SCIENTIFIC
AMERICAN

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Seconds Before the Big One: Progress in Earthquake Alarms

Earthquake detection systems can sound the alarm in the moments before a big tremor strikes—time enough to save lives

By Richard Allen | Friday, March 11, 2011 | 7 comments

Editor's note (3/11/11): This article is from the forthcoming April issue of Scientific *American. We are posting the text of the article early in light of the deadly Japan earthquake and resulting tsunami.*

Earthquakes are unique in the pantheon of natural disasters in that they provide no warning at all before they strike. Consider the case of the Loma Prieta quake, which hit the San Francisco Bay Area on October 17, 1989, just as warm-ups were getting under way for the evening's World Series game between the San Francisco Giants and the Oakland A's. At 5:04 p.m., a sudden slip of the San Andreas Fault shook the region with enough force to collapse a 1.5-mile section of a double-decker freeway and sections of the Bay Bridge connecting Oakland with San Francisco. More than 60 people died.

Over the years scientists have hunted for some signal—a precursory sign, however faint—that would allow forecasters to pinpoint exactly where and when the big ones will hit, something that would put people out of harm's way. After decades spent searching in vain, many seismologists now doubt whether such a signal even exists.

Yet not all hope is lost. Within seconds of an earthquake's first subtle motions, scientists can now predict with some certainty how strong and widespread the shaking will be. By integrating new science with modern communications technologies, the authorities could get a few tens of seconds' warning, perhaps even half a minute, to those in harm's way. That may not sound like much, but it is enough to send shutdown warnings to power plants and rail networks, automatically open elevator doors and alert firefighters.

The Loma Prieta quake was centered south of the Bay in the rugged Santa Cruz Mountains. After the ground started to shake, it took more than 30 seconds for the damaging vibrations to travel the 60 miles to San Francisco and Oakland, the scenes of more than 80 percent of the fatalities. If an earthquake early-warning system had existed back then, it could have provided perhaps a 20-second warning to the heart of the region. This is enough time to slow and stop trains, issue "go around" commands to airplanes on final approach and turn streetlights red—preventing cars from entering hazardous structures such as bridges and tunnels. Workers in hazardous work environments could move to safe zones, and sensitive equipment could enter a hold mode, reducing damage and loss. Schoolchildren and office workers could get under desks before the shaking arrived. The region would be ready to ride out the violence to come.

Such networks are being deployed all over the world in locations as diverse as Mexico, Taiwan, Turkey and Romania. Japan's system is among the most advanced. The nationwide network issues warnings via most television and radio stations, several cell phone providers, and the public address system of malls and other public spaces. In the three and a half years since the system came online, more than a dozen earthquakes have already triggered widespread alerts. People in factories, schools, trains and automobiles were given a few precious moments to prepare; following the alerts, there were no reports of panic or highway accidents. The U.S. is behind the rest of the world, but a new test bed being deployed in California should soon lead to a full-scale warning system in that fault-ridden state.

California is long past due for the next big one. If we build a warning system now, we can save lives.

From Waves to Warnings

The ground beneath our feet is moving. As the tectonic plates drift across the earth's surface, pieces of the continents grind past one another and collide like cars in a freeway pileup. The earth's crust—the outer layer of the plates that we live on—is elastic, but only to a point. At the plate boundaries, the crust bends until the strain becomes too great. When it snaps, the energy stored up over the preceding decades tears across the earth's surface, shaking everything in its path.

Hundreds of earthquakes occur every day. Fortunately, most are so small that we would never know about them without the help of sensitive seismometers. In daily earthquakes only three to six feet of the fault plane slips; humans cannot feel the shaking. In magnitude 5.0 earthquakes a mile or two of the fault plane ruptures; humans can easily feel movement, but modern buildings can withstand it. At magnitude 8.0 the rupture propagates for hundreds of miles across the fault plane, and the tear can extend up to the surface. It will rip a building in two.

By monitoring the buildup of strain between earthquakes, seismologists know that many areas of the crust are close to failure. But the detailed structure of the faults deep below the surface also plays an important role in both the nucleation and propagation of earthquake ruptures—a structure that cannot be sampled directly. For this reason, most seismologists do not believe it is possible to create a forecasting system capable of predicting a large earthquake hours or days before it strikes. For the foreseeable future, the best anyone will be able to do is to quickly detect a large earthquake and sound the alarm.

A few unique characteristics of earthquakes aid in this task. What we perceive as one extended jolt actually comes in stages. Energy from a break in the crust travels through the earth in two forms: P-waves and S-waves. Both types leave the fault surface at the same time, but there the similarities end. P-waves, like sound waves, are compression waves. They travel relatively quickly, but they do not carry much power. During an earthquake, you feel the P-waves as a sudden, vertical thump. S-waves are more like ocean waves, slow movers that contain most of the energy and bring the strongest shaking. The ground motion is horizontal and vertical, and they can bat entire buildings around like they were dinghies in the surf.

In addition, not all waves look alike; they take on different shapes depending on the size of the slip patch. The P-wave radiation for small slip patches has relatively low amplitude and high frequency—a small but sharp pulse. Bigger earthquakes rupture larger areas of a fault and have more slip, so the P-wave is larger in amplitude and lower in frequency. It is akin to the difference between the squeak of a small bird and the roar of a grizzly bear.

A single seismometer could estimate the magnitude of the earthquake based on just this information. Any P-wave with high amplitude and low frequency would trigger a warning. This single-station approach is the fastest way to give warnings near the epicenter. Yet the character of earthquake ruptures varies—not all magnitude 5.0 earthquakes look the same—and the specific sediments underneath the seismometer modify the P-wave. This variability increases the risk of both false alarms—warnings when there is no earthquake—and missed alarms when a damaging earthquake is under way.

To reduce the likelihood of both false and missed alarms, we can combine data recorded by several seismometers located a few miles apart. In this setup the sediments beneath each instrument would be different, so we can obtain an average estimate of the magnitude. This approach requires seismic networks that transmit instrument data to a central site and then integrate them. Yet it takes a few seconds to transmit and analyze the data, and in every passing second the damaging S-wave travels another two to three miles.

The best approach is thus to combine the single-station and network-based approaches, which provides the potential for both rapid warnings in the region near the epicenter and tens of seconds of warning to locations farther away.

Any system has to make a trade-off between the accuracy and the warning time available. As the seismic network collects more data on an earthquake, the predictions will improve, but the time until shaking will decrease. Some users may tolerate more false and missed alarms to have more warning time. For example, schools may prefer to get the warning sooner so children can take cover. A few false alarms a year provide the regular drills necessary so that everyone knows what to do. Nuclear power stations, in contrast, require only a second to shut down the reactor—but doing so comes at great cost. Operators there will want to wait until extreme shaking is certain.

Alerts Near and Far

Public earthquake warning systems have existed in one form or another for decades. In the 1960s Ja
seismometers into the tracks of the new Shinkansen bullet trains. Excessive shaking would sound an
chance to slow the train. Later, scientists designed systems that would use far-flung seismometers to
heaviest shaking. Mexico's network is designed to detect earthquakes near the coastline and broadca
aging metropolis of more than 20 million people built on a silty lakebed that amplifies seismic waves
and the city can provide more than 60 seconds of warning.

Mexico's system came online back in 1993. Two years later it would experience its first serious test.
8.0 earthquake struck just off the coast of Manzanillo. The warning system picked up the tremor anc
and radio stations in Mexico City and via a dedicated radio alert system similar to weather radio in t
officials were able to stop the metro system 50 seconds before the shaking arrived, and schools were

Japan's system, which went live in 2007, makes heavy use of personal technology. Alerts go out not
through special receivers in homes, offices and schools. Pop-up windows on computers show a real-t
location and the radiating seismic waves. A timer counts down to the shaking at your location and hi
phone providers broadcast a text message–like warning to all phones with a characteristic audible al
nuclear power stations, rail systems, airports and hazardous manufacturing facilities use dedicated c
to their needs.

Japan's experience shows that earthquake warning systems do not just help protect lives, they also h
earthquakes near Sendai, Japan, caused more than $15 million in losses to the OKI semiconductor n
fire, equipment damage and loss of productivity. The plant had to be shut down for periods of 17 and 13 days, respectively, following

em. In two similar earthquakes
since, the factory suffered only $200,000 in losses and 4.5 and 3.5 days of downtime.

The California Curse

California is earthquake country. In 2006 a consortium of universities and state and federal agencies joined forces to develop ShakeAlert, a warning system for the state. Right now a prototype system links together approximately 400 seismic stations and will soon send alerts to a small group of test users. The finished system will provide not only immediate single-station alerts to those near the epicenter but also widespread network-based alerts to those farther away. If all goes well, alerts will be available within five seconds after the first P-wave hits.

Yet California still has a long way to go before it can be blanketed with a comprehensive network such as Japan's. The 400 existing seismic stations are concentrated around the San Francisco Bay and Los Angeles metropolitan areas, leaving gaps elsewhere. Even though most Californians live near these two areas, the gaps both slow the system and reduce its accuracy, because it takes longer to detect the P-waves at multiple locations. In Japan instruments are spaced every 15 miles across the entire country. That level of spacing in California would deliver the best system performance, with fewer false and missed alarms and more warning time.

Those alerts, like Japan's, would leverage the networked gadgets that most people carry every day. Individuals would get an alert on their mobile phone indicating predicted shaking intensity, a countdown until the shaking starts, and perhaps a simple instruction such as "get under a table" or "move to your safe zone." Larger organizations with infrastructure spread over a region will likely want more detailed information such as a real-time map showing the wave progression and the distribution of ground shaking across the affected area.

Such a system would require only a modest investment compared with the potential dangers of a major earthquake—100 new seismic stations and upgrades to existing infrastructure, at a total cost of $80 million. In five years the system could be up and running. In six we could be very thankful that it is.