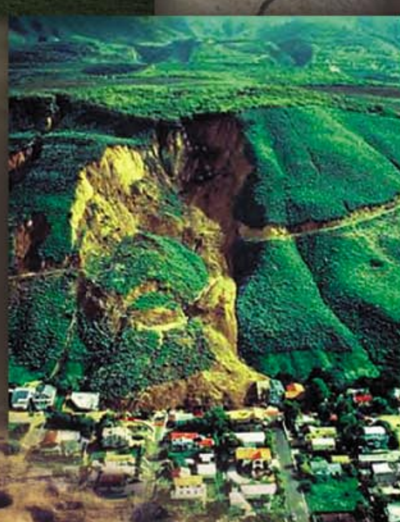
Living with Unstable Ground



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Living with Unstable Ground

by Thomas L. Holzer

American Geological Institute

in cooperation with

Association of Environmental & Engineering Geologists

Applied Technology Council & ATC Endowment Fund

U.S. Geological Survey

About the Author

Thomas L. Holzer is a research engineering geologist with the U.S. Geological Survey, where he has worked since 1975. He also is on the consulting faculty at Stanford University and has taught at the University of Connecticut. He received his B.S.E. from Princeton University and his Ph.D. from Stanford University. His research career has focused primarily on ground failure and how to reduce its impact on people and the built environment. His interests range from ground failures caused by humans to natural ones. He has authored more than 100 publications on ground failure, including editing Reviews in Engineering Geology volume VI, *Man-induced Land Subsidence*, published by the Geological Society of America. He has conducted many post-earthquake investigations, both domestically and internationally. He is presently developing a new methodology for mapping liquefaction hazard associated with earthquakes.

In 1995, he received the Distinguished Service Award of the Hydrogeology Division of the Geological Society of America. In 1998, he was the Geological Society of America and Association of Environmental and Engineering Geologists Richard H. Jahns Distinguished Lecturer. He is a fellow of the Geological Society of America and a member of the American Geophysical Union, the Earthquake Engineering Research Institute, and the Seismological Society of America.

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Satellite view of landslide dam caused by 2005 Kashmir earthquake (magnitude 7.6).

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Preface

Most of us take the stability of the ground for granted. However, many ongoing natural processes and human activities, and occasionally complex combinations of both, displace the ground. Whether ground displacements are large and catastrophic or small and slow, their cumulative impact during the lifetimes of humans or civilizations may be large and destructive. Parts of every state in the United States are affected by these instabilities of the ground. As the demand for land grows and humans increasingly modify their environment, more and more people will be exposed to these instabilities and suffer the consequences.

Living with Unstable Ground describes and discusses the causes and occurrence of unstable ground largely from a geoscience perspective. By understanding the geoscience context, you will be able better to address the threats that unstable ground poses to human well-being and safety. This practical guide will also increase your awareness and understanding of how you can build safely in areas with unstable ground and what society can do to reduce the impact of unstable ground.

I am grateful to the many individuals and organizations who provided illustrations and information for this book as well as technical reviews. Reviewers of all or part of the book include: Richard Bernknopf, Scott Burns, Chris Matthewson, Robert Moore, Jonathan Stock, Raymond Wilson, Michael Bennett, Dave Keefer, Jacquelin Richter-Menge, Wayne Thatcher, and John Tinsley. Individuals who were especially helpful with collecting illustrations and photographs include: Timothy Avery, Jonathan Godt, Lynn Highland, Randall Jibson, Suzanne Lacasse, Chris Poland, Mark Reid, Joanie Schirm, Roy Shlemon, Gerald Wieczorek, and Charley Williams. I am especially indebted to Julia Jackson for her editing skills and Julie DeAtley, DeAtley Design, for the superb graphic design. Finally, I wish to thank the American Geological Institute and the editor of the Environmental Awareness Series, Travis Hudson, for the opportunity to produce this book, and the U.S. Geological Survey for its support of my career-long effort to understand and map unstable ground.

Tom Holzer
March, 2009

Piazza San Marco

Venice, Italy

1 It Helps to Know

Most people are aware that earthquake vibrations cause the land surface to move back and forth, but are you aware that the land surface can also move permanently? These permanent movements of the land are known as unstable ground. A wide range of phenomena causes unstable ground. Ongoing natural processes and human activities, or complex combinations of both, may result in local or regional ground displacements. Fortunately, methods are available to identify, map, and reduce damage from areas of potential unstable ground.

What the Environmental Concerns Are

Unstable ground either directly damages the built environment, everything constructed by humans, or causes it to be more vulnerable to other hazards such as flooding. Two types of instability are important: localized ground displacement and broad regional displacement.

Localized displacement is not uniform and causes ground cracks and tilts that damage structures. Non-uniform displacements also break underground utilities such as water, sewer, and gas lines. Damage to gas lines is particularly dangerous because of the potential for explosions when leaking gas ignites.

Regional displacement changes the elevation of the ground over large areas. As a result, formerly high and dry areas may become more susceptible to flooding. In addition, changes of elevation in coastal areas alter the natural environment, principally by modifying habitats. Venice, Italy, provides a classic example of regional ground displacement threatening the built environment. This United Nations World Heritage Site and home of many art treasures was founded in the early 900's in the marshes of the Venetian Lagoon at the mouth of Po River to reduce attacks by land-based armies. It has survived barely above sea level for more than a millennium.

In the 1960's, residents noticed that the frequency of tidal flooding (Fig. 1), was increasing. Concerns about the viability of Venice led to studies

Fig. 1. Tidal flooding in St. Marks Square (left). Satellite image of the Venice Lagoon (top). These horses, originally above the Basilica doors, are now stored inside for protection.

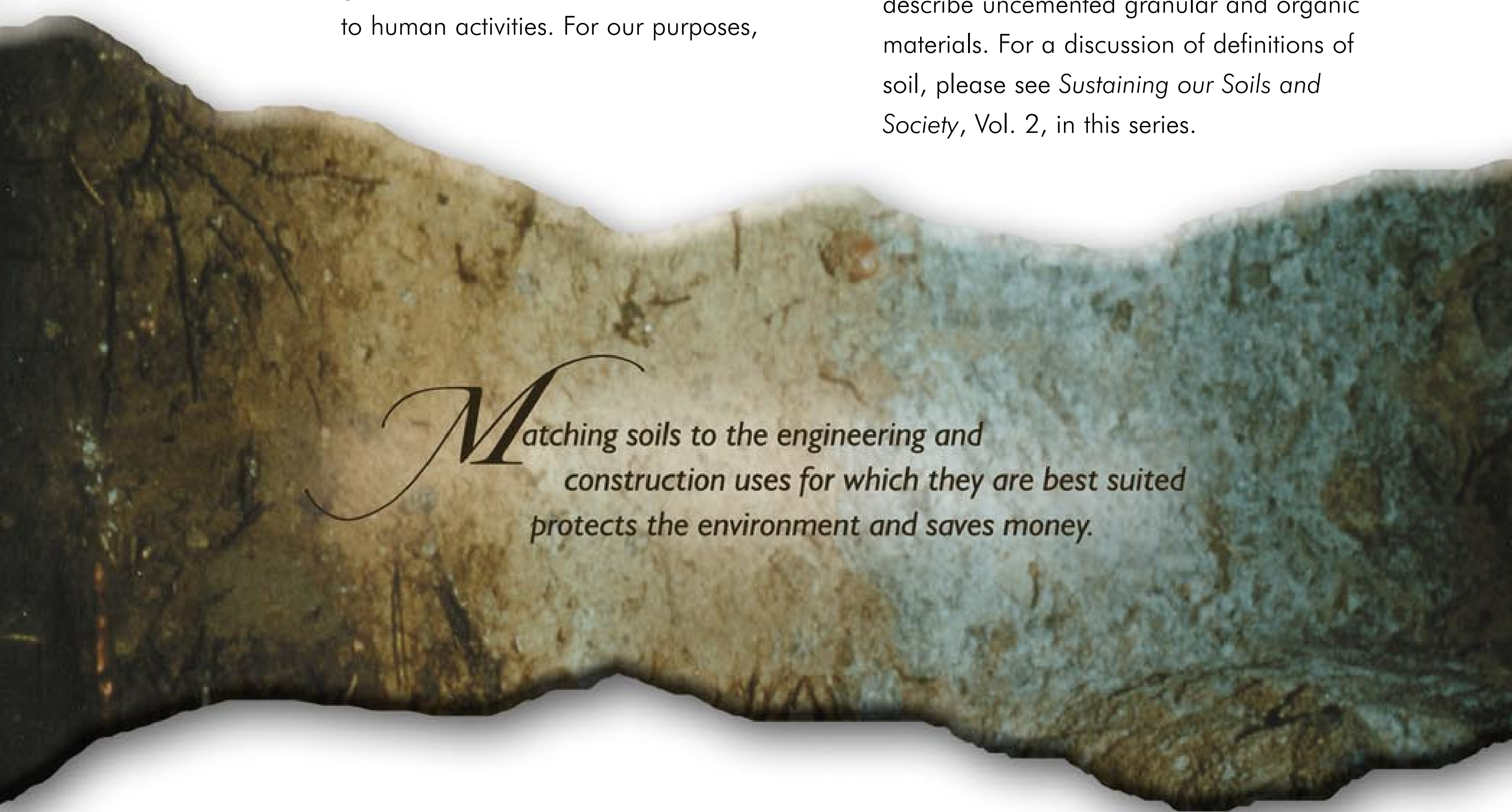
that showed that the floor of the lagoon and islands within it were slowly sinking. The primary cause of the sinking was the loss of groundwater being pumped from the aquifer below. As a result, water pressure in the aquifer was decreasing and the aquifer was compressing. When pumping near Venice was reduced, water pressures in the aquifer recovered. Although this measure stopped most of the sinking, the lowering of the ground surface was irreversible. To protect the city from tidal floods and reduce their height, Venice is installing costly sea gates that will close during periods of exceptionally high tide and slow down the entry of sea water into the lagoon.

Why Ground Becomes Unstable

Some processes that cause unstable ground are natural and others are related to human activities. For our purposes, unstable ground is classified into four broad categories based on the general cause of the instability:

- Problem soils;
- Slope movement;
- Catastrophic collapse into underground cavities; and
- Regional ground movement caused by deep seated processes.

Problem soils include many different soil types. All of these soils, however, are naturally occurring geologic sediment that can change volume and move, that is deform. The actual process by which they deform varies among soil types, but the processes are intrinsic to a given soil. These soils primarily consist of fine-grained mineral and organic sediments. The term soil is used here in the engineering sense to describe uncemented granular and organic materials. For a discussion of definitions of soil, please see *Sustaining our Soils and Society*, Vol. 2, in this series.



Matching soils to the engineering and construction uses for which they are best suited protects the environment and saves money.

The second category of unstable ground involves the action of gravity on a slope, such as landslides (Fig. 2). This category includes sudden slope failure, where the pull of gravity locally exceeds the strength of the soil or rock on the slope, and slow creeping displacements in soil on the slope.

The third category of ground instability involves collapse into underground cavities. Although mechanisms of collapse differ among the types of unstable ground in this category, the collapse is fundamentally attributable to the presence of either a natural cavity or human excavation such as an underground mine or tunnel. Sinkholes, closed topographic depressions associated with collapse into underground cavities, are an example of localized unstable ground (Fig. 3). Buildings undermined by a sinkhole may be totally destroyed, while buildings just a few feet away may remain undamaged.

The fourth category consists of broad regional movements. These movements may be either caused by human activity, such as the sinking of Venice, or driven by natural processes.

Fig. 2. This landslide in Laguna Beach, California, destroyed 18 houses in June, 2005. After an unusually wet winter, the slide started moving in the same general area as a landslide in 1978 that affected about 3.5 acres and damaged or destroyed 50 homes. Area of the former slide had been stabilized.

Fig. 3. Catastrophic collapse near Barstow, Florida, in the late 1960's destroyed two houses and formed a sinkhole. Groundwater slowly dissolved the underlying limestone and created an underground cavity into which the ground eventually collapsed.

Where Unstable Ground Occurs

At many places, human endeavors getting in the way of active geologic processes cause problems with unstable ground. At other places, human activity has either accelerated or triggered a natural geologic process. In general, unstable ground occurs at locations with distinctive or characteristic geology. The example of sinkholes illustrates how areas of potentially unstable ground can be recognized based on geology. For a cavity that causes a sinkhole to form, shallow bedrock must be soluble in groundwater. Fortunately, only a few rock types — limestone, marble, salt, and gypsum — are very soluble. Of these, limestone is the most widespread. Geologists can map areas underlain by limestone and thereby identify areas that are susceptible to sinkhole formation. Conversely, sinkhole activity does not occur in areas underlain by insoluble rock.

How to Live with Unstable Ground

As the result of much experience with unstable ground, geologists, engineers, and land-use planners have developed techniques and approaches for living with it.

- The role of the geologist is to identify potential unstable ground at both regional scales and at specific sites;
- The role of the engineer is to apply engineering theory and design techniques to reduce the impact of unstable ground; and
- The role of the land-use planner is to use this information to guide safe land development.

Most types of unstable ground can be dealt with if the potential problem is recognized before a construction project begins. Unfortunately, a few types of unstable ground are either difficult to predict or so massive that little can be done for small construction projects to minimize potential damage. Large landslides and collapse into underground cavities are two examples of the latter. Only costly or critical projects, such as large land developments or nuclear power reactors, can afford the sophisticated site investigation by geologists and design work by engineers that is required to evaluate these examples of unstable ground. Nevertheless, a savvy geologist may still be able to recognize and broadly outline regions of potentially unstable ground in these situations.

Society has adopted multiple approaches to cope with unstable ground.

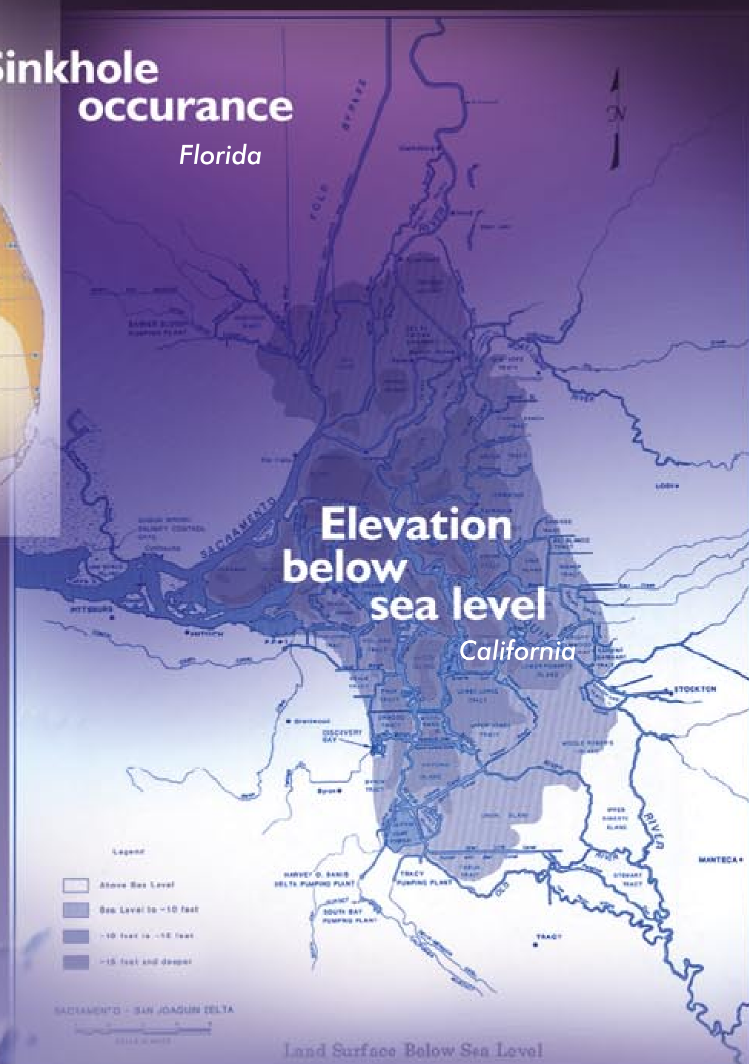
- Implementation of building codes that require consideration of adverse site conditions during construction, possibly with corrective engineering design;
- Regulation of land use in susceptible areas; and
- Construction of preventative structures such as levees and floodwalls in areas where the potential for flooding has been increased.

Knowledge of local geology is useful in determining the selection and implementation of the appropriate approach or approaches. Geologic understanding also helps to predict the frequency, severity, and potential locations of instability and their uncertainties (Fig. 4). The process of compiling this information is known as hazard assessment.

HAZARD MAPS

Sinkhole occurance

Florida



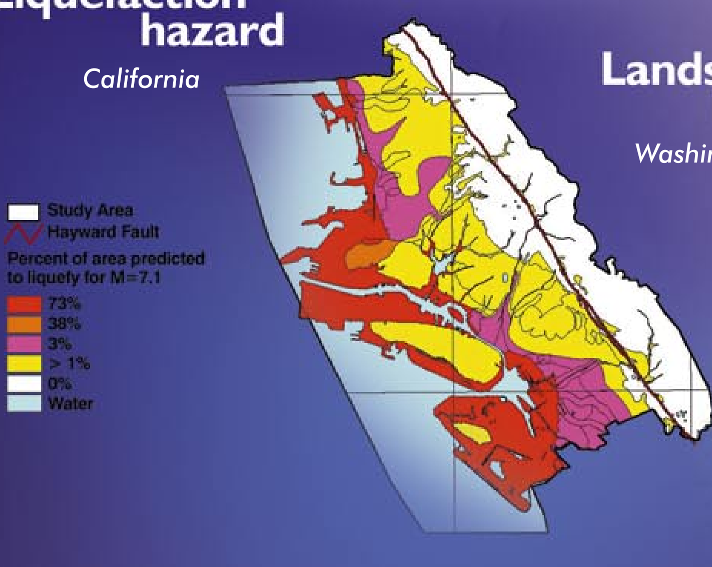
Elevation below sea level

California

Fig. 4. A first step in addressing unstable ground is to map areas of potential or known occurrence where property owners may be threatened. The maps shown here are examples of hazard maps. While most often used for informational purposes, they sometimes are used as regulatory maps.

Liquefaction hazard

California



Landslide hazard

Washington State

Flood zone

Louisiana

Leaning Tower of Pisa

Italy

2 Problem Soils

Many soils present special challenges when people try either to build on or modify them. The ground may become unstable in these situations because of inherent properties of the soil itself. Problem soils include a diverse range of soil types.

Soft Soils

Weak and compressible fine-grained soils containing large amounts of water are known as soft soils. These soils may be more than half water by weight. Structures built on such water-logged low-density soils that consist primarily of clay may slowly sink into the ground under their own weight. The sinking stems from the compressibility of the clay soil, which is caused by the large amount of water-filled open space between the grains of clay. The open spaces between grains in soil are called pores. When weight is placed on soft soils, the skeletal framework formed by the solid clay grains behaves like a sponge when it is squeezed, and water that fills the pores is expelled. The decrease in volume of the soil is caused by a reduction in the size of individual pores.

The Leaning Tower of Pisa in Italy is a classic example of the potential consequences of building on soft soil (Fig. 5). The tower may be the most famous and well-studied settlement problem in the world. Since 1173, when construction began, the 190-ft (58-m) high bell tower has settled about 8.2 ft (2.5 m) into the ground and tilted southward 17 ft (5.2 m). Careful measurements of its tilt since 1911 indicate that the tower continued to tilt slowly until 1995, when tilting was temporarily stopped by placing 780 tons (708 metric tons) of lead on the north side of the base of the tower as a counterweight. The tower was closed to the public in 1990 because of concern that it might topple over after a similarly constructed bell tower at the Cathedral of Pavia suddenly collapsed in 1989. After extracting soil from beneath the north side of the leaning tower to reduce the tilt to a safe level, it was reopened to the public in 2002.

Fig. 5. The tower, built in 1173, has settled 8.2 ft (2.5 m) into the ground and tilted 17 ft (5.2 m) because of consolidation and possible failure of the soft soil beneath it.

Fig. 6. Karl Terzaghi (1883-1963) pioneered the application of mechanics to understanding the physical behavior of soils. He is one of the most famous civil engineers of the 20^{th} Century, and he is the father of modern soil mechanics, now popularly known as geotechnical engineering. Among his major scientific contributions was the concept of effective stress, which recognized how the pressure of water trapped in soils controls the deformation of the soil. Before Terzaghi, civil engineers had developed a sophisticated understanding of how forces are transmitted in buildings and other structures, but their understanding of how soils responded to the forces imposed by these structures was poor and incomplete. Terzaghi, who preferred to sign his reports with the title "consulting engineer," viewed each engineering project as a continuum, beginning with local geology and ending with the measured response of the soil. In a sense, he also was an engineering geologist. For details about Terzaghi's interesting life, the reader is referred to Richard E. Goodman's excellent biography, Karl Terzaghi: The engineer as artist.

The explanation of the tilt rests in the geology beneath the tower, although the exact mechanism of the tilting is controversial. The tower sits on three distinctive geologic layers. The 33-ft (10-m) thick top layer consists predominantly of silts that were deposited either in lagoons or by the Arno River over the last few thousand years. Beneath this layer is a 98-ft (30-m) thick soft marine clay. These two layers rest on a strong incompressible sand layer. Some engineers have speculated that the tilt was caused by subtle differences in compressibility in the top layer directly beneath the tower. Others have speculated that the weight of the tower caused failure and flow of the marine clay. By either explanation, it is clear that the shallow silt layer and soft marine clay were not a good foundation for the tower.

Engineering geologists and civil engineers refer to the decrease in volume of water-logged soil when pore water flows from it as consolidation and the accompanying lowering of elevation of the ground surface as settlement. The physics of consolidation was first described in 1925 by Karl Terzaghi, an Austrian engineer (Fig. 6). Terzaghi proposed that a saturated soil senses two loads when a building is placed on it:

- The combined weights of the overlying soil and the building; and
- The pressure of water trapped in the pores.

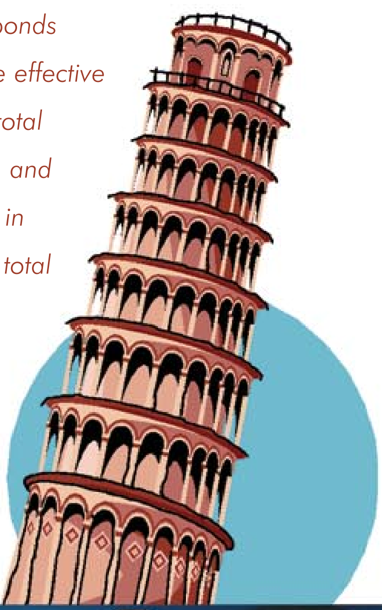
At a given depth, the difference between the total weight of the soil and building per unit area and the pore-water pressure is known as the effective stress (Fig.7). Terzaghi proposed that the effective stress controls how the soil skeleton, the solid framework formed by the individual grains of a soil deposit, deforms.

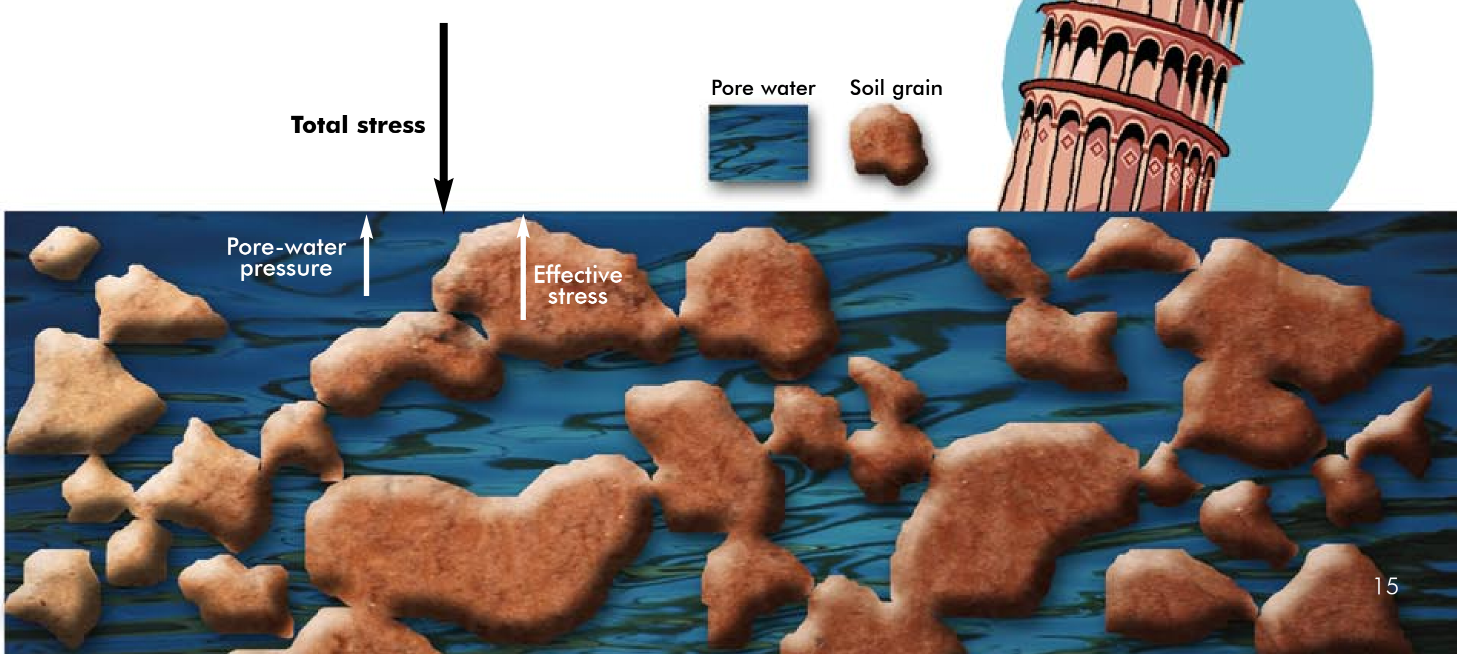
According to Terzaghi, when a building is placed on soil, the pressure of water in the pores of the soil increases to counteract the additional load imposed by the building. The effective stress on the soil is initially unchanged because both weight per unit area on the soil and water pressure rise by the same amount. The elevated water pressure beneath the building, however, causes water to flow from pores beneath the loaded area into the surrounding soil where water pressure is lower. As pore water gradually flows out of the soil beneath the building, the pore-water pressure decreases, the effective stress increases, and the soil consolidates. Consequently, the ground surface beneath the building slowly settles. The rate of settlement is determined by how quickly water can flow out of the soil, and the amount of settlement is determined by the compressibility and thickness of soil.

Although settlement is the principal problem associated with soft soils, they also may fail or flow away from areas where surface loads are imposed. Failure is caused by their low strength. This situation aggravates settlement problems by causing displacements to be larger than those produced by consolidation alone. It also can cause buildings to tilt.

Soft soils are common in parts of many cities located adjacent to water bodies. Areas underlain by soft soils often were formerly bays, lagoons, lakes, river courses, wetlands, or ocean that have been filled or drained. Before the era of environmental regulations, placement of fills into water bodies or marshy areas was a common way to create new developable land. Engineers have recognized for centuries the potential peril of building in areas with soft soils. To avoid placing the weight of structures directly on the soil, long wooden, steel,

Fig. 7. Changes of effective stress determine how a water-laden soil skeleton responds when a load is imposed upon it. The effective stress is the difference between the total stress (the load imposed on the soil) and pore-water pressure (water pressure in the pores). Thus, a change in either total stress or pore-water pressure will cause the soil skeleton to deform.





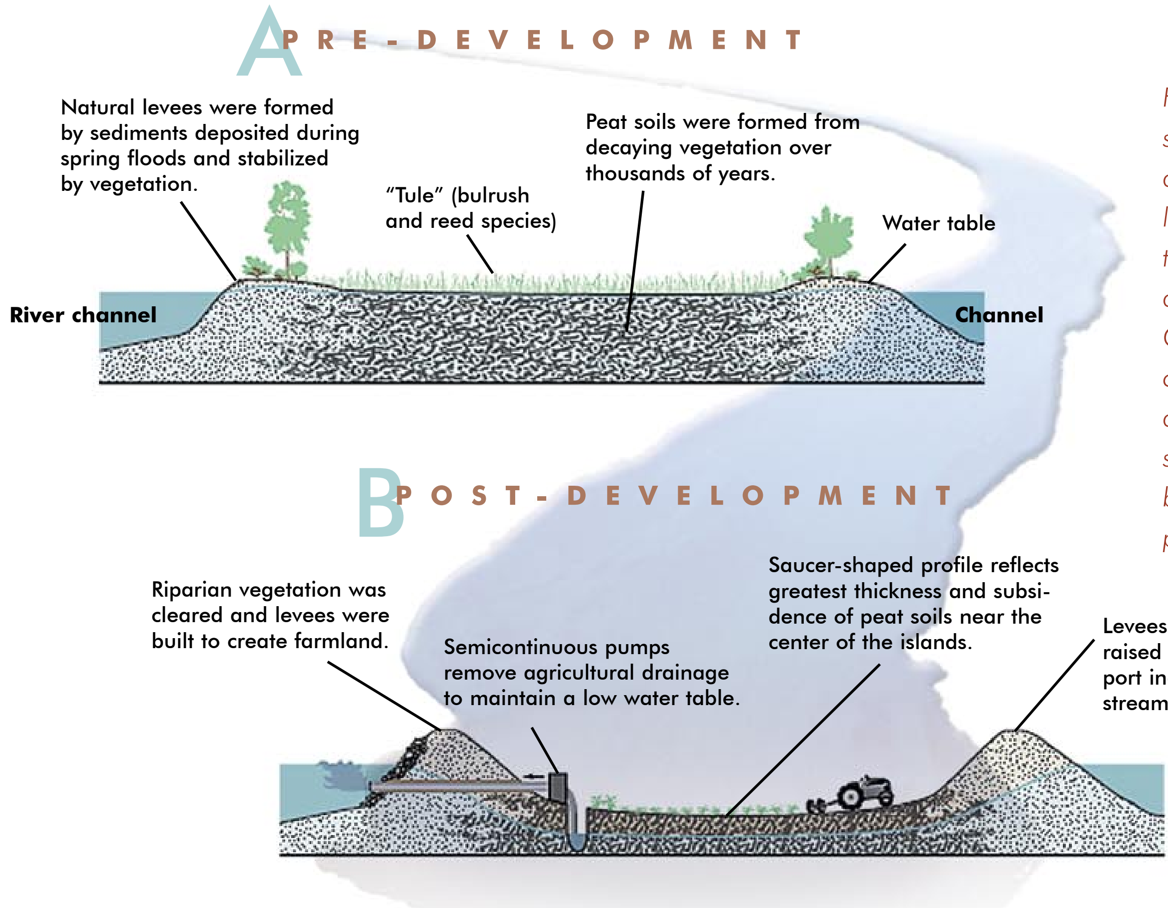


Fig. 8. A. Before draining, the surface of this island is nearly at river level and natural river levees protect it. B. Draining the land to enable farming also lowers the water table. Consequently, the underlying organic soil consolidates and decays, and the land subsides. Levees must then be raised and reinforced to protect the farmland.

or concrete posts known as piles are driven through the soft soil down to underlying firm soil to provide support and the structure is placed on the piles.

Areas with soft soils usually can be identified and mapped by geologists. These areas are often almost topographically flat. This facilitates their identification and mapping. In addition, soft soils in general are less than 12,000 years old. Soils older than 12,000 years tend to become stronger either from cementation or natural consolidation. Geologists generally can distinguish these older deposits from younger ones.

Organic Soils

Today in the United States, local, state, and federal government agencies often regulate drainage and development of wetlands — seasonally or permanently wet ground — to maintain their hydrologic function and to preserve them for wildlife habitats. Before these regulations were implemented, many wetlands were drained either to grow crops in the fertile organic soils of the wetland or to develop the land for housing and industry. Subsidence, lowering of the ground surface, is an inevitable consequence of draining wetlands underlain by soils that are rich in organic matter (Fig. 8). Because these areas typically are prone to flooding even in their natural state, the flooding problem is aggravated by the subsidence. Levees and pumps usually are required to remove storm and groundwater in order to protect areas developed on organic soils from flooding (Fig. 9). Some of the greatest loss of life in the United States from natural disasters can be partially attributed to organic-soil subsidence. About 3,000 people lost their lives in 1926 and 1928 in hurricane flooding that overtopped and swept away levees around the south shore of Lake Okeechobee, Florida. These levees had subsided about 5 ft (1.5 m).

Organic soils contain the decayed remains of the vegetation that grows in wetlands. The natural decay of the wetland vegetation is caused by the action of microorganisms that thrive under waterlogged conditions. The wetlands that are most susceptible to subsidence are underlain by organic-rich soils known as peat and muck. Peat soils are fibrous and retain fragments of the parent vegetation. Mucks consist of thoroughly decomposed organic matter and have a soft muddy appearance.

Two processes contribute to subsidence in areas with organic soils. One, soil consolidation, is already familiar to you. Lowering of the water table by drainage of the wetland causes the pore-water pressure to decrease and the effective stress to increase in the organic soil. This process causes consolidation just like that in soft soils. However, as the water table declines in an organic soil, a second process starts and often becomes the dominant process that causes the land to subside. Oxygen from the atmosphere enters the peat and muck above the water table, and both microorganisms and chemical reactions consume the solid organic material. The organic matter in the soil literally disappears, returning to the atmosphere as carbon dioxide and water vapor. Slowly, but inexorably, the land subsides either for as long as the water table is kept below the ground surface, or until the organic soil is completely consumed and the underlying mineral sediment or rock is exposed.

Approximately 39,000 mi^2 (101,000 km^2) of wetlands in the conterminous United States are underlain by organic soil and have potential for subsidence. About 3,630 mi^2 (9,400 km^2) of this land have subsided because of drainage. The maximum observed subsidence is 21 ft (6.4 m) in the estuary of the Sacramento and San Joaquin Rivers, northeast of San Francisco Bay, California. In this area, which is known locally as the Delta, about 1,400 mi (2,250 km) of levees are needed to protect 500 mi^2 (1,300 km^2) of land underlain by organic soil.

New Orleans, Louisiana, is the largest urban area in the United States that has been impacted by organic-soil subsidence. About 13.5 mi^2 (35 km^2) of urban land there are kept dry by a protective levee system and 21 pumping stations with some of the largest pumps in the United States.

Fig.9. Organic soil underlying the island to the right of the road has subsided since the land was drained for cultivation. The road is on a levee that protects this island in the Sacramento-San Joaquin River Delta, California, from floods. Note that the water level on the left is higher than the sunken ground surface on the right.

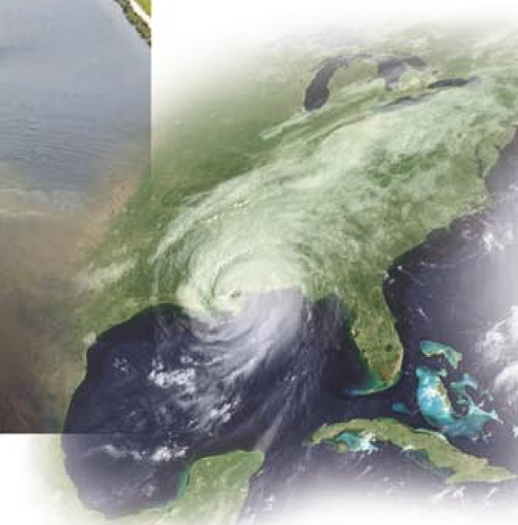


Fig. 10. When the levee failed along the 17th Street Canal in New Orleans during Hurricane Katrina (2005), sliding occurred along a soft clay layer inter-bedded in organic soil deposits beneath the levee allowing water in the canal to push the levee landward like a giant plow.

Organic soils also provide poor foundations for structures because of their low strength, as illustrated by one of the levee breaches that contributed to the 2005 flooding in New Orleans by Hurricane Katrina (Fig. 10). The 17th Street Canal levee failure was caused by sliding in the soil beneath the levee. As the storm surge caused water to rise up on the waterway side of the levee during the hurricane, water percolated down into the soil and caused the water pressure in the layer to rise and the effective stress to decrease. This process reduced the strength of the weak soil and allowed the water in the canal to push the levee landward like a giant plow.

Organic-soil subsidence also presents a long-term management problem. Once water is drained from an area, subsidence starts and can continue for centuries. Historical experience in both the Netherlands and England illustrates this problem. Drainage of organic soil, which was conducted centuries ago, started subsidence that has continued to the present. Not all wetlands are susceptible to significant organic-soil subsidence. Many wetlands are not underlain by organic soils. Geologists can map wetlands that are susceptible to organic-soil subsidence by determining thicknesses and physical properties of the soils beneath the wetlands. Such studies enable predictions of magnitudes and location of subsidence.

Unfortunately, not much can be done to stop organic-soil subsidence other than to return the water table to near the ground surface. This of course is not usually feasible in areas of on-going subsidence that are being either farmed or developed, because these activities require that the water table be maintained below the ground surface.

Expansive Soils

Soils that expand (swell) as they become wet and contract (shrink) as they dry are called expansive soils. The resulting volume change may be so large that the ground will move up and down several inches during a cycle of wetting and drying. In addition, large polygonal forming cracks may

Fig. 11. Expansive soil swells when it is wet and shrinks and cracks as it dries (foreground).

develop in the ground when the soil shrinks while it dries (Fig. 11). Where constrained, these soils generate large soil pressures when they become wet. The cycles of shrinking and expanding are most pronounced in regions that experience seasonal wetting and drying, so called Mediterranean climates.

The shrinking and swelling of expansive soils damages roads, airport runways, buried pipes, and buildings. The actual cause of damage usually is differences in the amount of shrinking or swelling that produces uneven displacement. This happens where there are (1) variations in soil moisture and (2) lateral variations or discontinuities in the soil profile. Typical damage consists of cracking of concrete floors, buckling and cracking of walls, racked doorframes resulting in binding doors, and cracking or uneven displacement of road pavement. The amount of soil expansion is inversely proportional to the weight that a structure places on the soil. Thus, heavy structures generally are less impacted by expansive soils than are lighter structures such as pavements, building slabs, and canal liners.

Soil grains in expansive soils are predominantly clay minerals that have the ability to adsorb large quantities of water. As the individual clay minerals adsorb water, they repel each other and the soil expands. Their ability to adsorb water derives from the electrical nature of the surface of the clay grains. These grains also are very small — less than 0.00008 in (0.002 mm) in diameter — so that a small quantity of clayey soil has a tremendously large surface area. For example, the total surface area of clay grains in a gram of smectite, a type of clay mineral that is commonly found in expansive soils, is about 8,600 ft^2 (800 m^2). This area equals one-fifth of that of a football field.

Expansive clay minerals are also sometimes present in significant quantities in shale, a layered rock consisting principally of clay-sized grains. These rocks are known as heaving shale. When areas underlain by heaving shale are graded for development and exposed to water, damaging shrinking and swelling can occur (Fig. 12).

Fig.12. Shrinking and swelling of the underlying inclined beds of heaving shale caused these "waves" in Jefferson County, Colorado.

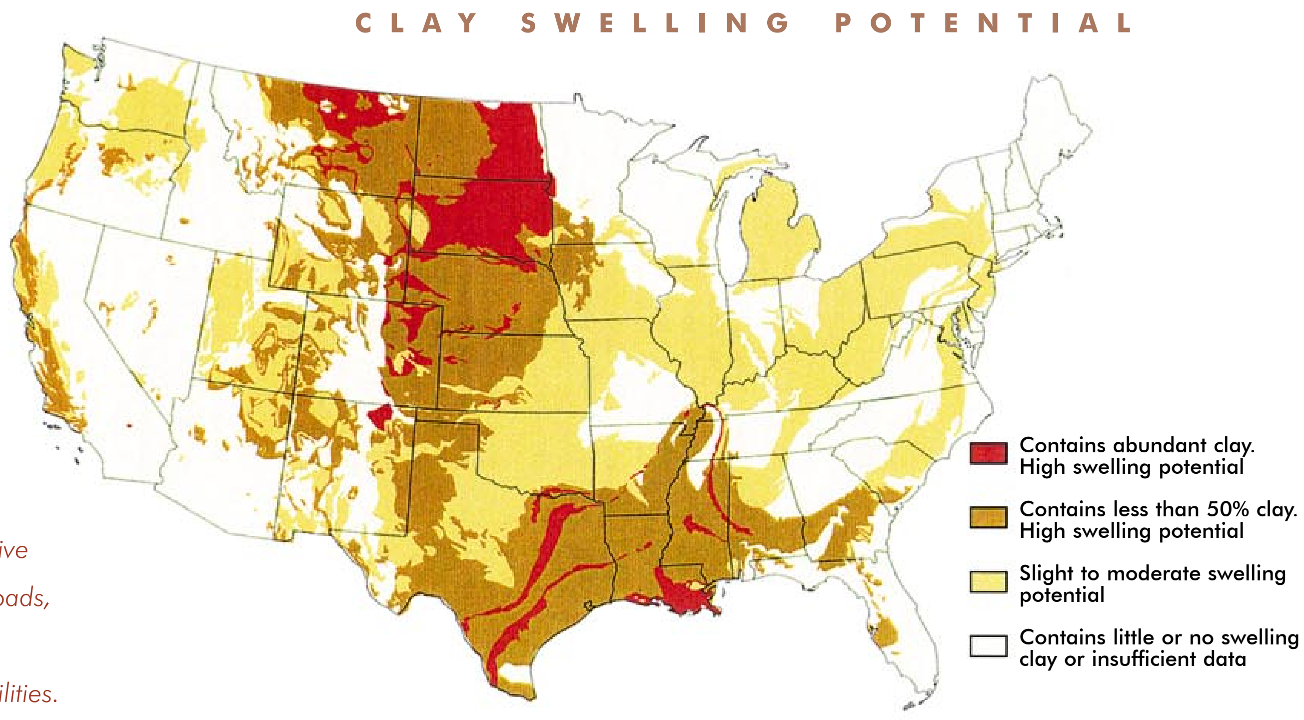


Fig. 13. Expansive soils damage roads, buildings, and underground utilities. Annual losses from swelling and shrinking soils have been estimated at $16 billion (2007 dollars), making it one of, if not, the most expensive natural hazards in the United States.

Fig. 13 shows areas in the United States with expansive soils. Expansive soils can be identified and mapped. An easily recognized indicator of their presence is polygonal ground cracking during drought. Expansive soils also have distinctive clay minerals like smectite that occur in recognizable geologic settings. For example, expansive soils that form in place by weathering of underlying rock usually can be associated with distinctive rock types. Thus, geologic mapping of these rock types can help identify areas where expansive soils are likely. Once a construction site with expansive soil is identified, a variety of approaches are available to reduce the potential problem. These approaches include

- chemical treatment of the soil with lime;
- compaction and saturation of the expansive soil;
- removal of the soil;
- placement of non-expansive soil on top of the expansive soil; and
- foundations that minimize the impact of the soil pressures created by the shrinking and swelling.

Collapsible Soils

Many settlers in arid parts of the western United States were surprised when they dug shallow excavations and filled them with water. The land area occupied by the pond would just collapse into the soil and form a large hole. This phenomenon continues to surprise unaware land developers in dry regions even today. Dry soils that are susceptible to large and sudden reductions in volume, when they become wet are known as collapsible soils. As water percolates into a collapsible soil, the structure formed by the individual grains of soil breaks down and this causes the ground surface to subside. Because subsidence commonly is localized, tension cracks may develop in the ground around the subsiding area.

The collapse, which is known as hydrocompaction, can be caused by water percolating from newly created ponds, irrigation, leakage from soil-lined canals, and storm runoff from roadways and roofs of buildings (Fig. 14). A few occurrences where hydrocompaction was caused by a rising water table have been reported (Fig. 15).

Fig. 14. As water percolated into soil around this gas station at Three Rocks, San Joaquin Valley, California, the station settled into collapsible soil in old earth flow deposits. Notice that as a result of hydrocompaction, the gas station sits below ground level. The pump area did not settle, causing a tilt in the overhanging roof.

This happens when an area is developed and then landscaped. If watering of the landscaping is extensive, recharge of groundwater causes the water table to rise and saturate the collapsible soil.

Collapsible soils are distinguishable by their low density. This low density derives from bonding and cementation that form between individual soil grains when the collapsible soil is deposited. This structure enables the collapsible soil to maintain its low density as it is buried by subsequent layers of soil so long as it remains dry. It also explains the susceptibility of the soil to collapse when water percolates into a collapsible soil for the first time. The bonds between individual soil grains weaken when they become wet, and the soil structure collapses from the weight of the overlying sediment and water. The structure formed by the grains is somewhat like a house of cards with water-soluble glue at points of contact between cards.

Hydrocompaction is predominantly observed in two types of geologic deposits, loess and earth flows. Loess is windblown dust that was created by the grinding action of glaciers. The dust grains in loess form an open soil structure when they settle from the air. Because loess is deposited in a dry state, it can maintain this open structure if not much water percolates into it.

Earth flows are rapidly moving mixtures of fine-grained sediment and water. These flows are common on alluvial fans, the giant aprons of sediment that form along the margins of valleys in arid regions. Earth flow deposits that are susceptible to hydrocompaction are ones that were never saturated with water after they were deposited. The lack of total rewetting is a result of the extreme aridity, which causes most of the subsequent rainfall and storm runoff to evaporate rather than percolate downward through the soil.

Damaging hydrocompaction has been reported in 17 states in the central and western United States. Collapsible soils are widespread in the central United States where large areas are covered by as much

Fig. 15. Cracks caused by hydrocompaction appeared in the Temecula Valley, Riverside County, California, after watering of lawns caused the water table to rise up into collapsible soils.

as 100 ft (30 m) of loess that was deposited by dust-laden winds associated with waning continental glaciers about 12,000 years ago. Extensive loess-covered areas are found along the Mississippi River Valley and in the states of Nebraska and Iowa, which were downwind from the retreating glaciers. Susceptible earth flow deposits are more localized than loess deposits, but are widely reported on alluvial fans in arid parts of the western United States.

Geologists can delineate areas underlain by collapsible soils because the soils occur in distinctive and readily recognized types of geologic deposits. In addition to conventional geologic mapping, delineating areas that are susceptible to hydrocompaction may require geotechnical testing to identify areas where soil densities are low.

If collapsible soil is present at a specific site, damage can be reduced or prevented by several techniques. The soil can be removed, compacted, and replaced. Compaction can be performed in place by pre-wetting, vibration, or simply dropping heavy weights on the land surface (Fig. 16). It also helps to divert surface runoff away from structures. Alternatively, cement grout can be injected into the soil to provide a strong skeleton to support structures. Treatment of the soil to reduce its compressibility or increase its strength is known as ground improvement in geotechnical engineering.

Frozen Soils

In high northern and southern latitudes, where subfreezing temperatures persist for long periods, freezing and subsequent thawing of the ground create instability. Seasonally frozen soil, which is known as frost, is common in temperate parts of North America. Frost-induced soil displacements, known as heave, crack foundations and roads. Problems with frozen ground, however, are greatest in the Arctic where

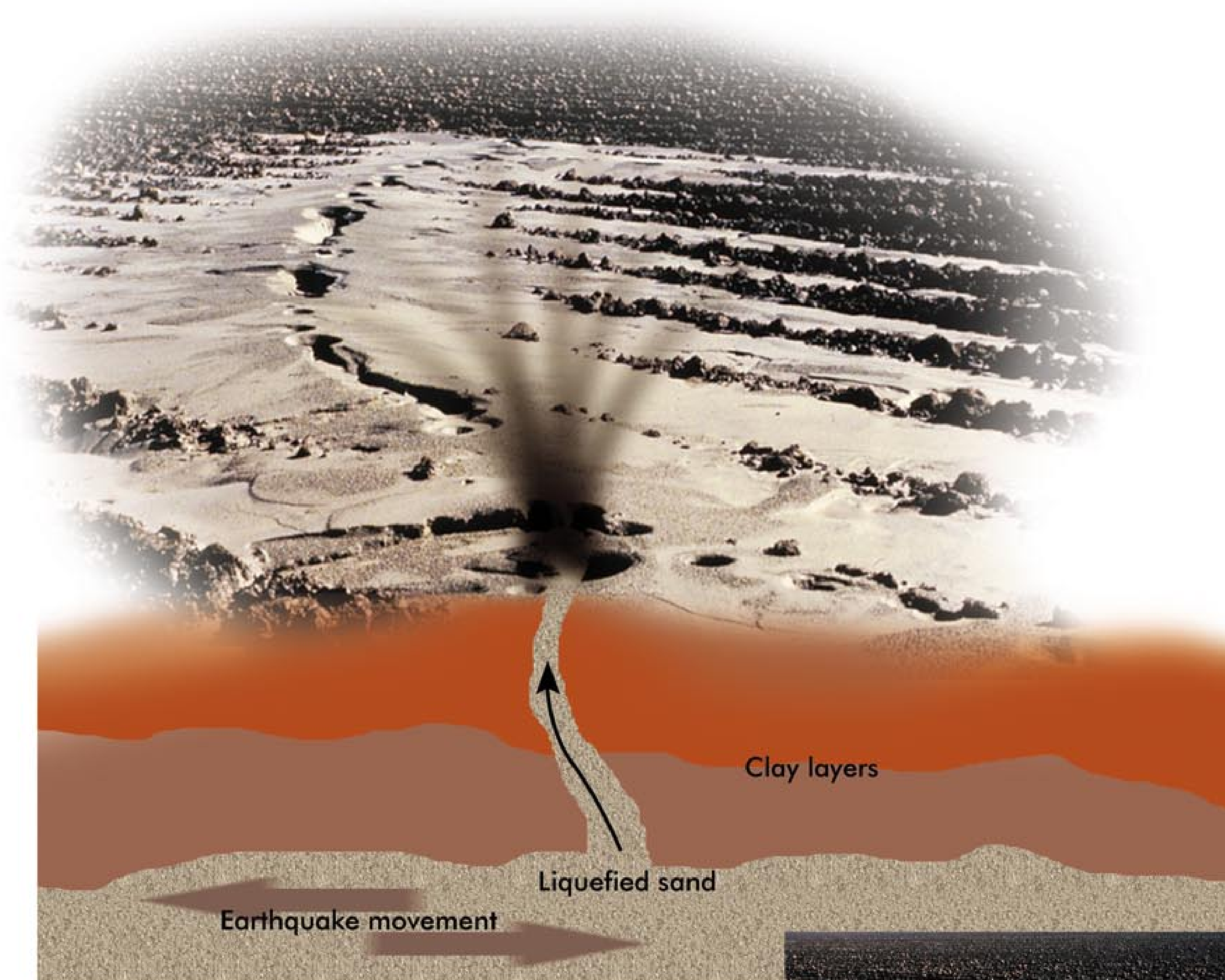
Fig. 16. A crane repeatedly dropped a 30-ton weight from a height of 85 ft. in order to compact the soil here. This ground improvement approach is commonly used to compact collapsible soils.

Fig. 17. Melting of underlying permafrost destroyed this house in Fairbanks, Alaska.

extensive sheets of thick permanently frozen ground, known as permafrost, are found. Permafrost occupies about 20 percent of Earth's land area. It covers 50 percent of Canada and Russia and 85 percent of Alaska.

Permafrost is very strong where it has a high percentage of ice. The strength of permafrost decreases, however, when the ice melts. Because summer temperatures at the land surface usually are above freezing, permafrost is typically overlain by an active layer of soil that thaws seasonally. This layer may have a liquid-like consistency and even become mobile and flow when it thaws. Permafrost also can be melted by human activity. Heated buildings, if not properly insulated from the permafrost, will simply melt their way down into the ground (Fig. 17). Other causes of melting are burial of water and sewage lines lacking insulation. Roads also must be carefully constructed to avoid disrupting local drainage that may cause uneven melting of permafrost.

Silts and clays are more prone to unstable thawing than sands and gravels. These fine-grained soils also expand or frost heave when water is available and are susceptible to cracking. Ice content is important in fine-grained soils. Typically, ice-rich permafrost is either avoided for construction purposes if at all possible or maintained in its frozen state. Sands and gravels, however, are generally stable when they thaw. Thus, maps of near surface soil textures in a permafrost area could be useful to assess the hazard posed by permafrost.



Liquefiable Soils

The problem soils discussed thus far generally are either fine grained or rich in organics. During many earthquakes, however, sands are the problem soil. When wet sand with open water-filled pores is strongly shaken, individual sand grains move and the volume of the pores decreases. This causes the pressure of the water in the pores to increase, and the effective stress in the sand to decrease. When the effective stress approaches zero, the sand loses its strength. At this stage, the sand is said to have liquefied. Liquefaction is primarily a concern in areas that are likely to be strongly shaken by earthquakes.

Fig. 18. When the underlying sand layer liquefied during the 1989 Loma Prieta, California, earthquake (magnitude 6.9), sand boils erupted along a ground crack.

Signs of liquefaction during earthquakes include eruption of muddy water and the formation of sand boils at the land surface (Fig. 18). The expulsion of water from the pores of liquefied sand causes broad lowering of the ground surface. This phenomenon is known as post-liquefaction consolidation. For example, elevation surveys of the Marina District in San Francisco, California, which were conducted before and after the 1989 Loma Prieta magnitude 6.9 earthquake, revealed that the ground surface had locally subsided as much as a third of a foot (11cm).

Damage from liquefaction happens after the sand has liquefied and lost its strength. Liquefied sandy soils that are not very dense may flow on even gentle slopes. This process is known as lateral spreading. This permanent horizontal displacement damages buildings and buried utilities for water, gas, and sewage (Fig.19). The ground also may slowly sway back and forth as seismic surface waves move through the liquefied soil. This swaying, known as ground oscillation, can damage underground utilities at the margins of the liquefied zone.

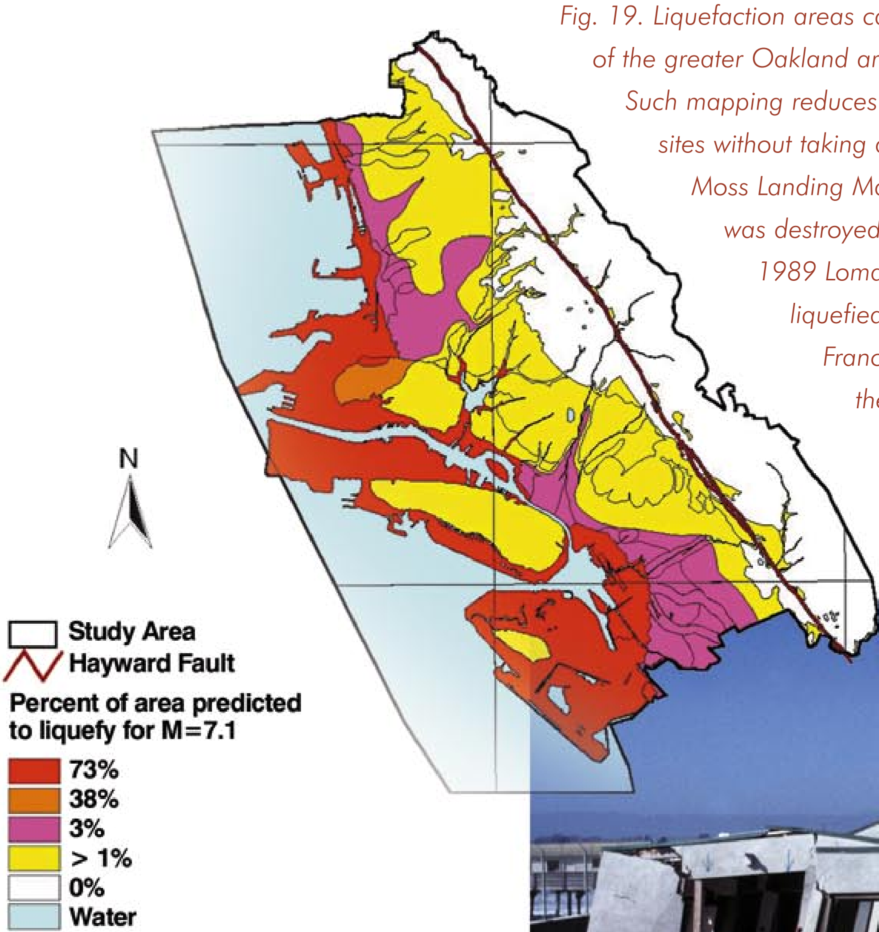


Fig. 19. Liquefaction areas can be mapped as shown in this map of the greater Oakland area on the east shore of San Francisco Bay. Such mapping reduces the chances of building on hazardous sites without taking appropriate steps to prevent damage. Moss Landing Marine Lab on Monterey Bay, California, was destroyed by lateral spreading caused by the 1989 Loma Prieta earthquake. This site also had liquefied and spread during the 1906 San Francisco earthquake (magnitude 7.8). After the 1989 earthquake (magnitude 6.9), the Lab was rebuilt nearby on soil not subject to liquefaction.

Structures also may sink into the liquefied sand (Fig. 20). River levees are particularly vulnerable to such sinking. These large earthen structures typically are built on flood plains, which include soils prone to liquefaction. Because of their weight, levees sink when underlying sands liquefy. The loss in the elevation of crests of levees reduces the degree of flood protection. If the sinking is uneven, cracking may increase their vulnerability to erosion by water flowing through the subsurface cracks.

Sands that are susceptible to liquefaction can be mapped by geologists, and damage from liquefaction can be reduced or prevented through engineering. Alternative approaches are either to modify the soil itself or construct special structural foundations. Modification of the soil, as discussed in the collapsible soil section, p. 22, is a form of ground improvement. Types of ground improvement that reduce liquefaction hazard include

- increasing the density of the sand by vibration;
- providing for rapid drainage of water so that pore pressure cannot build up; and
- injecting grout to strengthen the sandy soil.

One can also build a foundation, such as piles, that protects the structure from displacements associated with liquefaction.

Fig. 20. This building in Adapazari, Turkey, settled into liquefied soil during the 1999 Kocaeli earthquake (magnitude 7.4).

Soft Soils ▲

When weight is placed on fine-grained soft soils, the skeletal framework formed by the solid clay grains behaves like a sponge when it is squeezed, and water that fills the pores is expelled. The Leaning Tower of Pisa may be the most famous and well-studied settlement problem in the world.

PROBLEM SOILS

▲ Liquefiable Soils

Sands are the problem soil during many earthquakes. Damage from liquefaction happens after sandy soil has liquefied and lost its strength.

▲ Expansive Soils

Shrinking and swelling of expansive soils damages roads, airport runways, buried pipes, and buildings.

Frozen Soils ▶

Freezing and thawing of soil laden with ice can crack foundations and roads. Permafrost covers 50 percent of Canada and Russia and 85 percent of Alaska.

Collapsible Soils ▶

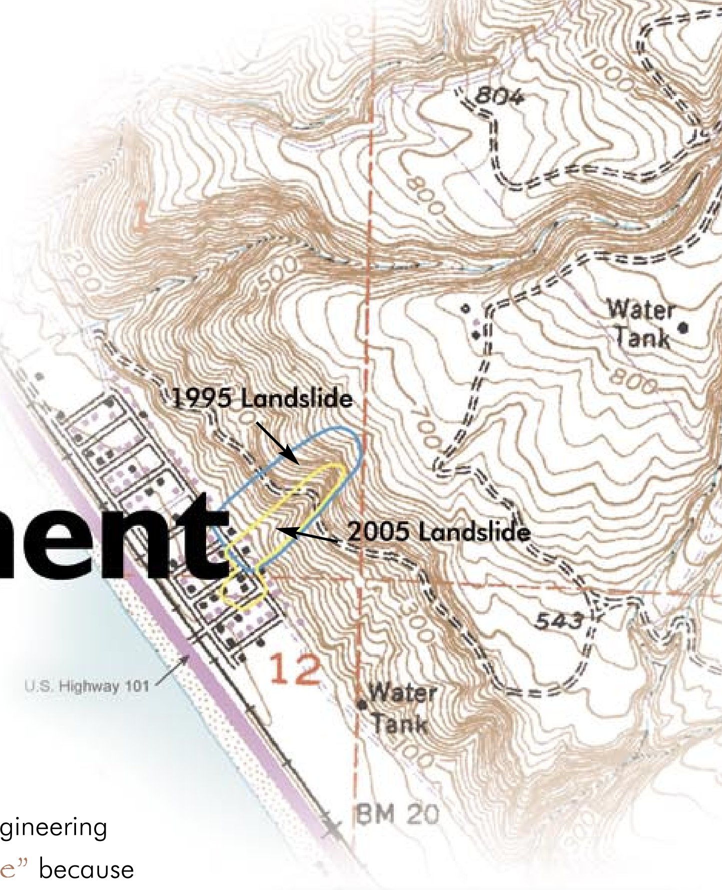
In collapsible soils, the structure formed by the grains is somewhat like a house of cards with water-soluble glue at points of contact between cards.

▲ Organic Soils

Subsidence, lowering of the ground surface, is an inevitable consequence of draining wetlands underlain by soils that are rich in organic matter.

La Conchita, California

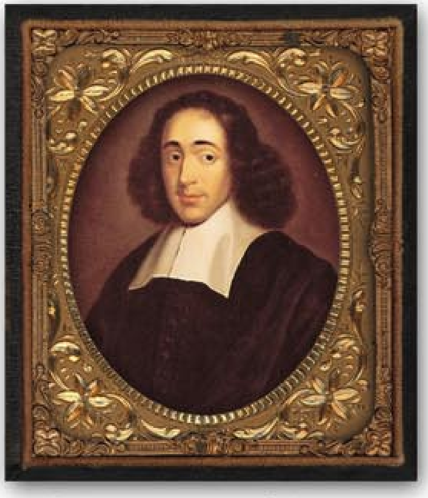
3 Slope Movement



In 1677, the Dutch philosopher Benedict Spinoza wrote that "Nature abhors a vacuum." If Spinoza had been an engineering geologist, he might have written "Nature abhors a slope" because Earth's gravity always exerts a downhill force on the rocks and soils that comprise the slope. This unrelenting tug of gravity can lead to physical displacement of these materials.

Slope movements are a common hazard in most mountainous and hilly regions of the world (Fig. 21). Although accurate estimates of the impact of these movements are not available, a 2005 study conducted for the World Bank suggests 5 percent (300 million people) of the world population is at risk. Approximately 66 million of these people live in areas with a significant hazard. The total land area affected is about 1.4 million mi^2 (3.7 million km^2). Some of the larger events have killed thousands of people.

Although "landslide" is the popular, catchall term for slope movements, geoscientists and engineers classify these diverse displacements by the type of movement and material on a given slope (Fig. 22). The following sections describe the types of slope movement that are most common and costly to the built environment. Falls and topples are not discussed although they are a widespread threat to motorists and houses at the base of steep cliffs.



Benedict Spinoza
1632-1677

Fig. 21. (Left) Aerial view of a massive landslide at La Conchita, California, north of Santa Barbara. The landslide occurred in the winter of 2005. The body of the slide turned into an earth flow that killed 10 people.

Slides

Blocks of soil or rock that have moved downhill along discrete sliding or failure surfaces are called slides or slumps. They are one of the better known classes of slope movement because of the occasionally large size of the sliding blocks and the spectacular damage they cause. In addition

Classification of Slope Movements in Soil and Rock

Type of Movement			Type of Material		
			Bedrock	Engineering soils Predominantly coarse	Predominantly fine
Falls			Rock fall	Debris fall	Earth fall
Topples			Rock topple	Debris topple	Earth topple
Slides	Rotational	Few units	Rock slump	Debris slump	Earth slump
	Translational	Few units	Rock block slide	Debris block slide	Earth block slide
	Translational	Many units	Rock slide	Debris slide	Earth slide
Lateral spreads			Rock spread	Debris spread	Earth spread
Flows			Rock flow (deep creep)	Debris flow (soil creep)	Earth flow

Fig. 22. Although 'landslide' is the popular, catchall term for slope movements, geoscientists and engineers classify these diverse displacements by the type of movement and material on a given slope.

to damaging structures, large slides can temporarily dam water courses and threaten downstream areas with catastrophic flooding. The slide shown in Fig. 23 began moving in the spring of 1983 near Thistle, Utah, in response to groundwater buildup from heavy rains the previous September and the melting of deep snow pack for the winter of 1982-83. Within a few weeks it damned the Spanish Fork River, obliterating U.S. Highway 6 and the main line of the Denver and Rio Grande Western Railroad.

Slides occur when the downhill loading is increased, or when the strength of the material making up the slope is reduced. Two changes of loading can destabilize a slope:

- an increase of the load at the head (uphill part) of the slide, or
- a decrease in the support at the toe (downhill part) of the slide.

Both changes increase the downhill driving force. Strengths are reduced when the soil or rock slowly weathers, or when water enters and saturates the soil. The latter raises pore-water pressures and decreases the effective stress.

...most costly single landslide in U.S. history.

Fig. 23. Aerial view of the 1983 landslide at Thistle, Utah. The town of Thistle was inundated under the floodwaters rising behind the landslide dam. Total costs (direct and indirect) exceeded $400 million, the most costly single landslide event in U.S. history.

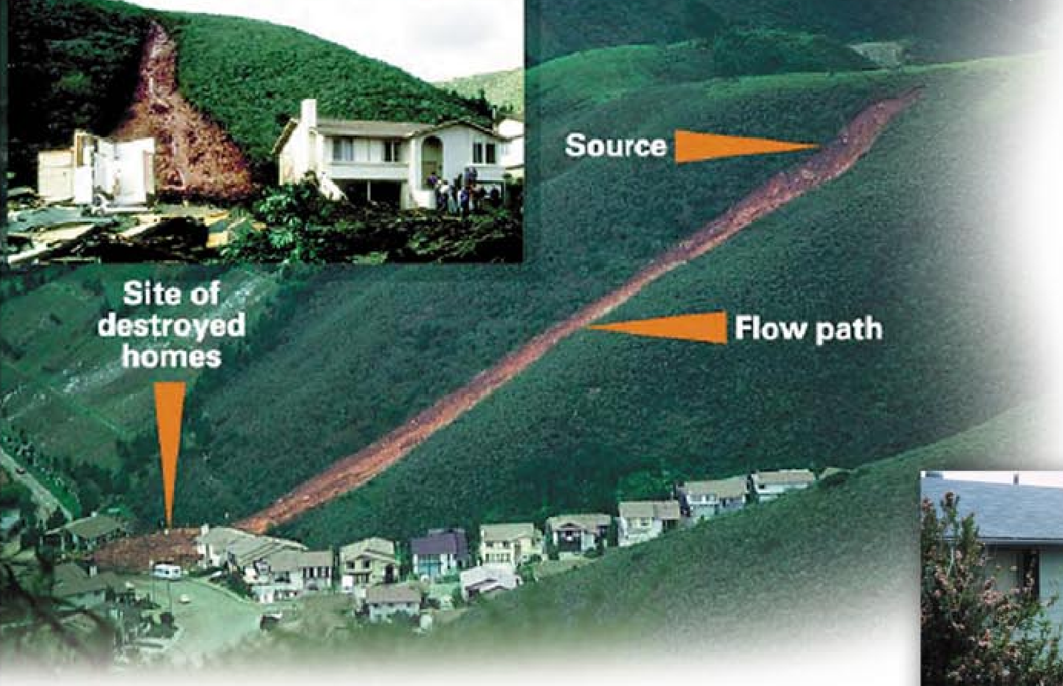


Fig. 24. (Left) This debris flow in 1982, killed 3 children and destroyed 2 houses in Pacifica, California, about 10 miles south of San Francisco.

Fig. 25. (Right) A debris flow partially buried and filled this house in Bountiful, Utah, in 1983.

Slides commonly are the result of improper construction practices. Slopes that are stable under natural conditions become unstable and fail when improperly graded for building sites or roads.

- Removing the toe area of an active or potential slide;
- Excavating too steeply into hillsides; or
- Placing heavy fills on the head of an active or potential slide

can significantly increase the downhill loading in the slope. Another potential destabilizing activity is the introduction of water from surface drainage projects, irrigation, leaky pipes, and septic tank systems to name a few typical sources of water. Such activities reduce the strength of the rock or soil.

Flows

In the classification scheme in Fig. 22, flows refer to slope displacements in which the whole moving part of the slope is deforming. These soil-water mixtures typically emerge from soils on slopes. They are an important type of slope movement because of the suddenness with which they develop and their downhill speed. Flows have been clocked at tens of miles per hour and can sweep away or bury unprepared residents and houses on hillsides and in valleys (Figs. 24 and 25). They commonly are triggered by high-intensity rainfall after the soil has become saturated during periods of prolonged rainfall. As the saturated soil begins to fail, perhaps as a slide, it liquefies, and the whole body of soil mobilizes. Flows laden with coarse-grained sediments are called debris flows. Flows laden with fine-grained sediments are called earth flows. Debris flows are typically fast moving and they tend to follow well established drainages. Earth flows often, but not always, move more slowly than debris flows. They generally form on sides of hills.

Soil Creep

Unlike slides and flows, soil creep, a shallow surface phenomenon, is a very slow moving and widespread type of slope

Fig. 26. A landslide in the Santa Cruz Mountains during the 1989 Loma Prieta earthquake (magnitude 6.9) buried part of and closed Highway 17, a major transportation artery between Santa Cruz and San Jose, California.

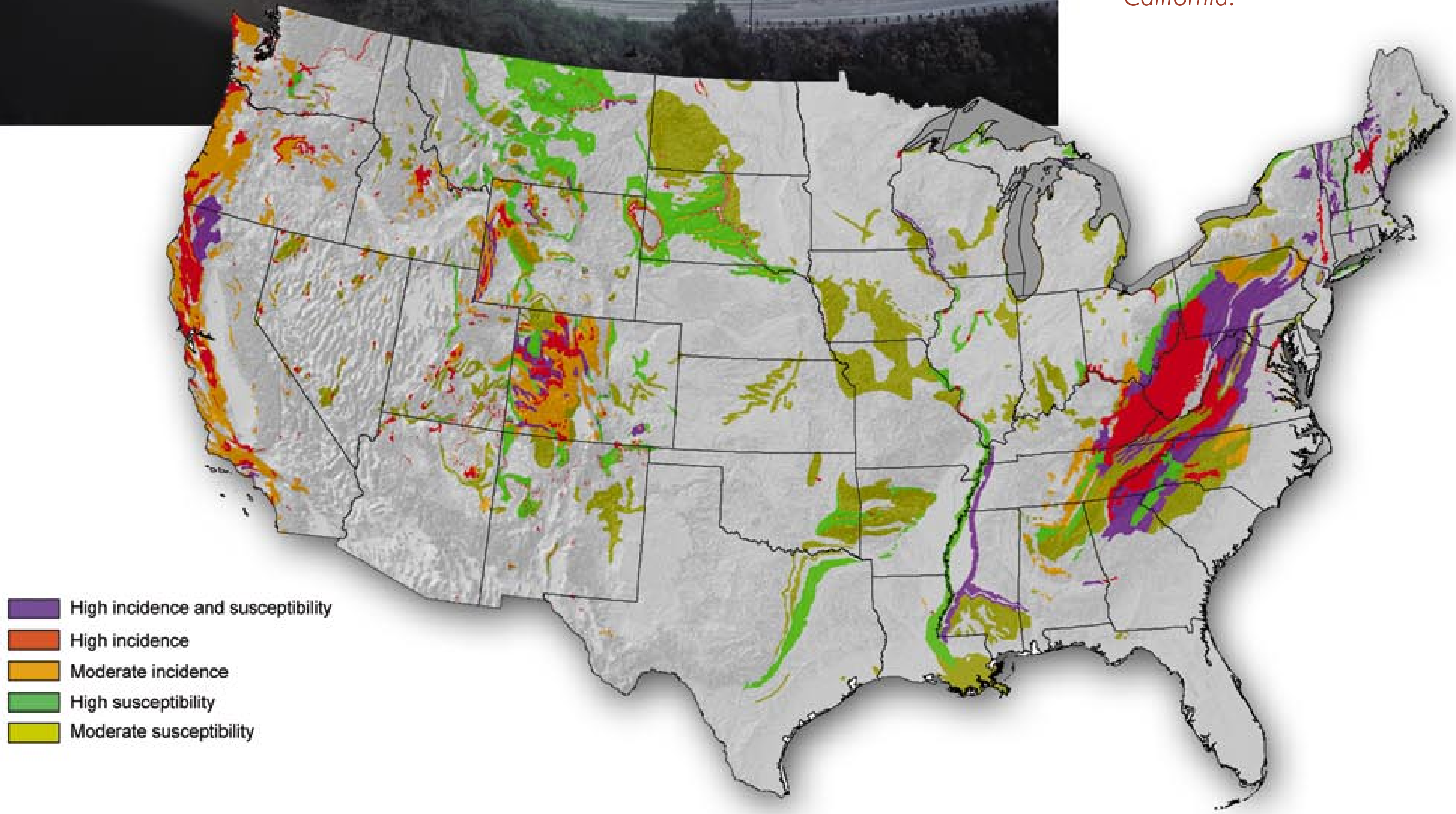


Fig. 27. The colors on this overview map of landslides in the conterminous United States denote differences in amount of area covered with landslides and landslide susceptibility.

movement. Measured surface rates of creep approximately range from 0.01 to 1.0 inch per year (0.025 to 2.50 centimeters per year). Creep usually is so slow that it can be recognized only from indirect evidence such as tilted fence posts and poles and bent trees. The tilting is caused by changes of the rate of creep with depth. Rates are highest near the ground surface and typically decline rapidly with depth. Rates tend to be higher on steep slopes. Soil creep is generally caused by cyclic displacements in which the slope expands perpendicular to the land surface and then contracts with a slight downhill component caused by the pull of gravity. Many processes — wetting and drying, freezing and thawing, and heating and cooling — can cause creep.

Earthquake Triggering

Strong shaking associated with earthquakes can also trigger slope displacements. In fact, seismically induced slope displacements are a significant hazard when mountainous and hilly terrains are shaken. The 1989 Loma Prieta earthquake (magnitude 6.9), which occurred in the Santa Cruz Mountains south of San Francisco, California, illustrates these hazards. More than 1360 landslides were observed within a 770 mi^2 (2000 km^2) area near the earthquake epicenter. The landslides damaged more than 200 houses and closed major highways (Fig. 26). Even areas that are not thought of as hilly may be susceptible if slopes are present. Extensive earthquake-induced landslides have been documented in the central United States in the area shaken by the 1811-1812 New Madrid sequence. From December 1811 to February 1812, three earthquakes in the Mississippi River valley with magnitudes greater than 7 strongly shook a broad region that included parts of Illinois, Indiana, Missouri, Arkansas, Kentucky, Tennessee, and Mississippi. The earthquakes caused hundreds of landslides in loess covered bluffs overlooking the Mississippi River valley. Most of these landslides still can be seen even today, and some continue to move.

Living with Slope Movement

A large portion of the United States is susceptible to damaging slope movement (Fig. 27). About half of the states suffer significant economic losses each year. Annual losses from slope movements amount to more than $3 billion (2007 dollars). Slope movements kill 25-50 people each year.

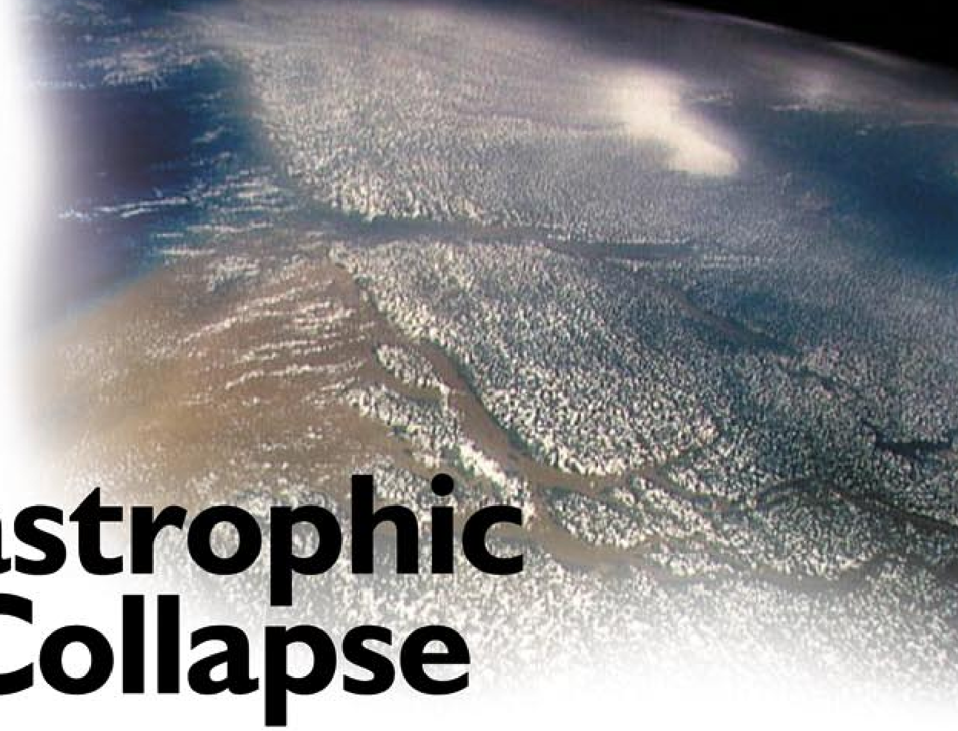
Preexisting and active forms of slope movement can be identified and mapped by geologists. Slope failures typically create distinctive irregular landscapes that include

- scarps, abrupt and continuous steps in the land surface,
- depressions, and
- hummocky topography, characterized by low ridges and closed depressions.

These features occur in areas where rock and soil types are too weak to support the natural slopes. By comparing locations of past failures with local geology and gradients of slopes, geologists can anticipate and map other potentially vulnerable areas (Fig. 28). These maps can be used to influence building on slopes by identifying hazardous areas. Fortunately, geotechnical engineers often can apply cost-effective techniques both to analyze and stabilize hill slopes where displacements are likely. Stabilization techniques include grading, dewatering, and reinforcing the soil or rock. Reinforcement may involve removing and rebuilding the slope. Flows, which typically endanger people living in valleys and at the base of slopes, can be directed away from buildings by placing long berms of soil and other diversion structures in their paths.

Fig. 28. Debris flows generally follow the drainage. The mapped area experienced debris flows and flooding during a large storm on June 27, 1995, in Madison County, Virginia. This debris-flow hazard map shows historical and potential debris flow and flood areas for that region.

Cajamar, Brazil



4 Catastrophic Collapse

Collapse of the ground into subsurface cavities or voids is a very widespread and potentially very damaging phenomenon because of the large depressions (sinkholes) created. Natural processes may produce these cavities or they may be the result of underground excavations, such as mining and tunneling.

Caverns

One of the most dramatic forms of land subsidence is collapse of the ground surface into natural underground caverns. These collapses are referred to as catastrophic subsidence because of the suddenness with which they sometimes form and the size and depth of the resulting closed depression or sinkhole (Fig. 29). Sinkholes more than 300 ft (100 m) across have been observed.

Fig. 29. This catastrophic collapse in Cajamar, Brazil, near Sao Paolo, on August 12, 1986, destroyed or damaged many houses. The collapse was caused by pumping groundwater from a shallow limestone aquifer.

Catastrophic subsidence occurs in areas that are underlain by rock that can be dissolved by groundwater. Soluble rocks include limestone, marble, salt, and gypsum. Limestone and marble (formerly limestone that has been changed by deep burial and heating in the Earth) are the most widespread soluble rocks. The solution process starts when rainfall flows through the soil and absorbs additional carbon dioxide and humic acid from decaying vegetation. These natural chemicals increase the acidity of the water and enable it to dissolve significant amounts of limestone (or marble) as it passes through cracks and pore spaces. The small cracks and pore spaces progressively enlarge and merge over time scales of tens and hundreds of thousands of years into a network of interconnected conduits and cavities.

In limestone areas, catastrophic subsidence is generally associated with caverns that predate human activity, because rates of solution of limestone are too slow to form caverns over human lifetimes. A few collapses, however, have been associated with human-induced

Fig. 30. Aerial view of sinkhole at Boling, Texas. Pumping of water from an oil well caused partial solution of salt in an underground salt dome and formation of a large underground cavity.

solution of salt beds (Fig. 30). Salt of course dissolves quickly and easily when in contact with water, and large voids can be created by human activity.

Naturally occurring sinkholes that collapsed long ago dot the landscape of many areas underlain by limestone. These landscapes, known as karst, are characterized by multiple large closed surface depressions and have a distinctive topography and hydrology. In addition to the sinkholes and caves, streams disappear abruptly underground into interconnected networks of caves and then reappear as springs. For more information see *Living with Karst*, No. 4, in this series.

Most modern occurrences of catastrophic subsidence in karst areas are triggered by human activity. The process of collapse usually involves downward displacement of soil into preexisting cavities (Fig. 31). Failure of rock around the cavity rarely contributes to collapse. Downward displacement of soil can be caused by both erosion of soil into an underground cavity and increasing the load on the soil above an underground cavity. Erosion and load increases can accompany a variety of activities including diversion of storm water into cavern systems, construction, use of explosives, impoundment of water in surface depression above cavities, and lowering of the water table.

More than 0.5 million mi^2 (1.4 million km^2) of land in 39 states are underlain by cavernous limestone and marble. More than 12,700 mi^2 (33,000 km^2) of this land are in urban areas. Of course, only a small portion of this land is actually underlain by voids and in danger of collapse. About 6,000 collapses have been documented in the eastern United States. The states with the largest number of active sinkholes include Alabama, Florida, Georgia, Indiana, Missouri, Pennsylvania, and Tennessee. A large portion of the United States is underlain by soluble rock and is potentially vulnerable to catastrophic subsidence (Fig. 32).

*Fig. 31. (**Before**) Sinkhole that formed on June 11, 2002, in Pine Hills, Central Florida, and created a 150-ft-wide and 60-ft-deep cavity. It forced evacuation of 100 occupants living in apartments in background. (**After**) Site was permanently stabilized with a 50-ft-deep wall consisting of 3-ft-diameter interlocking piles.*

Although geologists can map the distribution of soluble rock, predicting the location of underground cavities is more challenging. Detection of these cavities usually requires extensive drilling or geophysical exploration. Once detected, if the cavities are not too large, they may be filled with grout made of a cement or clay slurry. Stabilizing an active sinkhole may be a difficult task. Commonly practiced methods include filling the void or stabilizing the soil around a sinkhole. To permanently stabilize the collapse shown in Figure 31, 50-ft-long interlocking piles were driven into the ground to form an underground "wall" around the sinkhole.

Many collapses are caused by either lowering of the water table, which reduces support for the cavern ceiling, or by diverting of surface runoff into small preexisting voids, which cause them to erode and enlarge. Thus, stabilizing water tables and preventing surface runoff from entering the small preexisting voids often can deter collapse.

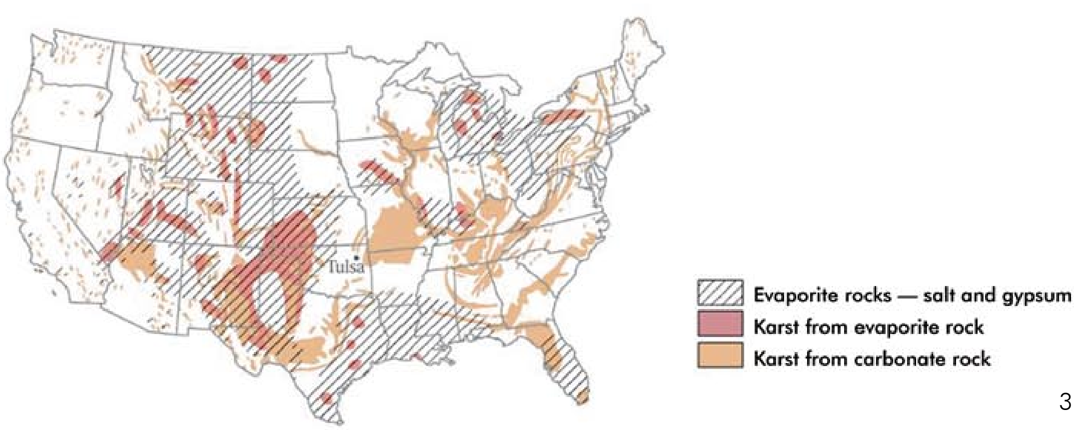


Fig. 32. The map shows areas in the United States underlain by soluble rock.

Underground Excavations — Mines and Tunnels

Many older underground mines and tunnels were excavated without concern for the future stability of the land (Fig. 33). Lowering of the land surface above mines is usually referred to as mining subsidence.

Mine workings are the most common type of subsurface excavation in the United States. Most mining subsidence in North America is associated with abandoned underground coal mines (Fig. 34). As coal was depleted and the mines became unprofitable, they were abandoned. Commonly, no maps of the underground mine workings were preserved. Thus, it is often difficult to determine if abandoned mine workings actually lie beneath a particular tract of land in a former mining region.

In these old underground mines, only part of the coal seam was removed. These areas of the mine are known as rooms. The subsidence is caused by the collapse of the rooms. Unmined portions, known as pillars, were left behind to provide support to keep the mines from collapsing on the miners. Subsidence occurs when the pillars, floors, or ceilings deteriorate and weaken and can no longer support the rooms. This unplanned collapse may take decades to happen so that the subsidence is greatly delayed. The nature of the subsidence depends on the size, depth, and extent of the rooms.

Subsidence is a planned consequence of the underground coal mining method known as longwall mining. By this method, the coal seam is removed along a single face known as the longwall and the roof above the mined-out seam is allowed to collapse as the longwall is laterally cut back by the miners. Subsidence is rapid above the collapsed seam, usually ending within months after removal of the coal and subsurface support.

Compared to coal mines, hazardous subsidence of abandoned tunnels and mining for metallic ores and limestone is generally less, although problems are severe in some areas. For example, hundreds of subsidence occurrences in Kansas, Missouri and Oklahoma have been associated with abandoned lead-zinc mines. One town in Kansas, Threce, has been so extensively undermined that its relocation has been considered. A few collapses of active salt mines in the United States have occurred as well (Fig. 35). These collapses are rare compared to those over coal mines, because salt mines are not nearly as abundant as coal mines. Collapses into active salt mines have been observed in Kansas, Louisiana, Michigan, and New York. These collapses typically are large.

Fig. 33. After this railroad tunnel was abandoned, the wooden timber supports decayed and the ground eventually collapsed (foreground) into the tunnel, Tiburon, California.

Surface effects from mining subsidence vary from gentle depressions that crack foundations to steep-walled pits and scarp-like faults that destroy structures. Gentle depressions also can affect drainage and reduce property values even in undeveloped areas. For example, property values in rural areas in Illinois affected by mining subsidence are discounted about 16 percent.

Approximately 3100 mi² (8,000 km²) of land in the United States is undermined of which 20 percent underlies urban areas. Most of these abandoned mines are in Pennsylvania, Illinois, and West Virginia, but an additional 19 states have experienced subsidence above abandoned mines.

Although it is costly, the most common technique used to prevent collapse of abandoned mines is to inject materials into the mine workings. In addition to the expense of injecting material, extensive exploration must be conducted to determine locations of the old mine workings.

Fig. 34. Aerial view of subsidence pits above an abandoned underground coal mine in the Powder River Basin of Colorado. Collapse is occurring above "rooms" in the mine where coal was removed. Areas that have not collapsed are above the pillars of coal the miners left to provide support. Note the dirt road for scale.

Fig. 35. This water-filled sinkhole has swallowed part of a forest. The sinkhole was caused by collapse of a room in the Retsof Salt Mine, New York, in 1994. The mine had been in operation for 100 years and the collapse occurred 1100 feet below ground surface.

Lin Pien, Taiwan

5 Regional Ground Movement

Both human activities and natural processes can induce deep-seated processes that lead to broad, regional movements of the land surface. For example, whenever groundwater or shallow petroleum is pumped from underground, the elevation of the overlying ground surface decreases. If the reservoir system is very compressible, the loss of elevation may be large. Geologists, who were the first scientists to study this phenomenon, refer to it as land subsidence. A few natural causes of unstable ground are rooted even more deeply in the Earth. The two most common processes in the United States are crustal movement during earthquakes and subsidence of river deltas.

Land Subsidence Caused by Withdrawal of Groundwater and Petroleum

The land surface subsides when consolidation of geologic sediment occurs in the underlying reservoir system. The consolidation results from a decrease in the pressure of water or oil contained in the pores of the reservoir sediment. When wells pump groundwater or oil, fluid pressure in the well decreases. Reducing the fluid pressure causes the effective stress in the sediment around the well to increase, consolidation to start, and the ground surface to subside. The physical process is similar to the sinking of buildings into soft soils except that the increase in effective stress is caused by decreasing the fluid pressure in the pores rather than by increasing the weight on the soil. Consolidation in groundwater aquifer systems occurs primarily in clay layers. This consolidation is not reversible. Reservoir sediment will not expand to its former volume even if water or oil pressure is restored. Thus, once land has subsided, it will not return to its original elevation even if pressure in the underground reservoir is restored. Permanent decreases of elevation greater than 33 ft (10 m) have been reported at some locations.

Flooding caused by loss of elevation is the most costly impact from land subsidence. Not surprisingly, flooding is most severe where land subsides adjacent to water bodies, particularly in coastal regions (Fig. 36). This situation causes permanent submergence unless

Fig. 36. As a result of pumping and withdrawal of groundwater, this cemetery in Lin Pien, Taiwan, subsided and flooded. Note the dike to protect the area from the ocean that can be seen in the background.

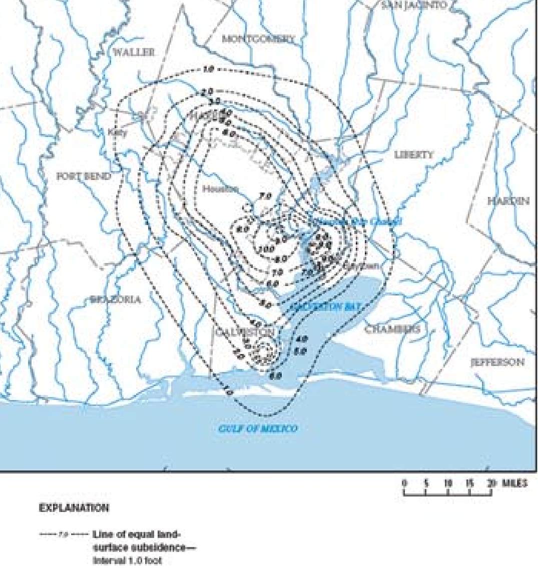


Fig. 37. Subsidence bowl caused by withdrawal of groundwater in the Houston, Texas, metropolitan area from 1906 to 1995. The subsidence of the shoreline along Galveston Bay has caused permanent flooding of the land.

the area is protected by dikes. In addition, because these regions are commonly subject to tidal and storm surges, loss of land-surface elevation of adjacent low-lying coastal land increases the frequency and severity of intermittent flooding.

A subsidence area is commonly referred to as a subsidence bowl because loss of elevation usually is greatest near the center and decreases outward (Fig. 37). Despite the irregularity of land subsidence, the resulting tilts of the ground surface are generally too small to be of practical importance. Changes in tilts, however, may be significant to aqueducts, which are designed with gentle slopes to cause the water that they convey to flow. Tilts associated with land subsidence in the San Joaquin Valley of central California caused costly design modifications and required rehabilitation of the California Aqueduct, the heart of California's water delivery system.

Land subsidence in some places is accompanied by ground failure. Displacements associated with these failures can be very damaging to structures. Earth fissures, which are large tension cracks, are common in subsidence bowls in desert areas of the southwestern United States where groundwater is pumped from sedimentary basins (Fig. 38). The number of earth fissures in the arid southwest has increased as communities have increased their demand for groundwater in response to growing populations.

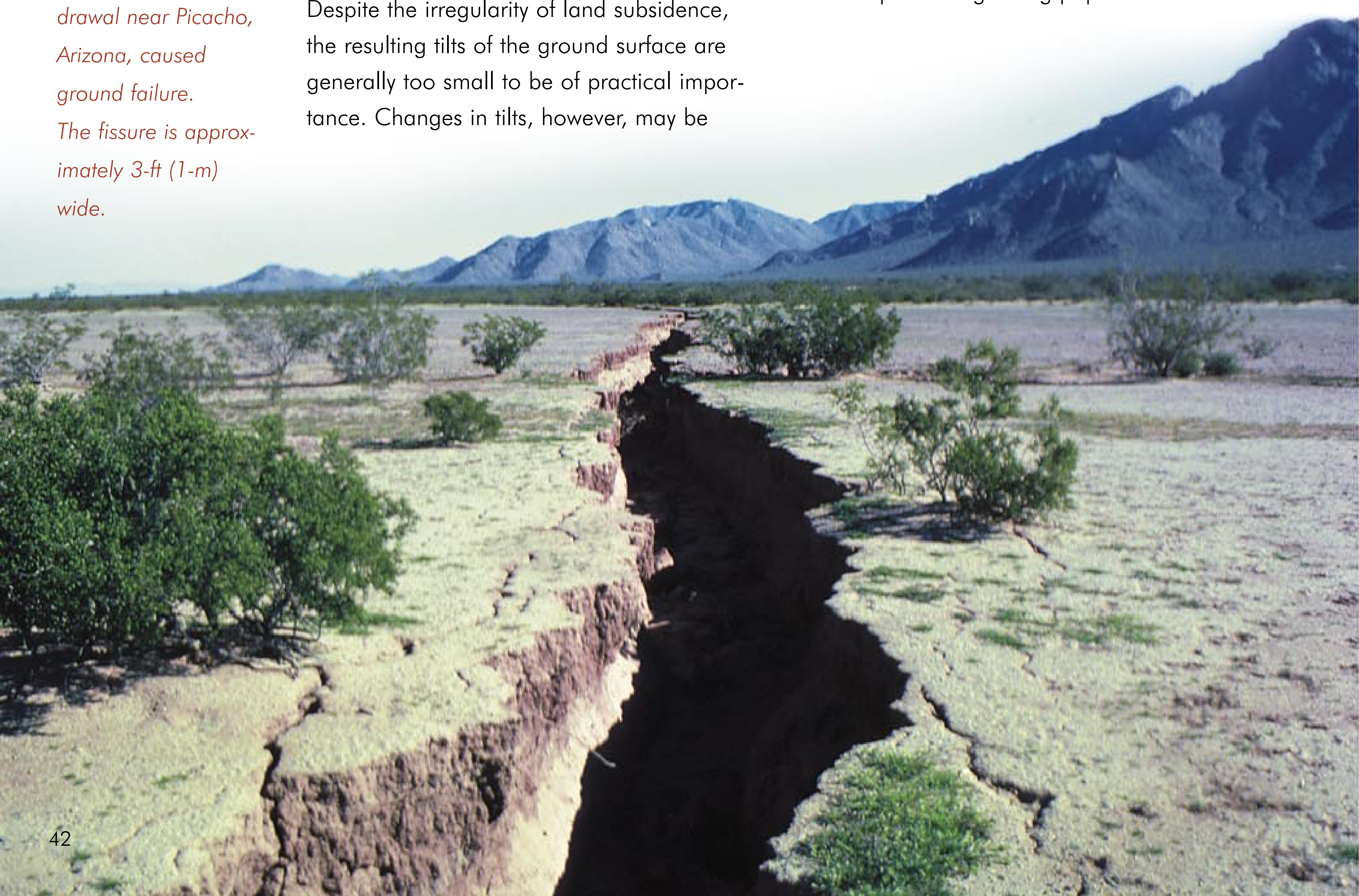


Fig. 38. Subsidence associated with groundwater withdrawal near Picacho, Arizona, caused ground failure. The fissure is approximately 3-ft (1-m) wide.

Fig. 39. Surface faulting caused by groundwater pumping damaged and deformed (note eaves) this house in Baytown, Texas, near Houston. The yard was formerly flat and even; the gentle ground flexure is the fault scarp.

Earth fissures form where there are abrupt lateral changes in the amount of subsidence. These changes cause the ground surface to bend, pull apart, and fail in tension. Surface faulting, which creates steps or gentle flexures in the landscape, is observed in several subsidence areas in the United States as well as at many locations internationally. These surface faults form slowly without earthquakes (Fig. 39). They occur on preexisting geologic faults that have been reactivated by pumping groundwater. In the United States, surface faults impact the greater Houston area of southeast Texas more than any other region. More than 86 active surface faults with a collective length of 150 mi (240 km) have been identified there. In fact, more faults are actively offsetting the land surface in the greater Houston area than in all of the earthquake-prone part of California. This ongoing fault offset is known as fault creep.

In the conterminous United States, withdrawal of underground fluids has permanently lowered the elevation of approximately 10,000 mi^2 (26,000 km^2) of land (Fig. 40). This total is about equal to the area of the state of Massachusetts. Withdrawal of groundwater has caused most of the subsidence, which is concentrated in the San Joaquin Valley and the greater Houston area. The largest subsidence area is in the San Joaquin Valley. Nearly half of the valley — more than 5,020 mi^2 (13,000 km^2) — has subsided at least 1 ft (0.3 m). However, at least 45 areas in 12 states in the United States have experienced land subsidence. These areas are principally in the southwestern United States, particularly in sedimentary basins in Arizona and California.

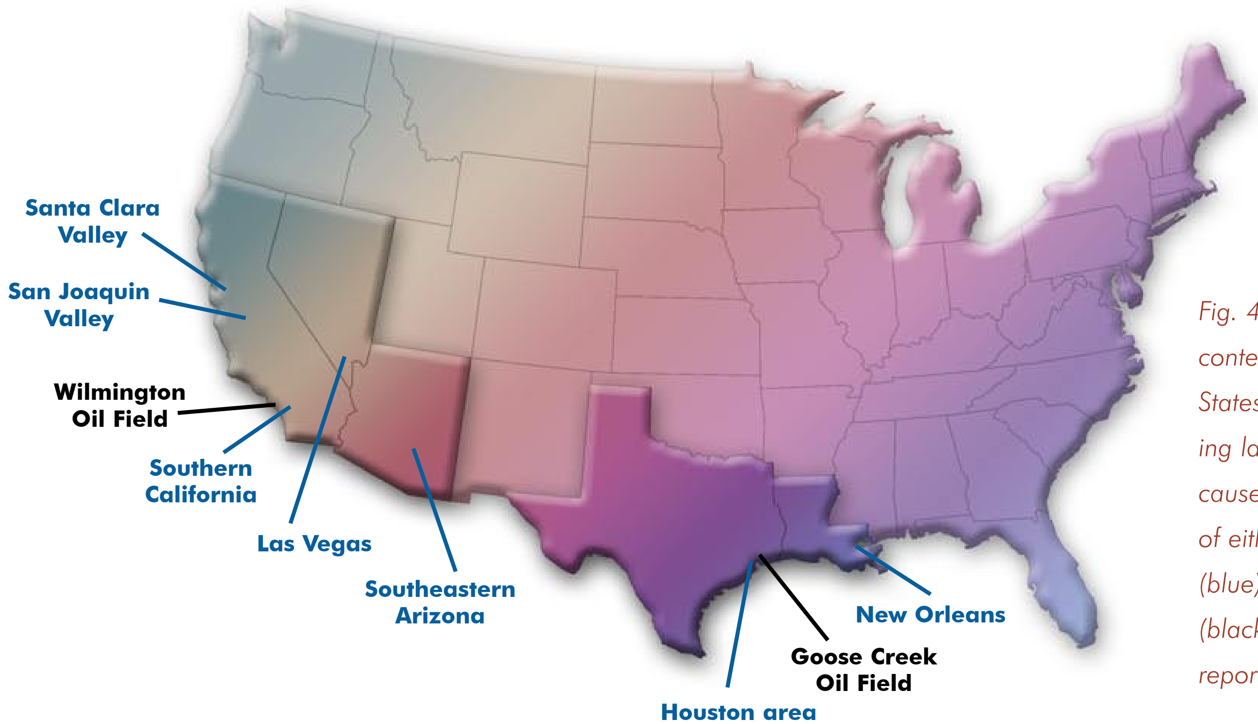


Fig. 40. Areas in the conterminous United States where damaging land subsidence caused by withdrawal of either groundwater (blue) or petroleum (black) has been reported.

San Francisco-Oakland Bay Bridge 1989, after the Loma Prieta Earthquake.

Coastal examples of subsidence occur in California in Long Beach and in the Santa Clara Valley as well as in the greater Houston, Texas, metropolitan region. In Long Beach, which is next to the Pacific Ocean, oil and gas production from the Wilmington Oil Field caused more than 19 mi^2 (50 km^2) of land to subside. Maximum subsidence was 29 ft (8.8 m). Subsidence affected approximately 40 mi (64 km) of waterfront and endangered port and U.S. Navy facilities. If pressure had not been added to the oil reservoirs through a concerted and coordinated effort by oil field operators, approximately 5 mi^2 (13 km^2) of urban real estate would have been inundated. In the Santa Clara Valley, approximately 17 mi^2 (44 km^2) of coastal land was lowered and would have been inundated by San Francisco Bay if levees had not been constructed to protect the land. In the greater Houston metropolitan region, more than 31 mi^2 (80 km^2) of low-lying coastal land next to Galveston Bay has been permanently inundated. This flooding has forced people to abandon houses.

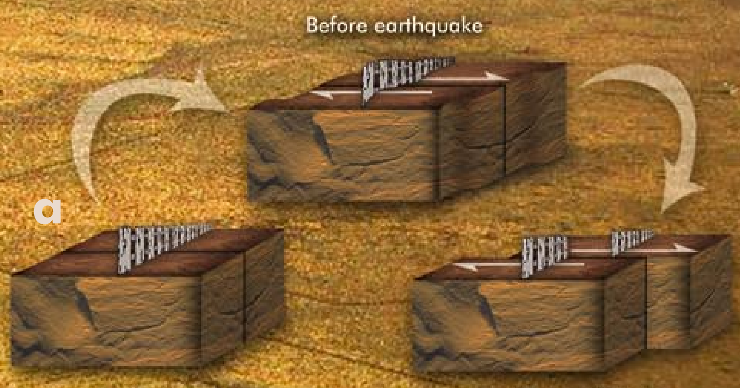
Aquifer systems that are susceptible to large amounts of consolidation in general consist of sediments that were deposited in the last 5 million years. Older deposits tend to be more cemented and not very compressible. Even if geologists anticipate where subsidence may occur if underground fluids are withdrawn, preventing or controlling subsidence is difficult and costly. State laws usually allow resource extraction without regard for adverse consequences such as land subsidence. Thus, mitigation usually requires either modification of state law or voluntary agreement by pumpers to change their fluid production procedures.

Crustal Movement During Earthquakes

During an earthquake along a preexisting fault, violent shaking accompanies the sliding or rupture that occurs when the fault moves. The fault movement or rupture is triggered by release of elastic strain that is stored in the rock comprising the Earth's crust near the fault. Few people are aware of the permanent regional displacement of the ground surface that also occurs when the elastic strain is released. Geologists call this regional displacement crustal movement. One of the important outcomes of the investigation of the 1906 San Francisco earthquake (magnitude 7.8) — the most devastating earthquake to the built environment in U.S. history — was the discovery that the release of elastic energy stored in rocks along a fault causes earthquakes. When Professor Harry F. Reid of John Hopkins University compared positions of benchmarks before and after the earthquake, he recognized that the benchmarks had moved systematically relative to their distance from the San Andreas Fault, which produced the great earthquake. He proposed that elastic strain had slowly built up in the Earth before the earthquake, and eventually the strength of the San Andreas Fault was exceeded. At this stage, the rocks snapped back along the fault to where they would have been if the fault had allowed the adjacent blocks of rock to move freely (Fig. 41). During great earthquakes, faults may rupture to depths of many miles and lengths of hundreds of miles. When this happens, a large volume of rock releases elastic energy. Thus, the ground surface within a large area near the fault, not just at the fault, permanently moves.

Crustal Movement during Earthquakes

San Andreas Fault




b

San Francisco Earthquake
1906

Fig. 41. San Andreas Fault in the Carrizo Plain of central California. The striking surface expression of the fault is caused by repeated offsets during large earthquakes, the most recent of which occurred in 1857. The 1906 San Francisco earthquake (magnitude 7.8) ruptured a part of the San Andreas Fault to the north of the Carrizo Plain and was the largest event to occur in the conterminous United States in the 20th Century. The 1906 earthquake produced a maximum offset along the fault plane of 20 feet.

a. *Diagram of a hypothetical long fence built at the beginning of an earthquake cycle on a fault like the San Andreas Fault. Initially the fence built immediately after a large earthquake is perfectly straight. As elastic strain begins to accumulate, the fence slowly deforms into an S shape. Finally, when the strength of the fault is exceeded, it ruptures and releases the stored elastic strain. This rupture simultaneously produces a large earthquake and slip on the fault. The fence is straight once more, but part of it was displaced and offset when the fault block moved. The earthquake cycle now repeats.*

b. *Fence offset by fault rupture along the San Andreas Fault in San Bruno, California, during the 1906 San Francisco Earthquake (magnitude 7.8). Upper part of hill has moved to the right relative to the bottom.*

Fig. 42. Tectonic subsidence in the 1999 Kocaeli, Turkey, earthquake. The waterfront of the community of Golcuk on the south shore of the Sea of Marmara, subsided beneath the sea.

Since 1906, crustal movement has been documented around the world during numerous earthquakes. In general, the bigger the earthquake, the larger the surface displacements and the region affected. Although these regional displacements do not damage buildings and other structures because they are fairly uniform, they become important where they are vertical and displace shorelines of water bodies. Submergence of coastal communities can be devastating (Fig. 42).

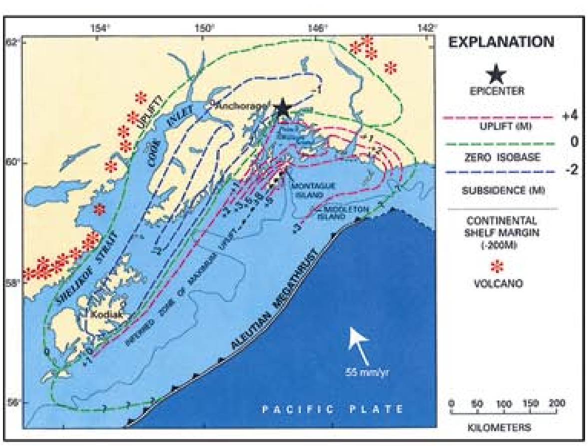


Fig. 43. As a result of vertical crustal movement in coastal Alaska associated with the March 27, 1964, Good Friday earthquake (magnitude 9.2), approximately 110,000 mi^2 (285,000 km^2) of land changed elevation.

The earliest description of vertical crustal movement in the United States during an earthquake comes from the three strong earthquakes that rocked the central United States and Mississippi River Valley during the winter of 1811-1812. The New Madrid earthquake sequence did more than trigger landslides, as discussed on p. 33. Boatmen on the Mississippi River reported that the direction of flow of the river reversed during one of the earthquakes. Geologists believe that this reversal was caused by slip along an active thrust fault that crosses the river at a nearly right angle. During the earthquake on this fault, the block of rock south of the thrust fault moved northward and up and over the northern block. This caused the southward-flowing river to temporarily reverse its course.

A well documented example of crustal movement occurred during the March 27, 1964, Good Friday earthquake (magnitude 9.2) in southern Alaska. The earthquake ruptured a segment of the boundary between the Pacific and North American tectonic plates where they collide.

The Pacific Plate plunges along a gigantic thrust fault beneath the North American Plate on which Alaska sits. The release of elastic energy during the 1964 earthquake caused an average uplift of 6 ft (1.8 m) along the coast of the Gulf of Alaska. The maximum observed uplift was 38 ft (11.6 m) in a 10-mi (16-km) wide belt on Montague Island. Approximately 110,000 mi^2 (285,000 km^2) of land and sea bottom either uplifted or subsided (Fig. 43).

Coastal Oregon and Washington sit above a giant thrust fault much like the one in Alaska. Some geologists believe the Pacific Northwest may be vulnerable to an earthquake similar in size to the 1964 Good Friday earthquake. Such an event might cause regional movements like those observed in 1964. Geologists believe that the last large earthquake on this fault was on January 26, 1700. In fact, part of the evidence for the event is ground displacement that created a ghost red cedar forest along the tidal reach of the Copalis River north of Gray's Harbor, Washington (Fig. 44). The trees died when crustal displacement associated with the 1700 earthquake caused coastal land to subside. Tidal salt water from the ocean then submerged the roots of trees, killing the forest.

The potential dangers of crustal movement have not been widely recognized, because major earthquakes usually have recurrence intervals or repeat times measured in centuries and it is only a significant problem in coastal areas. Scientists only recently have begun to develop the capability to anticipate these displacements and predict their frequency. Although approaches and public policies to reduce the impact of this type of ground instability are being developed, they have not been tested.

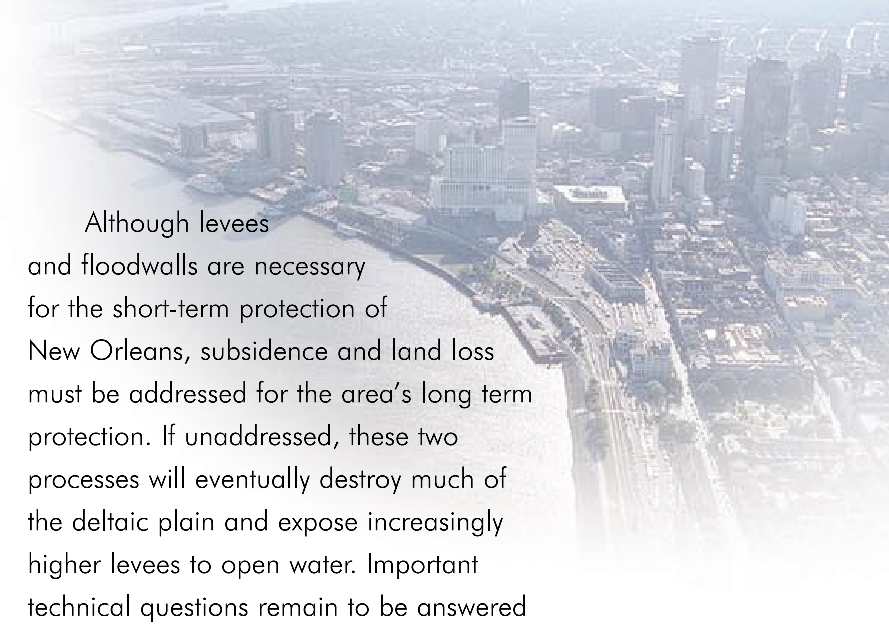
Fig. 44. During a great earthquake along the Washington state coast on January 26, 1700, subsidence enabled tidal salty water to enter this red cedar forest and kill the trees, creating a ghost forest along the Copalis River, north of Gray's Harbor, Washington.

Fig. 45. The Mississippi River Deltaic Plain in southern Louisiana rests on multiple lobes of sediment where the river formerly flowed into the Gulf of Mexico and deposited its bed load. Lobe 6, Mississippi "Bird Foot" Delta, is currently actively receiving sediment. The plain is sinking about 0.6 in/yr (1.5 cm/yr) relative to sea level. (Reprinted with permission from AAAS, please see credits p. 63).

Subsidence of the Mississippi River Delta

In addition to flooding, the geological activities of rivers, such as erosion and sediment deposition, affect society. These processes are particularly important where large rivers flow into the ocean and form deltas and deltaic plains. Under natural conditions, river velocity decreases at the mouth of a river, and the capability of the river to transport sediment decreases. This causes a lobe-shaped area of sediment to be deposited at the mouth of the river. As the lobe of sediment grows, it chokes off the river. Eventually the river jumps its banks during flood stage, finds a shorter path to the ocean, and begins creating a new lobe. Consequently, river deltas typically consist of merging lobes of sediment. Each lobe records the age and former location of the mouth of the river. Figure 45 illustrates this recurring process, and shows the lobes that underlie the 9,650 mi^2 (25,000 km^2) Mississippi Deltaic Plain in southern Louisiana. Geologists have identified six major lobes that record former positions during the last 6000 years of the mouth of the Mississippi River.

The location of parts of these lobes in open water of the Gulf of Mexico suggests that another and somewhat ominous process is occurring. The surface of the Mississippi Deltaic Plain is subsiding. In fact, studies indicate that it is subsiding at about 0.6 in/yr (1.5 cm/yr) relative to sea level. An important effect of this subsidence is a phenomenon known as land loss. As a result of subsidence, wetlands in the deltaic plain are converting into open water (Fig. 46). Since 1900, 1,890 mi^2 (4900 km^2) of wetlands in southern Louisiana have been lost. Currently, approximately 10 mi^2 (26 km^2) disappears every year, about one acre every 82 minutes. At its peak from 1955 to 1978, the rate of land loss averaged 42.9 mi^2/yr (111 km^2/yr), about one acre every 19 minutes.



Although the details of land loss remain a subject of active debate among scientists, most agree that natural subsidence and confinement of the Mississippi River between levees are the major contributors. Before humans occupied and modified the landscape of southern Louisiana, sediment from the Mississippi River washed into the wetlands and locally compensated for the subsidence. Sediments were transported into the wetlands by both the River flooding and storm surges caused by hurricanes. With the construction of levees along the Mississippi, this sediment was unable to find a pathway into the wetlands. Sediment now disappears directly into the deeper waters of the Gulf of Mexico. River sediments are no longer transported into and deposited in the wetlands during river floods. Beaches, which are the source of sediment carried into wetlands by storm surges, also are no longer replenished. Upstream dams trap significant amounts of sediment in their reservoirs and further compound the sediment supply problem.

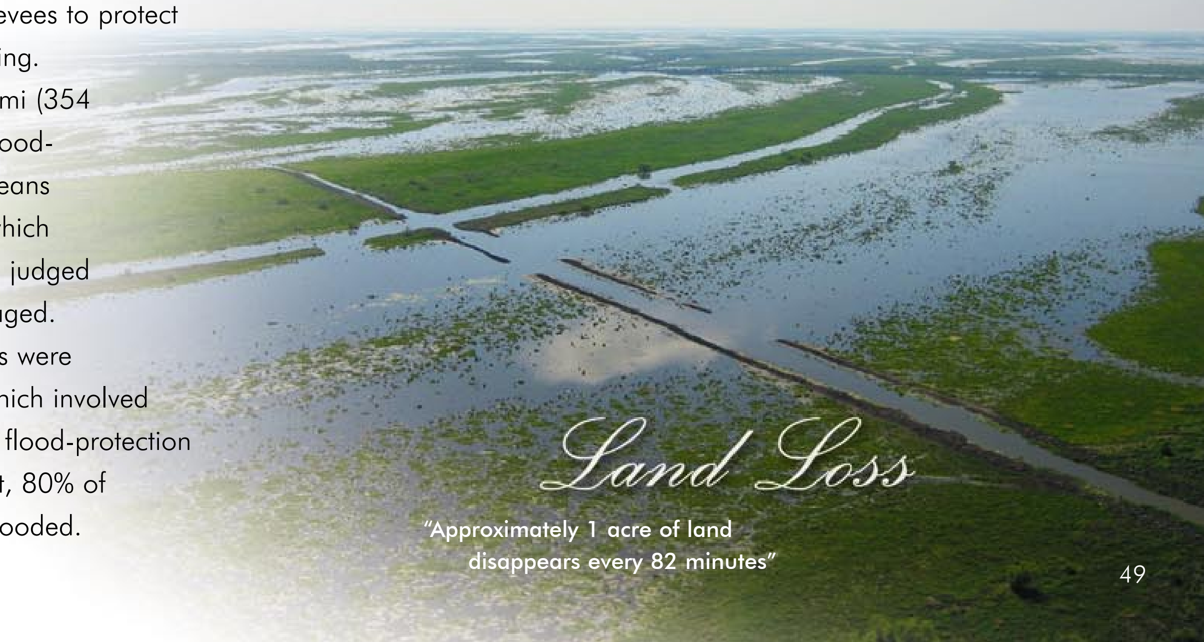
On August 29, 2005, Hurricane Katrina devastated New Orleans and adjacent parts of the Gulf Coast. The devastation focused the Nation's attention on the capacity of levees to protect the area from flooding. Approximately 220 mi (354 km) of levees and floodwalls near New Orleans were damaged of which 41 mi (66 km) were judged to be severely damaged. Initially, 50 breaches were identified, four of which involved actual failure of the flood-protection structure. As a result, 80% of New Orleans was flooded.

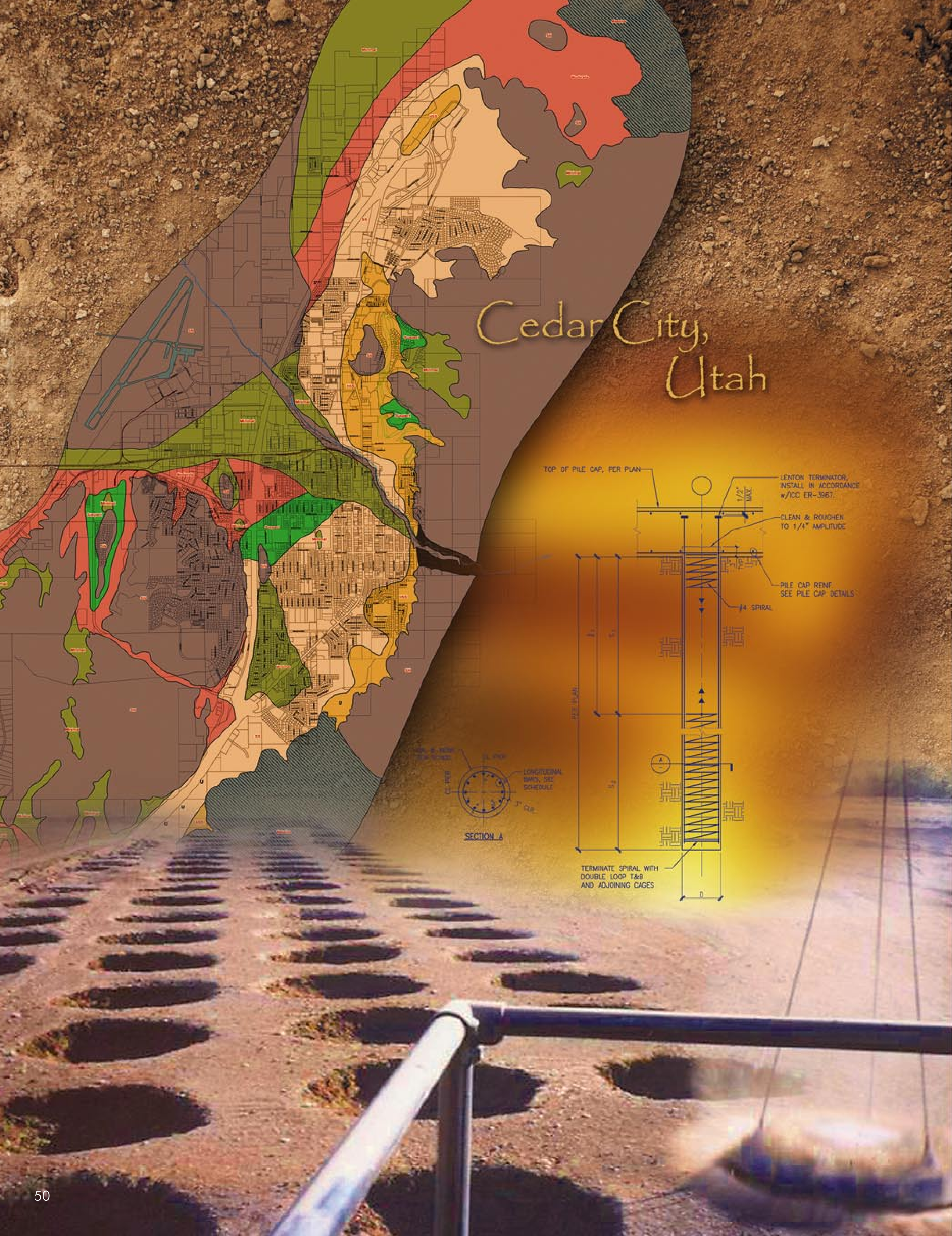
Although levees and floodwalls are necessary for the short-term protection of New Orleans, subsidence and land loss must be addressed for the area's long term protection. If unaddressed, these two processes will eventually destroy much of the deltaic plain and expose increasingly higher levees to open water. Important technical questions remain to be answered by scientists and engineers.

- Can the Mississippi River be managed to increase deposition of sediment in the wetlands?
- How much subsidence is natural and how much is caused by oil and gas production?
- And what is the impact on the viability of wetlands from canals that were dug through them for boat traffic and petroleum exploration?

The future of New Orleans and the Mississippi Deltaic Plain depends on developing a clear understanding of these processes and implementing sound public policies to accommodate them.

Fig. 46. Because the Mississippi River is confined between flood-control levees, sediment from the river no longer compensates for subsidence of its delta. Consequently, marshes subside below water level and convert to open water. Canals have also destroyed the marshes by permitting salt water to enter into and kill off the freshwater marsh vegetation.




Cedar City,
Utah
TOP OF PILE CAP, PER PLAN
LENTON TERMINATOR, INSTALL IN ACCORDANCE w/ICC ER-3967.
CLEAN & ROUGHEN TO 1/4" AMPLITUDE
PILE CAP REINF. SEE PILE CAP DETAILS
#4 SPIRAL
SECTION A
TERMINATE SPIRAL WITH DOUBLE LOOP T&B AND ADJOINING CAGES
D

6 Guidelines for Living with Unstable Ground

Mitigation is the practice of taking action before a hazard occurs to reduce its economic and physical impact. Many approaches to mitigate unstable ground already are in use in the United States. Selecting which approach to apply depends on both the type and severity of unstable ground. The political attitudes of citizens also determine the appropriate approach. What may be acceptable in one region may be unacceptable in another. For example, some communities may be more willing than others to accept government controls of land and building practice. In the simplest form of mitigation, property owners are left to their own devises to voluntarily take advantage of available engineering and construction techniques to reduce the consequences of building on unstable ground. This voluntary approach still requires both building public understanding about the hazard and the availability of cost-effective techniques to deal with it. If concerns about general public safety and welfare warrant, government may intervene and require landowners to implement certain practices to mitigate potential consequences. If the hazard is insurable, either voluntary or mandatory insurance can be offered. Geologists play a fundamental role in each of these approaches by providing information about the hazard.

Fig. 47. As this map of collapsible soil in Cedar City, Utah illustrates, areas of unstable ground can be mapped to alert prospective property buyers and developers to potential hazards. Once a hazard is identified, geologists and engineers use a variety of techniques to mitigate the problem. The engineering drawing is a design for a drilled pile. Piles are often used to support structures built on soft or weak soils. The photo at the bottom shows a way to compact low-density soil, such as a collapsible soil or liquefiable sand, by dropping a heavy weight on the surface.

Geologic Mapping and Engineering Design

Providing citizens, builders, and land developers with information about local hazards can be an important step toward mitigating them. Increasing understanding of the consequences of construction on unstable ground and mapping potentially hazardous locations encourages voluntary actions to mitigate the effects of unstable ground (Fig. 47). State and federal geological surveys and local agencies frequently produce educational products about natural and human-made hazards. Examples include regional maps of areas with problem soils, underground mines, sinkholes, and landslides. Hazard maps can promote the application of cost-effective techniques by engineering geologists to identify hazardous sites and by civil engineers to mitigate site-specific problems.

(Continued on page 54)

Construction Codes and Land-use Management

"Zoning is most effective in regions where risk is high."

Fig. 48. These homes in coastal Louisiana were elevated to reduce flood damage. Building codes and land-use regulations can require that owners of property build new structures at a specified elevation to avoid flood damage.

The impact of many types of unstable ground can be reduced through construction codes and land-use regulations. Codes and regulations mandate attention by builders and property owners. These approaches have been used extensively in the United States, and they have been well tested by litigation in the judicial system. Codes and regulations, however, must be enforced for this approach to be successful.

Construction codes, known popularly as building codes, are implemented and enforced in many communities to protect public safety and welfare. If a particular unstable ground hazard is known to exist within an area, codes can be modified to require contractors and builders to consider it. Grading ordinances, which are found in some building codes, for building on slopes illustrate this approach. Such ordinances originated in the United States after development on slopes in Los Angeles, California, became common, and builders were extensively grading and modifying hill slopes. After many costly slope failures, local building officials, engineers, and engineering geologists drafted a chapter for the building code that stipulated standards for modifying hill slopes. Enforcement of these standards through the code significantly reduced the frequency of slope failure. Application of codes to address seasonally frozen ground in parts of the United States is another example. By requiring foundations and pipes to be buried below frost level, damage from frozen ground is reduced. Figure 48 illustrates a straightforward construction technique, elevation of a structure, to reduce flood damage in areas where land has subsided. Construction of new structures above predicted flood-level elevations can be required by codes.

Land-use management through zoning by local government has long been used in many parts of the United States. Like construction codes, zoning is justified based on public safety and welfare. Although zoning can be an appropriate tool to deal with some hazards, the hazards posed by unstable ground are so variable that no general zoning approach is applicable. Zoning works best where the real and potential costs of unstable ground are sufficiently great to offset the impacts of controlling the use of property. In other words, zoning is most effective in regions where risk is high.

Figure 49 is an example of a regulatory hazard zone map. It was issued by the California Geological Survey to identify the parts of cities of Oakland, Berkeley, and Alameda that have a potential liquefaction hazard. Once a regulatory liquefaction hazard zone map is completed for a community in California, a state law mandates that the community use the building permit process to require land developers in these zones to conduct soil tests before they build. If the on-site soil testing by a licensed engineering geologist or geotechnical engineer confirms the existence of a serious liquefaction hazard, the community is required by law to insist that it be mitigated.

Fig. 49. Construction at a site in the liquefaction special studies zone (green areas) requires drilling to determine if a liquefaction hazard is present and if the hazard must be mitigated.

The legislative and scientific histories behind this map illustrate how regulatory hazard zoning often evolves. During the 1989 Loma Prieta earthquake, many property owners along the margins of San Francisco Bay were surprised by costly and damaging liquefaction. To reduce future surprises, the California state legislature enacted legislation that directed the California Geological Survey to delineate those parts of urban areas in the state that have soils with liquefaction potential. This delineation was feasible because engineering geologists had conducted research that demonstrated the practicality of liquefaction hazard mapping and engineers had developed cost-effective techniques to reduce the impact of liquefaction on structures. Hazard zoning is practical when the cost of site exploration is modest, mitigation is feasible, and the consequences of not addressing the hazard are significant.

When large areas are confronted with a common hazard that cannot be addressed cost effectively by individuals acting independently, allowing groups of property owners to form hazard districts is an alternative to regulatory zoning. This approach is viable for hazards like large active landslides. Once a district is established by vote, the costs of mitigation are paid for by the affected group through special taxation.

Engineering techniques to reduce the impact of unstable ground are specific to the type of hazard, and have been described in previous chapters. Many of these techniques are routinely applied in areas of the United States where problem soils, slope movements, and catastrophic collapse cause significant problems. Local building departments and professional associations of engineers and builders commonly provide engineers, builders, and contractors with information and instruction about how to apply these techniques.

Regulation of Resource Development

For types of unstable ground that are associated with resource development, such as mining and underground fluid withdrawal, government may find it prudent to exercise its power either to prohibit resource development or to control it in ways that minimize damage. This approach usually requires legislative findings that the benefits of unregulated resource development are outweighed by the harm it causes. The 1954 California Subsidence Act is an example of this approach. This legislation was passed in response to coastal land subsidence caused by pumping from the Wilmington Oil Field in Long Beach (Fig. 50). The Act empowers the State Division of Oil and Gas to require that the multiple independent oil field operators collaborate to maintain fluid pressures in reservoirs in an oil field at a level that will minimize destructive land subsidence.

Another approach is through environmental regulations. For example, if environmental impact assessments are required before resource development starts, consideration of consequences can often be required through this process.

Wilmington Oil Field, Subsidence (ft.) 1926-67

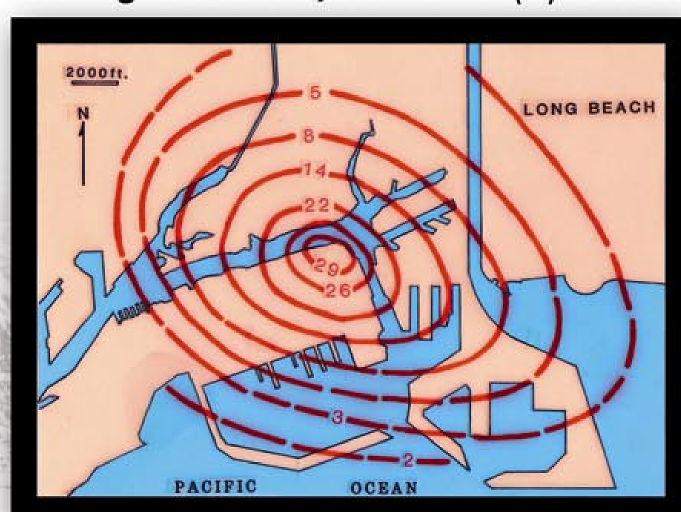


Fig. 50. Subsidence of coastal lands as a result of pumping from the Wilmington Oil Field in Long Beach prompted passage of the 1954 California Subsidence Act.

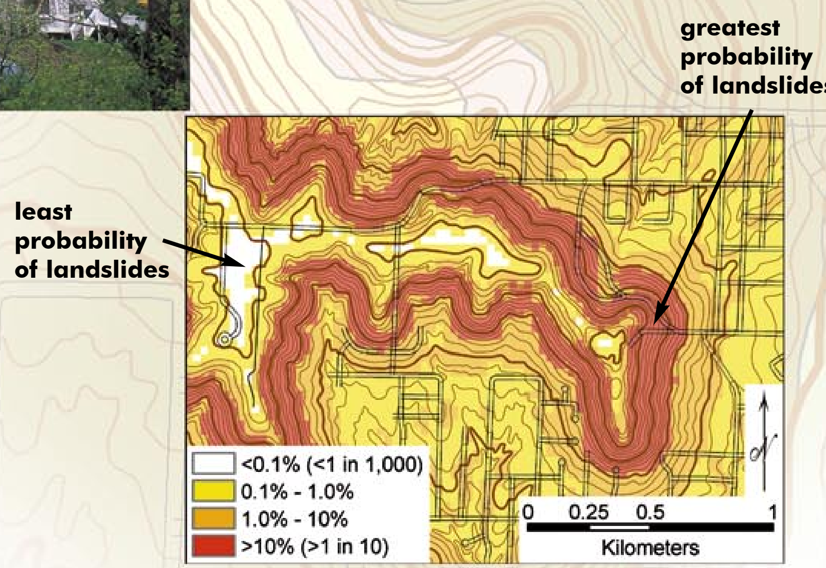
Government Corrections to Market Distortions

In the United States, government has intervened in a few cases where the costs of unstable ground are not borne by the party that causes the damage, but are borne by the impacted party. Economists call these external costs. When government intervenes to make the party that causes damage pay, it is known as internalizing the cost or correcting a market distortion. In other words, a market distortion occurs when parties engage in an economically beneficial practice that does harm to other parties, but only the harmed parties bear the cost of the damage. Under the Surface Mining Control and Reclamation Act of 1977, coal mine operators are required to reimburse surface owners for damage in some cases. Costs of damage are internalized through litigation by parties suffering damage and by payments negotiated by mining companies facing possible litigation.

The tax on groundwater imposed by the Santa Clara Valley Water District in northern California is another example of a government correction. Land subsidence is one consequence of pumping groundwater in the valley, but its impact is principally felt by property owners along the shoreline of San Francisco Bay who do not pump groundwater. The tax eliminates the cost advantage of groundwater over surface water and thereby reduces the incentive to pump groundwater.

Insurance

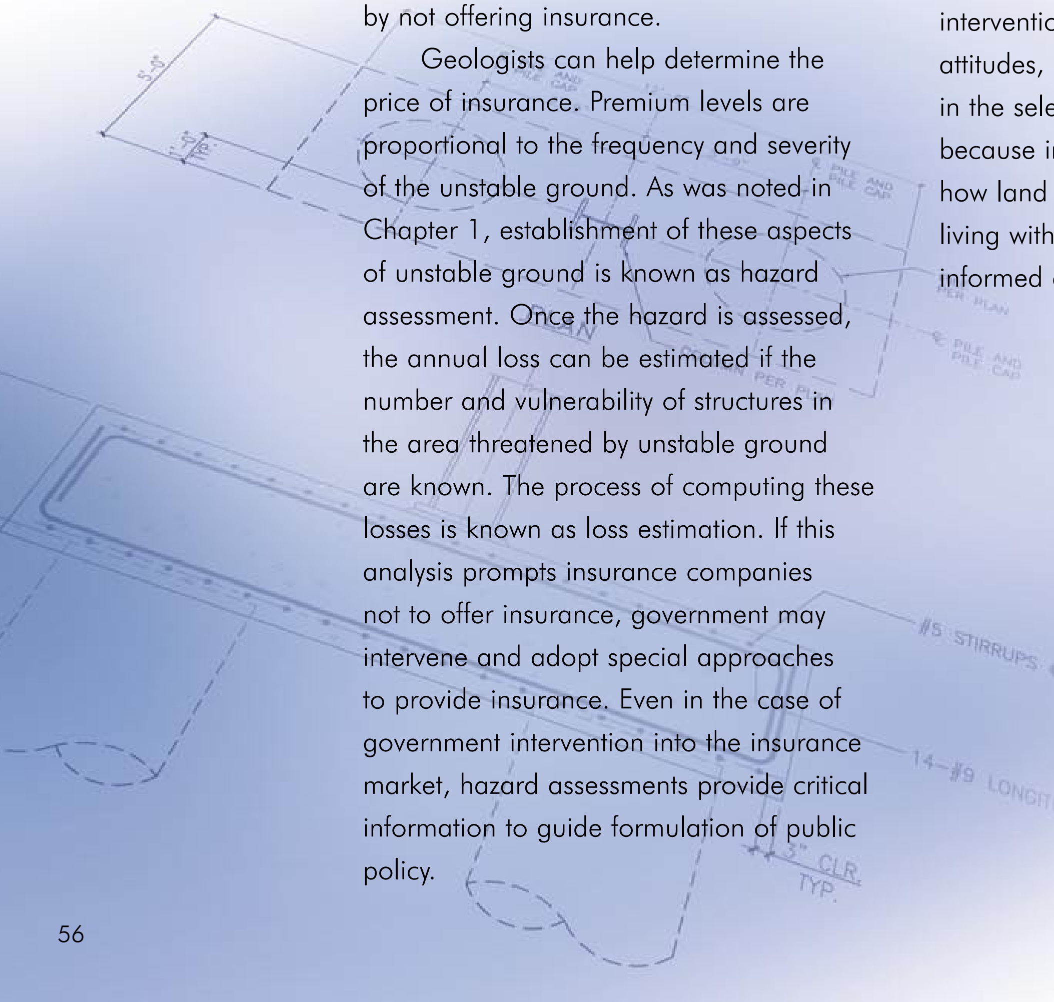
Insurance can be used to mitigate the consequences of unstable ground when the following criteria are met. First, a sufficiently



Insurance companies, local government officials, planners, developers, engineers, lending institutions, and landowners can use hazard maps based on geologic maps to assess risk and take appropriate actions.

large group is exposed to the hazard so that the average annual loss can be predicted. Second, which property owners and when they will be affected is not predictable. If only a few property owners are vulnerable to a particular hazard, and they know who they are, the hazard is not insurable because only owners who expect to have a loss have an incentive to purchase insurance. This situation is known as adverse selection. And third, the hazard to each property does not happen all at one time. Occurrence of a hazard can cause catastrophic loss for insurance companies. Although insurers have approaches for dealing with catastrophic loss, such as distributing their portfolio of insured properties over broad regions or purchasing insurance for catastrophic loss from reinsurance companies, insurers commonly prefer to reduce their exposure to catastrophic loss by not offering insurance.

Geologists can help determine the price of insurance. Premium levels are proportional to the frequency and severity of the unstable ground. As was noted in Chapter 1, establishment of these aspects of unstable ground is known as hazard assessment. Once the hazard is assessed, the annual loss can be estimated if the number and vulnerability of structures in the area threatened by unstable ground are known. The process of computing these losses is known as loss estimation. If this analysis prompts insurance companies not to offer insurance, government may intervene and adopt special approaches to provide insurance. Even in the case of government intervention into the insurance market, hazard assessments provide critical information to guide formulation of public policy.

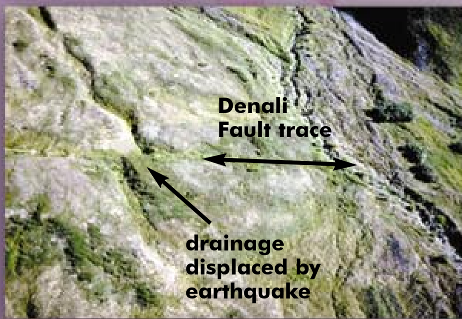


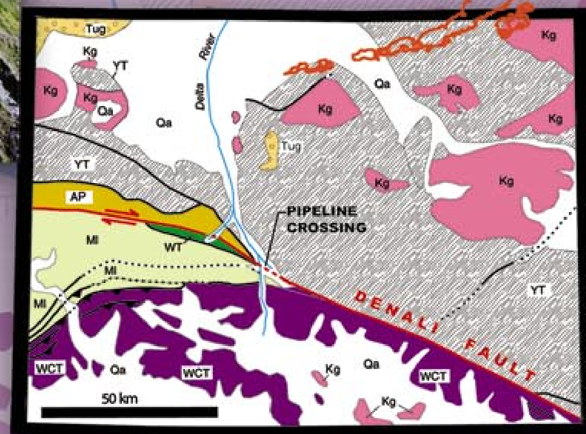
Engineering design for a pile cap. Pile caps connect the structure to the piles.

Living with Unstable Ground

Recognition of the problem is a critical step in living with unstable ground. Often property owners are not aware of the underlying instability because signs of unstable ground may begin as inconsequential cracking or minor flooding. Geologists can help identify potential areas of unstable ground because each kind of unstable ground has it own geologic attributes. Potential problems are more easily mitigated if they are recognized before construction begins. Thus, geologic mapping and investigations are particularly cost effective where new development is proposed. When a problem has been recognized, the impact often can be reduced. Modern society has had significant experience in dealing with unstable ground and has developed alternative mitigation strategies, (Fig. 51). These strategies range from engineering design to government intervention to insurance. Local political attitudes, however, are an important factor in the selection of the appropriate strategy, because implementation of a strategy affects how land is used and valued. In short, living with unstable ground requires an informed citizenry.

Fig. 51. On Nov. 3, 2002, the Trans-Alaska pipeline withstood 18 ft of offset where it crossed the Denali Fault without spilling a drop of oil. The fault offset occurred during the largest recorded earthquake for the Denali Fault (magnitude 7.9). A 1900 ft. section of the pipeline near the fault was designed to glide on Teflon shoes mounted on long horizontal steel slider beams that parallel the fault trend. The survival of the pipeline demonstrates the value of combining careful geologic studies of earthquake hazards and creative engineering design.





An earthquake offset the drainage shown in a 1976 aerial view of the Denali Fault, by 26 ft. horizontally and 5 ft. vertically. Sites such as this one provided the data for designing the pipeline fault crossing.

geologic map

GLOSSARY

aquifer A water bearing permeable rock or sediment capable of yielding significant water to wells and springs.

built environment Collectively, everything on Earth constructed by humans.

collapsible soil A dry soil with low density that breaks down when water is added to it.

consolidation An engineering term used to describe the decrease in volume of a water-logged soil when pore water flows from the soil. Called compaction in geology.

debris flow A rapidly moving mass of soil, rock fragments, and water.

earth flow A fast moving mass of soil and water.

Earth's crust The outermost layer or shell of planet Earth.

effective stress The difference between the total load or stress acting on a soil element and water pressure in the pores in the element. Effective stress controls the deformation and strength of a soil element.

epicenter The place at the land surface that lies directly above the point in the Earth's crust where an earthquake rupture initiates.

estuary The lower part of a river where the river currents are affected by ocean tides.

expansive soil Soil that expands or shrinks as its moisture content changes.

flow A type of slope movement involving soil and rock where displacements are occurring within the soil or rock mass.

frost Seasonally frozen ground.

ground improvement Engineering techniques that stabilize problem soils by decreasing their compressibility and increasing their strength.

grout Usually a cement or clay slurry that is either used to fill void space or injected into the subsurface.

hazard A natural or human-induced process with the potential to cause harm.

hazard assessment The process of compiling information on the frequency, severity, and locations of a hazard.

head The upslope part of a landslide.

heave A predominantly upward displacement of a surface from either expansion or displacement.

hummocky topography An irregular landscape characterized by low ridges and closed depressions.

hydrocompaction The break down of a dry low-density soil when water is added to it.

karst A type of topography with many closed depressions that forms on soluble rock like limestone by dissolution.

landslide A popular term used to describe all types of slope movement.

liquefaction The transformation of wet low-density sand into a liquid-like material when it is shaken by an earthquake.

loess A blanket of non-stratified wind-blown rock flour. The rock flour was created by the grinding action of glaciers. It typically is found adjacent to areas that were recently deglaciated.

mitigation Human activities that reduce economic and physical losses from a hazard.

permafrost Permanently frozen ground.

pile A steel, wood, or concrete post that is placed in the ground to support a structure.

pore The space or volume between sand or clay grains in a soil; may be filled with water if the soil is below the water table.

risk The consequence of a hazard occurring, often expressed as an annual loss of life and property or injury.

saturated The condition when the pores between individual grains in a soil are filled with water.

scarp Abrupt and continuous steps in the land surface.

settlement An engineering term used to describe loss of elevation of the ground surface. Called subsidence in geology.

shale A thinly bedded rock mostly consisting of clay-sized grains; it splits easily into layers.

sinkhole A closed topographic depression associated with collapse into an underground void.

slide A type of slope movement in which large blocks of soil or rock move downhill on a sliding or failure surface.

soil In engineering, uncemented granular material that may consist of both mineral and organic grains.

soil creep A type of slope movement in which soil on a slope moves slowly downhill.

soil skeleton The solid framework formed by the individual grains of a soil deposit.

soft soil Weak and compressible fine-grained soil containing large amounts of water.

subsidence A geologic term used to describe loss of elevation of the ground surface. Called settlement in engineering.

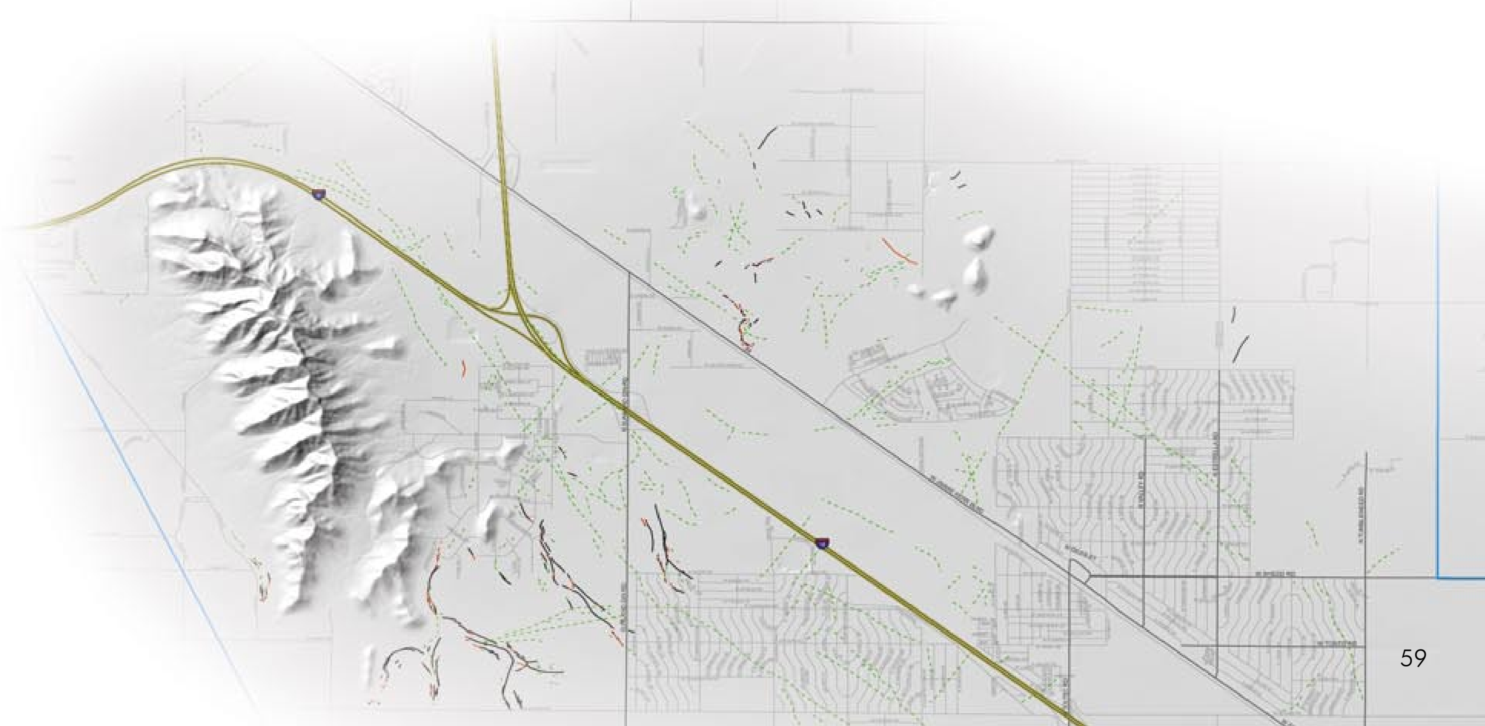
subsidence bowl A regional decrease of land-surface elevation caused by withdrawal of groundwater or petroleum from underground reservoirs. Usually subsidence is greatest near the middle of the subsidence area, causing it to be bowl shaped.

surface waves Slow rolling seismic waves that propagate in soil and rock along the land surface.

thrust fault A gently inclined fault in which the block on top of the fault plane moves upward and over the block beneath.

toe The downhill part of a landslide.

water table The surface connecting water levels measured in shallow wells.



Sources of

ADDITIONAL INFORMATION

Problem soils

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Organic soils

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Land subsidence caused by withdrawal of groundwater and petroleum

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Sources of Additional Information — Goose Creek Oil Field subsidence area, Baytown, TX (T. Holzer, USGS); Chelungpu Fault scarp at Tachia River, 1999 Chi-Chi earthquake, Taiwan (NISEE, UC Berkeley); Sinkhole in Polk County, FL (Hayward-Baker, Inc.).

Credits — Sinkhole in Winter Park, FL (J. Newton, USGS); Chelungpu Fault scarp at Kung Fu New Village, 1999 Chi-Chi earthquake, Taiwan (NGDC/NOAA); Before and After, Capuchinas Church, Mexico City, Mexico (T. Holzer, USGS).

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After

2005

Before

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