COHESION UNDER REDUCED GRAVITY AND IMPLICATIONS FOR TITAN AEOLIAN SEDIMENT TRANSPORT: PRELIMINARY MODEL AND RESULTS. J.F. Aliaga-Caro[1], D.M. Burr[2], B.R. White[1], J.R. Marshall[3], R. Greeley[4], and N.T. Bridges[5], [1]University of California, Davis (jfcaro@ucdavis.edu), [2]University of Tennessee, Knoxville, [3]Carl Sagan Center, SETI Institute, [4]Arizona State University, [5]Applied Physics Laboratory.

Introduction: The abundant aeolian dunes observed on the surface of Titan (covering ~20% of Titan's surface [1,2]) make the study of particle flow behavior and particle cohesive properties under reduced gravity relevant to understanding their formation and composition. Several authors have investigated the flow of fine powders and their cohesive behavior under reduced gravity conditions [3,4,5,6]. These studies indicate that under reduced gravity, any powder will exhibit enhanced cohesion.

Our aim is to extend these experimental studies to develop a numerical model to calculate angle of repose (AOR) under reduced gravity. To the authors' best knowledge, this is the first model to consider the effect of gravity on AOR. Here we present preliminary results.

Background and Model Parameters:

Interparticle Forces and Friction Force. The interparticle force is attributed to the van der Waals force given by:

$$F_{vdW} = \frac{Ad}{24s^2} \quad \text{(Eq. 1)}$$

where A is the Hamaker Coefficient (a material property), d is the particle diameter and s is the separation distance. A more realistic value for the cohesion force is given if d is replaced by the diameter of the asperities, l [3,7]. Typical values for glass are: A=6.5x10^{-20} J, l=0.2 µm and s=0.4 µm [7].

The friction force is simply taken to be:

$$F_f = \mu_s N \quad \text{(Eq. 2)}$$

where the coefficient of static friction (COF), μ_s, is taken to be a surface roughness parameter, and N is the contact force. For glass μ_s=0.9.

The force of gravity is:

$$F_g = mg = \frac{\pi}{6}\rho g d^3 \quad \text{(Eq. 3)}$$

where m is the mass of the particle, ρ is its density, and g is the gravitational acceleration.

Static Angle of Repose (SAOR). Results of the effect of reduced gravity on SAOR have been studied in [5,6]. Data are inconclusive as the magnitude of the change in SAOR due to a change in gravity varies by the method used to test it. Furthermore, the type of method appears to give different results – either an increase in angle or no change with a decrease in gravity.

Dynamic Angle of Repose (DAOR). In the most extensive dataset available, White [8] used a rotating drum to study the dynamic angle of repose at different gravity levels (defined as actual gravity/Earth gravity, g/g_o). His results using glass beads (d=1350 µm) and Monterey sand (d=400 µm) with densities of 3000 and 2650 kg/m^3 respectively indicate an increasing angle of repose with a decrease in gravity. In other experiments using d=530 µm glass beads the opposite behavior has also been shown to exist - DAOR decreases with increasing gravity levels [9].

Methods & Results: The AOR model presented here is based on a force balance between the force of gravity, van der Waals force and a friction force (Figure 1) for a sphere resting on a sloped surface. For this first iteration, contact electrification forces are neglected as being of lesser importance for static conditions.

SAOR data under Earth gravity are used to calculate AOR dependance on particle diameter, holding all other parameters constant. DAOR data are used to find the AOR dependance on gravity. No distinction is made between these two angles except to note that SAOR is a few degrees greater than DAOR [8]. Although experimental data yield a variety of results regarding the effect of gravity on SAOR, the largest dataset shows an increase in DAOR with decreasing gravity [8].

Static Angle of Repose. One set of data from [10] for glass spheres (density of 2760 kg/m^3) is available for comparison with our model (Figure 2). It can be seen that the force balance using the coefficient of friction for glass over-estimates the AOR. A better fit is μ_s=0.55. With this value the model and data are in agreement down to a diameter size of ~80 µm. The divergence of the proposed model from the experimental data towards lower particle diameters may be due to agglomeration of fine particles, which would lead to a higher effective weight and reduction of SAOR.

Dynamic Angle of Repose: The model is also compared with White's DAOR data. It is assumed that the only role of the tumbler rotation speed is to increase compactness of the sample and perhaps increase the AOR by a few degrees. The data at 1-gravity is used as a reference to adjust the COF if necessary until the desired angle output matches the data. The COF is increased to 0.58 for the glass spheres and by an additional factor of ~1.2 for the Monterey sand, to account for its non-spherical shape. The constant *A* and asperity *l* are left unchanged.

Based on the model parameters and physical arguments, the only variable affected by a change in gravity is particle separation, *s*. A hand-fitted median line in White's data is taken as reference at different gravity levels (Figure 3) for the AOR. Holding the particle diameter constant in the AOR model, it is found that in order to output the desired increasing AOR as gravity is decreased, the parameter *s* needs to decrease. But the decrease in *s* is not the same for both particle sizes.

For $g < 0.8g_o$ the data for the parameter *s* can be reduced to a linear function of gravity level by plotting (Figure 4):

$$\frac{s}{\left(\mu_s/d\right)^2} \text{ vs. } \frac{g}{g_o} \qquad \text{(Eq. 4).}$$

Discussion and Future Work: Preliminary results from our model have allowed for the study of the effect of gravity on particle separation and cohesive behavior. Further study into the forces involved at the microscopic level need to be performed to understand the decrease in separation distance as gravity is decreased. Future work will entail a more detailed study of the parameters to better understand the non-linearity of the reduced data for gravity levels above 0.8gs. How the coefficient of static friction for glass varies for micro-scales also needs careful consideration.

Titan dune sediments have been hypothesized to be cohesive [11]. Enhanced cohesion at reduced gravity may suggest a mechanism for this cohesive behavior.

How does this cohesive nature affect particle entrainment by wind and particle mass flux on extraterrestrial surfaces? We will improve current threshold models by incorporating the effect of interparticle forces and their change under reduced gravity to better estimate threshold wind speeds on Titan.

References: [1] Lorenz R.D. et al. (2006) *Science* 312, 724-727. [2] Radebaugh J. et al. (2007) *Icarus 194*, 690-703. [3] Qian G-H. (2001) *Particle Technol. Fluid 47,* 1022–1034. [4] Shao et al. (2006) *J. Thermophys. Heat Transf. 20,* 371-375. [5] Hofmeister P.G. et al. (2009) *AIP Conference Proceeding 1145,* 71-74. [6] Brucks A. (2008) *ASCE Conference Proceeding*. [7] Seville J.P.K. et al. (2000) *Powder Tech 113,* 216-268. [8] White, B.R. (1988) *AIAA-88-0648.* [9] Brucks. A. (2007) *Physical Review E 75,* 032301. [10] Wong A.C-Y. (2000) *Chem. Eng. Sci. 55,* 3855-3859. [11] Rubin D.M. et al. (2009) *Nature 2,* 653-658.

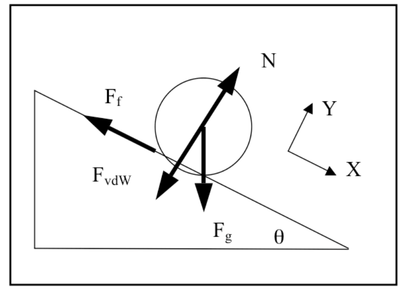

Figure 1. Force balance for proposed model. Terms as defined for Eqs. 1, 2 and 3.

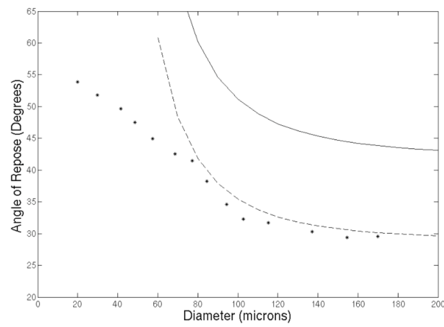

Figure 2. Static angle of repose vs. diameter. μ_s=0.9 (solid line), μ_s=0.55 (dashed). Data from [11] shown as dots.

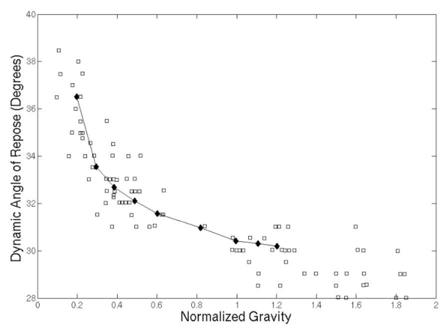

Figure 3. Glass beads data [8] (squares) under reduced gravity and the "median" line.

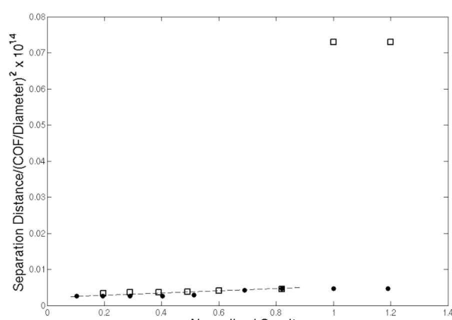

Figure 4. Linear dependance of separation distance, *s*, for gravity levels of 0.8g and below. Glass beads (squares) and Monterey sand (dots).