Shifting sands: New model predicts how sand and other granular materials flow

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Photo: Lucy Lindsey

Sand in an hourglass might seem simple and straightforward, but such granular materials are actually tricky to model. From far away, flowing sand resembles a liquid, streaming down the center of an hourglass like water from a faucet. But up close, one can make out individual grains that slide against each other, forming a mound at the base that holds its shape, much like a solid.

Sand's curious behavior — part fluid, part solid — has made it difficult for researchers to predict how it and other granular materials flow under various conditions. A precise model for granular flow would be particularly useful in optimizing processes such as pharmaceutical manufacturing and grain production, where tiny pills and grains pour through industrial chutes and silos in mass quantities. When they aren't well-controlled, such large-scale flows can cause blockages that are costly and sometimes dangerous to clear.

Now Ken Kamrin of MIT's Department of Mechanical Engineering has come up with a model that predicts the flow of granular materials under a variety of conditions. The model improves on existing models by taking into account one important factor: how the size of a grain affects the entire flow. Kamrin used the new model to predict sand flow in several configurations — including a chute and a circular trough — and found that the model's predictions were a near-perfect match with actual results. A paper detailing the new model will appear in the journal Physical Review Letters.

"The basic equations governing water flow have been known for over a century," says Kamrin, the Class of '56 Career Development Assistant Professor of Mechanical Engineering. "There hasn't been something similar for sand, where I can give you a cupful of sand, and tell you which equations will be necessary to predict how it will squish around if I squeeze the cup."

Blurring the lines

Kamrin explains that developing a flow model — also known as a continuum model — essentially means "blurring out" individual grains or molecules. While a computer may be programmed to predict the behavior of every single molecule in, say, a cup of flowing water, Kamrin says this exercise would take years. Instead, researchers have developed continuum models. They imagine dividing the cup into a patchwork of tiny cubes of water, each cube small compared to the size of the entire flow environment, yet large enough to contain many molecules and molecular collisions. Researchers can perform basic lab experiments on a single cube of water, analyzing how the cube deforms under different stresses. To efficiently predict how water flows in the cup, they solve a differential equation that applies the behavior of a single cube to every cube in the cup's grid.

Such models work well for fluids like water, which is easily divisible into particles that are almost infinitesimally small. However, grains of sand are much larger than water molecules — and Kamrin found that the size of an individual grain can significantly affect the accuracy of a continuum model.

For example, a model can precisely estimate how water molecules flow in a cup, mainly because the size of a molecule is so much smaller than the cup itself. For the same relative scale in the flow of sand grains, Kamrin says, the sand's container would have to be the size of San Francisco.

Neighboring chatter

But why exactly does size matter? Kamrin reasons that when modeling water flow, molecules are so small that their effects stay within their respective cubes. As a result, a model that averages the behavior of every cube in a grid, and assumes each cube is a separate entity, gives a fairly accurate flow estimate. However, Kamrin says in granular flow, much larger grains such as sand can cause "bleed over" into neighboring cubes, creating cascade effects that are not accounted for in existing models.

"There's more chatter between neighbors," Kamrin says. "It's like the basic mechanical properties of a cube of grains become influenced by the movement of neighboring cubes."

Kamrin modified equations for an existing continuum model to factor in grain size, and tested his model on several configurations, including sand flowing through a chute and rotating in a circular trough. The new model not only predicted areas of fast-flowing grains, but also where grains would be slow moving, at the very edges of each configuration — areas traditional models assumed would be completely static. The new model's predictions matched very closely with particle-by-particle simulations in the same configurations.

The model, run on a computer, can produce accurate flow fields in minutes, and could benefit engineers designing manufacturing processes for pharmaceuticals and agricultural products. For example, Kamrin says, engineers could test various shapes of chutes and troughs in the model to find a geometry that maximizes flow, or mitigates potentially dangerous wall pressure, before ever actually designing or building equipment to process granular materials.

Kamrin says understanding how granular materials flow could also help predict geological phenomena such as landslides and avalanches and help engineers come up with new ways to generate better traction in sand.

"Granular material is the second-most-handled material in industry, second only to water," Kamrin says. "I'm convinced there are a million applications."

Provided by Massachusetts Institute of Technology

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