Loma Prieta's Long-Distance Punch

Why did cities 100 kilometers away feel such strong shaking?

By RICHARD MONASTERSKY

Violent shaking and soil liquefaction in San Francisco's Marina district caused the lower floors of some buildings to collapse completely.

It took a full 25 seconds for the strongest seismic waves from the Loma Prieta earthquake last October to reach San Francisco and Oakland, roughly 90 kilometers from the epicentral region. Earthquake vibrations usually weaken as they spread away from the epicenter, but when Loma Prieta's waves finally rolled through the distant cities, they shook the ground with surprising force and wrought an unexpectedly severe toll in property damage and human lives.

As the Bay area struggled to its feet in the days following the Oct. 17 shock, engineers and earth scientists strove to account for the unusually strong long-distance shaking. Initially they focused on the soft natural sediments and landfill material underlying many of the damaged structures, including the collapsed portions of Interstate 880 in Oakland and the houses of San Francisco's Marina district. These unstable soils can amplify seismic waves, increasing the destructive shaking — a point driven home by the infamous 1906 San Francisco quake, which damaged buildings on the same areas hit hardest by Loma Prieta.

During last fall's quake, motion recorders located on soft sediments in the Bay area registered stronger vibrations than those on nearby hard rock, supporting investigators' initial suspicions. In many soft areas, shaking grew so intense that it momentarily turned waterlogged sediments into something resembling a liquid, allowing the ground to sink out from beneath buildings.

Yet for all the damage they caused, soft sediments don't tell the entire tale of the Bay area's loss. Records indicate that seismic stations located on hard rock in this region also shook harder than normal for a magnitude 7.1 quake.

Soft-sediment amplification clearly played a primary role in bringing down structures, but "it was not the only thing operating in San Francisco and Oakland," emphasizes seismologist Paul Somerville of the Woodward-Clyde consulting group in Pasadena, Calif.

Another major earthquake — centered closer to the Bay area and thus threatening even more destruction there — could well strike sometime within the next few decades, according to geologists' predictions. In order to know whether abnormally violent vibrations might recur and to plan accordingly, it's important to uncover the hidden factors behind Loma Prieta's stronger-than-expected shaking.

While several different factors could have boosted the seismic waves hitting the San Francisco area, Somerville and colleague Joanne Yoshimura have compiled evidence that fingers a phenomenon called critical reflection — the same process that allows light waves to travel miles through transparent optical-fiber cables without leaking out the sides.

To understand critical reflection, envision an underwater diver with a flashlight trying to signal a watchful partner in a boat. If the diver points the flashlight directly overhead, the water's surface acts like a window, allowing most of the light waves to pass into the air. But if the diver points the flashlight at a shallow angle to the surface, the surface acts like a mirror, reflecting the light back down into the water. Critical reflection depends on two conditions: light waves traveling faster through air than through water, and the flashlight beam hitting the surface at a shallow enough angle.

Inside Earth, critical reflections occur when seismic waves from an earthquake hit a boundary called the Mohorovičić discontinuity, or "Moho," which forms the border between the low-density crust and the higher-density mantle. Seismic waves move faster in the mantle than in the crust, so the Moho forms a density boundary that can reflect earthquake waves. Waves that strike the Moho at a shallow enough angle undergo critical reflection, heading upward toward the surface instead of continuing downward into the mantle. When these waves meet the Moho at precisely the critical angle, the reflection process actually focuses them, thereby strengthening the redirected waves.

All earthquakes produce some waves that bounce off the Moho, but the strength of the reflections varies from quake to quake and from one location to another. Some areas have a sharp density contrast at the Moho boundary, while others not far away can have a more gradual transition that does not produce strong critical reflections. Moreover, some quakes direct much of their energy toward the Moho, adding punch to the critical reflections.

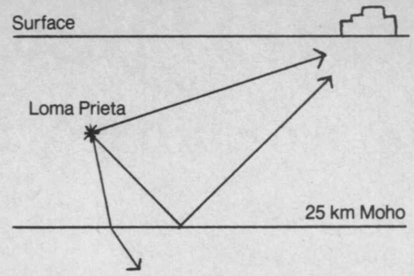
Could that reflected punch hurt? Somerville and Yoshimura think Loma Prieta answers that question. In their view, the critically reflected waves explain the abnormally strong shaking detected even by seismographs situated on rock in San Francisco and Oakland. "The motions were about a factor of two or three larger — at any site, rock or soil — because of the particular critical reflections," Somerville says. In other words, he asserts that the critical reflections more than doubled the peak shaking force for all sites in San Francisco. At particular locations, he adds, soft sediments boosted these already-amplified forces so that buildings on soft spots felt about five times the expected peak accelerations.

Somerville and Yoshimura point to a distinct pattern in the strong-motion records as evidence for the importance of

Moho reflections. The unusually intense waves shook only those stations located 50 to 100 km from the epicenter — exactly the region where critical reflections theoretically should reach the surface, according to their calculations. Closer to the epicenter, where Moho reflections theoretically would not hit the surface, the instruments recorded waves more typical of magnitude 7.1 earthquakes.

More evidence comes in the form of the waves' arrival times. Reflected waves and those traveling directly through the crust take separate paths through the Earth, and thus would reach a particular station at different times. At stations 50 to 100 km from the epicenter, the researchers note, the strongest waves arrived at a time matching the expected arrival of reflected waves. Somerville says he and Yoshimura have run a computer simulation confirming that critically reflected waves should be the strongest ones hitting the San Francisco region. They will present their case at the May meeting of the Seismological Society of America in Santa Cruz, Calif.

A critical jolt? Seismic waves hitting the Moho boundary at a steep angle pass down into the Earth's mantle, while waves hitting it at a sufficiently shallow angle reflect back up into the crust. Theoretically, this process can amplify the waves that hit at the "critical" angle — a potential factor in Loma Prieta'a extra-strong shakeup of San Francisco and Oakland.



David Boore, a seismologist with the U.S. Geological Survey in Menlo Park, Calif., agrees that Moho reflections did reach San Francisco, but he says they might not have been strong enough to cause the violent ground motions detected there. He cites several factors other than Moho reflection that might explain why San Francisco's shakeup exceeded the average for a region that far from the epicenter. Because of the way faults move during an earthquake, seismic waves traveling in some directions tend to be stronger than those heading in other directions. The Bay area may have had the misfortune to be sitting smack in the direction of these stronger waves during Loma Prieta, Boore says.

Moreover, he notes, many of the San Francisco recording stations on hard rock sites sit on hills. Seismologists believe hills can amplify quake waves under certain circumstances.

Researchers are still compiling and analyzing data from Loma Prieta, and Boore says it will take additional study to flesh out a full explanation of the quake's long-distance power. Knowing whether or not critical reflection played an amplifying role will have important implications for forecasting the shaking potential of future quakes. For instance, if Somerville and Yoshimura's critical-reflections theory proves correct, it could represent a bit of favorable news for the Bay area. Several well-known faults lace the region at distances much closer than Loma Prieta's epicenter, and geologists have predicted 50-50 odds for one of those faults generating a magnitude 7 quake by the year 2018. While a nearby quake of this magnitude would hit San Francisco even harder than Loma Prieta, the area would escape any compounding effects from critical reflections, which presumably would strike more distant — and less populated — regions.

But if Loma Prieta's amplification traces instead to other factors, those factors might similarly intensify future San Francisco shakeups. And in either case, the area still faces the danger of the unsteady sediments lurking beneath many of its structures. □