Scientists use 3D-printed rocks, machine learning to detect unexpected earthquakes

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Sandia National Laboratories geoscientist Hongkyu Yoon holds a fractured 3D-printed rock. Hongkyu squeezed 3D-printed rocks until they cracked and listened to the sound of the rocks breaking to be able to identify early signs of earthquakes. Credit: Rebecca Gustaf

Geoscientists at Sandia National Laboratories used 3D-printed rocks and an advanced, large-scale computer model of past earthquakes to understand and prevent earthquakes triggered by energy exploration.

Injecting water underground after unconventional oil and gas extraction, commonly known as fracking, geothermal energy stimulation and carbon dioxide sequestration all can trigger earthquakes. Of course, energy companies do their due diligence to check for faults—breaks in the earth's upper crust that are prone to earthquakes—but sometimes earthquakes, even swarms of earthquakes, strike unexpectedly.

Sandia geoscientists studied how pressure and stress from injecting water can transfer through pores in rocks down to fault lines, including previously hidden ones. They also crushed rocks with specially engineered weak points to hear the sound of different types of fault failures, which will aid in early detection of an induced earthquake.

3D printing variability provides fundamental structural information

To study different types of fault failures, and their warning signs, Sandia geoscientist Hongkyu Yoon needed a bunch of rocks that would fracture the same way each time he applied pressure—pressure not unlike the pressure caused by injecting water underground.

Natural rocks collected from the same location can have vastly different mineral orientation and layering, causing different weak points and fracture types.

Several years ago, Yoon started using additive manufacturing, commonly known as 3D printing, to make rocks from a gypsum-based mineral under controlled conditions, believing that these rocks would be more uniform. To print the rocks, Yoon and his team sprayed gypsum in thin layers, forming 1-by-3-by-0.5 inch rectangular blocks and cylinders.

However, as he studied the 3D-printed rocks, Yoon realized that the printing process also generated minute structural differences that affected how the rocks fractured. This piqued his interest, leading him to study how the mineral texture in 3D-printed rocks influences how they fracture.

"It turns out we can use that variability of mechanical and seismic responses of a 3D-printed fracture to our advantage to help us understand the fundamental processes of fracturing and its impact on fluid flow in rocks," Yoon said. This fluid flow and pore pressure can trigger earthquakes.

For these experiments, Yoon and collaborators at Purdue University, a university with which Sandia has a strong partnership, made a mineral ink using calcium sulfate powder and water. The researchers, including Purdue professors Antonio Bobet and Laura Pyrak-Nolte, printed a layer of hydrated calcium sulfate, about half as thick as a sheet of paper, and then applied a water-based binder to glue the next layer to the first. The binder recrystallized some of the calcium sulfate into gypsum, the same mineral used in construction drywall.

The researchers printed the same rectangular and cylindrical gypsum-based rocks. Some rocks had the gypsum mineral layers running horizontally, while others had vertical mineral layers. The researchers also varied the direction in which they sprayed the binder, to create more variation in mineral layering.

The research team squeezed the samples until they broke. The team examined the fracture surfaces using lasers and an X-ray microscope. They noticed the fracture path depended on the direction of the mineral layers. Yoon and colleagues described this fundamental study in a paper published in the journal *Scientific Reports*.

Sound signals and machine learning to classify

seismic events

Also, working with his collaborators at Purdue University, Yoon monitored acoustic waves coming from the printed samples as they fractured. These sound waves are signs of rapid microcracks. Then the team combined the sound data with machine-learning techniques, a type of advanced data analysis that can identify patterns in seemingly unrelated data, to detect signals of minute seismic events.

First, Yoon and his colleagues used a machine-learning technique known as a random forest algorithm to cluster the microseismic events into groups that were caused by the same types of microstructures and identify about 25 important features in the microcrack sound data. They ranked these features by significance.

Using the significant features as a guide, they created a multilayered "deep" learning algorithm—like the algorithms that allow digital assistants to function—and applied it to archived data collected from real-world events. The deep-learning algorithm was able to identify signals of seismic events faster and more accurately than conventional monitoring systems.

Yoon said that within five years they hope to apply many different machine-learning algorithms, like these and those with imbedded geoscience principles, to detect induced earthquakes related to fossil fuel activities in oil or gas fields. The algorithms can also be applied to detect hidden faults that might become unstable due to carbon sequestration or geothermal energy stimulation, he said.

"One of the nice things about machine learning is the scalability," Yoon said. "We always try to apply certain concepts that were developed under laboratory conditions to large-scale problems—that's why we do laboratory work. Once we proved those machine-learning concepts developed at the laboratory scale on archived data, it's very easy to scale it up to large-scale problems, compared to traditional methods."

Stress transfers through rock to deep faults

A hidden fault was the cause of a surprise earthquake at a geothermal stimulation site in Pohang, South Korea. In 2017, two months after the final geothermal stimulation experiment ended, a magnitude 5.5 earthquake shook the area, the second strongest quake in South Korea's recent history.

After the earthquake, geoscientists discovered a fault hidden deep between two injection wells. To understand how stresses from water injection traveled to the fault and caused the quake, Kyung Won Chang, a geoscientist at Sandia, realized he needed to consider more than the stress of water pressing on the rocks. In addition to that deformation stress, he also needed to account for how that stress transferred to the rock as the water flowed through pores in the rock itself in his complex large-scale computational model.

Chang and his colleagues described the stress transfer in a paper published in the journal *Scientific Reports*.

However, understanding deformation stress and transfer of stress through rock pores is not enough to understand and predict some earthquakes induced by energy-exploration activities. The architecture of different faults also needs to be considered.

Using his model, Chang analyzed a cube 6 miles long, 6 miles wide and 6 miles deep where a swarm of more than 500 earthquakes took place in Azle, Texas, from November 2013 to May 2014. The earthquakes occurred along two intersecting faults, one less than 2 miles beneath the surface and another longer and deeper. While the shallow fault was closer to the sites of wastewater injection, the first earthquakes occurred along the longer, deeper fault.

In his model, Chang found that the water injections increased the pressure on the shallow fault. At the same time, injection-induced stress transferred through the rock down to the deep fault. Because the deep fault was under more stress initially, the earthquake swarm began there. He and Yoon shared the advanced computational model and their description of the Azle earthquakes in a paper recently published in the *Journal of Geophysical Research: Solid Earth*.

"In general, we need multiphysics models that couple different forms of stress beyond just pore pressure and the deformation of rocks, to understand induced earthquakes and correlate them with energy activities, such as hydraulic stimulation and wastewater injection," Chang said.

Chang said he and Yoon are working together to apply and scale up machine-learning algorithms to detect previously hidden faults and identify signatures of geologic stress that could predict the magnitude of a triggered earthquake.

In the future, Chang hopes to use those stress signatures to create a map of potential hazards for induced earthquakes around the United States.

More information: K. W. Chang et al. Hydromechanical Controls on the Spatiotemporal Patterns of Injection-Induced Seismicity in Different Fault Architecture: Implication for 2013–2014 Azle Earthquakes, *Journal of Geophysical Research: Solid Earth* (2020). DOI: 10.1029/2020JB020402

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