Shifting sands, creeping soils, and a new understanding of landscape evolution

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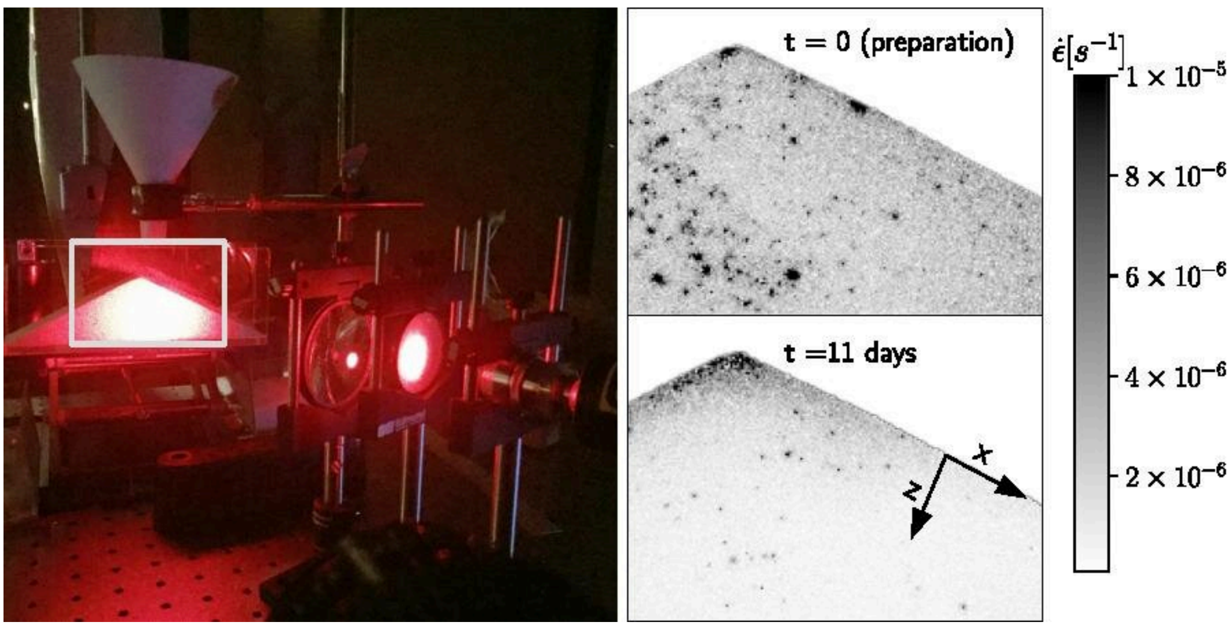

In the Jerolmack lab, diffusion-wave spectroscopy was used to study very small grain movements in piles of sand (shown in panel on the left). The data that was collected, depicted in strain rate maps (in panel on the right), shows that grain activity continues after 11 days without disturbance. Credit: Nakul Deshpande

A new study published in *Nature Communications* finds that piles of sand grains, even when undisturbed, are in constant motion. Using highly-sensitive optical interference data, researchers from the University of Pennsylvania and Vanderbilt University present results that challenge existing theories in both geology and physics about how soils and other types of disordered materials behave.

Most people only become aware of soil movement on hillsides when soil suddenly loses its rigidity, a phenomenon known as yield. "Say that you have soil on a hillside. Then, if there's an earthquake or it rains, this material that's apparently solid becomes a liquid," says principal investigator Douglas Jerolmack of Penn. "The prevailing framework treats this failure as if it's a crack breaking. The reason that's problematic is because you're modeling the material by a solid mechanical criterion, but you're modeling it at the point at which it becomes a liquid, so there's an inherent contradiction."

Such a model implies that, below yield the soil is a solid and therefore should not flow, but soil slowly and persistently "flows" below its yield point in a process known as creep. The prevailing geological explanation for soil creep is that it is caused by physical or biological disturbances, such as freeze-thaw cycles, fallen trees, or burrowing animals, that act to move soil.

In this study, lead author and Penn Ph.D. candidate Nakul S. Deshpande was interested in observing individual sand particles at rest which, based on existing theories, should be entirely immobile. "Researchers have built models by presuming certain behaviors of the soil grains in creep, but no one had actually just directly observed what the grains do," says Deshpande.

To do this, Deshpande set up a series of seemingly simple experiments, creating sand piles in small plexiglass boxes on top of a vibration isolation worktable. He then used a laser light scattering technique called diffusing-wave spectroscopy, which is sensitive to very small grain movements. "The experiments are technically challenging," Deshpande says about this work. "Pushing the technique to this resolution is not yet common in physics, and the approach doesn't have a precedent in geosciences or geomorphology."

Deshpande and Jerolmack also worked with long-time collaborator Paulo Arratia, who runs the Penn Complex Fluids Lab, to connect their data with frameworks from physics, materials science, and engineering to find analogous systems and theories that could help explain their results. Vanderbilt's David Furbish, who uses statistical physics to study how particle motions influence large-scale landscape changes, provided explanation for why previous models were physically inadequate and inconsistent with what the researchers had found.

The first experiments were seemingly easy: Pour a pile of sand into the box, let it sit, and watch with the laser. But the researchers discovered that, while intuition and prevailing theories say that the undisturbed piles of sand should be static, sand grain piles are in fact a mass of constant movement and behave like glass.

"In every way that we can measure the sand, it is relaxing like a cooling glass," says Deshpande. "If you were to take a bottle and melt it, then freeze it again, that behavior of those molecules in that cooling glass are, in every way that we're capable of measuring, just like the sand."

In physics, glass and soil particles are classic examples of a "disordered" system, one whose constituent particles are arranged randomly instead of in crystalline, well-defined structures. While disordered materials, a major focus area of Penn's Materials Research Science & Engineering Center, share some common behaviors in terms of how they deform when stressed, there is an important difference between glass and a pile of sand. The molecules that make up glass are always moving randomly at a rate that depends on temperature, but sand grains are too large to do that. Because of that, physicists expect that a pile of sand would be "jammed" and unmoving, but these latest findings present a new way of thinking about soil for researchers in both physics and geology.

Another surprising result was that the rate of creeping soil could be controlled based on the types of disturbances used. While the undisturbed sandpile continued to creep for as long as the researchers observed, the rate of particle motion slowed through time in a process called aging. When sand particles were heated, this aging was reversed such that creep rates increased back to their initial value. Tapping the pile, in contrast, accelerated aging.

"We tend to think of things that drive soil toward yield, like shaking from an earthquake that triggers a landslide, but other disturbances in nature potentially drive soil further away from yield, or make it harder for a landslide to happen," says Jerolmack. "Nakul's ability to tune it further or closer to yield was like a bomb that went off for us, and this is an all-new area."

In the near term, the researchers are working on follow-up experiments to recreate the impacts of localized disturbances using magnetic probes to understand how disturbances could lead a system further away from or closer to yield. They are also looking at data from field observations, from natural soil creep to catastrophic landslide events, to see if they can connect their lab experiments to what observers see in the field, potentially enabling new ways to detect catastrophic landscape failures before they happen.

The researchers hope that their work can be a starting point for refining existing theories that rely on a paradigm that, like a hillside whose soil particles have shifted over time, no longer holds weight. "When you observe something really counterintuitive and new, it's going to now take a long time before that turns into a model to use," says Jerolmack. "I hope on the geoscience side that people with sophisticated tools and techniques and experience will pick up where we've ended and say, 'I have a new idea for seeking this signature in the field that you wouldn't have thought of'—that natural handoff of scales and abilities and interests."

More information: Nakul S. Deshpande et al, The perpetual fragility of creeping hillslopes, *Nature Communications* (2021). DOI: 10.1038/s41467-021-23979-z

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