The Flow Of Granular Matter Under Reduced-Gravity Conditions

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Abstract. To gain a better understanding of the surfaces of planets and small bodies in the solar system, the flow behavior of granular material for various gravity levels is of utmost interest. We performed a set of reduced-gravity measurements to analyze the flow behavior of granular matter with a quasi-2D hourglass under coarse-vacuum conditions and with a tilting avalanche box. We used the Bremen drop tower and a small centrifuge to achieve residual-gravity levels between 0.01 \(g_0\) and 0.3 \(g_0\). Both experiments were carried out with basalt and glass grains as well as with two kinds of ordinary sand. For the hourglass experiments, the volume flow through the orifice, the repose and friction angles, and the flow behavior of the particles close to the surface were determined. In the avalanche-box experiment, we measured the duration of the avalanche, the maximum slope angle as well as the width of the avalanche as a function of the gravity level.

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BACKGROUND

All small planetary bodies about which remote-sensing or in-situ surface analyses are available show the occurrence of a layer of regolith. This regolith is a loose granular matter derived from meteoritic impacts and the subsequent production and re-accumulation of fine granular material on the surface. Due to the lower gravity levels on the surfaces of Mars-, Moon-, or asteroid-size bodies, the flow behavior of the regolith under a variety of environmental conditions is fairly unknown. We therefore performed granular-matter experiments under reduced-gravity levels to get some insight into the \(g\)-dependence of surface- and volume flows of granular assemblages.

PARTICLE PROPERTIES AND EXPERIMENTAL TECHNIQUE

As analogs to planetary regolith, which mainly consists of silicates, we chose samples of basalt spheres, glass spheres, and irregular sand. Table 1 lists the main properties of these samples. The first experiment releases, upon onset of the low-gravity phase, a small avalanche and allows the measurements of the duration, the maximum slope angle and the width of the resulting avalanche. The second experiment allows to observe the flow of granular matter through a small orifice in a quasi-2D hourglass setup. Here, the slope angles of the outflow and inflow parts, the volume flow, and the surface-flow properties of individual particles can be studied.

| Sample  | Size (range) [mm] | Shape   |
|---------|------------------|---------|
| Basalt  | 0.4 - 0.6        | spherical |
| Glass   | 0.1 - 0.2        | spherical |
| Sand I  | 0.2 - 0.6        | irregular |
| Sand II | 0.1 - 0.3        | irregular |

THE FORMATION OF REDUCED-GRAVITY CONDITIONS

Artificial zero gravity of 4.7 s was created by dropping the experiments in the drop tower Bremen, a 110 m evacuated tube, inside a pressurized experiment container. To reach the desired residual acceleration for the experiments of 0.3, 0.1, 0.03, and 0.01 \(g_0\) (\(g_0 = 9.814\)ms\(^{-2}\)), the experimental setups were mounted on a centrifuge with a diameter of 0.6 m and rotation axis parallel to the earth’s gravity. The centrifuge was operated at a well-defined speed so that a constant centrifugal acceleration could be obtained during the 4.7 s free-fall.

AVACANABLE-BOX EXPERIMENTS

The avalanche box has an inner dimension of 4 \(\times\) 4 \(\times\) 15 cm\(^3\). Three walls are made of aluminum and three of acrylic glass. The box was mounted upright on the centrifuge so that, due to the gravity of the earth prior to the drop, the granular matter was located at the bottom of the box. At the moment the experiment is released to free fall, the avalanche is launched by the vanishing
gravity of the earth and the dominance of the remaining centrifugal force. The avalanche was recorded with a black-and-white PAL video camera, whose images were subsequently binarized to ease evaluation. In the following, we will restrict ourselves to the analysis of the experiments carried out with glass beads. The top image of Fig. 1 shows the binarized final images of the respective avalanches at gravity levels of 0.01, 0.03, 0.1, and 0.3 $g_0$, whereas the bottom image shows an original snapshot of the final avalanche at 0.3 $g_0$.

Analysis of the image sequences shows that the time from launch to expiration of the avalanche increases with decreasing gravity, whereas the width of the expired avalanche increases with increasing gravity level (see Fig. 2).

Fig. 2 shows that the steepest angle of the slope increases with decreasing gravity. Due to the S-shape of the slope of the surface, increasing gravity shifts the position of the steepest part of the slope further away from the top of the ridge.

HOURGLASS EXPERIMENT

The hourglass consists of two chambers separated by a magnetically operated valve (Fig. 4). The upper chamber is filled with the granular-matter sample. Upon opening the valve, the granular particles trickle into the chamber below.

The upper chamber has a width of 50 mm. To ensure that the accumulated material does not reach the wall of the chamber too early, the lower chamber has a width of 70 mm. The depth (3rd dimension) of the hourglass is 5 mm. The walls are made of aluminum and glass. The backside features a vacuum connector to evacuate the experiment, which is also used to fill the upper chamber with the granular matter. The system could only be evacuated before the flight due to operational restrictions. The vacuum connector was connected to the outside of the drop capsule residing in the evacuated drop tower. For safety reasons, this connection had to be closed during the flight. During the flight, the pressure increased from 0.2 mbar to 1 mbar as the rotary feedthrough through the centrifuge was not fully vacuum-tight.

The hourglass was mounted on the centrifuge with its top facing towards the center and the glass of the window in parallel to the rotational axis to avoid a significant influence of Coriolis force. A force on the grains towards the smooth surface of the window is preferred over one perpendicular to the viewing direction.
FIGURE 4. Software output of the hourglass experiment. Empty parts are white, filled parts are black and flowing particles appear in gray. The upper friction angle and the lower repose angle are indicated. The inset shows an image of the hourglass experiment, performed at a gravity level of 0.01 $g_0$ with basalt spheres.

The experiment was recorded with a Vosskühler HCC-1000 C-MOS high-speed camera. The camera records 231 images per second with a resolution of 1024x1024 8-bit black-and-white pixels. Fig. 4 shows an image close to the end of a flight at 0.01 $g_0$.

The camera records each pixel at a different point of time (rolling shutter). Due to the 50-Hz oscillation of commercial power used to power the lights each pixel is subject to different lighting conditions. A computer program was written to correct the non-constant lighting and to allow precise analysis of the data. A screenshot of the software is also shown in Fig. 4. The area drained from basalt grains is shown in white. The size of this area is measured to calculate the volume flow as shown in Figs. 5 and 6. In areas of moving material, the brightness indicates the velocity of the particles. Velocities exceeding 1 pixel per frame (20 mm/s) cannot be distinguished by the evaluation algorithm. The software also evaluates both (left and right) repose angles in both (upper and lower) chambers (see Fig. 4).

The volume flow of the grains is perfectly constant over time and depends on the gravity level. According to theory, the volume flow depends on the square root of the gravity $[1]$. As shown in Fig 4 our measurements do not fully agree. The exponent we found is 0.60, slightly but significantly larger than theoretically predicted, and in agreement with earlier work [2]. The average values of the repose angles measured in our experiments are shown in Fig. 7. The repose angles in the lower chamber were determined before the accumulated material reached the walls of the chamber. The friction angle measured in the upper chamber shows a stronger dependency on the gravity level than the angle measured in the lower chamber. Surprisingly, the slope angle in the upper chamber has its maximum at 0.1 $g_0$.

Due to the high recording rate of the camera, it was possible to track the trajectory of individual basalt particles in the hourglass experiments. From the trajectories derived by image analysis, the flow velocity within and the total depth of the flow layer could be determined.

Fig. 8 shows the speed of the grains in each layer at a gravity level of 0.3 $g_0$ for the basalt spheres. The topmost layer is excluded for the determination of the velocity dependence as it mainly contains “tumbling” and, thus, not flowing grains. The non-moving particles were also excluded from the analysis. The resulting data (Fig. 9) show two characteristic properties: The decrease of the flow velocity with depth is highest at high acceleration levels and decreases towards low gravity values. At the same time, the depth of the flow increases with increasing gravity level.
As both, the normal force and the gravitational force, are proportional to the gravity level, the decay of the flow velocity with depth is expected to be independent of gravity. Measurements, however, do clearly not support this idealized picture. The difference between theory and experiment may be caused by a friction force increasing more than linearly with the normal force.

It must be clear that, as the depth of the surface flow strongly depends on the global volume flow of material through the hourglass (which depends on gravity), the gravity-dependence of intrinsic flow properties cannot easily be derived.

FIGURE 7. Repose angle in the bottom chamber and friction angle in the top chamber of the hourglass experiments with basalt spheres as a function of gravity level. Error bars denote the range between left and right angles.

FIGURE 8. Surface velocity of basalt spheres in the hourglass experiment at an acceleration level of 0.3 g₀. The velocity of each layer depends on the depth of the layer. The circles represent the size of the grains.

FIGURE 9. Decrease of the velocity per depth and the size of the flow in the hourglass experiments with basalt spheres as a function of the gravity level.

SUMMARY AND OUTLOOK

The measurements done with the avalanche box yielded results predicted by common sense: Increasing gravity results in faster avalanches and shallower slopes for materials of small spherical grains.

The volume flow through the hourglass showed a behavior unexpected by theory. Air pressure or humidity can be excluded as possible causes. Earlier experiments done under ambient pressure showed similar results [2]. The measurements’ deviation from the theory for the volume flow and its dependence on gravity is still unknown. The exponent of 0.60 for basalt significantly exceeds the expected value of 0.50. The exponent is even higher when the sand sample is used.

Size, velocities and repose angles of the surface flow showed clear dependencies on gravity. Theoretical expectations were not fully met. This may have been caused by a dependency on the global volume flow through the hourglass, which - in this specific experiment - depends on gravity and thus differs for all all measurements. To further analyze the surface flow, a setup with constant global volume flow could be of help.

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