Granular "van der Waals Bridges" and the Cohesion of Rubble-Pile Asteroids

Paul Sánchez and Daniel J. Scheeres, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO 80309-431 (diego.sanchez-lana@colorado.edu)

Fine regolith in rubble pile asteroids may act as a sort of "van der Waals concrete" that forms bridges that bind larger boulders and strengthens small asteroids, allowing them to rotate more rapidly. We test these ideas using DEM simulations.

Introduction:

It can be shown that the ideal tensile stress of regolith grains with van der Waals cohesion is inversely proportional to the grain size [1]. Thus the presence of fine regolith grains distributed throughout a rubble pile asteroid may serve as a matrix to strengthen the body and bind larger boulders to it. This implies that the modeling of fine-grain regolith distribution and packing may be as important as modeling the relative attraction of larger boulders that comprise the body.

The numerical codes that have been used to simulate "rubble pile" asteroids usually portray them as a collection of perfectly spherical, cohesionless, large grains (tens of meters)[2, 3, 4, 5]. It now has been accepted that cohesive forces in real asteroids could have an important role in the dynamics of these NEOs [6]. Furthermore, in a μG environment, it is the smaller regolith that would be most affected by cohesion, therefore affecting the behaviour of the entire asteroid. However, the simulation of this small regolith in a large scale simulation of a real-size asteroid may prove to be impractical due to the extremely large number of particles that would be needed. In order to calculate this effect we study a simpler system to help us devise a model that could be implemented in a larger simulation. The resulting dynamics show elastic and plastic behaviours before breaking, something that could easily be implemented via a soft potential without the need of the simulation of the regolith.

Simulation Method:

In our simulations we use self-gravitating systems that consist of two spherical "boulders", 1m in size that, though not in contact, are connected to one another through thousands of smaller, cohesive particles. After the settling process, the final geometry of these systems resembles that of a liquid bridge when it is formed between two small spheres due to adhesion.

Our numerical code uses a Soft-Sphere DEM [2] code that implements the cohesive forces between spheres as a contact force with a value given by:

$$f_c = A_h \frac{r_1 r_2}{r_1 + r_2} \quad (1)$$

where A_h is a modified Hamaker constant with a value of 3.6×10^{-2} N m^{-1} and r_1 and r_2 are the radii of the contacting particles [6]; here we assume a cleanlyness factor of 1. Normal contact forces are modelled through a linear spring-dashpot; tangential forces (static and dynamic friction) are modelled as a a stick-slip interaction through a linear spring and a coefficient of dynamic friction [7]. The regolith that forms the bridges consist of 2340, 4680, 7020 and 9360 particles between 2 and 3 cm in size. These four systems are termed L1, L2, L3 and L4 respectively.

Results:

In order to have a control experiment, we ran a simulation of a L1 non-cohesive system and followed the pulling procedure exactly as outlined above. Snapshots of this simulation are presented in fig. 1 (top). Fig. 1 (bottom) shows snapshots of the same L1 system, but with cohesive particles. Even though they have initially the same geometry their dynamics are very different as the snapshots reflect. Other systems with more particles conserve a similar geometry to that shown in Fig. 1, but with a larger bridge. The snapshots show the evolution of the system at points at which the changes are evident to the naked eye.

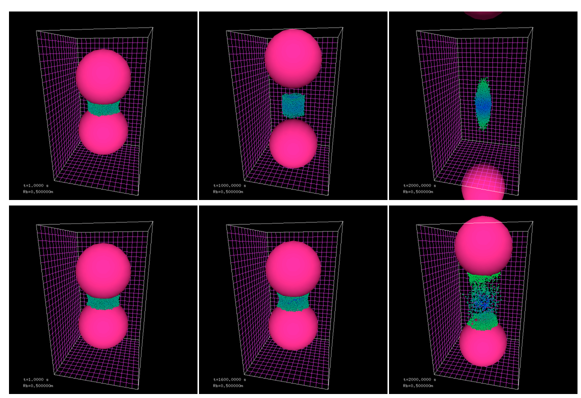

Figure 1: L1 system with non-cohesive particles (top) and with cohesive particles (bottom).

An analysis of the stress tensor of these two systems also reveals that the normal stress between the boulders is always much smaller for the non-cohesive systems. In addition, after the first pull ($f_p = f_g$), the normal stress reduces its value by two orders of magnitude. Further more, in the non-cohesive system, after the first pull, all components of stress go slowly towards zero. On the other hand, the cohesive system presents a very sharp change when the bridge finally yields to the pull, indicating a brittle fracture.

In order to find the exact force that is needed to separate the two boulders in our systems we plot Δf, the difference between the pulling force (f_p) we are applying on one of the boulders and the gravitational pull (f_g) due to the rest of the particles. Fig. 2 shows these results averaged over various simulations. Each different line represents a different system.

In fig. 2 the orange line represents the dynamics of the non-cohesive L1 system, whereas the other lines represent cohesive systems (L1, L2, L3 and L4 are coloured in blue, red, green and grey respectively). From this plot it seems evident that if cohesion is not present, the boulders begin to move apart as soon as a force greater than the gravitational attraction is exerted over them. For all the other systems, they start to move apart when Δf is about 4.5×10^{-4} N, this is approximately twice the gravitational pull, regardless of the number of particles forming the bridge.

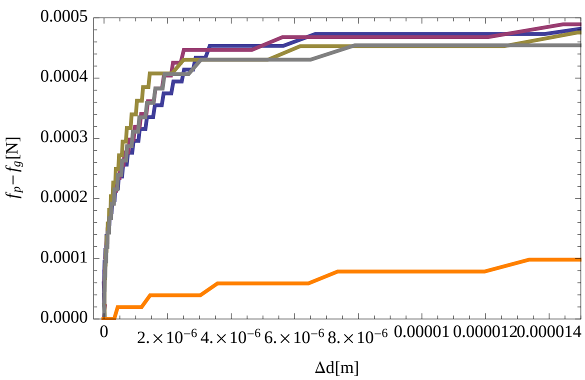

Figure 2: Net pulling force on the top boulder vs. the variation of the distance between both boulders. Cohesive systems: L1 (blue), L2 (red), L3 (green) and L4 (grey); the orange line represent a non-cohesive L1 system.

The formed bridges have their maximum packing fraction near their centre, with values that range between 0.55 to 0.6. The radii of the bridges increase with the number of particles as expected; near the centre their values are approximately 0.3, 0.35, 0.4 and 0.43. All cohesive bridges remain virtually unchanged and deform only slightly from their initial shape until they break. This is of course not the case for the non-cohesive bridge, which in the lack of other forces, conforms to the gravitational pull. In addition, after the cohesive bridges have yielded, there are no other sharp changes in motion or stresses except when the bridge is visibly broken, which means that the main role of cohesion is as a contact attractive force when the boulders are in static equilibrium and in close proximity. Our continuing investigations will determine if the same behaviour could be observed by pulling a boulder out of the surface of a cohesive granular bed.

If we assume that, in order for the bridge to yield, we need to overcome the gravitational attraction, the frictional forces and the cohesive forces, the value at which the bridge yields should represent the summation of frictional forces and cohesion. As the bridge is not deforming, but breaking as a brittle material, we could also assume that the role of friction, though not negligible, is not as important as cohesion. This is also evident if we remember that frictional forces, due to surface friction and geometrical arrangement, were also present in our cohesion-less system and they did not prevent the separation of the boulders.

The independence of the breaking force with respect to the number of particles shows that the grain contacts at the center of the distributions dominated the cohesive forces. We note that the total cohesive force at yield corresponds to the breakage of a few cohesive grains in contact. This implies that contact or force chains are important for controlling the strength of the matrix holding the larger boulders together. We hypothesize that a different settling mechanism may result in a larger number of contacts and hence a stronger matrix. This additional work will be presented at the conference.

Application:

Now we turn our attention to the application of these results to the simulation of asteroids. As explained in the introduction, most DEM simulations treat asteroids as collections of self-gravitating spheres. Though contacts in these systems are among multiple particles (SSDEM), for the purpose of the application of the results here presented, they can be seen as multiple binary contacts. Therefore, it should be possible to replace the smaller regolith in simulations with an effective cohesive force among the boulders that form the asteroid. In compliance with our findings, this force should at least act radially between pairs of particles and as long as they are in static contact or just some particle radii apart.

References: [1] D. J. Scheeres, et al. (2011) in *Lunar and Planetary Institute Science Conference Abstracts* vol. 42 of *Lunar and Planetary Inst. Technical Report*. [2] P. Sánchez, et al. (2011) *The Astrophysical Journal* 727(2):120. [3] P. Sánchez, et al. (2011) *Icarus* submitted. [4] P. Tanga, et al. (2009) *The Astrophysical Journal Letters* 706(1):L197. [5] D. C. Richardson, et al. (2005) *Icarus* 173(2):349 ISSN 0019-1035 doi. [6] D. Scheeres, et al. (2010) *Icarus* 210(2):968 ISSN 0019-1035 doi. [7] L. E. Silbert, et al. (2001) *Phys Rev E* 64(5):051302 doi.

Acknowledgements: P.S. acknowledges support from NASA grant NNXlOAJ66G and D.J.S. from NASA grant NNX08AL51G, both from the Planetary Geology and Geophysics Program.