PREDICTING 3D COHESIVE REGOLITH CLUMP SIZE ON AIRLESS BODIES A. V. Patel[1] and C. M. Hartzell[2], [1,2]University of Maryland College Park, ; [1]ap91119@gmail.com, [2]hartzell@umd.edu

Introduction: Regolith grains on the surface of airless bodies are acted upon by gravity, the centripetal force, cohesion, and the electrostatic force (the product of a grain's charge and local electric field strength). Cohesion and gravity oppose mechanisms to detach regolith from the surface. Cohesion dominates the behavior of sub-cm regolith on small airless bodies[1]. We previously developed a model to predict the largest single-layer regolith clump that is easier to detach from the surface than one of its constituent grains[2].

We extend our model to predict the size of regolith clumps to 3D clumps. Grains are approximated as monodisperse spheres of uniform density. The resulting 3D clump is easier to detach than an individual, constituent grain and its size is a function of grain size and central body gravity.

Force Model for Constraining Clump Size: A clump of grains is easier to detach than a single grain if the net downward force on a grain exceeds that on a clump. The net downward force is the sum of the gravity, centripetal force, and the cohesion acting on the clump (or grain).

Our model assumes grains in a clump have a local packing fraction φ ranging from φ_b, the bulk packing fraction of the regolith powder, up to 0.74, corresponding to face-centered cubic (FCC) packing[2]. A 3D clump is defined by a cross-sectional area A_b and a height h, so the gravitational force acting upon it is:

$$F_{g,clump} = A_b h \phi \rho g \tag{1}$$

The density of regolith ρ is assumed to be 3200 kg m^{-3}. Using the expression for the gravitational force on a 3D clump (Eqn 1), clump cohesion[3], and grain cohesion[4], we can solve for the maximum clump cross-sectional area $A_{b,max}$ that is easier to detach than an individual grain:

$$A_{b,max} \leq \frac{8A_h R^2 C_{FCC} + \frac{32}{3}\pi R^4 \rho (g - r_s\omega^2))}{A_h \phi C_{avg} + 8R\phi\rho h(g - r_s\omega^2)} \tag{2}$$

where R is the radius of the grains, C_{avg} is the clump mean coordination number (number of grains in contact with the clump), C_{FCC} = 12 is the grain mean coordination number (based on FCC packing), and A_h is the Hamaker constant for the regolith. The Hamakar constant for lunar regolith[3] is 0.036 N m^{-1}, and C_{avg} is empirically derived to be 4.5[4]. Eqn 2 gives the volume (the product of $A_{b,max}$ and clump height h) that is easier to detach than an individual grain, considering only the active forces.

Ideally, we would model clumps as cubic volumes with a uniform side length h, but this does not yield an analytical solution for clump volume. To keep our analytical solution for clump volume stemming from Eqn 2, we relate h to grain size through a, the discrete side length of an FCC packed cube, where $a = 8^{1/2} R$. Fig. 1 shows that the numerically solved cubic clump volume (black) is bounded by clump volume when h = 2a and h = 4a.

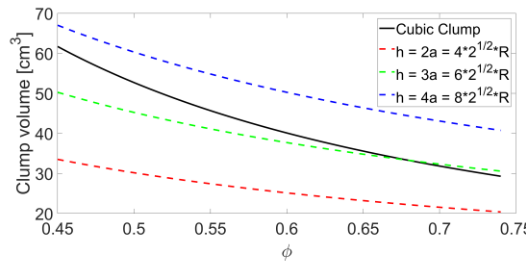

Fig. 1: Force constrained clump volume as a function of local packing fraction and clump height h, assuming 5mm grains on Bennu.

Clumps with heights 2a and 4a bound the volume of the cubic clump, and we find this relationship holds for other grain radii and surface gravities. The cubic clump volume approaches the h = 4a clump volume (the upper bound) as local packing fraction decreases (towards φ_b for rubble pile asteroids). Therefore, we will assume a clump height of 4a in our investigation.

The maximum number of grains per clump, as a function of surface gravity and grain size, is derived from Eqn 2 and clump volume:

$$N_{grains,max} = \frac{48\sqrt{2}}{\pi} \frac{A_h C_{FCC} + \frac{4}{3}\pi R^2 \rho g}{A_h C_{avg} + 64\sqrt{2} R^2 \rho g} \tag{3}$$

Eqn 3 is plotted as a function of gravity and grain size in Figure 2. Figure 2 shows that a clump composed of 57 2cm radius grains can detach on Bennu, but only single 2cm grains can detach under the substantially greater gravities of the Earth and Moon. However, 57-grain clumps of 25 micron radius grains can detach on Earth.

Geometric Model for Constraining Clump Size: Differences in the bulk and local packing fractions place a geometric constraint on clump size. Fig. 3 outlines our geometric model. A given bulk packing fraction φ_b can be produced via clumps (with a higher local packing fraction φ) separated by defects g_{defect}. The boundary of an isosceles triangle cross-section clump (base & height q) is defined by 3 defects, and the height of the clump is q.

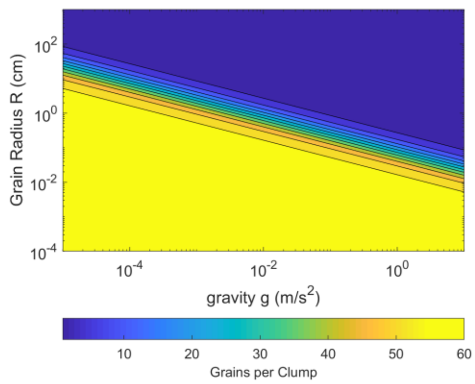

Fig. 2: The maximum number of grains per clump producing a clump that is easier to detach than its constituent grains (due to force constraints) as a function of net gravity and grain size.

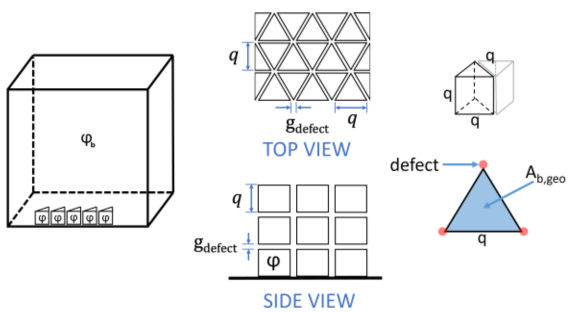

Fig. 3: Diagram of the geometric model. Total volume is discretized into identical 3D clumps.

Given this clump cross-section, we find defects per unit length X (i.e. $1/q$), clump cross-sectional area $A_{b,geo}$, and geometrically constrained clump volume $V_{b,geo}$ with our assumed clump height:

$$X = \frac{\phi^{\frac{1}{3}} - \phi_b^{\frac{1}{3}}}{g_{defect}\phi^{\frac{1}{3}}} \Rightarrow A_{b,geo} = \frac{1}{2}\left(\frac{1}{X}\right)^2$$
$$V_{b,geo} = 8\sqrt{2}R\phi A_{b,geo} \qquad (4)$$

Max Detachable Clump Volume: For a given regolith sample on a planetary body, a geometrically constrained clump (Eqn 4) will detach instead of a grain if it is smaller than the largest clump that satisfies the force constraint (Eqn 2). Just as our model previously predicted for single-layer clumps[2], our 3D model predicts that cm-scale grains can form large detachable clumps on Bennu. Fig. 4 shows clump size dictated by force and geometric constraints for mm grains on Bennu. Dashed lines give the max clump size from the force constraint, solid lines give clump size from the geometric constraint. Intersections give the max detachable clump volume and the lowest φ for detachment.

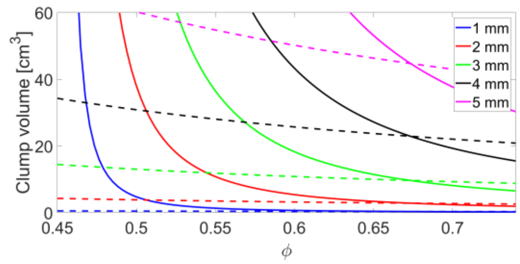

Fig. 4: Clump volume as a function of grain size and φ on Bennu, assuming φ_b=0.45.

Fig. 5 shows clumps for micron grains on Earth. Experimental work on terrestrial flour clumping through avalanching[5] demonstrates that 0.65mm clumps, or ~0.14 mm^3, form frequently. Fig. 5 shows that ~80 micron radius grains form clumps of that volume, which agrees well since flour ranges from 75-570 micron in diameter.

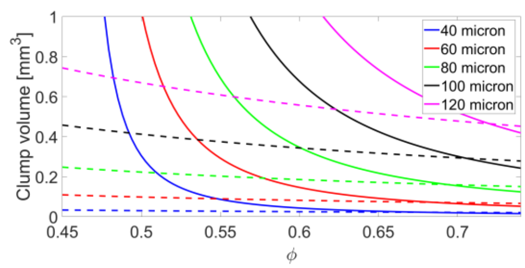

Fig. 5: Clump volume as a function of grain size and φ on Earth, assuming φ_b=0.45.

Conclusions: We have presented a model for 3D clumps that are easier to detach than individual, constituent grains. Clumps become larger as packing fraction decreases, and more porous as grain radius decreases. Clumps of grains up to cm's in size detach on Bennu, while micron-sized grains produce detachable clumps in Earth's high gravity environment. Reducing mean coordination number for grains predicts smaller clump sizes than experimentally observed for flour, suggesting that polydisperse, aspherical grains may cause more inter-grain contacts and larger clumps. These predictions may influence our interpretation of surface grains and boulders on small asteroids, which may, in fact, be clumps.

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References: [1] Scheeres D. J. et al. (2010) *Icarus, 210*, 968–984. [2] Patel A. V. and Hartzell C. M. (2019) *LPSC 2019*, Abstract #1584. [3] Sánchez P. and Scheeres D. J. (2013) *Icarus, 271*, 453-471. [4] Hartzell C. M. and Scheeres D. J. (2011) *PSS., 59*, 1758-1768. [5] Durda D. D. et al. (2014) *LPSC 2014*, Abstract #1777