EPSC Abstracts
Vol. 13, EPSC-DPS2019-646-1, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

# N-body simulations of rubble-pile aggregates with angular particles

**Fabio Ferrari** (1) and Paolo Tanga (2)
(1) Politecnico di Milano, Department of Aerospace Science and Technology, Italy
(2) Universitè Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France

## Abstract

In the last decades, in-situ and remote observations of asteroids have brought evidence to support the idea that celestial bodies up to a few hundreds meters in size may be piles of loosely consolidated material, namely "rubble piles" [6]. A popular method to study these bodies is through numerical N-body simulations of gravitational aggregation. We discuss here the reshaping dynamics of rubble pile aggregates and how these change depending on initial conditions given to particles. We show the main features of the numerical code used, including its capability of handling contacts and collisions between a large number of non-spherical particles. A comparative study between spherical and angular bodies is shown for the scenario under study.

## 1. Introduction

N-body gravitational simulations have been widely used in the past to reproduce the dynamics of rubble piles under several scenarios, such as gravitational aggregation [12, 13, 15, 17, 1], disruption after a collision [11, 10, 9], rotational breakup [19, 14, 2], reshaping [18], impacts [16]. All these studies consider classical N-body problem, with collision interactions between spherical particles. Experimental results on terrestrial applications of granular dynamics show substantially different dynamical behavior when granular media is made of spheres or angular bodies. One reason for that is because spheres can move and roll freely on each other and are not subject to any mechanism to hinder their motion as in the case of geometrical interlocking between angular bodies. In our study, we use a N-body code capable of handling the interaction between non-spherical angular bodies [7].

## 2. Numerical model

The code has a modular structure and implements several numerical methods of gravity and contact/collision interactions, to cover a wide range of dynamical scenarios and applications. To solve for N-body gravitational interactions, the code features a GPU-parallel octree implementation [4]. This allows for a significant reduction of computational time compared to direct $N^2$ integration. The code implements the Barnes-Hut algorithm [3], which groups particles using a hierarchical and recursive cubical subdivision of the domain. The GPU/CUDA implementation of the Barnes-Hut is inspired by the work of Burtscher and Pingali [5].

Contact and collisions are implemented based on Chrono::Engine library [8]. As mentioned, the N particles are treated as three-dimensional rigid bodies of arbitrary shape. Each body possesses rotational degrees of freedom, a tensor of inertia and a mesh to be used for collision detection. As for the case of gravity, contact are solved in parallel by proper subdivision of the domain, but this time through a CPU/OpenMP thread-parallelized structure. Once at contact, bodies exchange forces through collisions and surface interactions. A first family of forces are those related to surface properties of the material. These include dissipative forces due to friction and adhesive forces. Both can be enforced during the simulations and set to a desired value by tuning simulation parameters. A second family of forces are those related to the collisional process itself, which relate to the amount of momentum exchanged between the bodies at contact. For our simulations, we use a soft contact model. This allows to consider the visco-elastic behavior of the material at contact. From the numerical point of view, contacts are modeled using a spring-dashpot model at each contact point. The parameters of the spring-dashpot can be set to mimic the behavior and constitutive laws of a given material.

Figure 1: Sequence from a spin-up simulation

## 3. Simulations

We performed a wide range of reshaping simulations, under many degrees of freedom. The simulations are initiated by providing a set of initial conditions to an aggregate of bodies, which acts as a rubble pile asteroid. Initial conditions of particles include relative position and velocity of their center of mass, their angular position and spin rate. The simulations are then run until the system reaches an equilibrium condition. Simulations are run with two main goals. First, we run a comparative analysis to identify the role of particle shape in the formation of the aggregate. The properties and dynamical transient of aggregates with spheres are compared to those with angular bodies. Second, a parametric analysis is run to identify key parameters and quantify their effect in the formation and evolution of the aggregate. Figure 1 shows an example of the dynamical evolution of the initial aggregate after a spin-up.

## 4. Conclusion

The results highlight relevant differences in the properties of the aggregate when using spheres or angular bodies. Spheres appear to be poorly suited and not accurate to reproducing rubble pile reshaping scenarios. Angular bodies appear to be necessary to keep an adequate level of accuracy and realism in the simulation results.

## Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 800060. Part of the research work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

## References

[1] A. C. Bagatin, R. A. Alemañ, P. G. Benavidez, and D. C. Richardson. Internal structure of asteroid gravitational aggregates. *Icarus*, 302:343 – 359, 2018.

[2] R.-L. Ballouz, D. C. Richardson, P. Michel, and S. R. Schwartz. Rotation-dependent catastrophic disruption of gravitational aggregates. *The Astrophysical Journal*, 789(2):158, 2014.

[3] J. Barnes and P. Hut. A hierarchical o(n log n) force-calculation algorithm. *Nature*, 324:446–449, Dec. 1986.

[4] E. Blazquez, F. Ferrari, and M. Lavagna. Numerical simulation of n-body asteroid aggregation with gpu-parallel hierarchical treecode algorithm. In *Proceedings of the 27th AAS/AIAA Space Flight Mechanics Meeting*, 2017.

[5] M. Burtscher and K. Pingali. Chapter 6 - an efficient cuda implementation of the tree-based barnes hut n-body algorithm. In W.-m. W. Hwu, editor, *GPU Computing Gems Emerald Edition*, Applications of GPU Computing Series, pages 75 – 92. Morgan Kaufmann, Boston, 2011.

[6] C. R. Chapman. Asteroid collisions, craters, regolith and lifetimes. *In Asteroids: An Exploration Assessment. NASA Conf. Publ.*, 2053:145–160, 1978.

[7] F. Ferrari, A. Tasora, P. Masarati, and M. Lavagna. N-body gravitational and contact dynamics for asteroid aggregation. *Multibody System Dynamics*, 39(1):3–20, 2017.

[8] H. Mazhar, T. Heyn, A. Pazouki, D. Melanz, A. Seidl, A. Barthlomew, A. Tasora, and D. Negrut. Chrono: A parallel multi-physics library for rigid-body, flexible-body and fluid dynamics. *Mechanical Sciences*, 2013.

[9] P. Michel, W. Benz, and D. C. Richardson. Catastrophic disruption of asteroids and family formation: a review of numerical simulations including both fragmentation and gravitational reaccumulations. *Planetary and Space Science*, 52(12):1109 – 1117, 2004. Catastrophic Disruption of Small Solar System Bodies.

[10] P. Michel, W. Benz, P. Tanga, and D. C. Richardson. Collisions and gravitational reaccumulation: Forming asteroid families and satellites. *Science*, 294(5547):1696–1700, 2001.

[11] P. Michel, P. Tanga, W. Benz, and D. C. Richardson. Formation of asteroid families by catastrophic disruption: Simulations with fragmentation and gravitational reaccumulation. *Icarus*, 160:10–23, 2002.

[12] D. C. Richardson, P. Michel, K. J. Walsh, and K. W. Flynn. Numerical simulations of asteroids modelled as gravitational aggregates. *Planetary and Space Science*, 57:183–192, 2009.

[13] D. C. Richardson, T. Quinn, J. Stadel, and G. Lake. Direct large-scale n-body simulations of planetesimal dynamics. *Icarus*, 143(1):45 – 59, 2000.

[14] D. P. Sánchez and D. J. Scheeres. Dem simulation of rotation-induced reshaping and disruption of rubble-pile asteroids. *Icarus*, 218(2):876 – 894, 2012.

[15] P. Sánchez and D. J. Scheeres. Simulating asteroid rubble piles with a self-gravitating soft-sphere distinct element method model. *The Astrophysical Journal*, 727(2):120, 2011.

[16] S. R. Schwartz, P. Michel, and D. C. Richardson. Numerically simulating impact disruptions of cohesive glass bead agglomerates using the soft-sphere discrete element method. *Icarus*, 226(1):67 – 76, 2013.

[17] S. R. Schwartz, D. C. Richardson, and P. Michel. An implementation of the soft-sphere discrete element method in a high-performance parallel gravity tree-code. *Granular Matter*, 14(3):363–380, May 2012.

[18] P. Tanga, C. Comito, P. Paolicchi, D. Hestroffer, A. Cellino, A. Dell'Oro, D. C. Richardson, K. J. Walsh, and M. Delbo. RUBBLE-PILE RESHAPING REPRODUCES OVERALL ASTEROID SHAPES. *The Astrophysical Journal*, 706(1):L197–L202, nov 2009.

[19] K. J. Walsh, D. C. Richardson, and P. Michel. Rotational breakup as the origin of small binary asteroids. *Nature*, 454:188, July 2008.