Bearing capacity of granular material in low-gravity:

Implications for landing and moving on asteroid surfaces

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C. Sunday[1,2], N. Murdoch[1], S. Tardivel[3], P. Michel[2]

[1] Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO), Toulouse, France
[2] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France
[3] Centre National d'Etudes Spatiales (CNES), Toulouse, France

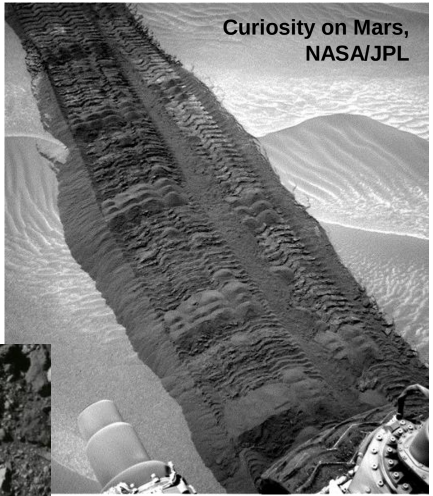
Overview

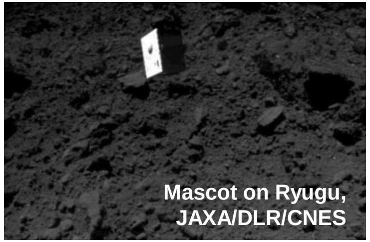
Motivation

- Knowledge of regolith strength and flow behavior in low-gravity environments is essential for the design and operation of sub-systems used for in-situ exploration during small-body missions
- Regolith properties like grain size, grain shape, cohesion, and internal friction will influence how much a lander sinks, how easily a rover gains traction, and how much (or how little) resistance is felt by a mechanism that interacts with regolith

Objectives

- To better understand how granular material responds when vertically loaded in a quasi-static state
- To demonstrate differences in the macro and micro-scale behaviors of granular material for different gravity levels





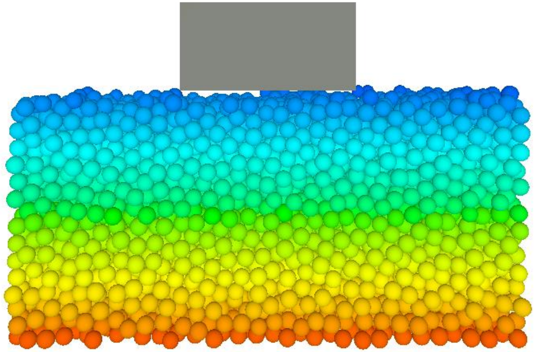
Method

Numerical simulations

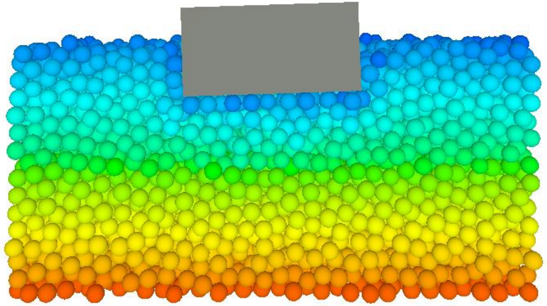
- We use the **Soft-Sphere Discrete Element Method** in the **Multicore module** of the open-source code **Chrono** (Tasora et. al 2015, Sunday et. al 2020) to simulate a plate sinking into granular material under different gravity levels
  - The plate is 100 mm x 50 mm x 50 mm in size. It's mass ranges from 1 to 6 kg
  - The material container is filled with ~12 000 **spherical particles** (glass-beads) that are 10 ± 0.5 mm in diameter
  - The simulation parameters were determined by comparing results from impact simulations against experimental data (Sunday et. al 2021 – in prep)

Analysis

- We measure the total distance that the plate penetrates into the surface (it's **sinkage**) and we observe the structure of the granular **force chains** that support the plate's load

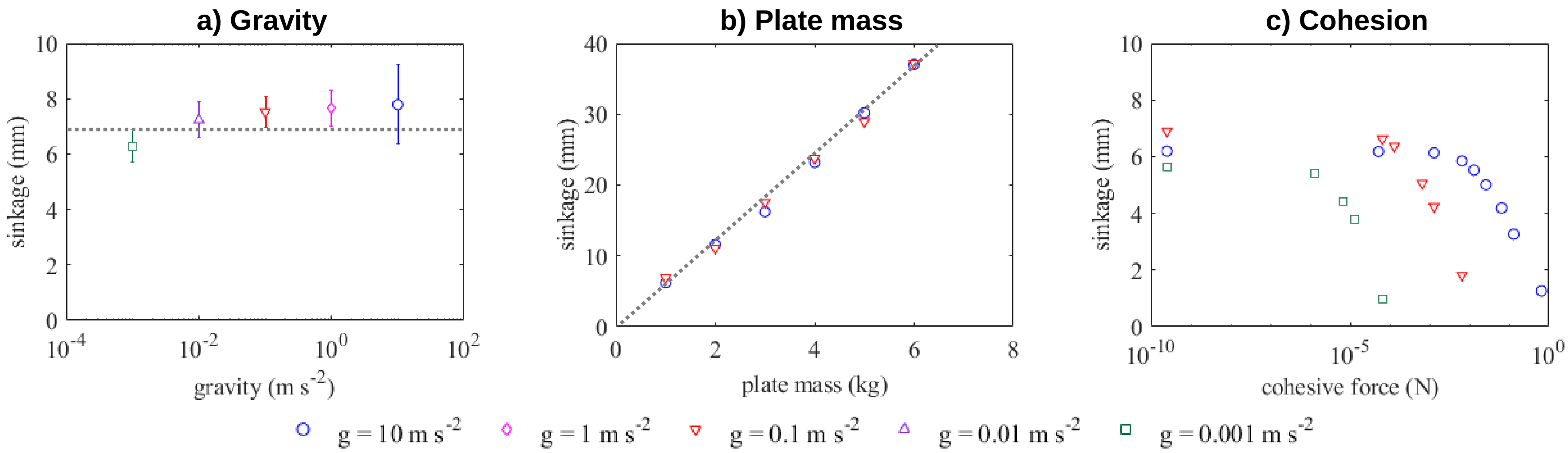


Beginning of simulation



End of simulation

Results – plate sinkage



a) Plate sinkage is more or less independent of gravity level. These results are consistent with parabolic flight experiments performed by Kobayashi et. al (2010) that show that wheel sinkage is constant for different gravity levels

b) Sinkage increases linearly with plate mass and the slope of the line is still independent of gravity level

c) Given the same cohesive force between particles, sinkage will decrease drastically as the gravity level decreases

Results – plate sinkage

Cohesion model (Scheeres et. al 2010)

$$F_c = -CR\hat{n}$$

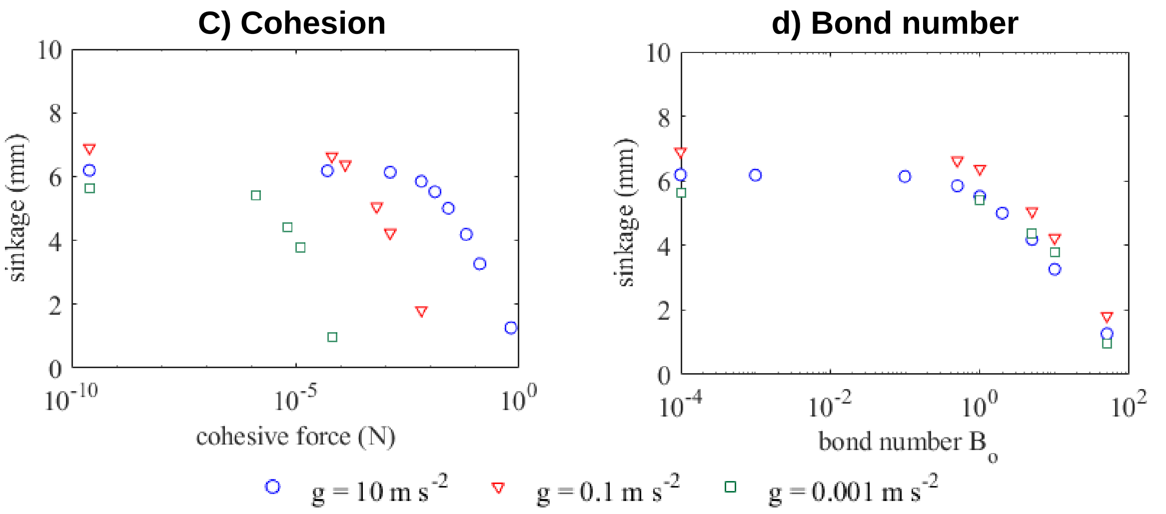
$$C = \frac{AS^2}{48\Omega^2}$$

$$R = \frac{r_i r_j}{(r_i + r_j)}$$

$A = 4.3\text{x}10^{-20}$ J,
$\Omega \sim 1.5\text{x}10^{-10}$m and $S = 0.75 - 0.88$

$$B_o = \frac{F_c}{W} = \frac{F_c}{mg}$$

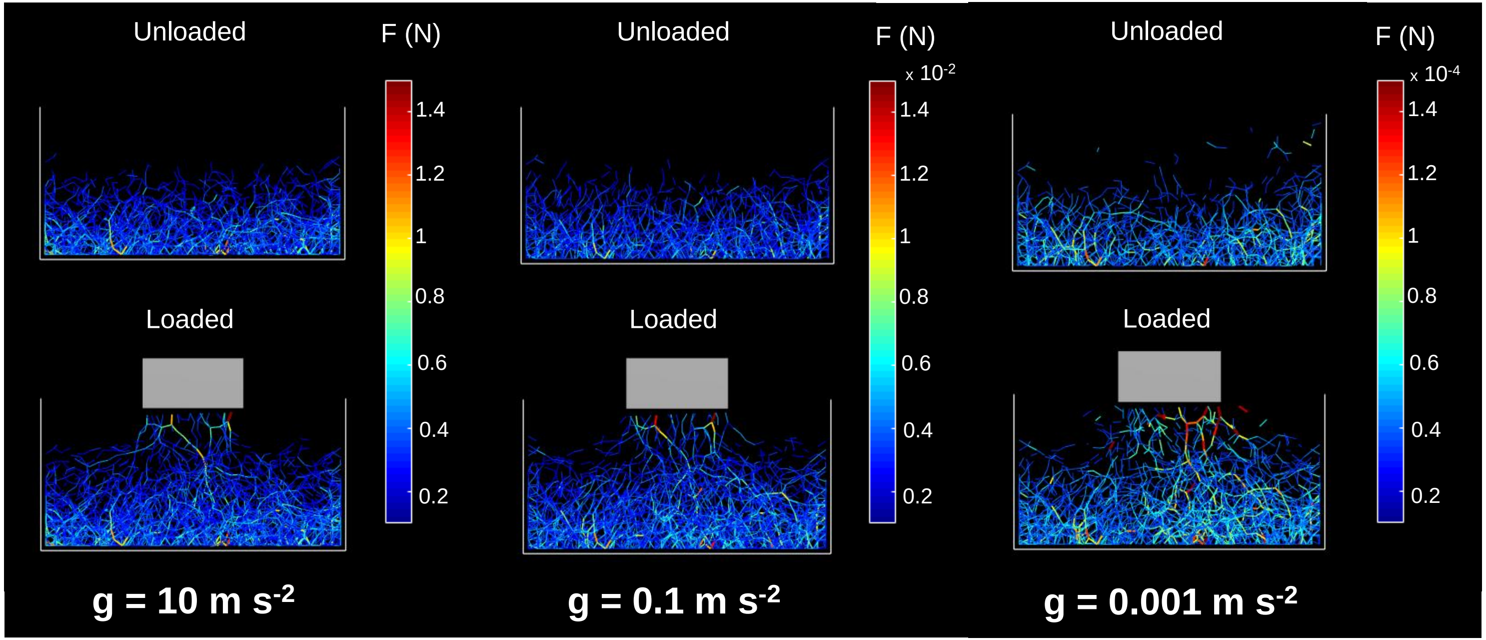
Where B_o **is the Bond number**, F_c **is the cohesive force** between the particles, and W **is the weight of the particle**



c) Given the same cohesive force between particles, sinkage will decrease drastically as the gravity level decreases

d) If the cohesive force is expressed as the Bond number, or the ratio between the cohesive force and the particle weight, then sinkage is the same for different gravity levels when the Bond number is the same

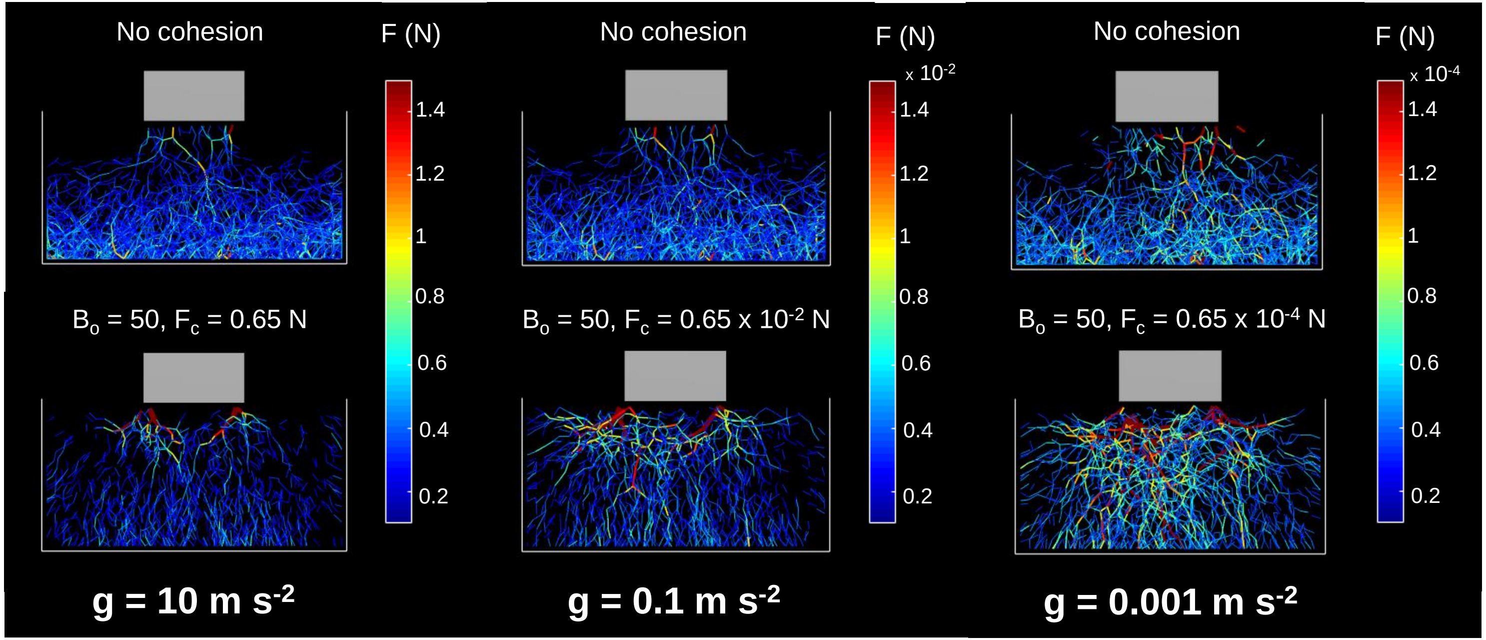
Results – force chain visualization



The plate load decreases as gravity decreases, so the magnitude of the load supported by the force chains also decreases as gravity decreases

Illustration of force chains before and after placing a 1kg plate on the granular material. Only particle contacts carrying larger than 1σ of the average contact load are shown.

Results – force chain visualization



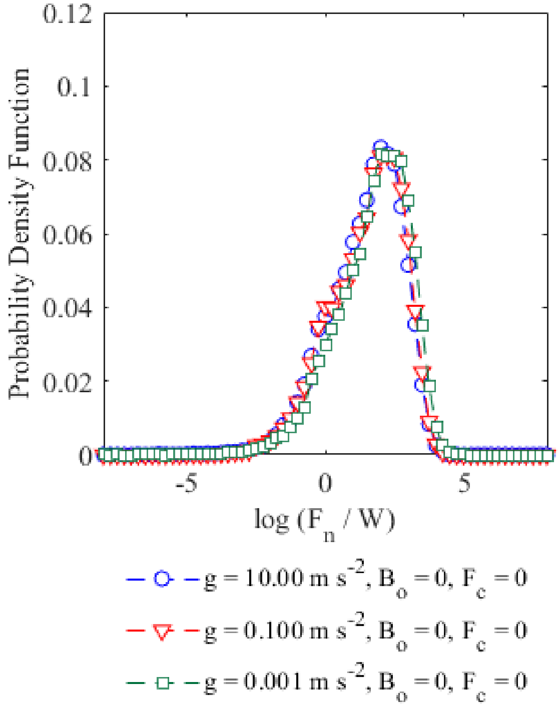
Unlike the force chain distribution in the cohesion-less material case, the web of 'strong' force chains in the cohesive material case appears to grow as gravity decreases

Illustration of force chains after placing a 1kg plate on cohesion-less and cohesive granular material. Only particle contacts carrying larger than 1σ of the average contact load (based on the average load in the cohesion-less case) are shown.

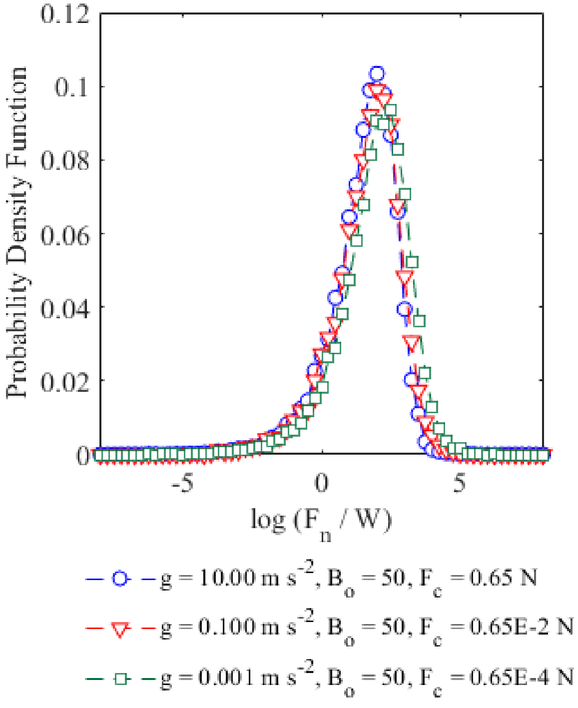
Results – distribution of force chains

- For every gravity level, about 64% of the particles in the system carry less than the average normal contact load
- In the absence of cohesion, the load distribution is the same for different gravity levels when the normal contact force F_n is scaled by the weight of a typical particle *W* (see Fig. a)
- For cohesive materials with comparable Bond numbers, a larger number of particles will carry larger loads as gravity decreases (see Fig. b)

a) Without cohesion



b) With cohesion



Conclusions

Conclusions

- **At the macro-scale** and in the absence of cohesion, a granular material will respond the same to a vertical load, regardless of gravity level (i.e. a rover or a lander will sink to the same depth on Earth as it will on an asteroid)
  - ➢ **For cohesive materials,** sinkage is the same for different gravity levels only when the cohesive force is scaled by the weight of the particle, or in other words, for materials with comparable Bond numbers
- **At the micro-scale** and in the absence of cohesion, the distribution of the contact loads in the system is the same for different gravity levels when the contact force is scaled by the weight of the particle
  - ➢ **For cohesive materials** with comparable bond numbers, the distribution of contact loads appears to shift to higher loads as gravity decreases
- Findings regarding the probability distribution functions for the force chains in the cohesion-less material match results from a similar analysis conducted by Chen et. al 2015

Future work

- More work is required to understand the micro-response (i.e. the distribution of force chains) of a granular material in response to vertical loading in different gravity levels, especially for cohesive materials

References and acknowledgements

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