EARTHQUAKE BASICS

LIQUEFACTION
What it is and what to do about it

■ ***Purpose***

This pamphlet, the first in a series, has been written by members of the Earthquake Engineering Research Institute (EERI) to explain the phenomenon of liquefaction and what can be done about it. This brief is intended for other EERI members, and local officials, public policymakers, and property owners who are faced with decisions regarding the hazard of liquefaction. It is not intended to replace evaluations conducted by a geotechnical expert to assess the hazard at any particular site. The discussion on the liquefaction process and its effects on the built environment is primarily meant for the design engineer. The discussion on options for mitigation, preparedness, response, and recovery is primarily aimed at policymakers. However, the effort was made to explain both the process and its public policy implications to all readers.

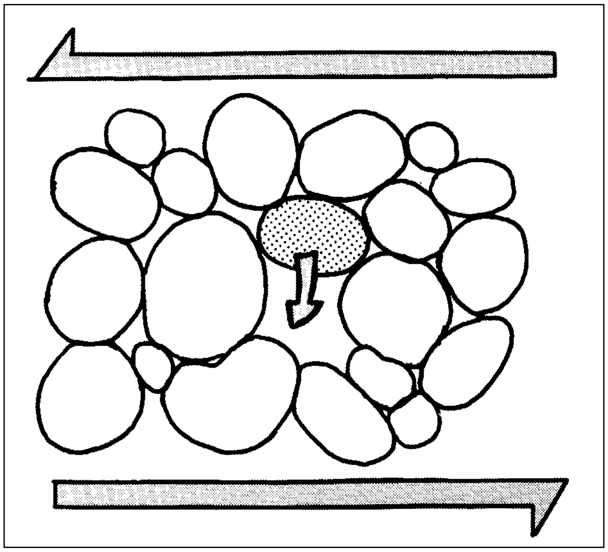
This brief is meant to be used with two slide sets that illustrate (1) the phenomenon of liquefaction and (2) mitigation options for liquefaction. The authors hope that the information presented here conveys, to policymakers in particular, that better understanding of the risk from liquefaction at a particular site or area leads to better decisions regarding mitigation options, response planning, and preparedness strategies. With good liquefaction opportunity and susceptibility maps as a starting point, public officials and private property owners can make informed decisions about how to concentrate limited resources to manage and reduce the risk.

Liquefaction Process

Liquefaction is a process by which sediments below the water table temporarily lose strength and behave as a viscous liquid rather than a solid. The types of sediments most susceptible are clay-free deposits of sand and silts; occasionally, gravel liquefies. The actions in the soil which produce liquefaction are as follows: seismic waves, primarily shear waves, passing through saturated granular layers, distort the granular structure, and cause loosely packed groups of particles to collapse (*Figure 1*). These collapses increase the pore-water pressure between the grains if drainage cannot occur. If the pore-water pressure rises to a level approaching the weight of the overlying soil, the granular layer temporarily behaves as a viscous liquid rather than a solid. Liquefaction has occurred.

In the liquefied condition, soil may deform with little shear resistance; deformations large enough to cause damage to buildings and other structures are called ground failures. The ease with which a soil can be liquefied depends primarily on the looseness of the soil, the amount of cementing or clay between particles, and the amount of drainage restriction. The amount of soil deformation following liquefaction depends on the looseness of the material, the depth, thickness, and areal extent of the liquefied layer, the ground slope, and the distribution of loads applied by buildings and other structures.

Liquefaction does not occur at random, but is restricted to certain geologic and hydrologic environments, primarily recently deposited sands and silts in areas with high ground water levels. Generally, the younger and looser the



■ *Figure 1*--Sketch of a packet of water-saturated sand grains illustrating the process of liquefaction. Shear deformations (indicated by large arrows) induced by earthquake shaking distort the granular structure causing loosely packed groups to collapse as indicated by the curved arrow *(Youd, 1992).*

sediment, and the higher the water table, the more susceptible the soil is to liquefaction. Sediments most susceptible to liquefaction include Holocene (less than 10,000-year-old) delta, river channel, flood plain, and aeolian deposits, and poorly compacted fills. Liquefaction has been most abundant in areas where ground water lies within 10 m of the ground surface; few instances of liquefaction have occurred in areas with ground water deeper than 20 m. Dense soils, including well-compacted fills, have low susceptibility to liquefaction.

Effect of Liquefaction on the Built Environment

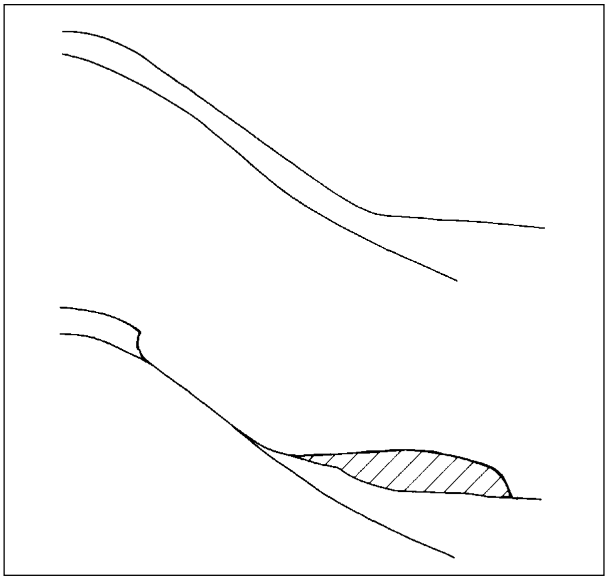
The liquefaction phenomenon by itself may not be particularly damaging or hazardous. Only when liquefaction is accompanied by some form of ground displacement or ground failure is it destructive to the built environment. For engineering purposes, it is not the occurrence of liquefaction that is of prime importance, but its severity or its capability to cause damage. Adverse effects of liquefaction can take many forms. These include: flow failures; lateral spreads; ground oscillation; loss of bearing strength; settlement; and increased lateral pressure on retaining walls.

Flow Failures

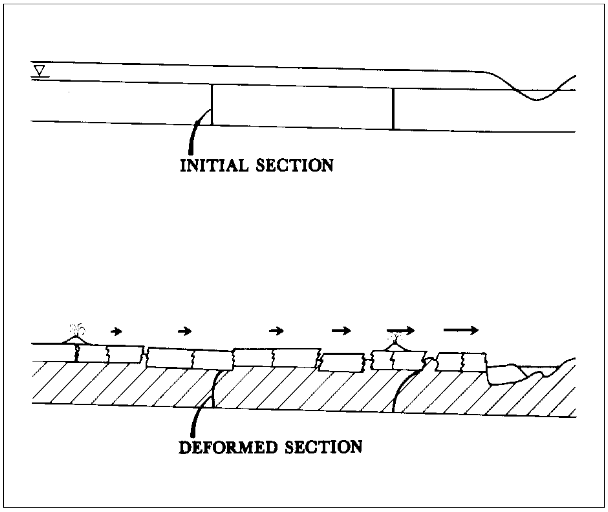
Flow failures are the most catastrophic ground failures caused by liquefaction. These failures commonly displace large masses of soil laterally tens of meters and in a few instances, large masses of soil have traveled tens of kilometers down long slopes at velocities ranging up to tens of kilo-meters per hour. Flows may be comprised of completely liquefied soil or blocks of intact material riding on a layer of liquefied soil. Flows develop in loose saturated sands or silts on relatively steep slopes, usually greater than 3 degrees (*Figure 2*).

Lateral Spreads

Lateral spreads involve lateral displacement of large, surficial blocks of soil as a result of liquefaction of a subsurface layer (*Figure 3*). Displacement occurs in response to the combination of gravitational forces and inertial forces generated by an earthquake. Lateral spreads



■ *Figure 2*--Diagram of a flow failure caused by liquefaction and loss of strength of soils lying on a steep slope. The strength loss creates instability and flow down the steep slope *(Youd, 1992).*



■ *Figure 3*--Diagram of a lateral spread *(Youd, 1992).*

generally develop on gentle slopes (most commonly less than 3 degrees) and move toward a free face such as an incised river channel. Horizontal displacements commonly range up to several meters. The displaced ground usually breaks up internally, causing fissures, scarps, horsts, and grabens to form on the failure surface. Lateral spreads commonly disrupt foundations of buildings built on or across the failure, sever pipelines and other utilities in the failure mass, and compress or buckle engineering structures, such as bridges, founded on the toe of the failure.

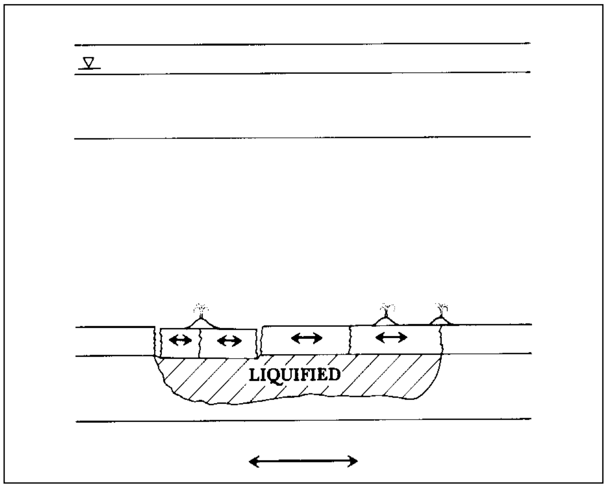
Damage caused by lateral spreads is severely disruptive and often pervasive. For example, during the 1964 Alaska earthquake, more than 200 bridges were damaged or destroyed by spreading of floodplain deposits toward river channels. The spreading compressed the superstructures, buckled decks, thrust stringers over abutments, and shifted and tilted abutments and piers. Lateral spreads are particularly destructive to pipelines. For example, every major pipeline break in the city of San Francisco during the 1906 earthquake occurred in areas of ground failure. These pipeline breaks severely hampered efforts to fight the fire that ignited during the earthquake; that fire caused about 85% of the total damage to San Francisco. Thus, rather inconspicuous ground-failure displacements of less than 2 m were in large part responsible for the devastation that occurred in San Francisco (*Youd and Hoose, 1978*).

Ground Oscillation

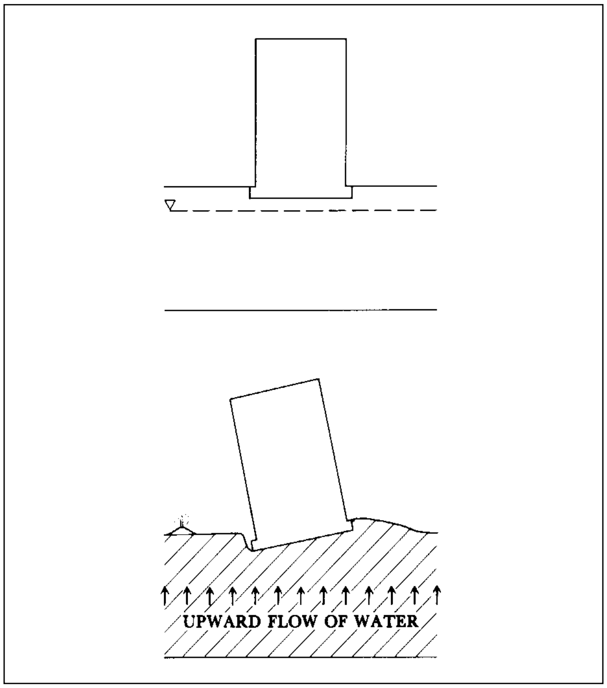
Where the ground is flat or the slope is too gentle to allow lateral displacement, liquefaction at depth may decouple overlying soil layers from the underlying ground, allowing the upper soil to oscillate back and forth and up and down in the form of ground waves (*Figure 4*). These oscillations are usually accompanied by opening and closing of fissures and fracture of rigid structures such as pavements and pipelines. The manifestations of ground oscillation were apparent in San Francisco's Marina District due to the 1989 Loma Prieta earthquake; sidewalks and driveways buckled and extensive pipeline breakage also occurred.

Loss of Bearing Strength

When the soil supporting a building or other structure liquefies and loses strength, large de-formations can occur within the soil



■ *Figure 4*--Diagram of horizontal ground oscillation caused by liquefaction in the cross-hatched zone decoupling the surface layers from the underlying ground. The decoupled layer oscillates in a different mode than the surrounding ground causing fissures to form, and impacts to occur across fissures, and traveling ground waves *(Youd, 1992).*



■ *Figure 5*--Diagram of structure tilted due to loss of bearing strength. Liquefaction weakens the soil reducing foundation support which allows heavy structures to settle and tip *(Youd, 1992).*

which may allow the structure to settle and tip *(Figure 5).* Conversely, buried tanks and piles may rise buoyantly through the liquefied soil. For example, many buildings settled and tipped during the 1964 Niigata, Japan, earthquake. The most spectacular bearing failures during that event were in the Kawangishicho apartment complex where several four-story buildings tipped as much as 60 degrees. Apparently, liquefaction first developed in a sand layer several meters below ground surface and then propagated upward through overlying sand layers. The rising wave of liquefaction weakened the soil supporting the buildings and allowed the structures to slowly settle and tip.

Settlement

In many cases, the weight of a structure will not be great enough to cause the large settlements associated with soil bearing capacity failures described above. However, smaller settlements may occur as soil pore-water pressures dissipate and the soil consolidates after the earthquake. These settlements may be damaging, although they would tend to be much less so than the large movements accompanying flow failures, lateral spreading, and bearing capacity failures. The eruption of sand boils (fountains of water and sediment emanating from the pressurized, liquefied sand) is a common manifestation of liquefaction that can also lead to localized differential settlements.

Increased Lateral Pressure on Retaining Walls

If the soil behind a retaining wall liquefies, the lateral pressures on the wall may greatly increase. As a result, retaining walls may be laterally displaced, tilt, or structurally fail, as has been observed for waterfront walls retaining loose saturated sand in a number of earthquakes.

Can Liquefaction Be Predicted?

Although it is possible to identify areas that have the potential for liquefaction, its occurrence cannot be predicted any more accurately than a particular earthquake can be (with a time, place, and degree of reliability assigned to it). Once these areas have been defined in general terms, it is possible to conduct site investigations that provide very detailed information regarding a site's potential for liquefaction.

Mapping of the liquefaction potential on a regional scale has greatly furthered our knowledge regarding this hazard. These maps now exist for many regions of the United States and Japan, and several other areas of the world. Liquefaction potential maps are generally compiled by superimposing a liquefaction susceptibility map with a liquefaction opportunity map. Liquefaction susceptibility refers to the capacity of the soil to resist liquefaction, where the primary factors controlling susceptibility are soil type, density, and water table depth. Liquefaction opportunity is a function of the intensity of seismic shaking or demand placed on the soil. Frequency of earthquake occurrence and the intensity of seismic ground shaking produced by those events are the major factors affecting liquefaction opportunity. To develop an opportunity map, an earthquake source model is required that includes locations of seismic source zones and quantitative estimates of the number and magnitude of the expected earthquakes in those zones.

These maps can be used in a variety of ways. At the local level in California, they have been incorporated as background documents in safety elements of the general plans that cities and counties are required to prepare. Although still not widely incorporated, information from these maps could also be translated into codes and ordinances. For example, the City of San Diego has developed and adopted provisions for the liquefaction hazard in its building code.

At the state level, the California Division of Mines and Geology is mapping liquefaction hazard zones throughout the state *(CDMG, 1992)*. These zones are defined as areas meeting one or more of the following criteria:

(1) areas known to have experienced liquefaction during historic earthquakes;

(2) all areas of uncompacted fills containing liquefaction-susceptible material that are saturated, nearly saturated, or can be expected to become saturated;

(3) areas where sufficient existing geotechnical data and analyses indicate that the soils are potentially liquefiable;

(4) areas underlain with saturated geologically young sediments (younger than 10,000 to 15,000 years old).

Individual properties within these hazard zones will eventually be required to obtain a site-specific geotechnical investigation to define the liquefaction potential.

What Are the Options for Mitigation?

There are various ways to mitigate a potential liquefaction hazard:

(1) *strengthen structures* to resist predicted ground movements (if small);

(2) *select appropriate foundation type and depth* (including foundation modifications in the case of existing structures) so that the ground movements do not adversely affect the structure (e.g., mat foundation to increase a foundation's rigidity; deep piles or piers that extend below a zone of liquefiable soil);

(3) *stabilize soil* to eliminate the potential for liquefaction or to control its effects (e.g., removal and replacement of liquefiable soils; in situ stab-ilization by grouting, densification, or dewatering; buttressing of lateral spread zones).

How Is the Choice of Mitigation Options Made?

The choice of mitigation options depends very much on the particular characteristics of the site. If there is not a significant lateral movement hazard, mitigation for a new facility is largely a matter of finding the most cost-effective solution to providing vertical support and control settlement. For existing facilities, mitigation is generally more difficult and expensive because of the presence of the structure. Techniques that densify the soil may be precluded for an existing facility because they would cause settlement of the structure.

When a lateral spreading hazard is present, the mitigating measures, to be effective, may in some cases need to be employed beyond the boundary of the specific site. This may preclude effective mitigation by an individual property owner, requiring instead action by public entities or groups of property owners.

Does Mitigation Work?

Several different ground improvement techniques have been used for sites identified as having the potential for liquefaction. For example, several sites had been improved in Treasure Island, Santa Cruz, Richmond, Emeryville, Bay Farm Island, Union City, and South San Francisco, California, prior to the Loma Prieta earthquake in 1989. The sites where ground improvements were carried out had little or no damage to either the ground or facilities built upon the improved sites even though they experienced peak ground accelerations ranging from 0.11g to 0.45g. In contrast, untreated ground adjacent to these improved sites spread, oscillated, or settled, due primarily to liquefaction (*Leighton and Associates, 1993*).

Is It Possible to Prepare for Liquefaction?

Reducing vulnerability and improving emergency response capabilities are two options to pursue in preparing for the possibility of liquefaction. With hazard zone maps, it is possible to identify areas potentially subject to liquefaction and to identify areas of minor and major concern. Emphasis in terms of developing appropriate public policy or selecting mitigation techniques should be in areas of major concern. (An example of an area of major concern in the San Francisco Bay area would be bay lands reclaimed by placing uncompacted fill under water.)

Public and private property owners can use hazards maps to understand where the most serious damage can be expected and what structures are most vulnerable. This information, in turn, can be used to decide where limited resources should be concentrated--and what mitigation strategies, if any, should be adopted. City and county governments can also use this information to decide if they want to regulate the risk through ordinance or code changes. If adequate maps exist, local governments could designate liquefaction potential areas, and require, by ordinance, site investigations and possible mitigation techniques for properties in these areas. Additional engineering could be required for new construction; essential services buildings could be strengthened or relocated; and additional redundancy could be built into lifelines systems, particularly underground pipes and critical transportation routes.

A call to the closest office of the U.S. Geological Survey is a first step in identifying available information. Liquefaction hazard zone maps, which are at the basis of developing regulatory strategies and other mitigation options, already exist for some of the most seismically active areas in the country.

What Are the Implications for Response?

Emergency response plans at the local jurisdictional level need to identify those areas most vulnerable to liquefaction. Sites where liquefaction can cause major problems can be identified using the liquefaction hazard or risk maps discussed above. Emergency plans might want to specify a reconnaissance survey of these areas immediately after an earthquake occurs. Problems resulting from liquefaction such as damage to underground pipelines also need to be factored into any emergency response planning. Emergency responders should expect interrupted water supply, and natural gas and sewage leaks. Back-up sources of water need to be identified or developed. In addition, the roadbeds in areas potentially subject to liquefaction may be seriously damaged, greatly complicating the ability to evacuate residents or to bring in emergency response equipment. These systems should have redundancy or alternatives.

What Are the Implications for Recovery?

Recovery and rebuilding in areas that have experienced damage due to liquefaction raise some special issues. One of the first decisions policymakers in the community face is whether to allow rebuilding in the damaged area. In the United States, it is most common for a jurisdiction to allow rebuilding, but with additional restrictions such as requiring detailed site investigations and possibly engineered foundations. The individual property owner also needs to decide if repair and rebuilding are feasible, particularly from a financial perspective. The community, usually a city or county, will need to decide if some sort of large- scale soil stabilization project should be attempted during rebuilding; one important determinant in this decision is the availability of funding. In general, for both individual property owners and public entities, it is much less expensive to reduce vulnerability to liquefaction before an earthquake than it is to pay for repair or retrofit measures after an earthquake. Once a community is in the process of rebuilding, community leaders and individual property owners should take advantage of every opportunity to mitigate the liquefaction risk. ■

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