DEM simulations of granular segregation in rubble-pile asteroids
PhD Project for J. Sautel (ENS Lyon)

Abstract

Rubble-pile asteroids are small celestial bodies made of individual blocks of regolith solely held together by their weak self-gravity. They have attracted much interest in recent years due to success of several space missions, among which the Hayabusa program which collected data and samples from 25143-Itokawa. One of the most striking features of theses bodies is the heterogeneity of their surface. While some regions consist in fine sand or powder, large boulders seem to accumulate in other parts. Several ideas have been proposed to explain this granular segregation but remain speculative to date. In this project, we propose to study segregation processes through DEM simulations and to investigate if the known mechanisms on Earth for sand piles still apply to asteroids.

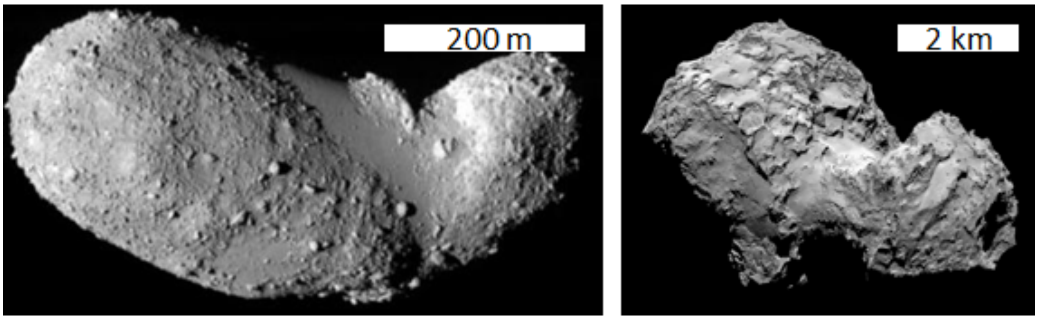

Figure 1. Left: 25143-Itokawa (by Hayabuza, JAXA) and right : 67P/Churyumov-Gerasimenko by ESA's Rosetta

Planetary science and space exploration of Solar System Bodies are constantly progressing with outbreaking results on many research fronts. The recent discovery of water vapor outgassing from the dwarf planet Ceres, as observed by HERSCHEL, is one of such impressive results. On the other hand, the Rosetta rendez-vous with comet 67P will be one of the greatest events in planetology in 2014. In this respect, the next step is to perform sample return mission from an asteroid (Hayabusa II, Osiris-Rex) as well as from Mars, or to visit binary and multiple asteroids. In many of these studies the physical characterization of the surfaces and interiors of the planetary bodies to be visited requires insight into their formation and evolution. In spite of this need, the interior of asteroids, comets and small satellites remains largely unknown. Fundamental parameters such as density, mass, macro-porosity, ice or volatiles content to mention some, are calculated making educated, but strong assumptions. This leads to a great uncertainty about the evolution of these bodies, uncertainty that is of paramount importance when it comes to hazardous NEOs as this could lead to erroneous mitigation strategies.
An additional complication is that a large fraction of small bodies is supposed to have a “rubble-pile” structure, i.e. they are gravitational aggregates with no, or low internal cohesion which governs their maximum spin rate, deformation, and disruption mode among others. The surfaces of these small bodies also show a large variety of ‘geological’ terrain with different surface roughness/smoothness (see figure 1).

In this project we intend to:

- Identify the physical parameters under which segregation occurs
    - We propose to simulated spherical and cylindrical asteroids under a central gravity field, using the Discrete Element Method (see III.b).
    - The effect of all parameters, either physical (grain size, asteroid size, material properties) or purely numerical (time step) will be investigated.
- Show that size segregation is not only a surface phenomenon
    - Previous works which have found or claimed that segregation in spherical geometry occurs only at the surface remain debatable. If the concentration in large grains increases

at the surface, due to the conservation of the total number of grains, it seems only reasonable that the concentration in smaller grains increases in the core.

    - Moreover, all experimental works reporting segregation on Earth indicate that bulk segregation is very common (if not systematic).
- Study the secondary segregation patterns
    - It is not enough to explain why large particles would rise to the surface of rubble-pile asteroids. This radial segregation cannot explain why large pebbles gather in some regions of the surface while finer grains accumulate in other regions.
    - Instead, there must be a secondary instability, which leads to azimuthal segregation (indications of this secondary instability are given in section III.c.

In this project, we will use the soft-sphere molecular dynamics method (MD), one of the Discrete Elements Methods (DEM). This method deals with deformable frictional grains colliding with one another. Although not flawless, it has been widely used in the past two decades and has proven to be very reliable (Schafer et al. 1996, Frenkel and B. Smit 1996, Radjai 1997). The DEM method aims at simulating granular assemblies using physical laws, rather than ad hoc rules (as opposed to cellular automata for instance). When two grains collide, they experience a repulsive elastic normal force, given by Hertz' law, in a dissipative term is added in order to model the inelasticity of the collisions. Grains also experience a tangential force (based on the Cundall and Strack model) which models a history-dependent solid friction and which allows residual stress to be maintained within the simulated material. The method is time-driven and the position, velocity and rotation speed of all grains are simultaneously (unlike in Monte-Carlo simulations) calculated using Newton's law of mechanics at the next time step using the forces and torques acting on each individual grain.

Preliminary results

Binary assemblies of grains, containing two species of grains (small and large) were simulated. The large grains are twice as big (in diameter) as the smaller grains and therefore, to ensure a half-and-half ratio in surface area, there are four times as many small grains. The initial positions of each grain is chosen randomly. In these preliminary tests, a gravity field is assumed, which remains valid only if the simulated asteroid remains circular (or spherical in 3D). In order to simulate the many causes for rearrangement in asteroids (YORP effect, tidal forces, impacts…) an "earthquake" is induced in the asteroid: the gravitational field is inverted for a short duration. This mimics the classical conditions in segregations on shaken granular material. During this phase, the grains accelerate outwards. After the "quake" the grains keep moving outwards due to their inertia but the velocity decreases until the motion is reversed leading to a collapse of all the grains. The process is repeated after the asteroid has come to a complete stop. Alternatively, one may simply expand the asteroid by artificially multiplying the distance of all grains to the center, and then letting is collapse. The results of both methods seem to be identical. The amplitude of this mechanical excitation is chosen so that the increase in overall radius of the asteroid does not exceed 10%.

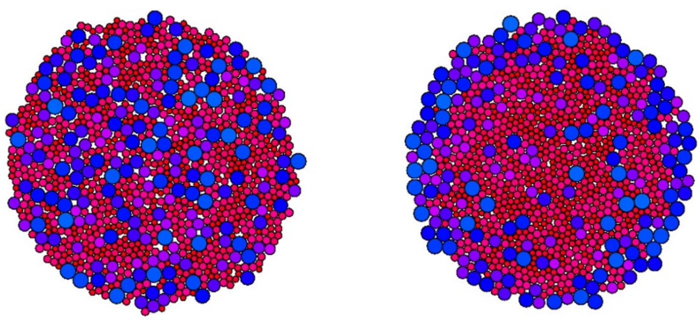

Figure 2. Simulated 2D asteroid (preliminary). Left: initial mixed state, Right: final state after 4000 quakes, showing segregation.

Figure 2 shows snapshots of an initial state and a final state (after 4000 quakes). As can be seen, the large grains have migrated to the surface while clearly the small grains sunk inside the asteroid. This very encouraging result indicates that DEM simulation are indeed a good tool for the study of rubble-pile asteroids. It shows that the Brazil Nut Effect can occur in a circular (or spherical) geometry, which a central gravitational field. 3D simulations were also performed. Figure 3 shows an example an asteroid made of 30000 grains (both an outside view and a cross-section). Initially the asteroid is well mixed but after typically a few 100 quakes, not a single small grain is visible at the surface. The cross section shows that the larger grains tend to gather in a spherical shell at the surface of the asteroid while its core is mostly composed of smaller grains.

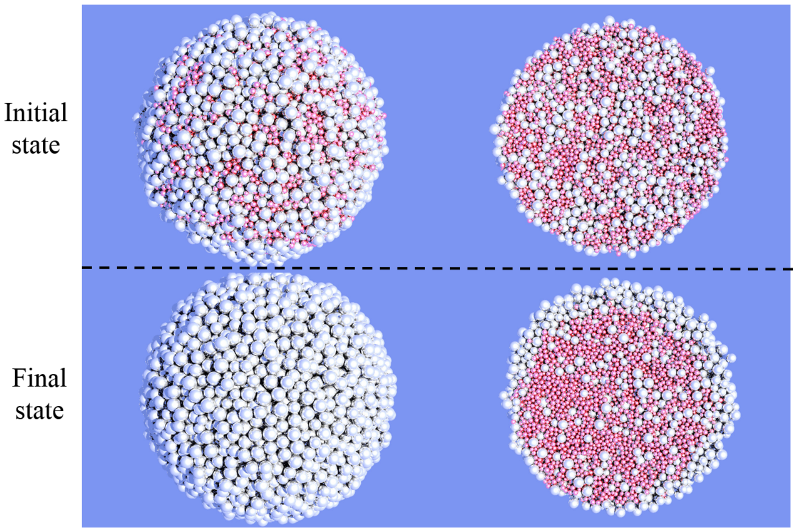

Figure 3. 3D DEM simulations (preliminary) showing the initial and final state (left: overall, right: cross-section)

The dynamics and time-scale of the segregation phenomena are expected to depend strongly on the simulation parameters (intensity of the quake, friction, inelasticity of the grains, size distribution…).