When the Ground Gives Way: Understanding and Predicting Soil Liquefaction Caused by Earthquakes

At 6:00 a.m. on February 9, 1971, a powerful earthquake struck beneath the San Gabriel Mountains north of Los Angeles. As thousands of people in the adjoining San Fernando Valley put down their morning cups of coffee and braced themselves against the shaking, a far more ominous phenomenon was taking place inside the Lower San Fernando Dam at the head of the valley. A layer of soil at the base of the earthen dam suddenly lost strength and slipped sideways as the embankment began to break apart. By the time the shaking stopped, a wall of broken earth just 5 feet tall stood between 15 million tons of water and what would have been one of the greatest dam disasters in U.S. history.[1]

Geological and geotechnical investigations revealed that the soil at the base of the dam failed due to earthquake-induced liquefaction, a phenomenon that was just starting to be understood at the time.

Liquefaction can wreak havoc. Following a 1964 earthquake in Niigata, Japan, geotechnical engineers were astonished to see four-story apartment buildings tipped like dominoes, the soil beneath them having lost the strength to support the structures. Earlier that year, liquefaction during a large earthquake in Alaska destroyed a neighborhood, disrupted roads and railroads, and compressed or buckled more than 250 bridges.[2] And after the 2010 and 2011 earthquakes in Christchurch, New Zealand, about 15,000 homes and many commercial buildings had to be demolished after liquefaction damaged them beyond repair.[3]

Soils across the United States, not just on the West Coast, are susceptible to liquefaction. When engineers recognized the dangers liquefaction could pose, they began re-examining historic U.S. earthquakes for signs of the phenomenon and quickly found many examples. Analysis of the 1906 San Francisco earthquake showed that liquefaction was responsible for 85 percent of the cataclysm's damage, as soil failures sheared off the water pipes that firefighters could have used to battle earthquake-induced fires.[4] Written records of the New Madrid earthquakes that

[1] Page, R. A., D. M. Boore, and R. F. Yerkes. 1995. The Los Angeles Dam Story. U.S. Geological Survey Fact Sheet 096-95. https://pubs.usgs.gov/fs/1995/0096.
[2] National Research Council. 1985. *Liquefaction of Soils During Earthquakes*. Washington, DC: National Academy Press. https://doi.org/10.17226/19275.
[3] National Academies of Sciences, Engineering, and Medicine. 2016. *State of the Art and Practice in the Assessment of Earthquake-Induced Soil Liquefaction and Its Consequences*. Washington, DC: The National Academies Press. https://doi.org/10.17226/23474.
[4] Youd, T. L., and S. N. Hoose. 1978. *Historic Ground Failures in Northern California Triggered by Earthquakes*. U.S. Geological Survey Professional Paper 993. https://pubs.usgs.gov/pp/1978/pp0993.

shook large portions of the Midwest from 1811 to 1812 contain many reports of the ground giving way. If a similar event were to occur today—given the industrialization of the Mississippi River Valley—the effects of liquefaction would be devastating.

Soil may be a common material, but it is also exceedingly complex. It contains particles of different sizes, shapes, textures, and chemical compositions pressed together in ways that differ for each particle. The presence of water further complicates its behavior.

A key advancement in understanding soil behavior came in the 1920s. Karl von Terzaghi, an Austrian engineer and geologist who would later join the faculty of Harvard University and eventually come to be known as the "father of soil mechanics," developed a simplified way to describe the stresses in soils. He realized that many of the complex interactions of soil particles and water could be captured in a single measure called effective stress, which helps describe how a soil will behave when it is disturbed or placed under additional stresses. Terzaghi's work led to improved designs for building dams, bridges, tunnels, ports, bulkheads, and many other structures.[5]

Following the 1964 earthquakes in Alaska and Japan, researchers realized they needed to know much more about why liquefaction occurs. Building on Terzaghi's work and on investigations conducted in laboratories and in the field, they developed a detailed theoretical understanding of how water-saturated soils behave in an earthquake.

Normally, soil particles rest against each other so that their weight is transferred to more consolidated materials deeper underground. However, when soil that is saturated by water is shaken, some soil particles lose contact with each other and their weight is borne instead by the water between the soil particles. This increases the water pressure within the soil, which further weakens the soil mass. What used to be solid ground becomes a thick liquid that can flow downhill or out from under overlying structures. At the same time, the heightened water pressure can force silt-laden water up through overlying soil layers, creating sand boils that look like miniature volcanoes.

Liquefaction may sound exotic, but anyone can observe it on a trip to the beach. If you tap your foot against wet sand, water will well up beneath your foot as the sand liquefies and the water pressure within it increases. If the sand is on a slope, the liquefied portion will run downhill until the water drains and the sand again settles into place.

In 1971, two geotechnical engineers at the University of California, Berkeley—Harry Bolton Seed, who studied under Terzaghi at Harvard, and Seed's graduate student Izzat M. Idriss—published a method of estimating whether liquefaction is likely to occur in soil under certain

[5] Terzaghi, K. 1960. *From Theory to Practice in Soil Mechanics: Selections from the Writings of Karl Terzaghi, with Bibliography and Contributions on His Life and Achievements*. New York: Wiley.

conditions.[6] At about the same time, Robert Whitman, a geotechnical engineer at the Massachusetts Institute of Technology, independently published a similar method.[7] Since then, engineers have used several variants of this method to retrofit existing structures, modify soils, and design new structures that can resist liquefaction-induced damage.

A 2016 National Academies of Sciences, Engineering, and Medicine consensus study report[8] looked at the variants on Seed and Idriss's original method to determine their accuracy, whether they can be improved, and how they should be used. Each variant has positive and negative aspects, explained Ellen Rathje, a professor of civil engineering at The University of Texas at Austin, who was a member of the study committee. "Our recommendation is that you should consider multiple techniques, not just assume one is correct and another is wrong," she said. "Look at them together to understand the deficiencies."

Knowing if a soil will liquefy is important, but an even more critical question to answer is what liquefied soil will do. Will it retain enough strength to hold up an overlying building? Will it settle, breaking up roadways, sidewalks, and runways? Will it stay in place or flow away, carrying pipelines, bridges, and other structures with it? "We need a more accurate assessment of not only whether liquefaction will happen but what the consequences will be," said Rathje.

Decisions involving hundreds of millions of dollars can hinge on these consequences. For example, many port facilities are built on loose fill that was placed alongside rivers and harbors to create land for development. Such soils are especially prone to liquefaction. When an earthquake hit Kobe, Japan, in 1995, port facilities were so damaged that shipping companies moved their operations elsewhere. Kobe's port was the sixth largest container port in the world, but dropped to 28th by 2013. "That was a striking example of what can go wrong and we can learn from it," said Yumei Wang, a geohazards engineer with the Oregon Department of Geology and Mineral Industries. Kobe, Wang noted, took a permanent hit.

An analysis of liquefaction consequences can also cut the other way. If the consequences are not severe, extensive retrofitting or other earthquake precautions may not be necessary. "Underprediction can lead to failures of things you have designed," Wang said, "but overprediction can lead to designing something much bigger and more expensive than you have to." As an example, Tom Holzer, a geologist with the U.S. Geological Survey, points to the many earthen dams that exist in the United States, which are very expensive to retrofit. He said, "If you don't need to do it, you can save a lot of money."

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[6] Seed, H. B., and I. M. Idriss. 1971. Simplified Procedure for Evaluating Soil Liquefaction Potential. *Journal of the Soil Mechanics and Foundations Division* 97(9):1249–1273.

[7] Whitman, R. V. 1971. Resistance of Soil to Liquefaction and Settlement. *Soils and Foundations* 11(4):59–68.

[8] National Academies of Sciences, Engineering, and Medicine. 2016. *State of the Art and Practice in the Assessment of Earthquake-Induced Soil Liquefaction and Its Consequences*. Washington, DC: The National Academies Press. Prepublication before final. https://doi.org/10.17226/23474.

Evidence of the value of wise investment in soil liquefaction remediation came when the Great East Japan Earthquake struck on March 11, 2011. The 9.0 magnitude earthquake—the fourth most powerful ever recorded—and the devastating tsunami that followed shook and flooded a large part of eastern Japan, including the coastal Sendai Airport. Flooding damage and soil liquefaction crippled most of the airport. But not one of the runways where the underlying soil had been stabilized during an expansion project in 2008.[9] Within 5 days, once debris from the tsunami was cleared, military flights were able to land, allowing the delivery of desperately needed aid and supplies.[10]

Both experimental and theoretical research endeavors are now focused on the consequences of liquefaction. Experiments on soil samples in laboratories reveal how soils behave under different levels of shaking. Computer simulations predict how soils in complex geological settings will behave. But the ultimate test of experiments and computer simulations is the real world. "We have theories, but it takes an earthquake and instrumentation to see how theories work," said Edward Kavazanjian, a professor of geotechnical engineering at Arizona State University.

The National Academies report, for which Kavazanjian chaired the authoring committee, called for the creation of large, publicly accessible databases containing information on past instances of liquefaction and their effects on the built environment. It also called for identifying places where liquefaction is likely and establishing field observatories and other instrumentation *before* an earthquake strikes. Wang drew a parallel with the aviation industry. "Planes all have black boxes that gather data to be analyzed after a crash," she said. "Instrumenting locations that have a high likelihood of earthquakes and liquefaction is basically putting a black box there."

The most recent and ambitious research endeavor takes a more comprehensive view of liquefaction risks. Today, geotechnical engineers usually base their recommendations and designs on one or at most a few levels of ground motion, such as the amount of shaking that can be expected to occur on average about every 2,500 years.

However, smaller, more frequent earthquakes can also cause liquefaction, and bigger ones can exceed the safety factors built into designs, observed Steven Kramer, a geotechnical engineer at the University of Washington. "It's like only blocking the middle linebacker," he said. "The smaller and bigger defensive players can get you, too."

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[9] Kazama, M., T. Kawai, J. Kim, and T. Mori. 2016. The geotechnical issues of the damage caused by the great east Japan disaster and reconstruction for the Tohoku region. *Japanese Geotechnical Society Special Publication* 2:1148–1153. doi: 10.3208/jgssp.ATC1-3-02.
[10] Yamaguchi, A., T. Mori, M. Kazama, and N. Yoshida. 2012. Liquefaction in Tohoku district during the 2011 off the Pacific coast of Tohoku Earthquake. *Soils and Foundations* 52(5):811–829.

Kramer helped develop a performance-based approach that takes the full range of possible earthquakes into account.[11] Though computationally demanding, the result is a set of predictions about how a soil will respond under different levels of shaking. These predictions indicate the severity of liquefaction that could occur, allowing the designers and owners of structures to balance the risks of losses against the costs of resisting earthquake damage. This approach recognizes all of the anticipated levels of earthquake shaking, said Kramer, rather than using safety factors in an ad hoc manner to deal with uncertainties.

Liquefaction will continue to be a major threat to life and property around the world. To cite just one example, about half of San Francisco's urban areas are susceptible to at least moderate liquefaction.[12] However, our improved understanding of liquefaction allows us to identify and remediate the greatest risks. "By getting the science more accurate, you're going to do a better job of knowing when to do something," said Holzer.

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[11] Kramer, S. L., and R. T. Mayfield. 2007. Return Period of Soil Liquefaction. *Journal of Geotechnical and Geoenvironmental Engineering* 133(7):802–813. doi: 10.1061/(ASCE)1090-0241(2007)133:7(802).
[12] Perkins, J. B. 2001. The REAL Dirt on Liquefaction: A Guide to the Liquefaction Hazard in Future Earthquakes Affecting the San Francisco Bay Area. Association of Bay Area Governments. Publication Number: P01001EQK. http://resilience.abag.ca.gov/wp-content/uploads/2010/10/Lq_rept.pdf.