

INTRODUCTION

Asteroids with sizes below a few km are mostly believed to be loose aggregates bound together primarily by self-gravity, known as rubble-piles. Historically, rubble-pile asteroids have been treated as essentially cohesionless aggregates. Recent evidence from high-resolution spacecraft in-situ observations (e.g. Hayabusa2 and OSIRIS-REx missions) show very low values for cohesion on the surface and in the body [1]. However, the physical nature and intensity of inter-particle interaction forces remain unclear, therefore, their effect on the macroscopic properties is not well understood.

Moreover, the mechanical properties of rubble-pile regolith and individual constituents (microscopic or particle-scale properties) could be different between its surface and subsurface layers, possibly influencing the aggregates response to natural or artificial impacts and high spin rates [e.g. 2].

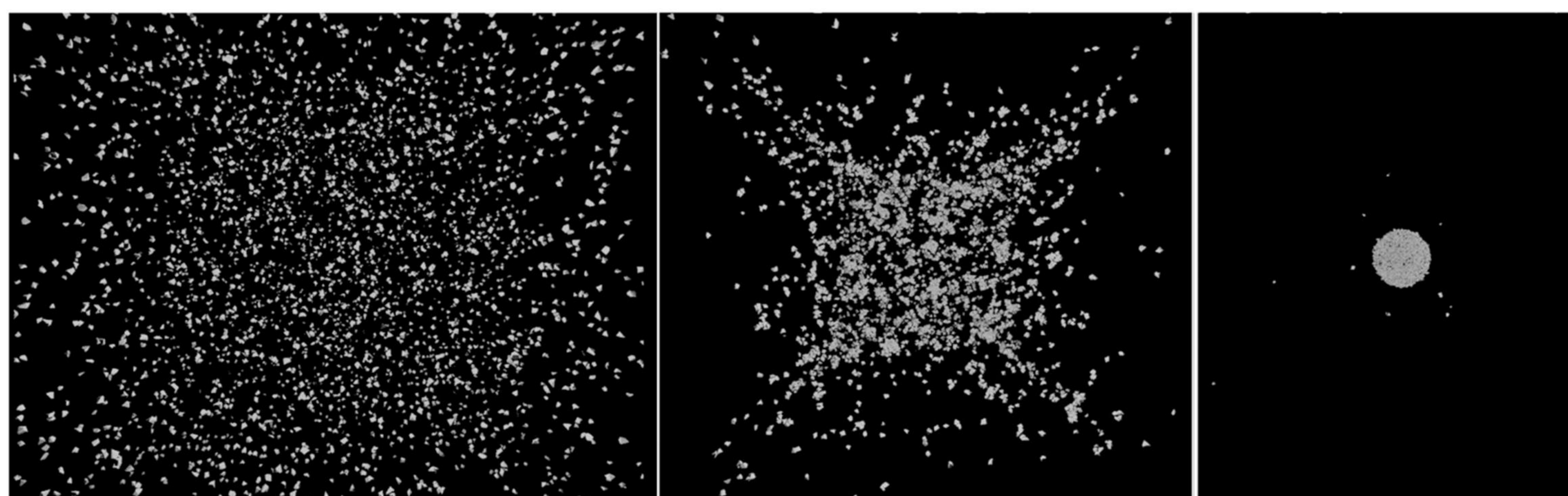
In this work, we investigate how the variation of particle-scale properties affect the macroscopic behavior of rubble-pile asteroids by simulating layered rubble-piles using GRAINS [e.g. 3, 4]. Following [5], we model a layered rubble-pile asteroid where the microscopic properties of the surface layer and the core are characterized by distinct mechanical parameters (such as cohesion, friction, and density). At this stage, we focus on varying only the density and size of the core and the surface layer, and examine the response of the aggregate during spin-up. In future work, we plan to explore a broader range of mechanical parameters and compute macroscopic properties, with the goal of comparing our results to observations and experimental data [e.g. 1, 6].

Understanding the mechanical properties and evolution of rubble-pile asteroids is crucial for both their scientific and technological exploitation, including the effective design of planetary defense strategies.

GRAINS

- GRAINS is an N-body Discrete Element Method (DEM) code based on multi-physics engine Project Chrono, designed for simulating the behavior of granular materials in rubble-pile asteroids.
- Individual **particles** can be modelled as **irregular shapes** instead of spherical bodies as random shaped convex hulls.
- The non-smooth and smooth contact models are implemented in GRAINS, for this work we adopted the smooth contact model.

Settling of a gravitational aggregate:

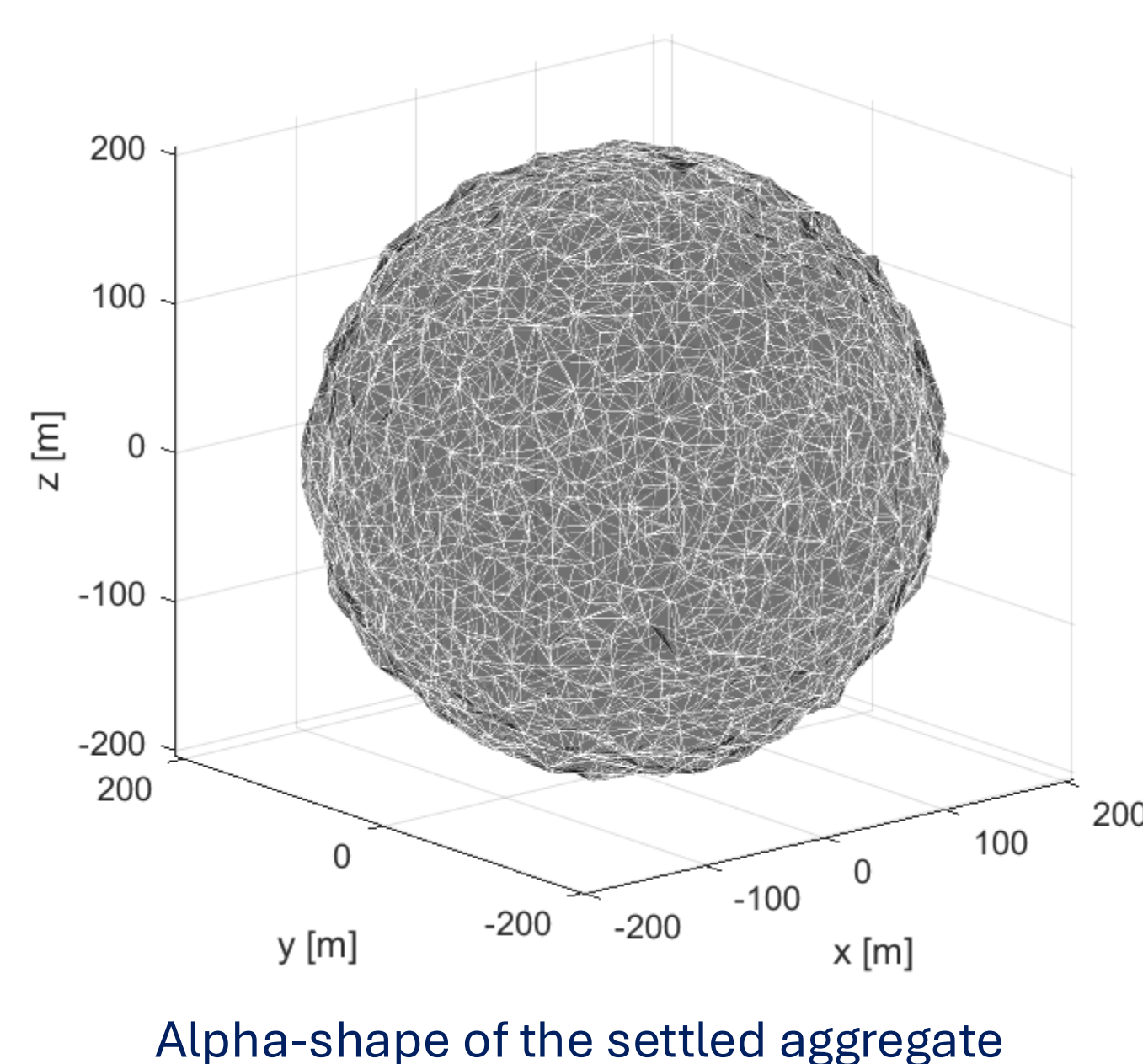


Snapshots from the simulation of gravitational aggregation to form a 5,000-body parent aggregate (monodisperse particle size distribution). Figure extracted from [7].

In order to have a realistic rubble pile model, the initial aggregate is obtained as the result of a process of gravitational aggregation:

- High number of irregular particles located at random positions in a cube with zero velocity and spin rate.
- Settled under self-gravity, particles reach a stable and nearly-spherical aggregate.

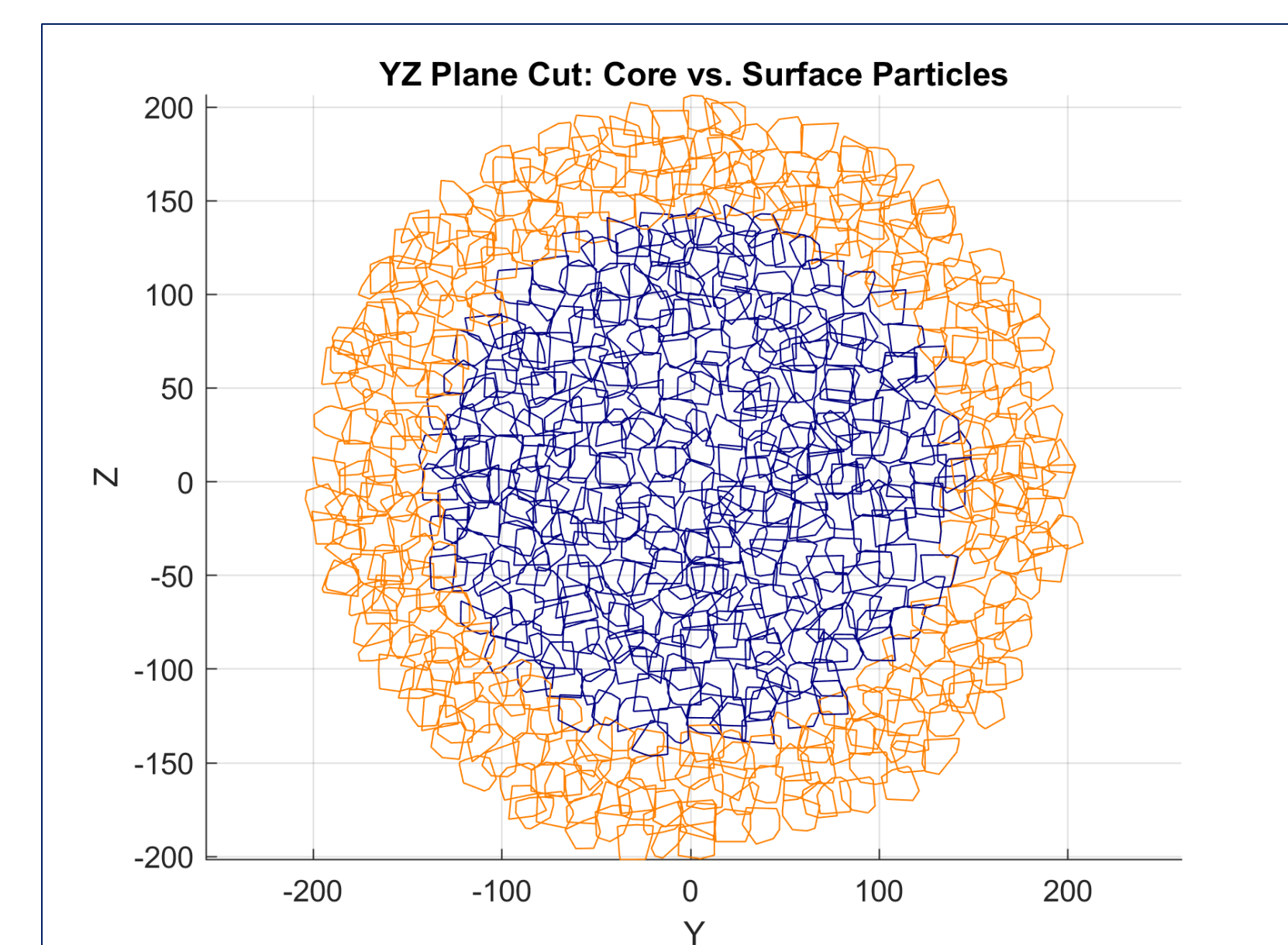
We obtain a rubble-pile with internal voids randomly distributed between irregular particles.



LAYERED RUBBLE-PILES

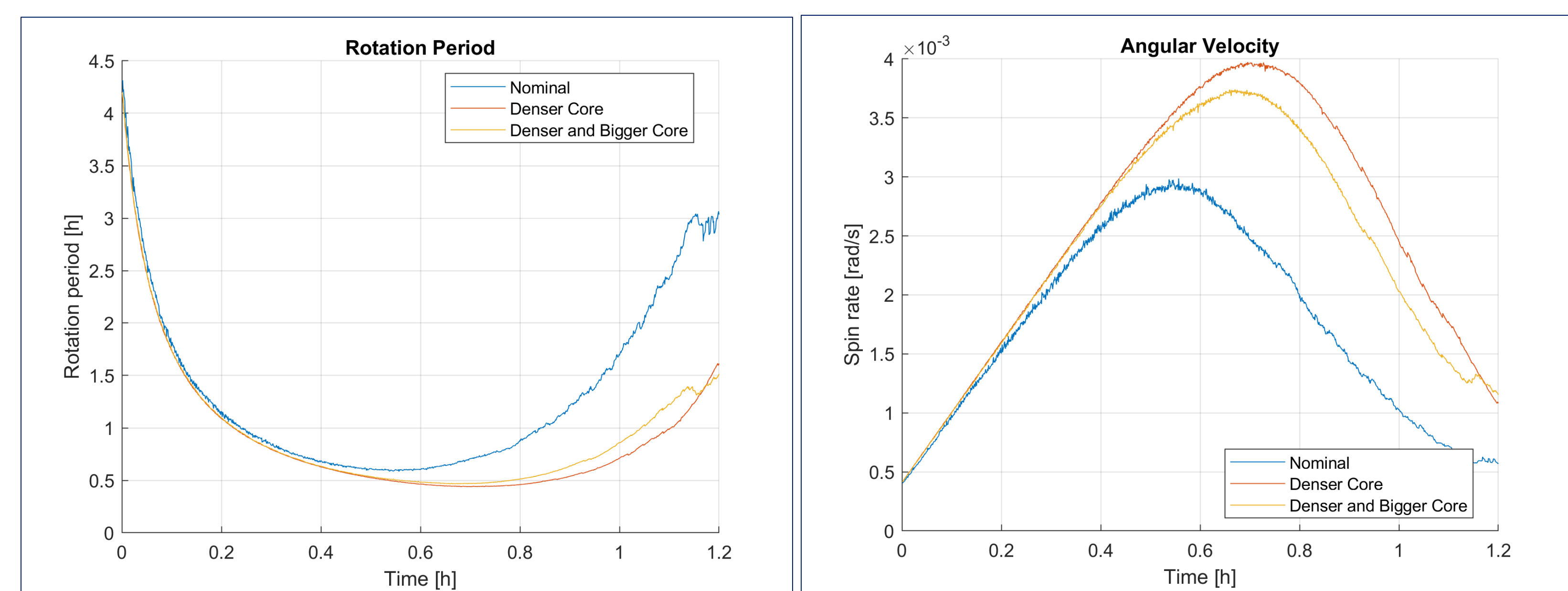
- After obtaining a settled aggregate, we define the **Nominal Case** as a non-layered rubble-pile with homogeneous mechanical properties throughout the entire body with approximately 8600 particles. This case serves as a baseline for comparison.

- Following [5], in order to investigate the influence of internal heterogeneity, we construct layered configurations by varying both the **dimensions** and **densities** of the core and surface layers keeping the overall bulk density of the object fixed.



Layered rubble-pile asteroid, each color represents the core and surface particles.

PRELIMINARY RESULTS



Rotation period (left) and angular velocity (right) as a function of time for three different scenarios: nominal case, denser core, and denser and bigger core.

- For each configuration, we spin-up the body in order to qualitatively assess its dynamical and structural evolution in a short period of time, constrained by the long computational requirements. By comparing the response of these layered structures to the Nominal Case, we aim to identify characteristic behaviors associated with compositional and structural heterogeneities.
- We observe that a denser core tends to be more stable compared to the homogeneous and under dense core scenarios as predicted by [5]. Additionally, when increasing the core dimension for the denser case, we find that mass shedding becomes more pronounced. For the under-dense scenario that we choose there are no significant variations on the behavior of the body compared to the Nominal Case.
- As next steps, we are conducting several simulations varying the cohesion for different core and surface layer densities and dimensions, to further characterize their influence on the overall mechanical behavior.



Spin-up video comparisons

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