Dynamic Shear of Granular Material Under Variable Gravity Conditions

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Abstract

THE purpose of this synoptic is to describe some simple experiments with granular materials that have been recently conducted on the NASA KC-135 aircraft during variable-gravity maneuvers. A small drum containing granular material was slowly rotated while the angle assumed by the slip surface was photographically recorded. Conventional wisdom has held that this "dynamic angle of repose" is a material constant, independent of gravitational level. The results presented here are contrary, suggesting instead an angle that varies with the reciprocal of the square root of gravity. This finding may have important consequences on the understanding of the particle physics of many active granular processes occurring in nonterrestrial gravity and may provide qualitative confirmation of some of the theoretical predictions of modern models of granular shear flows.

Contents

This work focused on the "dynamic" or "rapid-flow" regime of granular deformation, usually characterized by high shear rates. The objective of this study was to determine with simple experiments the effects of gravity on such granular flow. Of particular interest was whether change in a material's angle of repose could be detected with variation in the level of gravity.

Angles of Repose

It has generally been assumed that the angle of repose is a bulk material constant, probably controlled in some way by a variety of particle properties such as shape, roughness, size, cohesion, and resilience. The method of measurement chosen for this study was the partially filled rotating drum described by Franklin and Johanson.[1] The angle that the continuously downward-cascading material makes with the horizontal is often called the "dynamic angle of repose" or "kinetic angle of repose" and is usually several degrees less than the "static angle of repose."

In the rotating drum, the bulk of the material moves in solid-body rotation upward with the drum wall while a layer of rapidly shearing material moves downward along the chordal free surface. The stress ratio T_{xy}/T_{yy} within a shearing layer, referred to as the "dynamic friction coefficient," is closely related to the dynamic angle of repose. There are important distinctions to be made between the dynamic friction coefficient (within the shearing material) and the "critical dynamic friction coefficient" (at the interface between flowing and nonflowing material). Hanes and Inman[2] discuss these matters. In this study it has been assumed that factors that affect the dynamic friction coefficient or the critical dynamic friction coefficient will in a qualitatively similar way affect the dynamic angle of repose.

The classic work by Bagnold[3] suggests that for rapid shear flows the stress ratio should be independent of gravity even if changes in gravity cause variations in N, the volume concentration, or dU/dy, the shear rate.

Modern kinetic-theory models and discrete-particle computer models, such as those discussed by Walton and Braun,[4] predict a slightly altered picture. In these models, the stress ratio is found to depend considerably on the particle coefficient of restitution, e, on the particle coefficient of friction, f, to a lesser extent on N, and negligibly on shear rate. Low volume concentrations are predicted to produce slightly higher dynamic friction coefficients. Experimental endorsement of this theoretical effect has been supplied by the annular shear cell work of Hanes and Inman, who report a tendency toward higher shear/normal stress ratios with lower volume concentrations.

These modern findings suggest that the dynamic angle of repose may vary with gravity, but only if the changes in gravity are accompanied by changes in the interparticle coefficient of restitution, the coefficient of friction, or the volume concentration. Changes in the coefficient of restitution seem quite unlikely. Changes in the other two are discussed later.

Dimensional analysis has isolated an important similarity parameter:

$$G = g\left[(\rho_p - \rho)/\mu w^3\right]^{1/2} \tag{1}$$

where g is the gravitational acceleration, ρ_p the particle density, ρ the density of the interstitial fluid, μ the viscosity of the interstitial fluid, and w the rotation rate of the drum. With regard to the present study, the important variation suggested by Eq. (1) is the ratio g^2/w^3.

Experiment

The two granular materials chosen for this study were #0/30 Monterey sand (mean diam = 0.40 mm), and closely graded (#16–#14) glass beads (mean diam = 1.35 mm). The apparatus consisted of 22-cm-diameter by 10-cm-long drums that were belt-driven by a variable-speed electric motor. Rotation was about the horizontal axis. The inside surface of each drum was coated with grains of the test material to insure the no-slip condition. Experiments were conducted at rotation rates of near 3 rpm for the Monterey sand and near 6 rpm for the glass beads. These speeds produced a nearly steady, planar down-sloping surface in each case. The drums had transparent ends, allowing continuous photographic recording of the experimental variables. The angle of repose, α, was measured midchord at the surface and with respect to a line perpendicular to the indicated vertical. The gravity level was indicated by a digital accelerometer mounted next to the drum. The chord length was used to calculate the occupied volume, and from that, the mean volume concentration.

Presented as Paper 88-0648 at the AIAA 26th Aerospace Sciences Meeting, Reno, NV, Jan. 11–14, 1988; received Feb. 18, 1988; synoptic received Dec. 27, 1988. Full paper available at AIAA Library, 555 W. 57th St., New York, NY 10019. Price: microfiche, $4.00; hard copy, $9.00. **Remittance must accompany order.**

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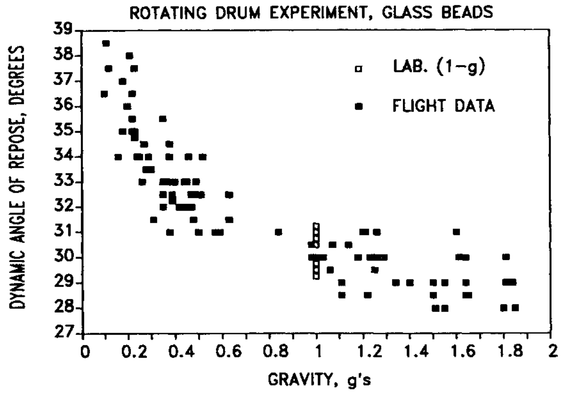

Fig. 1 The results of the rotating drum experiment using glass beads. Nominal drum rotation speed is 6.75 rpm.

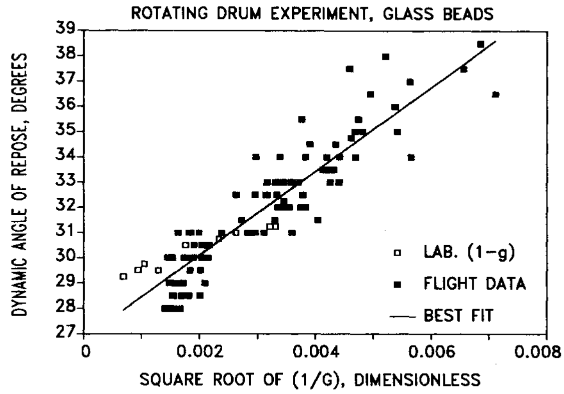

Fig. 2 The results for glass beads plotted as a function of the reciprocal of the square root of the dimensionless parameter G. The best fit line is shown. Regression $R^2 = 0.845$.

The reduced gravity environment was created aboard NASA's Johnson Space Center KC-135 "weightless" aircraft, which was flown out of Ellington Air Force Base, Houston, Texas. To achieve variable gravity, the aircraft was maneuvered through repeated parabolic trajectories. Gravity was increased to approximately 1.8 g during the concave-up portion of the maneuver and to a preselected low-g value during the concave-down portion of the flight path. Variable-gravity flights were completed on May 27 and 28, 1987. About 40 low-g maneuvers were completed on each 2-h flight, with the low-g portions ranging uniformly between 0 g and ½ g. The experimental record consists of 4 h of videotape recordings. In addition, 1-g experiments were run with both materials over a wide range of drum rotation rates at the laboratory in Davis, California.

Results and Discussion

Angle of repose vs gravity for the glass beads is shown in Fig. 1. Both flight and laboratory data are shown. A strong tendency toward larger angle of repose at lower gravity is evident. The results for Monterery sand are similar but do not show as strong an effect due to gravity.

The results for the glass beads in terms of G [Eq. (1)] are displayed in Fig. 2. The experimental data is well correlated with the dimensionless form, square root of $(1/G)$. Moving to the right in that graph corresponds to decreased gravity and/or increased from rotation speed. The best fit for the glass beads including the laboratory data was

$$\alpha = 26.79 \text{ deg} + 1662 \text{ deg} * \text{sqrt}\ (1/G)$$

$$(\text{Regression } R^2 = 0.845) \qquad (2)$$

The best fit for the Monterey sand including the laboratory data was

$$\alpha = 33.24 \text{ deg} + 799 \text{ deg} * \text{sqrt}\ (1/G)$$

$$(\text{Regression } R^2 = 0.728) \qquad (3)$$

The smaller gravitational coefficient (799 vs 1662 deg) for the Monterey sand is noteworthy.

The classic Bagnold theory did not predict the effects implied by the preceding equations. The modern theories would be qualitatively consistent with Eqs. (2) and (3) if there were changes in N, the volume concentration, accompanying the gravity changes. The experimental results from the flights verify that volume changes did occur with gravity changes, but the changes were significant only at very low gravity, while changes in angle of repose were observed over the full range of gravity levels.

A possible explanation may be that N was not spatially uniform, and a gradual rarefaction of the thin surface shearing layer occurred as gravity was reduced. Significant changes in the volume concentration of the thin shearing layer may not have resulted in noticeable changes in the computed average N. Support for this conjecture comes from the consistent observation of a deeper apparent shearing layer under reduced gravity and a more shallow layer at high gravity.

Recent work by Tüzün et al.[5] may offer another explanation. They found that the coefficient of friction between individual particles increases at low normal loads, with the effect being most pronounced for smooth particles. It is possible that the results reported here are due to reduced gravity producing reduced interparticle normal loads resulting in increased particle coefficients of friction and finally increased angle of repose. The fact that the smooth glass beads exhibited more variation due to gravity than the rough Monterey sand is also consistent with Tüzün's work. Future studies, including high-g centrifuge work, will attempt to take into account these and other considerations.

Some implications from this study to Planetary Geology include deeper shear layers, shorter slide-run-outs and steeper dune slopes in low-g environments. Potential industrial processes in space that require the handling of granular materials may experience increased difficulties in activities such as the emptying of bins and hoppers. Even some processes on Earth that may take place at nonstandard effective gravity may encounter altered dynamic angles of repose.

Acknowledgments

This work was supported by the National Aeronautics and Space Administration Office of Planetary Geology through the NASA-Ames Aeolian Consortium and by the Division of Aeronautical Science and Engineering, Department of Mechanical Engineering, University of California, Davis, Davis, California. The authors acknowledge the services of Judith Kavanagh of U.C. Davis, Dave Tucker and Rod Leach of NASA-Ames Research Center, and Otis Walton of Lawrence Livermore National Laboratory.

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