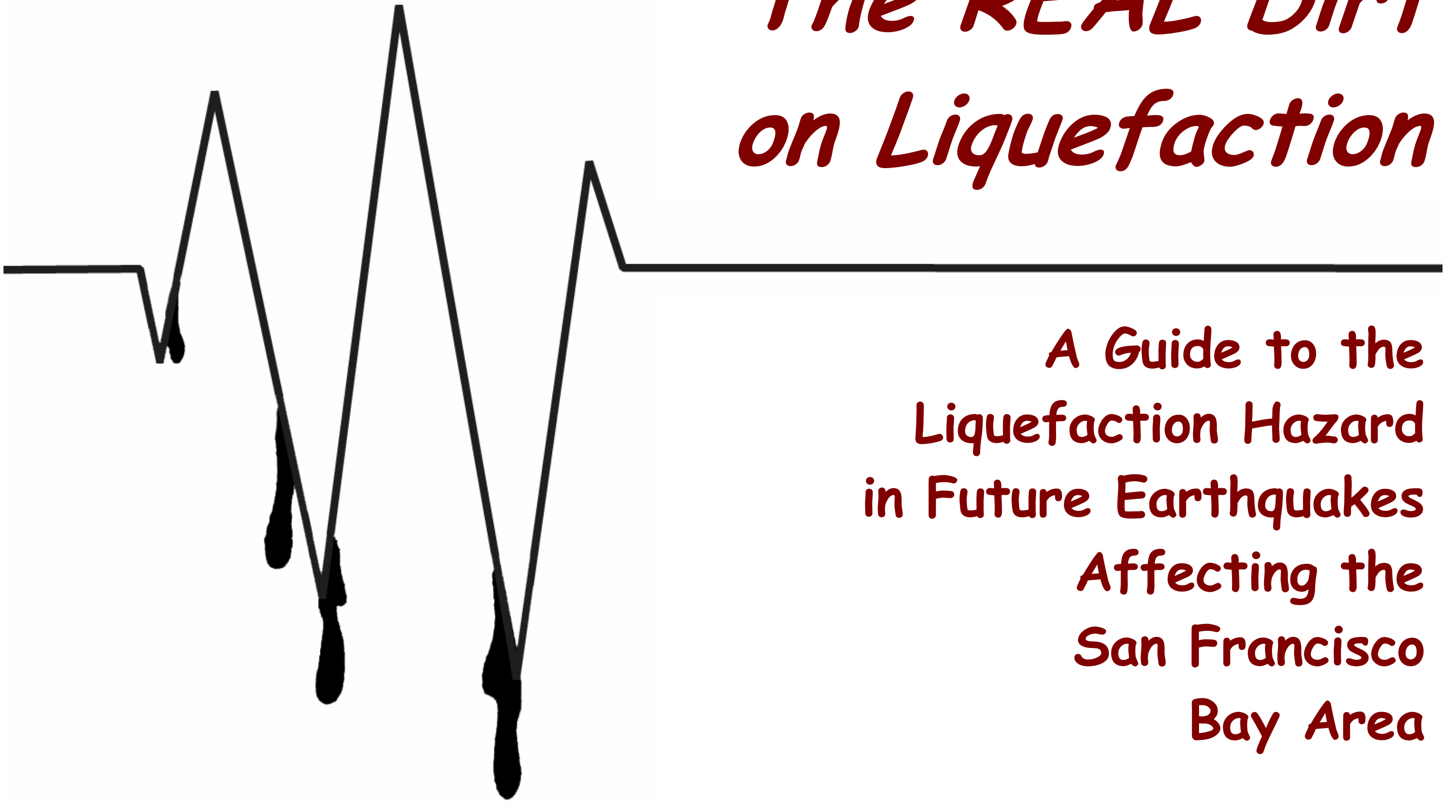
The REAL Dirt on Liquefaction



A Guide to the Liquefaction Hazard in Future Earthquakes Affecting the San Francisco Bay Area

February 2001

ASSOCIATION OF BAY AREA GOVERNMENTS

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For information on ABAG's Earthquake Program, liquefaction hazard maps by city and other earthquake impacts, see our Internet site at: *http://quake.abag.ca.gov*

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BACKGROUND

The purpose of this report is to serve as a catalyst for understanding and mitigating (through avoidance, engineering, planning and response) the liquefaction hazard in the San Francisco Bay Area. As such, the audience is not the geology or engineering community, but rather those who work for and with the local governments, utilities, businesses, and residents in our region.

This report is intended to supplement the maps prepared by William Lettis & Associates, Inc. (WLA), the U.S. Geological Survey (USGS), and the California Division of Mines and Geology (CDMG). It is not a substitute for site-specific advice from a licensed geologist or geotechnical engineer.

This ABAG report is part of a collaborative project with WLA and USGS funded by USGS. As part of this collaborative effort, WLA received funding from USGS to develop new regional consistent maps of Quaternary deposits (materials deposited in the last 1.6 million years) (Knudsen and others, 2000).

INTRODUCTION

Liquefaction problems in past earthquakes are not as significant as shaking, but can cause extensive damage.

The 1989 Loma Prieta earthquake caused a total of $5.9 billion in property damage. Most of the damage was due to ground shaking. However, approximately $100 million of that (1.6%) was due to liquefaction (Holzer, 1998, p.B4). ***We were lucky.*** In 1906, liquefaction-related damage to water supply pipelines prevented containment of the fire in San Francisco that destroyed about 500 city blocks. Thus, liquefaction can be indirectly blamed for 85% of the total damage to San Francisco in 1906 (Youd and Hoose, 1978).

Liquefaction damage, Marina District, 1989 Loma Prieta, California, Earthquake
Source – M. Bennett, U.S. Geological Survey

When the ground ***liquefies***, sandy materials saturated with water can behave like a liquid, instead of like solid ground. The ground may sink or even pull apart. Sand boils, or sand "volcanoes," can appear.

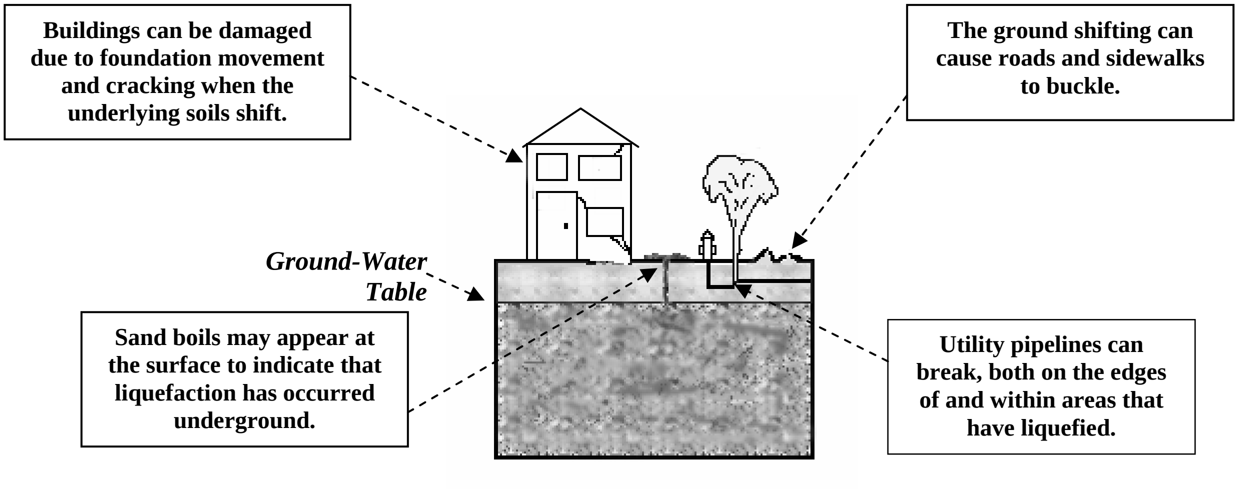
Liquefaction can cause ground displacement and ground failure such as lateral spreads (essentially landslides on nearly flat ground next to rivers, harbors, and drainage channels) and flows.

Our most vulnerable land falls into two general categories:

1. areas covered by the huge amount of fill poured into San Francisco Bay since 1845 to transform 77 square miles (200 square km) of tidal and submerged areas into land[1]; and
2. areas along existing and filled stream channels and flood plains, particularly those areas with deposits less than 10,000 years old.

Overall, ***shaking does more damage*** to buildings and highway structures than liquefaction. ***But liquefaction damage can be a significant threat for underground pipelines, airports (especially runways), harbor facilities, and road or highway surfaces.***

FIGURE 1 - POTENTIAL EFFECTS OF LIQUEFACTION



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[1] Source of fill area – Knudsen and others, 2000.

PART I - WHAT HAPPENS TO THE GROUND?

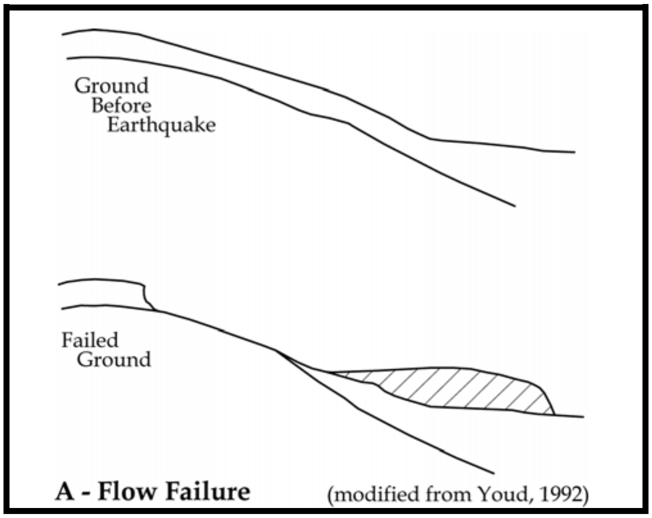
How Does the Ground Fail?

When ground liquefies and "fails," it may cause damage to our built environment. These failures take the form of:

- flows;
- lateral spreads;
- ground oscillations (or movement of the surface layer of ground separately from the underlying liquefied layers);
- loss of bearing strength (to hold up buildings or hold tanks and pipes underground); and
- settlement and differential settlement.

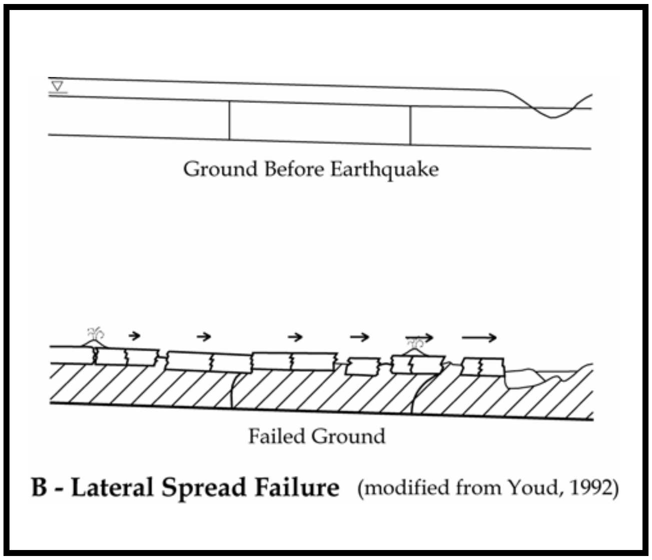
The following diagrams illustrate some of these effects.

FIGURE 2 –
GROUND FAILURE TYPES



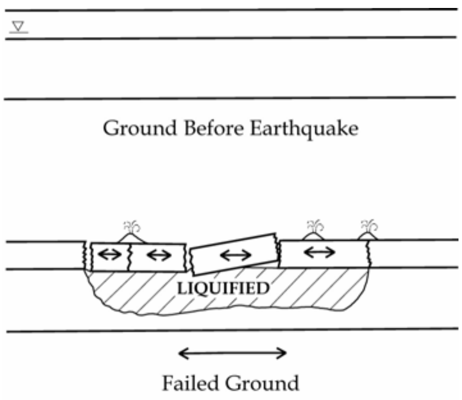
In a flow failure, large amounts of soil can quickly travel many feet.

Typically, "flows" occur on slopes of more than 3 degrees, while "spreads" are on less steep slopes (EERI, 1994). Thus, this type of ground failure is a type of landslide.



In a lateral spread failure, a layer of ground at the surface is carried on an underlying layer of liquefied material over a nearly flat surface toward a river channel or other bank.

Damage occurs to the surface layer when it is moved, including fissures and scarps. The surface deformation can damage building foundations and underground utilities, as well as result in increased pressure on retaining walls. Engineers can sometimes make rough estimates of the potential movement distance of a lateral spread. Data from the 1906 San Francisco earthquake show that some lateral spreads moved about 30% of the thickness of the saturated loose materials that liquefied (Pease and O'Rourke, 1998).

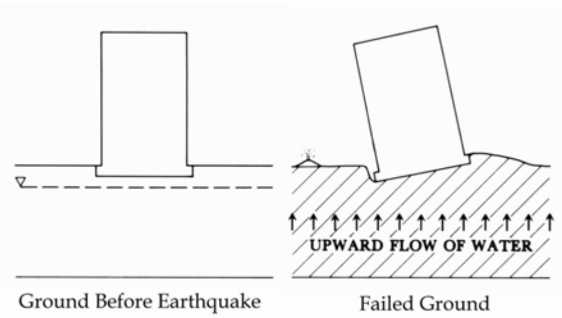


C - Ground Ocillation Failure
(modified from Youd, 1992)

When the ground is almost completely flat, liquefaction can still cause problems. When an underlying layer liquefies, the soil on top decouples, allowing it to oscillate back and forth, and up and down, in a different way than the surrounding ground. Large cracks can occur, and sections of the ground bang against one another.

Ground oscillation occurred in the Marina District of San Francisco during the 1989 Loma Prieta earthquake, and resulted in extensive sidewalk, road, and pipeline damage.

This type of failure can become a lateral spread if the ground shakes long enough.

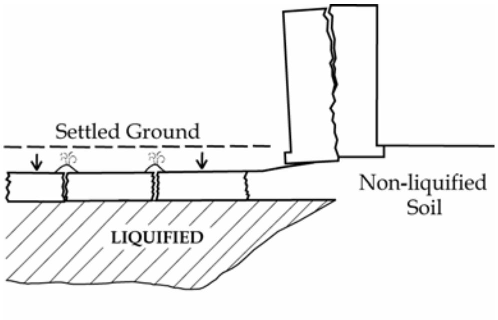


D - Loss of Bearing Strength
(Resulting in Tilted Building and "Floating" Tanks)
(Youd, 1992)

When soil liquefies, it becomes "weaker." It may lose its capacity to support buildings, particularly large buildings with poorly designed foundations. In addition, underground tanks and pipelines can "float" upwards, sometimes all the way to the surface.

The "classic" example of a bearing strength failure happened as a result of the 1964 Niigata, Japan, earthquake where several four-story apartment buildings tilted spectacularly.

Less well publicized, but more common, are problems with underground tanks at gasoline stations where the tank may rise enough to break connections between the tank and the pipes leading into and out of it.



E - Differential Settlement

Another common problem is settlement as soil compacts and consolidates after the ground stops shaking. Engineers can estimate the expected extent of settlement. Settlement can range from 1% - 5% of the liquefiable layer. In very loose sands, it can be as large as 10% of the thickness of the saturated loose materials that liquefy (Tokimatsu and Seed, 1984). Although small uniform changes are typically not damaging, the soil can settle unevenly. This problem, called differential settlement, occurs when the layers that liquefy are not of a uniform thickness, a common problem when the liquefaction occurs in artificial fills, particularly fills that have been placed during different times and using different techniques. Thus, using the 10% settlement estimate for loose materials, if the liquefying layers are 10 feet different in thickness, differential settlement of a foot can be achieved.

PART II - WHEN DOES LIQUEFACTION OCCUR?

The "Official" Definition

Liquefaction has been defined as "*the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore-water pressure*" (Youd, 1973, p.1).

But what does this mean? Where do we expect liquefaction to occur? The "recipe" below lists the three ingredients necessary for damaging liquefaction to occur.

FIGURE 3 - A RECIPE FOR LIQUEFACTION

Damaging liquefaction can only occur under very special circumstances.

There must be all of these ingredients – but even if all are present, damaging liquefaction, or even liquefaction, does not necessarily occur. Even if liquefaction occurs, the ground must move enough to impact our built environment.

Ingredient 1 - The ground at the site must be "*loose*" – *uncompacted* or *unconsolidated* sand and silt without much clay or stuck together

Ingredient 2 - The sand and silt must be "*soggy*" (water saturated) due to a high water table

Ingredient 3 - The site must be shaken long and hard enough by the earthquake to "*trigger*" liquefaction.

INGREDIENT 1 – "Loose" Sand

First, the soil in the area must be loose (that is, uncompacted or unconsolidated) sand without much clay or stuck together. A general map predicting the location of these materials can be made based on a specific type of geologic map showing the materials deposited in the last two million years – or Quaternary geologic maps.[2]

INGREDIENT 2 – High Ground-Water Table or Water Saturated

Second, the ground must be saturated with water (or below the ground-water table). This information can be collected from well logs, or interpreted given the topography.

Liquefaction Susceptibility Mapping

These ***two*** ingredients are built into the regional map of areas susceptible to liquefaction on the facing page (Knudsen and others, 2000). Information on liquefaction in past earthquakes is used to check and verify the assignment of various geologic units to liquefaction susceptibility categories. Our experience in past earthquakes is that maps of this type are fairly accurate at predicting general areas where damage to pipelines and roads is heavier, ***given equivalent levels of shaking – the third ingredient.***

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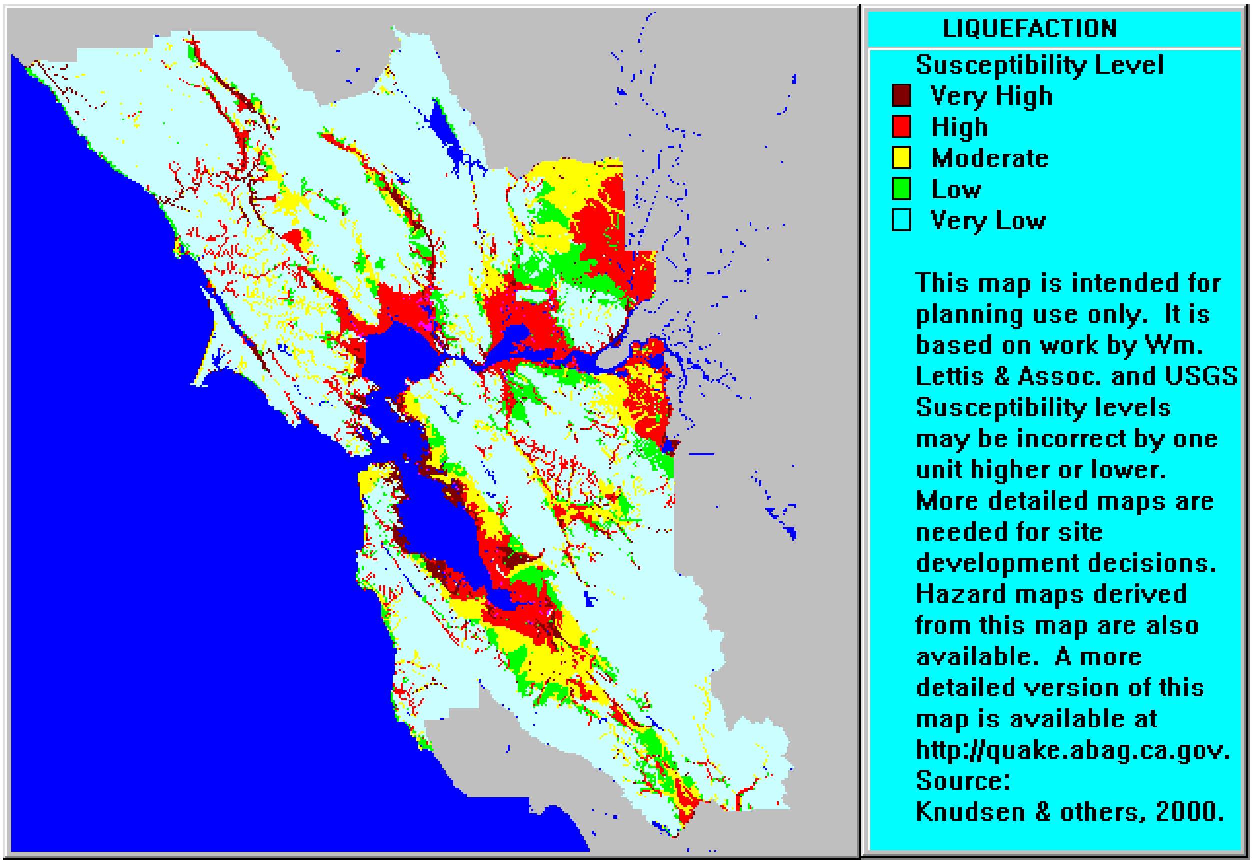
[2] These Quaternary maps are often supplemented with soil boring data, analysis of standard penetration test (SPT) blow counts, and analysis of cone penetration test (CPT) resistances (Power and Holzer, 1996, p.2; Knudsen and others, 2000, pp.3-4).

COLOR MAP PLATE –
MATERIALS SUSCEPTIBLE TO LIQUEFACTION
(will be entire Bay Area at 1:1,000,000) with highways



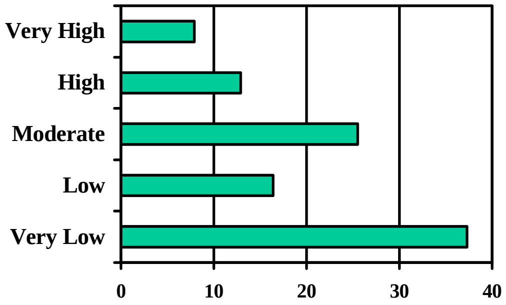
This map is intended for planning use only. It is based on work by Wm. Lettis & Assoc. and USGS Susceptibility levels may be incorrect by one unit higher or lower. More detailed maps are needed for site development decisions. Hazard maps derived from this map are also available. A more detailed version of this map is available at http://quake.abag.ca.gov.
Source:
Knudsen & others, 2000.

Note that, in the map explanation, the reader is "pointed" to the ABAG web site – not the USGS web site – because the liquefaction hazard scenario maps and user-friendly "city maps" will be at our site, as well. When people get to our site, we will point them to the file at the USGS site for access to the GIS file and the full documentation.

How Susceptible to Liquefaction Is Our Urban Land?

FIGURE 4 - PERCENTAGE OF URBAN LAND EXPOSED TO VARIOUS LEVELS OF LIQUEFACTION SUSCEPTIBILITY

Source – ABAG



As shown by the liquefaction susceptibility map on the previous page, large portions of the Bay Area are susceptible to liquefaction. If one uses moderate susceptibility as a cutoff for significant liquefaction concern, approximately half (46.3%) of the region's urban land is susceptible to liquefaction. On the other hand, only 17.7% of the non-urban land is significantly susceptible to liquefaction.

INGREDIENT 3 – Earthquake Shaking

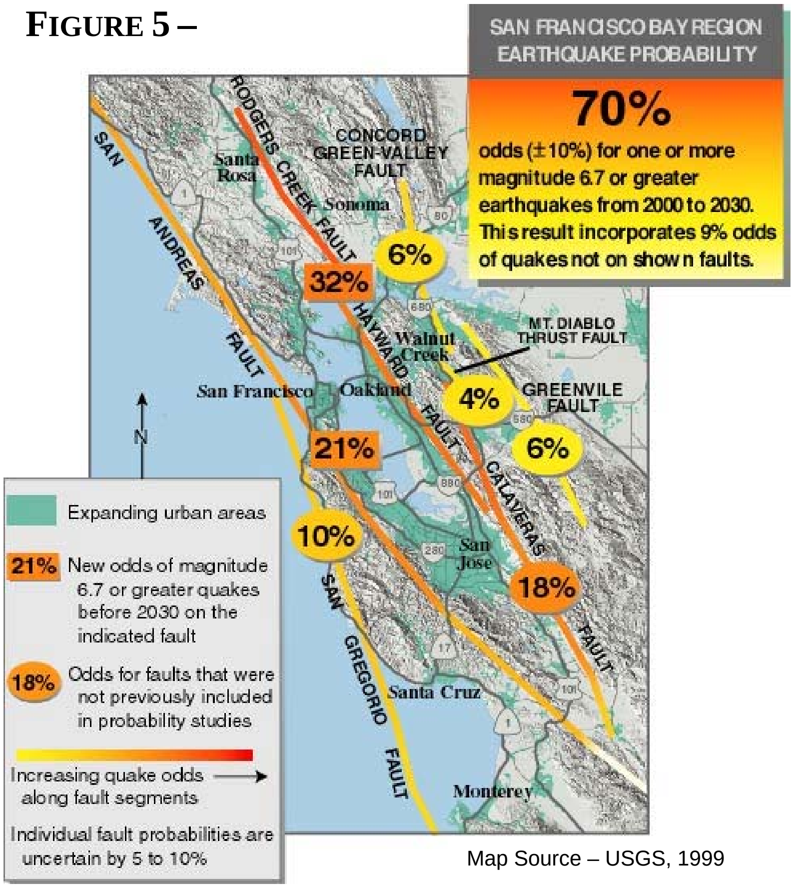
Yet we live with loose, saturated sand and silt susceptible to liquefaction every day and it does not liquefy. The ground needs to be shaken strongly for liquefaction to occur, and this shaking is usually the result of an earthquake. Thus, we also need **Ingredient 3 –** the site must be shaken long and hard enough by an earthquake to "trigger" liquefaction.

There are two components to this ingredient – the first relates to the probability of an earthquake occurring on a given fault, and the second relates to whether the strength of shaking at a particular location given a particular earthquake fault source is strong enough to trigger liquefaction.

Many Faults Are Potential Sources for Bay Area Earthquakes

The Bay Area is crossed by many active faults. The adjacent map shows that major active faults run through or adjacent to all nine Bay Area counties. Earthquakes caused by rupturing of longer faults or fault segments will cause strong shaking in several counties.

FIGURE 5 –



Map Source – USGS, 1999

How Hard Is Hard Enough ?

A liquefaction hazard exists when the ground is both susceptible to liquefaction (loose soil that is saturated with water) and exposed to strong enough shaking. Thus, the second component related to earthquake shaking and liquefaction hazard is an estimate of how far from the earthquake source (or fault) the shaking will be severe enough to trigger liquefaction.

The answer is based, in part, on just how susceptible the material is to liquefaction in the first place. In areas farther from the earthquake fault source, a material that has high liquefaction susceptibility may liquefy, but an adjacent material of moderate susceptibility may not. Only some materials with very high liquefaction susceptibility will liquefy when exposed to strong shaking (modified Mercalli intensity (MMI) VII), with less susceptible materials being triggered with very strong shaking (MMI VIII). (Intensity is a measure of shaking severity at a particular location.) Liquefaction in areas shaken less than MMI VII, or in areas mapped as having a low to very low liquefaction susceptibility, is a statistical possibility, but it is not likely. The following maps show liquefaction hazard in various earthquake scenarios in three simplified categories, graphically shown in Figure 6.

FIGURE 6 – LIQUEFACTION HAZARD BASED ON COMBINATIONS OF MODIFIED MERCALLI INTENSITY (MMI) AND LIQUEFACTION SUSCEPTIBILITY

MMI Value	**Description of MMI Shaking Severity**	**Summary Damage Description of MMI Used on 1995 Maps**	**Liquefaction Susceptibility Category**				
			Very Low	**Low**	**Moderate**	**High**	**Very High**
I.							
II.							
III.							
IV.							
V.	Light	Pictures Move					
VI.	Moderate	Objects Fall					
VII.	Strong	Nonstructural Damage			Moderately Low Hazard	Moderately Low Hazard	Moderate Hazard
VIII.	Very Strong	Moderate Damage			Moderate Hazard	Moderate Hazard	Moderate Hazard
IX.	Violent	Heavy Damage			**High Hazard**	**High Hazard**	**High Hazard**
X.	Very Violent	Extreme Damage			**High Hazard**	**High Hazard**	**High Hazard**

In the Bay Area, many artificial fills that are inherently susceptible to liquefaction are located on top of Bay mud, a material that significantly amplifies and lengthens shaking.

For purposes of mapping these earthquake scenarios, ***we have chosen not to show all possible areas of liquefaction, but rather the most likely areas of liquefaction***. We have spent considerable time validating the modeling used to produce these maps using a combination of statistical data from the Loma Prieta and Northridge earthquakes, as well as data from other researchers (for example, Kayen and Mitchell, 1997). See Technical Appendix C for more information. For information about ABAG's ground shaking maps, see our web site - **www.abag.ca.gov/bayarea/eqmaps**, as well as ABAG's two ***On Shaky Ground*** reports (Perkins and Boatwright, 1995, and Perkins, 1998).

INGREDIENTS
Loose Sand +
High Ground Water +
Earthquake Shaking =
Liquefaction Hazard,
NOT Damage

There Must Also Be Enough Movement of the Ground to Cause Damage

The entire Bay Area will not be exposed to severe enough shaking in any individual earthquake to liquefy soils everywhere, as shown on the maps on the following pages and in Table 1, below. As explained earlier, for liquefaction to occur, the ground must be both susceptible to liquefaction and be exposed to strong enough shaking to trigger liquefaction.

Even if liquefaction occurs, it is not always damaging. For damage to occur, the ground must move enough to impact our built environment. ***Even in the "high hazard" areas of these liquefaction hazard maps, only a small percentage of liquefiable materials actually liquefy and move significantly in any one earthquake. High hazard areas are where damage is more likely; ALL lifelines and structures in these areas will not suffer liquefaction-related damage. Even though an area is indicated as having a minimal hazard, this designation does not guarantee than no liquefaction-related damage will occur.***

Part III reviews the types of damage that can occur in these high hazard areas, as well as any statistics we have compiled on the likelihood of those damages occurring based, in part, on data from the Loma Prieta and Northridge earthquakes.

TABLE 1: Extent of Urban Areas Potentially Subject to Liquefaction Hazard

[See ABAG's Earthquake Program web site at http://quake.abag.ca.gov to view detailed liquefaction hazard maps for all 18 earthquake scenarios; only 4 general maps appear on following pages]

Earthquake Scenario	**Anticipated Earthquake Magnitude**	**Estimated Percentage of Urban Land Subjected to Strong Enough Shaking for Some Damaging Liquefaction to Occur** (See Figure 6 on Page 7 for Hazard Categories)		
	Based on USGS, 1999	**High Hazard**	**Moderate Hazard**	**Moderately Low Hazard**
MODELED Loma Prieta Event	6.9	0.00%	5.63%	15.73%
Peninsula-Golden Gate San Andreas	7.2	2.45%	14.90%	14.84%
Northern Golden Gate San Andreas	7.5	0.74%	9.63%	17.48%
Entire Bay Area - San Andreas	7.9	7.40%	19.72%	14.38%
Northern San Gregorio	7.3	0.26%	8.90%	15.05%
Southern Hayward	6.9	7.34%	14.41%	13.17%
Northern Hayward	6.6	3.35%	8.54%	15.65%
Northern + Southern Hayward	7.1	10.83%	14.89%	13.87%
Rodgers Creek	7.1	2.79%	6.87%	12.66%
Rodgers Creek-Northern Hayward	7.2	6.92%	10.74%	16.15%
Southern Maacama	6.6	0.03%	3.85%	3.70%
West Napa	6.5	0.64%	4.07%	6.71%
Concord - Green Valley	6.8	1.59%	8.66%	16.55%
Northern Calaveras	7.0	1.92%	11.90%	15.30%
Central Calaveras	6.6	0.27%	12.30%	15.38%
Mt. Diablo	6.7	1.71%	7.73%	11.37%
Greenville	7.2	0.58%	8.40%	13.37%
Monte Vista	6.6	0.92%	12.98%	6.09%

FIGURE 7 – COMPARISON OF ESTIMATED LIQUEFACTION HAZARD OF 1989 LOMA PRIETA EARTHQUAKE WITH LARGER BAY AREA EARTHQUAKE SCENARIOS

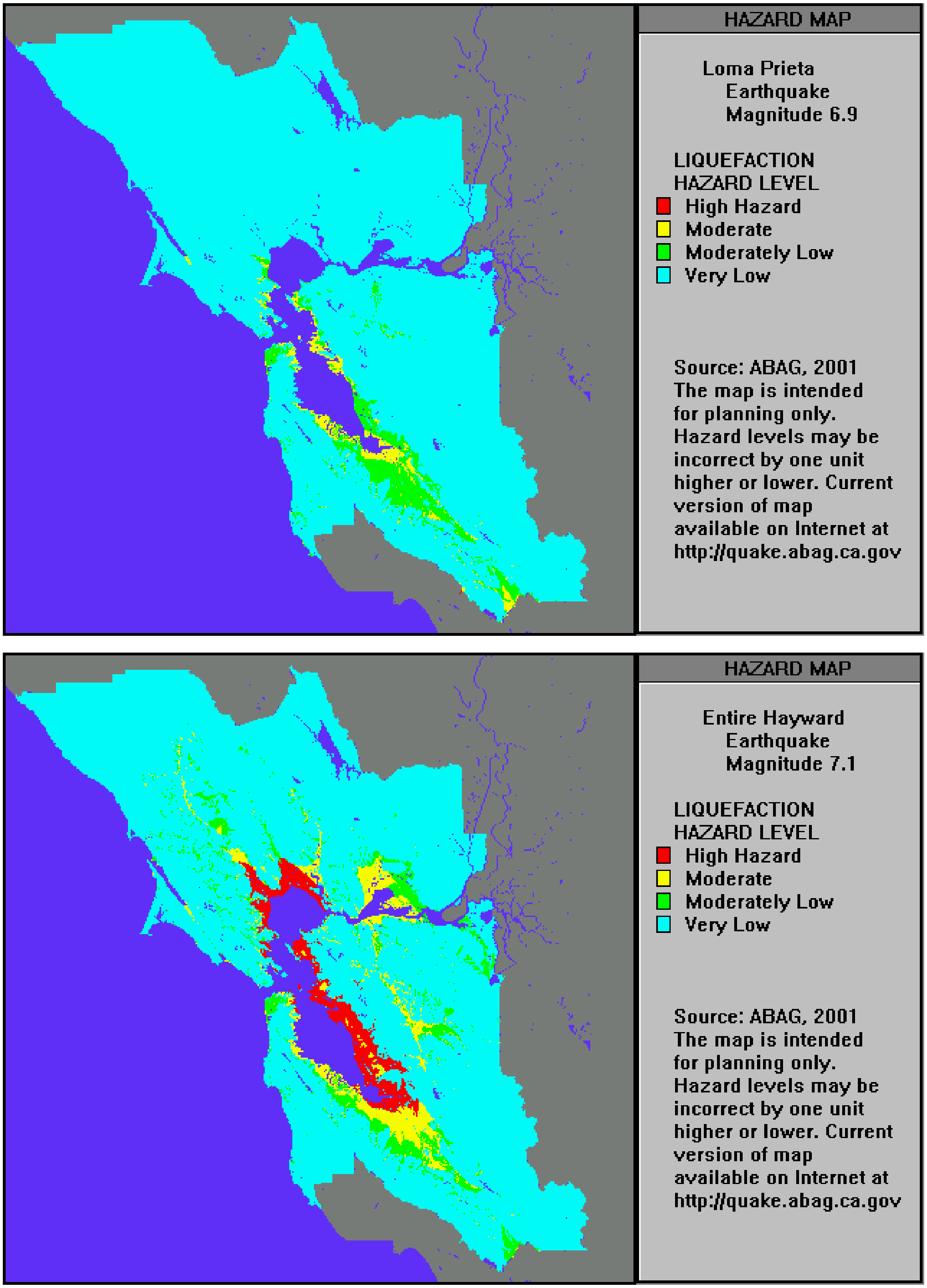
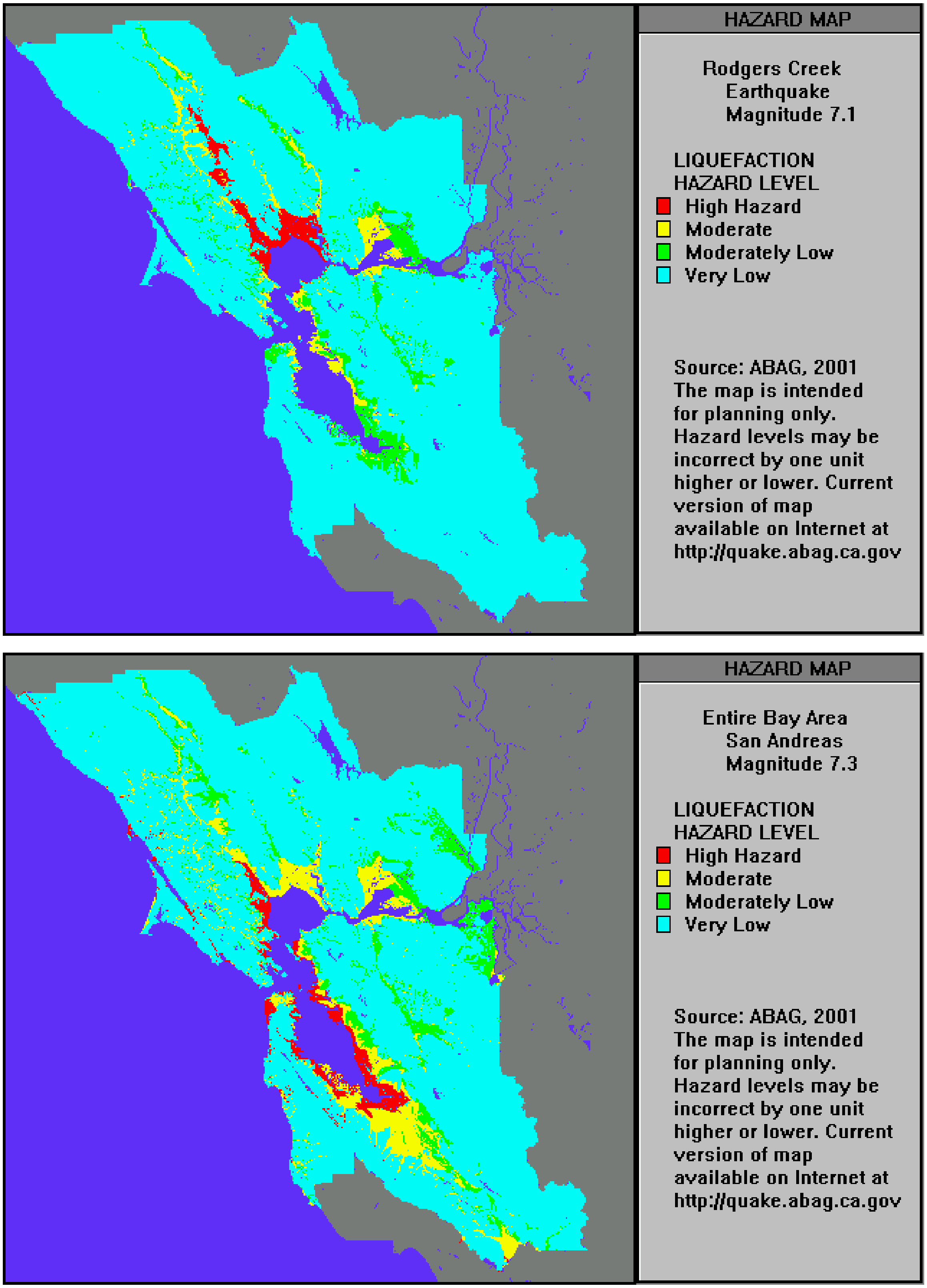


FIGURE 7 (CONT.) – COMPARISON OF ESTIMATED LIQUEFACTION HAZARD OF 1989 LOMA PRIETA EARTHQUAKE WITH LARGER BAY AREA EARTHQUAKE SCENARIOS



Source: ABAG, 2001
The map is intended for planning only. Hazard levels may be incorrect by one unit higher or lower. Current version of map available on Internet at http://quake.abag.ca.gov

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The map is intended for planning only. Hazard levels may be incorrect by one unit higher or lower. Current version of map available on Internet at http://quake.abag.ca.gov

PART III - WHAT HAPPENS TO OUR BUILT ENVIRONMENT?

Liquefaction Focuses its Impacts

The hazard from liquefaction is not nearly as great as from shaking. Rather, ***liquefaction is of concern because it focuses its effects on infrastructure, particularly infrastructure that is critical for emergency response.*** For example, a home may be no more likely to be uninhabitable following the Loma Prieta earthquake in an area mapped as very high liquefaction susceptibility than one outside of such an area, given equivalent shaking intensities. However, those buildings damaged may have foundation damage that is potentially more expensive to repair than shaking-caused structural damage. While shaking does most of the damage to highway structures, liquefaction is responsible for extensive damage to airports (particularly runways), harbor facilities, and road and highway surfaces. In addition, areas with high liquefaction susceptibility had more damage to underground water, sewer and natural gas pipelines in the Loma Prieta earthquake than areas with lower liquefaction susceptibility, given equivalent shaking intensities.

The following pages provide data on the impacts to various parts of our built environment, including:

- utility pipelines;
- highways, roads, and airport runways;
- harbor facilities; and
- buildings and other structures.

These pages contain summaries of the extent of liquefaction damage in the Loma Prieta earthquake, why damage happens, and existing programs of various utilities and government agencies to mitigate this hazard.

Example of liquefaction damage in the 1999 Izmit, Turkey Earthquake

Source – T. Holzer, U.S. Geological Survey

Utility Pipelines Leak –

What Happens?

In earthquakes, utility pipelines leak and break. The most vulnerable pipelines are typically those carrying sewage because they are made of the most brittle materials and do not have sealed joints. The next most vulnerable are water pipelines. Some pipelines carrying natural gas are also vulnerable, but utilities such as Pacific Gas & Electric are upgrading and replacing vulnerable pipelines as described below.

Why Does This Happen?

Utility pipelines can leak or break due to the passage of earthquake waves through the soil or due to permanent ground displacement (such as faulting, landsliding or liquefaction). Even though areas susceptible to liquefaction are a relatively small percentage of the areas in which pipelines are located, these liquefaction-susceptible areas have contained a disproportionate number of breaks.

What Were the Pipe Damage Statistics in the Loma Prieta Earthquake?

ABAG, in examining pipeline breakage statistics from the Loma Prieta earthquake, concluded that the damage to pipelines in areas mapped as highly susceptible to liquefaction experienced significantly greater damage than areas with lower susceptibility, given similar shaking levels.

First, the number of water pipeline leaks per mile of water pipeline in areas mapped as having high and very high susceptibility to liquefaction was four-to-six times ***greater*** than outside of these areas, given equivalent shaking intensities.

Example of main sewage treatment conduit rupture in the 1995 Kobe Earthquake

Source – Kobe Geotechnical Collection, Earthquake Engineering Research Center, Univ. of California, Berkeley

Second, the number of leaks per mile of natural gas pipelines was three-to-eleven times ***greater*** within the areas mapped as having high and very high susceptibility than outside of these areas, given equivalent shaking intensities. The gas pipeline leaks were predominately in cast iron and other older pipelines that are known to be vulnerable to earthquake effects.

Much of the pipeline damage occurred in areas where no surface expression of liquefaction was observed. Thus, these statistics show increased damage in areas mapped as being susceptible to liquefaction; they do not indicate that the damage was necessarily due to liquefaction. See Appendix C for more information.

Note that no damage surveys were conducted of sewer lines as a result of the Loma Prieta earthquake, so no data on statistical damage to these facilities are available. However, as stated above, sewer lines probably had more damage than water lines because they are more brittle and do not have sealed joints.

Utilities and the Seismic Hazard Mapping Program of the California Division of Mines and Geology (CDMG)

The following excerpt from CDMG Special Publication 117, Chapter 6 (1997) notes the concern of that organization for pipeline damage in areas subject to liquefaction:

> To date, most liquefaction hazard investigations have focused on assessing the risks to commercial buildings, homes, and other occupied structures. However, liquefaction also poses problems for streets and lifelines— problems that may, in turn, jeopardize lives and property. For example, liquefaction locally caused natural gas pipelines to break and catch fire during the Northridge earthquake, and liquefaction-caused water line breakage greatly hampered firefighters in San Francisco following the 1906 earthquake. Thus, although lifelines are not explicitly mentioned in the Seismic Hazards Mapping Act, cities and counties may wish to require investigation and mitigation of potential liquefaction-caused damage to lifelines.

PG&E's Gas Pipeline Replacement Program (GPRP)

Beginning in 1985, PG&E undertook a 25-year, $2.5 billion program, known as the Gas Pipeline Replacement Program (GPRP). As a result of the GPRP, many pipeline upgrades were installed both prior to and following the Loma Prieta earthquake. These upgrades are continuing. The newer pipelines are significantly less vulnerable to earthquake effects, including liquefaction, differential settlement, violent shaking, and ground strain, than the older types of pipe installed 50 – 100 years ago.

Gas pipelines being replaced in San Francisco

Source – W. Savage, PG&E

New Guidelines for Pipeline Systems Are Being Developed

In response to the lack of a national code for pipeline systems, the American Lifelines Alliance (ALA) is developing two guideline documents:

1. on the design of ***water transmission systems*** to resist earthquake hazards, including liquefaction, and
2. an *Appendix* to the American Society of Mechanical Engineers (ASME) *B-31 Piping Codes* for the design of better performing ***buried pipelines*** in earthquakes, not just water pipelines.

The projects are being funded by the Federal Emergency Management Agency (FEMA) under a cooperative agreement with the American Society of Civil Engineers (ASCE). Both of these documents should be available in early 2001 and will be able to be obtained from ASCE. Contact Thomas McLane, tmclane@asce.org. For further information on ALA, go to –

http://www.asce.org/aboutasce/alaoverv.html

Highways, Roads, and Airport Runways Buckle –

What Happens?

Highways, roads, and airport runways buckle. Pavement surfaces can be made impassable for most vehicles, and may need to be replaced.

Why Does This Happen?

Buckling occurs because of lateral spreading, ground oscillation, and differential settlement, as described on pages 2 and 3.

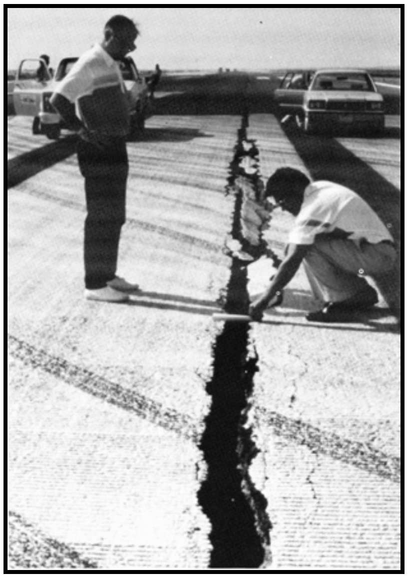
What Were the Road Damage Statistics in the Loma Prieta Earthquake?

Caltrans repaired approximately 10.5 miles (17 km) of damaged highway surface following the Loma Prieta earthquake at a cost of approximately $5.5 million. Data on costs of repairs to local roads are not readily available.

Our review of road damage information from the Loma Prieta earthquake indicates that the percentage of highway road surfaces repaired for strong and very strong shaking intensities (MMI VII and VIII) ranges from 1.4 to almost 12 times greater for areas mapped as having very high liquefaction susceptibility than for areas of higher susceptibility. See Appendix C for more information.

Were Airports Affected by Liquefaction in the Loma Prieta Earthquake?

Oakland International Airport (OAK) operations were affected by the Loma Prieta earthquake, in spite of its location over 40 miles from the fault source for the earthquake. The airport's main 10,000-foot runway, built on hydraulic fill over Bay mud, was severely damaged by liquefaction; 3,000 feet of the runway sustained cracks, some of which were a foot wide and a foot deep. Spreading of the adjacent unpaved ground resulted in cracks up to 3 feet wide. Large sand boils appeared on the runway and adjacent taxiway, a few as wide as 40 feet (EERI, 1990). As a result, OAK was immediately shut down to evaluate runway damage. A shorter 6,212-foot general aviation runway was used to accommodate diverted air traffic for a couple of hours before the main runway was reopened with a usable length of only 7,000 feet. This shorter runway length impacted cargo loads during takeoff. Over the 30 days following the earthquake, 1,500 feet of the 3,000 foot damaged section of the runway was repaired using an emergency repair order for resurfacing and crews already present during the earthquake. An adjacent taxiway was also damaged by liquefaction. Repairs of this taxiway segment and the final 1,500 feet of the main runway were completed six months later, after a competitive bidding process (T. LaBasco, S. Kopacz, and J. Serventi, Port of Oakland, personal comm., September, 2000). Repair costs totaled approximately $6.8 million, including $3.5 million for runway repairs, $2.2 million for taxiway repairs, and $1.1 million for repair of other (non-liquefaction related) damage. FAA funded approximately $5.5 million of the repairs, with the remainder funded by OAK (T. LaBasco and I. Osantowski, Port of Oakland, and J. Rodriguez, FAA, personal comm., September, 2000).



Liquefaction damage in the 1989 Loma Prieta Earthquake at OAK

Source – Geomatrix Consultants

Neither the San Francisco International Airport (SFO) or San Jose International Airport (SJC) were impacted by liquefaction in the Loma Prieta earthquake.

1989 Loma Prieta Earthquake - Alameda Naval Air Station

Source – J. Bray, University of California, Berkeley and U.S. Geological Survey

Significant damage also occurred to the Alameda Naval Air Station. Substantial liquefaction led to the closure of both the 8,000-foot and 7,200-foot runways. The terminal building had structural damage and was closed. Other damage occurred to piers, railroad tracts on piers, and the water- and gas-distribution system. Power was not disrupted. Helicopter pads also were not damaged and were used during the emergency operation. The two runways were repaired and reopened (one in December 1989 and the second expected in January 1990) (EERI, 1990). However, the facility was closed in 1995 and is now scheduled for reuse.

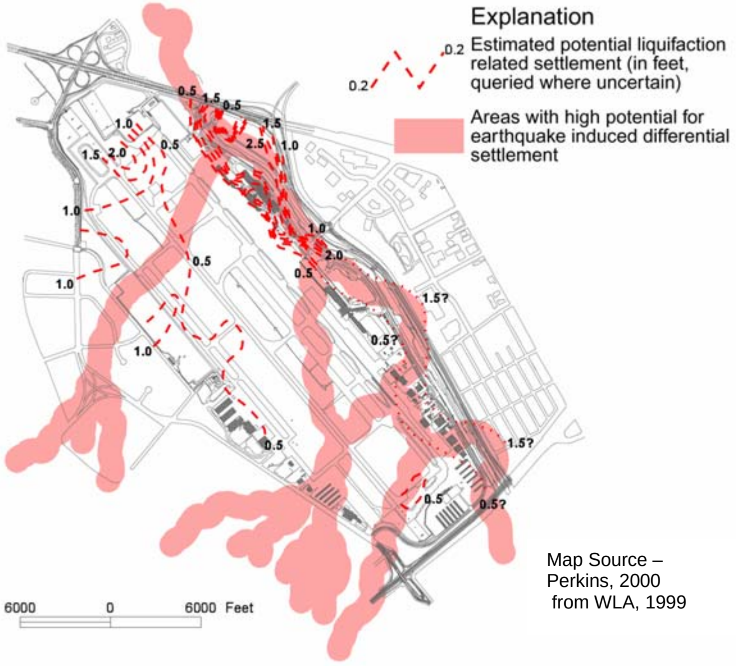
What Do We Expect Will Happen in Future Earthquakes?

It is usually not cost effective to retrofit roads, or even airport runways. If a future earthquake is more centrally located in the urban portion of the Bay Area, many more road closures and airport problems are expected than occurred as a result of the Loma Prieta earthquake. For example, while 17 of the 142 street and highway closures in the Loma Prieta earthquake, and 10 of the 140 closures in the Northridge earthquake were due to liquefaction, over 40 of the over 1600 closures in a Hayward fault earthquake may be due to liquefaction (Perkins and others, 1997 and Perkins and others, 1998). While 10+ miles of state highway had to be resurfaced after Loma Prieta due to liquefaction, we expect many more miles will need to be repaired after a Hayward fault event. ***Of more significance, all three commercial airports may be partially closed*** (Perkins, 2000). The potential problem with the Oakland and San Francisco International Airports is liquefiable fill on Bay Mud. The potential problem with the San Jose International Airport is that the runways cross a series of ancient stream channels.

Runway Program at the San Jose International Airport

SJC is currently extending a shorter runway to create a new full-length runway that should be far less vulnerable to damage because the pavement section is sufficient to "bridge" the stream channels shown as particularly hazardous in the adjacent map. Upon completion of this project, the existing full-length runway will be taken out of service and reconfigured in a similar fashion. Both projects should be completed by 2004.

(M. Wikowski, SJC, personal comm., 2000)



Map Source – Perkins, 2000 from WLA, 1999

Port and Harbor Facilities Are Damaged –

What Happens?

Ports and harbors are often built on artificial fill. In the Bay Area, this fill has typically been placed over Bay mud, which amplifies earthquake shaking. Ports consist of bulk storage facilities and warehouses, cranes to move large containers (typically on rails), and rail and other facilities that serve to connect the port to the land-side transportation system. Liquefaction can cause large areas to sink below the water surface. Rails can buckle, become misaligned, and rotate. Pavement surfaces also buckle, often in ways similar to roadways and airport runways.

Why Does This Happen?

Lateral spreading is a major problem with ports and harbors because the liquefied layer or material above the liquefied layer, even if virtually a flat-lying surface, can move toward the waterfront. Additional damage occurs due to ground oscillation and differential settlement, as described on pages 2 and 3.

How Vulnerable Were Our Ports in the Loma Prieta Earthquake?

The Port of Oakland handles 95% of the container cargo that travels under the Golden Gate Bridge, as well as some break-bulk, bulk liquid, and bulk dry cargo (personal comm., G. Joseph, Port of Oakland, September 2000). Damage to port facilities in 1989 was due primarily to liquefaction of the hydraulic fill. The most extensive damage was to the 7th Street Terminal, although the Howard, APL and Matson Terminals were also affected. Yard areas settled up to one foot relative to the pile-supported crane rails (EERI, 1990, pp.97-103; Kayen and others, 1998, pp.B69-B71).

How Vulnerable Was the Port in the Kobe, Japan Earthquake?

The Port of Kobe, Japan is one of the largest in the world, and handles over ten times the cargo of Oakland. Kobe's port suffered major damage as a result of the 1995 Kobe (Hyogo-Ken Nanbu) earthquake. The three main facilities consisted of perimeter quay walls filled with granular hydraulic fill on sea-bottom clay. As a result of the earthquake, large sections of wharf and warehousing areas sank and were covered with water. "Approximately 50 cranes [had] significant structural damage, … primarily due to the rails spreading and settling. …Even if the design had conformed to the current practice, severe damage may have occurred. But it would have been less" (EERI, 1995b, pp.71-72). Damage to the Port resulted in increased business at ports in Yokohama, Osaka and South Korea, in spite of the billions funneled into recovery. After three years, 10% - 15% of the business had not returned to Kobe (personal comm., G. Selvaduray, 2000).

1995 Kobe Earthquake –
Example of damage to port facilities

Source – Kobe Geotechnical Collection,
Earthquake Engineering Research Center,
University of California, Berkeley

How Does the Port of Oakland View Its Vulnerability to Future Earthquakes?

The Port of Oakland conducted studies of its vulnerability after both the 1989 Loma Prieta earthquake and the 1995 Kobe earthquake. The Port of Oakland experienced about 0.3 g peak ground acceleration during the 1989 earthquake, while the Port of Kobe experienced approximately 0.8 g, a significantly higher amount (Kayen and others, 1998, p.B61; EERI, 1995b, p.69). The Port of Oakland's studies show that, in comparison to Kobe, the soils in Oakland are muddier and less sandy. In addition, the Port of Oakland uses pilings, ranging from 20 to 100 feet in depth, rather than caissons – with the pilings considered a sounder approach. The 29 deep water berths in Oakland are 35-45 feet deep in comparison to Kobe where they are greater than 100 feet deep (personal comm., Mark O'Brien, Port of Oakland, 1995). The Port is in the process of analyzing the existing soil conditions for many of its existing berth embankments and local backlands at a cost of approximately $850,000. The evaluation will include the current seismic capacity of the embankments and local backlands, as well as what increasing level of soil improvements would be necessary to withstand increasing levels of seismic activity. Although these studies are not just for liquefaction, liquefaction is an integral component of the hazard assessment (T. LaBasco, Port of Oakland, 2000). The Port has a fundamental priority to remain in business and operational. It is concerned about permanent loss of business following a Bay Area earthquake to Seattle, Long Beach and Vancouver.

1989 Loma Prieta Earthquake –
Port of Oakland
7th Street Marine Terminal

Source – R. Kayen, U.S. Geological Survey and Loma Prieta Collection, Earthquake Engineering Research Center, University of California, Berkeley

Buildings and Other Structures *MAY* Be Damaged –

What Happens?

Buildings are not consistently more likely to be damaged to the point of being uninhabitable in areas mapped as having high or very high liquefaction susceptibility than outside of those areas, given equivalent shaking intensities. However, if a building is damaged by liquefaction, it is likely to have more extensive damage, and damage that is more costly to repair.

Why Does This Happen?

Repair of liquefaction-related damage is likely to require extensive foundation work that can be extremely expensive and may require demolition of the structure.

What Were the Building Damage Statistics in the Loma Prieta and Northridge Earthquakes?

ABAG examined the percent of homes red-tagged as uninhabitable after the Loma Prieta earthquake within and outside of areas mapped as having high or very high susceptibility to liquefaction. The fraction of pre-1940 single-family homes red-tagged in areas of high and very high liquefaction on the ABAG liquefaction susceptibility maps is about equivalent to two times ***less*** than outside of these areas, given equivalent shaking intensities. This apparent anomaly is consistent with damage patterns of four-story apartment buildings in the Marina District of San Francisco analyzed by Harris and Egan (1992): "The ground failure in the central part of the filled area appears to have mitigated much of the potential damage by dissipating seismic energy through liquefaction." Thus, some speculate that liquefaction may be viewed as a type of "natural" base isolation system. ABAG did not, however, examine the cost of repairing damaged homes after the Loma Prieta earthquake. (See Appendix C for more information.)

1989 Loma Prieta Earthquake –
Moss Landing Marine Laboratories
Showing structure "stretched" more than 5 feet due to lateral spreading

Source – L. Harder, Loma Prieta Collection, Earthquake Engineering Research Center, University of California, Berkeley

On the other hand, U.S. Geological Survey researchers examined data following the Northridge earthquake. "In the Balboa area, where most of the ground failure occurred, construction type and home vintage are nearly identical to the study area as a whole. …Average repair costs for the 315 properties impacted by ground failure…are found to be approximately 300% higher than for the 4,514 properties located outside of ground failure zones ($32,578 vs. $10,771). … Notably, over 6% of damaged homes affected by ground failure required demolition of both structure and foundation, as opposed to only 0.2% of homes unaffected by ground failure. Likewise, foundation repairs needed to be performed on 27.5% of damaged structures in ground failure zones as opposed to only 5% of damaged structures outside of these zones" (D. Ponti, personal comm., 1998).

The Seismic Hazard Mapping Program of the California Division of Mines and Geology

The Seismic Hazard Mapping Program (SHMP) and Act were modeled after the earlier Alquist-Priolo Earthquake Fault Zoning Act that deals with fault surface rupture. The SHMP program is intended to protect public safety from the earthquake effects of strong ground shaking, liquefaction, landslides, or other ground failure. As with the earlier mapping act, the implementation focus is on "structures intended for human occupancy." Thus, the focus of this program is on buildings and other structures, not on transportation and utility lifelines. This focus is consistent with that of the engineering community.

Based on the findings of ABAG and others, local governments reviewing proposed developments should expand on this program to ensure that transportation and utility systems are designed to minimize disruption, as well as note potential problems in emergency response due to likely utility disruptions and road closures.

The Story of Hydraulic Fill Dams in California

Upper San Leandro Reservoir
showing original hydraulic fill dam
and newer replacement dam

Source – J. Perkins, ABAG

In hydraulic fills, materials are mixed with water and pumped to the fill location where they are poured into place. As the water drains, the sand settles in distinct layers that are prone to liquefaction failure. In the 1971 San Fernando earthquake, shaking and resulting liquefaction caused a major slide of the top thirty feet of the Lower San Fernando Dam. This hydraulic-fill dam was very close to completely failing. Eighty thousand people living downstream of the dam were immediately ordered to evacuate. Most hydraulic fill dams were deemed to be unsafe and have been replaced with other types of dams (usually rolled earth dams in the Bay Area). Various other standards for dam structures have been improved and applied.

PART IV - WHAT CAN YOU DO NEXT?

We Recommend –

(1) Understand the hazard by looking at liquefaction susceptibility mapping.
(2) Use the most up-to-date and most detailed liquefaction map for your area of interest.
(3) Have a professional perform a site-specific analysis, if warranted, or if required by CDMG's SHMP mapping or other governmental agencies.
(4) Understand what may be recommended as mitigation.

TABLE 2: Sources of Liquefaction Hazard and Susceptibility Information Covering All Nine Bay Area Counties

	Description	**Reference**
First-Generation Mapping Mid-1970s	Liquefaction maps for a large part of the southern San Francisco Bay Area first appeared in a U.S. Geological Survey Professional Paper summarizing earthquake hazards in the region. The page-sized map (scale=1:380,000) and associated text calls attention to the problem of ground failures and highlights particular problems associated with sand layers within Bay mud.	Youd, T.L., Helley, E.J., Nichols, D.R., and Lajoie, K.R., 1975. "Liquefaction Potential" in Borcherdt, R.L, ed., ***Studies for Seismic Zonation of the San Francisco Bay Region***: U.S. Geological Survey (USGS) Professional Paper 941-A, pp. 68-74.
Second-Generation Mapping Mid-1980s	These maps, developed in the early- to mid-1980s, systematically used mapping of geology in valleys and along Bay margins, with associated estimates of ground-water table and data from historic earthquakes to develop first a "sample" map for San Mateo County (scale=1:62,500, or about 1 inch=1 mile), and, concurrently, an equivalent map for the entire San Francisco Bay Area at a less detailed scale (scale=1:250,000).	Youd, T.L., and Perkins, J.B., 1987. ***Map Showing Liquefaction Susceptibility of San Mateo County, California***: USGS Miscellaneous Investigation Series Map I-1257-G. Perkins, J.B., 1980. ***Liquefaction Susceptibility – San Francisco Bay Region***: ABAG (out-of-print effective with the publication of this report).
"Modern" Mapping 1992 - 2000	Starting in the mid-1990s, and armed with extensive new information from the Loma Prieta and Northridge earthquakes and funding from the U.S. Geological Survey, researchers at William Lettis & Associates and USGS have been revising the geologic mapping of the Bay Area's valleys and the Bay margins. Their most recent mapping (described in Technical Appendix A and shown at 1:1,000,000 earlier in this report) improves upon and incorporated the other two maps listed. A more detailed version of this map is available online on ABAG's internet site at quake.abag.ca.gov. ***The 2000/2001 maps supercede all earlier liquefaction hazard mapping by ABAG.*** This mapping is not a static product, and will be improved as WLA, USGS and CDMG complete work at more detailed scales (largely 1:24,000).	Knudsen, K.L., Sowers, J.M., Witter, R.C., Wentworth, C.M., and Helley, E.J., 2000. ***Preliminary Maps of Quaternary Deposits and Liquefaction Susceptibility, Nine-County San Francisco Bay Region, California***: U. S. Geological Survey Open-File Report 00-444. Digital Database by Wentworth, C.M., Nicholson, R.S., Wright, H.M., and Brown, K.H. Online Version 1.0. Knudsen, K.L, Noller, N.S., Sowers, J.M., and Lettis, W.R., 1996. ***Maps Showing Quaternary Geology and Liquefaction Susceptibility in the San Francisco, California***, 1:100,000 sheet: USGS Open-File Report 97-715, by WLA. Sowers, J.M., Noller, N.S., and Lettis, W.R., 1994. ***Maps Showing Quaternary Geology and Liquefaction Susceptibility in Napa, California***, 1:100,000 sheet: U.S. Geological Survey Open-File Report 95-205, by WLA.

The maps listed in Table 2, particularly the Knudsen and others (2000) map, are the basic map data that was combined with information on shaking levels and used in our regional assessment of liquefaction hazard. Additional maps and information relating to Bay Area liquefaction is listed in Table 3. The maps and information presented in Tables 2 and 3 were reviewed and, in some cases, compiled by Knudsen and others (2000). As techniques for mapping susceptibility have improved and data from the Loma Prieta earthquake have been processed, confidence in producing more detailed mapping has increased.

The maps produced by CDMG are the only maps that are required to be adopted by local jurisdictions and used in land use and permitting decisions. They are based on similar Quaternary geologic mapping to the mapping used in this project. The liquefaction susceptibility and hazard mapping produced for this project is not meant to replace CDMG's Zones of Required Investigations maps. However, the mapping produced for this project can be used to evaluate relative levels of hazard, something that CDMG's maps do not provide.

TABLE 3: Sources of Liquefaction Information Covering Only Part of the Bay Area

Area	Description and Comments	Reference
San Jose 1992	1:24,000-scale mapping of San Jose	Power, M.S., Wesling, J.W., Perman, R.C., Youngs, R.R., and DiSilvestro, L.A., 1992. ***Evaluation of Liquefaction Potential in San Jose, California***, Report to U.S. Geological Survey, Award No. 14-08-0001-G1359, by Geomatrix Consultants.
San Francisco and East Bay 1998	1:24,000-scale mapping of a portion of San Francisco. The principal difference between this mapping and the mapping of CDMG and others is that the areas of very high liquefaction susceptibility are subdivided to highlight particularly problematic areas.	Pease and O'Rourke, 1998. "Liquefaction Hazards in the Mission District and South of Market Area, San Francisco" in ***The Loma Prieta, California, Earthquake of October 17, 1989 – Liquefaction;*** U.S. Geological Survey Professional Paper 1551-B: Reston, VA, pp. B25-B59. (Mapping completed in 1994) Kayen, R.E., Mitchell, J.K., Seed, R.B., and Nishio, Shin'ya, 1998. "Soil Liquefaction in the East Bay During the Earthquake" in ***The Loma Prieta, California, Earthquake of October 17, 1989 – Liquefaction;*** U.S. Geological Survey Professional Paper 1551-B: Reston, VA, pp. B61-B86. Power, M.S., Egan, J.A., Shewbridge, S.E., deBecker, J., and Faris, J.R., 1998. "Analysis of Liquefaction-Induced Damage on Treasure Island" in ***The Loma Prieta, California, Earthquake of October 17, 1989 – Liquefaction;*** U.S. Geological Survey Professional Paper 1551-B: Reston, VA, pp. B87-B119.
San Francisco 2000 ***Oakland 2000*** ***San Jose (2001)*** ***(More to come)***	These 1:24,000-scale maps are unique because they show areas where site-specific investigations are required in compliance with California's Seismic Hazard Mapping Act. Because of this requirement, ***the map zones are in-out, that is, they show where studies are and are not required, not liquefaction susceptibility.***	California Division of Mines and Geology (CDMG), 1996. ***Seismic Hazard Zones Map – City and County of San Francisco***: CDMG Seismic Hazard Zone Map, 1:24,000. California Division of Mines and Geology (CDMG), 2000. ***Seismic Hazard Zones Maps - Portions of the Oakland East, Oakland West, San Leandro, Briones Valley, Las Trampas Ridge, and Hayward Quadrangles***: CDMG Seismic Hazard Zone Map, 1:24,000.

Several factors may lead to the decision to hire a consultant to perform a site-specific liquefaction analysis. For example:

(1) such an analysis may be required prior to construction of a new facility because the area is within a Zone of Required Investigation on one of the new California Division of Mines and Geology maps;
(2) the area is being considered for redevelopment, but experienced liquefaction during the Loma Prieta or Northridge earthquake
(3) the facility being proposed is critical for emergency response (such as a hospital, fire or police station, or emergency operations center) or is a high priority for functionality following an earthquake.

Who conducts the study? Typically, these investigations work most effectively if both engineering geologists and civil engineers are involved.

> The State Mining and Geology Board recommends that engineering geologists and civil engineers conduct the assessment of the surface and subsurface geological/geotechnical conditions at the site, including off-site conditions, to identify potential hazards to the project. It is appropriate for the civil engineer to design and recommend mitigation measures. It is also appropriate for both engineering geologists and civil engineers to be involved in the implementation of the mitigation measures – engineering geologists to confirm the geological conditions and civil engineers to oversee the implementation of the approved mitigation measures (CDMG, 1997).

What will such a study tell you and not tell you? The following table lists typical study components to help you understand the answer to this question.

TABLE 4: Components of a Site-Specific Liquefaction Analysis

[The following table is based on a summary of CDMG Publication 117 –
Guidelines of Evaluating and Mitigating Seismic Hazards in California (1997).]

Component	Purpose	Description and Comments
Screening Investigation	To evaluate the severity of potential seismic hazards, or to screen out sites included in these zones that have a low potential for seismic hazards	Information reviewed often includes topographic maps, geologic and soil engineering maps and reports, aerial photographs, water well logs, and agricultural soil survey reports. CDMG's Seismic Hazard Evaluation reports can help in this process. ***Note - if a screening investigation can clearly demonstrate the absence of seismic hazards at a site, and if the reviewing agency concurs, the screening investigation satisfies the requirement for a site-specific investigation of the Seismic Hazard Map Act!***
Quantitative Evaluation of Resistance	To assess (1) presence, texture, and distribution of unconsolidated deposits, (2) their age, (3) areas of flooding or historic liquefaction, and (4) groundwater level for analysis	Typically, this geotechnical investigation involves quantitative analyses using Standard Penetration Test (SPT) data and Cone Penetration Test (CPT) data. Often, these tests are both performed because each has strengths. These tests are supplemented with laboratory work to assess grain-size distribution, moisture content, void ratios, and relative density.
Evaluation of Potential Hazards	To evaluate (1) if the sediments are susceptible to liquefaction, and (2) if liquefaction occurs, what will happen to the ground?	The hazard assessment should consider two basic types of hazards: (1) site instability – including sliding, lateral spreading, flow failure; and (2) more localized hazards under or adjacent to key facilities, such as bearing failure, settlement, local lateral movement, and floatation of light structures or underground facilities.
Recommendations for Mitigation	To suggest ways to mitigate the hazard to acceptable levels	Specific forms of mitigation for large lateral spreads and more localized settlements or bearing failures are suggested. More specific information on these techniques is provided in Table 5 on the following pages.

The most effective way to avoid damage due to liquefaction is to avoid areas that are susceptible to this hazard. However, we often have to live with the potential for liquefaction. Recommendations for mitigating this hazard fall into three basic categories:
(1) stabilize the susceptible soil;
(2) strengthen the foundation of the building or facility structure; and
(3) strengthen the building or facility structure itself.
Each of these options has its strengths and weaknesses, based on cost and effectiveness, as shown in Table 5, below.

For further information, technical consultants and building departments should review the liquefaction report on ***Recommended Procedures for Implementation of DMG Special Publication 117 – Guidelines for Analyzing and Mitigating Liquefaction Hazards in California*** published by the Southern California Earthquake Center (Martin, Lew, and others, 1999). This report is available for free on the web at –
www.scec.org/outreach/products/liqreport.pdf.

TABLE 5: Techniques for Liquefaction Hazard Mitigation

Mitigation Technique	When It Works Best	When It Is Probably Inappropriate
Soil Stabilization – (1) One option is to remove the problem soils. (2) Soils can be "stabilized" by grouting, densification, or dewatering. Thus, the ingredients for liquefaction – loose, water-saturated sands, are no present. (3) If the principal problem is lateral spreading, "buttresses" can be installed to contain and limit the problem.	(1) Removal may be best when the area of potential liquefaction is relatively small and thin. (2) Soil stabilization has been practiced for a number of years and has been proven effective when exposed to shaking in, for example, the Loma Prieta earthquake. (3) Large areas subject to lateral spreading can be effectively mitigated through buttressing, particularly when only one owner is involved, or owners cooperate.	(1) It may be impractical or too costly to remove large amounts of soil. (2) Densification is not appropriate in areas with existing buildings because it will cause settlement, and perhaps differential settlement, of the existing structures. (3) Containment of lateral spreading does not mitigate bearing strength failures; problems with pipelines and roads will remain.

Ground improvement work at
Port of Oakland
7th Street Marine Terminal

Source – J. Egan, Geomatrix

TABLE 5: Techniques for Liquefaction Hazard Mitigation (Continued)

Mitigation Technique	When It Works Best	When It Is Probably Inappropriate
Foundation Strengthening – Two common techniques are (1) "mat" foundations, or (2) piles or piers that extend through the liquefiable soil.	These techniques work best when built into the design of new structures. However, sometimes they can be used to retrofit existing structures.	Foundation strengthening of individual structures does not mitigate liquefaction problems associated with a neighborhood. (1) Problems with pipelines and roads remain. (2) The techniques may not work when subjected to major lateral spreading.

Pile installation work at
Port of Oakland
7th Street Marine Terminal

Source – J. Egan, Geomatrix

Mitigation Technique	When It Works Best	When It Is Probably Inappropriate
Structural Strengthening – The structures themselves can be strengthened.	These techniques work best when built into the design of new structures. However, sometimes they can be used to retrofit existing structures.	Strengthening of individual structures does not mitigate liquefaction problems associated with a neighborhood. (1) Problems with pipelines and roads remain. (2) The techniques may not work when subjected to major lateral spreading.

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