Scaling Relations for Repose Angles of Lunar Mare Simulants

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Repose angles for lunar *mare* simulants were measured in rotating drum experiments during parabolic flight maneuvers. A range of flow behaviors from cascading through rolling was obtained under both vacuum and standard atmospheric pressures. Flow phenomenology is correlated with a Froude Number, and we obtain critical Froude Numbers demarcating the different flow regimes in analogy to studies performed on model granular materials in 1-g. Finally, a scaling relationship for repose angles of the form $\theta \propto \sqrt{\omega^2/g_{eff}}$ is obtained from experimental data over variations in effective gravity level g_{eff}, and drum rotation rate ω.

Introduction Measurements of repose angles in granular materials are notoriously sensitive to experimental methodology. In particular, the drained and poured angles of pile-based measurements are dependent on experimental design and technique. A reasonably well-controlled proxy measurement for these angles is the *dynamic* angle of repose obtained in rotating drum experiments. The drum containing simulant media rotates horizontally around its principal symmetry axis at a rotation rate ω. By varying the rotation rate, the range of stable repose angles can be explored.

Scaling Hypothesis When the ratio of average particle size d to drum radius R satisfies $d/R << 1$, results of drum experiments are not sensitive to particle size or drum geometry. Flow behavior for a given material satisfying $d/R << 1$ is determined primarily by the Froude Number, $Fr = \omega^2 R/g_{eff}$.

A scaling hypothesis for dynamic repose angles in drum experiments was first proposed in the work of Klein and White[1]. Repose angles measured under variable gravity were shown to scale with $\theta \propto g_{eff}^{-1/2}$ at constant rotation rate. Subsequent work under hyper-gravity conditions have suggested that the appropriate scaling parameter is $Fr^{1/2}$ [2].

Much of the prior work directed at investigating scaling forms for repose angles has been carried out using model granular materials with mono-disperse particle sizes. The experiments reported here make use of well-characterized lunar regolith simulants JSC-1A and GRC-3, and so may provide more relevant engineering constraints on repose behavior of lunar regolith materials.

Results In Fig. 1, measured surface angles for JSC-1A and GRC-3 are plotted against the scaling parameter $Fr^{1/2}$.

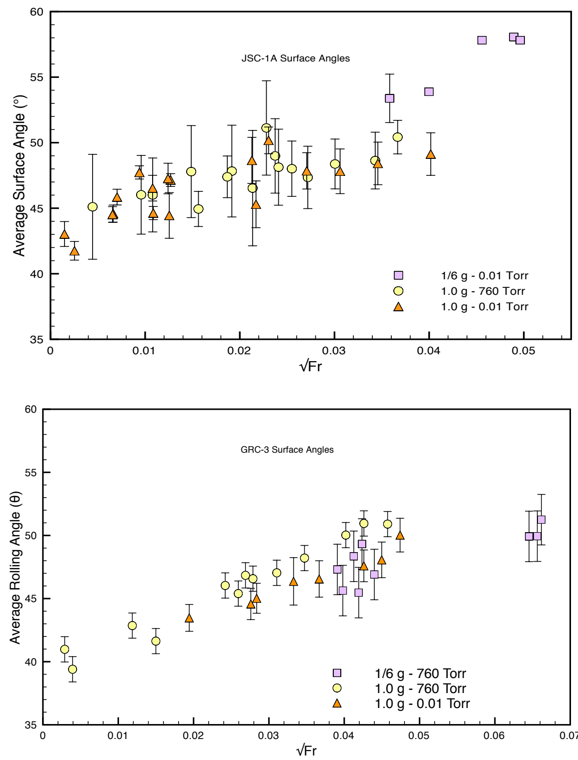

Figure 1: Measured surface angles for JSC-1A and GRC-3. Error bars indicate variance in the measurement sets. Uncertainty for some lunar $(1/6 - g)$ data is not available because each data point represents only one or two angle measurements.

Discussion 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. 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 are material dependent. 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.

References

[1] Klein, S. P., and White, B.R., Dynamic shear of granular material under variable gravity conditions AIAA Ann. **28** (1991).

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