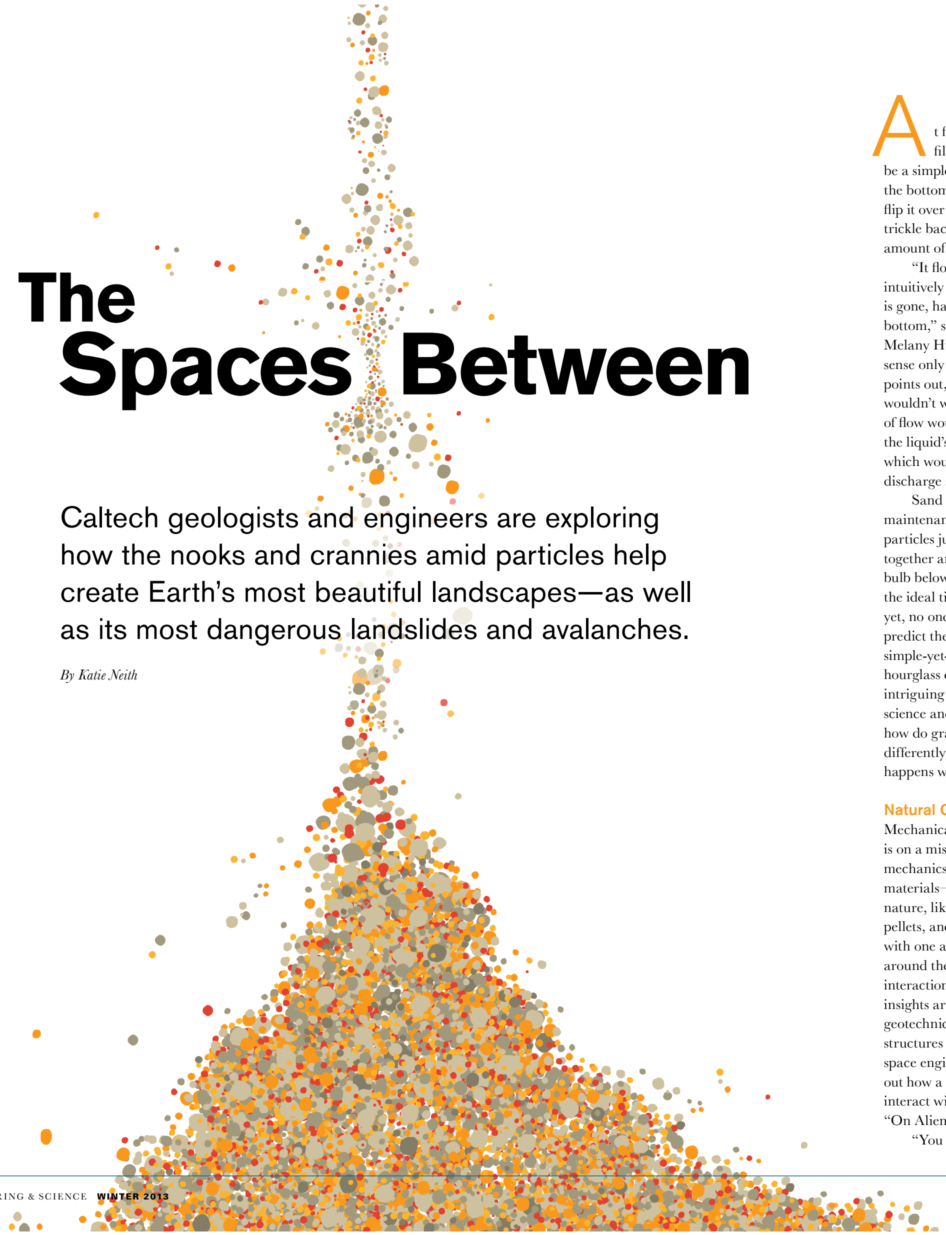


The Spaces Between

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.

"It flows 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-yet-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 space engineers interested in figuring out how a rover or spacecraft might interact with martian landscapes (see "On Alien Soil," page 33).

"You also have things like avalanches, or the way earthquakes nucleate in faults due to granular processes, or the extraction of hydrocarbons and the injection of fluids into reservoirs for geologic CO_2 sequestration—they're all related," says Andrade.

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.

"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: from 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 giant room he designed that's filled with chutes and tanks—a place where scaled-down versions of major landscape features like waterfalls and river deltas can be created.

"Most of the processes that shape Earth's surface happen over a long time compared to PhD dissertations or even our lives," says Lamb. "If we want to understand how a system works in its natural state—such as how and when a typical delta shifts over time—we have

Above, top: Hima Hassenruck-Gudipati, a senior studying mechanical engineering, pours sediment into a feed system for Mike Lamb's delta experiments in the Earth Surface Dynamics Laboratory. Above, bottom: To better understand the damage flowing water can cause, Lamb built several different kinds of artificial waterways, called flumes. The tilting flume pictured can be slanted to a steep 18 degrees; Lamb and his team can then send up to 10,000 gallons of water per minute—enough to transport fist-sized rocks and other types of debris—down the incline. The setup allows the researchers to gain insights into the consequences of mountain flooding while also predicting the impact of water erosion and its role in the evolution of mountain ranges over geologic time.

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

to make it evolve faster. Only then can we see these processes unfold."

One of the processes Lamb is exploring is how waterfalls help rivers cut into canyons over geologic time. Although waterfalls may seem like they're fixed in space, he says, they actually move upstream over long periods of time, as a sort of wave that cuts into the landscape. Because it's a process so slow that it can't really be observed in the field, Lamb has built a waterfall in the Flume Lab, using artificial rock made of polyurethane foam that erodes much faster than regular rock, but otherwise acts just like the bedrock on any local mountainside. In this way, he can speed up the processes and evaluate them as they are happening.

"We have found that coarse sediment is necessary to erode the pools at the base of waterfalls," Lamb says. "However, too much sediment will form a protective layer shielding the rock from erosion. This work suggests that the rates of waterfall erosion are set by a dynamic balance between the inputs of both water and sediment, both of which evolve under changing climate and tectonics."

Another tank in the lab models the way a river flows into an ocean or other large body of water, and what happens to sediment at that intersection. What happens, it turns out, is a delta—a fanlike landform made from sediment deposits at the mouth of the river. Over time, sections of the delta called lobes, as well as the river channel, shift around—a process whose dynamics are not well understood.

"I think our research speaks to people's desire to know what created and what impacts the beautiful landscapes around them," says Lamb. "Over geological time, we know that mountain ranges are rising and rivers are cutting through them, creating features like the Grand Canyon, but we still don't have a good understanding about how they formed, or how *fast* they continue to evolve."

Dune Songs

The same spaces between grains that shape what we see around us also sometimes shape what we hear. That's what Melany Hunt discovered when she first began, in the early 2000s, to try to pin down the conditions that lead to a unique phenomenon that occurs in some sand dunes, in which the dunes "boom." Loudly.

Called booming dunes, these mountains of sand play single notes—most often G, E, or F—when vibrations move through the sand grains. Those sounds can become amplified in the dune until the boom they create echoes across the desert. This phenomenon has been reported in more than 40 locations around the world, including South America, North Africa, and China.

What Hunt wanted to know is what makes these booming dunes different from the average silent pile of sand. "So we went out to the desert in Death Valley, generated the sounds, and tried to record them using seismic instruments. At the same time, we imaged the dunes using ground-penetrating radar," she says.

Generating the sounds on cue, however, required a little ingenuity. "You need an avalanche of sand to generate the sounds. That can happen naturally, with the wind just coming up and starting a slide on the surface. But the way we did it was to simply slide down the dunes on our back ends."

What their studies have shown is that in order for a dune to boom, there must be a top layer of relatively loose and very dry sand. When that dry top layer begins to slide, the friction between grains generates a whole range of sound frequencies on the dune's surface. If there is a wetter, more tightly packed layer of sand below the surface layer, that dense lower layer will reflect the sound waves, creating what is called a waveguide—a structure that conducts waves in a particular direction—in the loose top layer.

But if that entire range of sounds is 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 slide 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 flumes. Beyond hourglasses and deltas and creating avalanches by sliding down sand dunes, there are processes involving granular materials that not only result in the movement of materials but in threats to lives and property—processes such as big-time avalanches and landslides, and an earthquake-related phenomenon called liquefaction.

In addition to his work on the movements of waterfalls and the effects of river flows, Lamb also uses his Flume Lab to look at specific kinds of large-scale slides—mostly debris flows, or landslides.

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.

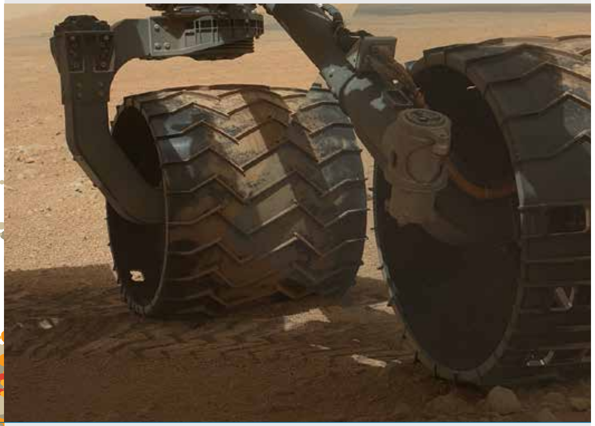
"If you see a big river canyon on Mars, you know that to carve that canyon, water must have at least been sufficient enough to move the sediment that's in the canyon," explains Lamb. "Sediment transport constraints allow us to put a minimum bound on the water discharges that might have carved these ancient river canyons on Mars."

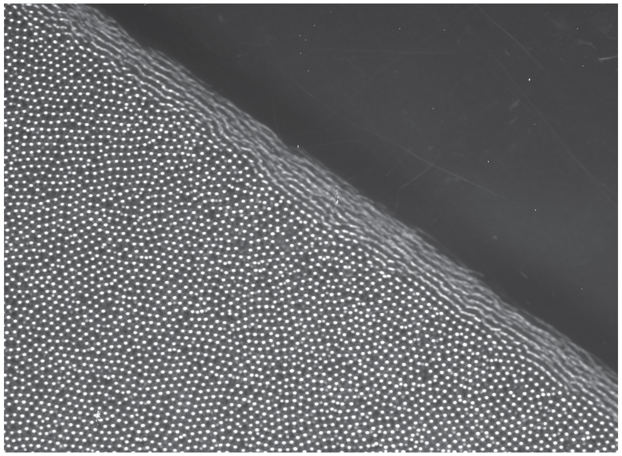
Mechanical engineer Melany Hunt has been involved in granular-flow simulations for planetary missions as well as research into terramechanics, or how different vehicles—including those like the Curiosity rover on Mars—interact with various terrains.

"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."





Above: A high-resolution image of a tiny, granular avalanche as it occurs in José Andrade's laboratory shows a blurry, flowing layer of material on the surface. Video recordings of his benchtop experiments give important clues into the lifecycle of an avalanche.

“When streams are steep enough, like in mountain areas, sometimes debris flows or landslides occur after a large storm in areas 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 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 riverbed 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 evacuations out of fear of debris flows.”

He notes that his research can have other, less disaster-oriented applications as well—such as in efforts to restore fish habitats in rivers.

“River restoration involves understanding how sediment movement works, since fish spawn in the spaces between gravel and cobbles,” says Lamb. “Salmon, for example, build nests out of certain-sized gravel by moving it around with their tails. If the gravel is too big, they can't move it, and if it's too fine there's no space for the eggs. By understanding how sediment moves, we are developing better strategies to restore river habitats.”

The Life of an Avalanche

In his work to dig deeper into the workings of major avalanches, José Andrade, like Melany Hunt, utilizes benchtop experiments to create tiny versions of such events. He uses a rotating drum to spawn a mini avalanche and a video camera to record the lifecycle of the event—when it's born, how long it takes to get to its peak velocity, and when it dies, which in avalanche parlance means coming to a final halt. The movies these recordings create help him construct mathematical models that not only reproduce those events but also provide the means for possibly explaining *why* the avalanche was born, why it peaked when it did, and why it died. In this way, Andrade says, his work isn't just about trying to mimic behavior, but also about trying to understand it.

“Avalanches are a neat problem, because for some reason they connect with humans—everyone thinks that they know what you're talking about,” he says. “They can imagine something rushing down a slope and eventually hitting either people or infrastructure downstream.”

And yet, as it turns out, we know a lot less than we think we do. The surprising thing about avalanches, Andrade says, is that they are very ordered . . . that there is structure in the middle of all the chaos. But it depends on how you look at it. Somewhat ironically, if you watch an avalanche closely, he says, you'll see what seem to be disordered grains of snow bouncing all over the place. It's only when you zoom out a little bit that you begin to see how organized avalanches actually are. In the laboratory, avalanches show a very distinct and repeatable pattern, flowing roughly at the same angle and stopping at an angle several degrees lower. This pattern is very ordered and consistent, Andrade says.

“We're at a very basic science level with our research, but essentially what models are trying to do at the end of the day is make predictions,” he says. “You're always trying to get to the point where you can give a tool to decision makers so they can evaluate when and how bad things could be for a given environment.”

> “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.”

Andrade also looks at the often-destructive and typically earthquake-induced transition of sandy ground to a more fluid phase, a process called liquefaction. One essential ingredient for liquefaction to occur is space, or pores in the ground—relatively loose soil or sand makes the perfect terrain for liquefaction. But that's not enough, says Andrade. Those pores have to be saturated with a fluid—usually water—and then something needs to “excite,” or shake, the soil, like an earthquake.

“When the ground is deforming because of an earthquake, the space between the grains wants to contract, but it can't because the water is there,” explains Andrade. “And so the grains squeeze the fluid that lives 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 floating in this water—that's what liquefaction is.”

By understanding those 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 ferociously on a model that seems to be able to explain why, so we're very excited about that.”

The Basics of Flow

Melany Hunt and some of her students have also recently begun to take a closer look at how liquids 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 got into the well hole 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 mountainside, “solid” sandy ground suddenly acting like a liquid, or solutions of liquids and solids in need of transportation, the elusive 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.” E&S

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, the Air Force Office of Scientific Research, and the Keck Institute for Space Studies (KISS).

Melany Hunt is the Dotty and Dick Hayman Professor of Mechanical Engineering, and a vice provost at Caltech. Hunt's work described in this article was funded by the NSF and NASA.

Michael P. Lamb is an assistant professor of geology whose work is supported by the NSF, NASA, the American Chemical Society, KISS, and Caltech's Terrestrial Hazard Observation and Reporting Center.