

ENVIRONMENTAL IMPACTS RELATED TO HYDROGEOLOGICAL SYSTEMS

NATURAL AND MANMADE DISASTERS

During the past decade geologists have been requested to participate in an ever expanding role of responsibility regarding the evaluation and protection of the environment. The earliest geologists described and catalogued rocks, fossils, and minerals. Subsequently they used this knowledge to develop mineral, water and energy resources. During The past twenty years there has been an increasing demand to use this same expertise to bring about remedial actions on “endangered environments” and to aid environmental planning and development. Geologists are now requested to provide solutions to properly manage hazardous, toxic, and radioactive wastes, as well as to cope with problems of catastrophes, both natural and man-made. With this responsibility, there has evolved a need for risk assessment and guidance for the development of insurance programs that will protect individuals against disaster. What are the risks, what are the chances for a reasonable risk assessment, and what are the limits of liability.

Ancient man must have looked upon a volcano such as Santorini (an island volcano in the Mediterranean), or upon the recent hurricanes such as Hugo or Camille in the USA as calamities totally unfathomable. In prehistoric times, disasters of this magnitude were the basis for a belief in gods’ venting their wrath upon mankind. These were similar to the Biblical flood of Noah, caused by a storm of such large magnitude that the entire Tigris and Euphrates valleys were inundated, and life was destroyed over a very extensive area. These were the kinds of natural disasters that were the basis for legends handed down by word of mouth over hundreds of years.

Natural catastrophes take place today; however, civilization has become more knowledgeable about their causes and impacts. Information is collected relative to the causes and effects of these natural phenomena. For example, during the last five years the scientific community has predicted, with considerable accuracy, hurricanes, earthquakes, volcanic eruptions, and tsunamis. Effective warning systems have been developed that save thousands of lives though emergency planning for the evacuation from danger zones. Special construction of buildings has been mandated in the event that one of these natural catastrophes should take place in a populated area. Modern civilization, however, still has not been able to cope with certain types of catastrophic phenomena- Worldwide, nearly 3 million people have died; some 820 million more have been injured, displaced or otherwise affected by natural disasters during the past 10 years; and property damage from individual] catastrophes has been in the billions of dollars. Hugo’s damage was in excess of 2 billion dollars; the October 19, 1989, San Francisco earthquake damage exceeded 10 billion dollars; and the more recent hurricane Camille caused damage to Florida and Louisiana in excess of 13 billion dollars.

In 1980 the eruption of Mt. Saint Helens in the state of Washington awakened many to the impact of volcanic hazards, and in December 1987, the United Nations General Assembly designated the 1990s as the International Decade for Natural Disaster Reduction. One of the first reports from this effort is “Reducing Disasters’ Toll,” by the United States National Research Council.’ This is one of a series of publications that have been and will continue to be published in the future as a result of cooperative international programs to reduce the impact of natural hazards. Man is now evaluating more carefully these natural phenomena and measuring their worldwide impact.

From 1650 to 1450 BC, major eruptions of Santorini caused such damage to the natural environment that climate around the world was affected; billions of tons of fine ash were thrown into the air; and day turned into night over much of the Eastern Mediterranean. Ocean tidal waves lashed against the shores of all the Greek Islands, Asia Minor, and North Africa. Therefore, even though this catastrophe was not studied and recorded, as are those of today, a record remains of the event over 3,500 years after it occurred. From a hydrogeologists’ perspective, the environmental impact was so great, even in a relatively unpopulated world,

that it left indelible historical evidence. The eruption was recorded by geologic, chemical, and biological time clocks. There is not a written record, at least none discovered to date; however, all available data from a great variety of sources can be pieced together to interpret the size and impact from this historical event. If this event were to happen in a relatively populated area today, such as the Mediterranean, the Gulf Coast of the USA, Japan, or Indonesia, the loss of life and damage to property would be a tragedy unknown to modern civilization.

The Santorini event was so violent that it has never been equaled in the memory of man. The eruption of Krakatau, the only natural event with gaugeable force, could not equal its violence. It was one of the world's all-time most spectacular natural environmental events. Another Santorini could happen and the hydrogeologist, geophysicist, and seismologist could predict, with some accuracy, where it would happen and sometimes, with adequate data, approximately when. But how can such a catastrophe be insured? What type of environmental planning must be carried out in these critically sensitive spots of the world?

There are many natural catastrophes for which hydrogeologists or other earth scientists have been able to identify and provide risk factors, locate potential areas of occurrence, and determine frequency, severity, and potential damage to property and life. These include landslides, mudslides, tsunamis, earthquakes, hurricanes, tornadoes, and catastrophic subsidence or sinkhole collapse.

Many of these catastrophes can be predicted with substantial accuracy using present day scientific knowledge, methodology, techniques, and instrumentation. Funding for research, and therefore accuracy of results, depends to a great extent on the perception of the public and its willingness to support financing of necessary research that will allow the most accurate modeling and predictions of these natural events.

Earthquake phenomena has also been the subject of extensive research in the Soviet Union, China, Japan, the United States, and certain other areas of the world that are impacted by frequency of earthquakes. In the United States, the U.S. Geological Survey and National Oceanic and Atmospheric Administration (NOAA) carries on extensive programs of research including a computerized maintenance of records of epicenters over the world and periodic earthquake probability maps rating the areas by frequency of earthquakes. This subject has received so much attention in the past that there are now textbooks and regular scientific journal publications; for example: NOAA earthquake frequency map; NOAA epicenter determination reports; Episodes, regular articles in an international geoscience journal; Geotimes, annual summary of the American Geological Institute; Geotimes, monthly summary on "Geologic Phenomena."

Earthquakes and volcanoes are related to major tectonic features of the earth's crust and can be of such a minor impact as an unobservable deep-seated intrusion of magma on the ocean floor or a quake on the Richter scale of a fraction of 1 that could occur unknown to the population. These incidents, however, are in sharp contrast to a large eruption such as a Santorini or Krakatau or an earthquake such as the 1909 San Francisco catastrophe. These are monitored in much detail by today's scientific community and are being used to gain more accurate knowledge of natural phenomena, some of which will effect the insurance industry much more in the future. There will come a time when all of these events will be the subject of insurance programs that will require risk assessments.

LAND SUBSIDENCE

There are a number of other natural phenomena that scientists can predict with a substantial degree of accuracy as to where, why, and when hazards may occur and the frequency and size of the hazard. This would include landslides, mudslides, and sinkhole collapse or catastrophic subsidence. Let us analyze problems associated with land subsidence.

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 also 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 and control. Although general understanding of subsidence processes is well developed, prediction of subsidence magnitudes, rates, and location is commonly impeded by incomplete understanding of specific details of the relevant processes and the inability to determine adequately subsurface conditions and physical properties of the deforming earth materials.

And third, although many types of mitigation methods are in use in the United States, studies of their cost-effectiveness would facilitate choices by decision makers.

Catastrophic subsidence takes place in areas underlain by limestone that is sufficiently massive, is pure, and has been subject to certain erosional conditions that resulted in dissolution of large segments of the rock (limestone carried away by solution) as to leave a Swiss cheese appearance in the rock itself.:

Natural phenomena, however, such as extensive periods of drought followed by heavy rains from tropical storms, can trigger catastrophic subsidence. The downward movement of the water table from shortage of rainfall over a long period and the loss of buoyant support of the water to the sediments, plus a subsequent heavy torrential rain, may act as the lubricant to the unconsolidated material causing a collapse of this material into the solution system. Where this happens, in an area of farms, commercial buildings, highways, and airports, big holes in the land surface can develop with substantial damage to property, animals, and humans. This situation is not unique to Florida but exists in many other parts of the United States. Europe, Southeast Asia, and the Middle East, in fact in approximately 25% of the area of the earth's landmass where limestones occur.

Extensive studies of this type of catastrophic event by many different scientific groups has provided substantial literature on the subject. Scientific groups involved in such studies include: A Panel on Subsidence of the Commission on Engineering and Technical Systems, Committee on Ground Failure Hazards of the National Academy of Sciences, and the Karst Commission of the International Association of Hydrogeologists. Results have been published in textbooks and volumes of symposia papers. Extensive work has been done by the U.S. Geological Survey, and the phenomena's so well known in Florida that catastrophic subsidence insurance is available. This is possible because of predictability on the basis of research regarding this phenomena and the perception of the public and the government that it comprises enough of a source of damage to warrant insurability. Some states, through cooperative programs with the USGS, have mapped in detail the areas where catastrophic subsidence can take place. Triggering effects that cause catastrophic collapse include:

1. Heavy withdrawals of groundwater by pumpage for industrial, agricultural, and municipal use.
2. Diversion of drainage in a karst area.
3. Excavation or use of heavy equipment.
4. Mine dewatering (for example, in South Africa where sinkholes caused the collapse of a three-story building where 29 men lost their lives).
5. Earthquakes.
6. Use of explosives.

CAUSES OF SUBSIDENCE

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; inciting of permafrost; liquefaction; and crustal deformation. This diversity and the broad range of impacts from subsidence are probably the major causes of a lack of national focus on subsidence. Instead, many industries, professions, and federal, state, and local agencies are independently' involved with aspects of subsidence. Resource development and land-use practices, particularly underground mining of coal, groundwater and petroleum withdrawal, and drainage of organic soils, are the primary causes.

Land subsidence, the 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 river 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 slow- rates of lowering. It has caused few casualties. Subsidence, however, increases the potential for loss of life in flood-prone areas by increasing the magnitude and size of areas susceptible to flooding.

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

From Panel on Land Subsidence, National Research Council, National Academy Press, Washington. D.C.. 1991.

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 recovers.

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.

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. Abandoned tunnels and underground mining of metallic ores, limestone, and salt contribute to a much smaller extent, although associated problems may be severe in some regions.

In general, coal-mine subsidence is caused by collapse of the mined-out or tunneled void. It occurs as both steep-sided pits 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.

Sinkholes

The sudden formation of sinkholes — catastrophic subsidence — is usually caused by movement of overburden into underlying cavities in soluble bedrock (Figure 4.3). 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 4.4). 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 its 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.⁷ 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.

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 framework of the reservoir soil or rock. When fluids are withdrawn, fluid pressures decline and support of the overburden is transferred to the solid framework. 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 is caused by pumping of groundwater

and petroleum.

Natural Compaction

Sediments compact naturally as they are buried by younger sediment. Maximum rates measured by geodetic surveys are about 12 mm per year. 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. 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.

Another very important impact from this subsidence is the destruction of productive estuarine marsh and coastal wetlands by either inundation or erosion. 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.

Hydrocompaction

Dry, low-density, fine-grained sediment may be susceptible when wetted to a loss of volume known as hydrocompaction. 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. 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 re-leveling 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.