Clogging in Granular Flow through a Bottleneck

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Introduction & Motivation

Granular flow through narrow openings is common in industry and nature, found in systems ranging from grain silos to crowd evacuations.

A key feature of these systems is **clogging**: the spontaneous formation of stable particle arches that completely block the flow. Unlike fluids, granular materials can switch between flowing and jammed states due to **collective interactions**.

Project Goal: We investigate the statistics of clogging using Molecular Dynamics (MD) with Brownian motion to simulate realistic conditions.

We focus on how jamming probability depends on:

- Orifice width D
- Friction coefficient μ
- Stochastic effects (Brownian noise)

Methodology: Molecular Dynamics

We simulate a two-dimensional silo containing $N = 200$ circular discs under gravity using a Discrete Element Method. Particle motion follows Newton's equations:

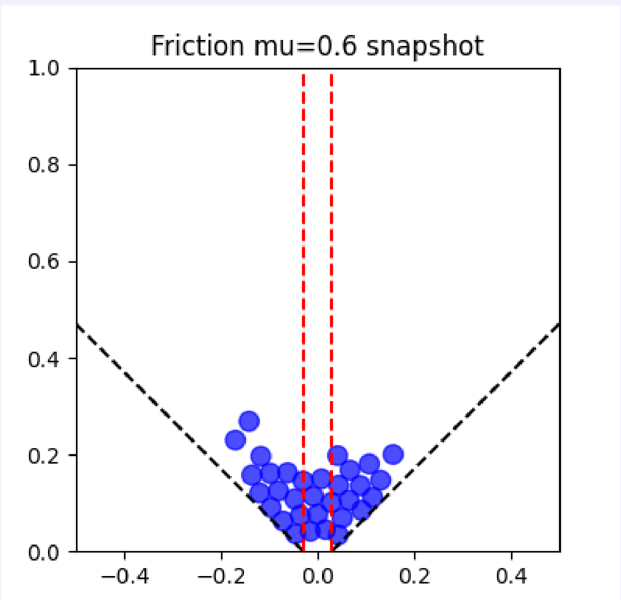
$$m\dot{\mathbf{r}}_i = m\mathbf{g} + \sum_j \mathbf{F}_{ij}^{\text{cont}} + \mathbf{F}_i^{\text{wall}} + \mathbf{F}_i^{\text{noise}} \tag{1}$$

Contact physics:

- **Normal force:** Linear spring–dashpot model, $F_n \propto \delta_{ij}$
- **Tangential force:** Coulomb friction limited by $|F_t| \leq \mu F_n$

This combination captures elastic collisions, energy dissipation, and stick–slip behavior essential for stable arch formation.

Visualisation: Clogged System



A jammed configuration showing a stable arch of particles at the orifice. Walls are black lines, orifice edges in red, and the arch location highlighted in blue.

Defining a Jam

A simulation is classified as **jammed** when both conditions are satisfied:

1. No particles discharge for a sustained time window Δt_{jam}
2. A mechanically stable arch spans the outlet

This definition avoids confusing transient slowdowns with true clogging events.

Methodology: Brownian Dynamics

To test the robustness of clogging, we treat the grains as Brownian particles subject to thermal-like agitation.

The Model:

- **Gravity ($m\mathbf{g}$):** The driving force pulling particles down.
- **Friction (μ):** Dissipates energy and stabilizes arches.
- **Brownian Noise ($\mathbf{F}^{\text{noise}}$):** A stochastic force added to Newton's equations to simulate vibrations or perturbations.

This approach (Langevin dynamics) ensures that jamming is a true physical phase transition and not just an artifact of the particles being perfectly still.

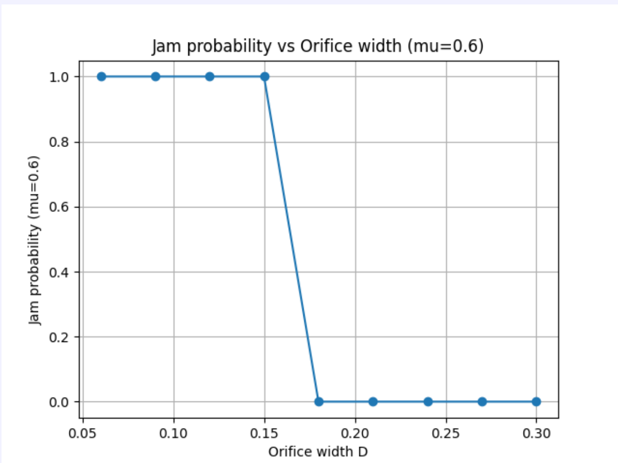
Results: Effect of Geometry (D)

The orifice width D is the dominant control parameter.

1. Small openings ($D \leq 0.12$):
Particles are forced into a narrow funnel. Few exit configurations exist, making the formation of blocking arches highly probable. The jamming probability approaches unity.

2. Transition regime:
As D increases, the mean number of discharged particles grows nonlinearly and the probability of forming a spanning arch rapidly decreases.

3. Large openings ($D \geq 0.18$):
Geometric constraints relax and the system enters a continuous flow regime where jamming becomes statistically negligible.



Jamming probability drops sharply as orifice width (D) increases, marking a clear phase transition from clogged ($P = 1$) to flowing ($P = 0$) state.

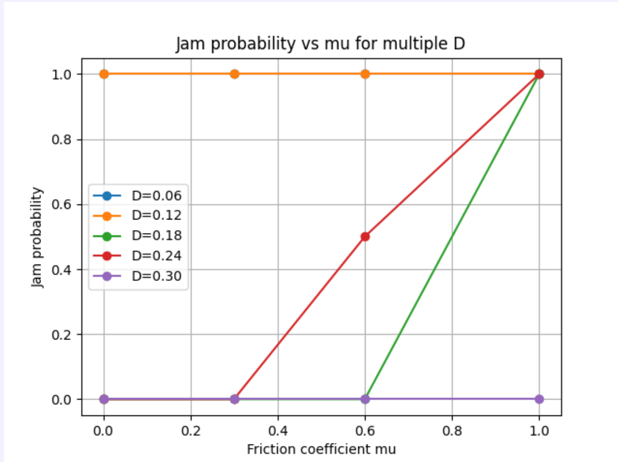
Results: Role of Friction (μ)

While geometry determines whether an arch can span the opening, friction controls its stability.

Intermediate openings:
Increasing μ significantly increases jamming probability. Friction stabilizes tangential contacts and force chains, allowing marginal arches to support the weight above them.

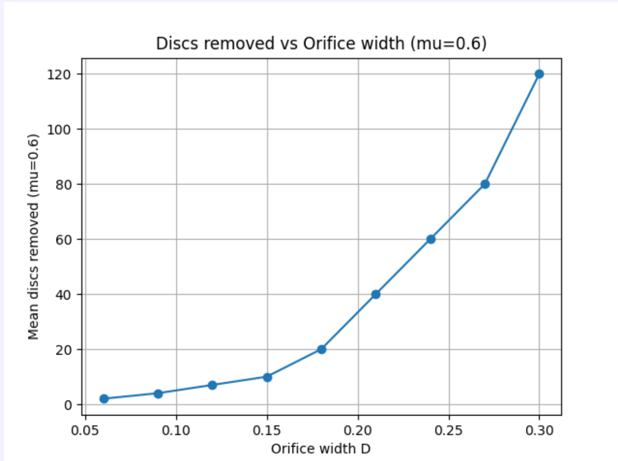
Large openings:
Friction becomes ineffective once the gap is too wide for coherent arch formation.

Remaining mass:
Low friction allows efficient rearrangement and discharge, while high friction leads to rapid stabilization and mass saturation inside the silo.



Friction dominates stability at intermediate widths ($D \approx 0.18 - 0.24$). High μ stabilizes arches, whereas very small or very large widths are insensitive to friction.

Results: Discharge Efficiency



Mean discharge count increases non-linearly with orifice width, reflecting rapid destabilization of arches for wider exits.

Conclusion & Outlook

Clogging is a collective phenomenon driven by the combination of **geometry** and **contact mechanics**.

Key Findings:

- **Small outlets** jam due to strict geometric constraints.
- **Intermediate outlets** jam because friction stabilizes the arches.
- **Large outlets** allow continuous flow.

We found that this transition is robust, persisting even with noise and variations in particle size.

Future Work: Future studies should extend this model to **three dimensions** and analyze the internal **force networks** to better understand how arches stabilize.