedderman et al., 1992). The mode of deformation and the velocity distribution are not spatially distributed in a homogeneous manner but in highly localised shear bands (Takahashi, 1981). Perturbing either control set can provoke large, geometry-driven rearrangements—an inevitable consequence of the material's discreteness—and may culminate in an imminent slope failure.

For assemblies of *rigid* grains, theory and laboratory studies converge on a *critical packing fraction* ϕ_c. Below this limit the material flows; above it the system becomes geometrically constrained and lacks the degrees of freedom required for sustained deformation. Crossing the blockage-to-flow transition entails a volumetric rearrangement that is activated only when the applied deviatoric stress exceeds a threshold magnified by the grains' own overburden pressure.

Predicting where and when the ensuing shear bands will form remains elusive. Their spatial position, shape, and stress threshold are key parameters reported across numerous experimental and numerical studies (Gravish et al., 2010; Hamm et al., 2011; Ness and Fielding, 2025; Tapia et al., 2013), yet progress is hindered by the opacity of most granular systems and the wide range of possible flow regimes.

To overcome these uncertainties and tackle this questions we developed a quasi-two-dimensional indentation set-up in which a rigid finger penetrates vertically into a compacted granular layer (Fig. 1a). The planar geometry, combined with high-resolution particle-image velocimetry, grants direct access to the velocity field and the dynamics of the localisation zones, allowing us to relate the onset of a spiral shear bands to both the packing fraction and the macroscopic indentation force.

Method and/or Theory

In this study we experimentally investigate the nucleation and evolution of shear bands in densely packed dry granular assemblies. The granular medium consists of spheroidal brass beads with diameters $38\ \mu m < d < 63\ \mu m$ poured into a quasi-two-dimensional cell of inner dimensions $40 \times 30 \times 10\ \mathrm{mm}^3$ ($W \times H \times T$). The front and back walls are 3 mm glass plates, allowing particle-image velocimetry through the front wall. Polydispersity suppresses crystalline ordering. Beads are dispensed through a set of cross-grids to obtain a uniform initial fill; the packing fraction ϕ is then tuned by gently tapping the side walls. *In situ* image segmentation of the front-wall monolayer yields the projected area fraction, which we extrapolate to a bulk ϕ. The indenter consists of a rectangular intruder ("finger") whose body spans the 10-mm gap and terminates in a semicylindrical tip of radius $R = 1.5\ \mathrm{mm}$. The finger translates vertically at constant speed while force and velocity fields are recorded; further measurement details follow Refs. (Hamm et al., 2011; Tapia et al., 2013).

Results

The experiments show that the deformation field is symetrical respect to the indenter and remain confined to a narrow region surrounding the intruder. Shear bands nucleate intermittently exhibiting a global spiral symmetry with origin at the tip of the intruder: each nucleation event coincides with a local maximum in the penetration force, followed by successive phases of erosion and accretion of grains around the finger that produce a monotonic force drop.

The initial compaction strongly affects the force amplitude, which is significantly higher in densely packed samples. Band localisation is likewise sensitive to density: for compact states ($\phi > 0.59$) the shear zones are sharp and well defined, whereas below $\phi \approx 0.59$ they become progressively diffuse.

This structural change is mirrored in the force signal. Marked saw–tooth fluctuations typify dense configurations, while they all but disappear in looser packs, signalling a transition toward a more hydrodynamic, free-flow regime.

Mechanics of the band geometry. A minimal description treats the intruder as a rigid body subjected to a plane-stress state with principal components $(\sigma_{11}, \sigma_{33})$ and sliding along a plane inclined at an angle ϕ_0, characterised by a friction coefficient μ.

In the quasi-static limit the system is in mechanical equilibrium; imposing the Mohr–Coulomb yield criterion then gives,

$$\frac{\sigma_{11}}{\sigma_{33}} = \frac{1 + \mu/\tan\phi_0}{1 - \mu\tan\phi_0}\,, \tag{1}$$

Interestingly, this Mohr–Coulomb-type criterion links the principal stresses to the geometry of the failure surface—captured by the angle ϕ—and to the granular material's intrinsic friction coefficient μ. In other words, once a quasi-elastic plane-stress field is prescribed and a constitutive law $\mu = \mu(\phi)$ is supplied, the Mohr–Coulomb relation suffices to predict the shape of the shear band observed in the experiments showing a logarithmic-spiral like form.

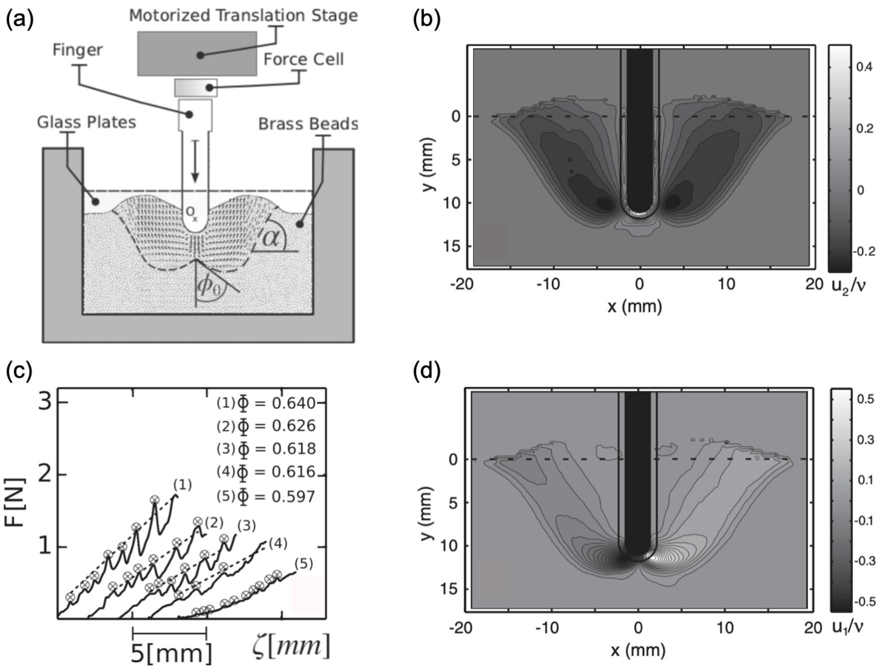

Figure 1: (a) Schematic of the configuration: the moving region is bounded by two shear bands, shown as dashed lines. The shape is parameterised in polar coordinates with origin at O, using the initial angle ϕ_0 and the tail angle α. (c) Indentation force F as a function of penetration depth ζ for different ϕ. The curves are intentionally offset for visual clarity. Circles mark the nucleation events. (b) and (d) display the normalised vertical and horizontal components of the velocity field, respectively.

In our analysis the dense packing is idealised as an elastic, isotropic, planar half-space loaded by a point force at its free surface. The finite width of the indenter is therefore neglected and the stress field is dominated by the radial component solution for a point load in plane elasticity (Johnson, 1985). A uniform hydrostatic overburden is then superimposed to account for the weight of the grains.

This minimal framework reproduces the logarithmic-spiral shear band observed in the experiment and predicts the peak indentation force attained just before band nucleation. Figure 1(b) compares the measurements with the semi-empirical model: the crossed-circle symbols mark the model predictions and fall squarely on the experimental trend for different initial packing fraction ϕ ranging from 0.59 to 0.64.

Conclusions

Our quasi-planar indentation experiments reveal that dense dry granular packs fail through the intermittent nucleation of conjugate spiral shear bands once the packing fraction exceeds a critical value $\phi_c \approx 0.60$. The force signal recorded during penetration exhibits sharp saw tooth drops synchronised with each localisation event, and the drop amplitude grows linearly with penetration depth.

During penetration, the finger compacts the grains, creating a consolidated halo that screens the side walls. Beyond this stage the material responds as if it were a semi-infinite continuum, so the pre-collapse stress field is well captured by the Boussinesq solution for an elastic half-space loaded by a point force and closing the problem with a Mohr–Coulomb criterion in which the internal friction μ rises steeply with ϕ, we recover both the logarithmic-spiral geometry of the bands and the peak indentation force. Hence a single pair of state variables, (μ_c, ϕ_c), links the bulk quasi-static rheology to the local failure morphology.

The agreement between model and experiment (Fig. 1b) demonstrates that, in the true quasi-static regime, spiral shear bands are governed by the pre-collapse elastic stress field and the packing-dependent frictional response.

References

Gravish, N., P. B. Umbanhowar, and D. I. Goldman, 2010, Force and flow transition in plowed granular media: Physical Review Letters, **105**, 128301.

Hamm, E., F. Tapia, and F. Melo, 2011, Dynamics of shear bands in a dense granular material forced by a slowly moving rigid body: Physical Review E, **84**, 041304.

Johnson, K. L., 1985, Contact mechanics: Cambridge University Press.

Majmudar, T. S., and R. P. Behringer, 2005, Contact force measurements and stress-induced anisotropy in granular materials: Nature, **435**, 1079–82.

Nedderman, R. M., et al., 1992, Statics and kinematics of granular materials: Cambridge University Press Cambridge, **352**.

Ness, C., and S. M. Fielding, 2025, Nonmonotonic constitutive curves and shear banding in dry and wet granular flows: Phys. Rev. Lett., **134**, no. 3, 038201.

Takahashi, T., 1981, Debris flow: Annual review of fluid mechanics, **13**, 57–77.

Tapia, F., D. Espindola, E. Hamm, and F. Melo, 2013, Effect of packing fraction on shear band formation in a granular material forced by a penetrometer: Physical Review E, **87**, 014201.