After the Big One: Understanding aftershock risk

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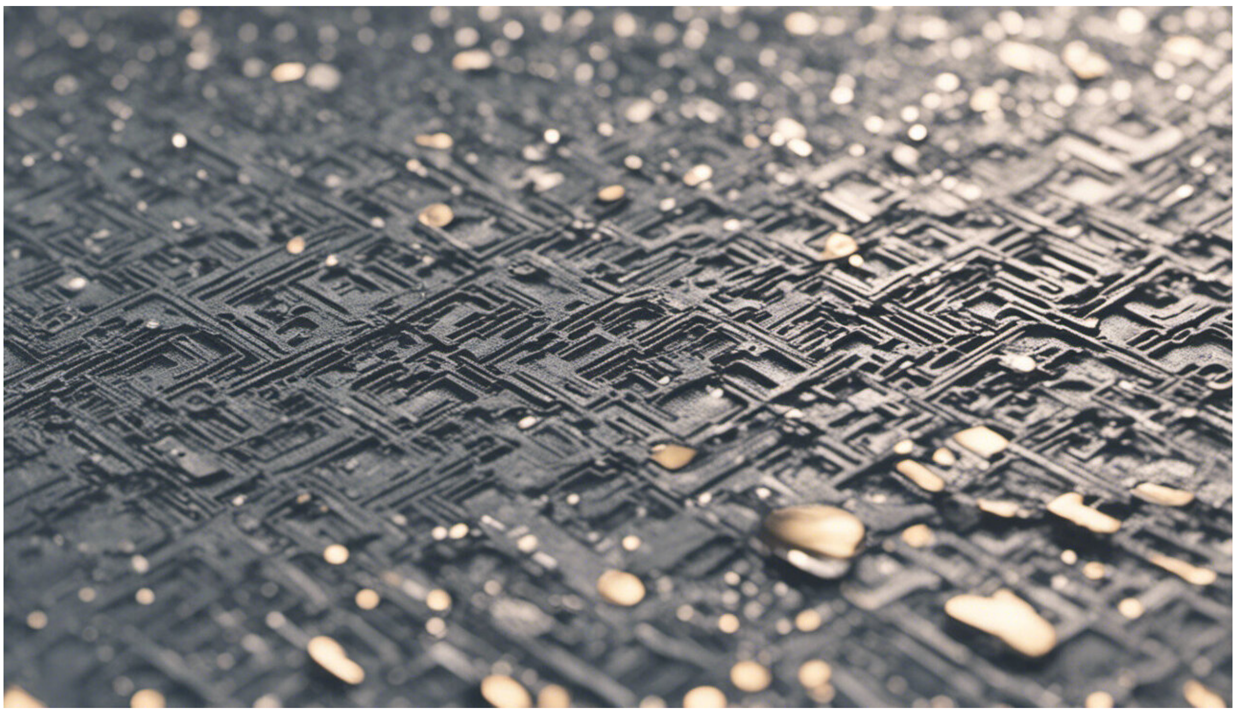

Credit: AI-generated image (disclaimer)

In early September 2018, a powerful earthquake on the island of Hokkaido in northern Japan triggered landslides, toppled buildings, cut power, halted industry, killed more than 40 people and injured hundreds. The national meteorological agency warned that aftershocks could strike for up to a week following the main event.

"A large earthquake will typically have thousands of aftershocks," said Gregory Beroza, the Wayne Loel Professor of geophysics in the School of Earth, Energy & Environmental Sciences (Stanford Earth) at Stanford University. "We know that a big earthquake changes something in Earth's crust that causes these aftershocks to happen."

The rarity of big quakes, however, makes it difficult to document and statistically model how large earthquakes interact with each other in space and time. Aftershocks could offer a workaround. "Aftershocks occur by the same mechanism, on the same geological faults and under the same conditions as other earthquakes," Beroza explained in a recent article in the journal *Nature*. As a result, interactions between the largest earthquake in a sequence, known as a mainshock, and its aftershocks may hold clues to earthquake interactions more broadly, helping to explain how changes on a fault induced by one earthquake may affect the potential site of another.

Here, Beroza discusses how scientists forecast aftershocks and why they're turning to artificial intelligence to build better models for the future.

What are the current methods for predicting foreshocks and where do they fall short?

GREGORY BEROZA: When a large earthquake slips, that changes the forces throughout the Earth's crust nearby. It's thought that this stress change is most responsible for triggering aftershocks. The stress is what drives earthquakes.

Scientists have noted a tendency for aftershocks to occur where two types of stress act on a fault change. The first type is called is normal stress, which is how strongly two sides of a fault are pushing together or pulling apart. The second type is called shear stress, or how strongly the two sides are being pushed past one another, parallel to the fault, by remote forces. Decreases in the normal stress and increases in the shear stress are expected to encourage subsequent earthquakes. Measures of these changes in the volume of rock around a fault are combined into a single metric called the Coulomb failure stress change.

But it's not a hard and fast rule. Some earthquakes occur where in a sense they shouldn't, by that metric. There are components of stress that are different from shear stress and normal stress. There's stress in other directions, and complex combinations. So we do okay at predicting where aftershocks will, and will not, occur after a mainshock, but not as well as we'd like.

What is an artificial neural network and how can scientists use this kind of artificial intelligence to predict earthquakes and aftershocks?

BEROZA: Picture a machine that takes inputs from the left. Moving to the right you have a series of layers, each containing a bunch of connected neurons. And at the other end you have an outcome of some kind.

One neuron can excite another. When you add lots of these layers with lots of different interactions, you very rapidly get an extremely large set of possible relationships. When people talk about "deep" neural networks, that means they have a lot of layers.

In this case, your input is information about stress on a fault. The output is information about the locations of aftershocks. Scientists can take examples of observed earthquakes and use that data to train the neurons to interact in ways that produce an outcome that was observed in the real world. It's a process called machine learning. Given this set of inputs, what's the right answer? What did the Earth tell us for this earthquake?

A pioneering effort to use artificial intelligence in this context published in *Nature* in August 2018. The authors fed a machine-learning algorithm estimates of stress changes and information on where aftershocks did or didn't occur for a whole bunch of earthquakes. They're not doing earthquake prediction in the usual sense, where you try to predict the time, place and magnitude of the earthquake. They're just looking for where aftershocks occur. The model doesn't capture the true complexity of the Earth, but it's moving in the right direction.

How might artificial intelligence approaches be applied to seismology more broadly?

BEROZA: In the Earth sciences in general, we have complicated geological systems that interact strongly in ways we don't understand. Machine learning and artificial intelligence can help us explore and maybe uncover the nature of some of those complicated relationships. It can help us explore and find relationships that scientists hadn't thought of or tested.

We also have very large data sets. The biggest seismic network I've worked with has something like 5,000 sensors in it. That's 5,000 sensors, 100 samples per second, and it runs continuously for months. There's so much data it's hard to even look at it.

The trend is for these data sets to be ever larger. Within a few years, we're going to be working with data sets of over 10,000 sensors. How do you make sure you're getting as much information as you can out of those massive data sets?

Our usual way of doing business isn't going to scale at some point. Techniques such as data mining and machine learning to help us extract as much information as we can from these very large data sets are going to be an essential part of understanding our planet in the future.

More information: Gregory C. Beroza. Machine learning improves forecasts of aftershock locations, *Nature* (2018). DOI: 10.1038/d41586-018-06030-y

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