Repose Behavior of Lunar Simulants

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Abstract

Repose behavior for lunar simulants has been characterized using an experimental rig onboard the Zero-G Plane, a microgravity aircraft. Utilizing the continual motion of rotating drums, measurements of repose flow behavior of lunar *mare* and lunar highlands simulants under varied gravity and pressure conditions have been conducted, resulting in a plausible scaling parameter for the angles of repose of the simulants JSC-1A, GRC-3, NULHT and OB-1. The relevant scaling parameter is $\sqrt{Fr}$ where $Fr = \omega^2 R/g_{eff}$ is the Froude Number, with ω the drum rotation rate, R the drum radius, and g_{eff} is the effective gravitational acceleration acting on the simulant. We find sufficient evidence in the data to support the scaling hypothesis for the angle of repose.

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1 Introduction

1.1 Lunar Regolith

Lunar regolith is a distinctive mixture of minerals, glass, and rock that covers the surface of the moon. With the continual blasting of ultraviolet radiation from the Sun and micrometeorite impacts, the regolith has undergone significant changes in structure. The blasting has left the top layer of regolith with a jagged microstructure - completely different than any granular materials on Earth. This layer of fine, powdery material measures a few meters in depth and sits on top of a more consolidated layer of regolith that has not been exposed to the UV blasting. The characteristic dark craters of the moon consist of lunar *mare*, younger regolith that has been brought to the surface by meteor collisions. The white, highlands regions consist of an older regolith mixture that has undergone ages of UV radiation.

Because of its unique structure, lunar regolith particles have a small size distribution, allowing the material to flow into smaller spaces than granular materials on Earth. If we were to return to the moon and establish a lunar base for future space explorations, the regolith properties would make a number of daily experiences taken for granted on Earth much more difficult. Lunar regolith can jam up electronics, get into every crevice of a building structure, and cause respiratory irritation if inhaled. In addition to daily living complications, lunar regolith is very cohesive, which changes the way one would build a lunar establishment.

Due to the unique properties of lunar regolith, there has been a strong movement within the *In Situ* Research Utilization (ISRU) program of NASA to study the lunar regolith before humans return to the moon. NASA has commissioned external companies, such as Orbitec, Inc. [Orbitec, Inc.], to analyze and recreate the unique structure of lunar regolith taken back to Earth from the Apollo missions. This new, fabricated granular material is called a "lunar simulant" because it has similar characteristics to lunar regolith but is fabricated on Earth. Different simulants are used to model the different regions of the moon. With the mass production of lunar simulants, many research groups can take on projects, which together encompass the problems created by lunar regolith.

1.2 Repose Angles

The angle of repose is a granular materials engineering property relating to the flow-ability of material. More specifically, the repose angle is commonly defined as the maximum angle a material will form a stable heap (measured from the horizontal). Repose behavior is particularly important for excavation and soil processing constraints.

In practice, two angles of repose are commonly defined. The *static angle* of repose is the measurement of the highest angle of repose achieved by a static pile relaxing after an avalanche event. It can be found by pouring a known amount of granular material into a pile on a flat plate, allowing it to form its characteristic conical shape. After the material has reached an equilibrium shape, one can then measure the angle it makes with respect to the flat surface. The angles of interest are the angle of highest stability in which a material will form a stable heap and the angle the pile relaxes to after an avalanche event. Fig. 1 shows an example of the static angle of repose.

Figure 1: Static Angle of Repose.

The static angle of repose is dependent on many parameters including the amount of material poured, the density of matter, surface roughness and environmental factors such as humidity. There are in fact other ways to measure the static angle of repose. For example, one could fill a flat bottomed box with a hole in the center with a known amount of granular material. The material will flow out through the hole in the bottom of the box [Dodds]. Once the flow has ceased, the remaining material will create an angle with the horizontal flat surface of the box which is also defined as the static angle of repose. Other methods exist, though not all the methods will return the same value for the angle of repose. Because this measurement is dependent on so many parameters, it is not a very robust measurement. We therefore study the alternate method of repose measurement - the *dynamic angles* of repose.

Like the static angle measurement, the dynamic angle of repose is the measurement of the build up and collapse of granular materials. Rotating cylinders half filled with a granular material are generally used to create the behavior. The dynamic angle of repose measures the steady state heap slope angle as the material continues to flow from the angle of highest stability to its relaxation angle. Before the drums begin to rotate, the material forms a flat mass at the bottom. At slower rotation rates, the granular bed is carried up along with the motion of the rotating cylinder until it reaches the maximum stability angle. This is the highest angle before the surface falls out of equilibrium. An avalanche event occurs and material that was once built up into an angle will collapse to a lower angle known as the relaxation angle. One can vary the rotation rates to explore a range of stable repose angles. Unlike the many dependencies of the static angle of repose, the dynamic angle of repose is contingent on the radius of the drum, the angular velocity, and the effective gravity, allowing for consistent and coherent data.

From a civil engineering perspective, the angles of repose for a given substance are extremely important information because they characterize flow properties of the material. In particular, knowledge of repose angles is essential in establishing processes and guidelines for excavation depths, wall angles, and other engineering constraints on soil processing. However, neither the static nor the dynamic angles of repose is a fundamental material property.

Instead these angles depend on the experimental conditions. Therefore, useful engineering data on repose angles requires that the experimental conditions reproduce as closely as possible the anticipated engineering environment. Of particular concern for lunar ISRU applications is a measurement of dynamic repose angles under vacuum conditions and reduced gravity of 1/6-g.

2 Overview and Background

Studies on fine powders in rotating drums have greatly influenced the experiment detailed in this thesis. The study of the fluidized layer of a fine powder by Castellanos *et al.* was used to aid in the design specifications as well as estimate flow behavior for our experiment [Castellanos *et al.*, 2001]. Although this work was performed under 1-g, standard atmospheric pressure (STP), it has been a useful source for experimental parameters.

Researchers at Monash University in Australia conducted a study which measured both the static and dynamic angles of repose in separate experiments [Forsyth *et al.*]. Both experiments were conducted under 1-g conditions and standard atmospheric pressure. Iron spheres of 400 micron diameter were used as the granular material. An induced magnetic field supplied by a pair of Helmholtz coils was used to simulate inter-particle forces. Both the static and dynamic angles of repose were found to increase approximately linearly with inter-particle force. This dependence is important because lunar soils exhibit strong inter-particle forces due to their intrinsic charge from UV bombardment.

Alberts *et al.* finds that for dry spherical particles, the angle of highest stability will be approximately 24°, independent of the material composition or the particle size distribution [Alberts *et al.*]. Further computation analysis by Nowak confirms this finding and expands the research to investigate the effects of a viscous liquid on the repose behavior [Nowak]. Dodds examined the effects of particle size and shape and found that decreased roundness and increased roughness will increase the angle of repose [Dodds] which directly applies to the experimental materials used in this thesis. Because the regolith has undergone the extreme conditions on the moon, the individual particles of lunar regolith are rough and jagged as well as elliptical. We expect to see an increase above the computed average angle due to the ellipticity and jaggedness of the particles.

Other researchers have studied the repose behavior in rotating drums in both reduced and hyper-gravity environments. Williams *et al.* studied the flowability differences of fine powders and non-cohesive materials in reduced gravity [Williams *et al.*, 2007]. In addition, Brucks *et al.* examined the repose behavior of fine particles under standard and hyper-gravity conditions at standard atmospheric conditions [Brucks *et al.*, 2007]. Brucks *et al.* also finds that granular materials may be characterized by a universal scaling parameter, known as the *Froude number*, further detailed in Section 2.3. Their results are consistent with repose modeling of granular materials done by Klein and White in reduced gravity conditions [Klein *et al.*, 1990]. These experiments focused on the importance of gravity for repose behavior and experimentally found that the angle of repose can be greater than suggested angle measurement by Alberts *et al.*

2.1 Static Angle Approximations

2.1.1 Mohr-Coulomb Analysis

There are many models that can be used to calculate the static angle of repose for a given granular pile. One such model is the analysis of a mass on an incline plane through the Mohr-Coloumb analysis. The Mohr-Coulomb analysis assumes that friction between the individual particles in the granular heap determines the repose behavior and is not dependent on the geometry of the pile. The maximum angle of stability can then be solved by computing the forces experienced by a object on an incline plane just before the object slides. Consider a particle placed at rest on an inclined plane depicted in Fig. 2.

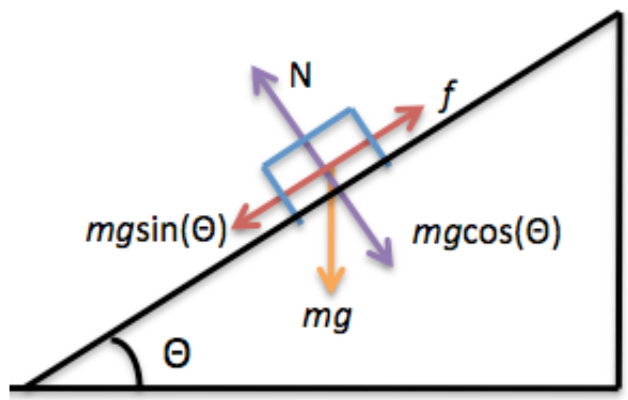

Figure 2: Forces on a mass resting on an inclined plane. A body of mass (in this instance, a granular particle) will experience forces due to gravity, friction and the normal force.

The particle experiences a force due to gravity (mg), the normal force exerted by the plane to the force of gravity ($mg\cos\theta$) and the frictional force acting parallel to the inclined plane (f). At the point just before an avalanche, the forces will be in equilibrium. Force balance yields

$$\sum \text{Fx} = mg\sin\theta - f = 0$$

and

$$\sum \text{Fy} = mg\cos\theta - N = 0.$$

Because the frictional force is proportional to the normal force at the point of an avalanche, the frictional force, $f = \mu_s \text{N}$. Canceling out the forces results in the coefficient of friction being equal to the tangent of the highest angle of stability or,

$$\mu_s = \tan\theta.$$

The maximum angle of stability, θ, depends only on the static coefficient of friction and not on gravity. This is a characteristic of this model of friction. In a more sophisticated model, frictional forces may involve non-linear behavior due to the microstructure of the object. This would manifest as a dependence on contact area and geometry.

2.1.2 Lattice Model

More sophisticated approaches to the repose angle determination have been developed. One such method can be found in the analysis of Alberts *et al.* which uses spherical geometry to calculate the angle of repose [Alberts *et al.*]. Alberts *et al.* model inclined granular packing using spherical particle in a hexagonal lattice. If a spherical particle is randomly placed on an inclined lattice of packed spheres, it is stabilized solely by three particles as indicated in Fig. 3. The three base spheres are in contact with each other and the sliding sphere sits in the interstitial space above the three spheres.

We define θ to be the local slope angle of the material heap that is tangent to the two supporting spheres, *i.e.* the plane that passes through the centers of the supporting spheres. If θ is small, the heap is stable and no collapse will occur. If θ is larger than the maximum angle of stability, θ_m, the newly added spherical particle will roll off its support and start an avalanche on the heap surface. The top sphere is only stable while the gravitational force vector points down within the plane drawn by the three base spheres, depicted by Fig. 3a.

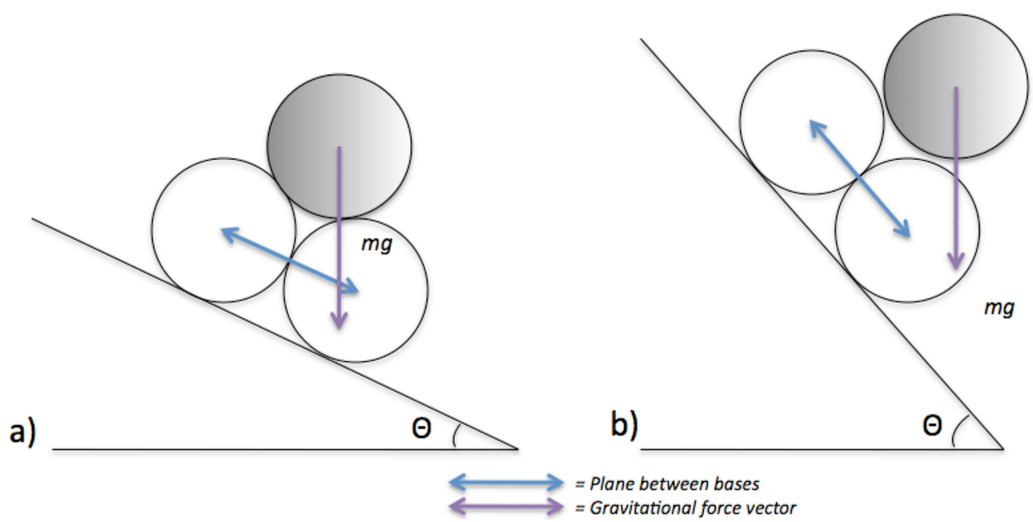

Figure 3: (a) The top spherical particle is stable so long as the gravitational force vector points through the plane created between the center points of the base spheres. (b) An unstable configuration, θ is greater than the maximum angle of stability, θ_m.

When solved numerically, this maximum stability angle equals 23.4°[Alberts *et al.*] and is independent of gravity. Although this is a more sophisticated analysis of spherical granular material flow behavior, gravity is again eliminated in the intermediate steps of the analysis. The final angle measurement is dependent on solely the geometry of the plane created between the base spheres and the local stability angle.

2.2 Dynamic Angle Approximations

We next turn to a model of dynamic repose angle more directly related to our experiment. One can imagine a singular particle inside a rotating cylinder. In an external reference frame, the particle experiences a normal force due to the wall's surface and a gravitational force. Fig. 4 displays the forces experienced by the particles in a rotating cylinder.

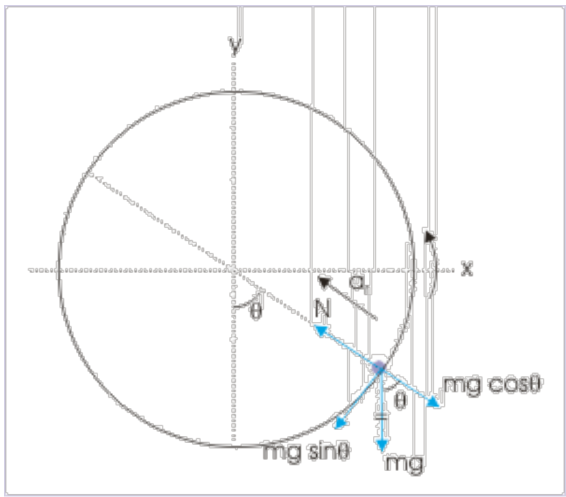

Figure 4: A force diagram of a mass in a rotating cylinder. Image Credit: Sunil Singh.

We can use the concepts of vertical circular motion to predict the repose behavior of granular material. Balancing the forces on a particle at any angle θ results in

$$\mathrm{N} = \mathrm{mgcos}(\theta).$$

The particle's motion is centripetal. Therefore

$$\mathrm{N}=\mathrm{m}\omega^2 R.$$

The particle's angular position is a function of the ratio of centripetal to body forces,

$$\frac{\omega^2 R}{g_{eff}} = cos(\theta).$$

We propose that this simple model has some relevance to stability criteria in our rotating drum experiments. Other research groups found that the granular media they were working with could be characterized by one or more engineering scaling parameters. An example of such was found in Brucks *et al.*

2.3 The Froude Number

The analysis of Brucks *et al.* proves to be noteworthy for angle of repose prediction, especially because this experiment characterized repose behavior under hyper-gravity [Brucks *et al.*, 2007]. The experiment utilized rotating cylinders to create a dynamic repose behavior in the hyper-gravity environment. Brucks *et al.* define a dimensionless scaling parameter called the *Froude Number* as the ratio of the centrifugal force acting on the particles inside the rotating drum to the effective gravity acting on the particle,

$$Fr = \frac{\omega^2 R}{g_{eff}}. \tag{1}$$

Here ω is the angular rotation rate of the drum, R is the radius of the drum, and g_{eff} is the effective gravitational acceleration experienced by the particles. This scaling parameter is comparable to the model described in the previous section. Brucks *et al.* finds that as the Froude number increases, the angle of repose increases.

The dimensionless Froude number is a plausible scaling parameter because it compares the magnitudes of two characteristic determinants of particle behavior. Scaling is evident when the behavior of a material is partially determined by a ratio of two or more quantities rather than a single property on its own. This is, in effect, a way of performing a multivariable analysis for a material. For scaling to be evident, data taken over a series of trials needs to collapse onto a single curve when plotted graphically. Fig. 5a and Fig. 5b show an example where scaling does not occur for a specific data set. The data points are scattered throughout the graph and one could not place a logical line of best fit connecting the majority of points. Fig. 5c is in sharp contrast. Notice how all the data points fall along the same curve. One could imagine a line of best fit passing along the data points. In addition, it would be easy to predict the continuation of the curve if more data points were to added to this graph. Fig. 5c is an example of scaling.

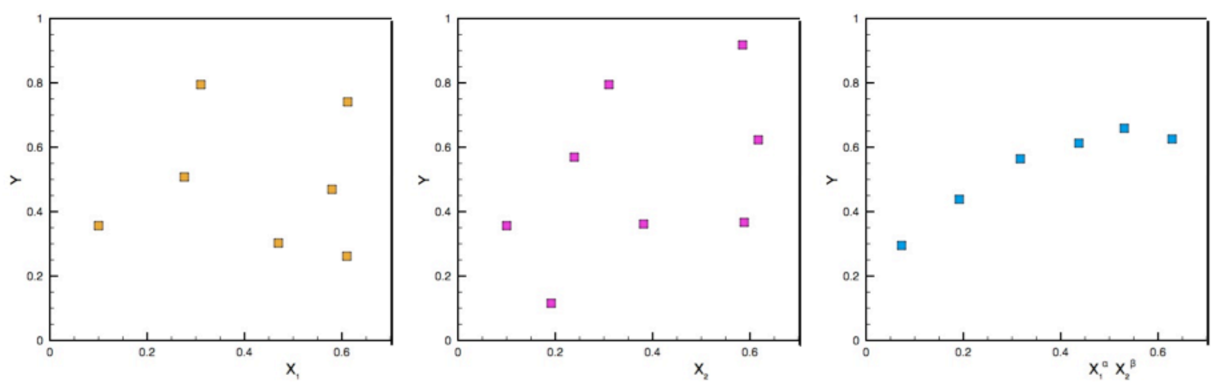

Figure 5: a) Dependent variable Y shows no correlation with parameter X_1. b) Dependent Y shows no correlation with parameter X_2. c) Dependent variable Y scales with the parameter $X_1^{\alpha} * X_2^{\beta}$

If the Froude number were a valid scaling parameter for all granular materials, we would see all of our angle measurements collapse onto a curve for all ranges of the Froude number. Each simulant would have its own scaled curve as it is material dependent. For example, a less cohesive material would most likely have shallower angles than a highly cohesive material for the same Froude number. This plausible scaling behavior of repose angles with the Froude number is investigated in this senior thesis to test its applicability to lunar simulants and reduced gravity. Should this scaling form be validated, it would prove to be a useful method in predicting repose behavior in varied gravity levels and rotation rates.

Another significant result in the literature is that interstitial gas likely have a considerable effect on granular flows. In all the previously described articles, the experiments and computer simulations were conducted at standard atmospheric pressure and at room temperature. It is believed that the combination of nitrogen and oxygen gases mix into a granular material and help the granular heap build up to a steeper angle. Humidity in the air could mix into the material and create "liquid bridges" between the individual particles. This too would allow the heap to build up to a higher, more steep angle. This conclusion is plausible but the results are only preliminary, and further research is necessary to investigate the role of interstitial gases in repose angle determination [Brucks *et al.*, 2007]. One of the goals of our repose angle experiment was to test this idea. Our experiment removes the effects of interstitial particles by means of a partial vacuum, and also tests realistic lunar soils simulants rather than monodispere, noncohesive, spherical glass beads used in other investigations.

3 Experimental Design

In the experiment detailed in this thesis, we utilized three rotating drums to create granular flow in lunar regolith simulants. This research began as a project through the Systems Engineering Educational Discovery (SEED) program through NASA. The SEED program is a student microgravity program where college research teams take on Mission Priority research topics relating to space exploration or lunar habitation. Each research team designs and builds an experimental rig and later tests it aboard NASA's Weightless Wonder, a reduced gravity airplane. Brief durations of reduced gravity are created as the aircraft flies in a series of parabolic arcs. The teams are given two flight days each with 30 parabolas of reduced gravity.

The central components in our experiment are three rotating aluminum drums with rotation axes perpendicular to local gravity. The drums are milled from 6061 T6 aluminum. The viewing window on each drum is flange-mounted polycarbonate and is sealed by an O-ring and bolted to the front face of the drum. The back slide of the drums have vacuum fittings allowing us to mount the drums to a diffusion pump for the low pressure trials. The rig was mounted to the floor of the reduced gravity aircraft. Each rotating cylinder was separately controlled by motor driver controls, allowing for a range of repose behavior exploration. More specifically, they are pulse-width modulation (PWM) controllers which give a more precise control to the operator. The PWM controllers allowed us to drive the drums in the 0.1 - 3.5 RPM regime. Three miniDV cameras, centered on the drum viewing window, are utilized to record the behavior for later analysis. Fig. 6 is an image of our current experimental setup, featuring all key components described above.

During testing, each drum was filled to 30% by volume with lunar simulants. Each drum contained one simulant per trial. On the first flight day, lunar *mare* simulants JSC-1A and

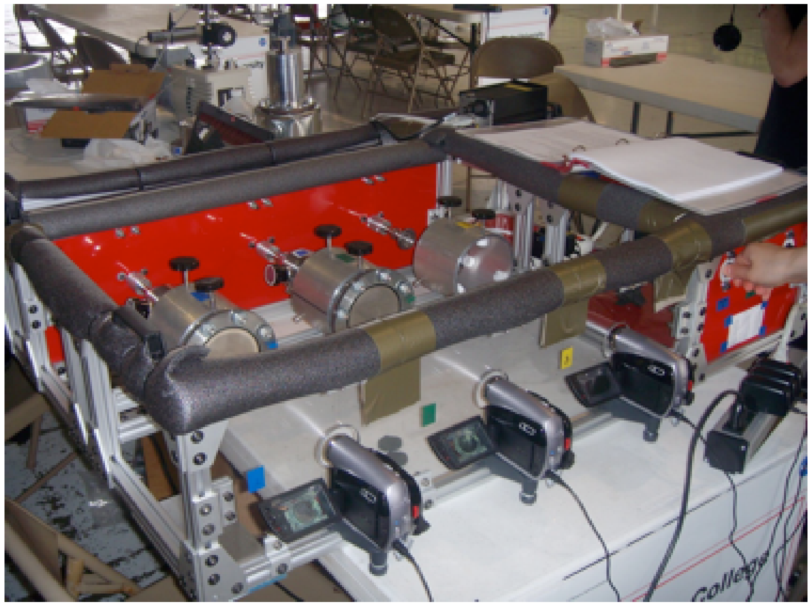

Figure 6: Experimental Rig. Each drum is loaded with one cup of lunar simulant, GRC-3 and JSC-1A in this particular image. Three miniDV cameras record the repose behavior for later analysis. Note the vacuum fittings for low pressure trials.

GRC-3 were under vacuum in the first two drums and the third drum contained GRC-3 at atmospheric pressure. Unfortunately, we encountered a pressure leak mid-flight on the first drum, rendering the vacuum data for GRC-3 unusable.

On the second flight day, lunar highlands simulants were investigated. The first and second drums contained the simulants OB-1 and NU-LHT1 in a vacuum. The third drum contained NU-LHT1 and was again held at atmospheric pressure. The behavior of these simulants was unexpected, complicating the analysis. Due to the extremely cohesive and clumpy nature of the simulants in reduced gravity environment, the 2G portions provide us with the only useable data for the current experimental setup. More information follows in the Results section.

To eliminate humidity from the simulant mixtures, the drums were baked out prior to the flight. For the drums being tested under a vacuum, we used a diffusion pump and an inline sub-micron filter to pump the drums down a range from $10^{-3} - 10^{-2}$ Torr. Because some trapped gases remained within the simulant bed at the bottom of the drum, we found it difficult to achieve pressures below 10^{-2} Torr.

At the start of each flight, we rotated the three drums at a high rotation rate to loosen the simulant from possible compaction during takeoff. We then decreased the rotation rate to a lower, target rotation rate calculated prior to flight using the Froude number and phase diagrams developed in [Brucks *et al.*, 2007]. Because the rotation rate of the drum can be manually monitored and adjusted with the use of motor drive controllers, a range of rotation rates were explored. The repose behavior was captured by three mini-DV camcorders aligned with the viewing window. Using ImageJ [ImageJ, 2008], the flight footage was examined at a frame-by-frame level to determine the repose angle measurements as well as to accurately calculate the rotation rates explored.

4 Flow Regime Comparisons

In the experiments detailed here, we found that the flow behavior of the lunar simulants was dependent on the drum rotation rate, ω, the geometry of the drum, the unique microstructure of each simulant and the effective gravitational acceleration acting on the particles. The primary parameters that were adjusted in this experiment are the rotation rate and the gravitational acceleration g_{eff}. The rotation rates were varied from $0.1 \leq \omega \leq 3.5$ RPM and the gravitational acceleration varied throughout the flight. Conducting experiments on both the ground and on the Zero-G plane allowed us to explore the repose behavior for the simulants at $g_{eff}/g_s = 1/6, 1.0$, and 2.0, where $g_s = 9.81 m/s^2$ is the surface gravitational acceleration for Earth.

We saw two types of repose behavior. As the drums turned at slower rotation rates we observed the “avalanching” regime. Here, the granular surface bed will build slowly to a maximum height, forming a steep angle designated by β. Any continued rotation of the drum will cause the heap to collapse to the lower angle, known as the relaxation angle (designated by α). The average surface angle is defined to be the average of the maximum and relaxation angles such that $\theta = (\alpha + \beta)/2$ [Brucks *et al.*, 2007]. As the drum is rotate at faster rotation rates we observe the “rolling” regime. The surface of the simulant will form a steady state heap slope angle as the material continually builds up and collapses. Here, the surface appears to remain flat however the transition between β and α is occurring so quickly it appears to have a continuous surface (as shown by θ). The relevant regimes in which we measured surface angles are shown in Fig. 7.

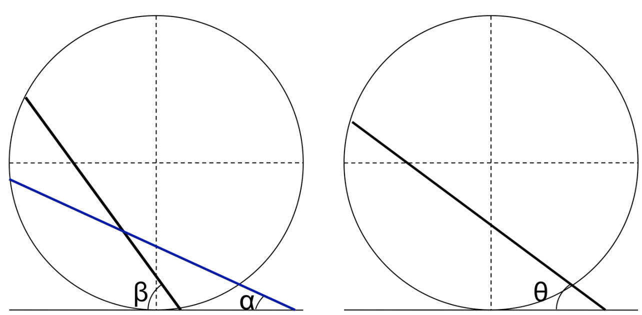

Figure 7: Surface angle regimes for lunar *mare* simulants. In the first regime, the simulant will build up to the maximum angle of stability β before collapsing to α, the relaxation static angle. In the second regime, the transition occurs so rapidly, the simulant maintains a constant flowing surface designated by θ.

More specifically:

1. For JSC-1A, $Fr < 10^{-3}$ corresponds to the avalanching behavior. The simulant GRC-3 demonstrates similar behavior for $Fr < 10^{-4}$. The lunar highlands only exhibited behavior in the avalanching regime. For both NU-LHT1 and OB-1, this slumping behavior was found for $Fr < 10^{-2}$.

2. JSC-1A: $10^{-3} < Fr < 10^{-1}$, GRC-3: $10^{-4} < Fr < 10^{-1}$ corresponds to the rolling motion detailed above.

3. $Fr > 10^{-1}$ corresponds to a regime in which centrifugal effects cause the surface of the simulant to have a continuously changing angle resulting in an S-shaped surface. We did not explore this regime in our experiments.

5 Surface Angle Measurements for the Lunar *Mare* and Highlands Simulants

In granular mechanics based literature, we found computer simulations that suggest $Fr^{1/2}$ is a robust scaling parameter for granular flow in heaping experiments such as ours. This holds true if the average grain size in the granular media d is much smaller than the drum radius R [Orpe *et al.*, 2001, Walton *et al.*, 2007]. In experiments where the condition $R >> d$ is not met, surface angles do not exhibit universal scaling with Fr [Walton *et al.*, 2007]. If the $Fr^{1/2}$ is a true scaling parameter, we should expect to see that all data collapses to a single scaling form, regardless of angular velocities and gravity levels. Each material would have its own scaling form depending on the microstructure.

5.1 Lunar *Mare* Simulants

We begin the analysis with the lunar *mare* simulants. From qualitative analysis, one can see that both simulants flow easily in our $1 - g$ environment. Orbitec manufactured JSC-1A is rather caky and has very fine particles. In fact, 50% of the particles have a diameter less than 20 microns [Orbitec, Inc.]. The GRC-3 simulant is markedly less cohesive than the JSC-1A. Visually, the simulant appears sandlike as one can see individual grains throughout the mixture.

We see a plausible scaling form for lunar *mare* simulant JSC-1A with respect to the parameter $Fr^{1/2}$. The data is suggestive, though ultimately non-conclusive due to the large uncertainties. The error bars represent the range between the critical stability angles, β and α. Granular flow is inherently unpredictable process and is particularly difficult to reproduce consistently in Regime 1. The flow of this lunar simulant is especially chaotic, making the measurement process particularly difficult. One may note a sparse collection of $1/6 - g$ data. Unfortuantely, the lunar parabolas offered a short window of available repose time. For many parabolas, there was not enough time for the transition between the critical stability

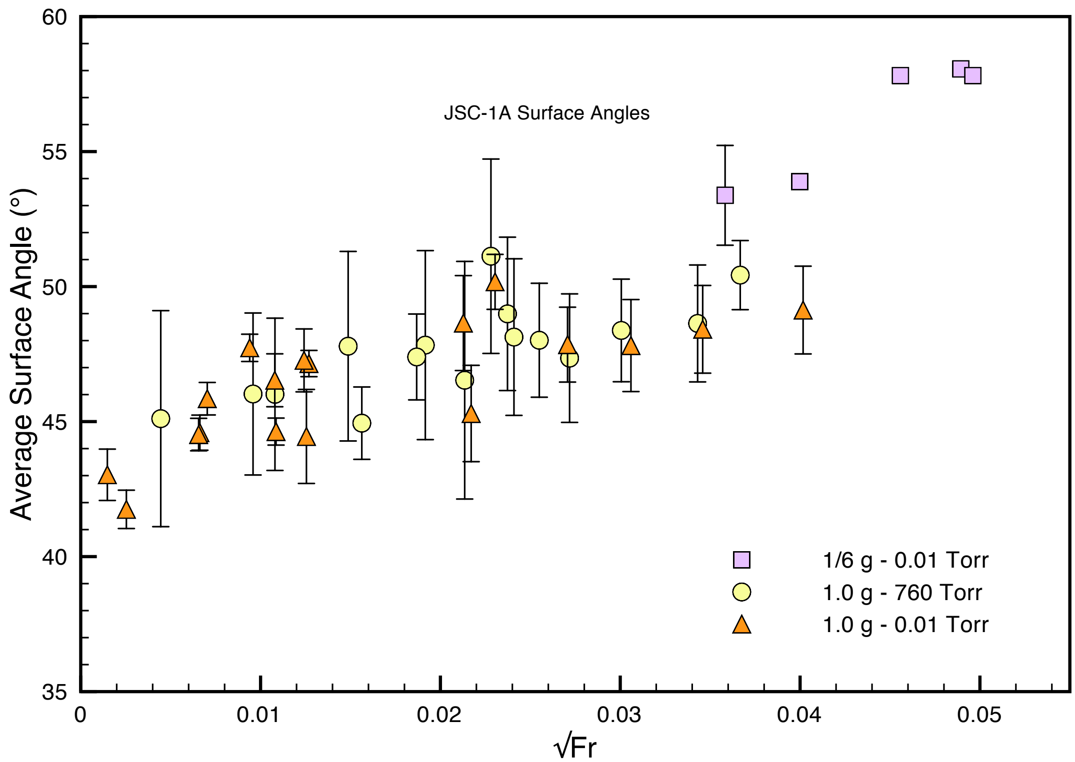

Figure 8: Measured surface angles for JSC-1A. Error bars indicate the upper and lower bounds of the measured angles. The top horizontal bars denote the average β measurements and the lower horizontal bars denote the average α measurement in each measurement set. Uncertainty for most lunar (1/6-g) data is not available because each data point represents only one or two angle measurements.

angles to occur. Lunar data is therefore limited to one or two surface angle measurements per Fr value.

We report the surface angle measurements for lunar *mare* simulant GRC-3 in Fig. 9. Again, there are uncertainties for the lunar data due to the few rotations and transitions available during each parabola. One noticeable difference between GRC-3 and JSC-1A is the more consistent and defined surface angle measurements. Because GRC-3 is much less cohesive, the repose behavior is similar at each collapse for a specific Froude number. The uncertainty in the data is therefore reduced in comparison to the average surface angle measurements of JSC-1A. One can see that the angles measured in the low - g environment are more chaotic and less defined than angles measured in the high - g trials for both *mare* simulants. This is consistent with the notion of microstructure being a determining factor for repose behavior [Dodds].

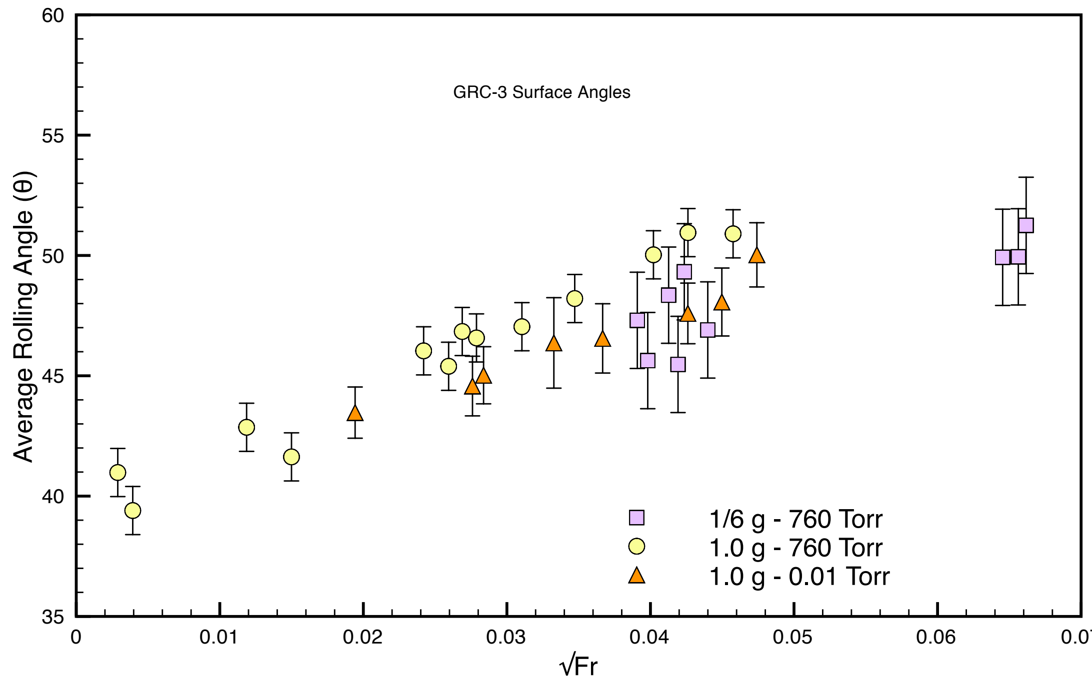

Figure 9: Measured surface angles for GRC-3. Error bars indicate the upper and lower bounds of the measured angles. The top horizontal bars denote the average β measurements and the lower horizontal bars denote the average α measurement in each measurement set..

5.2 Lunar Highlands Simulants

The lunar highlands simulants behaved much differently than the *mare* simulants. Visually, the highlands simulants are more cohesive and this became more apparent during the reduced gravity portions of our flight. For the lunar *mare* simulants, the distance between clumps of material was small such that the surface bed appears flat to the unaided human eye. The lunar highlands simulants have larger, wider clumps of material, which turned out to be problematic for the reduced gravity durations.

During the lunar parabolas, the simulants formed multiple large masses that stuck together. These large masses rolled along the inside wall of the drum and would tumble occasionally. No measurable repose behavior was observed. In ground testing, the simulants form less massive "chunks" that would sporadically roll down the surface, disrupting the flow beneath it. Though the simulants were less clumpy than in the 1/6-g durations, the unpredictable and repeatedly destructive behavior did not allow for repose measurements. Fortunately, the surface bed flattened out with the additional downward force during the 2 - g durations. The flow behavior changed to that of the described avalanching regime were we could measure a clear β and α for each collapse. This is in agreement with the experiments of Walton *et al.* where they found that the cohesiveness of a material varies with a change of gravity level, with the material appearing to be more cohesive as the effective gravity level decreases

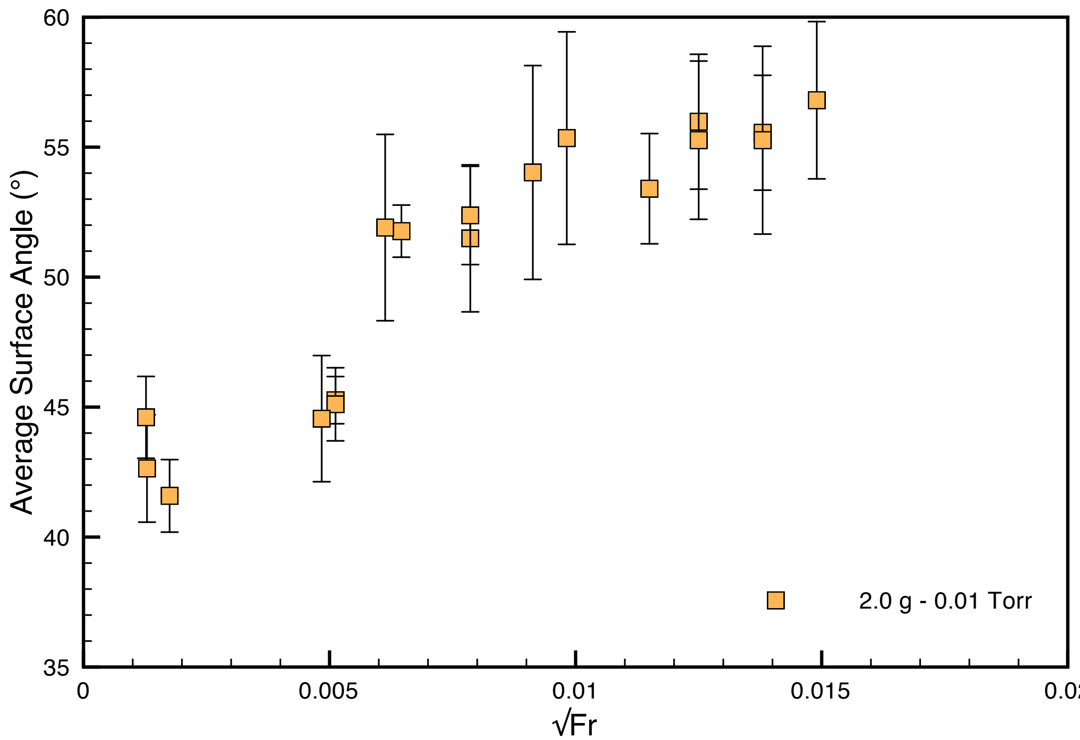

Figure 10: Measured surface angles for OB-1. Error bars indicate the upper and lower bounds of the measured angles. The top horizontal bars denote the average β measurements and the lower horizontal bars denote the average α measurement in each measurement set..

[Walton *et al.*, 2007].

Fig. 10 shows the surface angle measurements for lunar highlands simulant OB-1. Included in this graph is data solely from the 2 - g portions of the flight. Much like the data for JSC-1A, the data for OB-1 is suggestive for scaling with $Fr^{1/2}$ but the data is inconclusive due to the large deviations in the measurement sets. The added cohesion and heightened chaotic behavior added to the large discrepancies for each rotation rate.

The final simulant detailed in this thesis is lunar highland simulant NU-LHT1. Fig. 11 details the surface angle measurements for data taken in the 2 - g portions of the flight. The data set shows measurements of surface angles in a vacuum and at atmospheric pressure. Again, our data suggests that the affects of interstitial particles are minimal under the 10^{-2} Torr vacuum.

An interesting note is the sharp increase of surface angles seen in both the lunar highlands simulants in comparison to the lunar *mare* simulants. For the fairly cohesive simulant JSC-1A, the surface angles increase 15°as the $Fr^{1/2}$ increases from 0 to 0.05. The surface angles increase only 10°over the same range in Fr. In comparison, the surface angle measurements increase 15°as the $Fr^{1/2}$ only increases from 0 to 0.2. Highlands simulant OB-1 experiences

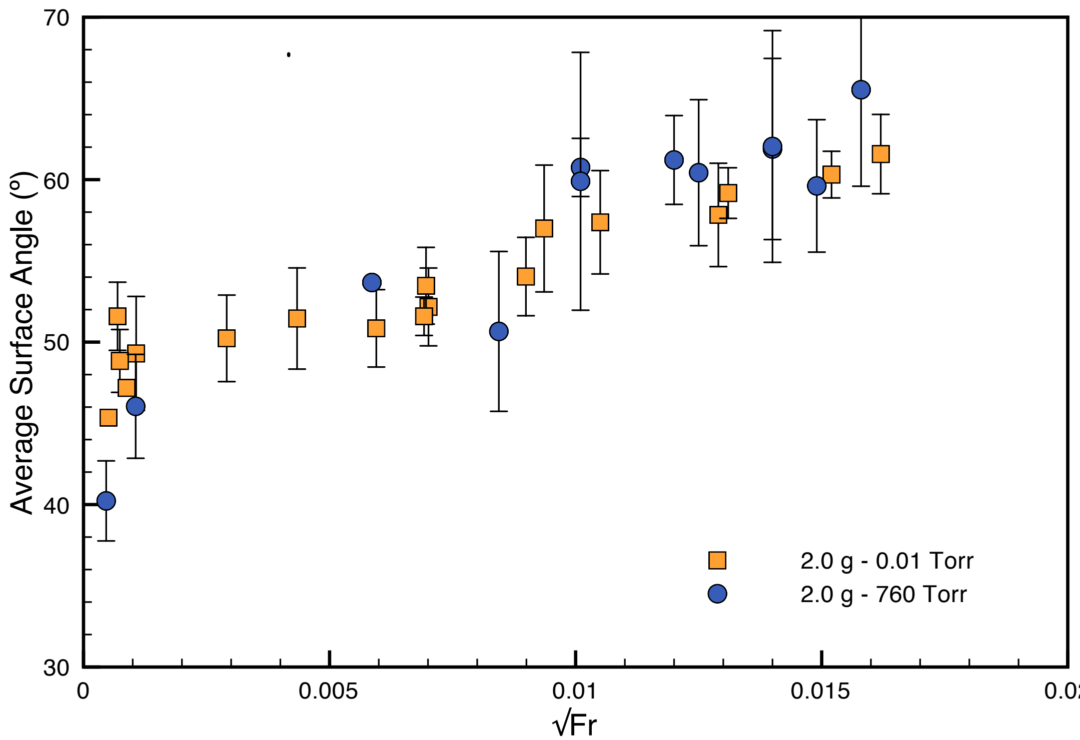

Figure 11: Measured surface angles for NU-LHT1. Error bars indicate the upper and lower bounds of the measured angles. The top horizontal bars denote the average β measurements and the lower horizontal bars denote the average α measurement in each measurement set.

a similar steep increase. It is interesting to see a direct correlation here with microstructure differences and the effects on the angles of repose. While our data from all four simulants is consistent with the scaling hypothesis, one would need more data sets to draw conclusive results.

The model of vertical, circular motion also proves to be interesting for our experiment. As $\frac{\omega^2 R}{g_{eff}}$ (the drum rotation rate) increases, we calculate that the $\cos(\theta)$ decreases. There is an apparent trend-line that passes through the data. Fig. 12 is a graph of repose behavior for lunar simulants NU-LHT1 and OB-1.

For both the lunar *mare* simulants and the lunar simulant NU-LHT1, our preliminary data suggests that the presence of interstitial atmospheric gasses did not significantly affect the repose behavior and stability. Although we did not achieve the perfect vacuum of the lunar surface, our trials were an indication of the independence of repose behavior from a partial vacuum of 10^{-2} Torr.

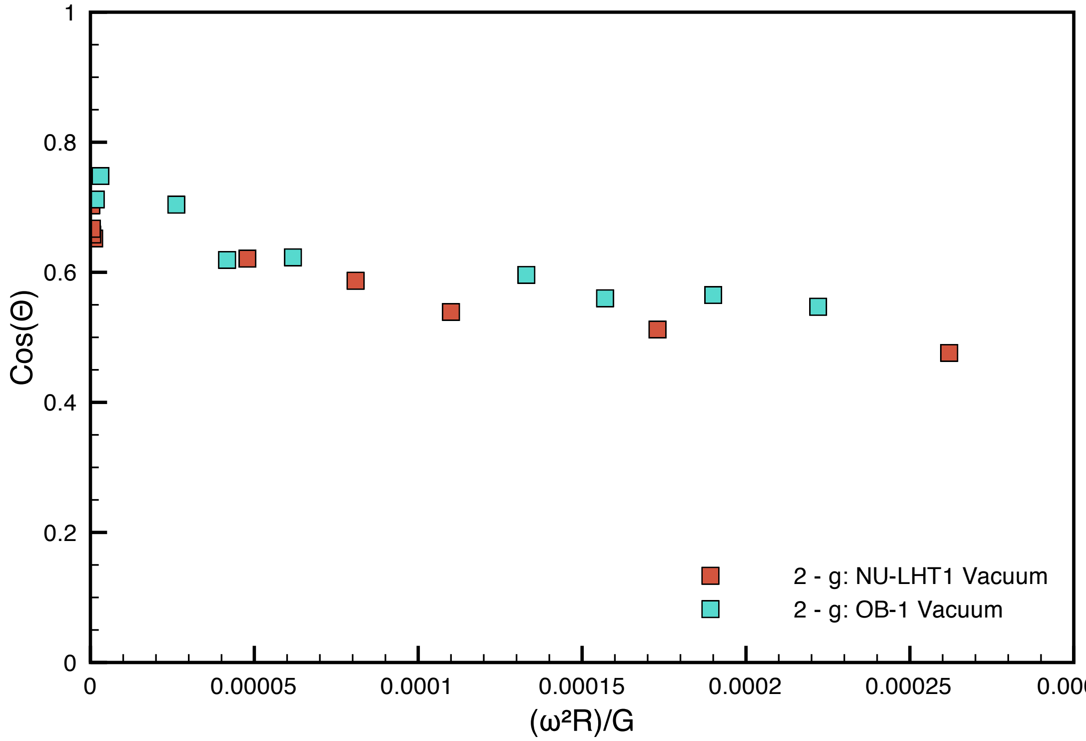

Figure 12: Measured surface angles for NU-LHT1 and OB-1. Plot of $\cos(\theta)$ to $\frac{\omega^2 R}{g_{eff}}$. No error bars are included in this graph but each angle measurement has uncertainties, much like in the previous graphs.

6 Conclusion

We have examined the repose behavior of two lunar *mare* simulants under both standard atmospheric and vacuum conditions at 1/6, 1.0, and 2.0 g and two lunar highlands simulants under both standard atmospheric and vacuum conditions at 2.0 g. We find that the repose behavior can be characterized by the Froude Number $Fr = \omega^2 R/g_{eff}$. Three flow regimes, avalanching, cascading, and centrifuging were observed. For JSC-1A, the critical transition between Regimes 1 and 2 occurs at $Fr \approx 10^{-3}$. For GRC-3, a much less cohesive simulant than JSC-1A, regime transition occurs at $Fr \approx 10^{-4}$, so that almost all measurements of GRC-3 take place in Regime 2. For both OB-1 and NU-LHT1, two extremely cohesive simulants, we saw that all surface angles in 2.0 g_s occurred at $Fr \approx 10^{-3}$ and all measurements of NU-LHT1 and OB-1 were in Regime 1.

Surface angle measurements were made in the avalanching and cascading regimes. We find no significant difference in surface angle behavior with ambient gas pressure in the range $10^{-2} - 10^{3}$ Torr. This is contrary to the hypothesis that interstitial gasses effect the cohesion between granular particles which would then raise or lower the measured repose angle of the heap over its vacuum value.

While our data is consistent with the scaling hypothesis $\theta \propto \sqrt{Fr}$, the data is clearly incomplete with respect to a final decision on the validity of the scaling hypothesis. For now, the scaling hypothesis remains an intriguing interpretation for the prediction of repose behavior in variable gravity. If this relationship was fully defined, the scaling parameter would prove useful to estimate the repose behavior of a granular material under arbitrary gravitational acceleration. This information would influence design properties for lunar excavation and exploration technologies such as excavators, hoppers, and structure design. In addition, repose information would help planetary geologists understand geological features on both the moon and Mars.

7 Future Directions

If one were to continue in this research, possible alterations to the current experimental rig could allow for more data. The drum diameter size is sufficient for the lunar *mare* simulants and repose data was taken under variable gravity conditions. For the lunar highlands simulants, we were unfortunately only able to study the $2-g$ portions of the flight as the diameter prohibited repose behavior in reduced gravity. One future change would be to purchase drums of a larger diameter to allow for full repose behavior.

If this alteration proves to be too difficult or expensive, one could switch focus from studying the dynamic angles of repose to examining the static angles of repose. Though we have seen that the static angles of repose have substantial variations between each measurement, a test with many trials could be insightful to repose behavior.

Given the potential for repose measurements of lunar simulants, it is important to obtain statistically significant data for surface angles under variable gravity. Further flight and ground data is needed to reduce the uncertainty in angle measurements, and allow the scaling hypothesis to be fully tested.

8 Acknowledgments

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References

[Castellanos *et al.*, 2001] Castellanos, A., Sanchez, M.A., and Valverde, J.M., The onset of fluidization of fine powders in rotating drums *Mater. Phys. Mech.*, **3**.

[Brucks *et al.*, 2007] Brucks, A., Arndt, T., Ottino, J., and Lueptow, R., Behavior of flowing granular materials under variable g., *Physical Review* **75**.

[Walton *et al.*, 2007] Walton, O., De Moor, C. P., and Gill, K. S., Effects of gravity on cohesive behavior of fine powders: implications for processing Lunar regolith *Granular Matter* **9**.

[Klein *et al.*, 1990] Klein, S. P., and White, B.R., Dynamic shear of granular material under variable gravity conditions AIAA Ann. **28**.

[Williams *et al.*, 2007] Williams, R., Shoa, R., Overfelt, R., The flowability of fine powders in reduced gravity conditions. Granular Matter(2008). **139-144**.

[Orpe *et al.*, 2001] Orpe, A. and Khakhar, D. V., Scaling relations for granular flow in quasi-two-dimensional rotating cylinders *Phys. Rev. E*, **64**.

[Orbitec, Inc.] JSC-1AF lunar regolith dust simulant manufactured by Orbitec, Inc. and provided by Juan Agui, NASA Glenn Research Center.

[Alberts *et al.*] Albert, R., Albert, I., Hornbaker, D., Schiffer, P., and Barabsi, A., Maximum angle of stability in wet and dry spherical media., *Physical Review* **56**.

[Forsyth *et al.*] Forsyth, A. J., S. R. Hutton, M. J. Rhodes, and C. F. Osborne. Effect of applied interparticle force on the static and dynamic angles of repose of spherical granular material. *Physical Review* **63**.

[Nowak] Nowak, S., Investigating the Angle of Repose and Maximum Stability of a Cohesive Granular Pile., *Thesis - Massachusetts Institute of Technology* June 2004.

[Dodds] Dodds, J., Particle Shape and Stiffness - Effects on Soil Behavior., *Thesis - Georgia Institute of Technology* November 2003.

[LEAG, 1990] Lunar and Mars Exploration Program Office, Developing a Site Selection Strategy for a Lunar Outpost, http://www.lpi.usra.edu

[ImageJ, 2008] Image Analysis Software in Java, http://rsbweb.nih.gov/ij/

[RhapSoft, 2009] Image Editing Software for Mac, http://www.livequartz.com/

[Final Cut 7, 2009] Video Editing Software for Mac, http://www.apple.com/