Abstract #178

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Modeling the influence of layering on impact-induced seismic waves in rubble-pile aggregates with GRAINS

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BACKGROUND & MOTIVATION

The DART Spacecraft impact of Dimorphos (Fig. 1) was the first full-scale demonstration of kinetic impact as an explicit planetary defense technique. The momentum exchange of the impact resulted in more than 4 times greater than expected change to Dimorphos' orbital period [1]. One reason for this under prediction is our continued uncertainty of rubble-pile asteroid's (loosely bound gravitational aggregates) composition.

The **internal structure of rubble-piles is unknown**. The size distribution seen in surface particles may be replicated through the body, resulting in a homogenous asteroid. Alternatively, there may be some internal structure resulting from granular motion. While on Earth the larger particles in a vibrated granular assembly tend to migrate upwards (Brazil Nut Effect), systems with reduced gravity demonstrate the reverse processes [3]. We consider an end point of this size segregation process in an aggregate with a layered structure consisting of an inner core of larger particles surrounded by a shell of smaller particles (like Fig. 2,b). **What effect would a layered structure have on the seismically induced surface modifications resulting from a DART-like impact?**

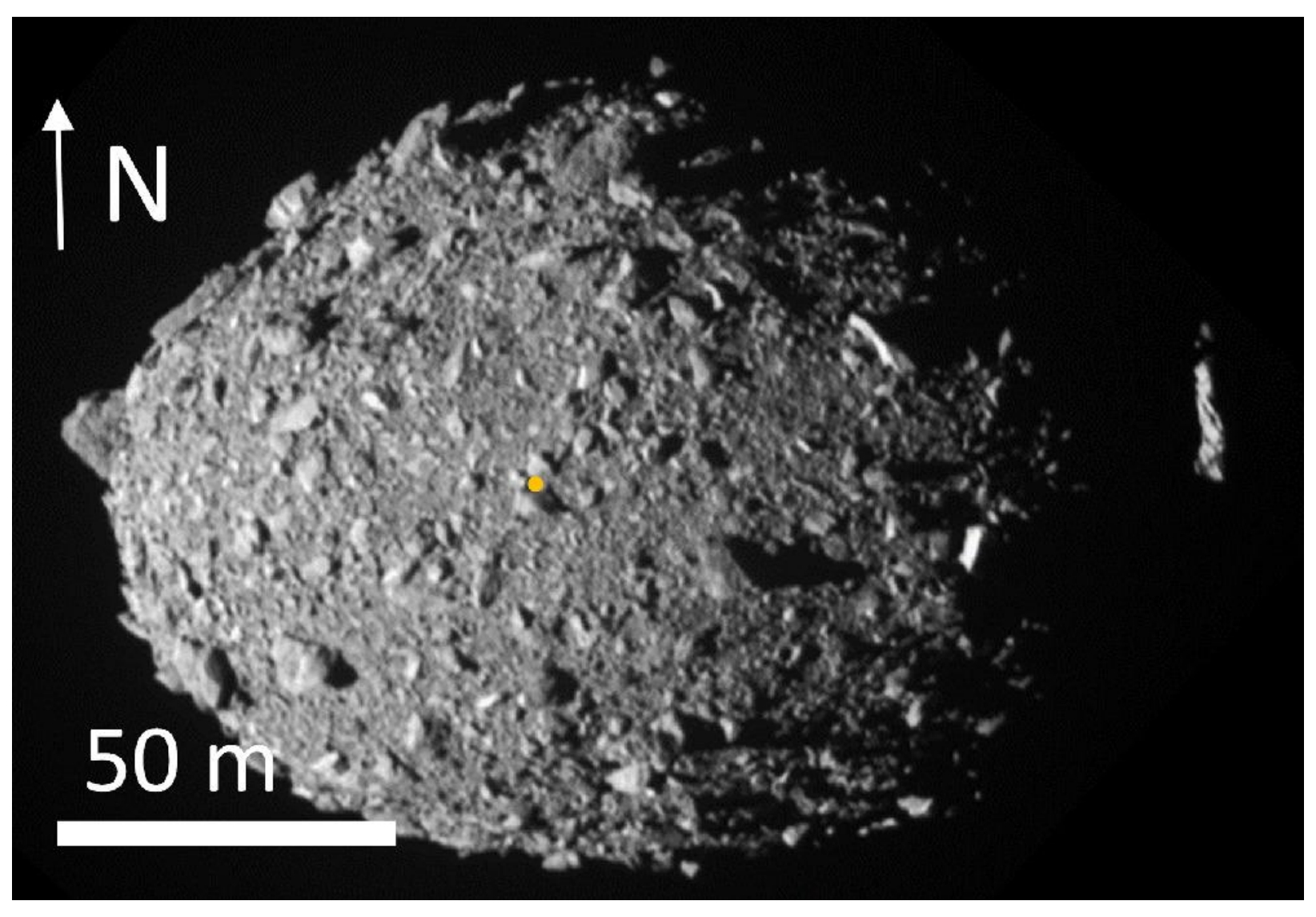

Figure 1. Image from [2] showing Dimorpohos 11 s before impact, with the orange dot representing the impact site. Image credit NASA / Johns Hopkins APL.

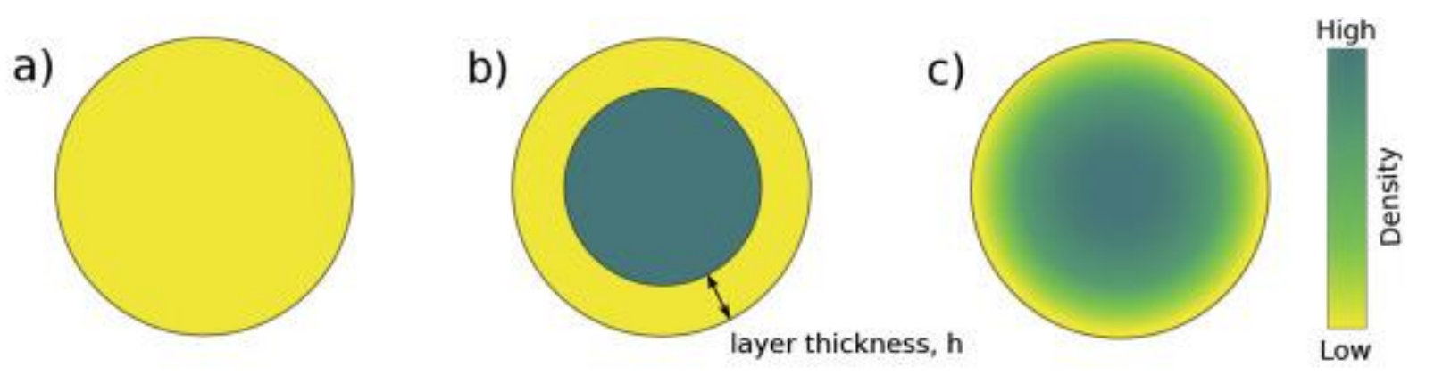

Figure 2. Image from [4] which shows the range of layered targets considered in their impact simulations. A represents a completely homogenous target, B a target with two distinct layers, and C one with a continuous porosity gradient.

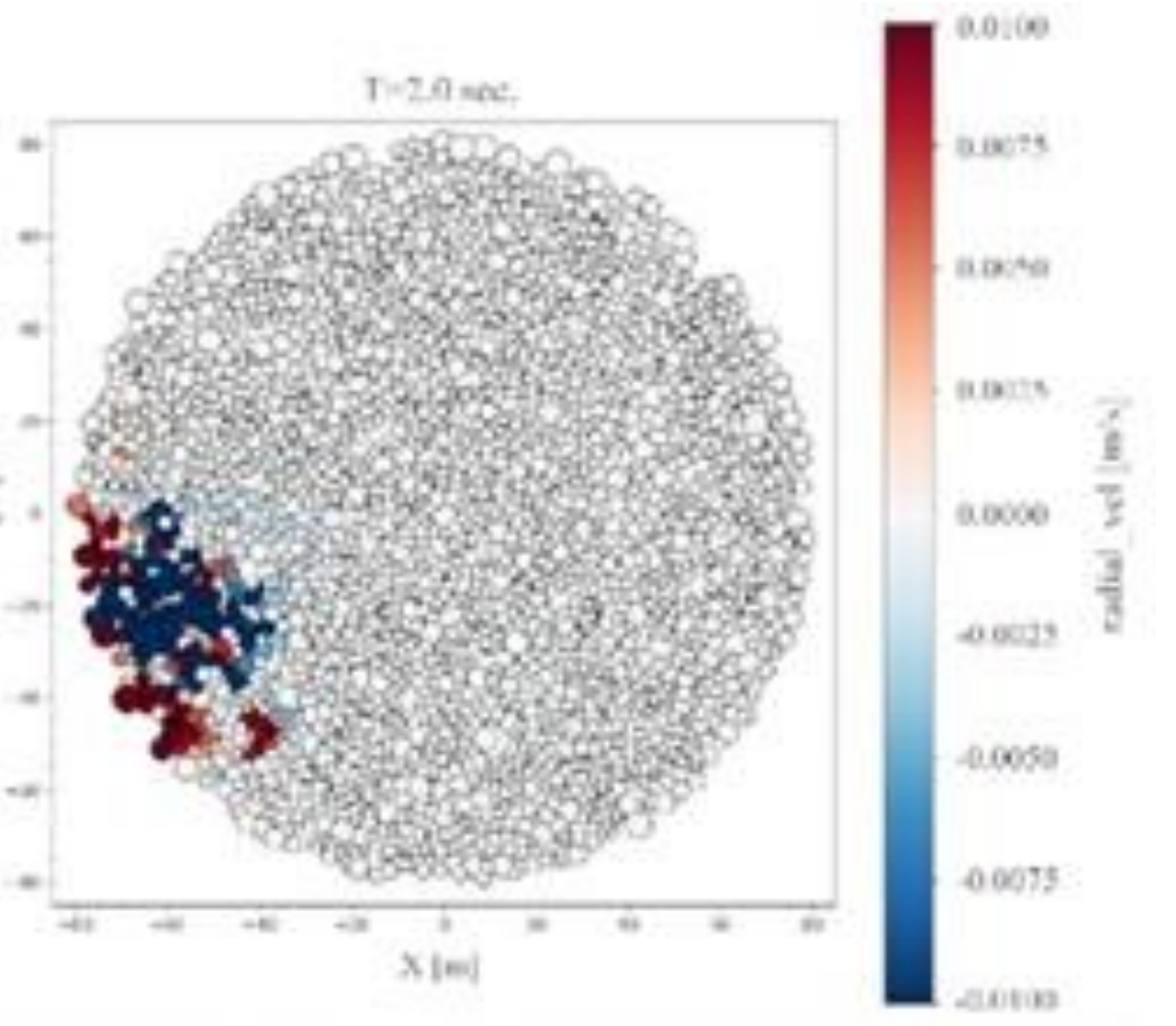

Figure 3. Image from [5], the spherical, meter-sized particles making up a Dimorphos-like rubble pile aggregate are colored by their radial velocity to track seismic wave propagation within the body as the result of a DART-like synthetic hyper velocity impact.

In [5], Tancredi et al. modeled seismic waves due to hypervelocity impact using a discrete element method (DEM) analog of Dimorphos; a 100,000-particle granular aggregate. In [5] the seismic waves resulting from a DART-like impact (Fig. 3) modified the surface up to 60 degrees from the impact site. In this work we use physically realistic aspherical particles to study how an aggregate's layered structure influences the range of surface modification. On the Moon, a similar layered structure has been suggested to increase the region over which seismically induced surface modification is active [6].

HYPOTHESIS: larger particles in the core increase the extent of surface effects

MODELING RUBBLE-PILES WITH GRAINS

We construct a layered rubble-pile using the particle-based simulation tool, GRAINS ([7], [8]). GRAINS simulates particle-particle contacts using soft-body DEM with the unique ability to model **non-spherical particles**. Particles are randomly shaped (up to 16 vertices) convex hulls subject to self gravity, Hertzian contact forces and friction. The size of particles within a distribution is given as their approximate spherical radius, R.

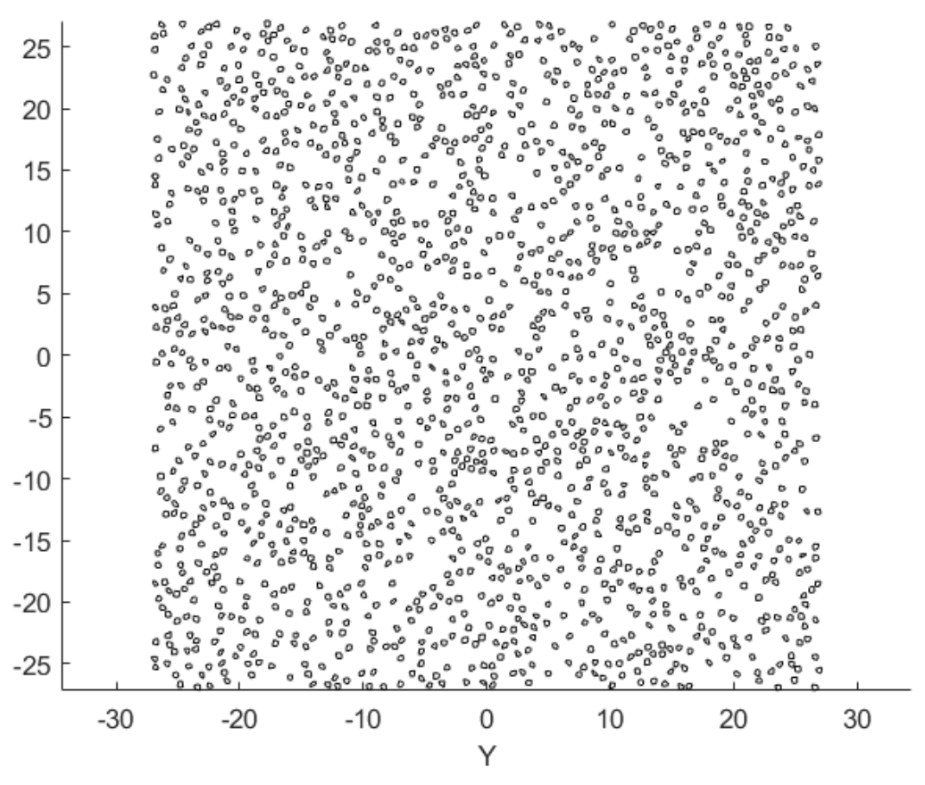

Figure 4. Initial particle cloud seeding for R = 10.

The **aggregation procedure** modifies that of Ferrari et al. [9] to create the layered structure:

- Randomly inserted particles (Fig. 4) aggregate under self-gravity (Fig. 5,A)
- The desired material (particle modulus and density) and bulk parameters (density, spin rate) are updated and the aggregate evolves for a 'settling' period (15 hr.) to ensure stability, resulting in an initial settled aggregate (Fig 5,B)
- For layered cases, the particles residing within the radius of the core are removed, scaled up by the desired factor, and then those which would still be enclosed by the core radius are re inserted
- A second evolution settling period is conducted to allow for any 'too large' overlaps between particles generated during the coring procedure (Fig. 5,C)

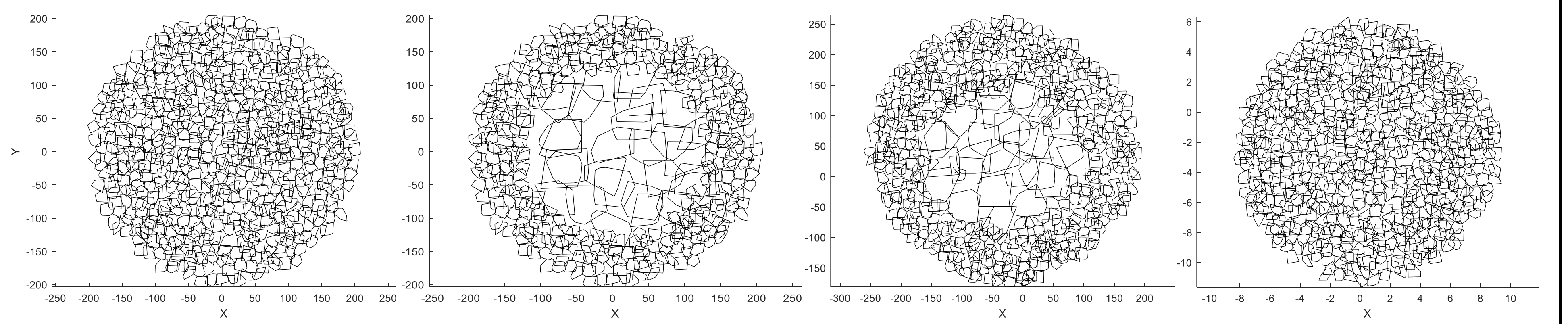

Figure 5. A) Initial rubble-pile of ~10,000 particles after allowing the seeding in Fig. 4 to aggregate, with elastic modulus E ~ 5 MPa and R = 10. B) The rubble-pile from A, but with a core (in this case of radius 125) replaced with particles 3x larger than those in the outer shell. C) The rubble-pile from B after 15 hours of simulated evolution time. D) An initial rubble-pile of ~10,000 particles with E ~ 5 GPa and R = 0.5. Note that the simulation environment operates in non dimensional units which are later scaled to produce SI units. For A-C the scaling factor is close to 3 while for case D it is approximately 1.

METHODOLOGY

At t = 0 a particle on the equator in the spin plane is designated the **synthetic impactor** and given a mass and **velocity equivalent to the DART Impact** (V = 6.6 km/s, M = 550 kg, [10]), directed **through the barycenter.** Since DEM models can't account for fracturing, melting and other plastic effects of hypervelocity impact [11], the energy of the synthetic impactor is scaled as in [5]. The synthetic impactor's mass $\boldsymbol{m_0}$ **and** $\boldsymbol{v_0}$ **are set corresponding to the residual seismic energy of the impact** as in Eq. 1, where f_{ke} is the seismic efficiency and ϵ the coefficient of restitution.

$$m_0 = \frac{M}{f_{ke}}\frac{(1-\epsilon)}{(1+\epsilon)}$$

$$v_0 = \frac{f_{ke}V}{(1-\epsilon)}$$

Equation 1. Synthetic impactor scaling.

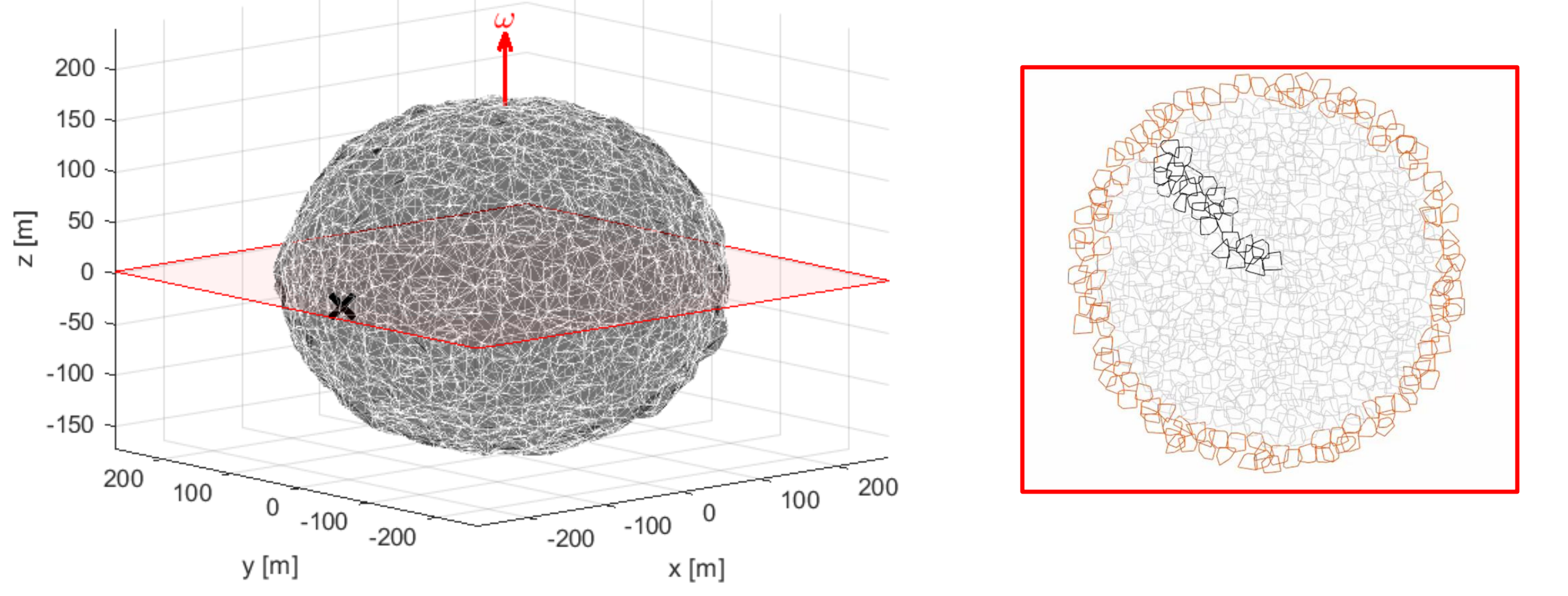

Figure 6. Left) Hull of the smaller homogenous aggregate. The aggregate spins with angular velocity omega about the red arrow pointing roughly parallel with the z axis. The black x marks the approximate site of the impact, with the red plane showing the intersection for visualizing wave propagation through a 2D projection. Right) XY projection from the left image showing the hull particles (in orange) used for tracking surface effects and depth particles (black) used for tracking the penetration depth.

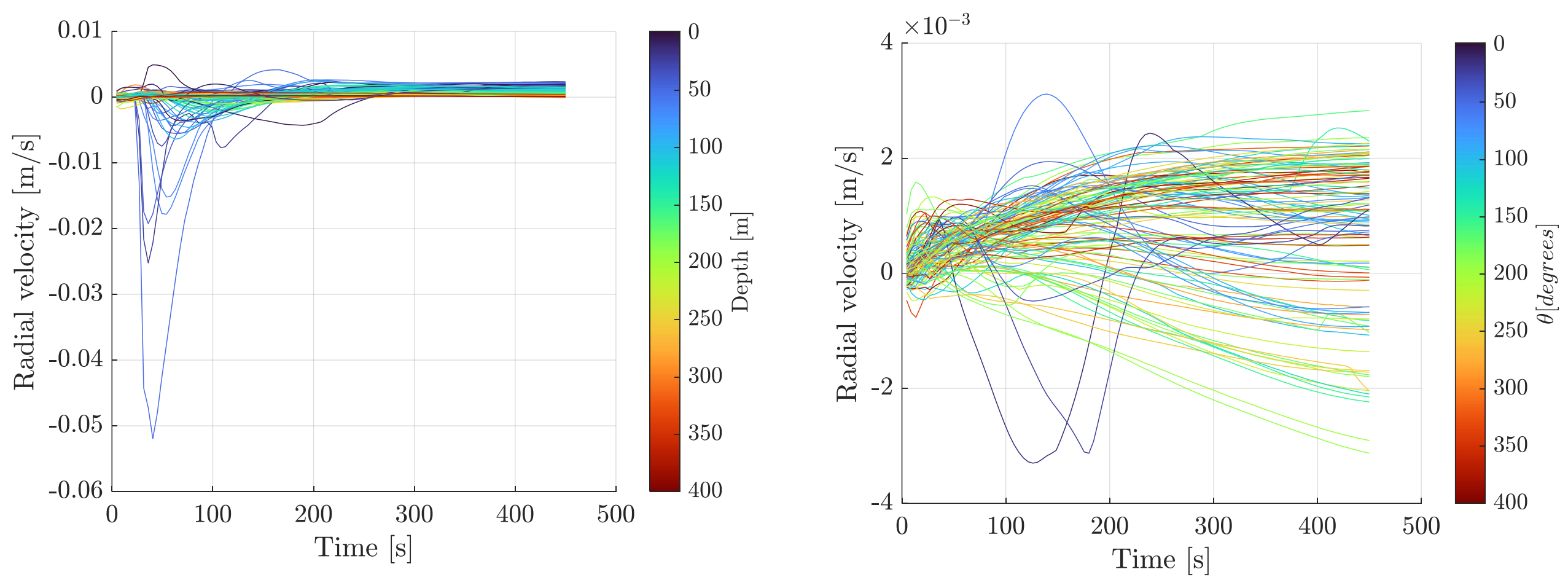

Figure 7. Left) Radial velocity of the depth particles (those in black on the right of Fig. 6) vs time, colored by their depth from the surface. Right) Radial velocity of the hull particles (those in orange on the right of Fig. 6) vs time, colored by their angle from the line connecting the impact site and aggregate's barycenter. This impact occurred for the homogenous aggregate (Np ~ 10k, R = 10, E ~ Mpa)

→ Measure particle velocities at depth and across the surface to determine extent of effect. Model parameters are given in Table 1. The radial velocities vs time for depth and hull particles (Fig. 7 left and right, respectively). Tracking the time and location of the extrema velocities reveals the extent of the initial seismic pulse throughout the aggregate.

R_p	E_p	μ	Np	ρ_p	ρ_b	SR	Δt
1 - 10 m	5 Mpa, 5 Gpa*	0.6	10k – 100k*	4 g/cc	~1.9 g/cc	~1x10^{-4} s	< 0.25 s

Table 1. Range of properties and aggregate and simulation parameters. R_p, E_p, N_p and ρ_p represent particle radius, particle elastic modulus, number of particles in the aggregate, and particle density. The aggregate bulk density is ρ_b and spin rate is SR. The Coulomb friction parameter is μ. The simulation time step is given as Δt. *Not yet tested.

PRELIMINARY RESULTS AND DISCUSSION

So far, synthetic impacts have been conducted in the larger aggregate cases with smaller E than used in [5], (Fig. 8). Settling the aggregates with E~GPa greatly increases construction time. **Preliminary results** are therefore from the Np = 10k rubble-pile with E = 5 MPa (initial model had already been constructed for a prior work, [8]).

- Low wave speed (~2 m/s) agrees with E~MPa and is roughly consistent for both homogeneous and layered cases (Fig. 9)
- Size of the core (closeness of core layer transition to surface) is important, and the large core case may increase the extent of surface effects (Fig. 10). More work is needed to assess our hypothesis.

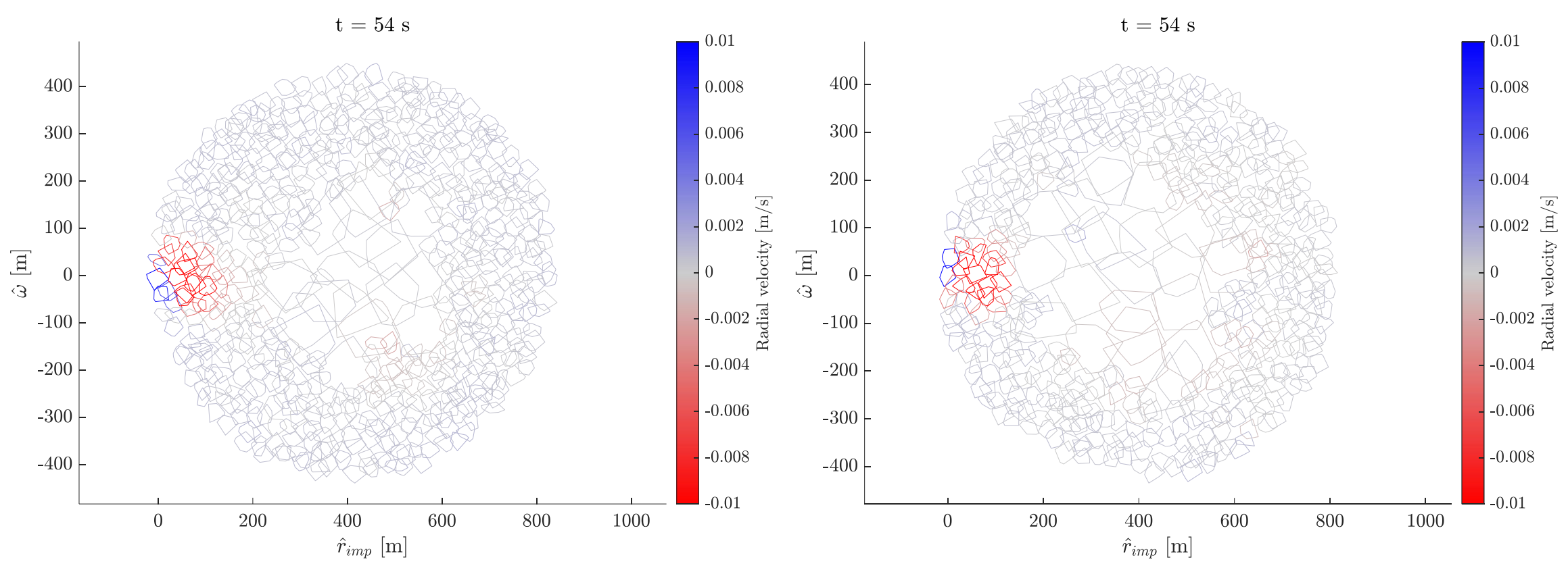

Figure 8. Synthetic impact at a given time after impact in two different layered cases (core of ½ the aggregate's radius on the left vs ¾ on the right). Particle are colored by their radial velocity, where negative indicates towards the barycenter.

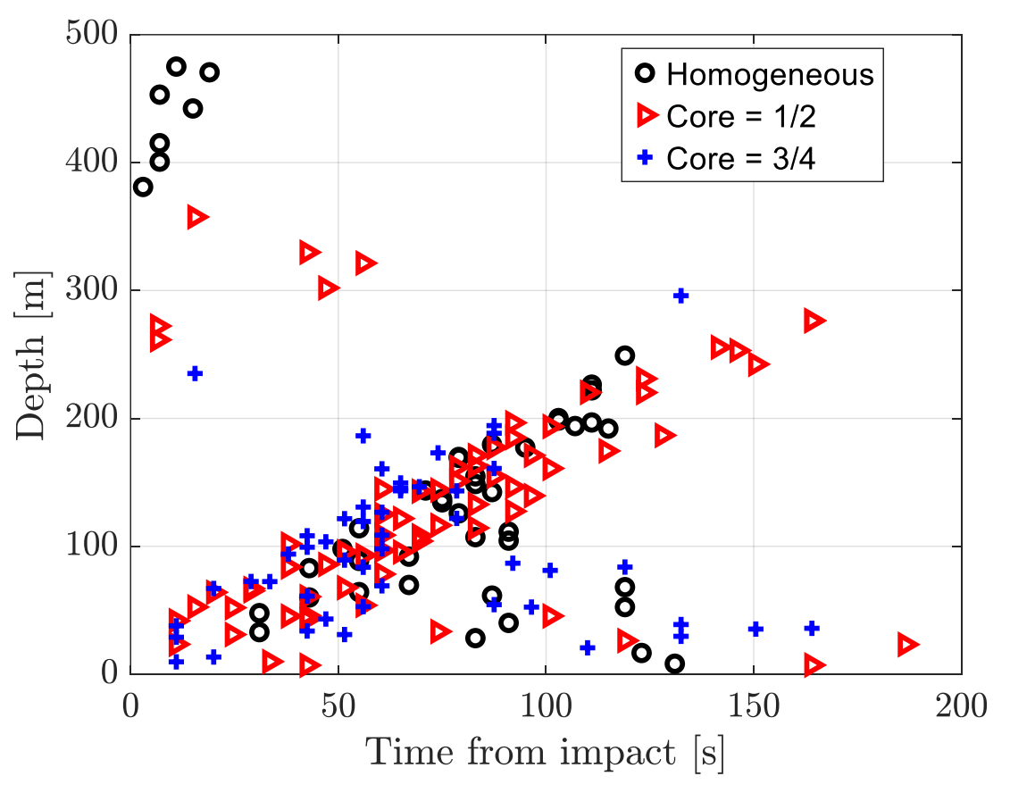

Figure 9. Particle depth vs time for particles in three different aggregates after experiencing the same synthetic impact. Data points track the leading wavefront by identifying the peak velocity. Wave velocity will be found by finding the slope in each case.

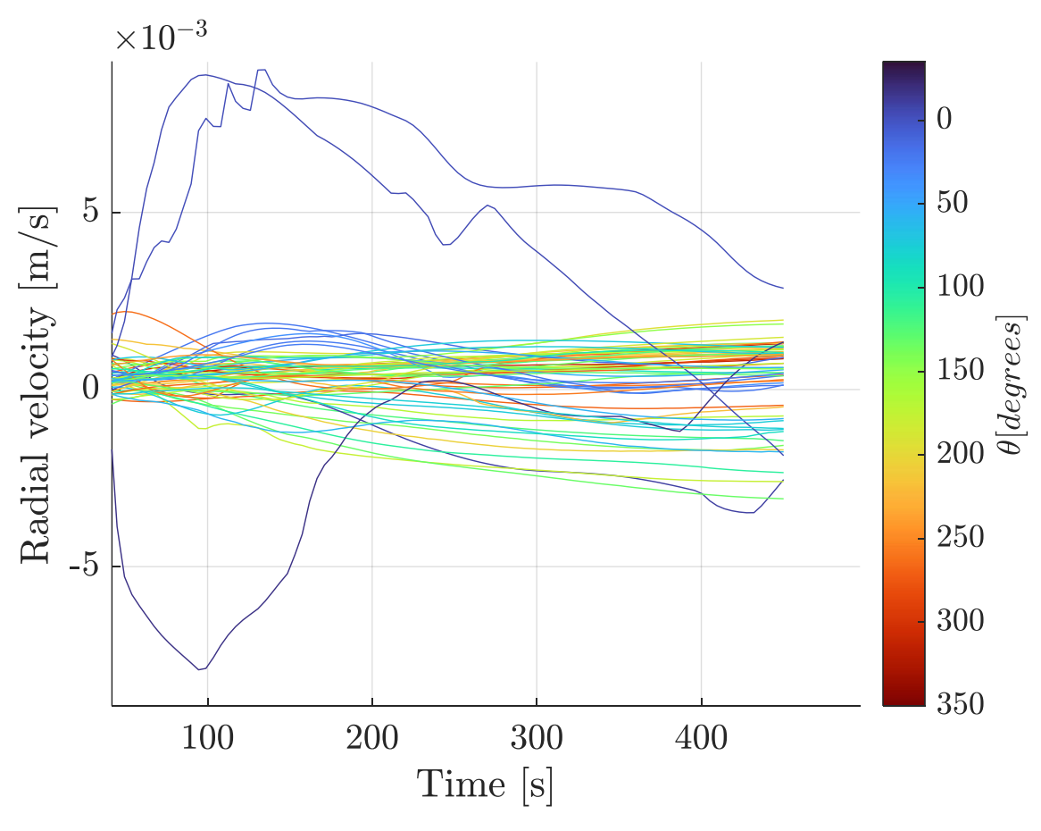

Figure 10. Radial velocity vs time for hull particles from the case on the right of Fig. 8

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