Repose Angles of Lunar Mare Simulants in Microgravity

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Abstract

Repose angles for lunar *mare* simulants were measured in rotating drum experiments aboard NASA's microgravity aircraft, *Weightless Wonder*. We measured both the maximum critical angle of stability and the static angle of repose for simulants JSC-1A and GRC-3 as a function of drum rotation rate. These measurements were conducted under vacuum to simulate conditions of the $1/6 - g$ lunar environment, and under standard atmospheric pressure to examine the effects of interstitial gasses on inter-particle cohesivity. We find no detectable difference in repose behavior between simulant flow at standard atmosphere and flow in a low pressure environment of 10^{-2} Torr. We further investigate a plausible scaling relationship for the dependence of repose angles on effective gravitational acceleration. 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.

Introduction

Lunar regolith is an unconsolidated aggregation of rock, mineral, and glass that extends from the lunar surface to depths ranging from centimeters to several hundred meters. Regolith in the *mare* regions of the moon is several meters thick on average, while the older highland regions have average regolith depths on the order of 10 m. Grain size in the regolith ranges from sub-micron particles near the surface, to larger, millimeter sized grains below the surface. The lunar regolith on the lit side of the Moon is subject to continual ultraviolet radiation and micrometeoroid bombardment. These processes have dramatically influenced the morphology and chemical structure of the surface regolith, leaving the lunar surface with a significant electrostatic charge, a rough, jagged microstructure, and high surface energy. As such, lunar regolith represents a unique and important granular material whose properties are little understood. In the experiments reported here, we consider one particular property of the lunar regolith relevant to engineering processes that may one day take place on the Moon.

The angle of repose of a granular material refers to the maximum angle (as measured from the horizontal) at which the material will form a stable heap. In practice, two angles of repose are commonly defined. The dynamic angle of repose measures the steady state heap slope angle obtained while the heap grows by continuous deposition. The static angle of repose measures the angle achieved by the surface of a static pile relaxing after an avalanche event.

The angles of repose characterize critical flow properties of granular materials. In particular, knowledge of repose angles is essential in establishing processes and guidelines for excavation depths and other engineering constraints on soil processing. However, neither the static nor the dynamic angle of repose is a fundamental material property. Instead these angles depend on 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 *In Situ* Resource Utilization (ISRU) applications is a measurement of dynamic repose angles of realistic lunar regolith simulants under vacuum conditions at $1/6-g$.

We report here the results of an experiment to measure the range of repose angles for lunar mare soil simulants under variable gravitational forces and under vacuum conditions of near mTorr pressures as well as standard atmospheric pressure and temperature (STP). Gravity plays an integral role in granular flows and in the thermodynamics of granular media. Finding a relationship between gravity level and the angles of repose is an important step in establishing protocols and design specifications for civil engineering processes on the Moon. The angles of repose are key parameters in the characterization of the stability of heaps and piles, and their values in the vacuum and reduced gravity of the lunar environment are currently unknown for most materials including lunar regolith simulants.

Sustained periods of microgravity are made possible by parabolic flights that offer variable gravitational levels for periods of up to thirty seconds. Our experiments were conducted on NASA's *W*eightless Wonder parabolic aircraft at Johnson Space Center, and made possible by the NASA Systems Engineering Educational Discovery (SEED) program.

Overview and Background

Dynamic angles of repose are most accurately determined using a rotating drum apparatus. In these experiments the material of interest is slowly rotated in a drum which is outfitted with a clear window for observing the granular flow. The drum is rotated around its principal symmetry axis at a rotation rate ω. Over a range of angular velocities, the granular material will exhibit constant-angle flow as surface particles at the top of the heap slide down the heap, mix into the contact layer with the rotating wall, and are brought back up to the top by the rotating wall. By varying the rotation rate, the range of stable repose angles can be explored. The minimum and maximum angles obtained in this fashion are related to the static and dynamic repose angles of interest in engineering applications.

Prior studies using a rotating drum-type apparatus have examined the influence of inter-particle forces on repose behavior in model granular materials [Forsythe *et al.*, 2001]. These 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 is important to the extent that lunar soils exhibit strong inter- particle forces due to their intrinsic charge from UV bombardment. Interstitial atmospheric gasses may serve to moderate inter-particle cohesive forces, potentially making measurements under standard atmospheric conditions less reliable as a predictor of flow behavior in the lunar environment.

Other studies have examined fine powders whose flow properties might be more similar to lunar soils. Castellanos *et al.* studied the fluidized layer in fine powder flows in a rotating drum at the repose angle [Castellanos *et al.*, 2001]. This work was also performed under constant $1 - g$, STP conditions. We have used the results of the Castellanos work to estimate the flow properties and design specifications for the experiment proposed here.

Recently, investigators have studied repose behavior in rotating drum experiments under both hyper- and reduced-gravity conditions. Brucks *et al.* examined the flow behavior of particles under effective gravitational accelerations between $1 - g$ and $25 - g$ [Brucks *et al.*, 2007] under STP conditions. Their results were consistent with the work done by Klein and White on model granular materials under reduced gravity [Klein *et al.*, 1990].

In the analysis of Ref. [Brucks *et al.*, 2007], in which repose behavior under hyper-gravity was studied, a phase diagram of flow behavior was obtained that appears to have universal applicability to repose measurements. Specifically, one can define the dimensionless Froude Number as the ratio of the centrifugal force acting on particles in the rotating drum to the effective gravitational force acting on the particles:

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

where 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. Values of $Fr \approx 10^{-4}$ result in repose behavior across the range of g_{eff} explored in the work of Brucks *et al.*

Regolith Simulants

In the experiments reported here, two well-characterized lunar regolith simulants are used. JSC-1A, manufactured by Orbitec, Inc. [Orbitec, Inc.], is a dark, bulk *mare* simulant with grain sizes $\leq$ 1mm. Production of GRC-3 was commissioned by NASA's Glenn Research Center to simulate the geomechanical properties of lunar *mare* samples returned during the Apollo missions. GRC-3 is less cohesive than JSC-1A, and has a larger average grain size.

Experiment Design

The experiment consisted of three rotating drums mounted to a flight rig as illustrated in Fig. 1. Each drum was partially filled with a lunar regolith simulant and had its principal symmetry axis perpendicular to local gravity. Three video cameras, each centered on a drum viewing window, recorded the drums as they rotated. The rotation rates were adjusted using pulse-width modulation (PWM) controllers that allow precise control of rotation rates. To obtain repose behavior in our experiment under lunar gravity conditions, we have designed PWM-controlled, geared motor systems to drive the simulant drums in the 0.1-3.5 RPM regime.

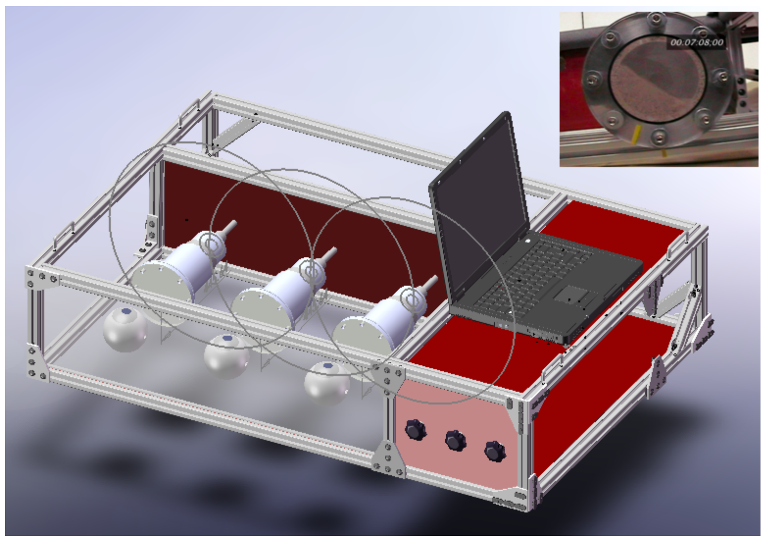

Figure 1: Experimental rig schematic and close-up of a simulant drum loaded with GRC-3 at a 30% fill. Each of the three drums has a video camera aligned with the drum view window to record simulant flow. The drums have vacuum flanged fittings and can be mounted to a diffusion pump for low pressure investigations.

Each drum is 5.5” in length with a 3.5” inner diameter. The drums are milled from 6061 T6 aluminum and each has a flange-mounted polycarbonate viewing window sealed by an O-ring and bolted circumferentially to one face of the drum. The drums were filled to 30% by volume with lunar soil simulants. Each drum contained one of two different lunar simulants, allowing us to make comparative measurements of repose angles in two different media under various pressure conditions. On the first flight day, JSC-1A and GRC-3 were under vacuum and the third drum contained GRC-3 at atmospheric pressure. Unfortunately, a pressure leak on one drum rendered vacuum data for GRC-3 unusable.

For experiments on the second flight day, the first and second drums contained the lunar highlands simulants OB-1 and NU-LHT1. The third drum was once again under atmospheric pressure and filled with NU-LHT1. These simulants proved to be extremely cohesive, complicating the analysis of repose behavior. Analysis of the data from these simulants is ongoing and will not be discussed in this report.

For experiments under vacuum, the drums were baked and pumped down prior to the flight using a diffusion pump, particle trap, and sub-micron particle filter. Pre-flight pressure measurements indicate that starting pressures were in the range of 10^{-3} – 10^{-2} Torr. We had hoped to achieve mTorr pressures, but trapped gasses within the simulant material made reductions in pressure below 10^{-2} Torr difficult to achieve. The drums retained sufficient vacuum for the duration of the flight. Given the small size of the drums, accurate, post-flight pressure measurements were not possible, but we estimate a diffusion rate of less than 0.5 micron (0.5 mTorr) per minute.

Before the drums began to rotate, the simulant media lay flat in the drums due to the force of gravity. As the drums began to rotate at a very low rotation rate, the simulant began to move with the drum. At a critical value of the rotation rate, the simulant achieved a constant, non-zero slope with respect to the horizontal. The rotation rate of each drum was adjusted to achieve the range of repose angles as functions of rotation rate. Target rotation rates were calculated using the Froude number and the phase diagram developed in [Brucks *et al.*, 2007].

Three mini-DV cameras were aligned with the viewing windows of the drums for recording the motion of the simulants in the drums. The video from each camera was analyzed after the flights using the software package imageJ [ImageJ, 2008]. The software permits a frame-by-frame analysis of the video stream including surface angle measurements and rotation rate determinations. We anticipated that the 180 measurements (thirty parabolas × two flights × three cameras) would be sufficient to provide statistically useful results given our experimental protocol. An accelerometer mounted to the rig provided time- coded information about local acceleration for use in synchronizing with the video from the cameras.

Video footage from the parabolas was correlated with accelerometer data to provide effective gravity vectors for each parabola. These vectors define the surface planes from which flow angles were measured in the drums. The accelerometer data is necessary because the flight trajectories do not always produce effective gravitational accelerations normal to the flight deck.

Technical Results

Our analysis of the flight data can be broadly divided into phenomenological observations concerning flow regimes and quantitative measurements of surface angle behavior as a function of Fr.

Phenomenology of Flow Regimes

The behavior of the flowing granular media is a function of the rotation rate of the drum, the geometry of the drum, the effective gravitational acceleration acting on the drum, and the microstructure of the material. The primary experimental parameters in our studies are the drum rotation rate ω and the effective gravitational acceleration g_{eff}. Different microstructures are examined by studying a relatively cohesive simulant (JSC-1A) and a less cohesive simulant (GRC-3). The drum rotation rates can be varied over the range $0.1 \leq \omega \leq 3.5$ RPM. By conducting experiments on the ground and in the *Weightless Wonder*, we explored repose behavior for both 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.

In general, we find that flow regimes for each simulant are well characterized by the Froude Number Fr (Eq. 1). We have identified three flow regimes in our ground and flight data.

1. For JSC-1A, $Fr < 10^{-3}$ corresponds to an avalanching motion in which the surface angle of the simulant builds up to the maximum angle of stability, β and then collapses to a smaller value deemed the static repose angle, α through avalanching. The simulant GRC-3 demonstrates similar behavior for $Fr < 10^{-4}$.
2. JSC-1A: $10^{-3} < Fr < 10^{-1}$, GRC-3: $10^{-4} < Fr < 10^{-1}$ corresponds to rolling motion in which the surface angle of the simulant reaches a constant value which is identified as the dynamic angle of repose, θ.
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.

The relevant surface angles measured in our experiments are shown in Fig. 2.

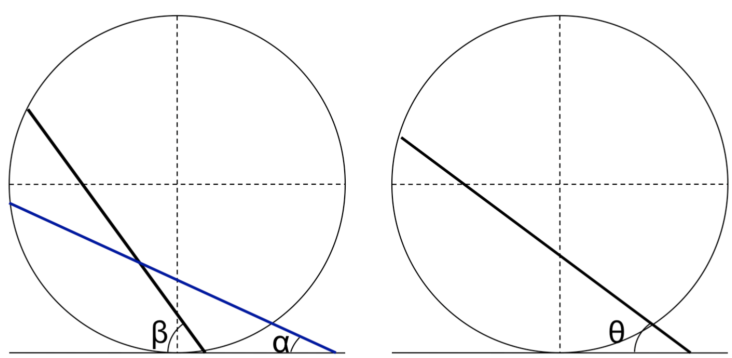

Figure 2: Surface angles measured in the the experiments. In regime 1, heap angle increases until the heap reaches the maximum stability angle β before collapsing to the static repose angle α. In regime 2, drum rotation rates are sufficient to keep the surface flowing freely at constant repose angle θ.

Surface Angle Measurements of JSC-1A and GRC-3

While no theoretical basis for a scaling hypothesis is known to the authors, computer simulations of granular flow in heaping experiments suggest that $Fr^{1/2}$ is a robust scaling parameter for the surface angle when 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].

In the experiments considered here, the $R >> d$ criterion is satisfied. We anticipate that, if $Fr^{1/2}$ is a true scaling parameter, we should expect that all surface-angle data for a given material at a fixed gas pressure should collapse onto a single scaling form for all gravity levels and angular velocities. In Fig. 3, measured surface angles for JSC-1A are plotted against the scaling parameter $Fr^{1/2}$. The data includes all $1-g$ experiments, a limited number of $1/6-g$ experiments, and $2-g$ measurements. The $2-g$ measurements were obtained from the parabolic flights during the ascent portions immediately following the microgravity descent portions of the flights. Reported surface angles for $Fr < 10^{-3}$ are obtained by averaging the critical stability angle β and the static repose angle α: $\theta = (\alpha + \beta)/2$ [Liu *et al.*, 2005].

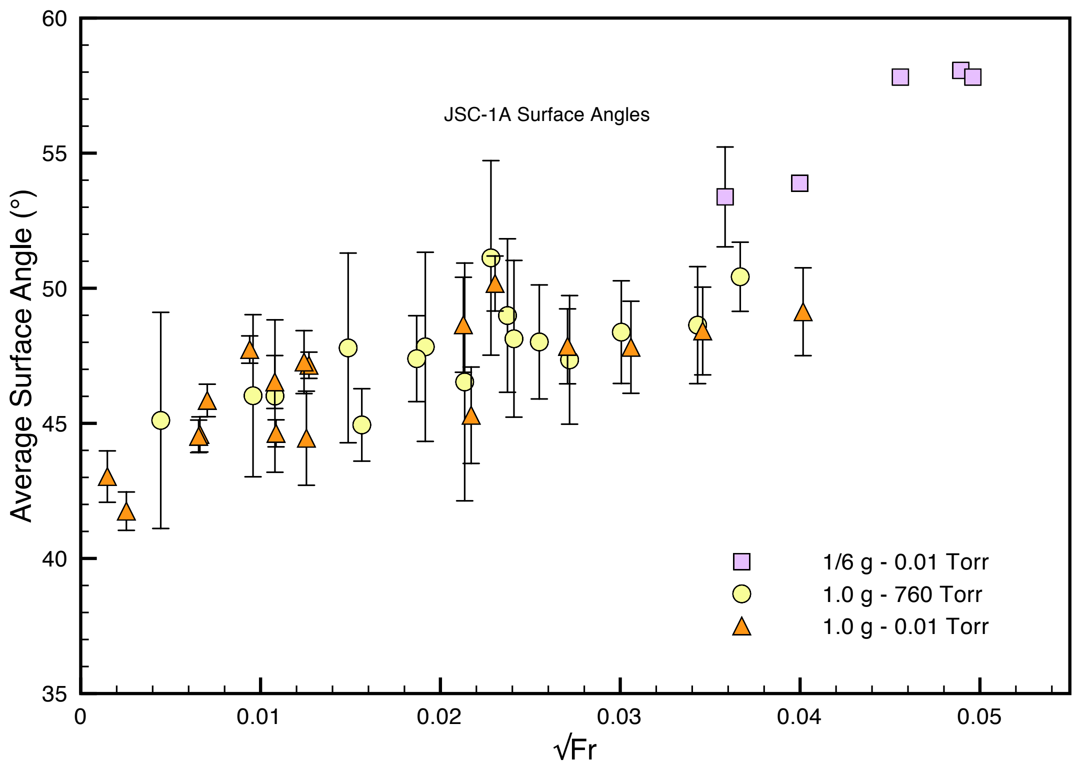

Figure 3: Measured surface angles for JSC-1A. Error bars indicate variance in the measurement sets. Uncertainty for most lunar ($1/6-g$) data is not available because each data point represents only one or two angle measurements.

Our JSC-1A data is suggestive of this scaling hypothesis, but given the large uncertainties in the measurement of surface angles, is ultimately non-conclusive with regard to scaling. Granular flow is an inherently chaotic process and is particularly difficult to reproduce consistently in Regime 1. For this reason, each data point in Fig. 3 has a large statistical uncertainty associated with it represented by the error bars. Each error bar is the variance of the measurement over five or more measurements for the $1 - g$ data. Estimating uncertainties in lunar data is difficult due to the short time available for each measurement at $1/6 - g$. Lunar data is typically limited to one or two surface angle measurements per Fr value.

Fig. 4 shows the surface angle measurements for GRC-3. Again, uncertainties for lunar data are quite large given the relatively few rotations available at each rotation rate. The GRC-3 simulant is markedly less cohesive than the JSC-1A. The relatively low cohesivity results in more consistent and well-defined surfaces. The uncertainty in the data is thereby reduced relative to the surface angle measurements for JSC-1A. From the preliminary data including apparent trends in the $1 - g$ and $1/6 - g$ data in Fig. 4, we conclude that universal scaling with $\sqrt{Fr}$ is plausible. While our data is consistent with the hypothesis, more data is necessary to draw conclusive results.

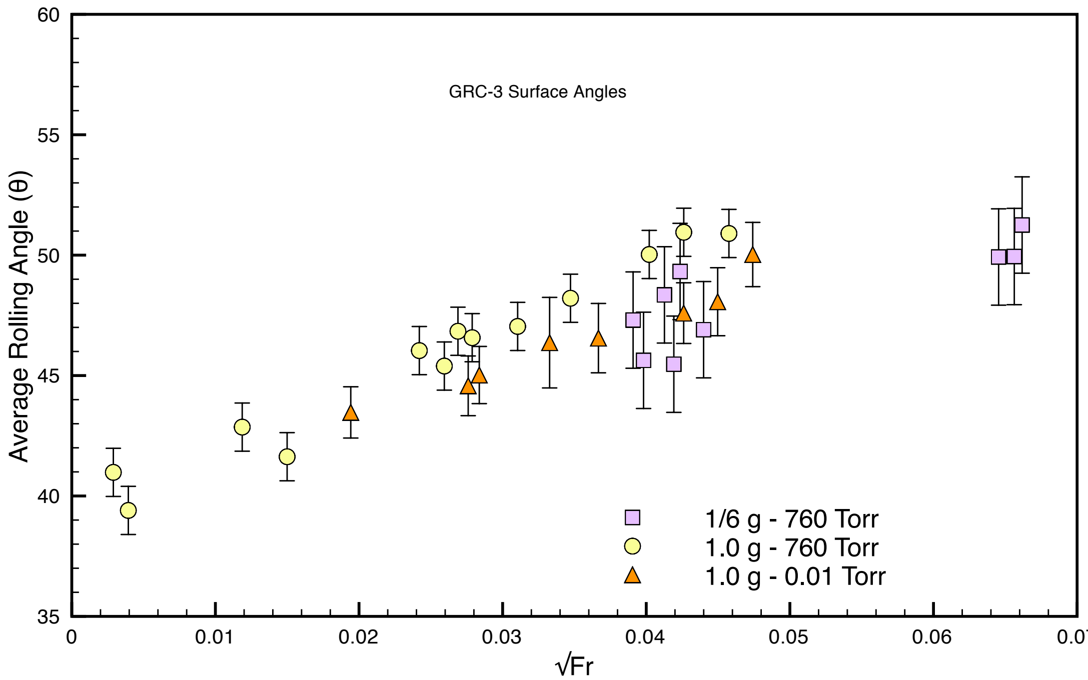

Figure 4: Measured surface angles for GRC-3. Error bars indicate variance in the measurement sets.

Data for both simulants suggests that the presence of atmospheric gasses does not significantly affect the stability of heaps. While our experiments did not achieve the near perfect vacuum of the lunar surface, the independence of repose angle on pressure down to 10^{-2} Torr suggests that future experiments can reliably be carried out under atmospheric conditions.

Conclusions

We have examined the repose behavior of two bulk lunar *mare* simulants under both standard atmospheric and vacuum conditions at 1/6, 1.0, and 2.0 g_s. We find that surface flow is characterized by the Froude Number $Fr = \omega^2 R/g_{eff}$. Three flow regimes, avalanching, cascading, and centrifuging were observed with transitions between regimes occurring at fixed values of Fr that is material dependent. 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.

Surface angle measurements were made in the avalanching and cascading regimes. We find no detectable difference in surface angle behavior with ambient gas pressure in the range $10^{-2} - 10^{3}$ Torr. This is contrary to the hypothesis that ambient gasses mediate (or moderate) a cohesive interaction between grain particles that raises (or lowers) the effective 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 definitively addressing the validity of the scaling hypothesis. The scaling hypothesis remains an intriguing possible interpretation for repose behavior under variable gravity. If such a relation was statistically tenable, it would provide useful estimates of repose angles under arbitrary gravitational acceleration. Such data will inform the design of a variety of lunar exploration technologies including hoppers, excavators, and structures. Further, reliable estimates of repose angles for Martian soils under appropriate gravitational and pressure conditions would be of great utility in understanding geological surface features on Mars.

Given the potential for such measurements, 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.

Acknowledgments

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