Liquid Sand

The liquidlike behavior of soils during major earthquakes causes considerable damage

By IVARS PETERSON

The shaking of an earthquake can, within minutes, turn a loose sandy soil saturated with water into a fluid porridge that no longer supports a building. Unless the building is designed to float, it will sink or tip over. This earthquake effect, known as soil liquefaction, probably contributed to the devastation that occurred last month in Mexico.

"This phenomenon of soil liquefaction sounds very esoteric," says earthquake engineer Ricardo Dobry of the Rensselaer Polytechnic Institute in Troy, N.Y., "but it happens over and over again. Most big earthquakes cause a lot of liquefaction."

The destructive power of soil liquefaction was first forcibly brought to the attention of earthquake engineers after the disastrous 1964 earthquake in Niigata, Japan (SN: 2/10/79, p. 90). In this earthquake, widespread liquefaction caused nearly $1 billion in damage. Last month's Mexican earthquake (SN: 9/27/85, p. 196) again reminded engineers of the danger when sand suddenly starts to flow like a liquid. Mexico City, partly built on an ancient lake bed, showed a patchwork of toppled structures hinting that at least some of the buildings had rested on patches of sand that for a moment couldn't bear a load.

Although soil liquefaction is only one small part of earthquake engineering, says George W. Housner of the California Institute of Technology in Pasadena, it's particularly important because of its potential effect on critical structures like nuclear power plants and large earth dams. "The consequences of a failure would be extreme," he says.

Soil liquefaction is also a "concealed hazard," Housner says, partly because the evidence is hidden underground and partly because few people are aware of the problem. Housner chairs the National Academy of Sciences (NAS) earthquake engineering committee, which is preparing a report on soil liquefaction during earthquakes. A draft version of the report was presented last month at a NAS seminar in Washington, D.C.

News of the Mexican earthquake, which happened to strike just as the seminar was starting, dramatically punctuated the meeting. "Maybe this will help focus attention on this seminar and the importance of the problem," Housner commented wryly when he announced the news.

In the last two decades, a great deal has been learned about soil liquefaction. When an earthquake shakes loose, wet sand, the sand grains roll and slide into more stable positions. The sand settles to form a denser layer. But the excess water, trapped among the sand particles, can't escape quickly enough, and the water pressure inside the mixture rapidly builds up. At some critical "pore" pressure, the sand grains lose direct contact because films of water now separate them. The mixture begins to behave like a liquid.


T.L. Youd

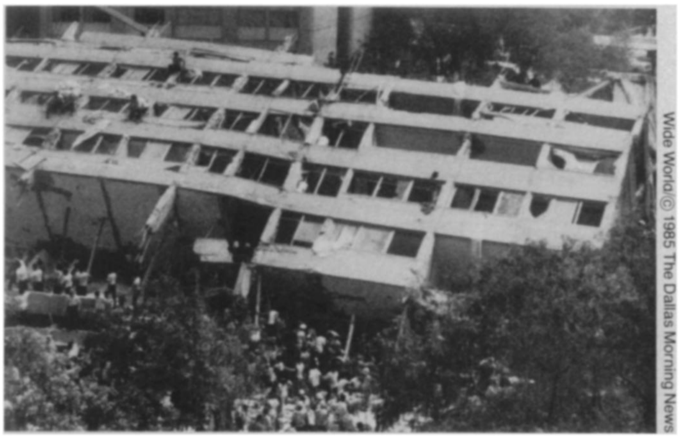
Soil liquefaction during a 1979 Imperial Valley earthquake generated fissures along a canal near El Centro, Calif.

Normally, the weight of a building or a dam and the weight of overlying soil are enough to keep a saturated sand layer firm and stiff. This is the same effect that turns a tightly held sock packed with wet sand into an effective hammer. But that strength disappears with an increase in pore water pressure during shaking.

Liquefaction occurs most readily if the soil is a fine sand because it takes hours for the water to make its way through the mixture's minute channels. A large-grained, permeable soil like gravel, on the other hand, drains very quickly. Clay soils, in which particles are effectively "glued" together, are also resistant to liquefaction.

Dams that consist of piles of loose sand are very vulnerable to earthquakes. "They liquefy, they flow, and they fail easily," says Dobry. During a 1971 earthquake, a large part of the upstream face of the 140-foot Lower Van Norman San Fernando Dam in California collapsed and slipped beneath the water. About 80,000 people, who lived downstream in Los Angeles, were forced to leave their homes for several days until the water level behind the dam was lowered.

"It was almost catastrophic," says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A toppled building in Mexico City shows that soil liquefaction may have contributed to the damage suffered during a recent earthquake.

In the 1886 Charleston, S.C. earthquake, sand boils like the one shown spouted a mixture of sand and water.

USGS

Dobry. "The earthquake ended just as the dam was starting to go. Most of us estimate that after 5 or 10 seconds more of shaking, it would have gone."

Although loose sand no longer goes into the construction of earth dams, a number of older dams of this type are still in use. In contrast, dams constructed from clay soils don't fail catastrophically, even when they are poorly built.

Perhaps the most common manifestation of liquefaction is the occurrence of "sand boils." These small, volcanolike features mark spots where a high fluid pressure, generated during an earthquake, has driven pore water to carve a channel that brings waterborne soil particles to the surface.

More subtle soil liquefaction effects are seen in the spreading of slightly inclined ground or the settling and subsequent flooding of large areas. Not only are buildings damaged, but also highways, bridges and pipelines often suffer. In the 1964 Alaska earthquake, about 250 highway and railroad bridges suffered damage because liquefied sand pushed bridge abutments toward the center of river channels. Liquefied soil is also known to have pushed underground storage tanks to the surface, even forcing them through asphalt pavement.

"There's a great deal to be learned by going into the field," says T. Leslie Youd of Brigham Young University in Provo, Utah. Detailed field studies have identified the types of geologic deposits, such as loose sand left in river valleys, that are most susceptible to liquefaction.

Moreover, deposits that liquefy during one earthquake are very likely to liquefy again in later earthquakes. This is the basis for a major study planned for the Imperial Valley in southern California where sand boils erupted and riverbanks collapsed during a 1981 earthquake. Instruments to measure ground movement and pore water pressure thread a site in the area of a prehistoric stream channel near the Alamo River. "We're now waiting for an earthquake to happen," says Youd.

Because very little detailed information is available on exactly what happens in wet sand during an actual earthquake, any data collected in the Imperial Valley study will be very valuable, says Youd. This information would help validate laboratory studies and computer simulations of soil liquefaction. An instrumented site on an artificial island near Tokyo has already provided one set of useful results after an earthquake in 1983.

Although progress has been made in assessing possible liquefaction hazards, some aspects of the problem remain uncertain. For example, earthquake engineers disagree about whether to focus first on a soil's loss-of-strength potential or on the pore pressure necessary to trigger a flow failure.

Is excess pore pressure a cause or a symptom, asks Robert V. Whitman of the Massachusetts Institute of Technology. The relative merits of these different approaches can be resolved only through observations of the actual effect of earthquake shaking on soils. "It can't be settled by experiments on small samples," says Whitman. "It can't be settled by more theoretical analysis."

In practice, almost any saturated, granular soil can develop increased pore water pressures when shaken. These pore pressures can rise significantly if the earthquake lasts long enough. At a given site, the important question is: What intensity and duration of shaking will cause liquefaction, or, conversely, can the soil survive the anticipated earthquake shaking without liquefying?

Experts have developed a variety of methods for testing soils and assessing liquefaction hazards, but they admit that the process is still very much an engineering art. "There are enough unknowns that we can't use one methodology to solve the whole problem," says Gonzalo Castro of Geotechnical Engineers, Inc. in Winchester, Mass.

Soils are complex materials that vary a great deal from place to place. Even in a single location, "there are no uniform sand deposits," says H. Bolton Seed of the University of California at Berkeley. So far, most laboratory studies have concentrated on clean sand. Seed is now studying sand-gravel mixtures because no satisfactory procedure exists for evaluating the safety of these soils.

Even "sensitive" clays can be a problem. Shaking can shatter a brittle clay to form a permeable rubble that acts like a pile of loose sand.

Furthermore, it isn't clear which meas-

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The settling of sandy soil after liquefaction during the 1964 Alaska earthquake caused extensive damage.

tently gives the system enough time to catch up. And the intermittent schedule may stimulate the production of enzymes.

Free radicals, which are credited with enhancing wound repair, have also been associated with cancer, but hyperbaric oxygen researchers note that they are treating life-threatening conditions and that they do not suspect use of hyperbaric oxygen will cause a problem. "Breathing oxygen at high pressure is not a new thing," says Lambertsen, noting that divers have been doing it for years. "The process turns off as soon as oxygen administration is stopped."

Al Tappel of the University of California at Davis, an expert in free radicals, says that while he is unaware of studies of hyperbaric oxygen and cancer, he suspects the link, if any, would be small because people naturally have protective enzymes against free radicals.

"From the clinical standpoint," says Davis, a former head of the Undersea Medical Society, "we have never seen any evidence [of carcinogenicity] to concern us."

What researchers fear today is "another simultaneous wave of not very scrupulous characters who set up chambers in offices to make a lot of money," says Davis. "It's an expensive modality. We're very concerned about overzealous uses."

A researcher monitors the effect oxygen poisoning has on vision. The subject here is breathing 100 percent oxygen at three atmospheres of pressure.

The therapy has proven its value as an adjunct for certain conditions, and controlled clinical trials are under way for other ailments. What would be most damaging now, say these researchers, is another unfounded rise in expectations. □

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urements at a site provide the best indications of a potential hazard. Data collected in the past or in other countries are sometimes difficult to use because the measurement techniques were different or standards varied.

Earthquake engineers are also far from being able to make accurate predictions about how much the ground will shift if an underlying sand layer liquefies, says Youd, because so many factors influence the process. Many more case histories are needed to shed light on exactly what happens, he says.

The problem is that there are very few places where both the characteristics of a shaking during an earthquake and the soil properties before an earthquake are known. Nevertheless, some researchers are digging into historical records and geological data for clues about past episodes. Photographs and written accounts of the 1906 San Francisco earthquake, for example, clearly show that soil liquefaction played an important role in destroying buildings resting on landfill and in breaking gas and water mains. Although the focus on soil liquefaction research is relatively recent, the problem has existed for as long as earthquakes have affected civilization.

Despite the uncertainties, soil liquefaction is a hazard that's now relatively recognizable, says William F. Marcuson III of the U.S. Army Corps of Engineers in Vicksburg, Miss., but selecting a solution can get very complicated. "There will never be a cookbook approach for seismic stabilization," he says. "It has to be done on a case-by-case basis."

Experience shows that soil liquefaction can damage all types of structures, from dams and towers to roads, pipelines and underground storage tanks. If a soil at a particular site turns out to be susceptible, then the structure must be abandoned, relocated or improved. Improvements, which include replacing or packing down loose sand, providing better drainage or rebuilding a structure on deeper pilings, may be very costly. On top of that, adds Marcuson, "We have little field experience for guidance."

To earthquake engineers, large earthquakes like the one that rocked Mexico, although a human tragedy, provide valuable information about what works and what doesn't work. How large a role liquefaction played in destroying buildings in Mexico City won't be known until a direct inspection takes place. Earthquake specialists are heading for the city to see at first hand what happened and to garner clues that could lead to better construction practices and remedial measures.

"Any progress that we make in understanding [soil liquefaction] is important," says Frank Press, NAS president and a geophysicist by training. "We respond to crises as they happen," he says. "That's wrong. We need to plan ahead to take this and other potential hazards into account." □

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