LISTENING FOR LANDSLIDES

SAMIR AMIR JUNG THAPA/EPA

A year after a devastating earthquake triggered killer avalanches and rock falls in Nepal, scientists are wiring up mountainsides to forecast hazards.

BY JANE QIU

Kodari is a ghost town on an empty Nepalese highway that cuts through some of the steepest slopes of the Himalayas. One year after the magnitude-7.8 Gorkha earthquake killed nearly 9,000 people, the once-buzzing trade centre looks like a battlefield where armies of giants once waged war. The road is littered with rusting cars and trucks smashed into bizarre shapes. Massive boulders rest on the wreckage of homes.

"It's a good example of building a town in the wrong place," says Kristen Cook, a geologist at the German Research Centre for Geosciences (GFZ) in Potsdam, as she climbs over the rubble from one of the landslides that crushed the town. The Arniko Highway, which runs through Kodari, is no stranger to such calamities, especially in the monsoon season. "It was in frequent repair and closure even before the earthquake," says Shanmukesh Amatya, landslide-division chief at Nepal's Department of Water Induced Disaster Prevention in Kathmandu. "The problem now is overwhelming."

The highway is not the only thing that keeps Amatya awake at night. The earthquake unleashed more than 10,000 landslides that blocked rivers and damaged houses, roads and other key pieces of infrastructure across the country. And the destruction didn't stop with the shaking. The hilly terrain, severely weakened by the quake, is now more likely to slip after strong rains and aftershocks — a legacy that is likely to endure for years. During the most recent monsoon, the area affected by landslides was about ten times greater than usual.

"It's a real problem for reconstruction," says Tara Nidhi Bhattarai, a geologist at Tribhuvan University in Kathmandu and chief

Locals peer at a landslide in Langtang, Nepal.

scientist of Nepal's National Reconstruction Authority — an agency established last year to manage the recovery efforts. "What are the safe places to rebuild, in a landscape that is evolving?"

To answer that, geoscientists are wiring up the mountains in Nepal and other seismically active countries. By monitoring how hillsides evolve, researchers are learning why strong shaking weakens a slope and makes it more prone to give way during aftershocks or rainstorms. The lessons from such studies could help to pinpoint when and where the side of a mountain will collapse.

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The significance goes beyond quake recovery. Himalayan nations are facing increasing risks from landslides because of deforestation, road construction, population growth and other changes that have pushed people to live in hazardous locations. Climate change may exacerbate the problem by melting glaciers and triggering increasingly extreme rainfall.

“There is a pressing need to monitor the risks in the long run,” says Amatya. “A nationwide early-warning system is long overdue.”

BIRD’S-EYE VIEW

A crowd eagerly looks on as Cook flies a drone through the skies near Listi, a small village perched on a mountainside above the Arniko Highway. With its four propellers, the little robot zips over landslide scars that run down from the ridge like gigantic frozen waterfalls.

A camera and other sensors on the drone provide data that let Cook build a 3D reconstruction of the landscape. She started the work last October and will take measurements every few months over the next few years. By scanning as many landslide-inflicted areas as possible, she says, “we will be able trace how they change over time and what’s the effect of monsoons”.

Such measurements of the surface will complement studies that track what’s happening underground. Not far from Cook is her colleague Christoff Andermann, another GFZ geologist, who is performing maintenance on a broadband seismometer, a device that measures shaking across a wide range of frequencies. Last June, the GFZ team installed a dozen such instruments, along with weather stations and river-flow sensors, across 50 square kilometres of landslide-riddled terrain.

Seismometers are a relatively new addition to landslide studies by the GFZ researchers and their colleagues. They started using the sensors only after an accidental discovery. In 2003, a set of seismic stations installed in Nepal to study deep structures in Earth’s crust picked up high-frequency noise from nearby rivers and shifting slopes. Arnaud Burtin, a seismologist now at the Earth Physics Institute in Paris, noticed a series of peaks in that noise before a debris flow in central Nepal that killed 45 people. He and his colleagues went on to identify[1] 46 debris flows from seismograms taken during that monsoon season. By comparing the data with information from weather stations, the team also determined how much rainfall was required to trigger slides.

Researchers have typically used satellite imagery or aerial photography to track landscape changes on a large scale, but these methods have relatively poor temporal resolution because images are taken days or months apart. Seismometers take snapshots hundreds of times per second, so they are ideal for monitoring slopes for instability, says Colin Stark, a geologist at the Lamont–Doherty Earth Observatory in Palisades, New York, who studies monster landslides using global seismic networks. When seismometers are placed strategically, he says, it’s also possible to precisely locate the source of seismic signals in a large area.

“Until recently, we had little idea why landslides are more likely to happen after an earthquake or how the slopes recover over time,” says Stark. But work over the past decade has revealed that cracks produced by an earthquake can boost the shaking in future shocks. Unpublished results from seismic stations, for example, show that on fractured slopes, ground motion can be up to 30 times what is measured in neighbouring, undamaged areas, says Jeffrey Moore, a geophysicist at the University of Utah in Salt Lake City. This means that minor aftershocks could trigger unexpected levels of landslides in damaged slopes that did not fail in the main shock, he says.

In some cases, the increased sensitivity can last for decades. A study[2] of a magnitude-7.4 earthquake in New Zealand in 1968 found that the quake triggered more landslides than expected in places that had been affected by a magnitude-7.8 shock 21 kilometres away and nearly 4 decades before.

Quake-stricken hills also have an increased sensitivity to rainfall, says Niels Hovius, a GFZ geologist who is leading the Nepal study. He and his colleagues have found[3] that after the magnitude-7.6 ChiChi earthquake that hit Taiwan in 1999, the rate of rainfall-triggered landslides in the affected area jumped by a factor of 22. “The government cleared up the mess and rebuilt, but the same happened again a couple of years later,” he says. If scientists can develop greater insight into the mechanisms that control slope behaviour after an earthquake, that could help authorities to make better decisions about rebuilding.

By analysing records after the ChiChi quake and three others with similar depths and slip mechanisms, Hovius and his colleagues also found[3] that it took up to four years for landslide rates to return to pre-quake levels at those sites.

In follow-up work, the team mined data from seismometers installed before ChiChi hit. The instruments were near roads, which made it possible to study subsurface properties by measuring how traffic vibrations travel through the ground. They found that the speed of seismic waves dropped markedly immediately after the quake. The velocities then recovered gradually, following roughly the same trajectory as the decline in landslide rates, says Odin Marc, a geologist at the GFZ, who presented the results last week at a meeting of the European Geosciences Union in Vienna. Over the same period, there were frequent, small surface displacements — presumably caused by the slow, creeping movement of Earth’s crust after an earthquake, a process known as post-seismic deformation.

The researchers suspect that subsurface materials are packed together tightly before the earthquake, like beads in a box. Strong ground-shaking causes the granular mass to expand, opening up holes and cracks that make the ground less dense. “This is why seismic waves travel at reduced speeds,” says Hovius. Post-seismic deformation causes the openings to fill in and the subsurface sediments to become compact once more. “It’s an internal healing process of the landscape,” he says.

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Data collected after the Gorkha earthquake support that. Preliminary results show that seismic-wave velocities close to the surface declined sharply after the shock — and the volume of water flowing through rivers increased by 50%. That backs up the idea that the quake opened holes and fractures in the subsurface, which then allowed groundwater to leak more freely through the cracks, says Andermann, who has been monitoring river flows and sediment transport in the region for the past decade.


BORJA SANCHEZ TRILLO/GETTY

Landslides devastated villages near Kodari, Nepal.

Such findings suggest a way to predict landslides. Looking back over their data, the researchers were able to identify peaks of seismic signals in the run-up to a major landslide last July. "These precursors represent a sequence of processes that culminated in the failure," says Hovius. "There was a systematic increase in the rate at which these precursor activities occurred, until the whole topography collapsed."

The GFZ team also found that seismic waves travel through the subsurface more quickly when the slope is drenched and pore spaces are filled with water. "We can see how quickly the effects of rainfall propagate into and through the subsurface" using seismic sensors, says Hovius. This effectively maps groundwater flow, a key factor in the strength of hillsides. With the seismic data, researchers can model the physics of slope stability and monitor changes in ground properties that might precipitate a landslide.

NEAR-ATOMIC BLAST

In the village of Langtang in northern Nepal, a pile of rubble 60 metres deep provides ample incentive to improve landslide forecasts. During the earthquake last year, a mixture of ice and rock crashed down several kilometres onto the valley floor — landing with an impact that released half as much energy as the Hiroshima atomic bomb[4]. The slide buried Langtang and nearby villages, leaving nearly 400 people dead or missing.

Research groups have been racing to understand where the avalanche began and whether the area is still at risk. One study[5] found 5 initiation sites between altitudes of 6,800 and 7,200 metres, along a 3-kilometre ridge where the earthquake shook up snow and glaciers. These swept down the slope, picking up rocks as they went.

Roughly 7 million cubic metres of debris filled the bottom of the valley, and another 10 million cubic metres still rest precariously on slopes more than 5,000 metres above sea level. A year after the quake, the sounds of falling rocks and shifting slopes frequently echo through the valley — a reminder of the remaining hazard.

The Langtang case shares features with increasingly common rock avalanches in high mountains in Alaska and the Alps, says Marten Geertsema, a glaciologist with the British Columbia Ministry of Forests and Range in Prince George, Canada. In all these places, glaciers are quickly retreating, leaving rocky hillsides exposed and prone to failure. And warming at high elevations may cause frozen bedrock to thaw, he says, making it more permeable to melt water and weakening the rocks. "Climate change might have primed the landscape for the devastation."

At high-risk sites in Nepal, researchers are combining seismological and other techniques to watch for signs that mountainsides are growing restless. On the steep slope facing Listi, the earthquake caused the lower part of the ridge to subside, resulting in a 5-metre opening that skirts the mountain for about 2 kilometres. This gigantic crack and many smaller ones nearby pose a serious threat to downslope settlements, says Amod Dixit, executive director of Nepal's National Society for Earthquake Technology (NEST) in Kathmandu. "They must be closely monitored."

Last August, Nick Rosser, a geologist at Durham University, UK, and his colleagues installed a series of instruments at ten locations across the slope — including strain meters to monitor changes in the cracks, accelerometers to measure ground vibration, and rain gauges. The data are relayed to a server at NEST, letting researchers track in real time whether the cracks are opening or contracting and how they respond to rainfall.

Although it is not yet a fully fledged early-warning system, the set-up can identify signs of major deformation that could cause the slope to fail. Thankfully, says Rosser, "the cracks are not growing at the moment". Settlements will be alerted to any impending danger, he adds.

The researchers are using information from the field and from lab experiments on slope materials to try to determine what kind of ground deformation and rainfall would cause landslides. "This is crucial for setting the criteria for triggering an alert," he says.

The Durham sensors are within the area covered by the GFZ seismic array, so the teams will pool their field data. Together with satellite imagery and other measurements, this information will provide unprecedented insight into how the mountains are changing and what kind of danger this might pose to communities there, they say.

At Listi, Cook is worried about a massive pile of debris that the drone has located high above the valley. The earthquake loosened a huge amount of rock and soil, but most did not make it all the way to the bottom. "They are just sitting there on the hillside," says Cook, pointing to a mass on her remote-control screen. The materials could all come down in heavy rain — as some did during the last monsoon. "They are time bombs waiting to explode." ■

Jane Qiu *is a writer in Beijing. Her trip to Nepal was supported by a grant from the Pulitzer Center on Crisis Reporting.*

1. Burtin, A., Bollinger, L., Cattin, R., Vergne, J. & Nábělek, J. L. *J. Geophys. Res.* **114,** F04009 (2009).
2. Parker, R. N. *et al. Earth Surf. Dynam.* **3,** 501–525 (2015).
3. Marc, O., Hovius, N., Meunier, P., Uchida, T. & Hayashi, S. *Geology* **43,** 883–886 (2015).
4. Kargel, J. S. *et al. Science* **351,** aac8353 (2016).
5. Lacroix, P. *Earth Planets Space* **68,** 46 (2016).