Unsteady rheology of dense granular flows from quasi-static to inertial regime

EPSRC Pioneering research and skills

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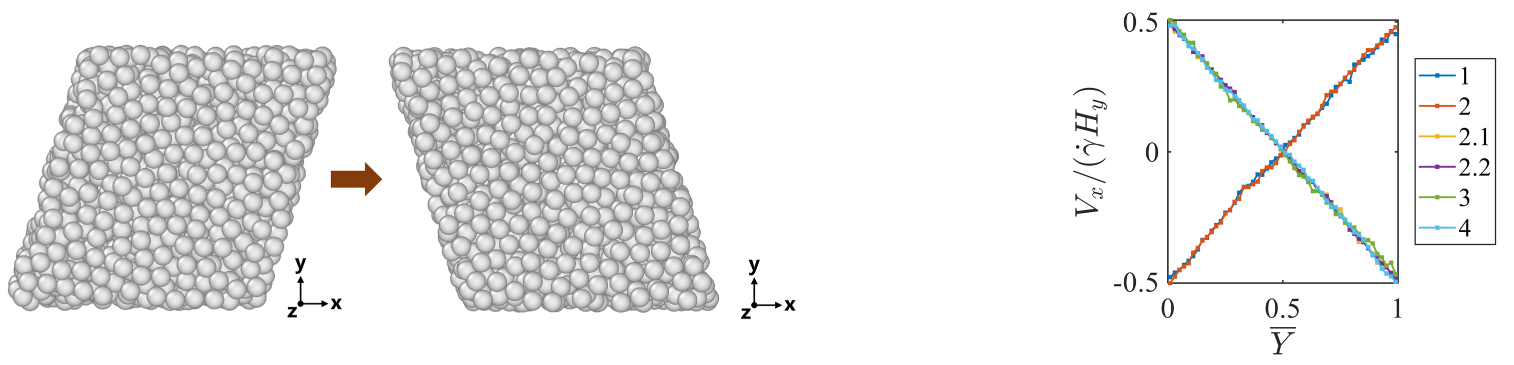
1 Introduction

- Dense granular flows are encountered in many industrial and geophysical processes, where the deformation rate often changes due to topographical variation, for example.
- It has been shown that the history effect is important for quasi-static flows. It, however, remains an open question how well a model without history effect can capture unsteady inertial flows.
- **We use simulations of shear-reversal and rate-change flows to demonstrate the evolution of stresses and microstructure during the unsteady state.**

2 Simulation methodology and setup

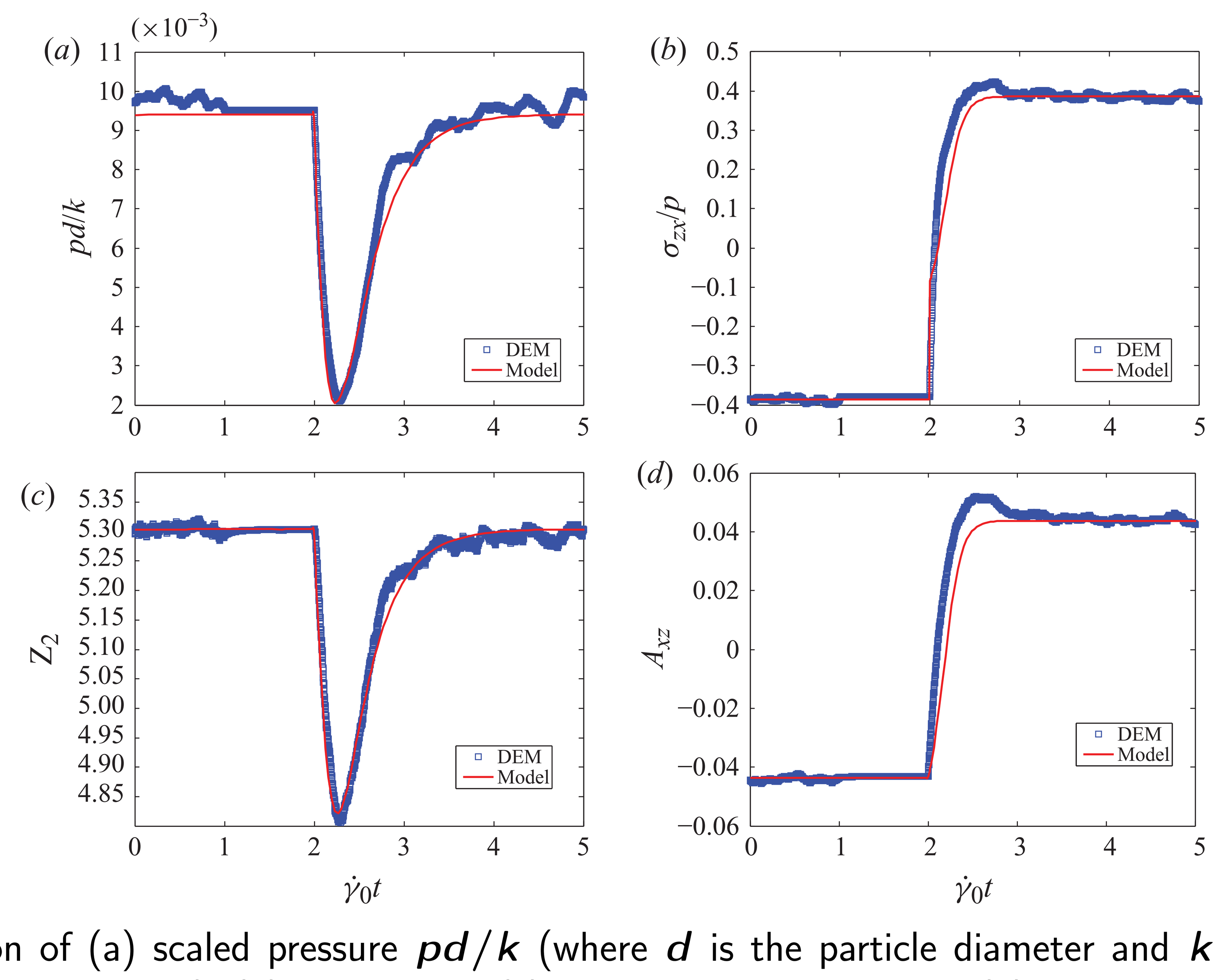
- Discrete element method (DEM) using LAMMPS
- 2000 monodisperse spheres in three dimensional triclinic simulation box
- Homogeneous simple shear flow using deforming box and the Lees-Edwards boundary condition
- A mechanical force $F_i = m y_i \frac{\mathrm{d}\dot{\gamma}}{\mathrm{d}t}$, where y_i is the particle coordinate in the shear gradient direction, is applied to each particle to realise 'instantaneous' velocity change



Visualisation of the particle assemblies (left) and streaming velocity profiles (right) to illustrate the shear reversal flow

3 Stress and microstructure evolution in quasi-static shear-reversal flow

The stresses of a granular material with solid volume fraction ϕ greater than the shear jamming volume fraction ϕ_c exhibit rate-independent characteristics. The evolution of stresses in unsteady shear reversal flow correlates well with that of the microstructure, which is characterised by the coordination number $Z = \frac{2N_c}{N}$ and fabric tensor $A = \frac{1}{N_c}\sum \mathbf{nn} - \frac{1}{3}\mathbf{I}$ where N_c is the number of contacts and N is the number of particles and $\mathbf{n}$ is the branch vector pointing from one particle centre to then centre of a contacting particle.

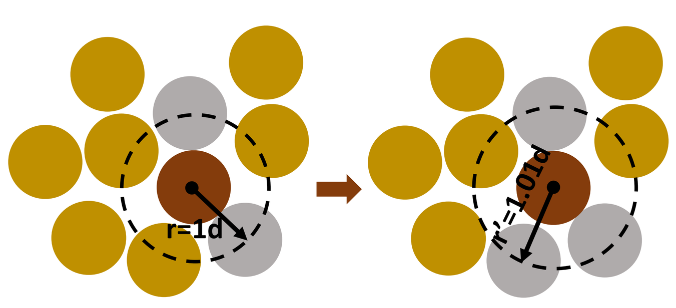


Evolution of (a) scaled pressure pd/k (where d is the particle diameter and $k = k_n$ is the particle stiffness), (b) stress ratio, (c) coordination number and (d) A_{xz} for an assembly subjected to unsteady shear under the constant volume condition with $\phi = 0.60$. Blue square symbols denote the data from DEM simulations and the red solid curves are the constitutive model results. The shearing was stopped during $1 < \dot{\gamma}_0 t < 2$. The interparticle friction coefficient μ is 0.5 and the inertia number $I \approx 0.0003$ at steady state.

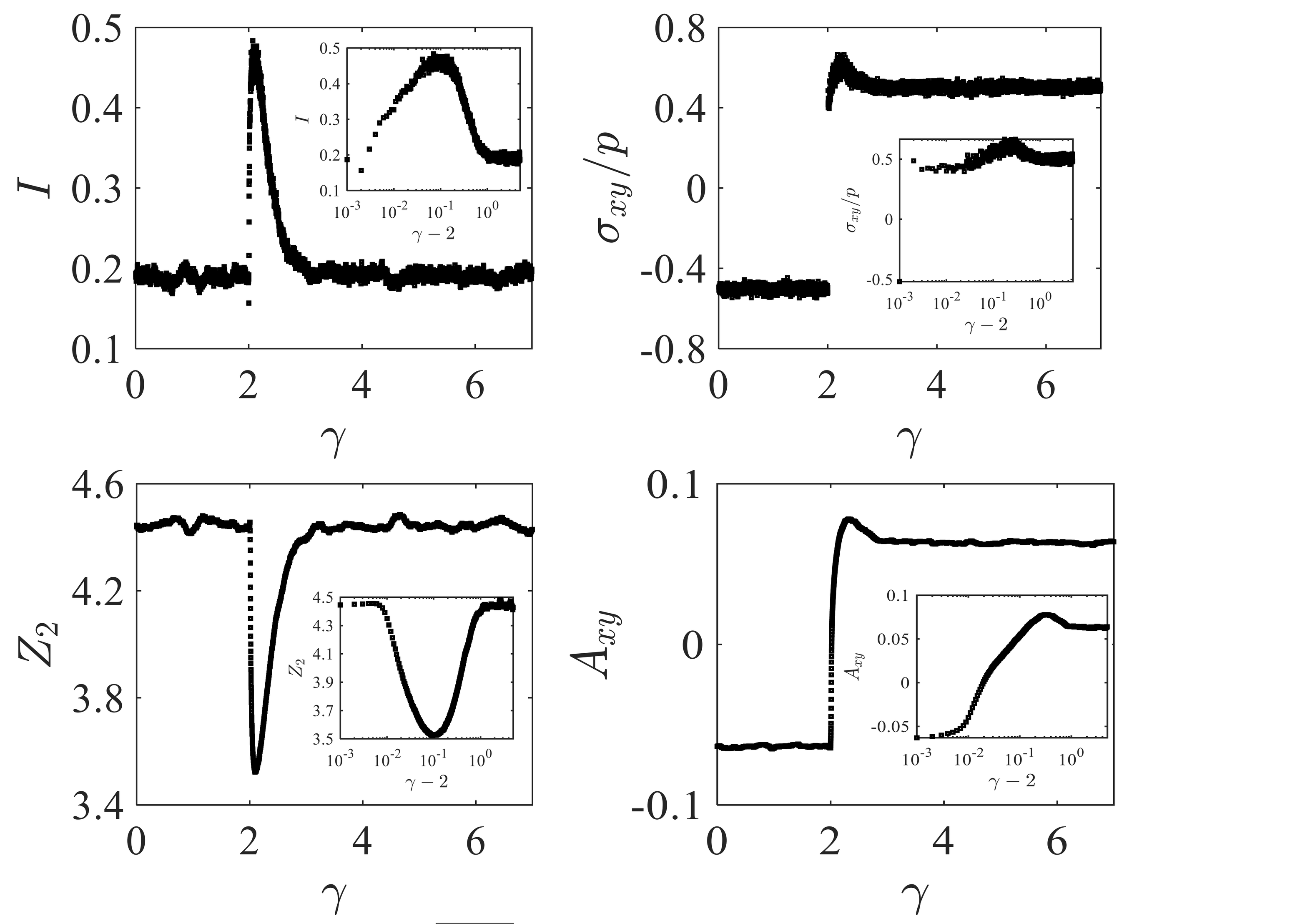
4 Microstructure characterisation in inertial flow

As binary collisions dominate in inertial flow, the definitions of coordination number and fabric tensor need to be suitably modified to be statistically meaningful.

- A cutoff distance of $1.01d$ is used to count the particles considered to be 'in contact'.
- The redefined coordination number and fabric tensor have been checked to vary insignificantly against the cutoff distance of $1.01d - 1.03d$.

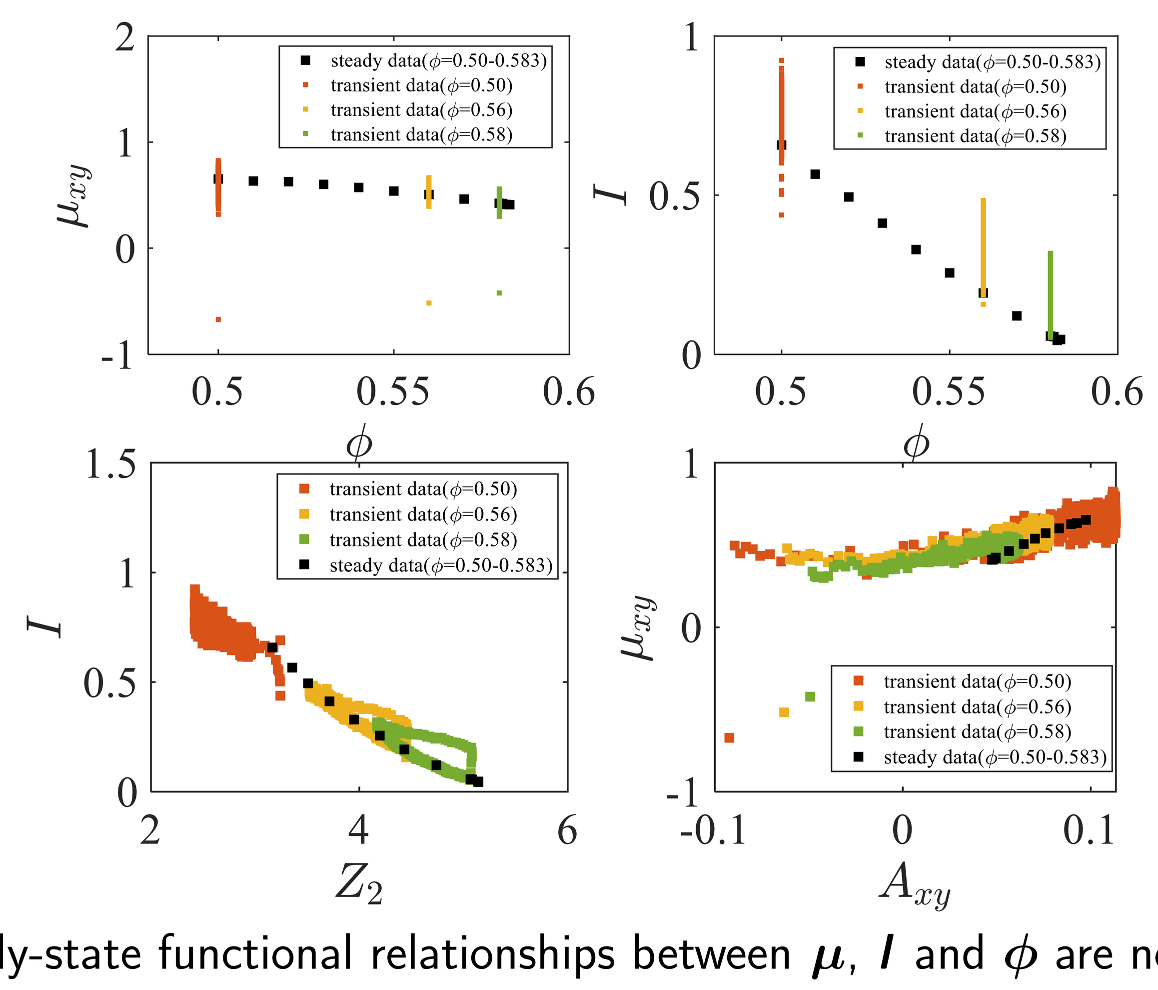


5 Stress and microstructure evolution in inertial shear-reversal flow



The inertial number $I = \dot{\gamma} d\sqrt{\rho/p}$ and stress ratio $\mu_{xy} = \sigma_{xy}/p$ change at shear reversal at $\gamma = 2$ and evolve over a significant strain about unity despite shearing at a contant volume. The redefined coordination number and the shear component of the fabric tensor display similar evolution pattern.

6 Modelling options in inertial shear-reversal flow



The steady-state functional relationships between μ, I and ϕ are no longer valid. The coordination number and fabric tensor are found to be promising in modelling the transient data.

7 Small disturbance with rate magnitude change

- The magnitude of shear rate $\dot{\gamma}\sqrt{m/k}$ is decreased from 4×10^{-4} to 2×10^{-4}.
- The stresses and microstructure have small deviations from the steady state and recover within 0.2 strain.