The Spaces Between

Caltech geologists and engineers are exploring how the nooks and crannies amid particles help create Earth’s most beautiful landscapes—as well as its most dangerous landslides and avalanches.

By Katie Neith

At first glance, an hourglass filled with sand appears to be a simple object. If all the sand is at the bottom of the apparatus, you can flip it over and watch as the grains trickle back down, marking a set amount of time.

“Sometimes the way you would intuitively expect—when half the time is gone, half the sand will be at the bottom,” says mechanical engineer Melany Hunt. And yet, that intuitive sense only applies to sand; as Hunt points out, “If it were a liquid, it wouldn’t work that way—the rate of flow would depend on factors like the liquid’s height above the neck, which would change the liquid’s discharge speed.”

Sand is much more low-maintenance and predictable: its particles just sort of temporarily lock together and tumble down into the bulb below at a set rate, making it the ideal timekeeping material. And yet, no one knows exactly how to predict the flow field. Indeed, the simple-sense complex mechanics of an hourglass encapsulate some of the most intriguing questions in geophysical science and engineering: Why and how do granular materials behave differently than liquids? And what happens when we combine the two?

Natural Grains

Mechanical engineer José Andrade is on a mission to understand the mechanics and physics of granular materials—how individual grains in nature, like those we see in soil, snow pellets, and porous rocks, interact with one another and the environment around them. Understanding that interaction is important because such insights are useful for everyone from geotechnical engineers trying to build structures on different types of soil to mathematicians studying how the movement of material changes the shape of Earth’s surface, the spaces between particles become really important when, for example, rock turns into sediment.

“Rock doesn’t have much space between its grains,” explains Lamb. “Rock turns into sediment when it either gets broken apart physically, or chemically through dissolution and weathering. We study all the steps in those processes: how rock turns into soil to how the sediment or soil then makes its way down the sides of mountains, through rivers, and out to ocean basins.”

Lamb does many of these studies in Caltech’s Earth Surface Dynamics Laboratory (or the Flume Lab), a huge room he designed that’s filled with sand dunes. In short, it’s the liquids we interact with martian landscapes (see “On Alien Soil,” page 33). And yet, that intuitive expectation is gone, half the sand will be at the bottom. And what they’re all related by, he says, is space. It’s the space between the particles that controls each and every one of these processes—and more. Without the spaces between particles, there would be no movement—no giant canyons worn by wind and water, no flowing rivers, no landslides or sand dunes. In short, it’s the liquids and gases located in between bits of granular material that are critical in determining how these substances move over land and through time.

For field geologist Mike Lamb, who works primarily on questions about how the movement of material changes the shape of Earth’s surface, the spaces between particles become really important when, for example, rock turns into sediment. Lamb and his team can then send up to 10,000 gallons of water per minute—enough to transport fist-sized rocks into a giant room he designed that’s filled with sand dunes. In short, it’s the liquids and gases located in between bits of granular material that are critical in determining how these substances move over land and through time.

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Students from Melany Hunt’s lab, along with a few volunteers, set up an array of 50 geophones for a seismic vibration experiment that allowed them to uncover wave speeds within the dunes, located at Dumont Dunes, California. The geophone strip was formed from Rob Clayton, professor of geophysics at Caltech, who uses it in earthquake studies.

Another tank in the lab models the large body of water, and what happens changing climate and tectonics.”

sediment, both of which evolve under sediment is necessary to erode the mountainside. In this way, he can just like the bedrock on any local regular rock, but otherwise acts foam that erodes much faster than the same spaces between grains that are emerging from the top layer, why is the boom a single note? “There’s only a certain frequency that’s transmitted efficiently through this waveguide, which is what you hear with this booming phenomenon,” explains Hunt. And it doesn’t happen every time. “You have to have the right conditions,” she adds. “The dune has to be large enough—at least 150 feet tall; it has to be very, very dry; and you have to have a slope to generate the sound in the first place.”

Debris Dangers
Of course, research into granular flow—the movement of discrete, solid particles—is not all fun and games. Beyond landslides and debris and creating avalanches by sliding down sand dunes, there are processes involving granular materials that not only result in the movement of materials but also threats to life and property—processes such as liquefaction. “Liquefaction is the process of energy conversion,” she says. “Getting a vehicle to move over granular materials, or loose grains, is always much less effective than anything else we can envision—they travel at incredibly slow speeds and are extraordinarily inefficient in terms of energy conversion,” she says. Mechanical engineer José Andrade points out that a deep knowledge of how foreign materials are likely to behave is essential for these scientific missions to other planets. He and his team are working on modeling the best way for a penetrator, or mole, to dig itself into martian soil; such a piece of equipment is likely to be a key part of the InSight mission to Mars being planned for 2016.

“We love our planetary science projects,” Andrade says. “What’s really exciting is that the understanding of the mechanics and physics of granular materials—understanding how the spaces between particles control both mechanical and behavioral features—is extremely important. In fact, it’s mission crucial in some cases . . . no matter what planet you’re on.”

On Alien Soil

Researching the way grains flow through space and time on Earth has led to some far-reaching applications—literally. Geologist Mike Lamb, for instance, has used results from his lab’s sediment transport experiments on Earth to do calculations for features on Mars, which has a number of dried-up channels. “If you see a big river canyon on Mars, you know that to carve that canyon, water must have at least been sufficient enough to move the sediment that’s in the canyon,” explains Lamb. “Sediment transport constraints allow us to put a minimum bound on the water discharges that might have carved these ancient river canyons on Mars.”

Mechanical engineer Melany Hunt has been involved in granular-flow simulations for planetary missions as well as research into terramechanics, or how different vehicles—including those like the Curiosity rover on Mars—interact with various terrains.
“When streams are steep enough, like in mountain areas, sometimes debris flows or landslides occur after a large area in storms where we would normally expect to see a river,” says Lamb. “In the Flume Lab, we are doing experiments in steep river flumes by directing flowing water over grains suspended in water rarely touch to see what conditions result in normal river transport of sediment, versus conditions that produce catastrophic debris flow in which tons of material come barreling down.”

In rivers, Lamb explains, sediment grains suspended in water rarely touch each other when they are flowing downstream—it’s only on the cobbled that they come in contact with each other. But in a debris flow, the grains collide with and scrape against one another and, somehow, that makes the behavior of debris flows quite different from that of rivers. It’s that difference that allows debris flows to pick up and carry large boulders long distances; it’s that difference that makes them so destructive.

“We’re trying to understand why mountain channels that usually transport sediment by river processes—which aren’t typically hazardous—sometimes switch to produce debris flows,” says Lamb. Understanding this switch, he adds, could also help explain why landslides often occur after wildfires. “It must have something to do with the spaces,” he says. “The key thing that makes debris flows different is that the spaces between grains are small. We hope our work can lead to better predictive models for helping response teams decide when, after a wildfire, to call for resources to protect communities, and when it’s too late.”

“Debris flows or landslides occur after a catastrophic event like in mountain areas, sometimes switch to produce debris flows,” says Lamb. “These processes have to be saturated with a fluid—usually water—and then something needs to ‘exist,’ or shake, the soil, like an earthquake.

“When the ground is deforming because of an earthquake, the space between the grains can’t contract, but it can’t because the water is there,” explains Andrade. “And so the grains separate. The fluid that fills in these spaces, which increases pressure in the water, which then pushes back on the grains, keeping them apart. Since the way that these grains transmit forces is by contacting each other, when a sand grain cannot contact its neighbor, it cannot transmit force anymore, and it starts effectively flowing in this water—that’s what liquefaction is.”

By understanding these basic mechanisms, Andrade has been able to start building models to help identify the precise conditions under which liquefaction might occur. This type of information would be particularly useful in earthquake-prone Southern California, where many homes and businesses are built on sandy ground.

“We’ve been very successful in predicting when liquefaction will occur in the laboratory, but we haven’t been able to explain why,” he says. “One of my students is working tirelessly on a model that seems to be able to explain why, so we’re very excited about that.”

The Basics of Flow

Melody Hunt and some of her students have also recently begun to take a closer look at how liquefied and sands mix, but from the other way around. They’re looking to see what happens when you have a pure liquid and you start adding particles to get to a granular flow.

“As you add solids to a liquid, what are the forces involved in moving that material?” asks Hunt. “For example, there are tanks full of nuclear waste—solids and liquids that need to be moved using a pump. It’s not pure liquid by any means, so how do you move a liquid with potentially heavy particulate matter in it? What are the forces that will be involved? What do you do with this stuff when you can’t predict its properties? These are the problems that we’re trying to figure out.”

She points to the Deepwater Horizon / BP oil spill in the Gulf of Mexico in 2010 as an example of how little people know about the interaction between solids and liquids.

“In trying to stop the spill, they were just injecting different substances—like drilling fluids or cement—into the pipe, hoping to clog it, without any real knowledge about what these things were going to do when they get into the well bore and mixed with the liquid,” Hunt says. With more information—information Hunt and her colleagues are currently trying to gather—future spills like this might be easier to halt or even reverse.

Whether it’s snow tumbling down a mountain or “silt” sand and silt suddenly acting like a liquid, or solutions of liquids and solids in need of transportation, the cluster and mysterious behaviors of these ubiquitous granular materials have yet to be cracked, but the effort continues.

“That’s the thing that keeps me excited about the work we do—the beauty of the behavior of these materials that are so very complex and difficult to understand,” says Andrade. “They give us gorgeous puzzles to work on.”

José Andrade is professor of civil and mechanical engineering. His research on granular materials is funded by the National Science Foundation (NSF), the Defense Threat Reduction Agency’s Defense Threat Management and Countermeasures Office of Scientific Research, and the Kast Endowment for Space Studies (KISS).

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