Team shows how rivers creep and flow to shape landscapes over time

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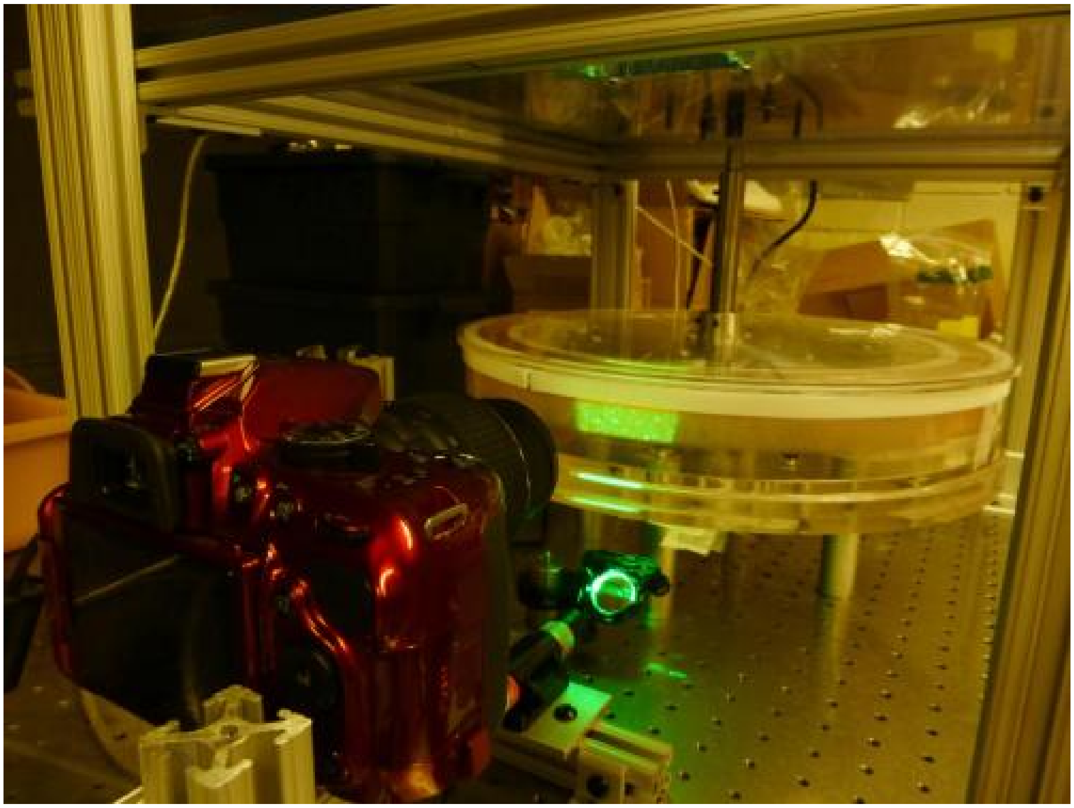

Researchers from the University of Pennsylvania spent two years constructing an 'idealized river,' a doughnut-shaped apparatus the size of a large fish tank. Within the 'river' a rotating lid drives the flow of liquid over a bed of spherical acrylic particles. By adding a fluorescent dye to the fluid and shining a laser through the apparatus, the team was able to produce images of the internal 'river bed' structure and precisely track the motion of individual particles over the course of days. Credit: University of Pennsylvania

Rivers drive the evolution of Earth's surface by eroding and depositing sediment. But for nearly a century, geologists have puzzled over why theoretical models, which use principles of physics to predict patterns of sediment transport in rivers, have rarely matched observations from nature.

"Anybody that needs to predict when particles on a landscape will move, such as when and how erosion will occur, needs better equations," said Douglas Jerolmack, an associate professor in the University of Pennsylvania's Department of Earth and Environmental Science in the School of Arts and Sciences.

Most models predict that rivers only transport sediment during conditions of high flow and, moreover, that only particles on the surface of the river bed move due to the force of the flowing water above. But using a custom laboratory apparatus, a new study led by Jerolmack shows that, even when a river is calm, sediment on and beneath the river bed slowly creeps forward. The study's new model of sediment transport—involving both the motion of surface grains pushed by flowing water and the creep beneath the surface resulting from interactions among particles—may substantially improve geologists' abilities to predict erosion rates and landscape evolution over time and could also help inform future civil engineering projects.

Jerolmack brought together a diverse team for the study, including Douglas Durian, a professor in Penn's Department of Physics and Astronomy, and Morgane Houssais and Carlos Ortiz, both Earth and Environmental Science postdoctoral researchers.

Their study will be published in the journal *Nature Communications*.

During flood events, rivers mobilize and erode large quantities of sediment. But for decades, geologists have faced a peculiar problem:

predicting, even roughly, how much sediment a flood of a given size will erode. Even within a single river, this quantity can fluctuate dramatically.

"Many people for a long time have assumed that the reason predicting particle erosion is hard is because there's turbulence and the flow force is fluctuating wildly," Jerolmack said.

He began to suspect that something else—besides more accurate fluid dynamics—was missing from sediment transport models when he noticed that the "threshold of motion," or the flow rate needed to begin mobilizing any sediment, was also highly inconsistent from flood to flood.

"The way in which the threshold of motion appeared to change from one flood to another made me suspicious that something else was going on, something not related to the fluid," he said.

Jerolmack, whose interests straddle the boundary between earth science and physics, is part of an interdisciplinary research group at Penn's Materials Research Science and Engineering Center that meets weekly. Through these meetings, he discovered that a lot of the strange behavior his research group observed in rivers was similar to behavior physicists and materials scientists observe in disordered materials, such as sand piles, foams and glass.

Jerolmack began discussing the problem with Durian, a soft-condensed-matter physicist whose work focuses on the structure and flow of disordered solids which lack a predictable molecular structure. The two researchers came to suspect that some problems facing sediment transport models might, indeed, have nothing to do with fluid dynamics but, rather, with the structure of the granular river bed itself.

"Granular-materials scientists understand that there's a changing resistance to motion all the time," Jerolmack said. "This led us to wonder if our system is just a subset of a broad class of systems other physicists have been studying."

When force is applied to a disordered solid like sand, the material undergoes structural reorganization, which can affect its resistance to motion. Jerolmack and Durian reasoned that rivers are granular systems where the force comes from the flowing current. Therefore the riverbed's granular structure would be altered by the flow, influencing its resistance to future motion.

"If the granular structure of the bed itself is changing over time, that could cause the threshold of motion to change from flood to flood," said Jerolmack.

To examine changes in a river bed's structure over time required a sophisticated experiment. Jerolmack recruited Houssais and Ortiz, who brought complementary expertise in river transport and small-scale particle dynamics, to tackle the problem. The team spent two years constructing an "idealized laboratory river," a doughnut-shaped apparatus the size of a large fish tank. Within the "river" a rotating lid drives the flow of liquid over a bed of spherical acrylic particles. By adding a fluorescent dye to the fluid and shining a laser through the apparatus, the team was able to produce images of the internal "river bed" structure and precisely track the motion of individual particles over the course of days.

From a series of experiments at different flow rates, the team observed three distinct types of sediment transport occurring simultaneously. Within the river itself, particles either flowed quickly and at lower concentrations near the surface of the water, or more slowly, at higher concentrations, near the river bed. But within the river bed itself, the researchers observed a third type of motion: exceedingly slow particle creep associated with structural rearrangements of the granular bed. All previous research had assumed these grains were immobile. This confirmed their suspicion that granular flow—flow resulting from grain-grain interactions—in addition to fluid dynamics, can contribute to the erosion of sediment in a river.

A significant implication of this discovery is that the elusive "threshold to motion" in a river might not actually exist; in other words, particle motion slows down, but does not stop, as the river current diminishes. Rather, even in calm rivers with slow currents, granular creep may still erode sediment, albeit imperceptibly slowly.

Image: USGS

Putting these insights together, the researchers confirmed their hunch that emerging theories describing the flow of disordered, granular systems can also describe all of the types of sediment transport observed in rivers; only a slight modification is needed to account for the fluid force. While sediment creep probably makes an insignificant contribution to erosion under high flow conditions, creep may represent the dominant erosional force during calm periods. But that idea remains to be tested in a natural system.

"We can't say anything about the level of creep in rivers because no one has ever measured it," Jerolmack said. "However, the slow creep of soil down a hillside due to gravity is well known, and a next step is to examine whether the underlying physics are the same."

The idea that creep may represent a missing mechanism in river erosion holds important implications. For instance, it's possible that by taking longer-duration measurements in the field, geologists will be able to capture more of the sediment transport due to creep, improving their overall erosion estimates within a system. This, in turn, may improve predictions of how a landscape will evolve over time.

"People often wonder how long they have to measure sediment transport in rivers to get a reliable result," Houssais said. "We were able to infer the time you need to overcome the variability of the system and show that this time increases the slower your system moves."

If the new theory proves robust in nature, it may also help inform future civil engineering projects.

"If you put a building on the soil, the ground will very slowly deform," said Ortiz. "People have thought hard about how to prevent that. The phenomena we document brings new perspective to why this deformation occurs."

"If we can understand when and how erosion occurs," Jerolmack said, "and show that our model is robust, some other smart person is going to take our result and develop a useful tool from that. We're producing a basic science result right now, but the applications are probably only as limited as our imaginations."

Provided by University of Pennsylvania

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