COHESIVE REGOLITH CLUMP SIZE PREDICTION ON AIRLESS BODIES
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Introduction: A regolith dust grain on the surface of an airless body is acted upon by gravity, cohesion, and the electrostatic force, the product of the grain's charge and local electric field strength. Grains can detach from the surface of an airless body through a variety of mechanisms, such as micrometeoroid bombardment, spacecraft operations, and electrostatic lofting. Cohesion dominates the behavior of sub-cm regolith on small airless bodies[1] and research into electrostatic lofting of individual grains revealed the preferential lofting of intermediately sized grains[2,3]. Terrestrially, it is observed (in a variety of fields dealing with cohesive powders) that clumps of small grains are easier to detach than individual small grains[4]. However, there is currently no model to predict when clumps will detach rather than individual grains, or the size of those clumps.

We present a model to predict the size of regolith clumps that are easier to detach than their constituent grains, as a function of grain size and central body size. Grains are approximated as monodisperse spheres of uniform density.

Force Model for Constraining Clump Size: In order for a clump of grains to detach rather than a single grain, the net downward force on a grain must exceed the net downward force on a clump. The net downward force is the sum of the gravity and the cohesion acting on the clump (or grain). Thus, in order for a clump to be detached rather than an individual grain:

$$F_{t,grain} + F_{g,grain} \geq F_{t,clump} + F_{g,clump} \quad (1)$$

We assume that grains in a clump have some local packing fraction of φ. The maximum value of φ is 0.74, face-centered cubic packing, and the minimum value is $(1 - P)$, where P is the assumed bulk porosity of the regolith. Assuming a clump consisting of a single layer of grains, the equations for gravitational and cohesion forces on clump[4] are as follows:

$$F_{g,clump} = 2A_b R\phi\rho g \quad (2)$$

$$F_{t,clump} = \frac{A_h A_b \phi C_{avg}}{8R} \quad (3)$$

where R is the radius of the grains, A_b is the clump cross-sectional area, C_{avg} is the mean coordination number, and A_h is the Hamaker's constant for the regolith. The Hamakar's Constant for lunar regolith[4] is 0.036 N m^{-1}, and C_{avg} is empirically derived to be 4.5[4], which is consistant for cubic packed regolith grains. The density of regolith ρ is assumed to be 3200 kg m^{-3}. Eqn 4 gives the expression for cohesion for a single grain, where C_{FCC} is 12 (mean coordination number for face-centered cubic packing).

$$F_{t,grain} = A_h R C_{FCC} \quad (4)$$

Substituting the expressions for the forces into Eqn 1 gives the maximum clump cross-sectional area $A_{b,max}$ that is easier to detach than an individual grain:

$$A_{b,max} \leq \frac{8A_h R^2 C_{FCC} + \frac{32}{3}\pi R^4 \rho g}{A_h \phi C_{avg} + 16R^2\phi\rho g} \quad (5)$$

Note that Eqn 5 is a function of grain radius and local packing fraction. Fig. 1 shows $A_{b,max}$ for a fixed R for different planetary bodies.

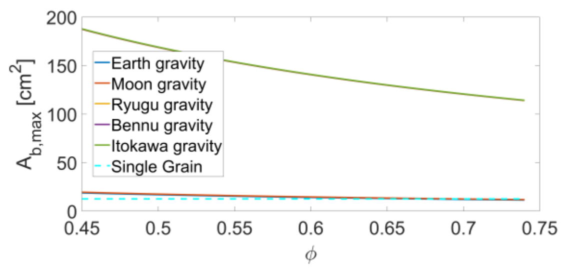

Fig 1: Maximum clump cross-sectional area as a function of local packing fraction, assuming 2cm grains.

Fig. 1 shows the largest clumps composed of 2cm grains that are easier to detach than individual 2cm grains. Clumps smaller than the sizes shown in Fig. 1 could also detach. At lower local packing fractions, larger clumps can be detached, due to the increased empty space associated with looser packing. The maximum clump sizes calculated for the asteroids considered are very similar because their gravities are close in magnitude. On the Earth and Moon, the clump size is not much larger than a single 2cm grain, indicating that clumps of 2cm grains will not detach on these bodies. Fig. 2 shows the number of grains per max clump size.

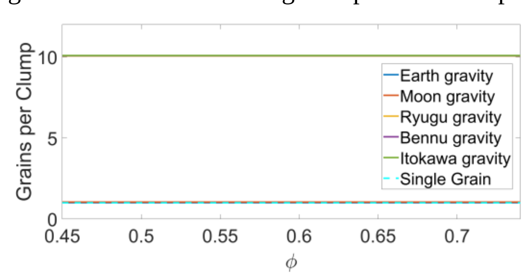

Fig 2: Number of grains per clump as a function of local packing fraction, assuming 2cm grains.

Fig. 2 shows that, for small asteroids such as Ryugu, Bennu, and Itokawa, the maximum loftable clump size contains approximately 10 grains, well above the single grain case. Note that while Fig. 1 shows a decreasing clump size as the local packing fraction increases, Fig. 2 shows that the number of grains per clump remains relatively constant. This indicates that the decreasing clump size is due primarily to the tighter packing of the grains at higher packing fractions.

Geometric Model for Constraining Clump Size: In addition to the force constraint on the detachment of a clump, the bulk and local packing fractions place a geometric constraint on clump size. A given bulk packing fraction can be produced via clumps (with a higher local packing fraction) separated by gaps, or defects. The boundary of a triangular single-layer clump is defined by 3 defects. A defect is a void that serves as the structural weak point from which a clump can detach from the bulk powder. Defects per unit length X determines the clump size for a given grain size, bulk packing fraction and local packing fraction.

We assume a bulk volume V with a bulk porosity P and regolith of grain radius R. The grains in the total volume are discretized into n uniform cubic volumes with side length q. These cubic volumes will be referred to as quadrants, each containing grains packed with the packing fraction φ.

$$V_s = \sum_{i=1}^{n} \phi V_{q,i} = \sum_{i=1}^{n} \phi q^3 = n\phi q^3 = \phi V_q \tag{6}$$

Eqn 6 demonstrates how the total volume occupied by the grains V_s is discretized into quadrants of volume $V_{q,i}$ packed with φ. Since these quadrants can have grains more tightly packed (higher φ) than the bulk porosity P, there exist gaps between these quadrants that do not contain any grains. These defects per unit length is described by the equation below:

$$X = \frac{L - V_\phi^{\frac{1}{3}}}{g_{gap} L} \tag{7}$$

$$V_\phi = \frac{V(1-P)}{\phi} \tag{8}$$

where L is the length of a side of the total volume V, V_φ is the is the volume of the quadrants described by Eqn 8, and g_{gap} is the length of a defect between grains. g_{gap} is assumed to be a maximum of $2R$ because a gap any larger than the diameter of a grain would easily allow a grain to occupy it. With 3 defects forming the vertices of a clump, the base of the clump is an equilateral triangle and the clump cross-sectional area is A_b:

$$A_b = \frac{\sqrt{3}}{4}\left(\frac{1}{X}\right)^2 \tag{9}$$

Determining Maximum Clump Volume: For a given regolith sample on a planetary body, a clump will satisfy both the force constraint (Eqn 1) and the geometric constraint (Eqn 9). If the clump size dictated by the geometric constraint is smaller than the maximum clump size satisfying the force constraint, then a clump rather than an individual grain will detach.

Largest Clump on Bennu. Due to their low gravity, asteroids produce loftable clumps for larger grain radii. Fig. 4 shows the clump size dictated by the force and geometric constraints for a variety of grain sizes on Bennu.

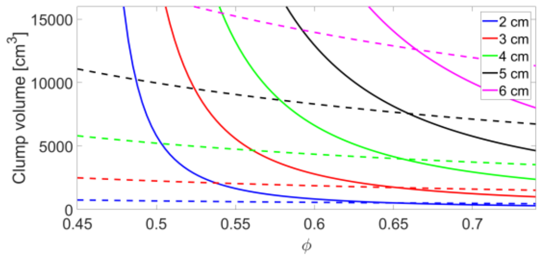

Fig 3: Clump volume as a function of grain size and local packing fraction on Bennu, assuming 55% bulk porosity. The dashed lines correspond to the maximum clump size from the force constraint and the solid lines represent the clump size from the geometric constraint.

In Fig. 3, clump volumes below the dashed lines are easier to detach than individual grains. The intersection of a dashed line with the solid line of the same color indicates the maximum clump size for that grain radius. The intersections occur at the lowest possible packing fraction for which lofting is possible, and the clumps become more porous as grain radius decreases. As the intersection point moves further left in Fig. 3, lofting becomes more realistic *in situ* since high packing fractions are difficult to achieve in nature.

Clumps on Earth. Fig. 1 indicates that 2 cm grains are incapable of producing loftable clumps on Earth. However, grains on the order of 5 microns produce 10 grain clumps (8186 micron^3) that are easier to detach than a single grain. The terrestrial clumping of micron scale grains agrees with observations.

Conclusions: Maximum regolith clump size depends on grain radius, gravity, bulk porosity, and local packing fraction. Clumps become larger as packing fraction decreases, and more porous as grain radius decreases. Clumps of grains up to cm's in size are easier to detach than individual grains on Bennu, while micron-sized grains produce loftable clumps in Earth's high gravity environment.

References: [1] Scheeres D. J. et al. (2010) *Icarus, 210,* 968–984. [2] Hartzell C. M. and Scheeres D. J. (2011) *PSS., 59,* 1758-1768. [3] Hartzell C. M. et al. (2013) *GRL, 40,* 1038–1042. [4] Sánchez P. and Scheeres D. J. (2013) *Icarus, 271,* 453-471.