1.0 INTRODUCTION

1.1 WORKSHOP AND GUIDANCE DOCUMENT OVERVIEW

The objective of this workshop and guidance document is to provide information on seismic hazards to water purveyors to assess the effects of earthquakes on their systems. The guidance document has been developed to be used as the text for the workshop.

One of the crucial elements of water system vulnerability assessments is earthquake hazard liquefaction and related permanent ground deformation. One of the main thrusts of the workshop is to develop an understanding by workshop participants of the effects of that hazard.

The workshop and guidance document first focus on establishing the concern about water system seismic vulnerability. Seismicity and earthquake hazards are described. Vulnerability of system components is established, followed by a discussion about overall system performance. Information on earthquake hazard information sources is provided. Supporting information is provided as an example of vulnerability assessment. Basics for emergency planning for water purveyors are described.

1.2 LIFELINE SYSTEM DEFINITION AND REASONS FOR SEISMIC MITIGATION

Lifeline systems differ from structures classically studied in earthquake engineering. ~~Lifeline systems can be defined as follows:~~

- Society is dependent on system performance both during normal function and during emergency response
- System performance depends on interaction of components
- System is distributed over a large area and requires hazard information for many sites.

There are three primary reasons for water purveyors to pursue earthquake mitigation:

- Responsible to community
- Minimize economic impacts
- Liability.

The non-performance of the lifeline system, and the financial impacts associated with non-performance, are usually much larger than the cost to repair direct damage. In other words, the financial impact of business interruption and/or fire damage resulting from an inoperable water system are usually much larger than the cost of repairing pipelines, tankage, or treatment plants damaged in an earthquake. The financial impacts of water system non-performance are borne by society (i.e., local businesses, property owners, taxing authorities) where as the cost of repair may be borne directly by the purveyor. may be eligible for Federal Emergency Management Agency (FEMA) grant for repair].

The cost of earthquake mitigation should be weighed against potential economic impacts (seismic risk will be discussed in the following subsection), and the least expensive cost alternatives should be pursued.

Water purveyors may be liable for financial impacts related to water system non-performance.

1.3 SEISMIC RISK

Seismic mitigation should be pursued at a level commensurate with seismic risk. Seismic risk is a function of the size of an earthquake that might occur, the probability of occurrence, and the consequences of occurrence.

The size of the earthquake and probability of occurrence are combined to generate seismic zonation maps, as included in the Uniform Building Code (UBC).

The UBC zonation maps ~~are~~ divided into five zones, 0 through 4. Lateral force design coefficients are provided for each zone. The design coefficients are selected to achieve the desired consequences described below. The basis for selection of these design coefficients is as follows.

- <u>Moderate or Operating Basis Earthquake</u> (OBE). Structure may under go minor repairable damage, but will remain functional. An OBE has a 50 percent probability of occurrence in 50 years (typical life of a structure), with a return period of 72 years.
- <u>Large or Design Basis Earthquake</u> (DBE). Structure may be heavily damaged and ultimately condemned, but remains standing for egress of building occupants. A DBE has a 10 percent probability of occurrence in 50 years with a return period of 475 years.

The design coefficients are different for each zone

A higher level of performance is required for water systems. Design coefficients should be more conservative than those presented in the UBC. The UBC does make provisions to increase the design coefficients for important facilities.

For some facilities where failure consequences would be catastrophic, maximum credible earthquakes (MCE) are considered. Facilities in this category include dams and nuclear power plants.

1.4 POST-EARTHQUAKE SYSTEM PERFORMANCE OBJECTIVES

1.4.1 Performance Objective Prioritization

This section defines and discusses service categories and associated priorities to mitigate earthquake damage and provide water service. Mitigating water system earthquake damage in order to maintain their function can be prioritized as follows.

1. Life Safety. Prevention of casualties caused directly from facility failure; examples are chlorine release and occupied building collapse.

2. Fire Suppression. Fire suppression is required immediately following an earthquake

3. Critical Services. Services for hospitals, critical communication equipment cooling, and kidney dialysis patients are required as soon as possible following an earthquake.

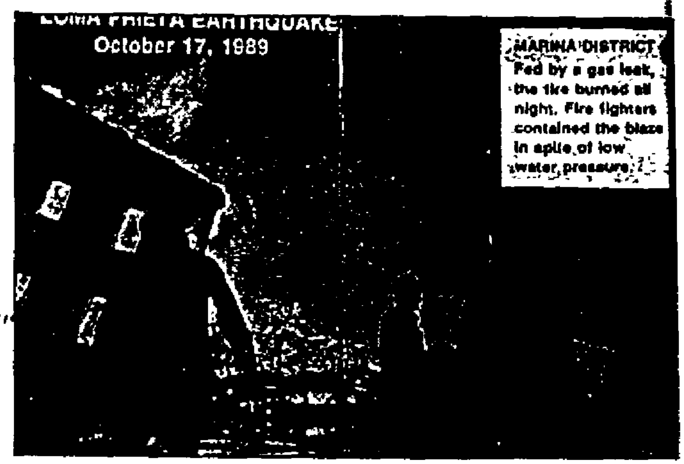
4. Drinking Water and Public Health. These are required in some form within three days following an earthquake; they could be provided using tank truck delivery or bottled water.

5. Water for Domestic, Commercial, and Industrial Use. Water for these uses is required to restore normal function to society for such items as fire sprinklers, cooling water for HVAC, computers (e.g., banking and communication), and industrial process water.

6. Property Damage. Direct damage to water system components or secondary effects from flooding due to reservoir/pipeline failure.

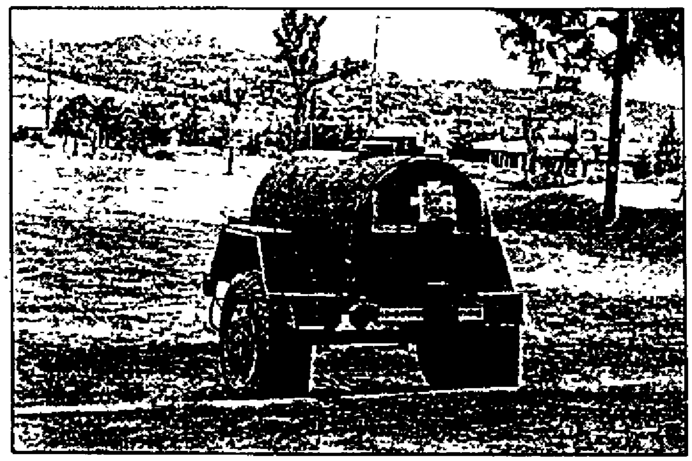
7. Irrigation.

Photograph 1-1. Chlorine cylinders replaced after toppling in Limon, Costa Rica Water Treatment Plant, breaking connecting pipe, and releasing a chlorine plume. One person went to the hospital.

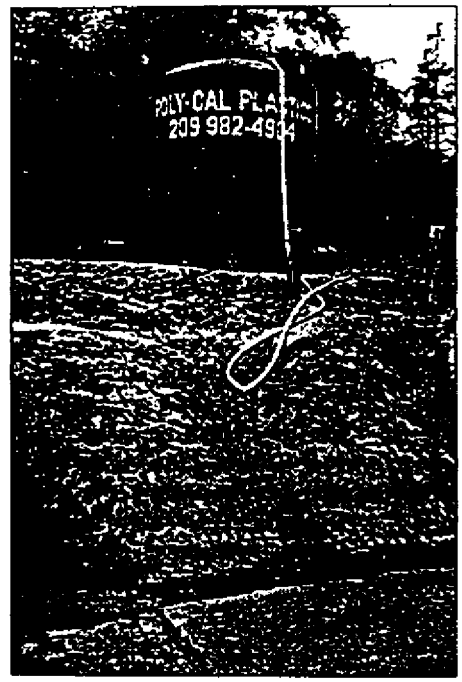


Photograph 1-2. Fire in the Marina District in San Francisco following the Loma Prieta earthquake. Both the municipal and auxiliary water supplies were out of service in the area. No wind the evening of the earthquake helped limit the spread of fire.

***Photograph 1-3.** Water truck distributing drinking water in Erzincan, Turkey. The water system was still being repaired one week following the event.*



***Photograph 1-4.** A water buffalo is used to distribute drinking water following the 1992 Landers earthquake in Landers/Big Bear, California.*



***Photographs 1-5 and 1-6.** Portable water tank and shower unit serving area near Loma Prieta epicenter six weeks after the earthquake.*

The objective of prioritization is to eliminate life-safety risks and optimize reduction of economic risk. Water for drinking and public health can be supplied using emergency response approaches such as hauling and distributing water with tank trucks and distribution of bottled water supplied by regional bottling facilities. There is no evidence that people in civilized countries have died following an earthquake as a result of dehydration. Spread of disease as a result of inoperable sanitary systems (water and wastewater) has been a problem in some earthquakes.

Dysfunction of lifelines has the potential for very large secondary losses resulting from business interruption. Most business cannot function without water or other lifeline services such as power, communications, transportation, and gas or liquid fuel. A decision on establishing a level of post-earthquake service should consider an acceptable lifeline outage duration's impact on function of business. Direct loss of property such as pipeline or pump station damage will be small to society as a whole compared to the losses from business interruption.

Different service function priorities require different combinations of system components to be functional. Components required to produce water for fire suppression usually include system storage reservoirs and the distribution system connecting the reservoir to fire locations. It would not necessarily include the transmission system connecting the dams and reservoirs. Restoration of service for domestic, commercial, and industrial use would include all system components required to make the system functional after the earthquake. Restoration of service to all customers could be achieved at a reduced flow with some of the system components being dysfunctional.

Lifeline system function is dependent both on performance of system components and the interrelationship of those components operating as a system. A simple example is a reservoir, transmission line, and pump station configured in series. All must be operable for the "system" to deliver water. Systems with parallel and/or interconnecting flow paths are more complex. Defining that interrelationship is crucial to understanding system performance.

1.5 POSSIBLE POST-EARTHQUAKE PERFORMANCE POLICY OBJECTIVES

Based on the system/component performance objective priorities, post-earthquake system performance/suggestions are suggested in Table 1-1. Suggested performance policies are provided for moderate earthquakes (OBE) that have a higher probability of occurrence and large earthquakes (DBE) that have a lower probability of occurrence. Dual levels of performance are typical in earthquake engineering. As part of each statement describing performance, the related priorities described above are shown.

TABLE 1-1

POST-EARTHQUAKE SYSTEM PERFORMANCE POLICY OBJECTIVES

Service Category/Priority	Operating Basis Earthquake	Design Basis Earthquake
Earthquake	50 percent chance of occurring in 50 years; 1/72-year return.	10 percent chance of occurring in 50 years; 1/475 year return.
Pipelines	Several failures.	Several tens of failures.
Facilities	Continuous power service. Minor, easily repairable damage to pump stations and reservoirs.	Power out for 72 hours. Minor damage to 70 percent of pump stations, tanks, and reservoirs; all remaining operable. Significant damage to remaining 30 percent making them inoperable.
1. Life Safety	Minimal life safety risk.	Minimal life safety risk.
2. Fire Suppression	Available in all areas.	Available from 70 percent of sources and/or reservoirs after valving off limited areas of damage.
3. Critical Service	Continuous full service to all areas at winter demand rates.	Service to 70 percent or service area at 70 percent of winter flows; potable water made available at centralized locations, both within 72 hours. Boil water order may be required.
4. Drinking Water/Public Health	Maintain good water quality.	
5. Domestic, Commercial, and Industrial Supply		Full service to all but a few areas within 7 days at winter demand rates. Full service to all within 1 month at winter demand rates.
6. Property Damage		
7. Irrigation	Full service to all areas at summer demand rates within 7 days.	Full service to all within 6 months at summer demand rates.

1.6 EXERCISE TO FOCUS ATTENTION ON RESPONSIBILITY FOR SYSTEM FAILURE

This exercise is designed to help focus attention on responsibility for potential system failure and implementation of earthquake damage mitigation programs. The exercise is a scenario located in the Pacific Northwest.

Seismic City is located in the Pacific Northwest with a population of approximately 30,000 people. It is located within commute distance of a large city. As a result, it is both a bedroom community as well as home to some light industry. The city grew rapidly in the 1970s and 1980s as it was considered a preferred location to raise a family. The central business district dates back to the 1930s. In recent years, many strip malls have been developed on the outskirts of town.

Question 1 - With what you have been told, how would you rate the quality of life in Seismic City?

Poor — Good
1 2 3 4 5

Seismic City's water supply comes from a river flowing through the center of town, and is supplemented by several wells. Soils along the river are liquefiable in an earthquake. The water distribution system pipelines are constructed of both cast iron and ductile iron, depending on when they were installed.

The area has been subjected to one OBE and one DBE over the past 50 years, the most recent being 25 years ago. Some damage occurred form each, but none was catastrophic. Locally, no one was injured.

Many people in town have heard of the potential for a subduction DBE earthquake. The police and fire departments have considered earthquake preparedness in some of their emergency planning documents. The public works department/water utility continues with a tight budget. The new EPA Safe Drinking Water Act is placing expensive demands on the City, requiring significant levels of spending to comply.

Question 2 - How concerned should local residents be about their safety and getting services following a DBE?

Not Concerned — Very Concerned
1 2 3 4 5

Question 3 - How concerned should public officials be about providing municipal services following an earthquake?

Not Concerned — Very Concerned
1 2 3 4 5

Question 4 - Being knowledgeable about water systems, how important do you think it is to assess the earthquake vulnerability of the Seismic City water system and implement upgrades as appropriate?

Not Important — Very Important
1 2 3 4 5

Question 5 - If system vulnerability/~~upgrade~~ is important, who is responsible for proceeding?

	Not Responsible				Very Responsible
Federal Government	1	2	3	4	5
State Government	1	2	3	4	5
Local Government/ Water Purveyor	1	2	3	4	5
Residents/Rate Payers	1	2	3	4	5
Engineers	1	2	3	4	5
Local Business People	1	2	3	4	5

Question 6 - Being knowledgeable about water systems, how important do you think it is to maintain earthquake insurance for improved property?

Not Important — Very Important
1 2 3 4 5

Question 7 - If system earthquake insurance is important, who is responsible for proceeding?

	Not Responsible				Very Responsible
Federal Government	1	2	3	4	5
State Government	1	2	3	4	5
Local Government/ Water Purveyor	1	2	3	4	5
Residents/Rate Payers	1	2	3	4	5
Engineers	1	2	3	4	5
Local Business People	1	2	3	4	5

In September, when vegetation is dry, a magnitude 6.5 earthquake occurs with the epicenter approximately 10 miles from Seismic City. There is strong ground shaking for approximately 10 seconds. Soils along the river liquefy and move down gradient.

Several unreinforced masonry buildings downtown collapse, and two people are killed.

The water treatment plant is damaged, primarily as a result of liquefied soils. There are over 100 breaks in cast iron pipe resulting in loss of fire protection. The fires at two sites spread to adjacent buildings, one of which houses a significant local employer.

FEMA has potable drinking water available in tank trucks within 72 hours. The U.S. Corp of Engineers sets up a portable water treatment plant to provide drinking water for distribution by trucks.

The water system, including treatment plant and pipelines, is back in service within one month, and in full service within three months.

Two deaths occur; buildings collapse, and fire destroys buildings at two sites.

The significant local industry goes bankrupt; they have fire insurance, but none for business interruption. Many of the local retailers cannot open until water service is restored loosing significant income; several borderline businesses go bankrupt. This is all with low interest loans from FEMA.

Local officials estimate it will take a decade for the community to recover.

Question 8 - Who is accountable for financial disruption of the community?

	Not Responsible				Very Responsible
Federal Government	1	2	3	4	5
State Government	1	2	3	4	5
Local Government/ Water Purveyor	1	2	3	4	5
Residents/Rate Payers	1	2	3	4	5
Engineers	1	2	3	4	5
Local Business People	1	2	3	4	5

2.0 SEISMICITY AND SEISMIC HAZARDS

Regional earthquake risk is driven by regional seismicity. Local or site-specific seismic hazards are a function of the geotechnical structure on which the area is founded. Five seismic hazards tend to dominate the earthquake threat to water supply systems:

- Ground shaking
- Liquefaction
- Settlement/densification and cracking
- Landslide
- Fault rupture.

Tsunamis and seiche may pose hazards in low-lying coastal regions.

Ground shaking can cause significant damage to treatment plants, pumping stations, and tankage, but accounts for a very small portion of pipeline damage. Faulting can produce extensive damage in buried pipelines within a few hundred feet of the rupture; however, where liquefaction occurs, widespread damage to buried pipelines and other facilities will also typically result.

Because these local seismic hazards have such a dynamic impact on earthquake damage, seismic hazard mapping is a crucial tool in minimizing seismic impacts. Therefore, this document has a significant focus on seismic hazard mapping.

The interaction of collocated lifelines also pose a seismic hazard in themselves. Collocated lifelines are those located near one-another, where failure of one may damage another.

2.1 SEISMICITY

Earthquakes are generated by movement between and within tectonic plates. Tectonic plates of interest in the continental United States include the North American Plate, the Pacific Plate, the Juan de Fuca Plate, and the Gorda Plate. The entire continental United States land mass is located on the North American Plate, except the eastern edge of California, south of San Francisco, and west of the San Andreas fault. The Pacific Plate abuts the North American Plate along the San Andreas Fault. The Pacific Plate is moving northwesterly relative to the North American Plate resulting in earthquake activity in California. Earthquakes in California tend to be centered 10 to 15 km deep, and often have surface faulting

From Cape Mendecino, north along northern California, Oregon, and Washington, two small plates, the Gorda Plate, to the south, and the Juan de Fuca Plate, to the north, are being formed at the interface with the Pacific Plate, moving easterly, and subducting under the North American Plate. This results in earthquakes between the North American Plate and the subducting plates called subduction earthquakes. Earthquakes occurring within the subducting plates are called intraplate earthquakes. The 1949 and 1965 earthquakes in Washington were intraplate earthquakes. Intraplate earthquake are thought to be able to be as large as magnitude 7.5 events. The 1992 Mendecino earthquake was a subduction earthquake. Subduction earthquakes are thought to be as large as magnitude 8.5 or 9.0. Intraplate earthquakes are approximately 40 to 60 km deep. Subduction earthquakes are approximately 20 km deep. Surface faulting is not expected in either case.

The entire North American Plate is under compression generally in a northwest/southeast direction. This compressive force sometimes causes surface faulting to occur in weakened sections of the North American Plate. These events, expected to be 10 to 15 km deep, are often referred to as crustal events. The Seattle fault is likely the remains of a crustal earthquake, as well as many of the faults in the Portland region.

The seismicity of any particular area is driven by its proximity to the tectonic structures described above. The UBC and the National Earthquake Hazard Reduction Program have mapped the United States based on probability of earthquake occurrence and size.

2.2 EARTHQUAKE PARAMETERS

Earthquakes and their effects are measured in different ways. Magnitude describes the size of an earthquake and is based on energy release. Richter magnitude is a logarithmic scale; for each increase in Richter magnitude of one, 33 times as much energy is released. Energy release is dependent on fault rupture length and offset distance.

Intensity describes the effects of shaking, or extent of damage at a particular location or site. Intensity at a site is governed by the magnitude of an earthquake the duration of shaking, the distance from the site to the earthquake epicenter or rupture surface, and local geologic conditions. The duration of the earthquake is dependent on the fault length and, therefore, the amount of energy released.

The Modified Mercalli Intensity (MMI) scale is a commonly used measure of intensity The scale is composed of 12 categories of ground motion intensity, from I (not felt, except by a few people) to XII (total damage) Structural damage generally initiates at about MMI VI for poor structures. MMI XI and XII are extremely rare. The MMI scale is subjective; it is dependent on personal interpretations and is affected, to some extent, by the quality of construction in the affected area. MMI is also affected by whether the ground liquefies, causing damage to the built environment.

Other earthquake parameters related to shaking are peak ground acceleration (PGA) and peak ground velocity (PGV). Both can be used to describe the intensity of shaking. PGA and PGV differ with the frequency of shaking. A plot of PGA or PGV versus frequency is called a response spectrum.

Permanent ground deformation (PGD), is sometimes used as a measure of expected or actual vertical and/or lateral movement caused by liquefaction, settlement, or landslide.

2.3 GROUND SHAKING

Ground shaking is the best-known hazard associated with earthquakes. It can cause scattered, but widespread damage. Ground shaking includes both horizontal and vertical motions that can last from several seconds up to several minutes during major earthquakes, and can be destructive at distances of several hundreds of kilometers, depending on the local soil conditions.

Photograph 2-1. Collapsed Hyatt Hotel in Baguio, Philippines.

Seismic design to mitigate ground shaking includes designing facilities to resist lateral and vertical ~~loads that move with~~ the shaking without being damaged, or isolating the facility from the shaking using base isolators. This can be described as traditional earthquake engineering.

2.4 LIQUEFACTION

Liquefaction is a phenomenon by which saturated, unconsolidated cohesionless soils lose their shear strength due to shaking and are temporarily transformed into a liquefied state. In the process, the soil undergoes transient loss of strength that commonly allows ground displacement or ground failure to occur.

Four basic types of ground failure are associated with liquefaction:

- <u>Flow Failures</u>. Soil materials flowing rapidly downslope in a liquefied state.
- <u>Lateral Spreading</u>. Limited displacement of surface soil layers down mild slopes or towards free faces such as river banks.
- <u>Rotation</u>. Buried objects lighter than the displaced liquefied soil, such as tanks, manholes, or gravity pipelines, float to the surface.
- <u>Loss of Bearing Strength</u>. Bearing capacity failure of foundations because of weakening of underlying or adjacent soil material that may result in structures sinking.

Photograph 2-2. Lateral spreading on road in Costa Rica.

Photograph 2-3. Floating manhole as a result of liquefaction following Niigata earthquake.

Photograph 2-4. Building settled as a result of liquefaction in Dagupan, Philippines.

Liquefaction often occurs in horizontal layers covered with competent soil layers above them. When these deeper layers liquefy, they can allow the soil layers that they are supporting to move laterally in solid blocks.

One of the damaging factors from liquefaction lateral spreading is the actual PGD that occurs. PGD is a measure of the distance a point moves permanently during and following an earthquake. Horizontal and vertical movements are both considered. Youd (1987) has done extensive work in developing a methodology to estimate maximum deformations at any given site. Youd's liquefaction severity index (LSI) is sometimes used to estimate the expected damage to pipelines, and to provide guidance in designing new facilities.

Experience has shown that five factors are important in determining the potential for a particular soil to liquefy.

1) Grain size distribution

2) Depth to groundwater

3) Density

4) Weight of overburden/soil depth

5) Amplitude and duration of ground shaking.

Two additional factors influence the grain size distribution and density:

1) Soil age

2) Soil origin.

The following is a discussion of each factor.

- Grain Size Distribution. Uniformly graded sand, with little fines or coarser grains (i.e., clean sand), is most likely to liquefy. It is more likely that evenly graded sands will be more dense. Silty sands and gravels are also susceptible to liquefaction under very severe cyclic loadings.

- Depth to Groundwater. If groundwater exists at the point in the soil column where densification is taking place, liquefaction can occur. The shallower the depth, the lower the weight of soil overburden and potential for densification to occur. Therefore, the shallower the groundwater, the more likely liquefaction will occur.

- Density. Liquefaction occurs principally in loose, saturated, cohesionless soils. Such a soil may densify when subjected to cyclic loading. This tendency to densify results in a reduced soil/water volume and an increase in pore water pressure if the inter-granular pores are filled with water. When the pore water pressure becomes equal to the total mean stress, the soil loses its strength and liquefies. If the soil is dense to begin with, there will be a smaller opportunity for liquefaction.

- Weight of Overburden/Soil Depth. Interpartical stresses increase the greater the overburden pressure. The greater the interpartical stresses, the lower probability that liquefaction will occur. Liquefaction usually occurs at depths less than 30 feet. It seldom occurs at depths greater than 50 feet.

- Amplitude and Duration of Ground Shaking. The ability of a soil to withstand earthquake-induced ground shaking without failure depends on the severity of the ground motion—amplitude and duration. More severe motions are more likely to cause ground failure. Liquefaction of soils under stress conditions induced by an earthquake can occur either near the epicenter of small or moderate earthquakes, or at some distance from moderate to large earthquakes.

- Soil Age. Weak, cohesionless soils are typically young. With time, two factors act to increase the strength of a typical soil: compaction changes the voids ratio, and various chemical processes act to cement the soil grains together. A rule of thumb is that deposits older than Late Pleistocene (greater than one-half million years old) are unlikely to liquefy except under the most vigorous ground shaking, while Late Holocene deposits (less than 3,000 years old) are most likely to liquefy.

- Soil Origin. Soil deposited by fluvial processes are deposited rapidly and have little chance to achieve a dense packing of grains. Similarly, manmade non-engineered fills, particularly below the water table, may have similar shortcomings. These will liquefy easily. On the other hand, glacially deposited sediments, particularly those over which a glacier has passed, are generally rather dense already and are less likely to liquefy.

Photograph 2-5. Aerial view of Dagupan, Philippines, located on alluvial deposits. Extensive liquefaction occurred in this area in the 1990 earthquake.

Possible liquefaction mitigation measures include the following.

- Avoid the areas where liquefaction/lateral spreading will occur:
  - Use directional drilling to cross rivers below liquefiable materials.

- Stabilize liquefiable material:
  - Replace material with engineered (compacted) fill. Note that an adequate width must be replaced to resist movement of adjoining liquefiable soils
  - Contain with retaining walls.
  - Densification by vibration - Drop weights 2 to 200 tons from up to 120 feet.
  - Vibroflotation - Jet holes in ground with vibration on 5- to 10-foot centers and backfill with sand on withdrawal.
  - Stone columns - Jet holes into ground with vibration on 5- to 10-foot centers. Backfill with gravel on withdrawal. Ston columns provide strength and drainage.
  - Permeation grouting - Penetrate voids with grout using silicates, cement, or chemicals.
  - Compaction grouting - Expand cavity in predrilled hole and pump in grout (applicable to insitu building foundations).
  - Compaction piles - Ground consolidates during pipe installation.
  - Deep soil mixing - Advance large diameter hollow-stem auger and pump in cement slurry mixing with soil.
  - Drainage - Gravity or pumped

- Establish foundation below liquefiable material:
  - Piles
  - Excavate to good material.

- Weight neutrally:
  - Add mass concrete.

- Move with the material:
  - Heavy matt to span settlement - Flexible pipe connections
  - Flexible ductile, restrained joint pipe.

- Accept damage.

2.5 SETTLEMENT/DENSIFICATION AND CRACKING

Settlement, consolidation, or densification are similar to the phenomena that occur in liquefaction, without water being present. This results in settlement that is usually minimal compared to PGD from liquefaction-induced sand boils, lateral spread, or lateral flows. Cracking or lurching is lateral movement of soils towards free faces resulting in formation of crevices. They may occur in areas where lateral spreading would have occurred, except there was no groundwater present.

Mitigation for settlement/densification is similar to some of the mitigation measures employed for liquefaction to increase soil density or strength.

2.6 LANDSLIDE

Landslides can be triggered by earthquakes. Vulnerability to landslide is dependent on slope, soil shear strength, and loading.

Sometimes a threshold grade of 15 percent is used as a preliminary guideline for identifying landslide vulnerability. Landslides may also be influenced by soil moisture content and local geologic formations.

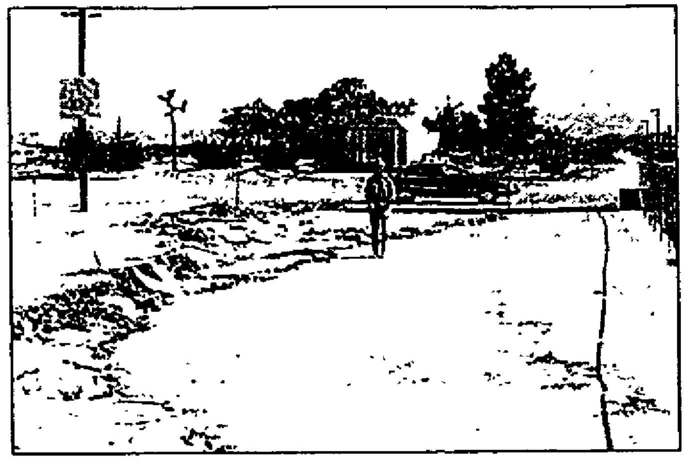
Vulnerability to landslide can be mitigated by avoiding vulnerable locations if possible. This can sometimes be accomplished for pipeline installation by installing the pipeline below the slip plain using techniques such as directional drilling. Landslides can sometimes be mitigated by improving drainage or implementing a structural solution.

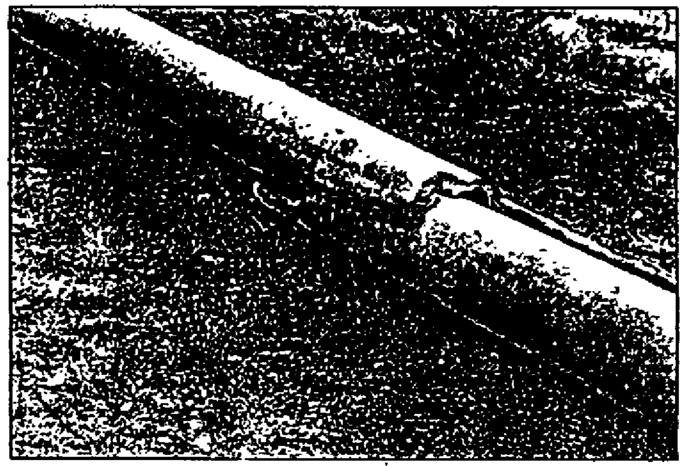
Photograph 2-6. Landslide into Tacoma Narrows following 1949 earthquake.

2.7 FAULT RUPTURE

Faulting can produce localized damage to water supply system components/structures near or crossing surface extensions of the fault. Faults have offset as much as 15 feet in instances such as the San Andreas Fault in the 1906 San Francisco earthquake. Of the representative component/structure types within water supply systems, pipelines are most likely to be located within or crossing known faults.

Permanent offsets of several feet can shear all but the most carefully designed and detailed buried or aboveground pipeline. To mitigate this hazard, fault crossings should be avoided where possible. When pipelines must cross known fault traces, they can employ special designs at the location of historical fault ruptures. Faulting at such locations need not always occur at exactly the same trace; however, such pipelines may still be threatened if the rupture location and offset distance exceeds the length of the flexible link.





Photographs 2-7 and 2-8. Movement along this fault trace in the Landers earthquake resulted in telescoping of this asbestos cement pipeline.

2.8 COLLOCATION

Collocated lifelines may have an impact on one another as follows.

- Explosion of natural gas or liquid fuel lines.
- Flooding/undermining by broken liquid-carrying pipelines.
- Failure of a structure intended for one primary purpose, that also supports another lifeline, such as a highway bridge supporting a pipeline.
- Collapse of a structure onto a lifeline, such as a building falling on a fire hydrant.