AIAA'88

AIAA-88-0648

Dynamic Shear of Granular Material Under Variable Gravity Conditions

S. P. Klein and B. R. White
University of California
Davis, CA 95616

AIAA 26th Aerospace Sciences Meeting
January 11-14, 1988/Reno, Nevada

Dynamic Shear of Granular Material Under Variable Gravity Conditions

by

S.P. Klein* B.R. White**
College of Engineering
University of California
Davis, California 95616

ABSTRACT

This paper describes some experiments with granular materials which recently have been conducted aboard the NASA KC-135 aircraft during variable gravity maneuvers. The main experimental apparatus consisted of a small drum containing granular material which was rotated slowly while the angle assumed by the slip surface with respect to the horizontal was observed and recorded photographically. Conventional wisdom has held that this "dynamic angle of repose" was a material constant, independent of (among other things) gravitational level. The results presented here are quite 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 many active processes in Planetary Geology involving granular materials and may provide qualitative confirmation of some of the theoretical predictions of modern models of granular shear flows.

Introduction

Scientific studies on the mechanics of granular material usually have been specialized to one of two limiting flow regimes. The study of slow "quasistatic" deformations in which the particles maintain enduring contacts appears to have begun with Coulomb(1) and Reynolds(2). Modern studies of this flow regime often use methods derived from plasticity theory. The field is reviewed by Desai & Siriwardane(3). At the opposite extreme are granular flows in which particle contacts are considered to be instantaneous collisions. This "dynamic" or "rapid-flow" regime is usually characterized by high shear rates. The present work is devoted to this type of flow.

The flow of granular materials plays a significant role in many diverse fields such as geology, industrial processing, agricultural materials handling, energy production, and even astrophysics. Granular flow considerations are dominant in such processes as rockslides, bedload sediment transport, avalanches, sand dune dynamics, handling of seeds and pills, use of ceramic pellet flow in high temperature energy production, flow of rings around planets, and even the act of pouring dry cereal into a breakfast bowl.

The least complicated case is for material composed of identical hard spherical grains with no interparticle attraction or cohesion, and an interstitial fluid that can be ignored. These idealizations are thought to be reasonably valid for a variety of applications such as the flow of glass beads and well-worn dry sand as used in these experiments.

R.A. Bagnold(4,5) was responsible for the pioneering work dealing with the flow of granular materials in which particle collisions were considered important. He called the rapid-flow regime the "grain-inertia region". Bagnold's experimental and theoretical contributions span the 1930's through the 1980's. His work has stood the test of time, and more sophisticated theories developed over the past ten years support his major assertions such as the quadratic dependence of stress on shear rate.

There has been an explosion of activity in rapid granular flow over the past ten years. Present theoretical efforts by numerous

---

* Graduate Student, current address, Engrg. Dept., Yuba College, Marysville, CA 95901
**Professor AIAA member.

researchers tend to be mainly in two areas: (i) Refinement of the "kinetic theory" models in which the grains of the granular flow are made analogous to the molecules of a dense gas. The classic work of this type was by Ogawa[6]. (ii) Discrete particle simulations of granular flow using the computer to describe and follow each particle. The work in this area began with Cundall[7]. In addition, experimental work has been performed for a variety of flow geometries, most common being inclined planes, vertical chutes, and annular shear cells.

The value of the gravitational acceleration "g" comes into all the theoretical models of granular flow. The work reported here is believed to be the first experimentation on granular shear flow to be done at reduced gravity, and may be the first to have been done at anything other than earth-g. Certainly a large amount of high-g centrifuge work has been done, but it has been predominantly low shear-rate testing such as the study of the collapse of earth structures. Bagnold's[5] work, "Experiments on a Gravity-Free Dispersion of Large Solid Spheres in a Newtonian Fluid Under Shear" was not actually gravity-free, but instead used neutrally-buoyant spheres suspended in a fluid at earth-g.

The objective of this study was to determine the effects of gravity on granular flow characteristics. Of particular interest was whether any measurable change in a material's angle of repose could be observed with variation in gravity. In addition, it was hoped this study would provide qualitative information about grain flow mechanics and dispersive stresses at the limit of low gravity. To meet these objectives two devices were built and experiments were carried out aboard NASA's KC-135 "weightless" aircraft. The devices used were a rotating disc shear cell and a horizontal-axis rotating drum.

Angles of Repose

When a flat bed of granular material is tilted up to a certain critical angle the slope collapses as some of the particles slip downward. Measurement of this maximum bed angle with respect to the horizontal is one of several methods of defining a material's "static angle of repose". It is near 30° for a typical granular material. Brown and Richards[8] review six methods for experimentally determining the angle of repose. It has generally been assumed that the angle of repose was a bulk material constant, probably controlled in some way by a variety of particle properties such as shape, roughness, size, cohesion and resilience. In the simplest static case with identical hard, non-cohesive spheres, it can be argued that the angle of repose is fixed by geometry.

Consider a bed of spheres packed in a simple cubic pattern with a "stray" surface particle centered at a low spot touching four bed particles. The volume concentration (volume of the solid particles divided by the bulk volume) for the simple cubic packing is 0.52. When the bed is tipped up to an angle of 35.3° the stray particle can roll through the low spot between the lower two of the four bed particles it was initially contacting. Until the bed is raised to 35.3° all such stray surface particles remain in place. If the situation is repeated, but with the bed packed in a rhombohedral ("close-pack") pattern, the stray surface particle will contact three bed particles. The geometric calculation in this case shows that the volume concentration is 0.74 and that the stray sphere will begin to roll when the bed is tilted up 19.5°.

Natural beds do not pack in the organized cubic or rhombohedral pattern but are instead randomly packed. A random assembly of identical spheres will pack with a volume concentration of approximately 0.63, or midway between the two cases mentioned above. It may be more than a coincidence that the experimental value of the angle of repose for identical spheres is about 27°, midway between the previously-mentioned calculations of 19.5° and 35.3°. The main point made here is that static geometric calculations do not depend on the value of gravity if it is greater than zero. (At zero-g a singularity exists; angle of repose, and for that matter "horizontal", can not be defined.)

In contrast to the static situation described above, the method of measurement chosen for this study was the partially-filled rotating drum described by Brown and Richards. The angle that the continuously downward-cascading material makes with the horizontal is called the "dynamic angle of repose". Brown and Richards report reasonable agreement between the measurement of the dynamic angle of repose using this method and several standard methods of measurements of the static angle of repose. The maximum or static angle of repose at which an avalanche is initiated is usually several degrees greater than the dynamic angle of repose maintained while the avalanching is occurring. In the rotating drum, the bulk of the material at any moment is moving slowly upward with the drum wall while a thin surface layer moves rapidly downslope.

Fig. 1 shows a surface parcel of material slipping downslope. At the interface between the parcel and the underlying material a normal stress T_{yy} and a shear stress T_{xy} exist. The weight of the parcel per unit bed area (or "immersed weight" if buoyancy is considered) is "mg". Under steady, parallel flow conditions, the forces on the parcel due to these stresses must just balance the weight of the parcel, requiring that:

$$T_{xy}/T_{yy} = \tan(\alpha) \qquad (1)$$

where "α" is the angle of inclination of the bed with respect to the horizontal. The ratio T_{xy}/T_{yy} is referred to as the "dynamic friction coefficient", and its quantitation, both theoretical and experimental, is of central importance in granular shear flows. Bagnold[5] first used an annular shear cell in the laboratory to measure this stress ratio. More recently, similar measurements have been reported by Savage & Sayed[9], and Hanes & Inman[10,11]. The latter discuss the relationship between the dynamic friction

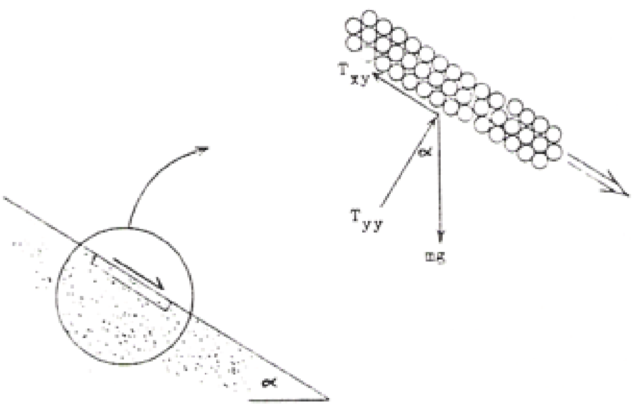


Fig. 1. Stresses on a surface parcel of particles slipping in steady motion.

coefficient and the dynamic angle of repose suggested by Eq. 1. There are some assumptions behind Fig. 1 and Eq. 1 which may not be valid for the rotating drum, but for this study the tangent of the dynamic angle of repose is considered only to be qualitatively similar to the dynamic friction coefficient.

Bagnold's classic work[5] suggests that the dynamic friction coefficient, and thus the dynamic angle of repose, should be independent of gravity level. Bagnold found that when the material is in the grain-inertia region both the shear stress and the normal stress are proportional to the same quantities:

$$T_{yy} = k_{yy}\, \rho_p (F(N)) D_p^{\,2} (dU/dy)^2 \qquad (2)$$

$$T_{xy} = k_{xy} \rho_p (F(N)) D_p^{\,2} (dU/dy)^2 \qquad (3)$$

where k_{yy} and k_{xy} are constants, ρ_p is the density of the particle, F(N) is an increasing function of the volume concentration, D_p is the particle diameter, and U is the x-direction velocity. Eqs. (2) & (3) predict that the stress ratio is independent of gravity even if changes in gravity cause variations in N, the volume concentration, or dU/dy, the shear rate. On this basis it appears reasonable to predict that variation of gravity level will not cause noticeable changes in the dynamic angle of repose.

Modern kinetic-theory models and discrete-particle computer models, such as those by Lun & Savage[12] and Walton & Braun[13], predict slightly altered versions of Eqs. (2) & (3). In these equations, the function F(N) is found to depend also on "e", the particle coefficient of restitution, and on "f", the particle coefficient of friction. In addition, the new function differs in form between the shear stress and the normal stress, resulting in a dynamic friction coefficient (T_{xy}/T_{yy}) which is not constant. The models predict the shear/normal stress ratio to depend considerably on "e" and "f", to a lesser extent on N, and negligibly on shear rate. Low volume concentrations are predicted to produce higher dynamic friction coefficients, with the effect being less pronounced as the particles are made more elastic and less frictional. At high coefficients of restitution and modest coefficients of friction (appropriate for glass spheres), the models predict only a slight increase in the dynamic friction coefficient at low volume concentrations. Experimental endorsement of this theoretical effect has been supplied by the annular shear cell work of Savage & Sayed[9] and Hanes & Inman[10], who report a tendency toward higher shear/normal stress ratios with lower volume concentrations.

These modern findings lead to the expectation that the dynamic angle of repose and the dynamic coefficient of friction may vary with gravity, but only if the changes in gravity are accompanied by significant changes in the volume concentration. In the present study, one device, the horizontal-axis rotating drum, had no restriction on the expansion of the granular material under observation. The other device, the rotating disc shear cell, maintained a constant volume concentration.

Dimensional analysis has proved very helpful in this study. The angle of repose measured with the rotating drum may depend on the following variables.

$$\alpha = \alpha\ (g, w, D, \rho, \mu, \rho_p, D_p, N, f, e, S)$$

where "ρ_p", "D_p", "N", "f", and "e" have previously been defined, "g" is the gravitational acceleration, "w" is the rotation rate of the drum, "D" is the diameter of the drum, "ρ" is the density of the interstitial fluid (air in this case), "μ" is the viscosity of the interstitial fluid, and "S" is some shape factor such as sphericity. N, f, e and S are dimensionless. There are a large number of possible dimensionless groups that could be formed from the remaining variables. The ones chosen were the ones most intuitively satisfying:

$$\alpha = \alpha\ (G,\ D/D_p,\ N,\ f,\ e,\ S) \qquad (4)$$

where we define the dimensionless parameter

$$G = g\ ((\rho_p - \rho)/\mu\, w^3)^{1/2} \qquad (5)$$

With regard to the present study, the important variation suggested by Eqs. 4 and 5 is the ratio g^2/w^3, since all other variables are set once an experiment starts. Moreover, it is well known that increased drum rotation rates produce slightly larger angles of repose, so it may be expected that the angle of repose will vary with gravity (and "G") in an inverse fashion.

Experimental Considerations

The two granular materials chosen for this study were #0/30 Monterey sand, a well-sorted beach sand, and very closely graded (#16 - #14) glass beads. The Monterey sand was chosen

	Glass Beads	Monterey Sand
Mean grain diameter, D_p, mm	1.35	0.40
Density, ρ_p, g/cc	3.00	2.65
Volume Concentration, N		
Loosely packed	0.59	0.59
Tightly packed (vibrated)	0.63	0.625

Table 1. Characteristics of Test Material

because of its wide use in geotechnical research, and the desire to test a representative natural material. Glass beds were chosen because they are close to the ideal materials described by the theories, and for consistency with much of the annular shear cell work cited. The table below summarizes the important material characteristics measured using standard sieving, weighing and submersion techniques.

All grain flows of this study were intended to be in the rapid-flow or grain-inertial regime. As mentioned, the theoretical models referenced are specific to this regime, and most natural granular flows in air are in this regime. Bagnold[5] suggests that the grain-inertial region becomes fully established for "Bagnold Numbers", B above 450. B is a dimensionless number which is influenced by a combination of particle size, density and concentration, fluid viscosity, and overall shear rate. For typical loosely packed coarse sand in air, B = 450 is reached when the shear rate reaches 1 sec^{-1}. For all the experiments reported here, the shear rate was estimated to be at least 10 sec^{-1}, so it was thought that the assumptions of the rapid-flow regime were valid.

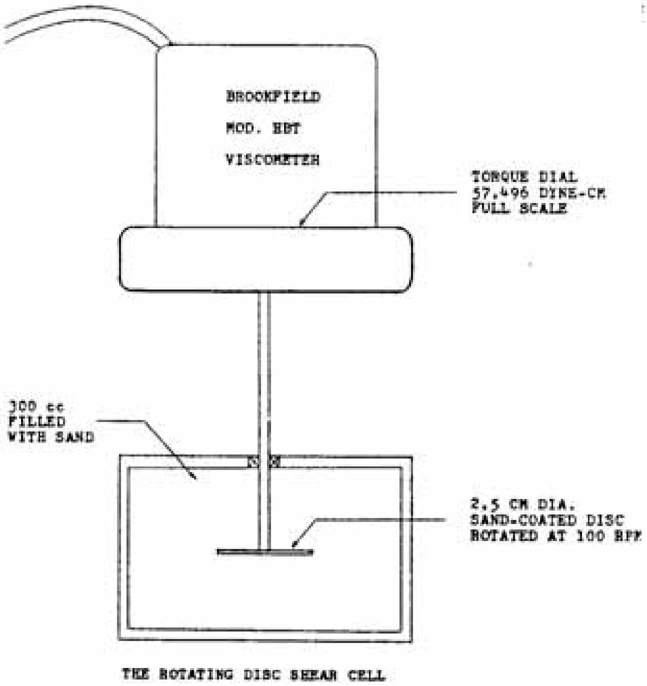


Fig. 2. Schematic of the rotating disc shear cell.

Fig. 2 is a schematic of the rotating disc shear cell. Monterey sand was contained in a closed cylinder of 300 cc volume. A 2.5 cm diameter disc positioned in the center of the cylinder was connected to a vertical shaft which passed through a bearing at the top of the cylinder. The disc was coated with grains of Monterey sand to inhibit slip at the disc. The external shaft was connected to a model HBT Brookfield Viscometer which rotated the disc and measured the shearing torque. On the manually-read viscometer dial, a full-scale reading of 100 corresponded to an actual torque of 57,496 dyne-cm. The sand filled the container when loosely packed with the disc spinning at 100 RPM. Thus, it was presumed that the volume concentration in the container, and the shear rate at the disc were nearly constant.

The shear stress at the disc was reflected in the measurement of the shearing torque, but the apparatus provided no measurement of the normal stress at the disc. Qualitatively, the normal stress was expected to reduce linearly as the weight of the "overburden" sand reduced with gravity, until, at some point, the dispersive stresses extended to the top of the container. At gravity levels below that point, because of the fixed volume, little or no further drop in normal stress would be expected. If, as theory predicted, the dynamic friction coefficient were constant for these conditions, then the measured torque also would follow the same form, shown hypothetically in Fig. 3. Of particular interest would be the value of the y-intercept and its relation to the dispersive stresses at zero gravity.

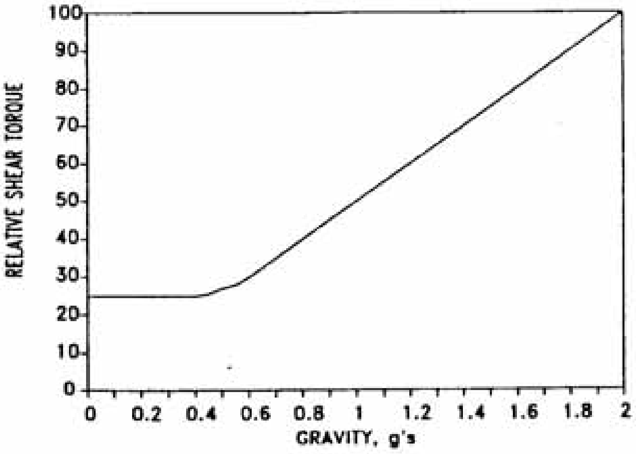
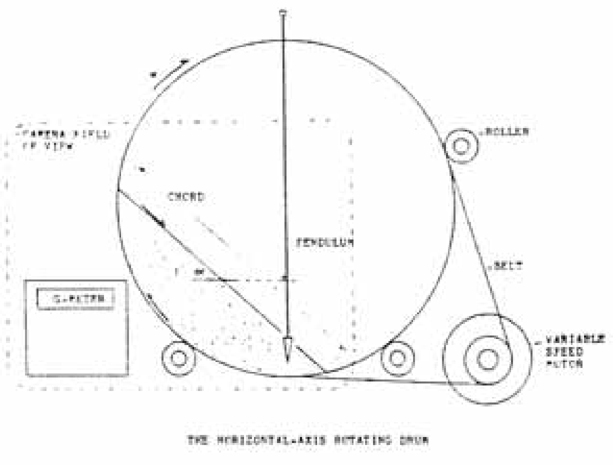


Fig. 3. Expected form of the response of the rotating disc shear cell to changes in gravity.

As it turned out, this apparatus never performed as envisioned. It is described here and the data obtained are included later in the interest of thorough documentation. A mistake was made in choosing an undamped viscometer to drive the disc. In fluids there is no need for damping, but in granular materials the disc rotation may oscillate in a "stick-slip" mode making it difficult to read a stabilized torque. This problem was mentioned by Hanes & Inman[11]. Additionally, the viscometer was constructed so that it required at least a small amount of downward gravity to read properly, so measurements could not be made at or near zero gravity. A great deal of modification to the viscometer using various dampeners and different types of discs resulted in an apparatus that worked in the laboratory but, as it turned out, not dependably under the difficult conditions of flight.

Fig. 4 shows a schematic of the horizontal-axis rotating drum apparatus. A 22 cm diameter by 12 cm long drum was belt-driven by a variable speed electric motor. Two drums, one containing Monterey sand, the other containing glass beads, could be interchanged without dismantling the apparatus, thus avoiding the possibility of a disastrous sand spill aboard the zero-g aircraft. The inside surface of the drums were coated with grains of the test material to insure the no-slip condition. A relatively small amount of material (362 grams) was used in each drum in an attempt to keep the motion nearer to the parallel flow situation implied in Fig. 1. As suggested in Brown & Richards, experiments were conducted at optimal rotation rates in the 2 - 8 RPM range. At these speeds the material formed a nearly steady, planar down-sloping surface.

The drums had transparent ends allowing continuous photographic recording of the experimental variables. As indicated in the schematic, these included the gravity level, the angle of repose, the vertical reference (pendulum), the chord length, and the rotation rate. The angle of repose was measured at mid-



THE HORIZONTAL-AXIS ROTATING DRUM

Fig. 4. Schematic of the horizontal-axis rotating drum device.

chord and with respect to a line perpendicular to the indicated vertical. The electronic g-meter displayed the instantaneous acceleration of gravity to the nearest 0.01 g. The chord length was used to calculate the occupied volume, and from that the mean volume concentration. Photography was by close-up video tape recorder with the audio input used to record other pertinent information, such as motor settings.

Fig. 5 is a laboratory photograph of the basic apparatus with both interchangeable drums. Earth-gravity experiments were run in order to assess the effect of drum rotation rate on the measured angle of repose. Rotational speeds were varied from 1.5 to 12 RPM, far exceeding the optimal range of speeds to be used during the variable-g flights. The results are displayed in Fig. 6. While the measured angle of repose does rise with increased rotational speed, it is quite gradual. On this basis, it was inferred that small changes in rotation rate during the variable-g flights would not greatly influence the measured angle of repose.

Creating a Reduced Gravity Environment

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. The shear cell and rotating drum devices were attached to a common instrument stand which was secured to the floor of the aircraft using vibration isolation mounts. To achieve variable gravity, the aircraft was maneuvered through repeated parabolic trajectories as illustrated in Fig. 7. Gravity was increased to approximately 1.8 g's during the concave-up portion of the maneuver, and to a pre-selected low-g value during the concave-down portion. At the minimum altitude of 7000 meters the aircraft attained its maximum speed of 230 m/s, and at the maximum altitude of nearly 10,000 meters, the airspeed was minimum at 135 m/s. Points of change in the concavity coincided with a steep 45 degrees climb and a 45° descent, which gave the flight path some similarity to a giant rollercoaster. The effect on personnel has been known to be similar as well[14].

The pilots were able to maintain a desired gravity level on a given parabola to ±0.02 g. The time period of the reduced-gravity environment depended on the g-level selected. Typically, the aircraft could sustain the following time periods of reduced gravity: zero-g for 23 seconds, 1/6 g for 30 seconds, 1/3 g for 40 seconds, and 1/2 g for about 60 seconds. Approximately 40 consecutive maneuvers, or 40 periods of high-g and 40 periods of low-g, were completed in each day's 2 hour flight.

Variable Gravity Experiments

Variable gravity flights were completed on May 27, 28, 1987. As described above, about 40 low-g maneuvers were completed on each flight, with g-levels ranging uniformly between zero-g

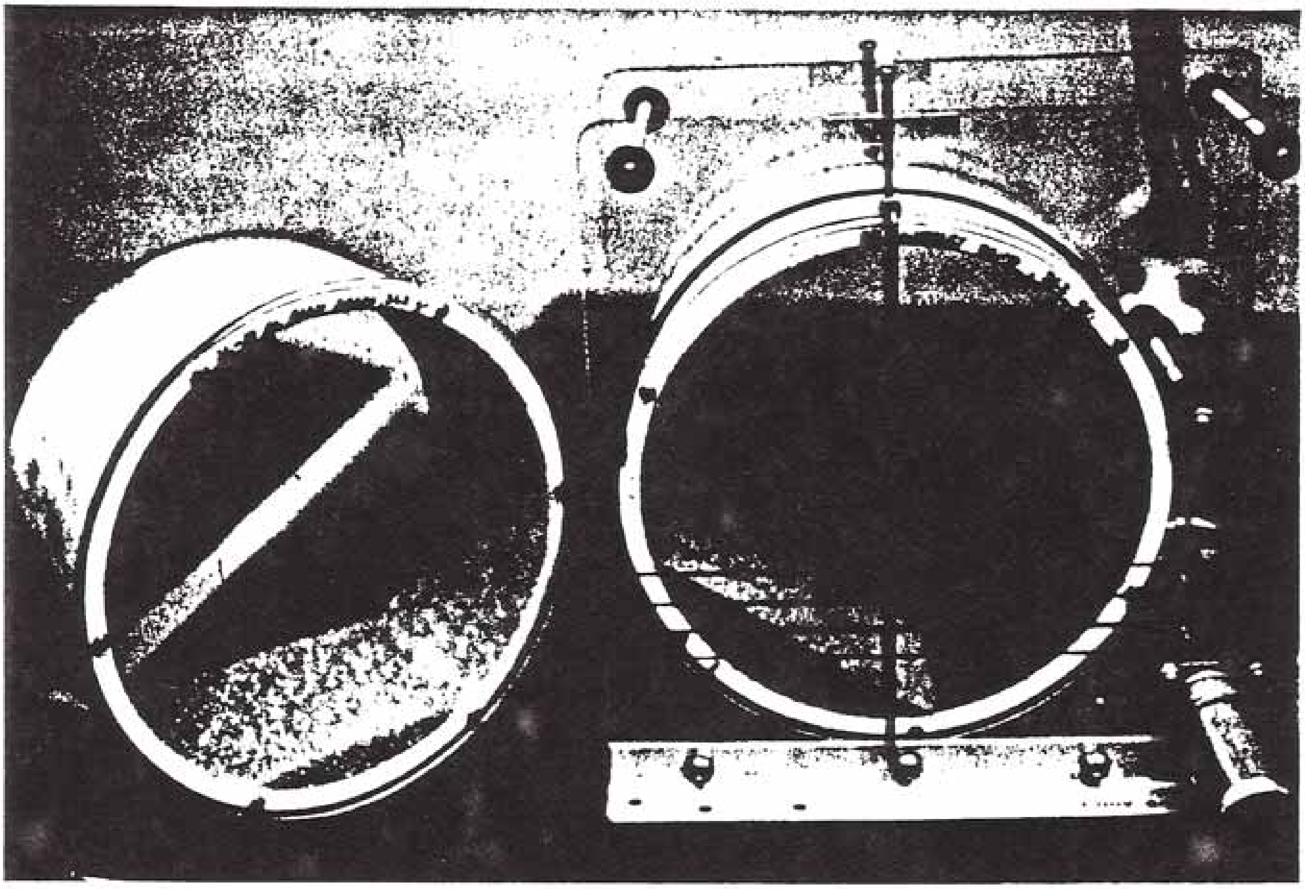


Fig. 5. Photograph of the rotating drum device showing the interchangeable drums. Glass beads on left, Monterey sand on right.

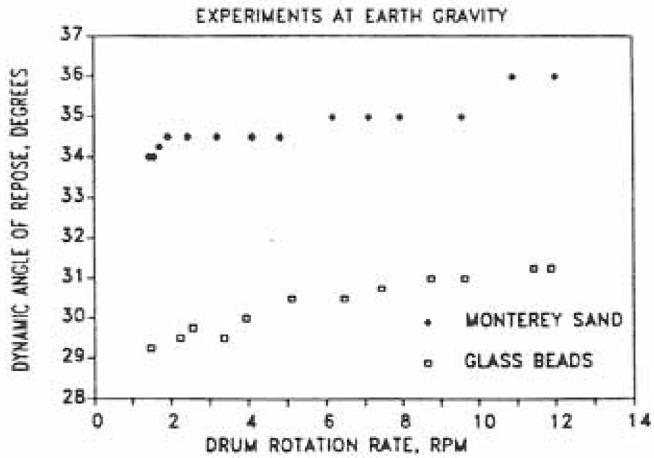


Fig. 6. Laboratory results at 1-g for the rotating drum device. The effect of changes in rotation rate is shown to be minimal for both Monterey sand and glass beads.

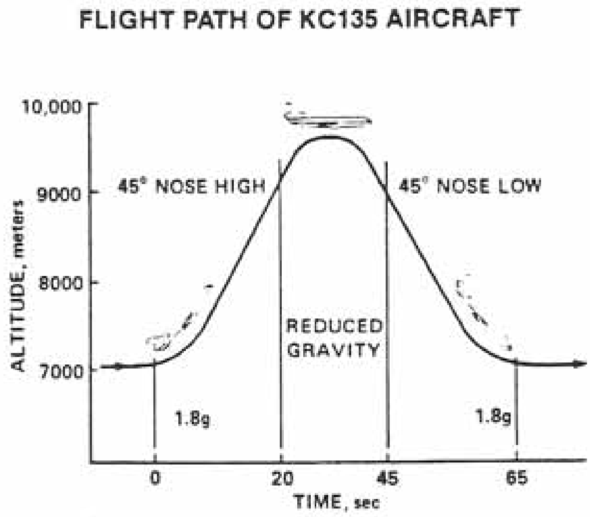


Fig. 7. The parabolic trajectory flown by the KC-135 aircraft for the variable gravity maneuver.

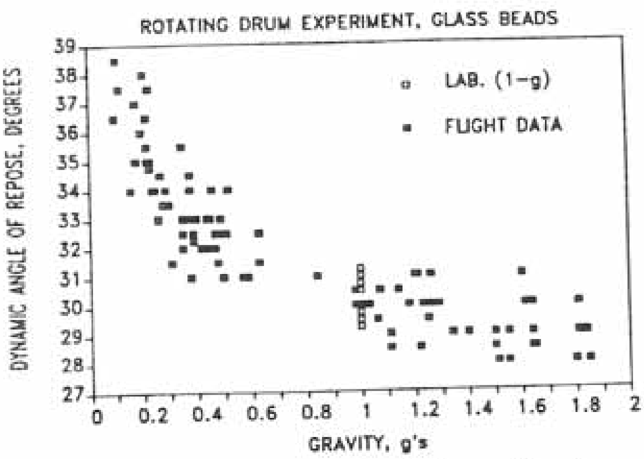


Fig. 10. All the experimental results for the rotating drum using glass beads. Nominal drum speed is 6.75 RPM.

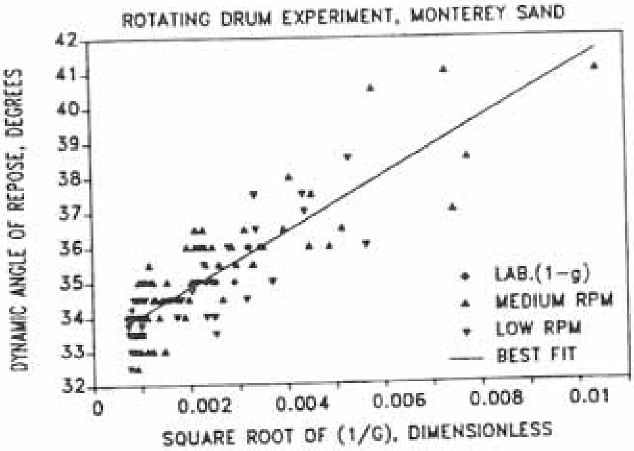


Fig. 11. All the data for Monterey sand in the rotating drum plotted against the reciprocal of the square root of the dimensionless parameter G. The best fit line is shown. Regression R^2 = 0.728.

Mathematical regression was used to study different possible empirical models of the data in Figs. 9 and 10. The criterion used here as a measure of the adequacy of a fitted model was the "R^2" value, which indicates the proportion of the total variation in the results that is explained by the model. Attempts to fit the data just to the rotation rate w, or to functions of w, resulted in the lowest R^2 values. Fitting to g, or functions of g, gave much better R^2 values. The best R^2 values were obtained using models containing both w and g. Many models with high R^2 could be constructed with different combinations of functions of w and g. The one chosen was the one that was compatible with the dimensional analysis, and consistent with physical arguments:

$$\alpha = \alpha_0 + C * \mathrm{sqrt}\,(1/G) \quad (6)$$

where α_0, and C are material constants, and G is the dimensionless parameter defined by Eq. 5.

To compute G, g was taken in meters/s/s, and w in radians/s. The value used for the viscosity of air was 18×10^{-6} Kg/m/sec. The density difference between air and Monterey sand was taken as 2650 Kg/m^3, and between air and glass beads as 3000 Kg/m^3.

The results in terms of Eq. 6 are displayed in Figs. 11 and 12. The experimental data is very nicely correlated with the dimensionless form, square root of (1/G). Moving to the right in those plots corresponds to decreased gravity and/or increased drum rotation speed. The best fit for the Monterey sand (including the laboratory data) was:

$$\alpha = 33.24^\circ + 799 * \mathrm{sqrt}(1/G)$$

and R^2 = 0.728

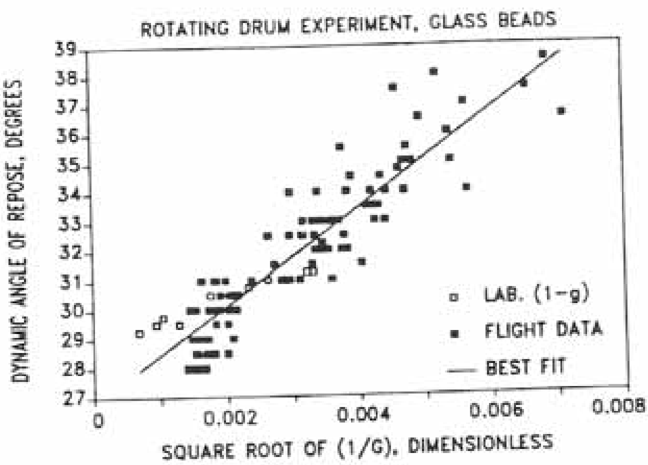


Fig. 12. All the data for glass beads in the rotating drum plotted against the reciprocal of the square root of the dimensionless parameter G. The best fit line is shown. Regression R^2 = .845.

The best fit for the glass beads (including the laboratory data) was:

$$\alpha = 26.79^\circ + 1662 * \mathrm{sqrt}(1/G)$$

and R^2 = 0.845

A very encouraging aspect of the best fit models is that they agree quite nicely with the laboratory data, which were taken under the most stable, dependable conditions. The fact that the models fit both the constant-g laboratory data, with large changes in w, and the near-constant-w flight data, with large changes in g, is favorable evidence that g and

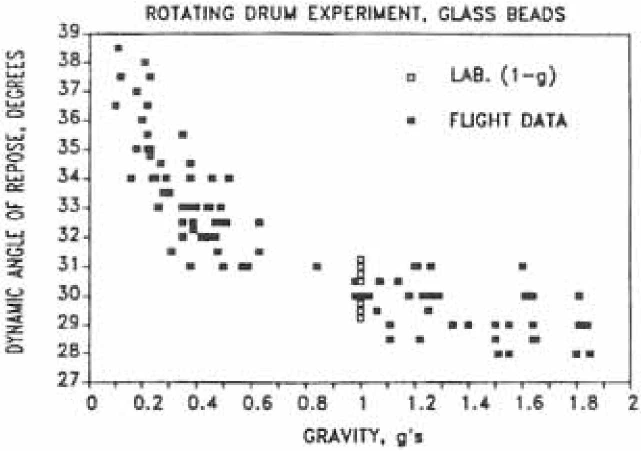


Fig. 10. All the experimental results for the rotating drum using glass beads. Nominal drum speed is 6.75 RPM.

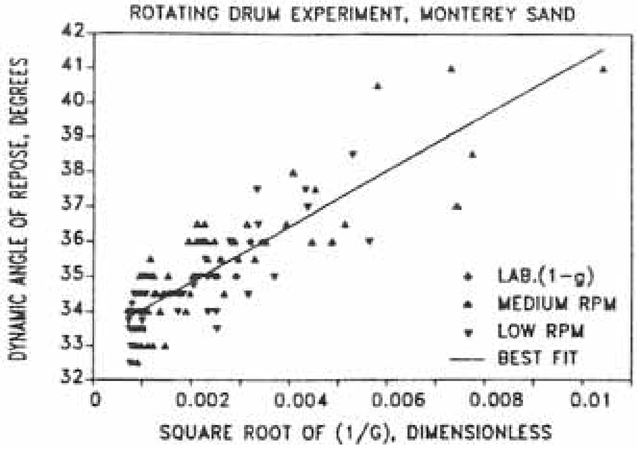


Fig. 11. All the data for Monterey sand in the rotating drum plotted against the reciprocal of the square root of the dimensionless parameter G. The best fit line is shown. Regression R^2 = 0.728.

Mathematical regression was used to study different possible empirical models of the data in Figs. 9 and 10. The criterion used here as a measure of the adequacy of a fitted model was the "R^2" value, which indicates the proportion of the total variation in the results that is explained by the model. Attempts to fit the data just to the rotation rate w, or to functions of w, resulted in the lowest R^2 values. Fitting to g, or functions of g, gave much better R^2 values. The best R^2 values were obtained using models containing both w and g. Many models with high R^2 could be constructed with different combinations of functions of w and g. The one chosen was the one that was compatible with the dimensional analysis, and consistent with physical arguments:

$$\alpha = \alpha_0 + C * \text{sqrt}(1/G) \quad (6)$$

where α_0, and C are material constants, and G is the dimensionless parameter defined by Eq. 5.

To compute G, g was taken in meters/s/s, and w in radians/s. The value used for the viscosity of air was 18 x 10^{-6} Kg/m/sec. The density difference between air and Monterey sand was taken as 2650 Kg/m^3, and between air and glass beads as 3000 Kg/m^3.

The results in terms of Eq. 6 are displayed in Figs. 11 and 12. The experimental data is very nicely correlated with the dimensionless form, square root of (1/G). Moving to the right in those plots corresponds to decreased gravity and/or increased drum rotation speed. The best fit for the Monterey sand (including the laboratory data) was:

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

$$\text{and } R^2 = 0.728$$

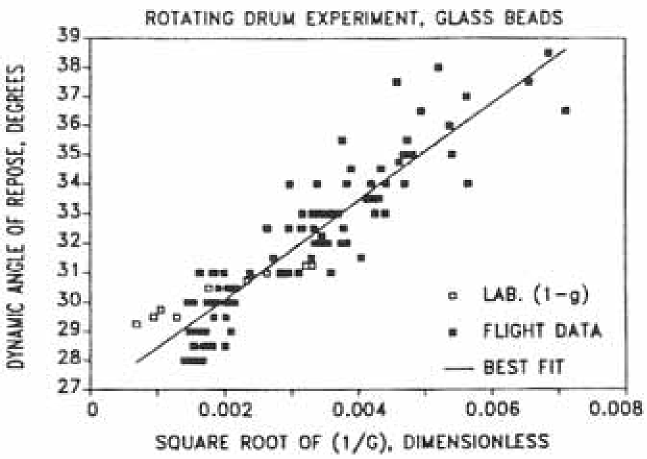


Fig. 12. All the data for glass beads in the rotating drum plotted against the reciprocal of the square root of the dimensionless parameter G. The best fit line is shown. Regression R^2 = .845.

The best fit for the glass beads (including the laboratory data) was:

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

$$\text{and } R^2 = 0.845$$

A very encouraging aspect of the best fit models is that they agree quite nicely with the laboratory data, which were taken under the most stable, dependable conditions. The fact that the models fit both the constant-g laboratory data, with large changes in w, and the near-constant-w flight data, with large changes in g, is favorable evidence that g and w are being handled correctly in the parameter G. Although the constants in the empirical Eq. 6 are expected to be dependent on the material, and perhaps on the specific apparatus used, the form of Eq. 6 is thought to correctly describe the effects of g and w on the dynamic angle of repose.

The classic Bagnold theory did not predict these effects. Some modern theories predicted the same effect as Eq. 6 if there were changes in the volume concentration accompanying the gravity changes. The chord in the rotating drum was measured from the videotape records, but not with high precision because of limited screen resolution. Knowing the chord length and the dimensions of the drum allowed calculation of the total volume occupied by the material, and from that, the average volume concentration, N. However, non-uniform concentration distributions could not be resolved.

The results though scattered, suggest that volume changes did occur with gravity changes. However, considering the inaccuracies of the estimates of volume, the changes were not significant except at very low gravity. Fig. 13 displays N versus the parameter square root of (1/G) for Monterey sand. Most of the data points are clustered in the same region. The eight or so points outside the cluster are for gravity levels below 1/4 g (This value corresponds to approximately 0.004 units on the horizontal axis). These low-gravity observations tend to substantiate the prediction of increased dynamic friction coefficient at low volume concentrations by the modern theories of Lun & Savage[12] and Walton & Braun[13].

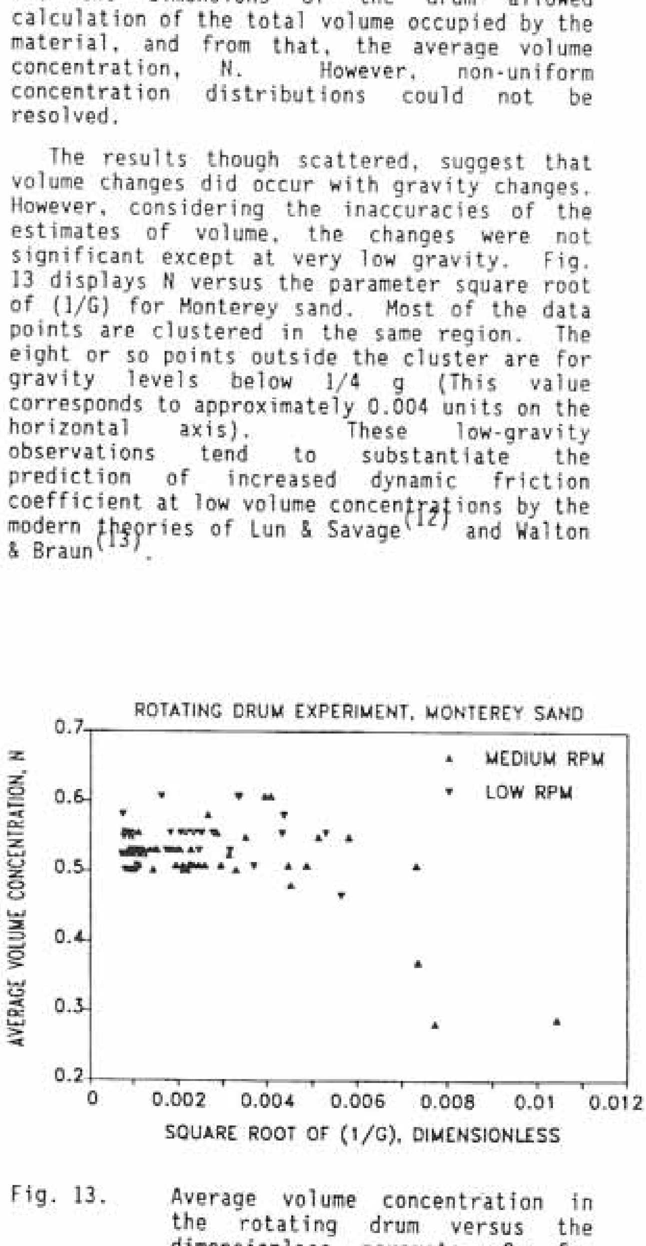


Fig. 13. Average volume concentration in the rotating drum versus the dimensionless parameter G, for Monterey sand. Flight data only. Values calculated from geometry using the chord length. Low gravity and higher rotation rates result in rarefication.

Changes in angle of repose were observed over the full range of gravity levels, while the argument above only applied to the extreme low-g end. A possible explanation may be that N was not uniform spatially, and a gradual rarefication of the thin surface shearing layer was taking place as gravity was reduced. Significant changes in the volume concentration of the thin shearing layer may not have resulted in noticeable changes in the chord length. Support for this explanation comes from the consistent observation of a deeper apparent shearing layer under reduced gravity, and a more shallow layer at high gravity. A look at Fig. 1 and Eq. 3 suggest a deeper, less concentrated shearing layer is probably necessary at low g. From Fig. 1, it is evident that at lower g the shear stress T_{xy} must drop. From Eq. 3, reduced T_{xy} would result when N is reduced and/or the shear rate is reduced. A deeper, less concentrated shearing layer accomplishes both.

Summary

Dynamic angles of repose of two granular materials were measured under variable gravity using the rotating drum method. The angles were found to be a function of gravity and a weak function of drum rotation rate. Angles of repose varied as the reciprocal of the square root of gravity in a way consistent with dimensional considerations. Modern kinetic-theory models and discrete-particle computer models give a possible explanation for this behavior. They predict a moderate increase in the dynamic friction coefficient and dynamic angle of repose as volume concentrations become low. However, volume expansion was detected only at very low gravity, whereas the variation in angle of repose was observed over all gravity levels. It may be that volume concentration was not spatially uniform, and that there was a gradual rarefication of just the thin shearing layer, which did not show up as a noticeable change in the average concentration. Resolution of non-uniform concentration was not possible with the record from these experiments. Future studies, including high-g centrifuge work, will attempt to include these and other considerations.

Some implications from this study to Planetary Geology include deeper shearing layers, shorter slide run-outs and steeper dune faces in low-gravity environments (i.e., less than one-half earth gravity). Potential industrial processes in space which require the handling of granular materials may expect to encounter increased difficulties in activities such as the emptying of bins and hoppers.

Acknowledgements

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, California.

The authors acknowledge the tedious data reduction that was carried out by Judith F. Kavanagh. Also acknowledged are the services of Dave Tucker and Rod N. Leach of NASA Ames Research Center, Moffett Field, California; and, Otis Walton of Lawrence Livermore National Laboratory.

References

1. Coulomb, C.A., 1776, "Essai Sur Une Application des Regles Des Maximis et Minimis a Quelques Problemes De Statique Relatifs a L'architecture", ed. Mem. Acad. Roy. Divers Sav., 7, 343-382.

2. Reynolds, O., 1885, "On the Dialtancy of Media Composed of Rigid Particles in Contact", Phil. Mag., 20, 469-481.

3. Desai, C.S. & Siriwardane, H.D., 1984, "Constitutive Laws for Engineering Materials with Emphasis on Geologic Materials", Prentice-Hall.

4. Bagnold, R.A., 1941, "The Physics of Blown Sand and Desert Dunes", Chapman & Hall.

5. Bagnold, R.A., 1954, "Experiments on a Gravity-Free Dispersion of Large Solid Spheres in a Newtonian Fluid Under Shear", Proc. Roy. Soc. London, Ser. A, 225, 49-63.

6. Ogawa, S., 1978, "Multitemperature Theory of Granular Materials", Proc. of U.S.-Japan Conf. on Cont. Mech. and Stat. Mech. of Granular Mat.

7. Cundall, P.A., 1974, "A Computer Model for Rock-Mass Behavior Using Interactive Graphics for Input and Output of Geometrical Data", U.S. Army Corps of Engineers (Missouri river division), Tech. Rep. No. MRD-2074.

8. Brown, R.L. & Richards, J.C., 1970, "Principles of Powder Mechanics", Pergamon Press.

9. Savage, S. & Sayed, M., 1984, "Stresses Developed by dry Cohesionless Granular Materials Sheared in an Annular Shear Cell", J. Fluid Mech., 142, 391-430.

10. Hanes, D. & Inman D., 1985, "Experimental Evaluation of a Dynamic Yield Criterion for Granular Fluid Flows", J. Geophys. Res., 90, 3670-3674.

11. Hanes, D. & Inman, D., 1985, "Observations of Rapidly Flowing Granular-Fluid Materials", J. Fluid Mech., 150, 357-380.

12. Lun, C.K.K. & Savage, S.B., 1987, "A Simple Kinetic Theory for Granular Flow of Rough, Inelastic, Spherical Particles", J. Appl. Mech. (To appear.)

13. Walton, O.R. & Braun, R.L., 1986, "Viscosity Granular-Temperature and Stress Calculations for Shearing Assemblies of Inelastic, Frictional Disks", Journal of Rheology, 30:5, 949-980.

14. Katz, D.R., 1987, "My Life with the Horror", Outside Magazine, Vol. XII, No. 9, 58-89.