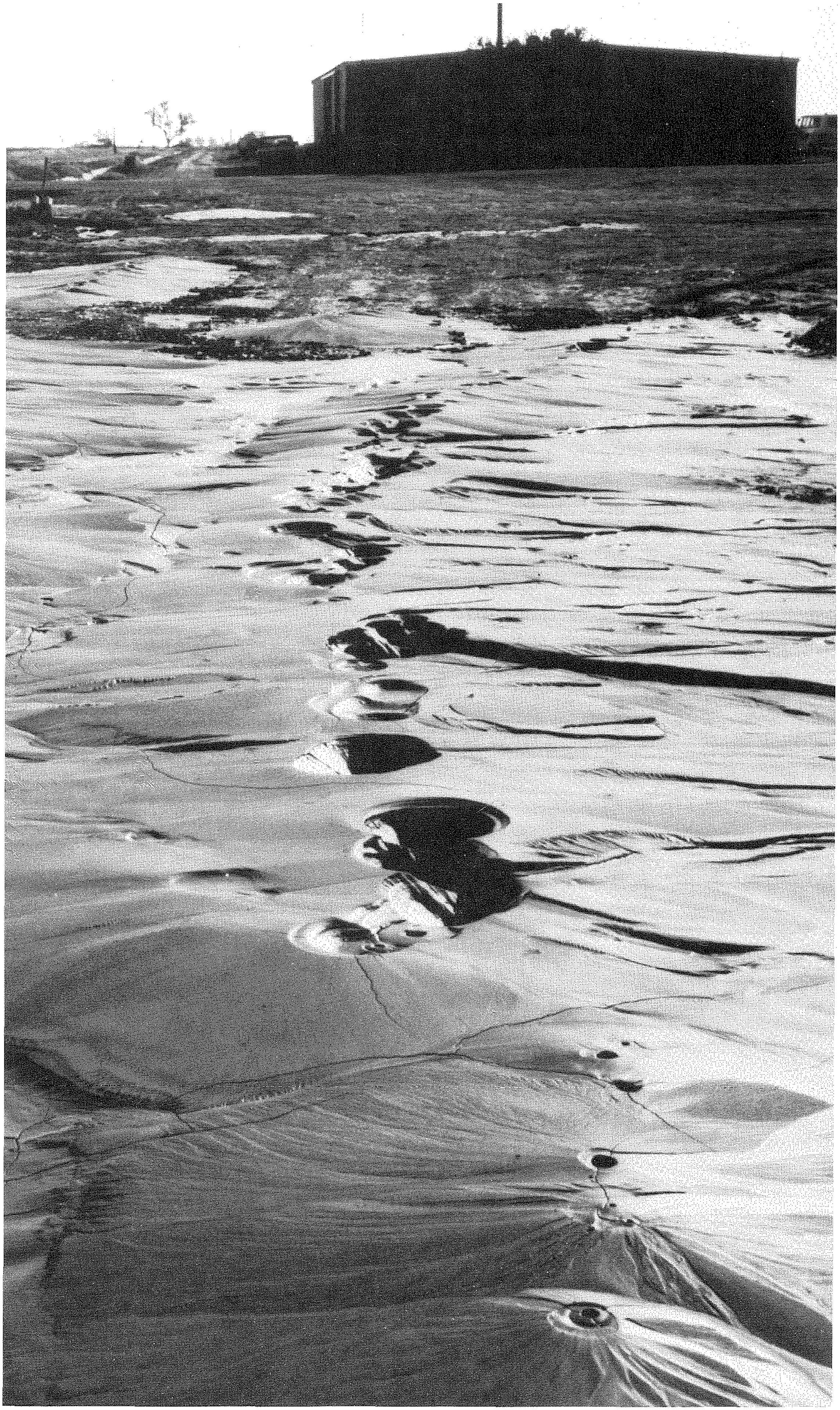


Liquefaction

by Ronald F. Scott

Liquefaction has progressed since 1964 from the status of a curious, rather mysterious event accompanying earthquakes to a well-documented, fairly well-understood and predictable process.

Sand boils were formed as liquefied sand erupted from a fissure in a field during and following the 1979 Imperial Valley earthquake.

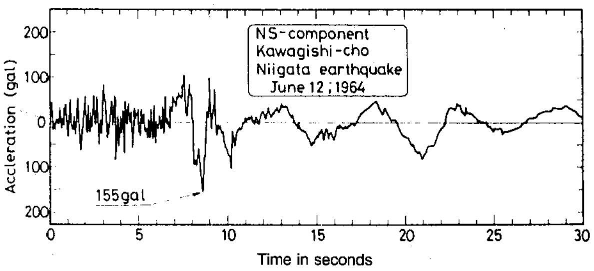
The recent Loma Prieta earthquake brought the phenomenon of soil liquefaction into the public eye in southern California. The damage in San Francisco's Marina area was widely attributed to liquefaction, and there have been dark hints that it may have played a role in the collapse of the upper deck of the Nimitz Freeway. Later reports indicate widespread liquefaction events at Moss Landing, Santa Cruz, and other areas of strong ground motion caused by the earthquake. The term "soil liquefaction," used initially by a few geotechnical engineers and geologists, became a popular media buzz-word for newspaper, radio, and television reporters who besieged the offices of soil engineers (including this one) in the few weeks following the earthquake. What is soil liquefaction? What conditions give rise to it? How hazardous is it? Where can it happen in the Los Angeles area? Are there any palliative measures? If one has a home or other property in an area deemed to be potentially liquefiable, what can be done? Since I've had a lot of practice at this lately, I'll try to provide some relatively nontechnical answers for *E&S* readers.

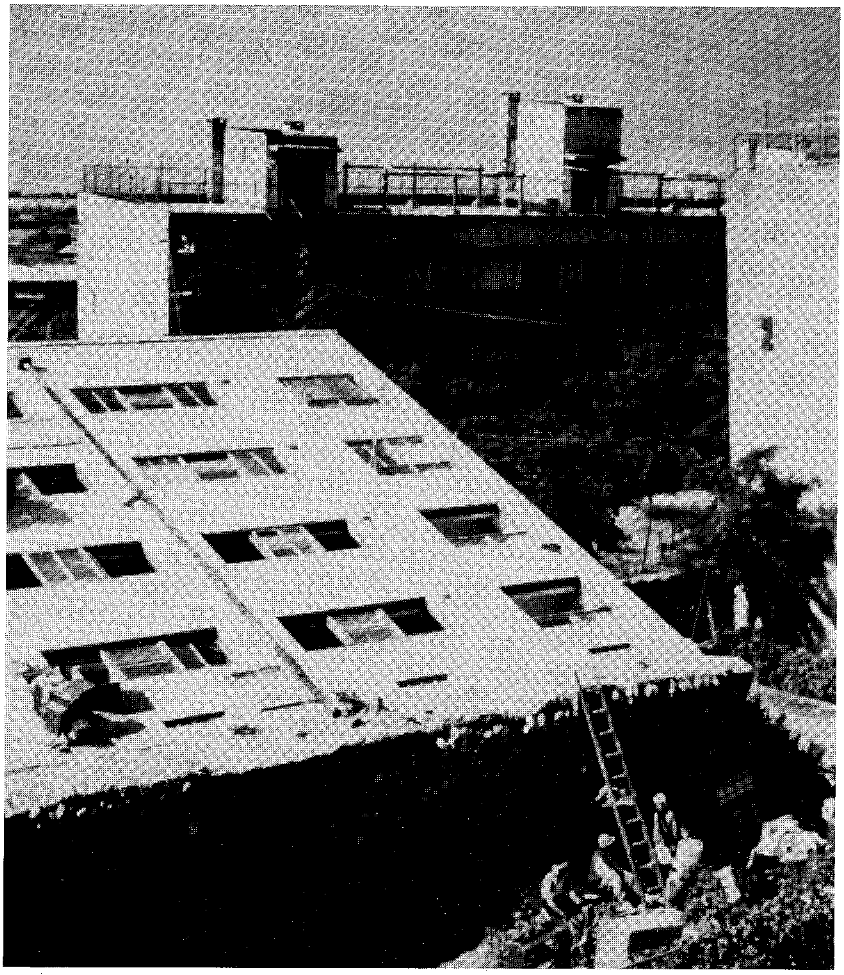
Soil liquefaction has occurred to a greater or lesser extent in all earthquakes; as indicated by contemporary accounts, it has been recognized for centuries without a clear understanding of its mechanisms. Substantial structural damage was associated with liquefaction in the 1960 Chilean earthquake, but detailed engineering attention first focused on liquefaction as a major problem in two 1964 earthquakes—in Alaska (March) and in Niigata, Japan (June). In the United States virtually the entire earthquake engineering community devoted their efforts to the Alaskan event because of its size (magnitude 8.4) and diverse effects, so that the somewhat smaller (magnitude 6.6) but still immensely destructive Niigata earthquake went virtually unnoticed here for some time. Professor George Housner visited Japan later in 1964 (see page 32) and told me about the situation in Niigata, suggesting that I go and see it. I formed a team of soil engineers and applied for a grant from the National Science Foundation to do this. We traveled to Niigata in 1965. Because of its location on alluvial deposits at the coast, Niigata was devastated by widespread liquefaction and its effects. We were deeply impressed by the potential of sand liquefaction for damage, and all of us began to study the phenomenon in diverse ways.

Liquefaction played a role in some of the damage in Alaska and emerged again as a villain in the partial collapse of the Lower San Fernando Dam in the 1971 San Fernando earthquake. Possibly because that failure looked like a more-or-less simple slope failure and involved some highly technical analysis, liquefaction did not catch on then with the media. But with an undiluted form of it in fairly level ground in the Loma Prieta earthquake, liquefaction has now, in 1989, arrived as a hot topic.

What is liquefaction and under what circumstances does it develop? It's a phenomenon associated with fine- to medium-sized (0.1 to 0.5 mm diameter) cohesionless sands when they are in a relatively loose state and saturated with water. If the same material were dry, it would

A strong-ground-motion recorder obtained the accelerations of the 1964 Niigata earthquake in the basement of one of the Kawagishi-cho apartment buildings, which are shown settled and tilted below. The record begins as a typical, high-frequency, firm ground motion, but at about 7 seconds changes to a lower-frequency, sloshing motion as the ground below the building partially or completely liquefies.





become denser and the surface would simply settle on shaking, which causes some of the unstable particles to tumble into spaces between lower, adjacent particles. When the soil is saturated with water, however, propagation of the earthquake waves through it again dislodges some grains, but now their fall into lower spaces is hindered by the water's presence. For a short period of time they are suspended in the liquid. Thus the weight (in liquid) of such particles is no longer borne by the underlying grain structure through solid contacts, but is instead transferred to the liquid, whose pressure rises. In weak shaking only a few grains are moved and the pressure of the water in the pores of the soil rises a small amount. In more intense shaking or shaking of longer duration virtually all of the particles in a mass are disturbed and suspended in the water for a short span of time. In this case almost all solid contact between the particles is lost, so that the soil mass has none of the properties of a solid, which it formerly possessed, but becomes a liquid with the density of the soil/water composite and a viscosity higher than water alone. The liquefied state persists until the particles settle out to form a new, denser structure of contacting solid sand grains, and the water pressure has reverted to hydrostatic once more. The amount of time this takes depends on the size of the grains (smaller grains mean a longer duration) and the dimensions of the liquefied mass (bigger means longer). Typically liquefaction endures for a few minutes but may last up to 10 or 15 minutes.

Besides the presence of a relatively loose, saturated sand and, of course, the strong ground motions caused by an earthquake, another requirement for significant liquefaction is a water table within 10 to 15 feet of ground surface. There is no direct instrumental evidence for the depth to which a soil can liquefy, but calculations indicate that it should generally be limited to the upper 50 to 60 feet of soil profile.

If the soil is fairly uniform all the way to the ground surface, then, depending on the depth of the water table, a general subsidence takes place, and water may appear at the surface. This is unusual in nature since plants and cultivation impose a finer layer of somewhat cohesive soil in the top few feet. In this case, as I view it, if the underlying layer of sand should liquefy, the water has no immediate egress to the surface, since there is an upper confining layer of lower permeability. It finds its way to the surface, however, discontinuously through root or animal holes or cracks, possibly generated by the earthquake. Since it's under pressure from the over-

Liquefaction in the 1989 Loma Prieta earthquake caused lateral spreading of the ground, which tore apart the UC Santa Cruz marine biology building at Moss Landing (top right). Diesel-fuel-filled tanks (top left), also in Moss Landing, settled and tilted on the liquefied sand. The sand boils (above) appeared under the approach spans of the San Francisco Bay Bridge in the same earthquake.

burden, the saturated, liquefied sand will emerge at the surface as fountains as high as a few feet. The remains of these fountains are variously called sand boils, sand volcanoes, and mud fountains, and are a sure indication of liquefaction. The sandy water in the jet falls down around the hole, the sand settles out to form a volcano-like structure, and the water runs off. A subsequent aftershock can reliquefy the material, the fountain is revivified, and the new spout may erode the former volcano feature. Although these are usually ephemeral phenomena, "fossil" sand boils have been identified by Kerry Sieh and his students in his investigations of the San Andreas fault movements at Pallett Creek, and researchers in South Carolina have also found evidence of sand boils presumably caused by the 1884 Charleston earthquake.

The consequences for a structure underlain by a suddenly liquefied sand are fairly obvious—it settles and generally tilts. At the same time, however, the liquefaction of the foundation soil also isolates the building from all but the first few seconds of strong ground motion, so it actually experiences less intense shaking than it would if the ground had remained solid. Frequently, structures that have experienced liquefaction of their foundation soil are relatively undamaged structurally—if you consider settling a few feet and tilting up to 70 or 80 degrees "undamaged." Of course, all connecting utilities are disrupted, and the cost of straightening up the building and reconnecting it may amount to more than half the cost of constructing it from scratch.

Liquefaction, although possibly causing large amounts of property damage to ordinary structures, has not generally been associated with a hazard to life.

In Niigata in 1964 an underground, hollow, reinforced-concrete, sewer junction box floated to the surface when the soil liquefied (top). Lateral spreading in the 1989 earthquake destroyed a coastal highway in Moss Landing (bottom).

Houses and other buildings settle because they are heavier than the liquefied soil, but just the opposite can happen to structures that are buried—pipes for water, sewer, gas, and petroleum, underground storage tanks, and subway tunnels. In most cases the density of these structures is less than that of the suddenly dense liquid in which they find themselves, and consequently they float, tending to rise toward the surface. The amount of movement depends on the relative densities involved, the size and connections of the structure, and the duration of time for which the soil remains liquid.

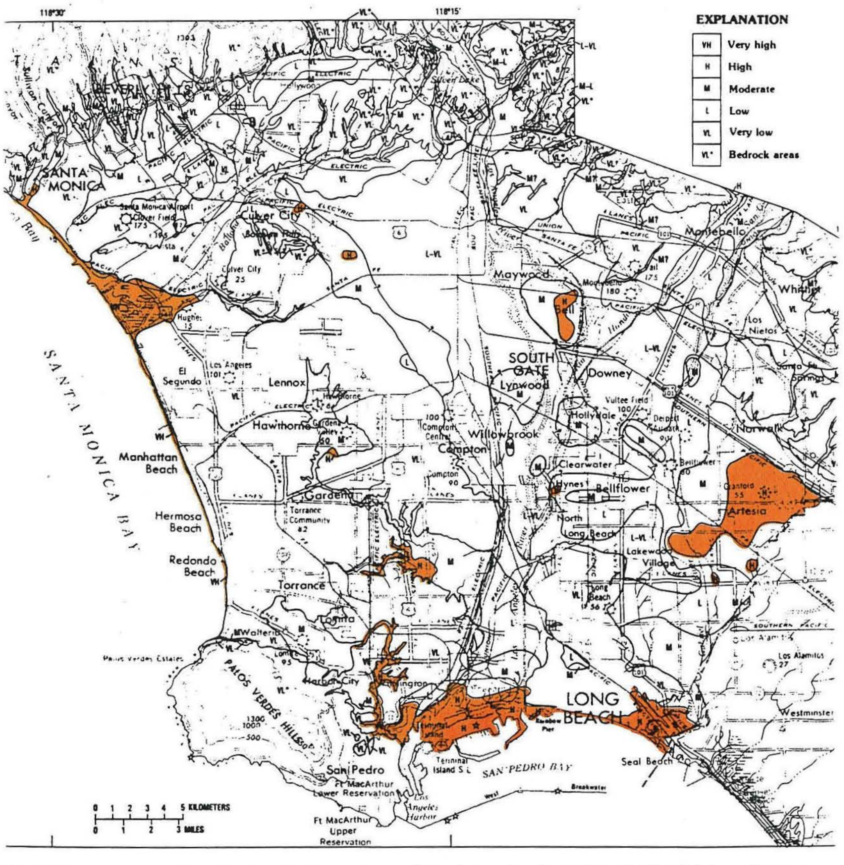
Because of the isolation it affords from the strong ground shaking, liquefaction, although possibly causing large amounts of property damage to ordinary structures, has not generally been associated with a hazard to life. For other structures, however, such as dams, liquefaction can contribute to collapse, with potentially large numbers of casualties, depending on the dam's location. Although the evidence and analyses of the recent event are not all in yet, apparent liquefaction of old fill material in the Marina area of San Francisco caused substantial ground settlements and lateral movements leading to structural damage and breakage of utilities in the soil. So when fire broke out, there was insufficient water to fight it because the water pipes had broken. At Moss Landing, down the coast, lateral spreading of the ground on small slopes accompanied liquefaction and tore apart structures and foundations.

Liquefaction will occur in the Los Angeles area where the above conditions of relatively loose sandy soils, high water table, and seismic potential exist, that is, generally along the coastal zone—Marina del Rey, Manhattan Beach, Redondo Beach, the Long Beach area, and portions of Huntington Beach and Orange County. Isolated regions also exist inland. A US Geological Survey report (noted under the map at left) gives a detailed survey of the liquefaction hazard in Los Angeles and Orange Counties.

Possible mitigating measures range from none to a variety, depending on the structures involved and financial resources available. It would be a good idea, perhaps, not to buy a vacant lot in a liquefiable area for the purpose of constructing a residence. If you already live in a single-family house in a liquefiable area, there is practically nothing you can do except move, if the hazard disturbs you sufficiently. At the other end of the structural and financial spectrum, for large enough structures such as power plants, big buildings, and, say, natural gas storage tanks, several approaches are possible. Sometimes the liquefied soil can be removed by excavation and replaced by a properly compacted fill. Or the liquefied soil may be stabilized chemically, or the structure supported on piles driven to a deeper, firmer layer of material. All of these techniques are expensive, but the expense may be justified by the location and the value of the construction required.

Liquefaction has progressed since 1964 from the status of a curious, rather mysterious event accompanying earthquakes, to a well-documented, fairly well-understood and predictable process. The liquefaction in the San Francisco Marina was predicted for an earthquake of that size, for example. Our research—laboratory, field, and analytical—will continue in the attempt to understand and analyze the phenomenon still better and to arrive at techniques to predict its occurrence and protect against it. □

This US Geological Survey map shows relative liquefaction susceptibility in the Los Angeles area based on current understanding of geology, soil, and water-table conditions.



SOURCE: J. L. Ziony, ed., *Evaluating Earthquake Hazards in the Los Angeles Region—An Earth-Science Perspective*, USGS Professional Paper 1360 (Washington D.C.: US Government Printing Office, 1985).

Ron Scott last wrote for E&S *in the Fall 1988 issue on an entirely different subject—baseballs. But studying soil behavior is what he* really *does, and he's been particularly busy since the implication of liquefaction in damage caused by the recent Loma Prieta earthquake. Scott holds a BSc (1951) from Glasgow University and ScD (1955) from MIT. He joined the Caltech faculty in 1958 and is currently the Dotty and Dick Hayman Professor of Engineering.*