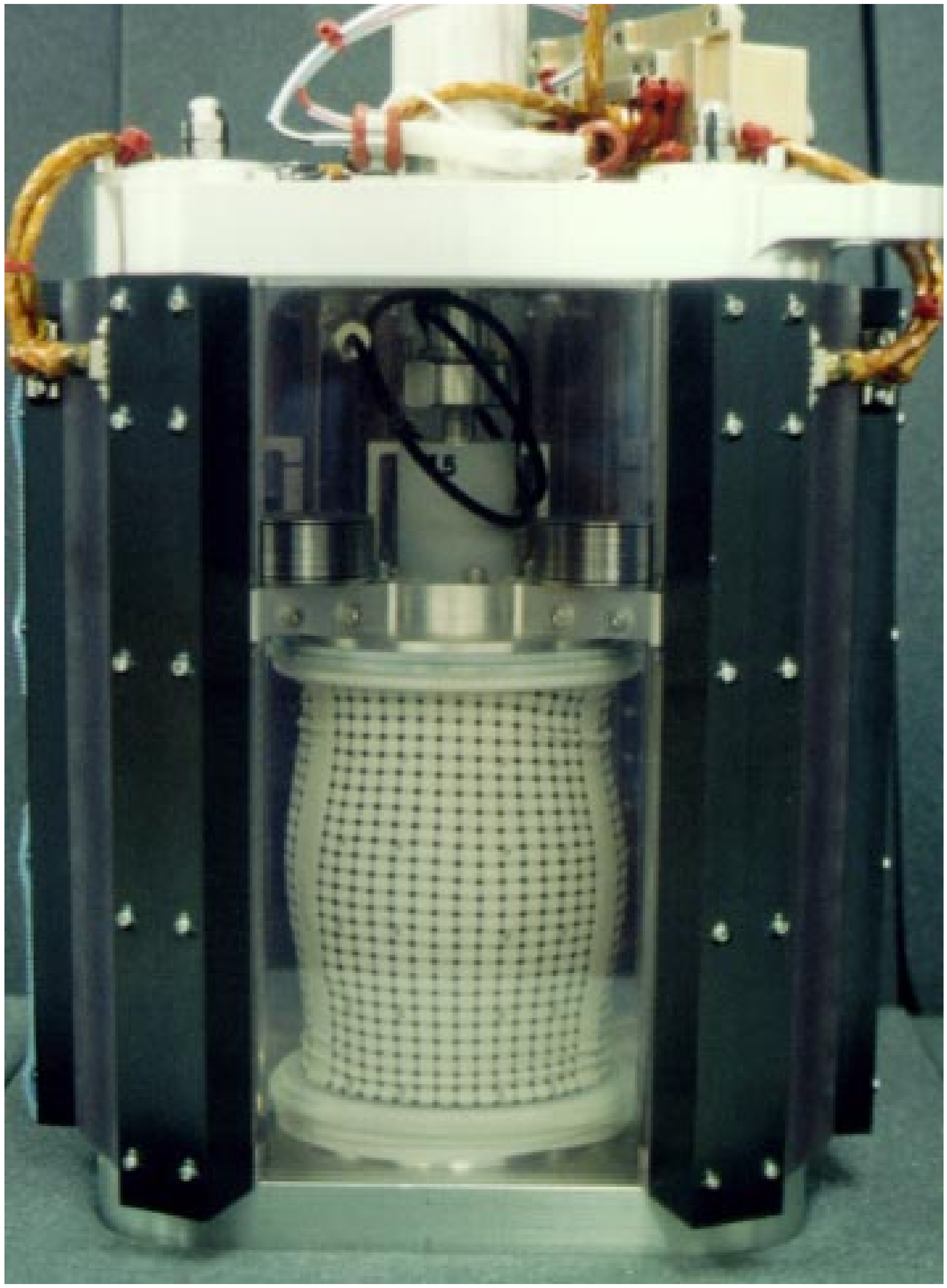
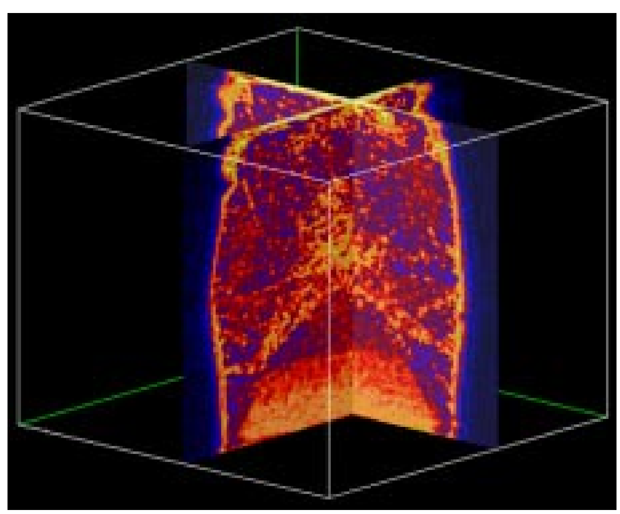
Second round of space experiments to better understand the behavior of soils, powders, and other solid particles under very low confining pressures



Mechanics of Granular Materials

STS-89



MICROGRAVITY
RESEARCH PROGRAM

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Introduction

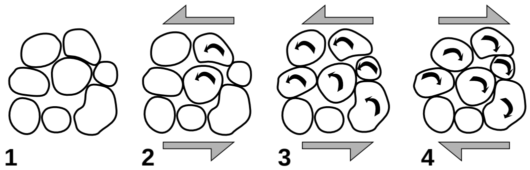
Anyone who has ripped open a vacuum packed pouch of coffee has experienced a fundamental aspect of granular mechanics: a singular shift in conditions can drastically change the properties of a bulk material. While the atmosphere presses on the pack, the grains push against one other, locking each other in place, creating a stiff "brick." Once pressures are released, the grain assembly becomes very weak and soft, and moves about freely, almost like a liquid.

During critical, unstable states — like liquefaction of saturated, loose sand during an earthquake — gravity acts as a "follower load" that makes the structure collapse. Even under laboratory conditions, this is too rapid to allow detailed study of intergranular forces and conditions. Further, gravity-induced stresses complicate the analysis.

To understand how granular materials behave under low stresses, NASA has sponsored the Mechanics of Granular Materials (MGM) experiment for flights aboard the U.S. Space Shuttle. In orbit, MGM uses the weightless environment of orbital flight to test soil under very low pressures. The results will further understanding of the behavior of granular materials and help in conceptual and analytical modeling. This will be applied to improving foundations for buildings, managing undeveloped land, and handling of powdered and granular materials in chemical, agricultural, and other industries.

The first flight of MGM, on STS-79 (September 1996) was highly successful. One of the main findings is that the lower the confining pressure on the dense specimens, the higher the friction angle becomes (*i.e.*, the specimens become stiffer). The second flight, scheduled for STS-89 in January 1998, will comprise twice as many experiment runs and expanded test conditions.

MGM traces its origins to studies to help design the wire mesh wheels for the Lunar Rover Vehicles driven by astronauts on the last three Apollo missions in 1971-72. Results from MGM may be applied in the future to advanced rovers for the exploration of Mars in addition to terrestrial needs.



The packing of particles can change radically during cyclic loading such as in an earthquake or when shaking a container to compact a powder. A large hole (1) is maintained by the particles sticking to each other. A small, counterclockwise strain (2) collapses the hole, and another large strain (3) forms more new holes which collapse when the strain reverses (4). (after T.L. Youd, "Packing Changes and Liquefaction Susceptibility," *Journal of the Geotechnical Engineering Division*, **103**: GT8, 918-922, 1977).

Science

The principal strength of particulate materials — whether they are coffee, soil beneath a house, or sand under your wheels on Mars — is intergranular friction and geometric interlocking. Billions of grains, ranging from large to microscopic, contribute to the total strength of the material. Moisture and air trapped within the soil can also affect its behavior if loading occurs faster than the entrapped fluid can escape. As the pore water pressure or air pressure increases, the effective or intergranular stresses or pressures decrease, weakening and softening the soil. When the external loading equals the internal pore pressure, the soil liquefies.

This is relevant to many fields, not the least being earthquakes which can loosen compacted soil and compact loosened soil. When this happens, buildings sink and buried structures float to the surface, as happened in the San Francisco Bay area in the 1989 Loma Prieta earthquake. Yet another example can be seen on the Moon in the terraced walls of crater Copernicus. After the impact that formed the crater, gases trapped in the soil caused the lunar soil to lose strength and slide. The mechanics of soil under medium to high integranular stresses are well known, but the behavior under low stresses is not. Studies under high stresses have been carried out on Earth for decades. But studies under low effective stresses have been hampered by the Earth's gravity. The weight of the soil has many effects on the test, including making it difficult to maintain a stable specimen at low stresses.

The weightless environment of space allows soil mechanics experiments at low effective stresses with very low confining pressures. In space, specimen weight is no longer a factor, and the stress across the specimen is constant. This allows correct measurements that can be applied to larger problems on Earth. Information to be examined by MGM includes load, deformation, and fluid pressure data gathered during testing, as well as changes in the soil structure, including the formation of shear bands and change in density.

Scientific investigations with MGM will span the STS-79 and -89 missions. STS-79 gathered useful scientific data and calibrated the MGM apparatus to understand its behavior.

Granular mechanics touch on many disciplines

Numerous technologies involve bulk solid-flow processes, including: storage, handling, processing and managing coarse grains materials and powders; the designs of silos, powder feeders, conveyors, and systems for processing coal, ash, limestone, cement, grain, pharmaceuticals, fertilizers.

Geologic processes are closely related. Wind and river transport processes are controlled by the properties of cohesionless granular assemblies. Liquefaction phenomena observed in unconsolidated and cohesionless soil deposits during earthquakes are governed by constitutive, dilatancy, and stability properties. When intergranular stresses or pressures become very low, as during earthquake-induced liquefaction, the soil-water composite momentarily acts like a viscous liquid, allowing buildings to sink and tilt, bridge piers to move, and buried structures to float.

Principal Investigator: Dr. Stein Sture, University of Colorado at Boulder.

Project Scientist and Co-investigator: Dr. Nicholas C. Costes, Marshall Space Flight Center, Huntsville, Alabama.

Project Manager: Buddy V. Guynes, Marshall Space Flight Center, Huntsville, Alabama.

Cover pictures show an MGM test cell after flight (top), and a computerized tomography (CT) scan cross-section of a specimen. High-resolution images from this fact sheet are on-line at: *http://science.msfc.nasa.gov/newhome/headlines/msad06jan98_1.htm*. (University of Colorado, LANL pictures)

For STS-89, the software has been modified to expose the sand to a broader range of loading conditions.

Potential applications of MGM results

- Soil mechanics, geotechnical engineering
- Earthquake engineering
- Mining (open pits, strip mines, tunnels, shafts)
- Granular flow technologies (grain silos, powder feed systems; handling of coal, ash, pharmaceuticals, and fertilizers)
- Coastal and offshore engineering
- Geological and geophysical processes (wind and water erosion of soil, slope development and decay, deposit of volcanic materials)
- Off-road vehicle engineering
- Planetary geology
- Microgravity handling of powders

Hardware

The heart of the second MGM experiment is a set of six test cells, each containing a sleeve of 1.3 kg (2.8 lbs.) of sand, 7.5 cm in diameter by 15 cm tall (3 x 6 in.).

These experiments use Ottawa F-75 banding sand, a natural quartz sand (silicon dioxide) with fine grains (0.1 to 0.3 mm diameter) and little variation in size. Because Ottawa sand is widely used in civil engineering experiments and evaluations, its use on MGM will allow results to be compared directly with results from experimental results already obtained on Earth. The soil specimen is contained in a latex sleeve that is 0.3 mm thick and printed with a grid pattern so cameras can record changes in shape and position.

Each specimen is contained in a test cell shaped like an equilateral prism and comprising a Lexan jacket sandwiched between metal end plates connected by guide rods. Within the Lexan jacket the cell is filled with water and pressurized to keep the specimen confined and stable during launch and re-entry. Special platens of polished tungsten carbide (for hardness and low friction) are placed on the top and bottom ends of the specimen. An electric stepper motor on top of the test cell moves the top platen up and down. A load cell measures the force imparted to the specimen.

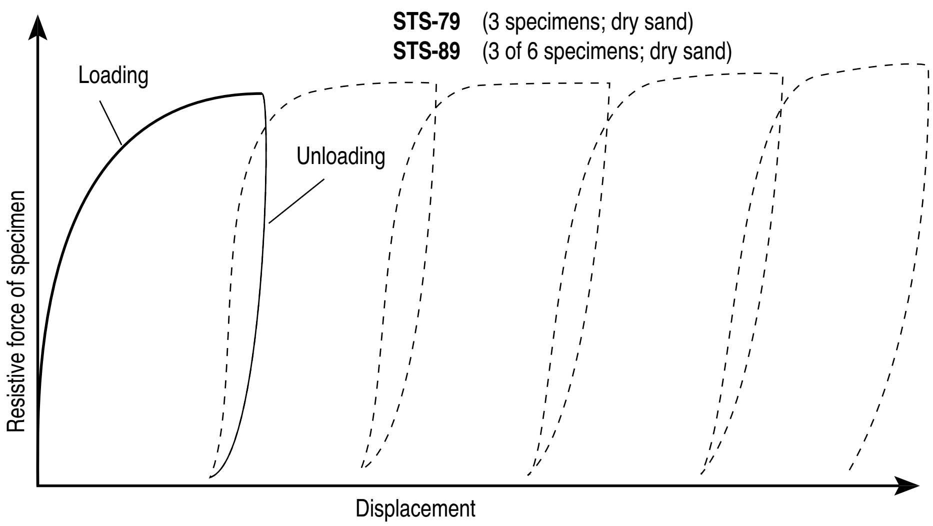
During the experiment, a test cell is held on a rigid test/observation pad mounted between an array of three CCD cameras and banks of small light-emitting diodes. The MGM video control system electronically interleaves the images for a video recorder. The systems are controlled by the Payload General Support Computer (PGSC), a laptop computer operated by the flight crew.

MGM hardware was designed and developed by Sandia National Laboratories, U.S. Department of Energy, in Albuquerque, N.M.

Operations

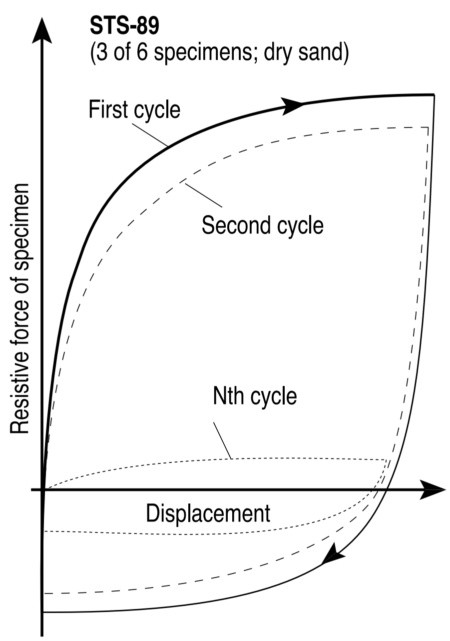
At the start of MGM activities in space, the crew opens the lockers and removes the test cells from their storage positions. One test cell is installed on the test/observation pad and the others are stored until needed. The crew connects the PGSC and the video system, and connects electrical lines for power and data. They also insert new memory cards for the start of experiments with each new test cell. The crew activates each experiment sequence via the PGSC, but the experiments will be automatic once started.

Using the PGSC, the crew commands the stepper motor to drive the platen against the specimen at a speed of 35 mm/hr (1.4 in/hr). This compresses the specimen by 37.5 mm by the end of the experiment. During the relief phase of each cycle, the specimen may expand by up to 9 mm as the individual grains shift and realign. The latex sleeve will move with the sand so the grid pattern reveals changes to the cameras.



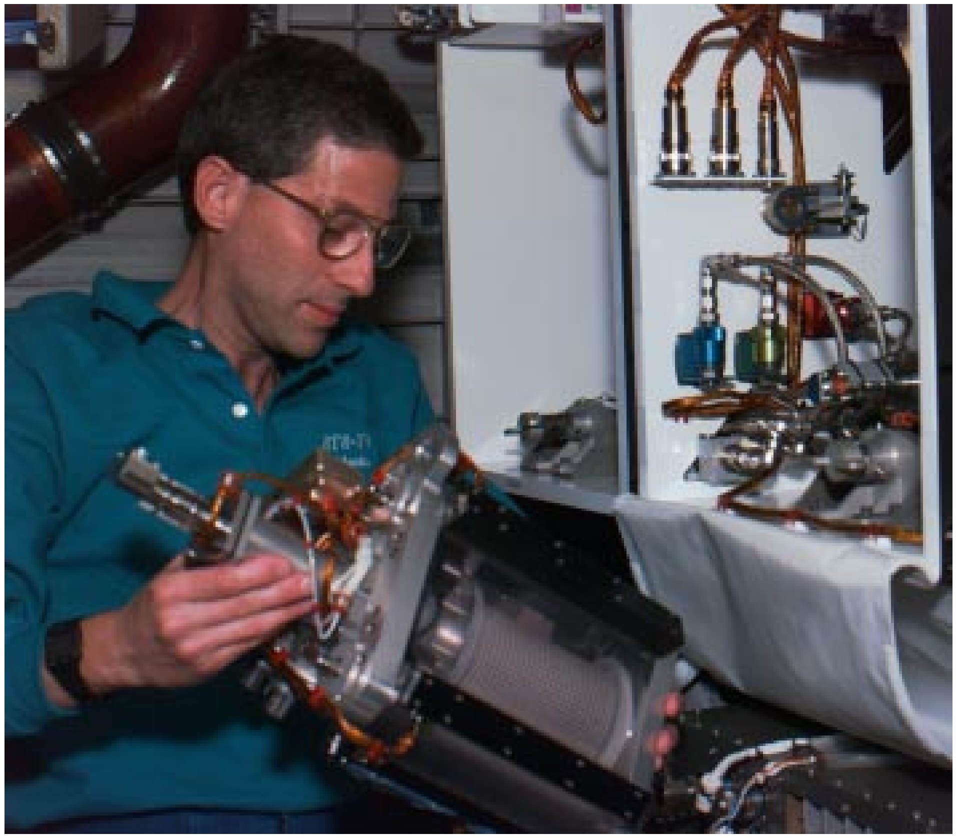
On STS-89, three MGM test cells will be subjected to five cycles of compression and relief (top) and three will be subjected to shorter displacement cycles that simulate motion during an earthquake (right). In the compression/relief tests, the sand particles will rearrange themselves and slightly reexpand the column during relief. Ultimately, each cycle will slowly shorten the column while making it wider. Total displacement is expected to be about 38 mm (1.5 in.).

In the short displacement tests (right), the specimen's resistance to compression decreases, even though the displacement remains the same. The specimens will be cycled up to 100 times or until the resistive force is less than 1% that of the previous cycle. The force and displacement scales of the two graphs are different, with the displacement expected to total about 0.5 mm (0.02 in.) after 5 cycles, and 5 mm (0.2 in.) after 100 cycles. The curves shown are representative of the forces and displacements expected during the tests.



The test will proceed in five discrete cycles, consisting of a compression and a rebound. The specimen is expected to increase in volume and decrease in density. This means the specimen actually gets bigger and looser as it is compressed, the same phenomenon often seen processes involving granular materials.

Six MGM test cells will be flown on STS-89. On STS-79, air filled the gaps between sand grains. On STS-89, the sand will be less dense (65% vs. 85%). The experiments will repeat the STS-79 sequence both for calibration against the STS-79 specimens and for scientific data. Then the other three test cells will load their specimens with small-displacement compression/extension cycles. These conditions match those of an earthquake.



Astronaut Jerome Apt installs an MGM test cell, in its water jacket, in a locker in the Spacehab module for experiment runs during STS-79. Operations and equipment for STS-89 will be identical.

STS-79 preliminary results

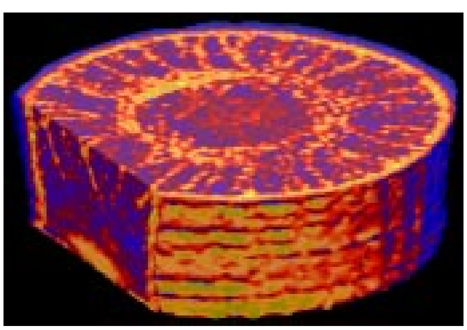
All three MGM test cells were processed as planned during the mission. Data include three video images of each cell taken every second, plus nearly 15 megabytes of pressure measurements.

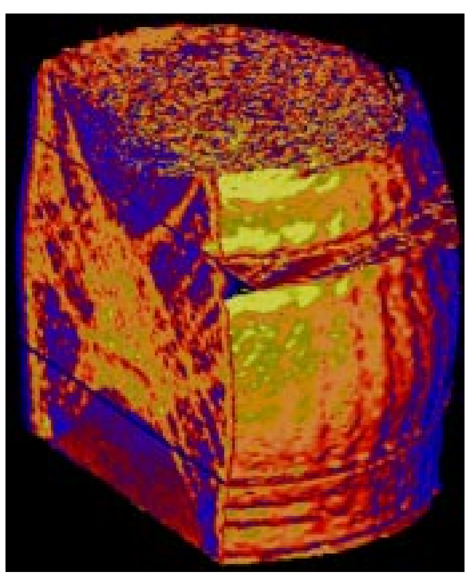
After return to Earth, each specimen was impregnated with an epoxy to stabilize the sand column so it could be handled. A silhouette of each cell was obtained every 5° (72 edge profiles in a full rotation) and converted into measurements of the cell diameter vs. preflight diameter.

Next, the cells were examined by computer tomography (CT scan) at Los Alamos National Laboratory. A 1024x1024-pixel image was made every 1 mm along the length of the specimen for up to 120 images per column. From this, three-dimensional images were produced to reveal internal details. The last examination involved sawing the columns into disks to allow detailed inspection under an optical microscope.

The CT scans show features unlike those seen in ground-based tests. Cross-sections have areas of generally uniform density outside of shear zones. Cross-sections at right angles to the axis of compression show lower and higher density areas seeming to separate into radial streams, tied together toward the center of the specimen, and at right angles to the outer surface. In vertical sections, a shear cone and shear plane are visible.

The data processing and analysis effort thus far has been very successful and shows exciting results giving researchers unique data on the mechanics of granular materials. One finding is that gravity appears to hinder load oscillation phenomena which are much more distinct in the flight data than in ground testing. New peak strength and friction angle information show promise of proving a long-term hypothesis in the geotechnical community. ❑





CT scans of the specimens on STS-79 reveal internal cone-shaped features and radial patterns not seen in specimens processed on the ground. The lighter areas are the densest in these images. CT scans produced richly detailed images allowing scientists to build 3D models of the interior of the specimens that can be compared with microscopic examination of thin slices. (LANL images)

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