Loma Prieta: Saved by a Short, Sharp Shock

The initial strong tremors were over in less than 10 seconds; had they lasted longer, many more structures might have collapsed

San Francisco

ONE REASON the Loma Prieta earthquake didn't leave Northern California looking like Soviet Armenia was undoubtedly the quality of building construction. But Californians shouldn't be too smug. They owe some of their good fortune to a major stroke of luck.

The strong shaking associated with the quake was over in only 6 to 10 seconds. Had it gone on for much longer (the similiar-sized Armenian earthquake shook the ground for 30 seconds), damage would have been much more severe. Soils in many regions around the Bay Area would have liquefied, probably bringing down many more buildings, and a lot of structures now known to have been close to collapse would have been finished off.

That is the message to emerge from intense studies of the quake's impacts conducted over the past 2 months. The results were described in a series of meetings of seismologists and engineers held in the San Francisco Bay Area last week.*

California's relative good fortune is directly connected to the way the San Andreas fault failed. The 40 to 50-kilometer rupture that caused the quake began at a central point along the fault and traveled outward in two directions at once. Had the fault ruptured unidirectionally, the strong shaking could have lasted 20 to 30 seconds. That would have tumbled structures that are now known to have been stressed to their limits. Says Vitelmo Bertrero, a civil engineer at the University of California, Berkeley: "A few seconds more, and we would have had many large buildings collapse."

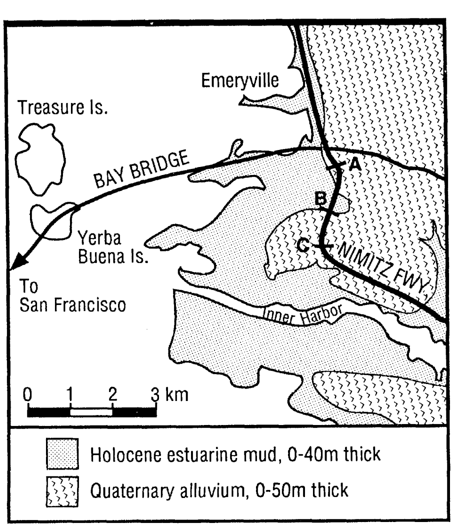
Supporting Bertrero's point, UC Berkeley engineer Stephen Mahin points to side-by-side masonry buildings of different heights—and therefore different resonant frequencies—in Oakland and San Francisco that pounded against each other during the earthquake. In several cases, large diagonal cracks developed in the taller building, suggesting that a few more blows would have brought it down.

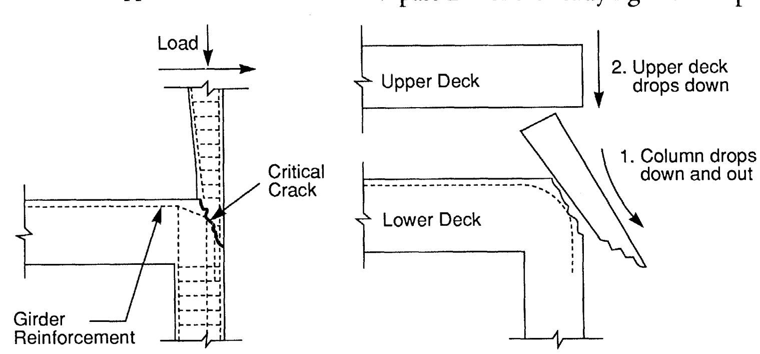
Another hazard—one that was the topic of much speculation early on—was the liquefaction of sandy, loose fill, a condition that was widespread in the Marina district and throughout the Bay Area. But engineers now realize that this actually contributed little to building collapse, according to UC Berkeley engineer Raymond Seed. It would have, though, had the strong shaking gone on longer. That's because water-saturated, sandy soils require several seconds of jostling before the sand particles become surrounded by water and transformed into a liquid slurry. The soils that liquefied did so only at the very end of the earthquake, Seed said. "Had liquefaction occurred earlier in the event, or had strong shaking persisted for a longer duration . . . the associated settlement would have been damaging to many more structures."

If not the underlying liquefaction, what did devastate the Marina? Seed and others have concluded that the primary culprit was the amplification of the quake by the soft Marina soils. The resulting strong shaking preyed on a structural weakness in the wood frame homes: Their "soft" first stories—garages with few if any internal walls or supports—crumpled under the weight of the two to four stories above them.

As with the homes in the Marina, soil performance and vulnerable construction were also the major factors in the collapse of a 1-mile stretch of double-decker elevated freeway on route 880. The part of the highway that collapsed was built on bay mud deposits, while the parts that remained standing were on firmer and older alluvial soils (see map). Following the earthquake, a team from Columbia University's Lamont-Doherty Geological Observatory and the U.S. Geological Survey placed strong motion instruments at six locations near the structure—on rock, alluvium, and mud, as well as on parts of the structure that remained standing, to measure movements during the many aftershocks that rolled through the area. They found that the bay mud amplified the ground movement in frequencies that were close to the structure's apparent resonant frequency, an unhappy coincidence that probably led to the freeway's demise by maximizing its motion during the earthquake. Seismometers placed on the freeway showed its natural resonance frequency to be 2 to 4 cycles per second, and the bay mud was found to produce a five- to eightfold amplification of ground motion in the 3 to 5-cycle range.

The magnified shaking that resulted exposed a tragic flaw in the design of the connection between the columns supporting the upper and lower decks of the roadway (see diagram), according to UC Berkeley engineer Jack Moehle, who has spent the past 2 months studying the collapse. When





Mud and flaws. *The two-tier stretch of route 880 built on mud (points A to B) collapsed, while the portion built on alluvium (B to C) remained standing. The mud amplified ground movement, causing cracks in the supports.*

*A technical briefing held at the University of California, Berkeley, sponsored by the Earthquake Engineering Research Institute and the UC Berkeley schools of engineering, environmental design, and public policy; a special session at the annual meeting of the American Geophysical Union in San Francisco; and a congressional field hearing on the earthquake, held in San Francisco.

A Blessing in Disguise

If a bridge is long enough, an earthquake may impel its ends in different directions relative to each other, with potentially disastrous results. That's what the Loma Prieta earthquake did to the Oakland Bay Bridge, a University of California engineering team reported last week. During the quake, the eastern section of the bridge lurched eastward, yanking two 50-foot segments of roadway off their supports, like drawers pulled too far out of a dresser.

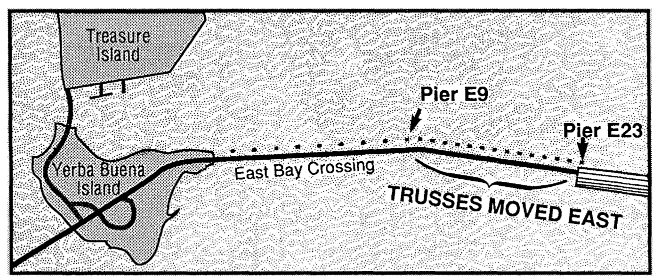
While that sounds awful, in fact the collapse of the two small stretches of roadway in the eastern third of the bridge, with the loss of only one life, may have been a blessing in disguise: By relieving strain on the bridge to the west, it may have prevented a more catastrophic failure.

The roadway segments that fell were the upper and lower roadways at pier E9, mid-way across the eastern stretch of the bridge. Abolhassan Astaneh and his engineering research team at the University of California at Berkeley have found evidence that inertial forces within the bridge pulled the trusses and roadway east of E9 toward Oakland by about 7 inches relative to the rest of the bridge.

That movement tugged on the roadway segments over pier E9. Normally, each roadway is held fixed to the pier by 40 1-inch diameter bolts, but those bolts were sheared by the jolt, and the roadways were pulled off the 6-inch shelves that supported their westward ends. If the bolts had held, says Astaneh, the forces would have been transferred to pier E9 itself, possibly leading to an even greater tragedy. "Most likely you would have had collapse of that pier," Astaneh told *Science*. "The decks, the cars, at least some segments of the bridge would have gone down to the water."

With a bit more movement, the roadways over pier E23—the easternmost pier of the bridge—would have collapsed as well. The anchoring bolts failed there also, according to Astaneh. "Believe it or not, [the roadway] moved so much that it was sitting only 1 half-inch on the seat. So if you had a half-inch more movement, you would have had two parts of the bridge failing the way [E9] did."

The bridge was reopened on 17 November, 1 month after the earthquake. The seats supporting the roadway have been extended 2 inches, to allow more safe slippage in a similar earthquake. The replacement bolts, although stronger than their predecessors, remain the weak link. But if they give way in the next big one, that may again be a blessing in disguise. ■ **M.B.**



Under stress. *Bolts sheared at E9 and E23.*

the freeway was constructed, steel reinforcing rods running horizontally under the roadway were bent downward at their ends, to intermesh with the vertical rods running up the lower support columns. This left a triangular region of column immediately above that junction with inadequate reinforcement, Moehle said. During the earthquake, the concrete cracked along a diagonal line that followed the downward bend of the horizontal reinforcements, causing the upper columns to fall out and away and the upper deck to drop.

San Francisco's Embarcadero Freeway, a double-decker roadway of similar design, showed diagonal cracks identical to those that precipitated the 880 collapse. With longer shaking, it would likely have fallen as well, according to UC Berkeley's Mahin.

In general, the intensive study of the Loma Prieta earthquake has reinforced what engineers already knew. Most of the structures that collapsed were built before the development of modern earthquake codes and were located on soft soils that amplified the ground movements. But engineers have been starved for actual data on such ground movements and how they influence buildings. Loma Prieta was in that sense an experimental goldmine.

"A wide variety of buildings have been instrumented, and I think this earthquake is going to give us a very special opportunity to evaluate our design and analysis procedures," Mahin told the audience at the Berkeley briefing. About 40 buildings in the affected area were equipped with strong motion sensors, yielding an unprecedented volume of data for engineers to work with. Their findings will help guide the improvement of codes for new buildings, as well as schemes for retrofitting those older buildings and highways that, due to their construction or location, are at greatest risk.

Retrofit methods used in the past have been rather hit-or-miss, Mahin said. Some buildings that had been strengthened with cross-braces or other means did well in the earthquake, but others failed. Careful evaluation of the patterns of damage may lead to the development of more reliable retrofitting techniques.

And additional information to guide future construction could come from experiments with some of the structures that were left standing. This month, for example, the UC Berkeley engineering team is using the portion of the 880 viaduct that remains standing to simulate earthquakes and test various types of reinforcement that have been proposed by the California Department of Transportation to strengthen similar structures.

Such experimentation, either with full-scale structures or with models, is critical, Mahin says. Current codes allow buildings to be designed to standards that may result in some damage during a major earthquake. But, he notes, "you assume that if you provide certain details, and certain structural systems, that [the buildings] won't catastrophically collapse." Mahin says computers cannot be relied on to model accurately how those details and systems will perform. It requires actual hands-on experiments.

Hence, a plea for research funds, but of a very particular kind: The Japanese, Mahin says, require that construction companies put 1% of their sales income into earthquake engineering research. "Any building over 14 stories has to have experimental data that validates that all the members and joints in the building will sustain the earthquake," he says. "Nobody does that for any structure here."

Seismologists last week argued before the House of Representatives subcommittee on science, research, and technology for more funding for strong motion sensors to collect data on the Hayward fault, which runs through downtown Oakland. Mahin agrees with this, but he points out that the next Hayward earthquake will kill thousands of people unless engineering research is used to improve building safety.

■ Marcia Barinaga