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Asteroid Regolith Strength Modelling Informed by Bennu Sample Measurements

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Abstract Informed by findings about the sample from asteroid Bennu, we apply a new simulation methodology to better understand how Van der Waals (VdW) forces work between spherical and non-spherical particles. Then we find a theoretical model that relates particle size and shape, as well as porosity and connectivity to the tensile strength of a self-gravitating aggregate and apply the model to calculate the strength of the surface of asteroid Bennu based on the experimentally measured value of particle-particle cohesion.

Introduction The strength of granular asteroids has been the focus of many research efforts as it could explain why asteroids are observed to have high spin rates that exceed their self-gravity. About a decade ago, the source of this cohesive or tensile strength was traced back to the VdW forces that exist between any two particles in contact [1]. These VdW forces would allow the small pebbles and dust in a small asteroid to act as weak cement keeping the larger rocks and boulders in place, providing the needed strength. This finding was based on simulations with spherical particles, as VdW forces vary as the particle diameter d, and the number of contacts across a surface varies as $1/d^{2}$, tensile strength varies as $1/d$.

Recent theoretical work [2] claims that the cohesive VdW force between real particles is particle-size independent, depending only on the particles' surface roughness. If this is so, and assuming that all particles have statistically the same roughness, the magnitude of the cohesive force should be a constant. This makes tensile strength, and so the cohesive strength, dependent on $1/d^{2}$.

In 2020, the OSIRIRS-REx mission successfully collected a sample from the surface of asteroid Bennu. Calculations in [3, 4, 5] showed that the surface of Bennu should be near cohesionless. Collected particle sizes range from submicron dust to a stone 3.5 cm long. Millimeter-scale and larger stones typically have hummocky or angular morphologies [6]. Keeping this mind, we carry out new simulations using the LMGC90 code, which implements a Non-Smooth Contact Dynamics Method [7], allowing us to simulate polyhedral regolith and keeping cohesive forces as a constant.

The Contact Dynamics (CD) method In CD, particles are assumed to be perfectly rigid and to interact through mutual exclusion and Coulomb friction. The frictional contact interactions are described as complementarity relations, without regularisation, between the relative velocities of the particles and the corresponding forces at the contact points. As a direct consequence, the characteristic time of the system is determined by the dynamics of the particles and larger time-steps than in regular methods can be used. Particle motion is no longer regular but includes speed jumps reflecting multiple collisions and collective friction between particles.

Figure 1: Simulation setup to measure the tensile strength of a granular bridge [8]. (Left) initial state, (right) bridge failure. Colours indicate motion direction.

Simulation Setup The simulation setup carries out a direct measurement of the tensile strength of a self-gravitating granular system formed either by spherical and polyhedral particles. To do this, we place two large (1m) boulders connected by cm size, cohesive regolith (see Fig. 1). The regolith are dodecahedrons and their axis ratios (a_y/a_x and a_z/a_x) vary between 0.4 and 1. We also carry out simulations with spheres in order to directly compare against our previous findings [8].

The boulders are pulled apart by increasingly opposing forces until the bridge is broken. During this process, we monitor the dynamics of the particles forming the bridge. The pulling forces as well as the cohesive forces between the grains, and the time step of the simulations are graduated so that the process is quasi-static [9]. The constant cohesive force is set to $f_0=9\times10^{-7}$ N and the increments in pulling force are done in steps of 2% of the total gravitational attraction on one of the boulders every 5 s.

Results Tensile strength can be directly measured from the micro-structure of the system [9] and estimated using a modified Rumpf equation. However, a diameter for a polyhedral particle is not uniquely defined and is difficult to relate particle size to tensile strength. In fact, the results for particles with the same a_x would all line up on one particle size if we followed the common procedure to extract particle size distributions. However, if we instead define an equivalent diameter d_{eq} as the diameter of a sphere that has the same volume as the non-spherical particle, it is possible to observe a trend (see Fig. 2(left)) and a collapse of all measurements and the prediction ($\sigma_T=Z_c v f_0/\pi d_{eq}$), where Z_c is the connectivity number and v is the filling fraction.

Fig. 2 (Left) Tensile strength σ_T as a function of mean equivalent particle diameter d_{eq} for all particle shapes (color level). The black dashed line is a fit in the form of $1/d^2_{eq}$. (Right) Upper and lower limits of the tensile strength of granular media formed by particles with the characteristics of the sample taken from asteroid Bennu. The dashed, green line is the upper limit of the tensile strength of Bennu's surface.

Applying the model developed here and the material parameters obtained from the sample and Bennu, and taking 1 mm as the d_{eq} of the average particle size (average sample particle size = 1.2 mm) that was measured for the sample, the tensile strength should be approximately between 0.001-0.01 Pa; certainly close to be strengthless even in a small asteroid.

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