National Aeronautics and
Space Administration

Educational Product	
Educators & Students	Grades 5-8

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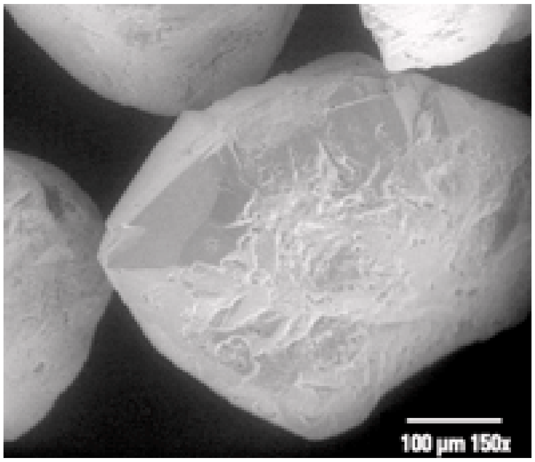
Educational Brief

Using Space for a Better Foundation on Earth
Mechanics of Granular Materials

For the Educator

Anyone who has ripped open a vacuum-packed pouch of coffee has experienced a fundamental aspect of mechanics of granular materials: a single shift in conditions can drastically change the properties of a bulk material. While the coffee pack is sealed under vacuum (negative pressure), the grains push against one another, locking each other in place, creating a stiff “brick-like” material. Once pressure is released, the grain assembly softens and moves freely, almost like a liquid.

The principal strength of granular materials—whether they are coffee, soil beneath a house, or sand under a rover’s wheels on Mars—is the friction between between particles. Billions of grains, ranging in size from large to microscopic, contribute to the total strength of the material. Moisture and air trapped within the soil also affect its behavior if a load is applied faster than the entrapped fluid can escape. As the water pressure or air pressure within the pores increases, the effective or interparticle stresses or pressures decrease, weakening and softening the soil. When the external loading equals the internal pore pressure, the soil liquefies.



What look like boulders after a landslide are just sand grains seen under an electron microscope. Each tiny facet can stick to another grain and cause internal friction.

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 October 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.

Liquefaction phenomena

Sandy soils are usually good foundation soils as long as they are not subjected to shaking, a dynamic load condition. The packing density and degree of saturation (how much of the pore space is filled with water) are the main factors that will determine how the sand deposit will react to a dynamic or cyclic load effect (*e.g.*, earthquake load). When sandy soil deposits lie under the ground water table level in an earthquake-prone zone (like the U.S. West Coast or Japan), there is a high risk of sand *liquefaction* during a strong earthquake. Liquefaction occurs where loose packing of sand grains (*i.e.*, large void volumes between sand grains) exists under the water table (also called fully saturated sand layer). Cyclic loads, such as those caused by an earthquake, will cause sand particles to lose contact with each other as a result of a sudden increase in the pore water pressure. Therefore, the soil will have zero strength since there is no contact between particles. We say the soil liquefied. After the excess pore water pressure dissipates, the sand particles will settle in a more dense condition, which will result in excessive settlement for buildings and structures.

Studying soil strength in space

Detailed understanding of this phenomenon is needed to improve techniques for evaluating building sites here on Earth and, eventually, on the Moon and Mars, and to improve industrial processes that handle powdered materials. Research can only go so far on Earth because gravity-induced stresses complicate the analysis and change loads too quickly for detailed study. Going to orbit, though, opens new possibilities. The Mechanics of Granular Materials (MGM) experiment uses the microgravity of orbit to test sand columns under conditions that cannot be obtained in experiments on Earth. This new knowledge will be applied to improving foundations for buildings, managing undeveloped land, and handling powdered and granular materials in chemical, agricultural, and other industries. The microgravity environment of space allows soil mechanics experiments at low effective stresses with very low confining pressures to proceed slowly for detailed study. Specimen weight is no longer a factor, and the stress across the specimen is constant. This yields measurements that can be applied to problems on Earth.

MGM has flown twice on the Space Shuttle (STS-79 and -89), involving nine dry sand specimens. These were highly successful, showing strength properties two to three times greater and stiffness properties ten times greater than conventional theory predicted. On the STS-107 mission (scheduled for 2002), MGM scientists will investigate conditions with water-saturated sand resembling soil on Earth. Three sand specimens will be used in nine experiments.

Education standards

This education brief presents basic concepts related to strength properties and liquefaction phenomena in granular materials in a simple format suitable for school students (grades 5-8). Students are asked to conduct two experiments on sand to gain a qualitative understanding of strength liquefaction of sand. Education standards for grades 5-8 met by this classroom activity are listed below. For brevity, standards which are not met are not included in this list.

National Science Education Standards
(National Academy of Sciences)

Science as Inquiry
- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

Physical Science
- Structure and properties of matter

Science In Personal and Social Perspectives
- Natural and human-induced hazards
- Science and technology in local, national, and global challenges

History and Nature Of Science
- Nature of science

Standards for Technological Literacy
(International Technology Education Association)

Design
- The attributes of design.
- Engineering design.

Abilities for a Technological World
- Abilities to apply the design process.
- Abilities to use and maintain technological products and systems.

SAND LIQUEFACTION

Introduction

The coffee bricks found in grocery stores are a good example of how a **granular** material can behave differently based on its conditions. When the coffee pack is made, it is sealed under **vacuum**. This causes the grains to push against one another, locking each other in place. This creates a stiff "brick-like" material. When the package is opened, air enters and outside pressure is released. The coffee becomes very weak and soft, and moves about freely, almost like a liquid.

The main strength of granular materials – coffee, soil beneath a house, or sand under a rover's wheels on Mars – is **friction** and **interlocking** between particles. Billions of grains contribute to the total strength of the material. Water trapped within the soil also affect its behavior if a force is applied (called loading) faster than the water can escape. As the water pressure increases, the pressures between grains decrease. This weakens and softens the soil. When the water pressure is the same as the forces on the soil, the acts like a liquid. This is called **liquefaction**.

Figure 1. Excessive settlement in a building as a result of sand liquefaction. Earthquake of July 29, 1967, Caracas, Venezuela (National Geophysical Data Center)

This is important in many ways. First, earthquakes can make soil very loose. When this happens, buildings can sink in the ground (Figure 1) and buried structures float to the surface. This happened in the San Francisco Bay area in the 1989 Loma Prieta earthquake. It also happened on the Moon many times when meteors struck and formed craters. Gases were trapped between the lunar soil particles and caused the soil to lose strength and slide.

Sand liquefaction

Sandy ground is usually a good place to build a building. If earthquakes are common in that area, however, this might not be true. The soil **density** and amount of water in the soil determine how the ground will react to an earthquake. When sandy soil under the ground is very wet, there is a high risk of sand liquefaction (Figure 2) if an earthquake occurs. A loose packing of sand grains (*i.e.*, large volumes between sand grains) is shown in Figure 2a. The **loads** that develop during an earthquake will cause sand particles to lose contact with each other as a result of a sudden increase in the water pressure between the

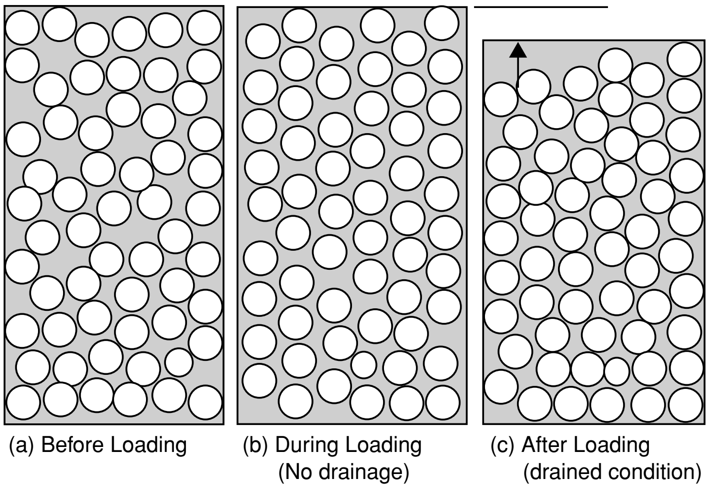


Figure 2. Representation of liquefaction in sands. (Credit?)

grains of sand (Figure 2b). Without the grains touching each other, the soil has no strength and the soil has liquefied. After the earthquake, the water pressure decreases and the sand settles (Figure 2c), which can result in settlement of buildings and structures.

Studying soil strength in space

Research can only go so far on Earth because gravity-induced stresses complicate the analysis and change loads too quickly for detailed study. Going to orbit, though, opens new possibilities. The Mechanics of Granular Materials (MGM) experiment (Figure 3) uses the **microgravity** of orbit to test sand columns under conditions that cannot be obtained in experiments on Earth. This new knowledge will be applied to improving foundations for buildings, managing undeveloped land, and handling powdered and granular materials in chemical, agricultural, and other industries.

The microgravity environment of space allows soil mechanics experiments at low **effective stresses** with very low **confining pressures** to proceed slowly for detailed study. Specimen weight is no longer a factor, and the stress across the specimen is constant. Small measurements in space can be applied to larger problems on Earth. MGM has flown twice on the Space Shuttle (STS-79 and -89), involving nine dry sand specimens. These were highly successful. They showed strength properties two to three times greater and stiffness properties ten times greater than expected. On the STS-107 mission (scheduled for 2002), MGM scientists will experiment with water-saturated sand resembling soil on Earth. MGM can also benefit from extended tests aboard the International Space Station, including experiments under simulated lunar and Martian gravity in the science centrifuge.

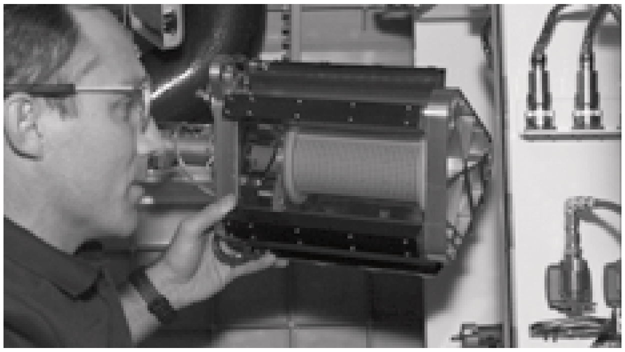


Figure 3. An astronaut inserts a soil sample module into the MGM apparatus in the Space Shuttle middeck. (NASA)

Materials

1. Large rubber balloon
2. Filter paper (~30 micron pore size; coffee filters are a good substitute)
3. Rubber stopper or cork (no special size needed) with hole large enough for a drinking straw.
4. Clean dry sand (~500 grams [17 oz.]) (from hardware, aquarium, or pool supply store)
5. Drinking straw
6. Small funnel
7. Water

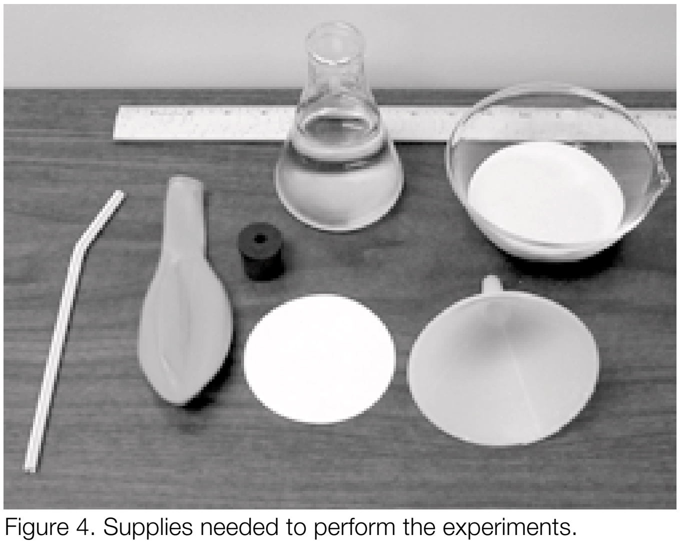


Figure 4. Supplies needed to perform the experiments.

Friction properties of sand

1. Drill a hole through the center of the rubber stopper with size equal to the straw and insert the straw. Then, cut the filter paper and glue it to the bottom of the rubber stopper (Figure 5).

2. Pour sand in the balloon (Figure 6). Stop when the balloon is approximately half full.

3. Hold up the balloon unsealed and squeeze it (Figure 7). Describe what you observe.

4. Attach the rubber stopper to the balloon and continuously suck out the air (a vacuum pump will give better results) until it becomes very hard (Figure 8). Squeeze the balloon while keeping the vacuum on, or while top is pinched closed. Describe what you observe.

Simulation of sand liquefaction

1. Remove straw, stopper, and vacuum pump, then repeat steps 2 and 3 of the previous section.

2. Fill the balloon with water as shown in Figure 9. This works best when you have enough water to ensure that the sand is completely wet, but you do not want the sand to be freely moving. Expect to add a volume of water equal to about half the volume of sand. A little extra water is okay. Massage the balloon and sand to help wet the sand and allow air to escape. A little air at the top of the balloon is okay. Tie the end of the balloon.

3. Hold balloon in one hand, and slowly squeeze the balloon. Record your observations.

4. Hold balloon in one hand, and squeeze the balloon in a series of quick pumping movements. Record your observations.

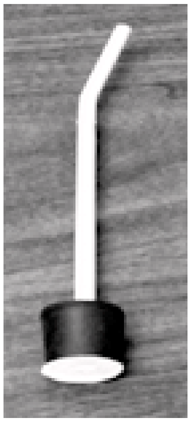


Figure 5. The rubber stopper with the straw.

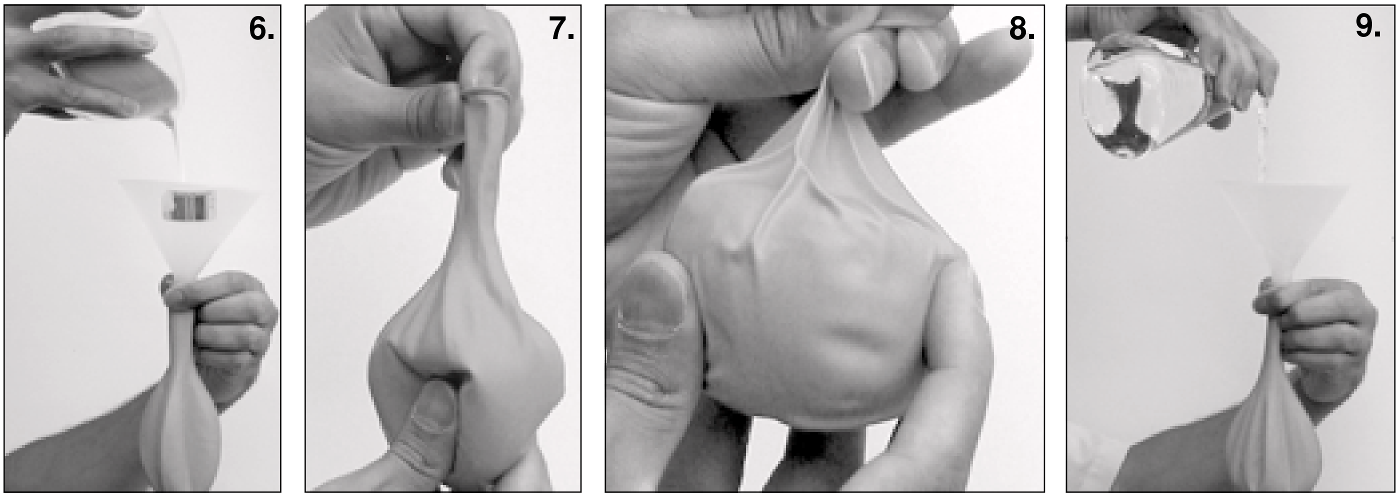


Figure 6. Sand fill process. 7. Balloon filled with sand and vented to atmosphere. 8. Sealed balloon under vacuum. 9. Filling balloon with water.

Report

Write a report about the experiment and answer these questions:

1. When you squeezed the dry sand in step 3, how did it feel?
2. Compare your observations with the dry sand steps 3 and 4. In which case is the sand harder (stronger)? Why?
3. What happened to the sand grains when you squeezed the balloon with the wet sand?
4. What happened to the sand grains when you quickly squeezed / pumped the balloon with the wet sand?
5. When you walk on the beach, why do your feet sink in the sand?
6. Extension: Consider clay (modeling clay is a good example). How do you think it would behave in the above experiments? Why do you think clay behaves this way?

1. ________________________

2. ________________________

3. ________________________

4. ________________________

5. ________________________

6. ________________________

Comments and explanations for the educator

Friction properties of sand

The dry sand (Step 3) should move very easily when squeezed. There is very little to keep the sand from moving: little frictional resistance is needed because there are low forces between the particles. When a vacuum is placed on the sand (Step 4), the particles are being pulled together and it takes more force to squeeze the sand. Two things are causing this: 1) the grains interlock so particles are in each other's way and must work harder to move around each other, 2) the grains are pulled together by the vacuum, and the higher force between the particles increases the frictional resistance of the grains to being moved.

Simulation of sand liquefaction

Do not overfill the balloon: Students do not need to have water-balloons at their disposal.

The idea with this experiment is to cause the soil to liquefy. When you slowly squeeze the sand, it will feel similar to the dry sand. It will move fairly easily, but will not flow like a liquid. You can also feel the 'grittiness' of the sand moving grain-on-grain (caused by friction). As you slowly move the sand, the water can move in and out of pore spaces, so you have particles in contact and they are transferring forces caused by your squeezing. When you pump it in your hand, it will relax and the pumping will get easier, and you will not feel the grittiness of the sand. What is happening is that you are increasing the water pressure because the water does not have time to move in and out of the pore spaces. As the water pressure increases, the water starts transferring the forces caused by the quick squeezes leaving no forces between the grains. This allows the grains to move around freely, as if it is a viscous liquid (such as molasses). This can be felt by the pumping hand, or if you place a finger on the surface while it is being pumped. Also, you can easily change the shape of the sand by this method, so if you start out by making the balloon somewhat flat or rectangular, it will return back to a round-ish shape from the pumping.

More information on liquefaction is at *http://www.ce.washington.edu/~liquefaction/html/main.html*

Report

Possible answers to the questions:

1. The sand felt soft, somewhat gritty, when squeezed.

2. The sand was stronger under the vacuum. Under low pressure, it can still be squeezed and the gritty texture is still present. Under a high vacuum, it can be very difficult or impossible to deform the sand by squeezing it between one's fingers. The sand under vacuum is stronger because the vacuum pulls the sand grains together, causing an interlocking structure. Also, because of the higher forces pulling the sand grains together, the friction is also higher. In order to move the grains, the higher friction must be overcome, so it takes more force.

3. The sand moved easily, but felt very gritty as it moved.

4. After a series of pumps, the grittiness disappeared and it felt as if only water was being pumped.

5. On the beach, the dry sand moves easily under one's feet. It is sometimes hard to walk very fast because the sand does not stay in place. This is because the sand is in much the same conditions as the dry sand in the balloon (with no vacuum). There is very little holding the sand together, so there is very little friction on sand. Without that friction, the sand has very little strength and will move when one steps on it. This is much the same problem as one has with building sand castles.

6. Clay has much smaller particles and with even a very small amount of water (some water is often present in soils) it sticks together. This is due to its physical and chemical characteristics. In these experiments, consider using the idea of modeling clay (such as Play-Doh™.) It will squeeze through your hands, but it will stay together. (Sand particles, on the other hand, do not stay together (Question 5).) Under a vacuum, the clay will also be stronger. During the quick pumping, the student would not attain the freely flowing liquid-like state (liquefaction) because even if there are not outside forces holding the clay together, it holds itself together. It does not require outside forces to cause friction to hold itself together, as sand does.

Glossary

confining pressure — the initial load per unit area on a plane at right angles to the direction of the load
density — the mass per unit volume of a substance
effective stress — the average stress carried by the soil particles
friction — a force that resists motion when one object slides over the surface of another
granular — having a grainy texture
interlocking — to connect together so that the individual parts affect each other in motion or operation
liquefaction — the conversion of a solid or a gas into a liquid
load — anything that must be supported or moved
microgravity — an environment in which the apparent weight of a system is small compared its actual weight due to gravity
vacuum — a space in which the pressure is significantly lower than atmospheric pressure

Web links

Mechanics of Granular Materials experiment home page at NASA, *http://mgm.msfc.nasa.gov/*
Mechanics of Granular Materials experiment home page at the University of Colorado at Boulder, *http://bechtel.colorado.edu/~batiste/*
Putting the squeeze on sand will expand understanding of soil mechanics (Jan. 6, 1998). *http://science.nasa.gov/newhome/headlines/msad06jan98_1.htm*
Soil mechanics experiment makes clean sweep (Feb. 4, 1998) *http://science.nasa.gov/newhome/headlines/msad04feb98_1.htm*
Microgravity research at NASA, *http://microgravity.nasa.gov*
Microgravity research on STS-107, *http://microgravity.nasa.gov/STS-107.html*
NASA education web site: *http://education.nasa.gov/*

Acknowledgements

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Using Space for a Better Foundation on Earth
Mechanics of Granular Materials
Teacher Reply Card

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Please take a moment to respond to this questionnaire. Please respond by mail.

Future versions will allow you to respond through the Internet at

http://ednet.gsfc.nasa.gov/edcats/teacher_guide

The page will instruct you on how to enter your responses.

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____ Community college
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Number of others?
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____ Other:

2. What is your home or school 5- or 9-digit Zip code? _ _ _ _ _ - _ _ _ _

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☐ Excellent ☐ Good ☐ Average ☐ Poor ☐ Very poor

Fold along line and tape closed.

4. How did you use this teacher's guide?
- ☐ Background information
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- ☐ Integration into existing curricula
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- ☐ Demonstration
- ☐ Hands-on activities
- ☐ Interdisciplinary activity
- ☐ Science and mathematics standards integration
- ☐ Other. Please specify: ____________________

5. Where did you learn about this teacher's guide?
- ☐ NASA Education Resource Center
- ☐ NASA Central Operation of Resources for Educators (CORE)
- ☐ Institution/school system
- ☐ Fellow educator
- ☐ Workshop/conference
- ☐ Other. Please specify: ____________________

6. What features of this teacher's guide did you find particularly helpful?

____
____
____

7. How can we make this teacher's guide more effective for you?

____
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8. Additional comments:

____
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