Mitigating Losses from Land Subsidence in the United States

Panel on Land Subsidence
Committee on Ground Failure Hazards Mitigation Research
Division of Natural Hazard Mitigation
Commission on Engineering and Technical Systems
National Research Council

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Executive Summary

More than 44,000 km^2 of land in 45 states in the United States has been lowered by the types of subsidence considered in this report. Underground mining of coal, groundwater withdrawal, and drainage of organic soils are the principal causes of subsidence. Approximately 8,000, 26,000, and 9,400 km^2 of land has subsided from each of these causes, respectively. In addition, about 18 percent of the conterminous United States is underlain by cavernous limestone, gypsum, salt, or marble and is locally susceptible to catastrophic collapse into sinkholes.

Annual costs from resulting flooding and structural damage exceed $125 million. Although these costs are small relative to those of many other earth-science hazards, their geographic distribution is not uniform. Thus, localized areas bear disproportionate shares of these costs. In addition to this uneven cost distribution, parties damaged by subsidence associated with resource removal commonly are stymied from reimbursement by legal recovery systems that are in conflict with doctrines that establish rights to resource removal.

Many examples are available of successful efforts at federal, state, and local levels to mitigate specific subsidence problems. The efforts include public information programs, mapping programs, regulation of resource development, land-use management and building codes, market-based methods, and insurance programs. Despite these successes, continued mitigation of subsidence requires action in three areas.

First, basic earth-science data and information on the magnitude and distribution of subsidence are needed to recognize and to assess future problems. Such data include geodetic, geologic, hydrogeologic, hydrologic, soils, and land-use information. These data, in both map and tabular formats, help not only to address local subsidence problems but to identify national problems. Collection of these data in general should be overseen by earth-science agencies, particularly state geological surveys and the U.S. Geological Survey. Channels of communication should be developed to designate levels of government and interest groups advising them of the availability of this information.

Second, research on subsidence processes and engineering methods for dealing with subsidence is needed for cost-effective damage prevention or control. Although general understanding of subsidence processes is well developed, prediction of subsidence magnitudes, rates, and location is commonly hampered by incomplete understanding of specific details

of the relevant processes and the inability to determine adequately subsurface conditions and physical properties of the deforming materials. Even when a specific subsidence occurrence is well understood, however, U.S. experience with engineering designs to accommodate ground deformation, and methods to control it, is modest. New funding is needed to support research on subsidence processes by the U.S. Geological Survey, Bureau of Mines, Bureau of Reclamation, and Agricultural Research Service, and on engineering methods by the Federal Highway Administration, Corps of Engineers, Bureau of Reclamation, Federal Housing Administration, and Soil Conservation Service.

And third, although many types of mitigation methods are in use in the United States, studies of their cost-effectiveness would facilitate choices by decisionmakers. Such studies should be funded by the Federal Emergency Management Agency, National Science Foundation, and industrial and professional organizations.

1
The Subsidence Problem

INTRODUCTION

This report reviews the land subsidence problem in the United States and the measures that have been applied to mitigate it, and it assesses the effectiveness of research, engineering, and technical solutions in reducing losses incurred by subsidence. It addresses subsidence that occurs naturally, as well as that caused by land development and resource extraction. Resource and land development practices, mainly underground mining, groundwater and petroleum withdrawal, and the drainage of organic soils, are key contributors to the problem. Public and private responsibilities and capabilities for reducing subsidence-related losses on the federal, state, and local levels are examined and their effectiveness evaluated. The report concludes that if its findings are implemented, they would reduce and more equitably distribute subsidence losses in the United States.

Land subsidence, loss of surface elevation due to removal of subsurface support, at rates that are of practical significance to man-made structures, affects most of the United States. Subsidence is one of the most varied forms of ground failure affecting the country, ranging from broad regional lowering of the land surface to local collapse. Its practical impact depends on the specific form of the surface deformation. Regional lowering may either aggravate the flood potential or permanently inundate an area, particularly in coastal or riverine settings. Local collapse may damage buildings, roads, and utilities and either impair or totally destroy them. Fortunately, subsidence is more hazardous to property than to life, because of the typically low rates of lowering. It has caused few casualties. Subsidence, however, increases the potential for loss of life in flood-prone areas by increasing the depth and size of areas susceptible to flooding.

Subsidence is caused by a diverse set of human activities and natural processes, including: mining of coal, metallic ores, limestone, salt, and sulfur; withdrawal of groundwater, petroleum, and geothermal fluids; dewatering of organic soils; pumping of groundwater from limestone; wetting of dry, low-density deposits, which is known as hydrocompaction; natural sediment compaction; melting of permafrost; liquefaction; and crustal deformation. This diversity and the broad range of impacts from subsidence in fact probably are the major causes of the lack of a national focus on subsidence. Instead, many industries, professions, and federal, state,

TABLE 1 Types of Land Subsidence*

Collapse into voids
Mining
Sinkhole
Compaction
Underground fluid withdrawal
Natural compaction
Hydrocompaction
Liquefaction
Drainage of organic soils
Melting of permafrost
Crustal deformation
Volcanism
Seismic
Aseismic
Postglacial deformation

* Subsidence discussed in this report is in italics.

and local agencies are independently involved with aspects of subsidence. Most occurrences of subsidence in the United States, however, are induced by human activity. Resource development and land-use practices, particularly underground mining of coal, groundwater and petroleum withdrawal, and drainage of organic soils, are the primary causes.

The common association of land subsidence with either the exploitation of natural resources or land development practices is an important aspect of subsidence. These activities have economic benefits. Problems often arise because those who benefit from the activity that causes subsidence may not bear the full cost. In fact, some parties who incur damage may not profit at all from the activity causing the subsidence. In addition to the equity issue, specific subsidence problems may be aggravated by legal and institutional barriers that prevent legal recourse to injured parties. Legal recovery theories conflict in some states with other doctrines that establish rights to resource recovery.

This is the second report prepared under the auspices of the National Academy of Sciences/National Research Council Committee on Ground Failure Hazards Mitigation Research. These reports summarize ground failure problems that affect the United States and outline methods to mitigate their impact. In defining its purview, the committee was charged with reviewing those ground failure topics that were not receiving adequate scrutiny by other Academy committees. Thus, three causes of subsidence, including the melting of permafrost, crustal deformation, and liquefaction, were not treated, since they fall under the mandates of existing committees (Table 1). The panel also did not consider rising sea level, despite its obvious relevance to coastal flooding, an important aspect of the nation's subsidence problem. Such a study has been published by the National Research Council Committee on Engineering Implications of Changes in Relative Mean Sea Level (1987).

CAUSES AND EFFECTS

The types of land subsidence considered in this report (Table 1) affect parts of at least 45 states (Figure 1). More than 44,000 km^2 of land, an area equal to half the state of Maine, has been lowered. In this section both the causes of and effects from subsidence are reviewed. (For detailed technical discussion of mechanisms the reader is referred to the references in the Appendix.)

Collapse into Voids—Mines and Underground Cavities

Collapse of surficial materials into underground voids is the most dramatic kind of subsidence. Buildings and other engineered structures may be damaged or destroyed, and land may be removed from productive use by such ground failure.

Mines

Underground excavations have been constructed in the United States since the early 1700s. Most of the voids with which subsidence has been associated in the United States were created by coal mining, and this report focuses on that activity. Abandoned tunnels and underground mining of metallic ores, limestone, and salt contribute to a much smaller extent, although problems may be severe in some regions. For example, hundreds of subsidence occurrences in the Midwest have been associated with failures of abandoned underground lead-zinc mines. A singular, but spectacular and complex, example was the catastrophic drainage of Lake Peigneur and disappearance of about 27.6 ha of land at Jefferson Island, Louisiana, on November 20, 1980 (Figure 2). The collapse was triggered by the drilling of an oil well inadvertently into an underground salt mine in the Jefferson Island salt dome; damages totaled hundreds of millions of dollars (Autin, 1984).

In general, coal-mine subsidence is caused by collapse of the mined-out or tunneled void. It occurs as both steep-sided pits (Figure 3) and broad, gentle depressions. Subsidence depends on the number, type, and extent of the voids. For example, it is a planned consequence of the longwall mining method for coal, in which most of the coal seam is removed along a single face, the longwall. By this method, the roof above the mined-out seam is allowed to collapse as the longwall advances laterally as mining progresses. Subsidence above longwall mines is rapid, generally ending within a few months after the removal of subsurface support. Subsidence above mines with partial extraction is usually unplanned. By this method, only parts of the coal, the rooms, are removed. The unmined portions, the pillars, are left to provide support. Collapse into the rooms occurs when the pillars, floors, or ceilings deteriorate. Subsidence resulting from collapse into rooms may take years to decades to manifest itself. Examples of collapse occurring 100 years after mines were abandoned have been documented.

Coal is found in 37 states and mined underground in 22 states (HRB-Singer, 1980). Approximately 32,000 km^2 of land is undermined, and it is anticipated that the area will ultimately grow to about 162,000 km^2. Approximately 8,000 km^2 of the undermined area, most of which is in the eastern United States, already has experienced subsidence. The U.S. Bureau of Mines estimates that 1,600 km^2 of land in urban areas is threatened (Johnson and Miller, 1979). Seventy-one percent of this area is in Pennsylvania, Illinois, and West Virginia.

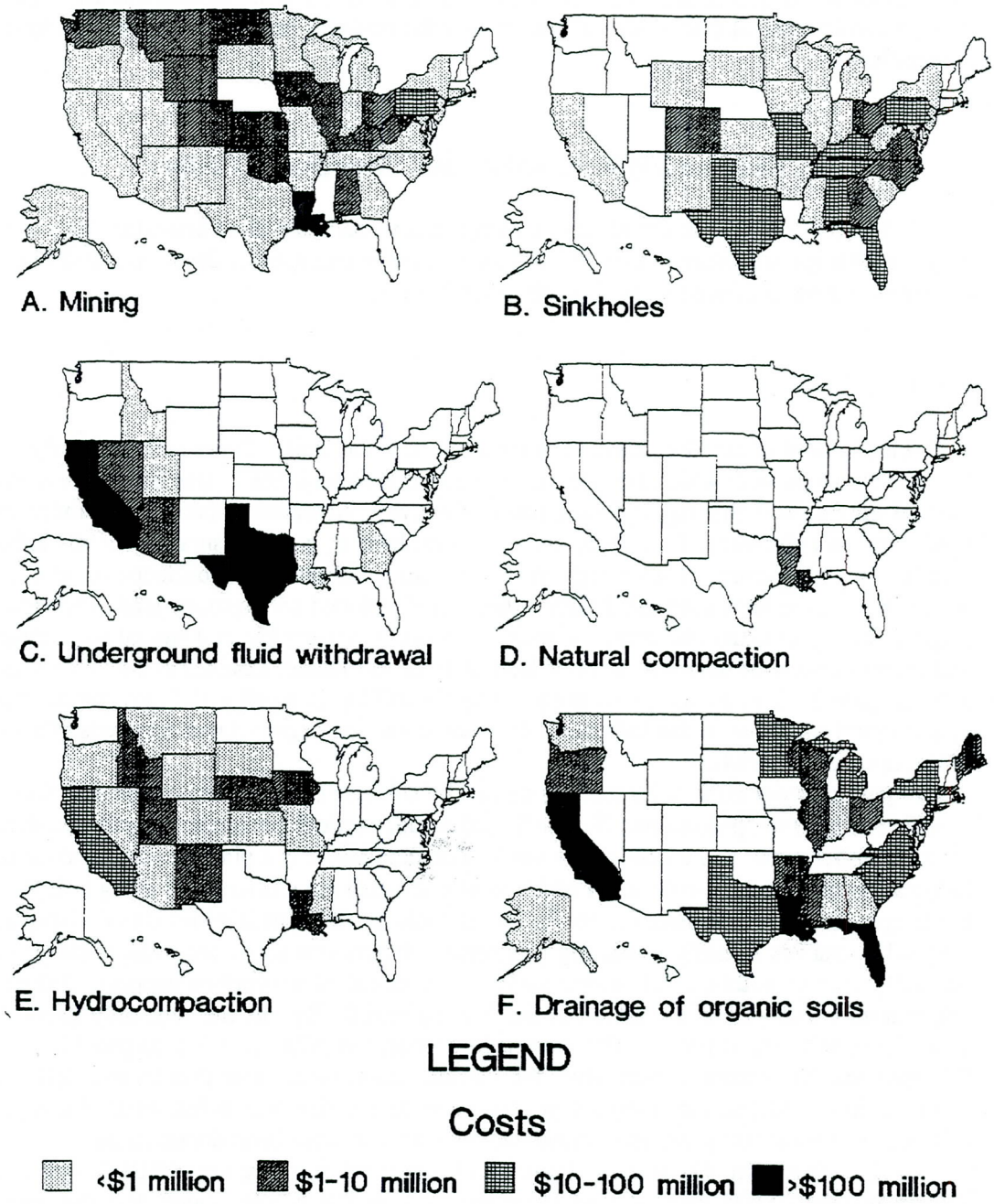

FIGURE 1 National distribution of subsidence problems by state. Costs were compiled from published and unpublished sources for the purpose of providing an order-of-magnitude, state-by-state comparison. Only relative importance is suggested by maps, because the time periods on which estimates are based vary by state, and costs were not converted to constant dollars. In general, costs are conservative estimates.

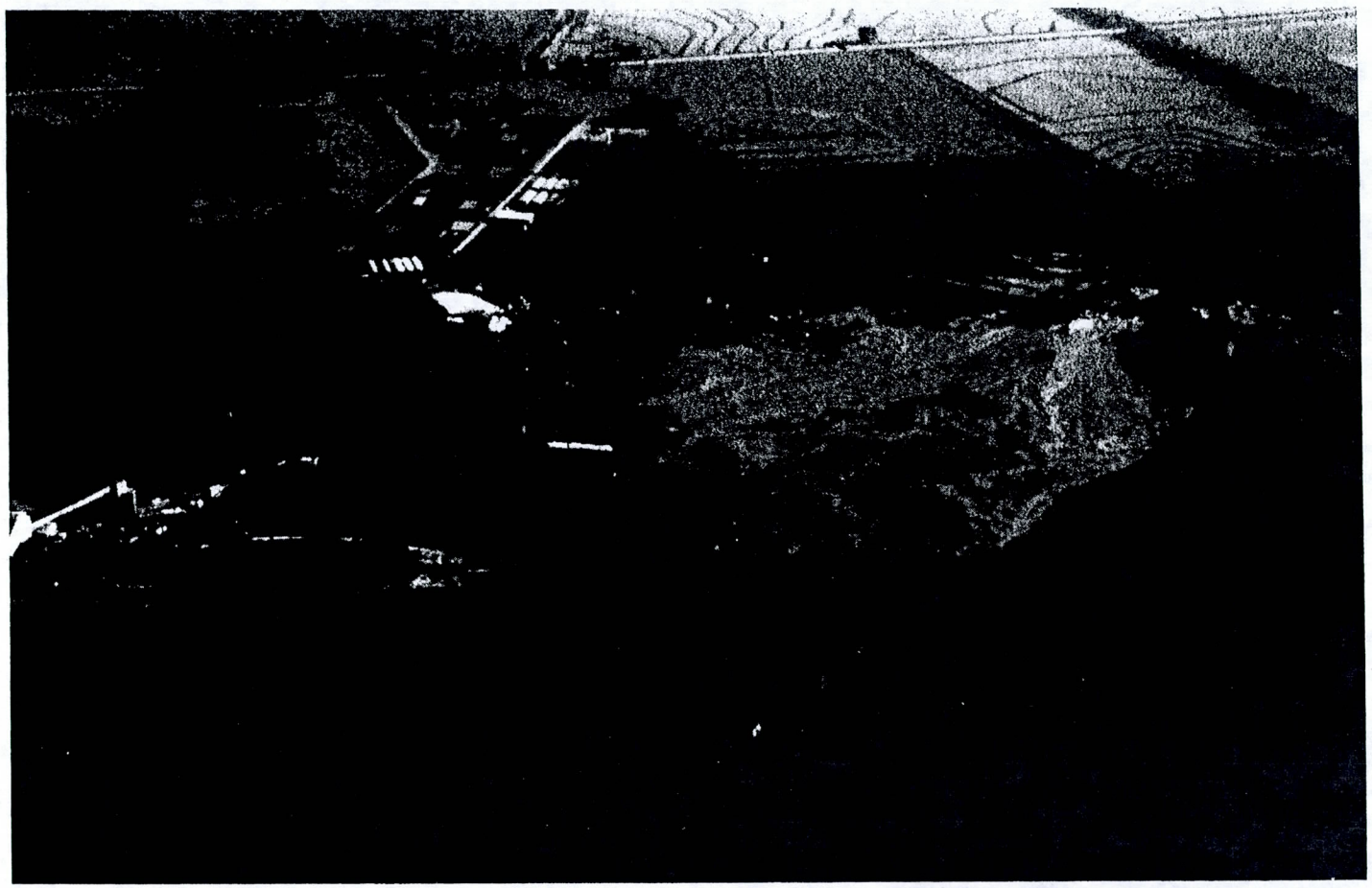

FIGURE 2 Aerial view of bed of Lake Peigneur, site of November 2, 1980, Jefferson Island, Louisiana, collapse. Drilling for petroleum exploration inadvertently penetrated an underground salt mine and caused the catastrophic drainage of Lake Peigneur into the salt mine. Collapse into the mine caused the disappearance of 27.6 ha of land. Note area of rotational slides in the background and area of flows in the foreground. Collapse is obscured by light-colored slurry in right center of photo. Slurry area is about 0.5 km across. (Photograph courtesy of Robert L. Thomas.)

FIGURE 3 Oblique aerial view of subsidence pits above abandoned coal mines in the Sheridan, Wyoming, area. Diameter of pits ranges from 5 to 50 m. (Photograph courtesy of C. Richard Dunrud.)

Sinkholes

The sudden formation of sinkholes—catastrophic subsidence—is usually caused by movement of overburden into underlying cavities in soluble bedrock (Figure 4). Failure of the bedrock is rarely believed to be a major factor in catastrophic subsidence. Most catastrophic subsidence in the United States is associated with carbonates such as limestone, but occasionally it is associated with evaporites such as gypsum and halite (Figure 5). Although most historical collapses are man-induced, the cavities in the bedrock usually antedate human activities. This is particularly true of carbonates, because rates of solution are so low. Cavities in halite can be an exception because of the high solubility. For example, several dozen sinkholes have formed in the last 30 years in Kansas as a result of solution of salt beds by leaks through casings of brine-disposal wells. A recent example is a 60-m-wide and 33-m-deep sinkhole that formed in the summer of 1988 near Macksville, Kansas (Geotimes, 1988). Catastrophic subsidence is most commonly induced by water-table lowering, rapid water-table fluctuation, diversion of surface water, construction, use of explosives, or impoundment of water.

Davies and others (1976) indicate that more than 1.4 million km^2 of land in 39 states is underlain by cavernous limestone and marble. More than 30,000 km^2 of this area lies beneath Standard Metropolitan Statistical Areas inhabited by 33 million people (HRB-Singer, 1977). Of course, only a small portion is actually underlain by voids and at risk. Newton (1986) estimates that more than 6,000 collapses have occurred in the eastern United States since about 1950 (Figure 6). The states with the largest number of active sinkholes include Alabama, Florida, Georgia, Indiana, Missouri, Pennsylvania, and Tennessee.

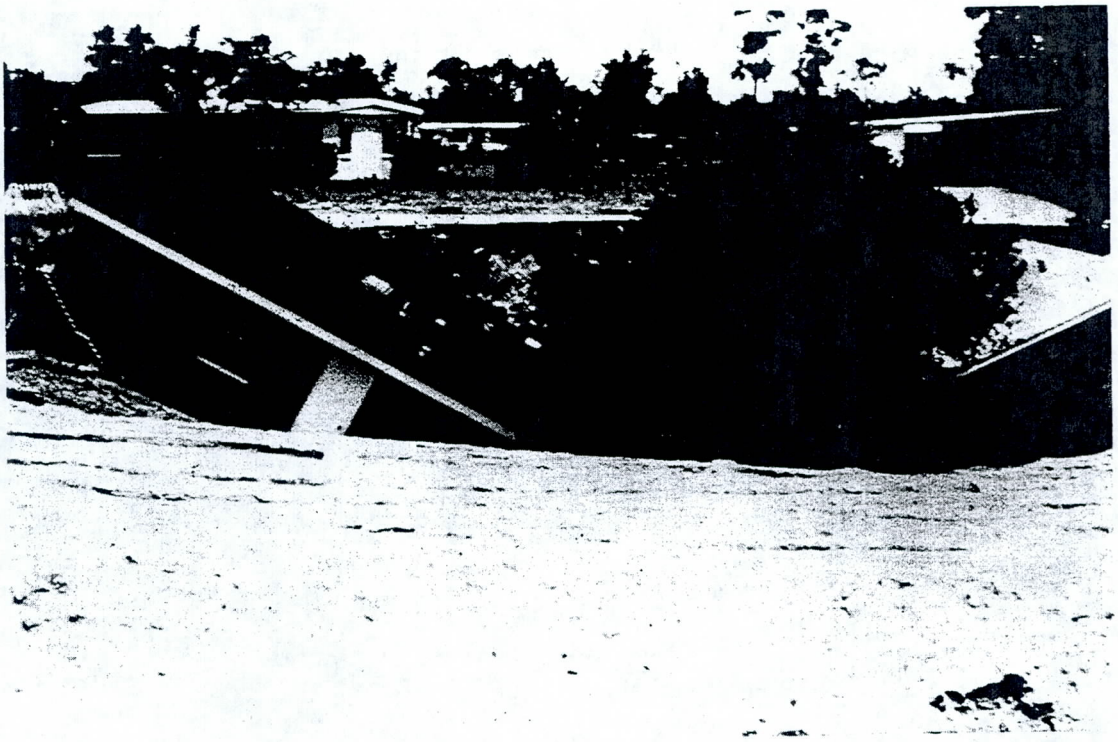

FIGURE 4 Catastrophic subsidence caused by collapse of overburden into voids in limestone near Barstow, Florida, that destroyed two houses. (Photograph courtesy of Florida Sinkhole Research Institute.)

Sediment Compaction

Sediment compaction typically causes broad regional subsidence. Exceptions include ground rupture and hydrocompaction. Rates of subsidence usually are low, ranging from a few millimeters to centimeters per year, but total subsidence may reach several meters as it accumulates over decades.

Underground Fluid Withdrawal

The weight of the overburden above underground fluid reservoirs is supported by both fluid pressures and stresses transmitted through the solid skeleton of the reservoir soil or rock. When fluids are withdrawn, fluid pressures decline, and support of the overburden is transferred to the solid skeleton. If the reservoir soil or rock is compressible, large and permanent loss of pore volume or compaction will occur as it adjusts to the new stresses. In geothermal reservoirs, significant thermal contraction also may occur as the reservoir cools during exploitation.

Most of this type of subsidence in the United States is caused by pumping of groundwater and petroleum. More than 31 areas in 7 states have subsided. The two largest areas are in the San Joaquin Valley, California, and Houston, Texas, areas, where 13,500 and 12,000 km^2, respectively, have subsided because of groundwater withdrawal. Maximum elevation loss from this type of subsidence has been 9 m in the San Joaquin Valley (Figure 7).

Two coastal areas in California and Texas where subsidence caused or threatened inundation and increased flooding potential have suffered the most from this type of subsidence.

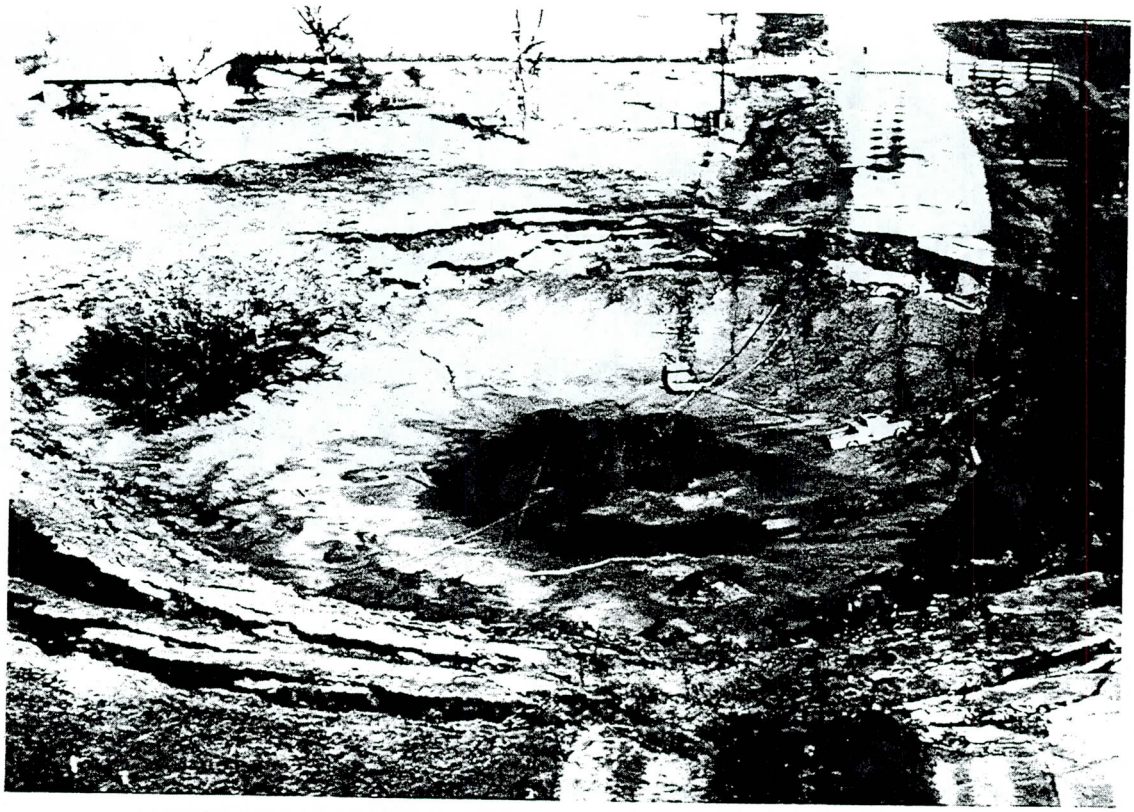

FIGURE 5 August 11, 1983, catastrophic subsidence over the Boling salt dome, Texas. Diameter of depression is about 75 m. (Photograph courtesy of Boyd V. Dreyer.)

Petroleum withdrawal in Long Beach, California, caused parts of the city's harbor facility to subside almost 9 m from 1937 to 1966. Groundwater withdrawal in Houston, Texas, has caused some coastal areas to subside by more than 2 m. About 80 km^2 of land has been inundated, and several hundred square kilometers, including the 500-unit Brownwood subdivision in Baytown, which was abandoned in 1983, have been added to the area susceptible to flooding by storm surges (Figure 8).

Inland areas are not immune to damage from this subsidence. Changes of surface gradients can affect either the design or operation of canals. For example, canals in the State Water and the Central Valley Projects in California and the Central Arizona Project have been affected. Other causes of damage in inland areas include subsurface deformation and ground rupture. Subsurface deformation shears or crushes well casings and diminishes the productivity of water and oil wells. Ground rupture, including faults and earth fissures, is particularly devastating to man-made structures. Faulting has damaged hundreds of houses in Houston, Texas (Figure 9a), and caused the catastrophic failure in California in 1963 of the Baldwin Hills reservoir that claimed five lives. Earth fissures (Figure 9b) are an increasingly common occurrence as groundwater withdrawals increase in alluvial basins in the desert parts of the Sun Belt.

Natural Compaction

Sediments also compact naturally as they are buried by younger sediment (Figure 10). Probably nowhere in North America is natural subsidence occurring more rapidly than in the

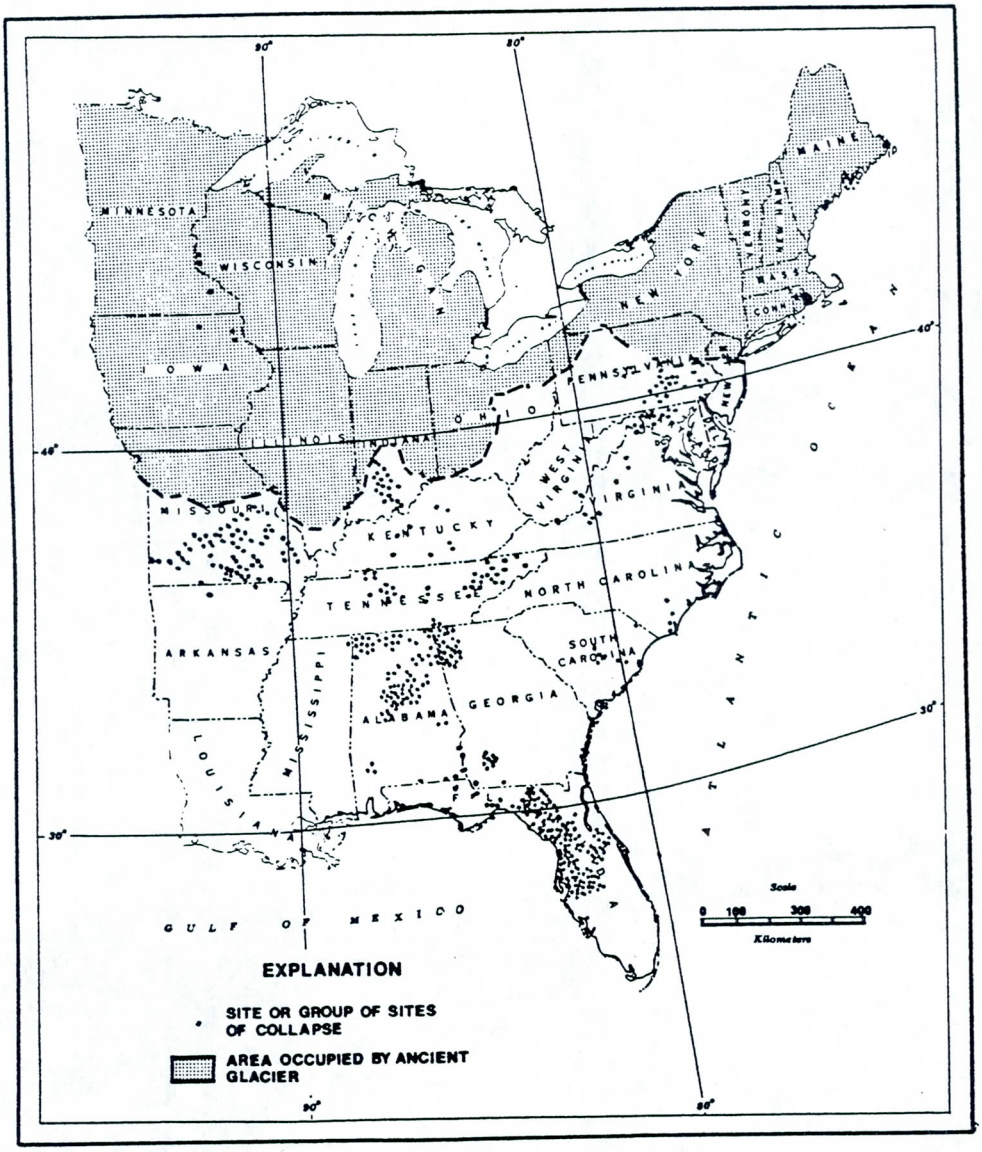

FIGURE 6 Sites of active sinkhole development in the eastern United States (from Newton, 1986).

Mississippi River Delta area of southern Louisiana, where about 3,900 km^2 of land is subsiding, at least in part through natural compaction. Estimated average rates of subsidence range from 8 to 11 mm per century (Penland and others, 1988). Maximum rates measured by geodetic surveys are about 12 mm per year (Figure 11). The abandoned town of Balize, approximately 130 km southeast of New Orleans on the tip of the Delta, is an example of the long-term implication of this subsidence. Balize, which was abandoned during a yellow fever epidemic in 1888, was more than 1.2 m below marsh level in 1934 (Russell and others, 1936). Today the abandoned town sits more than 3 m below sea level.

Increased flooding potential is the principal impact of this type of subsidence, because affected areas commonly are low lying and naturally subject to flooding. Thus, subsidence exacerbates a preexisting problem. The flood problem is particularly acute in coastal areas

FIGURE 7 Approximate location of maximum subsidence in the United States caused by groundwater withdrawal. Point is west of Mendota, California, in the San Joaquin Valley. Subsidence of 9.0 m occurred from 1925 to 1977. Signs indicate the former elevations of the land surface in 1926 and 1955, respectively. (Photograph courtesy of Richard L. Ireland.)

FIGURE 8 Flooding and damage in Houston, Texas, subsidence area caused by Hurricane Alicia, August 1983. Area had subsided about 2 m because withdrawal of groundwater increased its vulnerability to storm surges. (Photograph courtesy of H. Crane Miller.)

where long recurrence intervals between large storm surges and tidal floods diminish public perception of the problem. Documenting subsidence problems in coastal areas may be difficult if other types of subsidence are occurring and sea level is changing. For example, subsidence caused by drainage of organic soil and withdrawal of underground fluids is common in many deltaic areas. A well-studied example of this complexity is Venice, Italy, where increases in the incidence of tidal flooding (Figures 12a and b) prompted an investigation, which discovered that the mean elevation above sea level had decreased from 130 to 110 cm since the turn of the century. About 14, 41, and 45 percent of the 20-cm average elevation loss was attributed to natural compaction, sea-level rise, and withdrawal of ground water, respectively (Gatto and Carbognin, 1981).

Another very important impact from this subsidence is the destruction of productive estuarine marsh and coastal wetlands by either inundation or erosion. Thousands of hectares of low-lying coastal land along the Gulf of Mexico are converted each year to open water by natural subsidence (Figure 13). This process, referred to as coastal land loss, results in a significant loss of habitat for birds, fish, crustaceans, and reptiles and has a profound impact on the commercial fishing, shrimping, oystering, and fur trapping industries. In addition, salt-water intrusion into these areas destroys agricultural usage.

The most severe land-loss problem in the United States is in southern Louisiana. Channelization of the Mississippi River has caused riverborne sediment, which normally offsets land loss by replenishing beaches and wetlands, to discharge directly offshore into the Gulf of Mexico. The rate of land loss in southern Louisiana currently is about 130 km^2 per year;

FIGURE 9 Ground ruptures associated with land subsidence caused by groundwater withdrawal. (a) Damage to house from faulting in the Houston, Texas, area. (b) Tension crack in southcentral Arizona that has been enlarged by erosion into 1-m-wide gully. (Photograph courtesy of Thomas L. Holzer.)

approximately 3,200 km^2 of land has been lost in the last 80 years. Nationally, more than 150,000 km^2 of coastal marsh has been lost since 1954 (Gosselink, 1980).

Hydrocompaction

Dry, low-density, fine-grained sediment may be susceptible when wetted to a loss of volume known as hydrocompaction (Figure 14). These sediments, known as collapsible soils, generally are of two types: mudflow deposits in alluvial fans and wind-deposited, moisture-deficient silt called loess. Most collapsible soils have anomalously low densities because they remained moisture deficient throughout their postdepositional history. When water percolates through the root zone into this type of sediment, the soil structure collapses and the soil compacts. Very localized subsidence, typically 1 to 2 m, may result.

Damaging hydrocompaction has been reported in 17 states. The three largest affected areas are the alluvial slopes of the western San Joaquin Valley and loess-covered areas in the Missouri River basin and Pacific Northwest. The major impact has been on design and operation of hydraulic structures—canals and dams. Locally significant impact has been incurred by buildings and highways. Irrigation for agriculture also has caused differential subsidence that required releveling of fields.

Organic Soil

Drainage of organic soil, particularly peat and muck, induces a series of processes, including biological oxidation, compaction, and desiccation, that reduce the volume of the soil. Biological oxidation usually dominates in warm climates (Figure 15). The principal areas of organic soil subsidence in the United States are the greater New Orleans, Louisiana, area; the Sacramento-San Joaquin River Delta, California; and parts of the Florida Everglades. Maximum observed subsidence is 6.4 m in the Sacramento-San Joaquin River Delta. About 9,400 km^2 of land underlain by organic soil has subsided in the United States because of drainage. An even larger area is susceptible to subsidence. About 101,000 km^2 of the conterminous United States is covered by peat and muck soils (Stephens and others, 1984); more than 26,000 km^2 of organic wetlands is in standard metropolitan statistical areas (HRB-Singer, 1977).

Increased flooding is the most serious problem caused by organic soil subsidence. The low relative elevation of organic soil areas makes them vulnerable to flooding even in their natural state. Levees and pumps to remove storm and groundwaters usually are required to protect areas developed on organic soils. For example, about 35 km^2 of land in New Orleans is kept dry by a protective levee system and 21 pumping stations. About 2,250 km of levees are required to protect 1,300 km^2 of farmland underlain by peat in the California Delta. Even construction of levees does not guarantee prevention of flooding. About 3,000 people lost their lives in 1926 and 1928 in hurricane flooding that swept away levees around the south shore of Lake Okeechobee, Florida, where subsidence of about 1.5 m had occurred.

The high compressibility of organic soils also makes them a poor foundation material for engineered structures. Consequently, special construction practices that rely on piles driven to firm materials are commonly employed. These practices have led to subsiding of the land surface relative to the structures (Figure 16).

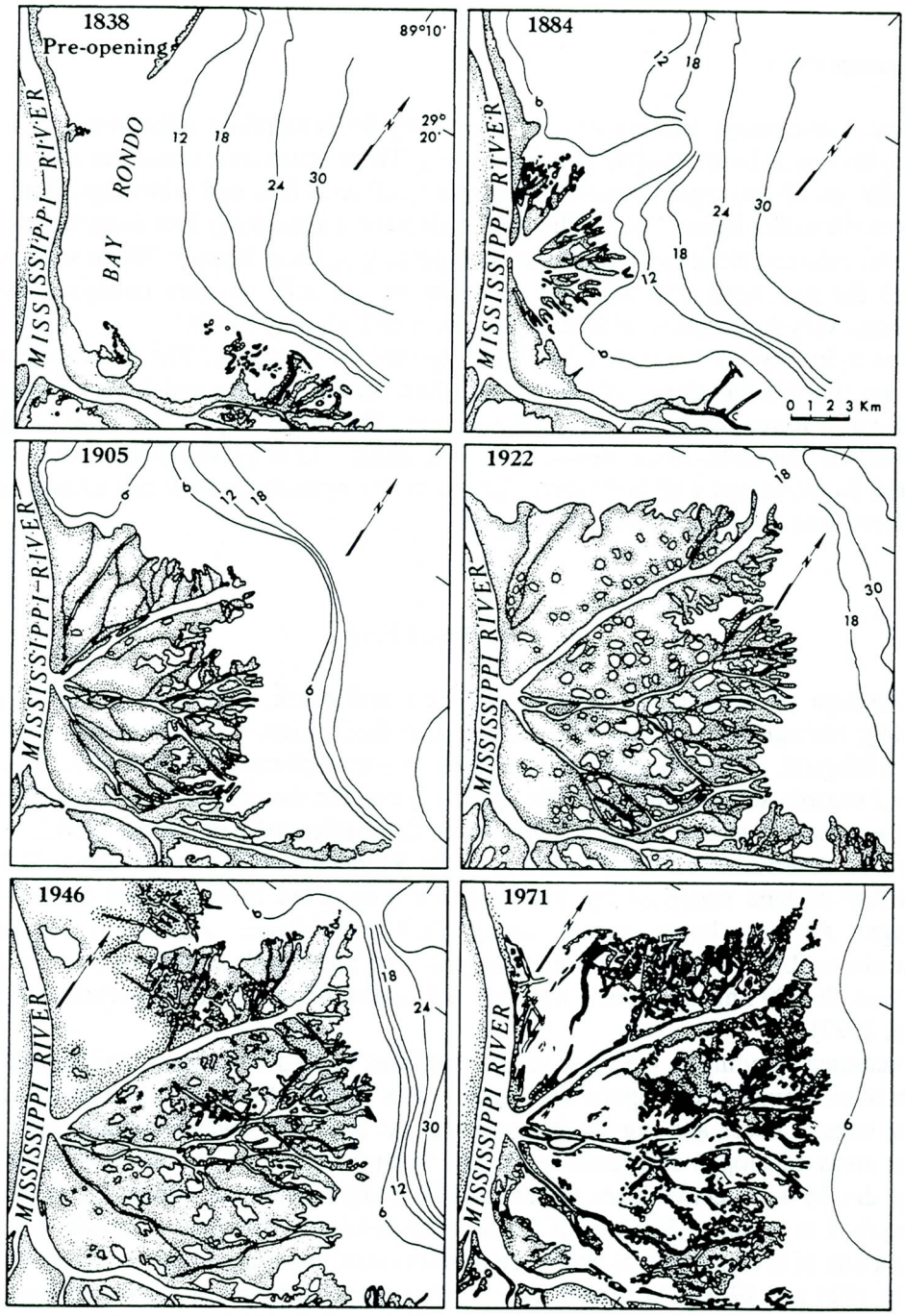

FIGURE 10 Historic maps illustrating natural compaction at Cubits Gap in Mississippi River Delta. In 1862, an oyster fisherman dug a trench along a low section of river levee. Flooding in 1862 enlarged the trench and a small delta began to form. As the tributaries prograded seaward, compaction of deposits landward caused bays to form and by 1971, substantial submergence had occurred. By the late 1980s, about 75 percent of the original land was lost to subsidence (from Coleman, 1988).

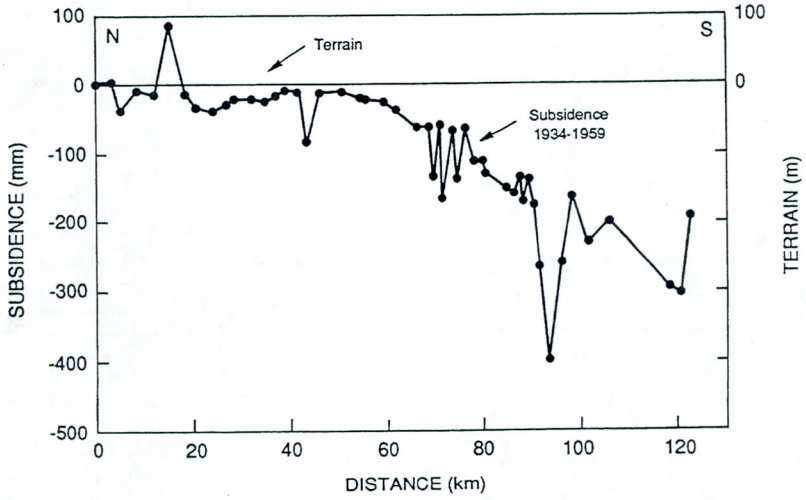

FIGURE 11 Subsidence profile from Oskya, Mississippi (north), to New Orleans, Louisiana (south), illustrating regional subsidence from 1934 to 1959 of Mississippi River Delta. Subsidence is believed to be caused by crustal deformation and compaction of sediments beneath the Delta.

ECONOMIC AND LEGAL ASPECTS

The average annual damage cost from all types of subsidence is conservatively estimated to be at least $125 million (Table 2). The costs are dominated by subsidence from underground mining of coal, drainage of organic soils, and withdrawal of underground water and petroleum. These costs consist primarily of direct structural and property losses and depreciation of land values, but they also include business and personal losses that result from periods of repair. Although total annual damage cost of subsidence to the nation is small relative to the nation's economy, subsidence imposes substantial costs on both individual cities and neighborhoods. Examples of cities where cumulative damage costs from subsidence are more than $100 million include Long Beach, California; Houston, Texas; and New Orleans, Louisiana. In other areas, the hazard is more localized. Seemingly random collapses threaten both the safety and viability of selected neighborhoods and businesses. Examples include Scranton, Pennsylvania, and Seattle, Washington, where collapse of abandoned coal mines has damaged surface structures.

Most mine-subsidence damage in the United States is associated with abandoned coal mines over which urban growth has occurred. Damage in urban areas has been estimated to cost more than $30 million annually (HRB-Singer, 1977). Even in rural areas, however, subsidence affects field drainage, reduces crop yields, and lowers property values. A study in Illinois indicates that property values in rural areas affected by subsidence were discounted an average of 16 percent (Illinois Department of Energy and Natural Resources, 1985).

Costs of preventive measures and damages from sinkhole activity or catastrophic subsidence, which was incurred primarily in the eastern United States since 1970, are more than $170 million (Newton, 1986). The costs are dominated by a $130 million expenditure at five dam sites to minimize or eliminate sinkhole activity. A factor that helps to keep damage costs low is that sinkhole potential is usually evaluated during siting of major engineered structures in limestone terrane. This cost is considered a type of mitigation cost.

Damage costs from compaction caused by withdrawal of underground fluids are dominated

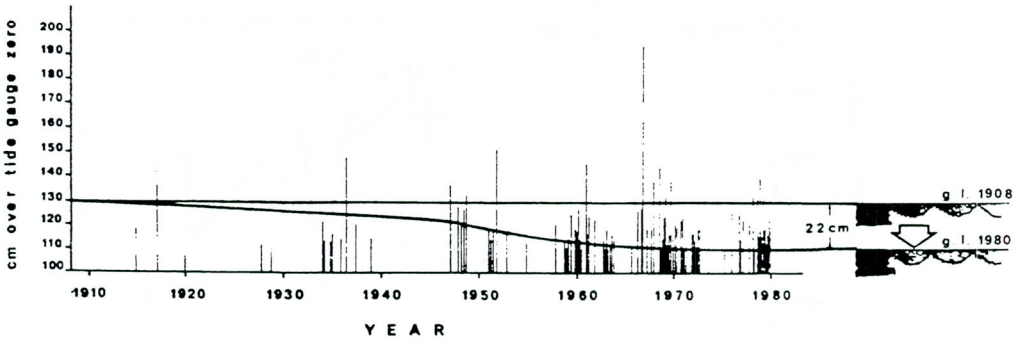

FIGURE 12 Subsidence and flooding in Venice, Italy. (a) Flood heights and frequency, 1908-1980. Frequency of floods, locally known as *acqua alta*, increased with time as subsidence lowered mean elevation of Venice (Gatto and Carbognin, 1981). (b) *Acqua alta* in *Piazza San Marco*. (Photograph courtesy of Laura Carbognin.)

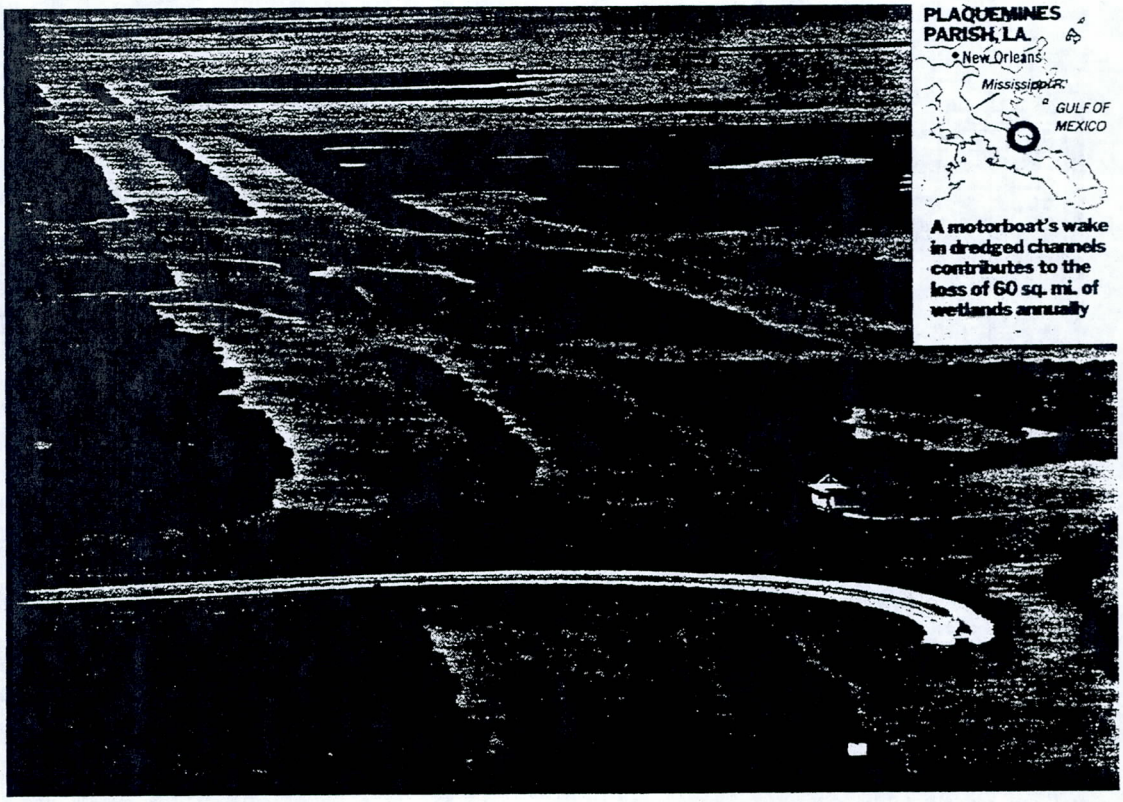

FIGURE 13 Regional land subsidence and diversion of sediment carried by Mississippi River directly to the Gulf are contributing to the disappearance of more than 130 km^2 of wetlands annually in southern Louisiana.

by large losses in a few areas. For example, although subsidence caused by petroleum withdrawal at Long Beach presently is under control, mitigation costs were about $150 million from 1937 to 1966 (Mayuga, 1970). Jones (1977) estimates that damages in the Houston area averaged $31.7 million per year from 1969 to 1974, the period covered by this study. Costs were approximately equally divided between decreased property value and damage; most derived from flooding and inundation. Costs in inland subsidence areas are caused primarily by changes of gradients of canals, repair of subsurface damage to wells, and ground rupture. These costs probably have been smaller than flooding-related costs, although few firm estimates are available. Prokopovich and Marriott (1983) estimate that postconstruction rehabilitation of California's Central Valley Project canals, one of the largest canal systems affected by subsidence, cost $34 million. The only available estimate of damage to well casings is that by Roll (1967) for the Santa Clara Valley, California, where more than $4 million was spent to repair or replace well casings. Estimates of damage from ground rupture also are incomplete. Clanton and Amsbury (1975) estimate losses in the Houston area at several million dollars. Failure of the Baldwin Hills reservoir because of ground rupture caused losses of $15 million.

Losses from natural compaction, particularly in the Mississippi River Delta, are difficult to estimate because of the uncertain value of coastal wetlands. Annual revenue losses are possibly on the order of millions of dollars.

Nationwide hydrocompaction damages and prevention expenditures are very poorly documented. The most costly individual impact that has been documented was on the California

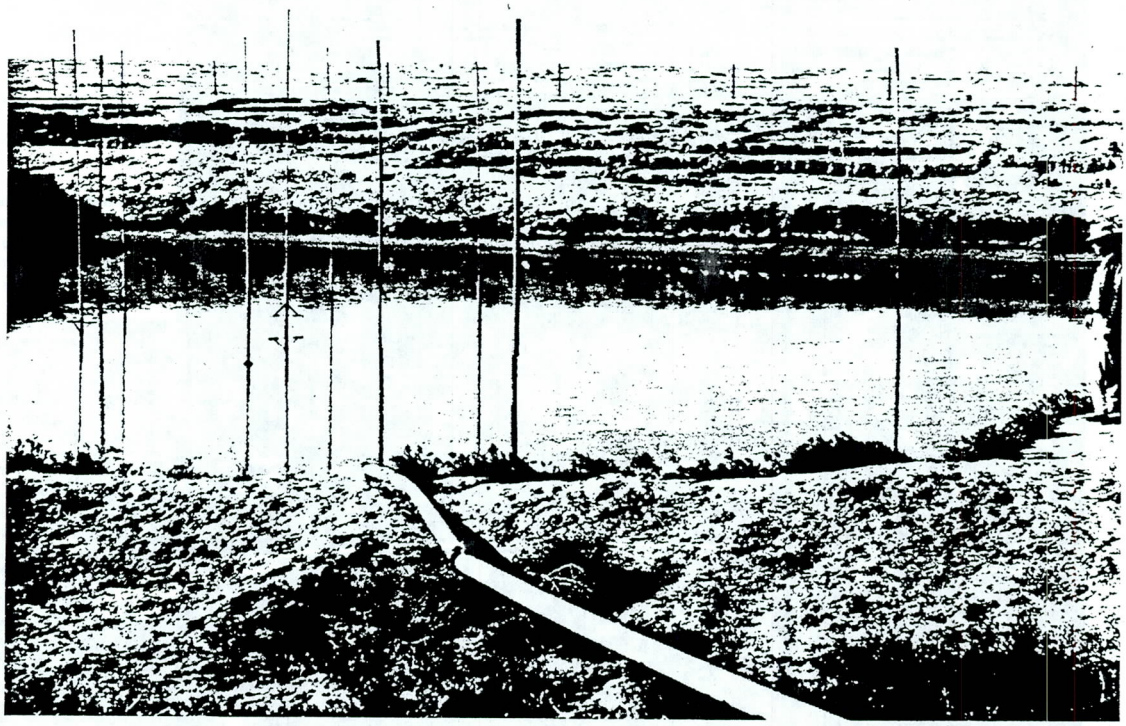

FIGURE 14 Hydrocompaction of test plot in San Joaquin Valley, California. Water has infiltrated from pond and caused collapsible soils to compact as they became wet. Note extensive ground cracking in background around margin of subsidence depression. Poles were used to measure compaction at different depth intervals. (Photograph courtesy of California Department of Water Resources.)

Aqueduct along the western margin of the San Joaquin Valley, where an aggregate length of 155 km of canal was built on collapsible soils (James, 1974). Investigations and prewetting to compact foundations resulted in a mitigation cost of $20 million (Curtin, 1973). Design modifications to the nearby Central Valley Project led to an $8 million mitigation cost (Prokopovich and Marriott, 1983). The most costly reported urban incident is a $3 million decrease of property value in Cedar City, Utah; property damages were about $1 million (Kaliser, 1982). Even areas with humid climates have incurred significant costs. For example, collapsible soils added more than $2.5 million in mitigation costs to interstate highway construction in Louisiana (Arman and Thornton, 1972).

The incremental increase in the cost and prevention of flood damage caused by organic soil subsidence is difficult to separate from total flood-related costs in areas developed on organic soils. Flood prevention measures in these areas, such as levee construction, clearly are expensive. In the Everglades region of south Florida, a special flood-control district with an annual budget of $69 million is required to manage an extensive water-control system, including 1,284 km of levees, with a replacement value of about $1.5 billion. Just one part of New Orleans's levee system, the Lakefront Levee, cost $27 million ($240 million in 1976 dollars) to build in 1926 (Wagner and Durabb, 1976). Levee repair, dewatering of flooded areas, and flood damage in the California Delta cost about $177 million from 1969 to 1983 (Prokopovich, 1985).

Structural damage costs from differential subsidence caused by drainage of organic soils

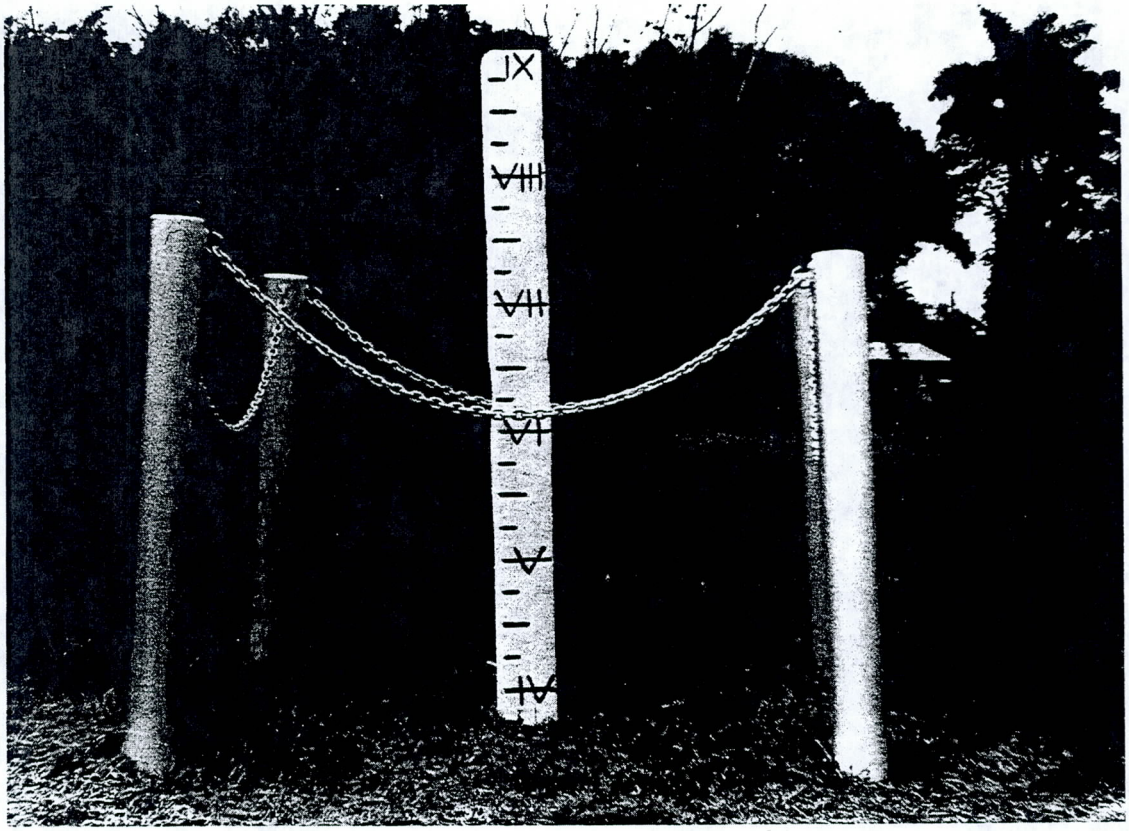

FIGURE 15 Concrete monument set on rock beneath organic soil in Belle Glade, Florida, an active subsidence area. Elevation painted on monument is feet above mean sea level. Dates show former elevation of land surface. Photograph was taken October 1987. (Courtesy of George H. Snyder.)

appear to be high. HRB-Singer (1977) estimates that approximately $30 million (in 1977 dollars) is spent annually in New Orleans to repair damages and maintain property. Earle's (1975) study in New Orleans indicates that costs are disproportionately distributed. Forty-five percent of his homeowner sample incurred problems; 5 percent encountered serious problems.

The dollar value of economic losses from subsidence reveals only part of the nation's subsidence problem. Inequitable aspects of both economic incentives and the American legal structure are major factors in the nation's subsidence problem, particularly where subsidence is caused by resource extraction or land use. Often existing legal or market incentives do not encourage the developer of a resource to consider the costs imposed on others who do not receive the benefit of development. These are termed external costs.

External costs cause misallocation of society's resources. Social costs, the costs to society as a whole, are greater than private costs when there are external costs. Thus, for example, a mine operator who has caused subsidence on land that he does not own receives all of the benefits of ore production but pays only the private cost, a portion of the social cost. The surface property owner affected by subsidence, however, receives none of the benefits, yet bears the external costs from the actions of the mine operator. This misallocation of resources is corrected when the mine operator pays all of the social costs, private and external, of the mine operation.

FIGURE 16 Organic soil subsidence in Florida Everglades. Piles supporting structures rest on firm layer beneath organic soil. As organic soil decreased in thickness, ground surface subsided, leaving structures elevated. (Photograph courtesy of John C. Stephens.)

TABLE 2 Estimated Annual Losses (in millions) from Land Subsidence

Mines	$ 30
Sinkholes	10
Underground fluid withdrawal	35
Natural compaction	10
Hydrocompaction	Not available
Organic soils	40
TOTAL	$125

SOURCES: Jones (1977), Newton (1986), Propokovich and Marriott, (1983), HRB-Singer (1977).

In evaluating external costs, several dimensions are worth noting. External costs from subsidence can stem from past activities, as in the case of abandoned mines, and can be viewed as a one-time imposition of some level of external costs on the future. Alternatively, past and current activities can cause a continuing subsidence problem. These types of external costs are direct. External costs from subsidence also may be indirect. These include situations where subsidence increases the potential for economic damage from other natural events. Increased susceptibility to flooding from storm surges of low-lying coastal areas is an example.

Another category of external costs potentially presents a special dilemma. This involves situations where the external cost is borne in perpetuity by future generations. For example, consider where drainage of organic soil causes land to subside below sea level or alters the freshwater-saltwater balance. In such cases, land may simply disappear because of inundation, or the ecology may change, and thus a permanent loss is passed on to future generations.

At common law the principal means to prevent externalities by transferring external costs to the actor who created them is the tort system. That system generally has a two-fold purpose: (1) to compensate worthy victims for damages they have suffered by the negligence of others (thus imposing the costs of the damage on the actor who created them), and (2) to act as a deterrent to negligent activity, that is, to encourage the actor to decide not to engage in an activity if it creates a cost that can be transferred back to that actor in a tort or lawsuit.

There are at least three reasons the legal system does not provide an adequate mechanism for transferring subsidence costs onto the actors that create them (Amandes, 1984). First, in many states, such as those applying the English common law doctrine of absolute ownership of groundwater, the legal system does not allow a party injured by subsidence to recover from the person causing the subsidence. In those states, ownership of the groundwater is said to be absolute, and any effects created by groundwater withdrawal must be borne where they fall. Similarly, the legal system may not provide a recovery mechanism for a surface owner injured by the subsidence caused by underground mining. Second, even in those jurisdictions that allow recovery of subsidence damage, lack of public understanding about the causes and effects of subsidence may prevent members of the public from recognizing their damages and the identity of those who caused them. Even if some members of the public can successfully recover their losses, any members of the public who do not or cannot recover their losses will leave external costs that are not internalized. Third, because many of the damages caused by subsidence are indirect, the full cost of subsidence may not be recognized. For example, a flood may inundate 1,000 ha when it would have inundated only 500 ha in the absence of subsidence. The owners of the property whose inundation was caused by the subsidence may not recognize the role played by subsidence in expanding the flooded area. From an economic point of view, these indirect costs are as significant as direct costs and, if they are not recognized and recovered, they will not be internalized.

When traditional legal mechanisms fail to provide adequate control over external economic costs, governments may create statutory or regulatory controls to compensate for the deficiencies in the common law. These are not always limited to recovery for negligent performance of an activity. Legislation can remove the element of negligence by establishing strict liability for surface damages. Alternatively, administrative regulation may be used to address local subsidence problems by either imposing taxes that internalize the external cost or regulating resource removal or usage (Amandes, 1984).

Given that subsidence commonly is a phenomenon characterized as imposed external cost due to legal conflicts or market failure, what are the barriers to mitigating external costs? At least three barriers inhibit the design of appropriate public policy measures. First, a significant barrier is simply the lack of availability and public understanding of the scientific literature; it is difficult to mitigate the unknown. Second, subsidence is not typically viewed as a catastrophic event or even necessarily the primary cause of large economic damages. As such, on the agenda of preparations for natural hazards, subsidence is low. Third, the potential for long delays in the observance of phenomena causes significant problems for public policy response.

2
A Survey of Current Mitigation Measures

INTRODUCTION

The many causes and forms of land subsidence have led to a broad variety of efforts to mitigate subsidence problems in the United States (Figure 17). These efforts address problems in areas that are either already developed or proposed for development. The following survey of these efforts demonstrates that no single approach is applicable to all cases. Approaches that are in use include voluntary and educational measures such as public information and mapping programs to raise public consciousness, regulatory schemes that require subsidence prevention or control, land-use management and building codes to reduce damage, market-based methods to transfer the costs of subsidence to the parties causing it, and insurance programs to distribute cost more equitably.

PUBLIC INFORMATION PROGRAMS

Many problems related to land subsidence are hazardous only if they are unexpected. An informed public can minimize its exposure to financial loss and personal injury from subsidence-related problems, even in areas where little can be done to arrest the underlying subsidence process itself. For this reason, public information programs are under way in most areas with major subsidence problems, ranging from very informal ones conducted by local college professors to highly organized ones conducted by special-interest agencies. In addition, many federal and state earth science agencies, such as the U.S. Geological Survey, Soil Conservation Service, and state geological surveys, commonly publish nontechnical literature on subsidence problems.

The objectives and scope of these programs vary. In its most restricted form, the effort may be addressed to a narrow audience of engineers, architects, geologists, land-use planners, code administrators, and insurers who directly confront subsidence-related problems in the course of their work. Detailed technical information is disseminated through professional societies, federal and state scientific and regulatory agencies, and county and municipal agencies charged with land development, regulation, and the subsidence problem for the public at large.

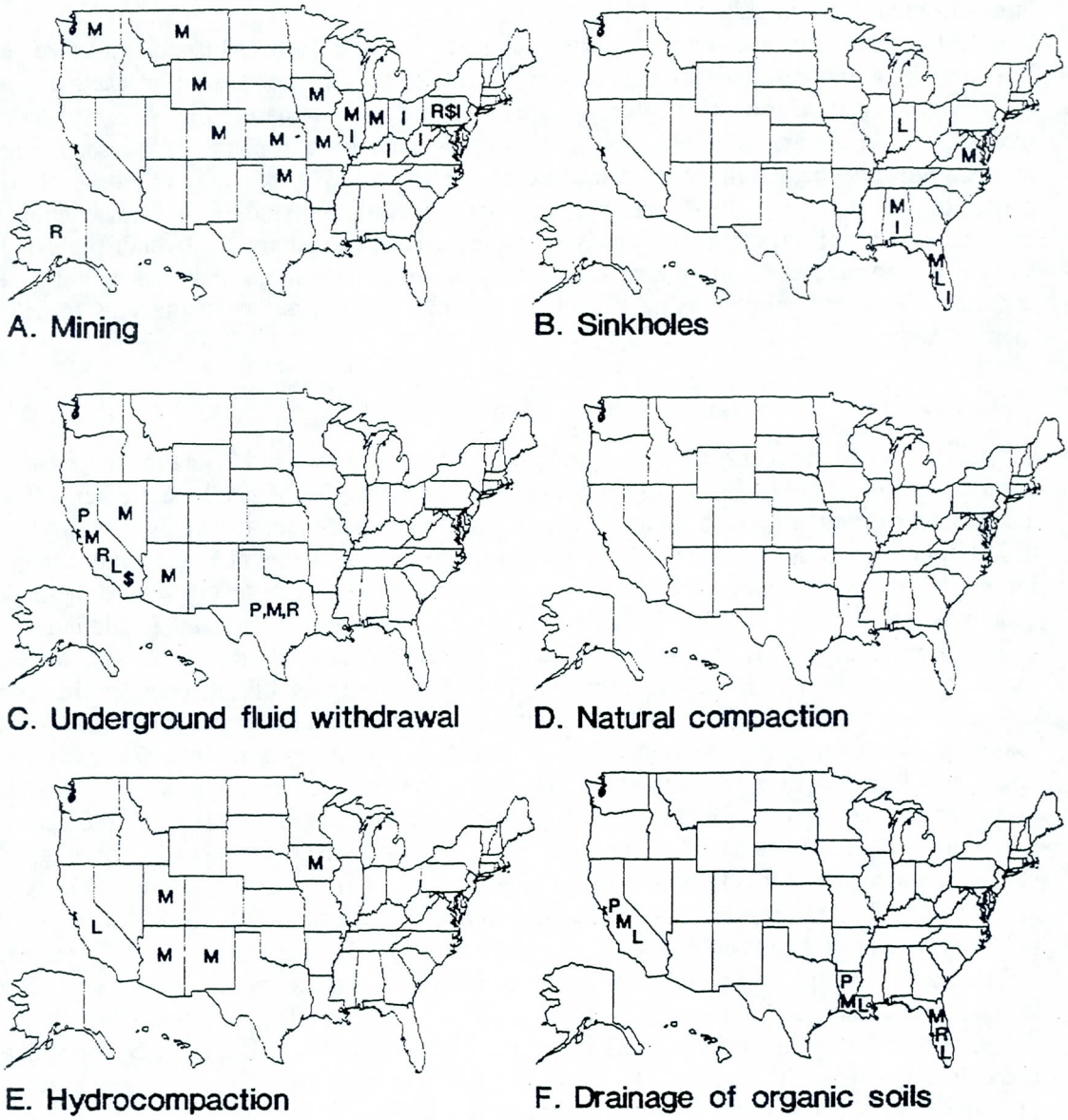

FIGURE 17 Summary of mitigation measures by state for each type of subsidence.

Information activity is generally the first activity to be undertaken in a subsidence-affected area, beginning even before the general public may become aware that a problem exists. Similarly, such activity persists in areas where subsidence has successfully been arrested, even after the issue has receded from public attention.

As the severity of subsidence increases, so does the need for greater public involvement. In managing a major subsidence problem, two kinds of public information are needed. First, the public must be alerted to the specific area involved and the nature of the hazard so that individuals can assume an active role in managing their own exposure to personal injury or loss. Second, the public information program must foster a general awareness of what causes the subsidence problem and what options are available, since an informed public is more supportive of the sometimes-costly measures needed to manage the overall problem. A survey of information efforts under way in several subsidence areas shows that, with these common objectives, programs in different regions rely upon a variety of methods to deliver their message.

Mining

Illinois provides an example of the educational role state laws and insurance programs can play in improving public awareness of subsidence problems (DuMontelle and others, 1981). The insurance program covers damages caused by mine subsidence, and the policy provides a description of particular hazards homeowners may face. In the 34 counties most prone to coal-mine subsidence, insurance is automatic unless the homeowner specifically waives the policy. This provision causes a high level of awareness of the hazards in these areas. In addition, state law requires that homeowners receive notice 6 months before the start of mining activities that may cause subsidence of their property. In the remaining 64 Illinois counties, insurance coverage is not automatically provided, leaving homeowners with a greater responsibility for assessing their own risks and determining whether they need to seek out the state's insurance coverage. That residents who are not affected by mine subsidence nevertheless have a high awareness of subsidence-related hazards is demonstrated by the fact that more than 80 percent of claims made under the state insurance program are for damage not related to mining. The state geological survey has programs under way to ascertain the causes of those problems that are not related to mining and has prepared publications, brochures, billboard displays, and radio segments to enhance public awareness of the problems. It also works with other state and local agencies to provide needed information in the event of subsidence damage to pipelines, streets, foundations, and cultivated fields.

Colorado has published a special booklet for the homeowner that describes subsidence above inactive mines (Turney, 1985). It describes how homeowners can evaluate the subsidence hazard and what actions they can take to minimize damage.

Sinkholes

In Florida, despite wide public awareness of the sinkhole problem fostered by the news media, understanding of the causes of collapse remains somewhat limited. Toward this end, the U.S. Geological Survey, Southwest Florida Water Management District, and Florida Sinkhole Research Institute offer circulars and lectures, slide shows for use in public schools, and an ongoing educational program for engineers, geologists, and insurers who must deal with the problem on a technical basis (Beck and Sinclair, 1986). In addition, the Florida Sinkhole Research Institute publishes a quarterly newsletter, *Update*.

Underground Fluid Withdrawal

In the Houston, Texas, area the most dangerous and potentially costly problem related to subsidence is intermittent flooding and permanent inundation of coastal areas. Accordingly, the Harris-Galveston Coastal Subsidence District devotes most of its public information effort to the flooding hazard. The district annually adopts a plan setting specific targets and objectives for civic and media presentations, news releases, publications (including the quarterly newsletter *Subsidence Update*) and in-school programs. This integrated program to inform the public of subsidence-related flood hazards has been so successful that the district reports that many flood victims in the area identify subsidence as the proximate cause of damage even when it is not. Thus, part of the district's program is devoted to helping residents distinguish subsidence-related flooding from other flooding problems, such as inadequate drainage, so that appropriate remedial actions can be taken where possible. Another aspect of the district's program is its effort to foster an awareness of the causes of subsidence and of options for managing the problem. In a recent survey the district found that 73 percent of area residents had heard of subsidence and, of those, 61 percent could correctly identify the cause. This high degree of public awareness is critical in an area where management of the underlying problem—excessive groundwater withdrawal—calls for concerted conservation efforts and public support for construction of surface-water treatment and transmission facilities.

Hydrocompaction

Public information efforts to reduce damaging hydrocompaction have been limited primarily to popular serials of state geological surveys, for example, *California Geology* and *New Mexico Geology*. Articles in these serials have both identified where problems with hydrocompaction are occurring and described proper construction practices. These serials, widely distributed among practicing professionals such as engineering geologists and geotechnical engineers, help alert them to areas where special precautions need to be taken.

Organic Soils

The public information role of local government is illustrated in southern Louisiana, where the Terrebonne Parish Consolidated Government has an intensive education campaign under way to provide information about the problems of flooding, land loss along the shoreline and interior canals, and saltwater encroachment in cultivated areas. In addition to conducting detailed technical studies, the parish develops circulars, brochures, billboard displays, and slide shows aimed at a wider audience. Included in the eighth-grade curriculum in area schools is a course of instruction covering the mechanics of subsidence and possible remedies.

MAPPING PROGRAMS

The hazards and economic costs associated with land subsidence depend upon its proximity to populations, manmade structures, and water bodies. For this reason, mapping programs are an important element in efforts to identify and manage subsidence problems. Such programs are frequently an early step in subsidence-hazard-mitigation efforts. Depending upon the type of subsidence involved, the scope and objectives of these programs vary, as does the degree of interaction among federal, state, and local agencies. This section presents representative examples of subsidence mapping programs carried out in recent years.

Mining

In 1977, Congress passed the Surface Mining Control and Reclamation Act (SMCRA) to mitigate the impact of past surface and subsurface coal mining and to regulate future mining activities. As part of this act, revenues from a tax on current coal operations are deposited in the Abandoned Mine Reclamation Fund, and the Office of Surface Mining Reclamation and Enforcement (OSMRE) was created to administer the fund. To determine the reclamation needs of the states, OSMRE contracted with many states to map general locations of abandoned mines.

As an example of the studies carried out at the state level, the state of Washington conducted an inventory and identified 10 problem areas where abandoned mines posed immediate hazards or the danger of subsidence. Additional subsidence emergencies outside the inventoried areas led to a 1984 cooperative agreement between Washington and OSMRE to conduct a more-exhaustive inventory and mapping effort. The objectives of the agreement were to map abandoned mines by county and by quadrangle; to categorize the sites by severity of hazard, accessibility, and proximity to population; and to rank the sites for remedial action. By 1985, 84 problem areas were identified and mapped, of which 26 were assigned priority for remedial action and 5 were targeted for more detailed mapping and assessment.

Similar activities have been carried out in other states. For example, Colorado has conducted extensive statewide mapping of real and potential subsidence problems at scales ranging from 1:2,400 to 1:50,000. About 900 abandoned coal mines and over 7,000 abandoned metal mines were inspected, and results were summarized in a state map published at a 1:1,000,000 scale (Bucknam, 1982). Indiana and Wyoming each mapped underground coal mines at 1:24,000 scales. Montana inventoried its abandoned mines statewide on a scale of 1:250,000.

As follow-up to the SMCRA inventories, some states have initiated special subsidence mapping studies. For example, the Montana Department of State Lands prepared detailed maps for a 1,600-ha mining area in the northeast corner of the state, which has historically been prone to subsidence problems.

In addition to the mapping program sponsored by SMCRA, other efforts are under way at the federal, state, county, and municipal levels. In Illinois, the state geological survey has published maps in connection with the state subsidence insurance program enacted in 1979. These maps, at a scale of 1:100,000, show mined-out areas along with shafts and other features and provide information about susceptibility to, as well as the history of, subsidence problems. In Iowa, mapping efforts date back to the 1890s, when the Iowa Geological Survey first published maps of active and abandoned lead and zinc mines in Dubuque County. At present, the survey keeps over 1,450 coal-mine maps on file. In addition to its ongoing mapping efforts, the survey provides assistance to county and municipal authorities concerned about future mine-subsidence problems.

In addition to routine mapping programs, special mapping studies are sometimes initiated in response to immediate environmental concerns. In 1979, for example, congressmen from the tri-state mining area of Oklahoma, Missouri, and Kansas sought assistance from the U.S. Bureau of Mines. Over a period of several years, the bureau worked with the state geological surveys to map abandoned mine sites, appraise subsidence hazards, and propose remedial actions.

Sinkholes

Mapping efforts in areas susceptible to sinkhole collapse range from compilations of existing sinkholes and geologic conditions favorable for sinkhole development to detailed studies that consider the potential for sinkhole development.

The smallest-scale map available is that by Davies and others (1976), who mapped areas in the conterminous United States underlain by cavernous limestone and marble. The map, published at a scale of 1:7,500,000, identifies broad areas where there is a potential for catastrophic subsidence.

Several states have undertaken mapping at larger scales. The Alabama Geological Survey, in cooperation with the U.S. Geological Survey and the State Department of Transportation, has supported mapping of catastrophic subsidence from sinkhole collapse. The program has produced detailed maps of subsidence features for 38 counties and identified potential areas of subsidence and triggering mechanisms. This effort has been the basis for resolution of a number of court cases involving subsidence, as well as the implementation of a state insurance program. Mapping at an even more local scale is illustrated by the city of Huntsville, Alabama, which is planning a series of special maps, building design criteria, and codes to be used in subsidence-prone areas within the city limits.

The Virginia Division of Mineral Resources (Hubbard, 1983) recently completed a mapping study of karst features in the northern part of the state and has a similar study under way in the southern part. Susceptibility to future catastrophic subsidence in Florida has also been addressed in recent mapping (Sinclair and Stewart, 1985).

Underground Fluid Withdrawal

Mapping plays an important role in both identification and management of subsidence problems caused by fluid withdrawal. Maps of water levels in aquifers are commonly used for prediction and monitoring purposes, both in areas where subsidence is actively occurring (for example, Houston, Texas) and in areas where subsidence is arrested (for example, Santa Clara Valley, California). Maps of subsidence determined from releveling of geodetic control networks are the basic tool used to study the evolution and areal distribution of subsidence (Figure 18). For example, in the Houston area, maps of changes of surface elevation dating back to 1906 have been used. The National Geodetic Survey has performed comprehensive relevelings at regular intervals, including recent relevelings in 1973, 1978, and 1987. These are supplemented with limited releveling projects, such as those carried out in 1976 and 1983. This frequent updating of the maps permits monitoring of the performance of remedial programs by the Harris-Galveston Coastal Subsidence District and ensures that residents will have up-to-date information about the flood hazards they face. Other maps prepared by the district include predicted subsidence for up to 40 years (Harris-Galveston Coastal Subsidence District, 1985).

Maps at scales ranging from 1:24,000 to 1:250,000 of ground ruptures associated with land subsidence are available in several areas, including parts of southern Arizona; Fremont Valley, California; Houston, Texas; and Las Vegas Valley, Nevada. Three of the areas include cities—Phoenix, Houston, and Las Vegas—that have undergone explosive growth in the last two decades. Availability of maps in these two areas has improved public awareness of the hazard and encouraged voluntary efforts to avoid construction on these damaging surface ruptures.

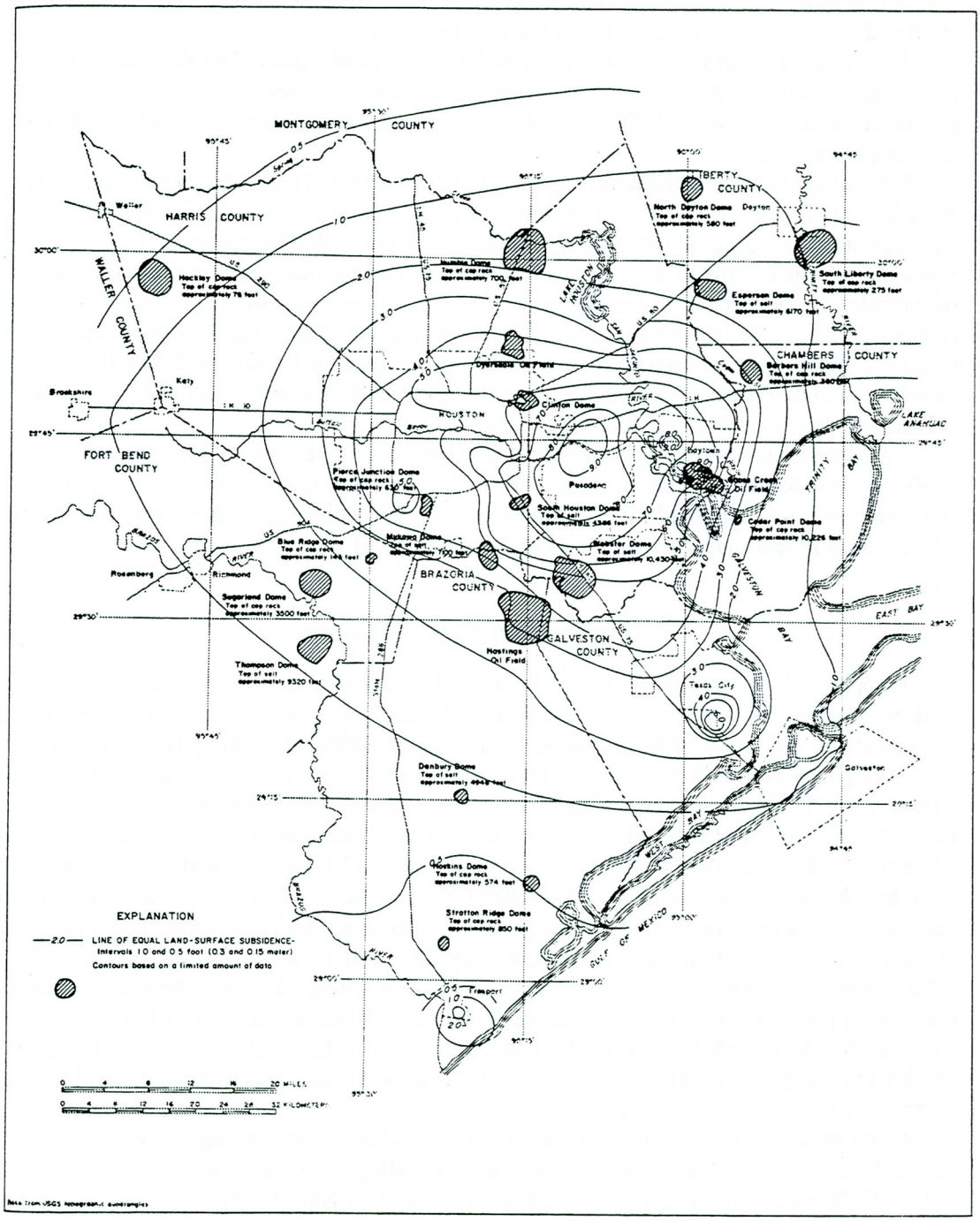

FIGURE 18 Map of land subsidence in the Houston-Galveston, Texas, area from 1906 to 1978. At least 12,200 km^2 has subsided 15 cm or more. Note that the eastern part of subsidence bowl underlies Galveston Bay. (From Gabrysch, 1982.)

Hydrocompaction

Mapping of areas prone to hydrocompaction ranges from general efforts to identify the type and distribution of collapsible soils to more specific efforts to locate and quantify subsidence hazards. In the latter case, the susceptibility to subsidence hazards is determined by combining data about soil distribution with laboratory data on soil properties. The result is a map of "collapse probabilities."

This mapping approach has been applied in Iowa, where one-third of the state is covered by loess deposits subject to collapse when saturated. The state map of collapse probability was prepared by combining maps of clay-content contours with laboratory data relating clay content to collapsibility (Handy, 1973).

In Arizona the U.S. Soil Conservation Service has worked with state authorities to develop a state map of major soils, identifying those most susceptible to collapse (Soil Conservation Service, 1975). In New Mexico a general assessment and mapping program is under way, following incidents of soil collapse in the northern part of the state. The Utah Geological and Mineral Survey has mapped a 8,100-ha area with collapsible soils in the vicinity of Cedar Creek (Kaliser, 1978).

Organic Soils

Nationwide recognition of the ecologic significance of wetlands, the provenance of organic soils, has led to their extensive mapping at both local and national scales. Not all wetlands, however, are underlain by peat and muck, the type of organic soil that is prone to subsidence when drained. Hence, use of these maps for assessing subsidence potential is limited. Soil surveys prepared by the Soil Conservation Service of the U.S. Department of Agriculture are widely available and potentially provide more-useful information, because they identify soil types in wetland areas including peat and muck, technically known as histosols. Soil surveys, however, are based on shallow excavations and do not map total organic soil thickness, and thus are of limited use for estimating potential magnitudes of subsidence. Nevertheless, these surveys provide a useful starting point for areal investigations of subsidence.

The thickness of a peat and muck deposit is probably the most useful parameter for assessing subsidence potential. Accordingly, maps of peat and muck thickness have been a common element of areal organic soil subsidence investigations (Snowden and others, 1980; Newmarch, 1981).

REGULATION OF RESOURCE AND LAND DEVELOPMENT—PREVENTION AND CONTROL

Regulation of the activity that causes subsidence is the most direct approach to subsidence mitigation. Approaches to preventing or controlling subsidence to minimize damage vary widely. In the case of resource extraction, they range from banning resource extraction to controlling how materials are removed. In the case of land development practices that cause subsidence, they range from banning development to regulating construction practice.

Mining

Subsidence damage resulting from mineral extraction can be prevented or controlled by leaving some material behind for support or totally refilling mined-out volumes. In active

mines pillars of unmined material can be designed to support the overlying strata, pillars can be constructed to replace the mined material, or the mine can be filled with lower-cost materials.

Subsidence due to active coal mining is regulated by the SMCRA. To ensure compliance with these regulations, operators are required to post a bond. This act requires coal mine operators to submit a Subsidence Control Plan as part of their permit application. In the plan the operator must identify the mineral extraction methods to be used and plans for subsidence control or methods to be used to prevent material damage resulting from subsidence. The plan must spell out the measures to be taken for reducing the probability of subsidence, such as backfilling, stowing, or supports, as well as measures to be taken on the surface to prevent material damage to structures or reductions in land values or plan for possible future land use. The specific mitigation measures, several of which are identified in the regulations, are left to the discretion of the operator.

Leaving unmined pillars suitable for long-term support of the overlying strata results in incomplete use of the resource being mined. In addition, if the long-term supports are underdesigned, subsidence will eventually occur. Thus, full-extraction mining with planned subsidence is permitted by SMCRA.

Subsidence can be prevented or controlled if some suitable support is provided in lieu of the removed material. This can be accomplished in several ways, the most feasible of which is to fill the voids with low-cost solid material. Hydraulic filling is the most widely practiced method of mine filling. It involves transporting or flushing the fill material with water through pipelines and boreholes to the point of stowage in the mine.

Hydraulic filling of abandoned underground coal mines with subsidence problems is supported by a tax imposed by SMCRA on each ton of coal mined. Revenues from this tax may be used only to reclaim abandoned mine lands. Subsidence is addressed on a priority basis, with the most potentially dangerous situations receiving highest priority. This reclamation program is not aimed at preventing the initial subsidence of lands over mines; its purpose is to mitigate subsidence of undermined lands and to impede future subsidence of such lands.

In addition to government subsurface stabilization programs, commercial and industrial developments in mining areas have included subsidence prevention or control measures. For example, in a suburban Pittsburgh shopping mall, the site grading plan accounted for a mined-out coal seam by placing the mall at the base of the mined coal and using the excavated material from above the mine to develop parking areas around the mall. The excavation involved 4.6 million m^3 of soil and rock.

Sinkholes

Catastrophic subsidence associated with the formation of sinkholes is most commonly triggered by either groundwater-level declines caused by pumping, or diversion of surface runoff. Thus, the occurrence of catastrophic subsidence can be prevented in principle by controlling these two activities. To date, attempts in the United States to control activities that trigger subsidence have been limited, and no controls have been required by regulation. Catastrophic subsidence problems are usually dealt with by after-the-fact maintenance. Design and construction of the Pellissippi Parkway extension in Tennessee, however, offer an exception (Moore, 1984). Special efforts were made to divert runoff along the parkway from entering the underlying cavernous system and eroding overlying sediment. These efforts included paved

ditches and asphalt curbs in areas of potential collapse and improvement of flow into natural drainage depressions to minimize erosional enlargement.

Filling underground voids with grout has been successfully used to prevent catastrophic subsidence (Ryan, 1984). Grouting is commonly used in general engineering practice to strengthen foundations and stop the flow of underground water. Its application to sinkhole prevention differs from the more common applications in that larger volumes of grout are required, and the strength of the grout is lower. Particularly because of the volume, the economic viability of the technique is limited in most situations to major engineering works, and the technique has been used sparingly (Ryan, 1984).

Dynamic compaction, a soil-improvement technique that consists of the repeated dropping of a heavy steel weight, has been successfully used in Florida and South Africa to prevent postconstruction catastrophic subsidence (Guyot, 1984). Even where the method does not cause collapse of the preexisting voids, analysis of the resultant surface deformation may aid their detection.

Underground Fluid Withdrawal

Several alternatives are available to control subsidence caused by withdrawal of underground fluids. Prevention or control measures include repressuring the withdrawal zone by injection or enhanced recharge and reducing the amount of fluid withdrawn.

Operation of the Wilmington oil field in Long Beach, California, provides a well-documented example of subsidence control through repressuring by injection (Mayuga, 1970). Subsidence, which ultimately reached almost 9 m, was first recognized in 1941. Repressuring by injection of water started in 1954 under the threat of litigation; major injection (57,000 m^3 per day) began in 1958. By 1966, repressuring had arrested subsidence throughout most of the subsidence area. The experience with the Wilmington oil field led to passage of the California Subsidence Act of 1958. The act provides for arresting or ameliorating subsidence caused by petroleum withdrawal by requiring the repressuring of subsurface formations. The law applies only to coastal areas subject to flooding or inundation.

Repressuring also has been practiced in the Santa Clara Valley, California, by construction of special aquifer-recharge facilities along stream beds around the margin of the valley where the aquifer system is unconfined. Although the primary purpose of the recharge is to mitigate basin overdraft, it has the collateral benefit of arresting subsidence.

Reduction of groundwater withdrawal in the Houston-Galveston, Texas, area provides an example of subsidence control by regulation. In 1975, the Texas legislature authorized formation of the Harris-Galveston Coastal Subsidence District for the purpose of mitigating flooding. Authority to regulate groundwater withdrawal through a permit process was delegated to the district. The district has imposed cutbacks of pumping that are really selective in order to stop subsidence in the coastal area, where the flood hazard is greatest. The district is subdivided into large zones, based on amounts of subsidence that have taken place and on the potential effects of subsidence if withdrawal continues. In each of these zones a goal has been set for reducing groundwater use. For example, in Zone 1, which is adjacent to the coast, groundwater pumpage is to be reduced by 1990 to 10 percent of the total water use in the area; in Zone 8, which is the most inland area, pumpage may continue unabated, but no exports out of the area are permitted. The district also reduces groundwater use by encouraging conservation of water and voluntary use of surface water that has been made available by local

water agencies. A shortcoming to the district's authority is that it cannot restrict groundwater use where surface-water supplies are unavailable.

Hydrocompaction

No regulations are in force to control or prevent damage from hydrocompaction, although mitigation techniques are available. Damage can be prevented by diverting surface drainage from structures or controlled by precompacting foundations. A few examples of paving areas to divert surface water from structures have been reported (Peck and Peck, 1948). Preconstruction wetting of foundations, known as prewetting, has been extensively practiced in the United States to compact foundations beneath hydraulic structures such as dams and canals where postconstruction percolation of surface water into the subsurface is difficult to prevent (Lofgren, 1969). Alternative techniques that have been tried primarily on an experimental basis, but which offer promise, are vibroflotation and dynamic compaction (Lovelace and others, 1982). These methods, which densify the soil by dynamic forces, are specialized methods that require some degree of proprietary equipment and knowledge of application (Figure 19).

Organic Soils

Organic soils presently cannot be developed for agriculture or urban use if drained without incurring subsidence. Rates can be slowed, however, by controlling water-table depths and practicing good land management. Unfortunately, regarding agricultural use, crop yield studies indicate that water-table depths of 30 to 60 cm for pasture grass and 60 to 90 cm for most brush and field crops are desirable in temperate climates. Thus, at optimum drainage levels for good production of these crops, subsidence occurs at undesirable rates. Seasonal flooding can reduce subsidence, as will growing water-tolerant crops such as rice.

Barring a breakthrough in the science of organic soil conservation, subsidence will continue on organic soils. Meanwhile, these steps could be taken to obtain maximum agricultural use of organic soils and minimize subsidence: keep water tables as high as crop and field conditions permit and put drained soils into productive use as soon as possible. In areas of urban development, dewatering should be minimized as much as possible. Suitable lightweight fill should be added at required intervals, which would mitigate the need for ongoing water-table lowering.

LAND-USE MANAGEMENT AND BUILDING CODES

Land-use management and regulations in the presence of real or potential subsidence is an alternative to regulating resource development. Land-use planning and zoning, specialized building codes, official maps, and constraints for public utilities accomplish this.

The appropriate land-use planning response to subsidence depends on the nature of the subsidence. For example, conventional local land-use planning and zoning, which apply to land areas or districts of relatively small extent, have limited applicability in dealing with broad regional types of subsidence from fluid withdrawal. For small tracts of organic soils, regulatory schemes such as zoning may be feasible. For large tracts, such as the San Joaquin-Sacramento River Delta, the Florida Everglades, and the Mississippi River Delta, historical experience has taught that careful preplanning based on land capability and economic opportunities is essential for successful development. Agencies with regulatory powers then help implement the plans

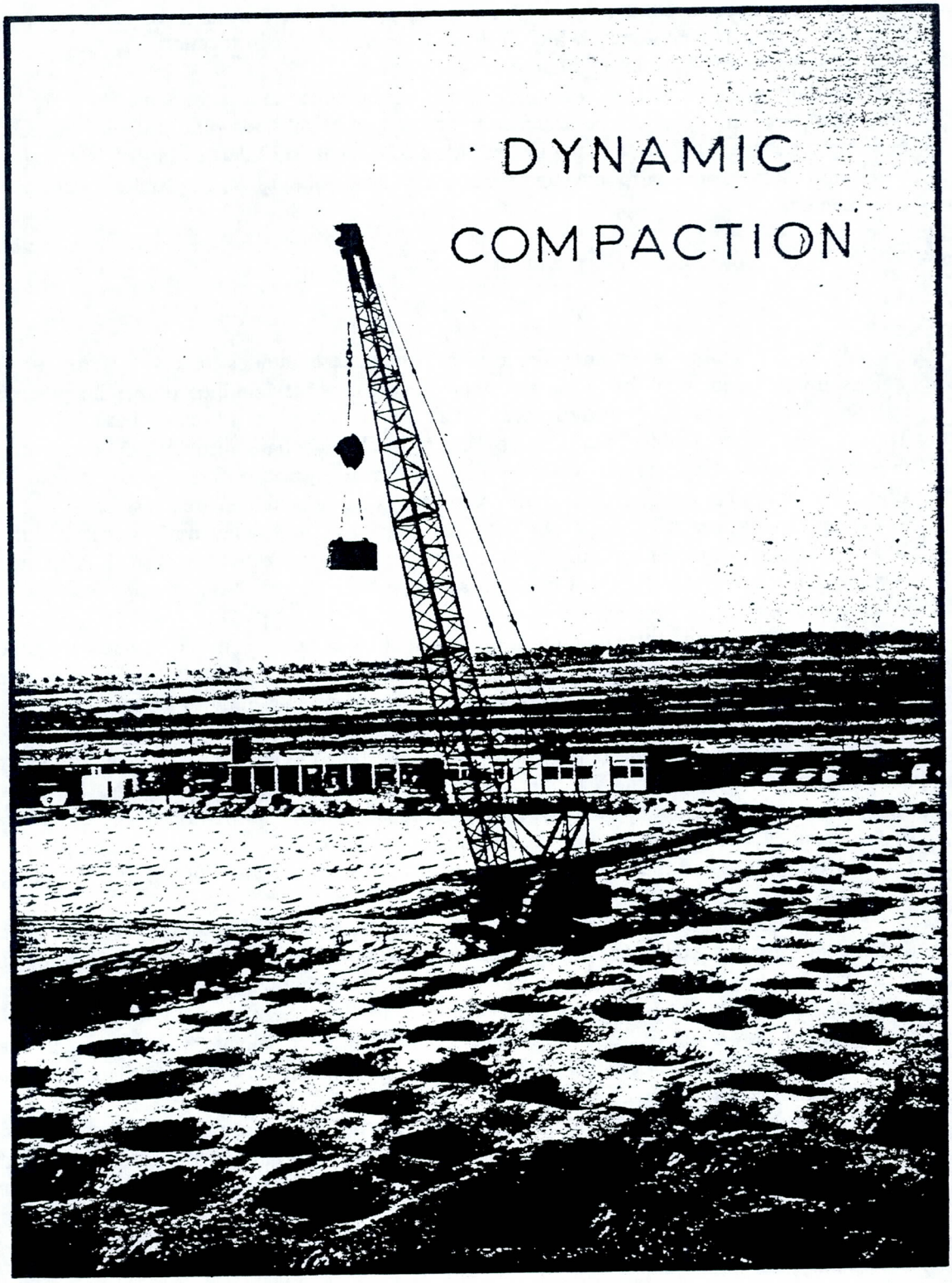

FIGURE 19 Experiment conducted by New Mexico State Highway Department to test feasibility of precompacting collapsible soils by dropping a heavy weight on the ground. (From Lovelace and others, 1982.)

and building codes to control construction techniques. In the case of localized subsidence in karst areas and over mines, which is even less predictable in location and in time, the cost-effectiveness of land-use regulation can be questioned.

Building codes are an alternative to land-use regulation for some situations. Buildings and other facilities sometimes can be designed to accommodate subsidence movements. Although building codes are rarely used in the United States to mitigate subsidence, they often recognize special problems that require investigation and evaluation of subsidence problems before site development.

Mining

Although planning and zoning authorities in most communities underlain by mines are well aware of the potential for subsidence, local governments seldom incorporate this potential into land-use plans or zoning ordinances. There are probably two principal reasons for this. The first reason is that while broad areas subject to localized collapse usually can be identified, the likelihood of collapse at any particular location during a given period of years is relatively slight. The second reason is that in some communities the undermined area is so large relative to the few incidences of damage per year that special controls may not be cost-effective. Also, depressed communities working to revitalize their local economies, such as those in northeastern Pennsylvania, are not likely to advertise their susceptibility to subsidence while seeking investments in the area.

Land-use planning authorities in other countries have incorporated mine-subsidence potential into the planning process. In Great Britain, mining in many areas is incorporated as an element of the development permission process. Most mining in these areas is carried out by the longwall technique, with which subsidence is predictable. New development can either be delayed until after the subsidence takes place or designed to minimize damage. In the city of Whangerei, New Zealand, a zoning scheme has been developed that requires actions to minimize subsidence damage depending on the degree of subsidence risk. In Zone 1, removal of the subsidence hazard is required before approval will be given for subdivision of land or for new construction. In Zone 2, special construction measures are required for subsidence damage resistance.

Subsidence-resistant design could be incorporated into building codes in areas of abandoned coal mines as well, so as to permit full extraction without serious structural damage in areas of active mining. The goal of resistant designs is to minimize damage, since prevention of damage is not always cost-effective. The difficulty for the designer is selection of reasonable parameters of movement or force that will effectively minimize damage without prohibitively increasing cost. Chen and others (1974) summarize allowable ground deformations for active mining in Europe and Japan.

The two basic approaches in subsidence-resistant design are to use either a flexible or rigid slab. Basements or other projections below ground level are discouraged. Support of structures on slabs at the ground surface is structurally desirable because it allows the ground to move freely below the structure.

Flexible structures having a pin-jointed steel frame with cladding designed to move relative to the frame offer many advantages in a subsidence-prone area. Since 1956 a form of flexible construction known as CLASP has been used for over 2,000 buildings in Great Britain. Bell (1978) reviewed the performance of buildings built with the CLASP system over a 15-year

THE NETHERLANDS - A MILLENNIUM OF SUBSIDENCE MANAGEMENT

One of the oldest records of man-induced subsidence appears to be on the organic soils of the old grassland polders in the western part of the Netherlands. The low-moor peat soils in these old polders, with elevations initially near sea level, were reclaimed between the ninth and thirteenth centuries. Initially excess water was drained by gravity through sluice gates that were opened at low tide. Around the beginning of the thirteenth century, drainage problems that were in part attributable to subsidence led to the installation of hand- and horse-powered pumps. This system of drainage continued until the fifteenth century, when the land surface had subsided to such an extent that windmills were required to pump out the excess drainage water (Figure 20). By the nineteenth century, total subsidence ranged from 1 to 2 m. About 1870, pumping stations powered by steam, and later by diesel and electric motors, were placed into operation. The increased drainage caused subsidence to accelerate. Whereas the first 1 to 2 m of subsidence occurred in a millennium, the next 0.5 m took only a century.

The complex development of land and water resources in the Netherlands required water resources management that could operate effectively, swiftly, and fairly. In the twelfth century, when the first regional waterworks came into operation, the first management groups, called waterboards, were established. From the fourteenth through sixteenth centuries, region after region developed its own waterboard. With time, the more powerful boards assimilated smaller local boards. They also increasingly assumed responsibilities, formerly belonging to villages and farmers, for the maintenance and repair of dikes, dams, and sluices. These waterboards possessed great powers in the Middle Ages. They were responsible for all justice in the area of water administration and could even impose capital punishment on offenders.

About 1840, changes in the Dutch constitution gave the provincial governments power to recognize these boards and create new laws and regulations for them. This led to a more democratic structure within the boards and the election of representatives by landowners. Today, about 200 waterboards staffed with expert technical and administrative personnel manage these water resources of the Dutch polders.

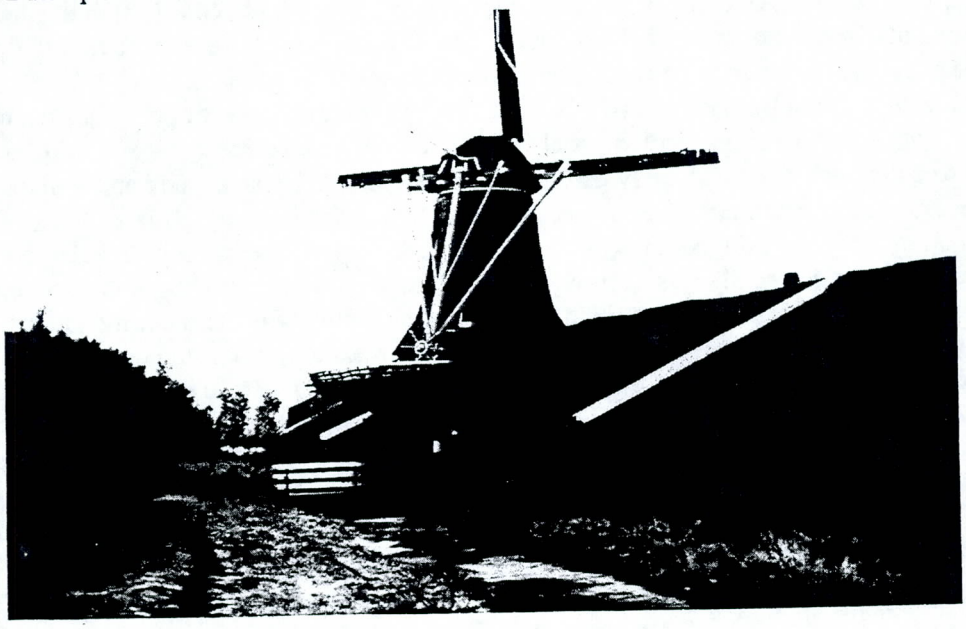

FIGURE 20 Dutch windmills have played an important role in organic soil subsidence in Holland because they have been used to facilitate drainage of areas underlain by organic soils. (Photograph courtesy of John C. Stephens.)

period (1957-1971) in the Nottinghamshire area and concludes that it worked well. Such designs have not been used in the United States.

Rigid structures are another approach to subsidence. Usually, the foundation consists of a thick slab or raft stiffened by thick shear walls. Such structures may be provided with facilities for jacking them level if tilting should occur. In some cases, rigid structures have been used in conjunction with a three-point support system. The structure can tilt without distress and be jacked back into position (National Coal Board, 1978). Cochran (1971) estimates that a 0.15-m-thick reinforced concrete slab would add 4 percent to the purchase price of the average new house built in western Pennsylvania.

The Institution of Civil Engineers (1977) provides considerable information on how to design structures, transportation networks, and utilities that may be subjected to subsidence. Yokel and others (1981) and Baker (1974) also suggest construction procedures in subsidence areas.

Design criteria for flexible structures that substantially reduce the risk of damage rarely exceed 5 percent of a building's cost (Wardell, 1969). However, the use of rigid designs to protect a building may add significantly to its cost (Mieville, 1971).

Sinkholes

Catastrophic subsidence associated with sinkholes is usually not specifically considered in land-use plans or zoning regulations in the United States. Assessment of the potential for site-specific catastrophic subsidence is difficult and expensive. In addition, the reliability of site-specific assessments tends to decrease as the area under investigation increases. The usual approach is voluntary subsurface investigations—usually for large buildings—and taking structural measures when the risk is found to be high. An innovative attempt is being made by the city of Huntsville, Alabama, which is planning a series of special maps, building-design criteria, and codes to be used in subsidence-prone areas. Siting of hazardous-waste facilities in Florida offers another exception. State regulations there require that the potential for catastrophic subsidence be considered in the site-selection process.

Although building codes have not been used to mitigate catastrophic subsidence, some foundation designs are particularly well suited for sinkhole areas (Sowers, 1975). Drilled piers to solid rock are extensively used in sinkhole areas to bypass voids and collapsible soil and rock. Reinforced mats can be used to resist failure from cavity collapse. If cavities are small, they may be bridged or straddled with batter piles. Because of the large range of potential subsurface conditions even within small areas, however, it is clear that consideration of this type of subsidence by building codes should allow for engineering judgment on a case-by-case basis. These areas also require special exploration techniques, including test drilling, logging, geophysics, and remote sensing to properly locate areas of potential collapse. This comprehensive approach with special exploration and engineering is illustrated by route selection and construction of a natural gas pipeline in central Alabama (LaMoreaux and Newton, 1986). Geologic, geophysical, and hydrological surveys were conducted to find the route with the least potential for catastrophic subsidence, and then construction employed special design features to tie the pipeline to stable bedrock in case collapse occurred.

Underground Fluid Withdrawal

Land-use planning and zoning are potentially applicable to mitigating at least two of the hazards from land subsidence caused by fluid withdrawal—flooding and ground rupture.

Flood-plain zoning, in fact, already is used in many subsidence areas, although the motivation for its use has been solely to address flooding. Subsidence complicates flood-plain zoning because the area affected by flooding increases with time as the land subsides. The time-dependent increase in flood potential in and adjacent to zoned areas has not been seriously considered in subsidence areas to date and is a troublesome complication that needs to be considered. Land-use planning and zoning also can be used to mitigate ground rupture, since susceptible areas can be identified. An example of how this might be accomplished is the Alquist-Priolo Special Studies Zones Act of 1972, codified in California Public Resources Code as Division 2, Chapter 7.5. Under the act, the California State Geologist must delineate "special studies zones" along earthquake faults that pose the threat of surface rupture. The act provides for public safety in areas subject to surface-fault rupture by requiring developers to prepare geologic reports, cities and counties to recognize fault hazards in approving projects, and sellers of real estate or their agents to disclose fault hazards. An even more comprehensive example, related to public information, is a Santa Clara County, California, ordinance that enforces preconstruction geologic investigations that require all sellers of real estate within flood, landslide, or fault-rupture zones to provide buyers with a written statement of the geologic risk.

The threat of flood damage to structures in areas undergoing subsidence also can be addressed through building codes by requiring that structures be built at higher-than-normal grades. Examples that were required by codes include structures in flood-prone areas built on piers (Figure 21) in the Houston-Galveston, Texas, area and placement of fill at higher-than-normal elevation in anticipation of additional subsidence in Long Beach, California.

Hydrocompaction

Land-use controls and building codes are particularly well suited to mitigating damage in urban areas from hydrocompaction, although they have not been applied for this purpose. Identification of areas underlain by collapsible soils commonly is feasible on the basis of laboratory and field investigations (Curtin, 1973), and special building requirements can be stipulated. For example, surface runoff can be diverted from structures, precompaction can be required, or structural designs similar to those that are applicable to mining or sinkhole areas can be mandated.

Organic Soils

Land-use planning and zoning regulations affecting development in wetlands are common. These restrictions, however, are aimed primarily at preserving wetlands and controlling runoff and flooding, rather than preventing subsidence damage, but they have the effect of reducing subsidence damage. State laws in Massachusetts, Connecticut, New Hampshire, and others prohibit development in wetlands. A regional approach is taken in the San Francisco Bay area, where the Bay Conservation and Development Commission regulates development in organic "bay mud" areas. A very large number of cities and counties prohibit the development of wetlands through zoning; these include such widely dispersed communities as Coon Rapids, Michigan; Dartmouth, Massachusetts; Little Silver, New Jersey; Richmond, California; Broward County, Florida; and Hempstead, New York.

The New Orleans, Louisiana, area provides a classic case history that documents where in the absence of land-use controls specific to subsidence, much greater costs were incurred

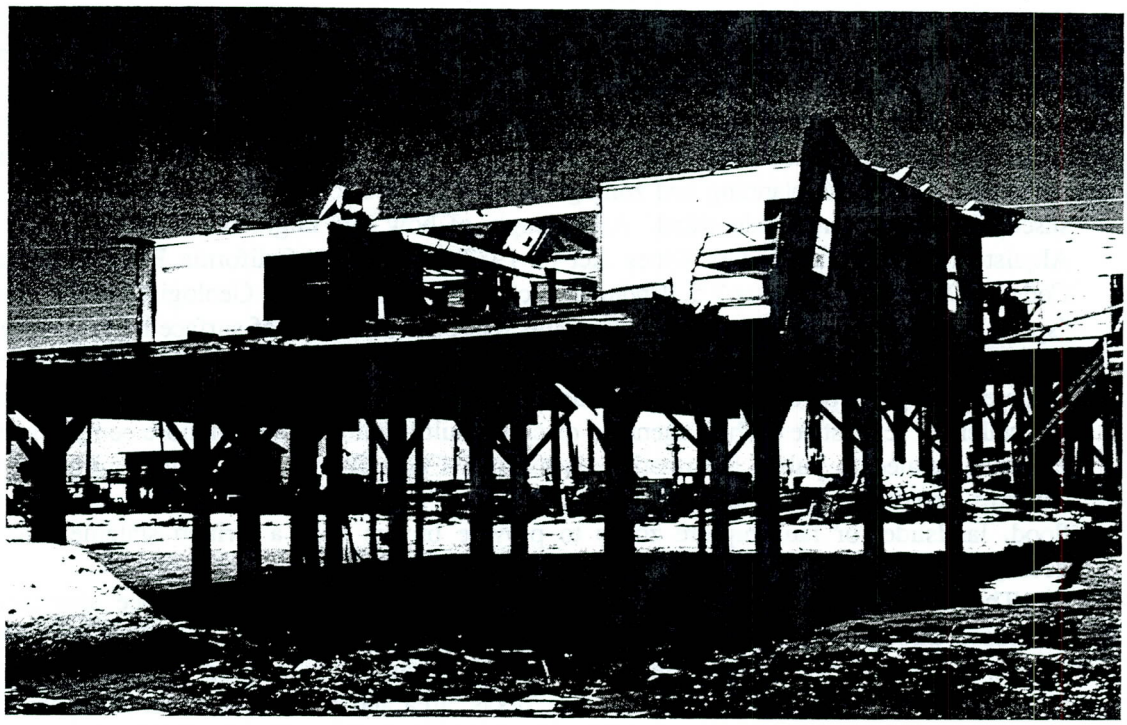

FIGURE 21 Beachfront house built on stilts in the Houston-Galveston area to reduce potential for damage from storm surges. Damage is from high winds caused by Hurricane Alicia, 1983. (Photograph courtesy of H. Crane Miller.)

(Earle, 1975; Mumphrey, 1975). Much of the present problem resulting from differential subsidence within the city of New Orleans could have been avoided through ordinances. The following three-tiered system of regulatory and management guidelines for development in organic soils regions has been proposed to mitigate subsidence hazards (Mumphrey and others, 1976; Mumphrey and Brooks, 1978):

1. **Comprehensive Zoning Ordinance**. This is an all-encompassing local land-use control to determine whether or not development will be allowed in an area sensitive to land subsidence and related flooding.
2. **Subdivision Regulations**. This second level of land-use control would govern the partitioning of subsidence-prone land into lots for sale. These regulations would include requirements as to development densities, lot sizes and configurations, road design and construction standards, minimum drainage requirements, and minimum flood elevations (Imperial Calcasieu Regional Planning and Development Commission, 1974; Mumphrey and Brooks, 1978).
3. **Building Codes**. The third level of local land ordinances applies at the more detailed level and regulates all aspects of on-site construction, including lot grade, piling and foundation preparation, utility installation, structural specifications, and product design and performance standards (Imperial Calcasieu Regional Planning and Development Commission, 1974; Mumphrey and Brooks, 1978).

Predevelopment strategies can be most effective in avoiding subsidence-related hazards in areas of organic soils. If possible, permitted uses of land in subsidence-prone areas or organic

soils should be restricted to agricultural, recreational, and limited public purposes. Use for permanent residences and industry should be severely restricted where possible.

The state of Florida has mitigated water-resource problems that include flooding associated with organic soil subsidence by establishing about six large water-resource management districts that cover almost the entire state. These districts regulate land use, zoning, drainage, and irrigation and control the construction and operation of canals, dams, and other structures that affect water levels. The oldest and largest of these governing bodies is the Central and South Florida Water Management District, which covers the southeastern part of the state, including the Everglades and adjacent coastal land.

Building codes can be used to address problems of differential subsidence in organic soil areas. Several elements of the problem can be addressed:

1. Site drainage, clearing, and filling techniques should be carefully reviewed. Improper clearing practices, such as burying tree roots and stumps, can cause serious homeowner problems through differential foundation settlement. If a site is to be cleared, the vegetation should be removed from the site, not buried.

   Drainage and filling methods should provide for the greatest degree of safety from flooding and groundwater contamination. A "Modified Wet Method" and "Modified Fill Method" have been recommended to substantially reduce the amount of initial and continued subsidence (Kaiser Engineers and Burk and Associates, 1976; Mumphrey and Brooks, 1978). In many coastal regions, these reclamation methods depress the water table below mean sea level but provide for sufficient quantities of fill material to raise the land surface elevation above normal flood levels.
2. Utility lines, including water, gas, telephone, electricity, and sewers, can be laid in trenches with special underground cradle structures to support manholes (Mumphrey and Brooks, 1978). Because of the high potential for failure of utility lines due to differential subsidence, threaded connectors between gas mains and house feeder lines should be prohibited (Earle, 1975). In existing developments, stress-resistant natural gas connections should be used.
3. Building piles should be driven to a specific depth or to a point of refusal to further penetration. Precautions must be taken to avoid drainage that will lower the water table below the base of any pilings, thus undermining their support, strength, and stability.
4. Foundations need to be evenly supported once pilings are in place. The most commonly used foundation in subsidence-prone areas is the slab-on-pilings technique. While this technique provides for a stable foundation, the surrounding area continues to subside, producing differential subsidence and the problems inherent to this process. It is particularly important that fill material to remediate for differential subsidence be more permeable than the underlying organic sediments so that combustible gases release to the atmosphere. To further minimize the chance of explosions, additional fill material should not be placed under concrete slab foundations if voids are created by subsidence, as this replacement has been known to impede the escape of methane gas from broken gas mains or from the decay of organic soils.

MARKET-BASED METHODS

The objective of market-based mitigation efforts is to internalize the cost of subsidence by transferring external costs to either the parties responsible for it or the consumers of the

products of those parties. Internalizing subsidence costs may be done by taxes or fees on the parties causing the subsidence or by requiring those parties to carry out prevention measures directly. Litigation also can be used to internalize costs. To date, market-based mitigation methods have been applied primarily to subsidence caused by mining and withdrawal of groundwater.

Mining

Two market-based methods have been used to mitigate mine subsidence: (1) requiring mining companies either to try to prevent subsidence or to compensate those damaged by it and (2) taxing extracted material to cover costs of public prevention programs or reimbursement of victims. The first method is illustrated by the Pennsylvania Bituminous Mine Subsidence and Land Conservation Act of 1966 that requires bituminous coal miners to take measures to prevent "damage as the result of caving-in, collapse, or subsidence" to public buildings, dwellings, or cemeteries. Under this act, owners of buildings that existed in 1966 can receive compensation from mining companies for damage due to mining after that date. The second method is illustrated by the federal Surface Mining Control and Reclamation Act of 1977, which taxes each ton of coal mined to provide funds for reclamation of abandoned mine land. The tax may be used only to stabilize subsiding areas and not to provide relief for subsidence damage. This act also requires underground coal mine operators to prevent damage from subsidence.

Sinkholes

The causes of catastrophic subsidence are generally complex, and it is difficult, although not always impossible, to charge the cost of damage to the party causing it. For example, recent litigation prompted by flooding caused by seepage from a reservoir built on limestone in Alabama led to a $10 million settlement paid by the company that had impounded the water.

Underground Fluid Withdrawal

Resolution of subsidence problems due to the withdrawal of groundwater and other fluids usually requires a regional approach. Although use of market-based methods is not widespread, these methods are very suitable for most examples of subsidence induced by withdrawal of underground fluids, because resource extractors can be identified. This approach is used in the Santa Clara Valley, California, where both surface water and groundwater are managed by the Santa Clara Valley Water District. The district imposes a tax on groundwater pumpage that eliminates the cost advantage of groundwater over surface water.

Hydrocompaction

For many major engineering projects where hydrocompaction damage or its prevention is a consideration, costs are already internalized. For example, along the west side of the San Joaquin Valley, California, hydrocompaction caused $8 million in damage and added $15 million to construction costs of canals. The costs, which were incurred by the canal builders and operators, were passed on to water users.

Costs are also internalized for many smaller structures, since damage commonly is caused by runoff from the structure itself. Questions of liability may arise, however, when a property

owner incurs damage caused by drainage from adjacent property or has purchased a structure whose design did not consider hydrocompaction.

Organic Soils

To a limited extent, costs of organic-soil subsidence already may be internalized. Construction of levees and flood-control works is commonly a public cost supported by bonds. For the most part, however, the costs of subsidence damage are not distributed equitably.

INSURANCE

Insurance programs to provide relief from subsidence damage have been used in several areas to distribute losses more equitably and encourage risk-reducing actions. Programs have been implemented to insure against losses from coal-mine subsidence and catastrophic subsidence associated with sinkhole collapse. Although it was not intended to mitigate subsidence, the National Flood Insurance Program offers relief to those impacted by flooding aggravated by subsidence.

Mining

Coal-mine subsidence insurance is available in Pennsylvania, Illinois, West Virginia, and Kentucky and is under consideration in several other states. In addition, Colorado offers a special Mine Subsidence Protection Program that is publicly managed and privately administered. Participants must pay a one-time fee of $100 for an inspection of building conditions at the time of enrollment and an annual fee of $35.

These programs limit the cost of protection to the group that will benefit. The programs insure only in areas subject to subsidence, share risk only among those exposed to subsidence, and do not differentiate the degree of risk.

Although the Pennsylvania insurance program was adopted in 1961, this state-run program has not been widely used by homeowners, since it requires purchase of a separate policy. The Illinois program calls for subsidence coverage to be included with the basic property insurance policies unless the homeowner specifically waives it. The result has been a much larger group of insureds and lower rates than in Pennsylvania. The relatively new insurance programs in West Virginia and Kentucky are patterned after the Illinois program. Experience with the Colorado program is limited, because it was established in 1988.

Sinkholes

Starting in 1969, all homeowners' policies in Florida were, if requested by the owner, required to include sinkhole coverage. Few requests were made for the coverage, however, and in 1973 the state Insurance Commissioner mandated that sinkhole coverage be included in all homeowners' policies. In 1981 sinkhole coverage was extended to all structures, although insurance companies were given an option not to provide coverage for commercial and government buildings. Alabama also has sinkhole insurance available to the owners of undeveloped property. Sinkhole damage has been a small cost for the insurance industry.

Underground Fluid Withdrawal and Drainage of Organic Soil

The National Flood Insurance Program covers damage by flooding, which, as previously

noted, can be aggravated by subsidence. The incremental cost to the program from subsidence is not known, but it is potentially very large, as shown in this example. The Texas Gulf Coast experienced three major rainfalls in 1979. As a result of the flooding from these three storms, the federal government, through the National Flood Insurance Program, received over 17,000 claims totaling $170,000,000. A large part of the developed area has subsided. In 1979 over 102,000 flood insurance policies were in force in the subsidence area in Harris and Galveston, Texas, with $4.8 billion in flood insurance exposure.

3
Findings

INTRODUCTION

Efforts in three general areas are needed to mitigate the nation's subsidence problem. First, a broad range of earth-science data, the data base, must be collected in order to assess locally and regionally the incidence and potential impact from each type of subsidence. Although some of these data are already available, they must be converted to the appropriate scale and format to be useful. This often will require collection of additional field data. Second, technical research is needed both to improve the capability to predict the time, rate or magnitude, and place of subsidence and to develop engineering designs that are resistant to subsidence damage. And third, institutional methods of subsidence mitigation need to be evaluated for their cost-effectiveness and suitability for each type of subsidence. Although many different approaches have been tried in the United States, few studies of the methods themselves have been conducted.

Our greatest concern is that efforts to reduce the federal deficit, which have jeopardized the small but effective subsidence research programs disseminated throughout the federal government, will halt scientific and technical progress at the federal level. Data and research results from these federal programs historically have complemented state and local efforts by establishing much of the technical basis for the recognition of subsidence potential, as well as its prevention or mitigation. Basic earth-science data collection and research on subsidence processes are legitimate roles for the federal government. Without funding for this work, agencies such as the Bureau of Mines, U.S. Geological Survey, and Agricultural Research Service are unable to provide the data and techniques required by state and local government and industry to mitigate subsidence in a timely and cost-effective manner.

DATA BASE

Mitigation of subsidence requires many types of basic earth-science data, including geologic, hydrogeologic, soils, hydrologic, geodetic, and land-use information as well as information on the incidence and areal distribution of the subsidence itself. Many of these data are routinely collected in map form by the many federal, state, and local agencies. However,

they rarely are collected primarily for subsidence mitigation. Consequently, without further interpretation and field work, their usefulness for subsidence mitigation is limited.

Findings

In areas of the nation where geologic or hydrologic conditions conducive to subsidence exist and activities can trigger subsidence, detailed mapping programs to identify potential subsidence areas are needed. These should be associated with a data base developed to identify the areas of potential subsidence that includes an inventory of sizes, shapes, frequency, predictability, and triggering mechanisms. These maps should be accompanied by the necessary graphics and text to be understandable by the general public, legislators, planners, and regulators. The information should be presented in a manner that will be useful to:

- provide guidelines for building design and codes,
- provide a basis for development of land-use planning maps as an instrumental resource in land-use management,
- develop actuarial data for insurance purposes, and
- guide location, management, and monitoring of landfills for municipal, hazardous, and toxic wastes.

Implementation

Primary data collection and mapping should be carried out by state geological surveys, the U.S. Geological Survey, and the Soil Conservation Service. Special research to define mapping criteria and identify and solve complex causes of subsidence should be the responsibility of federal agencies such as the U.S. Geological Survey, Bureau of Mines, and Agricultural Research Service.

TECHNICAL RESEARCH NEEDS

Technical research in two areas is needed to improve our capability to mitigate subsidence: (1) prediction of specific subsidence occurrences and (2) subsidence-resistant design of structures.

Subsidence Prediction

Although the mechanism for each of the six types of subsidence considered in this report is generally understood, the ability to predict time, place, and magnitude or rate of subsidence is frequently impaired by either inadequate mapping or incomplete understanding of details of the subsidence process and difficulty in determining the parameters that control the process.

Findings

To improve our predictive capability of subsidence, the following research needs were identified:

- Mining—monitoring of the extent of subsidence and subsurface deformation in coal fields to provide data for the development of predictive models for subsurface conditions peculiar to the United States
- Sinkholes—remote sensing and geophysical methods to identify subsurface voids and provide better understanding of triggering factors

- Underground fluid withdrawal—methods to reliably determine the spatial distribution of compressibility of underground fluid reservoirs before they are developed
- Natural compaction—methods to predict compaction, particularly its rate
- Hydrocompaction—methods to reliably identify collapsible soils and to predict magnitude of settlement, particularly for routine engineering investigations
- Organic soil—better methods to identify carbon content and temperature within soil profiles; development of truck and field crops suited for high water tables

Implementation

In many cases, federal and state agencies already have the expertise and mandates to conduct this research. However, reduced funding, particularly at the federal level, has jeopardized fundamental research on subsidence processes. Before seeking additional funding, these agencies need to establish priorities collectively and seek to improve coordination of their research effort on ground failure, both with other federal agencies and with state agencies. The U.S. Bureau of Mines has been primarily responsible for research on mining; the U.S. Geological Survey for underground fluid withdrawal, natural compaction, sinkholes, and geologic aspects of mining; the U.S. Bureau of Reclamation for hydrocompaction; and the Agricultural Research Service for organic soils. Agencies concerned with construction, such as the Army Corps of Engineers, Soil Conservation Service, and Federal Highway Administration, should be involved in establishing these priorities, since they frequently spend large amounts on very specific subsidence problems.

Engineering Design and Construction

A number of engineering solutions are available to prevent or minimize subsidence damage to structures, transportation facilities, and utilities. However, the movement and resulting damage to structures in response to subsidence ground movements needs to be better documented. Methods also exist to backfill underground mines and voids in soluble rock. Little is known of the long-term effectiveness of void backfilling methods and materials.

Findings

- Mining and sinkholes. Studies of building movements and the resulting damage should be conducted in areas subject to local collapse, particularly mining. This would improve our ability to design subsidence-resistant structures. Techniques and costs of presubsidence support of buildings should be evaluated against postsubsidence damage repair. Use of geofabrics and earth reinforcement for construction of slabs, roads, and dikes with more resistance to subsidence damage should be examined.

The effectiveness of mine backfilling techniques and materials should be evaluated. Core drilling, sampling, and downhole inspection using TV cameras would provide data for evaluation and improving procedures. Partial mine filling can reduce subsidence by reducing the size of voids and providing lateral support for existing mine pillars. The effectiveness and cost of this procedure should be evaluated relative to total void filling. Research on less-costly materials handling systems, such as pumped slurry, could result in improved, cost-effective void-filling procedures. Fiber-reinforced grout columns should be tested.

- Hydrocompaction. Cost-effective methods to stabilize collapsible soils are needed. Such methods need to be developed for small structures, for example, houses, as well as large engineering projects.

- Organic soils. In agricultural areas, new crop varieties that tolerate shallow water tables are needed. Chemical treatment can inhibit organic soil degradation.

Implementation

Although research on construction and void backfilling can be conducted or funded by a number of agencies and industries, it appears appropriate to assign responsibilities for this type of subsidence research to the U.S. Bureau of Mines. Necessary technology-transfer inputs could be obtained by assistance from appropriate professionals and the National Institute of Standards and Technology. Agencies concerned with roads, canals, and dams are the ones most frequently confronted by hydrocompaction. The primary agencies are the Federal Highway Administration and Bureau of Reclamation, although there is also a role for the Federal Housing Administration because of the explosive growth in the western part of the Sun Belt. The Agricultural Research Service historically has had responsibility for organic soil research.

MITIGATION MEASURES—RESEARCH AND IMPLEMENTATION NEEDS

Because of the diverse causes of and impacts from land subsidence, as well as the need to consider the status quo when mitigation is necessary, mitigation measures must be, in general, designed for each situation. General approaches to mitigation of subsidence rarely will apply to all types of subsidence. Another consequence of the diversity is that governmental responsibilities for mitigation measures primarily fall to state and local governments. The appropriate role of the federal government is to provide national coordination and information, provide technical assistance to state and local governments, and fund research on mitigation techniques.

Regulation of Resource Development

Introduction

When development of natural resources causes subsidence, governments sometimes find it necessary to exercise their power either to prohibit the resource development or to control it in ways that minimize subsidence damage.

Findings

Legislative regulation of resource development reflects a decision that the benefits of unregulated resource development are outweighed by the harm caused. Therefore, such regulation is most appropriately considered when there is sufficient information regarding the relationships between resource development and subsidence costs. Sufficient information of this kind still needs to be developed.

Implementation

The federal government can encourage the development and dissemination of technologies for evaluating these relationships through programs of the appropriate agencies of the Departments of Agriculture, Housing and Urban Development, and Interior. Where the federal government is itself involved in resource development, it can take steps to ensure that subsidence is one of the factors considered as part of the development process. Where states are responsible for the regulation of resource development, the appropriate state agency should consider whether procedures for addressing subsidence should be integrated with the resource

development process. Such an agency may be able to accomplish this directly through administrative regulation, or it may be necessary for state legislatures to take action through the legislative process.

Land-Use Management and Construction Codes

Introduction

Land-use management in the United States is primarily the responsibility of state and local governments operating within the constraints of state enabling legislation. The federal role is limited to the collection and dissemination of information, although the federal government may require land-use regulation as a condition of participation in a federal program, as in the case of flood insurance.

Because of variations in subsidence characteristics, there is no general zoning approach to the prevention or mitigation of subsidence damage. Zoning is most efficiently used where the risk and potential cost of subsidence are high enough to offset the impacts of controlling the use of property. Zoning can be used to restrict the use of land to levels consistent with the hazard, but short of prohibition of all uses. Zoning will be most effective where risk is very high or where the value of the surface land and improvements is low. Moreover, where the zoning prohibits any use of property in a subsidence-risk area, the question will arise of whether a taking in violation of the Fifth Amendment of the U.S. Constitution has occurred. Where subsidence risk is very high, the most cost-effective approach may be direct acquisition of the land affected or of the development rights of the land.

Construction techniques sometimes can be used effectively to eliminate or limit subsidence damage, but these are now seldom used in connection with subsidence hazards in the United States.

Findings

Research needs to be done specifically on local codes and ordinances that can be used to reduce subsidence damage. Since the subsidence-damage problem, except in the case of increased flooding in areas of lower elevation, is primarily economic, the costs to the community of subsidence damage compared with those of zoning restrictions must be examined. The relative costs of prohibition of development, limits on development, and outright purchase of land in subsidence-risk areas need to be examined. An optional zoning approach that should be studied is the imposition in high-risk areas of a requirement that subsurface investigations be undertaken and appropriate engineering measures be taken to prevent or reduce subsidence damage.

Studies also need to be made of building code provisions that can reduce subsidence damage. These could be applied in connection with the zoning approach suggested above.

Implementation

Because land-use and building regulation is a local responsibility, the studies recommended above will have to be carried out by local planning agencies and by related professional groups, such as the Planning Advisory Service of the American Planning Association. Building codes are generally a local government responsibility, but model codes are prepared by such organizations as the International Conference of Building Officials (ICBO), the Building Officials and Codes Administrators, Inc. (BOCA), and the Southern Building Code Congress International (SBCCI). These organizations should consider the inclusion of subsidence-related

provisions in model codes, similar to ICBO's Uniform Building Code, which has provisions for earthquake damage reduction.

Federal involvement should consist of the dissemination of information and research on building technology by the National Institute of Standards and Technology, National Science Foundation, and Department of Housing and Urban Development; and research of land-use regulation by the National Science Foundation.

Market-Based Methods

Introduction

There are a few examples of effective systems for market-based methods to internalize subsidence costs. The Surface Mining Control and Reclamation Act of 1977 requires mine operators to reimburse surface owners for damage in some cases, and a tax on groundwater in the Santa Clara Valley eliminates the cost advantage of groundwater over surface water. Subsidence costs are also internalized through litigation by parties suffering damage and by payments negotiated by resource extractors facing possible litigation.

Findings

Studies need to be carried out on the relative costs and benefits of different approaches to resource taxation for different types of extraction that could result in subsidence. Studies should also be made of the overall costs of resource taxation compared with leaving the problem of cost distribution to litigation.

An approach that could effectively internalize the cost of subsidence resulting from resource extraction would be state legislative action requiring that extractors take measures to prevent subsidence and be responsible under specified circumstances for subsidence damage on the surface resulting from extraction. This approach is applied by the federal government to some coal-mine subsidence, but its application is currently very limited.

Implementation

Cost-benefit studies could be carried out by university researchers and consultants and funded by industry groups for whom subsidence-related litigation is potentially a significant cost, and possibly by the National Science Foundation. Action to require resource extractors to bear subsidence mitigation and damage costs must be taken by state legislatures.

Insurance

Introduction

Insurance is a viable form of relief for the types of subsidence that meet the following criteria. An "insurable risk" is generally defined as presenting itself to a sufficiently large and homogeneous group of exposure units to permit reasonably accurate prediction of average losses, where the loss is definite but unpredictable in time and place and where there is no threat of a major catastrophe of unknown proportions. Experience with coal-mine and sinkhole subsidence, and with flooding, suggests that insurance, if properly structured and executed, may equitably, expeditiously, and predictably provide relief for property damaged by subsidence or by flooding aggravated by subsidence.

Findings

1. Information regarding the incidence of insurable types of subsidence needs to be developed in conjunction with property insurers in states where those types of subsidence are widespread.

2. Basic questions regarding underwriting/coverage, claims/value, and administration/program structure for subsidence-insurance programs should be addressed in conjunction with any state legislative efforts to authorize such insurance. Early decisions should be made regarding whether subsidence-insurance availability will be mandatory or voluntary, the type and dollar amount of coverage to be available, and whether insurance should or should not be interrelated with land-use controls or other mitigation measures.

3. In flood-prone riverine and coastal areas, methodologies are needed to determine the incremental contribution of subsidence to flooding costs, and criteria need to be developed for establishing priorities for remapping flood zones in subsidence areas.

Implementation

The following state and federal agencies are identified to develop the information and methodologies given above:

Finding 1. state geological surveys in conjunction with the U.S. Geological Survey

Finding 2. state insurance administrators, property insurance companies doing business in each affected state, and appropriate staff of state legislatures

Finding 3. the Federal Emergency Management Agency

Appendix
Technical References on Land Subsidence

Mining:

Brauner (1973a, b), Dunrud (1984), Ege (1984), Fejes and others (1984), Gray and Bruhn (1984), Kratzsch (1983)

Sinkholes:

Beck (1984), Ege (1979), LaMoreaux and Newton (1986), Sowers (1975), Zwanzig, (1976)

Underground Fluid Withdrawal:

Holzer (1984), Poland (1984), Poland and Davis (1969)

Natural Compaction:

Bredehoeft and Hanshaw (1968), Coleman (1988)

Hydrocompaction:

Curtin (1973), Dudley (1970), Handy (1973), Lofgren (1969), Lovelace and others (1982)

Drainage of organic soils:

Stephens (1969), Stephens and others (1984)

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