8 Types of land subsidence, by Alice S. Allen, Bureau of Mines, U.S. Department of the Interior, Washington, D. C.

8.1 INTRODUCTION

Land subsidence is merely the surface symptom, and the last step, of a variety of subsurface displacement mechanisms. Not all of these mechanisms are well understood. Subsidence processes are concealed below ground; their development to the point of surface deformation may involve long periods of time; and for at least some mechanisms, significant evidence may lie outside the area directly beneath the surface subsidence. Furthermore, at some sites more than one condition favourable to subsidence occurrence may be present and require consideration in analyzing causal mechanisms and devising remedial procedures.

Subsidence is a familiar accompaniment of a variety of natural events that comprise the geologic history of many areas. For practical reasons geologic processes that are accompanied by subsidence have been examined for evidence that the range in their rates of progress extends into a time frame that may produce damaging effects in terms of man’s time scale. The processes investigated are those that remove or rearrange subsurface materials to produce void space or significant volume reduction--solution, underground erosion, lateral flow, and compaction--or, in the case of tectonic activity, deep-seated downward displacement. For all of these naturally occurring geologic processes, examples of related surface subsidence have been found, though some are rare (Allen, 1969). The incidence of subsidence is greater where some of these geologic processes are set in motion or accelerated by man’s engineering activities that involve excavation, loading, or changes in the ground-water regime.

The term "subsidence" is used in this discussion in a broad sense to include both gentle downwarping and the collapse of discrete segments of the ground surface. Displacement is principally downward, although the associated small horizontal components have significant damaging effects. The term is not restricted on the basis of size of area affected, rate of displacement, or causal mechanism.

An overview of favorable geologic settings and engineering operations that may contribute to land subsidence is presented as background for the specialized treatment of subsidence caused by ground-water withdrawal, which is the subject of this guidebook. Topics on which information is widely available are mentioned briefly. More space is given to topics for which published information is less readily available for most readers. Mining subsidence is not reviewed, but several examples of interaction between mining and natural geologic processes are cited. Subsidence in regions underlain by permafrost and in areas of active volcanism is not discussed.

8.2 THE ROLE OF SUBSURFACE SOLUTION IN SUBSIDENCE

Common soluble components of earth materials that may be associated with subsidence include salt, gypsum, and the carbonate rocks--limestone and dolomite. The roles that these soluble materials play in the development of surface subsidence depends in part on the degree of their solubility, and in part on other physical characteristics.

8.2.1 Salt

Although rock salt (sodium chloride) is one of the most soluble of the common earth materials, the presence of underlying salt deposits has only rarely been associated with surface subsidence under natural conditions in recent times. This is in part because the original occurrence of salt deposits is limited geographically, and in part because salt deposits have already been removed to considerable depths except in arid climates by the leaching action of ground water. Collapse breccias found in strata overlying salt-bearing horizons constitute geologic evidence that subsidence has taken place under natural conditions in the geologic past. Collapse breccias due to solution along the margins of underlying salt deposits have been reported from the Michigan Basin (Landes, 1963), the Delaware basin of West Texas and southeastern New Mexico (Maley and Huffington, 1953), and in the western Canadian area underlain by evaporites of the Prairie Formation (DeMille and others, 1964).

In south-central Kansas where salt deposits still exist at depths between 90 and 120 m, a dramatic example of natural subsidence in historic time was documented in photographs in 1879 (Johnson, 1901, Pls. 136-138). A deep crater about 60 m in diameter was discovered disrupting a cattle trail. The interrupted tracks of a wagon that had passed 3 weeks earlier were clearly seen on both sides of the sinkhole. Another sinkhole about 130 km to the northeast carried away a railroad station overnight (Johnson, 1901, p. 713, footnote).

Indirect evidence of natural subsidence is the presence of surface depressions occupied by lakes or swamps in areas where underlying salt deposits have been undergoing dissolution. The eastern boundary of the Kansas salt deposits is fairly abrupt where salt deposits 60 m thick are missing in wells a few miles to the east. Above, the blunt edge of the salt is a narrow belt of marshes, swamps, and lakes, many of which contain salty water (Bass, 1926). Lakes also occur overlying salt domes in Louisiana (Barton, 1936, O’Donnell, 1935). At an oil-producing operation at Sour Lake dome in Texas, Sellards (1930) described one lake that had formed under natural conditions, and a large sinkhole that appeared in 1929 which was attributed to removal of salt in the saturated water that had been produced along with the oil over a long period of time.

The incidence of subsidence in some areas underlain by salt deposits has been stimulated by salt mining operations. In Cheshire, England, where salt has been mined since pre-Roman times, the effects of solution subsidence on the topography and on structures have been spectacular (Calvert, 1915; Howell and Jenkins, 1977; Wallwork, 1973). Early mining was by the room-and-pillar method in which pillars were left to support the surface. As unsaturated ground water gained access to old mine workings, the dissolution of pillar salt led to surface subsidence, though it was limited as the ground water in contact with the salt became saturated. When methods of salt production changed to pumping the so-called "wild" brines, surface subsidence was greatly accelerated. Water levels were lowered by continued pumping, and additional under-saturated ground water circulated randomly through the cavernous saltbeds, continually removing any protective envelope of saturated brine that may have developed. The topography, previously modified by natural solution subsidence, was further changed by the development of craterlike depressions 10 to 200 m in diameter, and linear hollows over 200 m wide and 8 km long. Streets and railroad tracks were distorted. In Northwich, very few pre-1900 buildings survived the subsidence damage. In the 1970’s, natural brine pumping is being phased out, and most salt production is by controlled solution mining. Fresh water or undersaturated brine is injected through boreholes into deeper deposits of massive salt, creating regularly spaced solution cavities about 90 m in diameter. Mature cavities are maintained in stable condition by flooding with saturated brine.

A recent investigation of subsidence related to salt dissolution in Kansas found only five subsidence events due to salt mining over an 88-year period, and eight subsidences related to oil and gas operations (Walters, 1977). The rare subsidence occurrences were attributed to aquifers above the salt not being adequately isolated by surface casing or, in the case of salt-water disposal wells, casing failures which permitted flow of unsaturated brine across the salt.

8.2.2 Gypsum

Gypsum ($CaSO_4 \cdot 2H_2 0$) is a soluble rock-forming mineral which, with its anhydrous counterpart, anhydrite, occurs abundantly in marine evaporite basin deposits. Evidence that surface subsidence was caused by dissolution of gypsum in past geologic times includes collapse features in rocks overlying gypsum deposits in the Roswell basin, New Mexico (Bean, 1949), and in the southern Black Hills of South Dakota and Wyoming (Bowles and Braddock, 1960), and solution-subsidence troughs in the gypsum plain of west Texas and southeastern New Mexico (Olive, 1957).

Sinkholes on the present-day land surface have been reported in areas underlain by gypsum-bearing rocks in New Mexico (Bean, 1949; Morgan, 1942) and Oklahoma (Fay, 1959) in the United States and at various localities in Europe (International Association of Engineering Geology, 1973).

In addition to collapse and sinkholes that overlie deposits of relatively pure gypsum, subsidence may also be associated with rocks and soils that contain minor amounts of gypsum. Klein (1966) described several types of gypsum occurrence in a very arid part of the San Joaquin Valley, California, which were investigated by the Bureau of Reclamation in connection with locating and designing a large water-transfer, pump-storage, and irrigation project. Along margins of periodic shallow lakes, efflorescent accumulations of gypsum contained solution cavities that were believed responsible for damages to canals and embankments. Weathered-shale bedrock contained secondary gypsum in veinlets and seams, which made up from 2 to 5 per cent of the rock mass. Similar veinlets and seams of gypsum characterized the weak, clayey gravel in one of the abutments of the St. Francis dam near Los Angeles, which failed disastrously in 1928 soon after the reservoir had been filled. Solution of gypsum was cited as a likely contributor to disintegration of the weak foundation material (Ransome, 1928).

The presence of small quantities of gypsum (1 to 3 per cent of dry weight) appears to be a general indicator of soils in the San Joaquin Valley that are susceptible to subsidence on wetting, but the role played by the gypsum is conjectural. Bull (1964) concluded that the gypsum content cannot be used exclusively as an indicator of potential subsidence, and he did not consider solution of gypsum to be a major cause of the subsidence. Differences in gypsum content of subsiding and nonsubsiding soils reflects compositional differences in their source areas, and possibly the removal of gypsum from nonsubsiding soils by water percolating from streams. Klein (1966) believed that the presence of gypsum contributed to the flocculation of clay particles influencing the size and amount of pore space, and shared responsibility for the low density of these deposits with the presence of trapped air inherited from their mudflow origin. Noting that much of the gypsum occurred as minute efflorescent crystals coating the small voids characteristic of the subsiding soils before hydrocompaction, he suggested that gypsum supplemented the clay minerals as a weak and easily soluble cementing agent.

8.2.3 Carbonate rocks

The carbonate rocks, limestone and dolomite, are responsible for the most widespread incidence of subsidence related to solution, not because of a high degree of solubility, but because of wide geographic distribution. A great deal of information is available on solution features in carbonate rocks (Internat. Assoc. of Engineering Geology, 1973; Tolson and Doyle; 1977, Transportation Research Board, 1976). LaMoreaux, LeGrand, and Stringfield (1975, p. 45-47) list more than 50 symposia and conferences on hydrology of carbonate rocks held throughout the world in the past 30 years.

The incidence of sinkhole development may be greatly increased when equilibrium conditions are disturbed by man’s construction projects or mining operations, particularly those that alter ground-water levels or increase surface infiltration. Newton (1976) reported that more than 4,000 induced sinkholes, areas of subsidence, or other-related features have occurred in Alabama since 1900, most of them since 1950. In Missouri, 97 catastrophic surface failures have been recorded since the 1930’s, of which 46 were attributed to man’s activity (Williams and Vineyard, 1976). Subsidence accelerated by dewatering of underground mines in carbonate terrain has been described by Foose (1968).

Collapse at the ground surface may appear suddenly, but is the culmination of a sequence of processes starting with the development of solution openings in bedrock. Interconnecting systems of solution passageways develop over geologic time and persist, owing to a combination of the slow rate of dissolution of carbonate rocks and their high compressive strength, which maintains the integrity of the cavity systems. Subsequently, unconsolidated overburden materials may be slowly washed down into bedrock cavity systems. The resulting voids in the overburden may become enlarged until the remaining cover is too thin to support the surface and collapse takes place.

8.3 THE ROLE OF SUBSURFACE MECHANICAL EROSION IN SUBSIDENCE

Subsurface mechanical erosion is the term used for an infrequently recognized phenomenon in which temporary subsurface flow channels are developed in unconsolidated or friable materials that may lead to surface collapse. The term "piping" has also been used for this process. Water percolating through pervious surficial materials becomes diverted to a more or less horizontal path on reaching the water table or a less pervious stratum. The water, which transports grains of silt and sand, finds an outlet along a nearby valley wall or cliff face or internally in caves, mine openings, or boreholes. Erosion tends to work headward from the outlet, creating and enlarging a tunnel that intersects the vertical flow channel of concentrated percolation water. As tunnel enlargement and upward propagation of the roof reduce the support capacity of the surface materials, the ground surface collapses to produce sinkholes.

In order to produce surface subsidence, the subsurface erosion mechanism is believed to require three conditions (Allen, 1969): (1) A pervious, easily erodible material must be overlain by material sufficiently competent, at least temporarily, to form a roof above the developing tunnel; (2) water must have access to the erodible material with sufficient head to transport grains of silt or sand; and (3) some sort of outlet must be available for disposal of the flowing water and the sediment grains that it transports. Examples of subsidence attributed to subsurface erosion in a variety of geologic materials are summarized in Table 8.1.

Table 8.1. Occurrences of subsidence due to subsurface erosion.

Location (Reference)	Surface expression	Erodible material	Roof	Channel development	Outlet
Kanus, China (Fuller, 1922)	Circular holes 1.5-6 m diam.; vertical walls	Loess	Dry loess	Tunnels up to 1 m wide, 3 m high	Ravine walls; plateau rims
Kamloops, B.C., Canada (Buckham and Cockfield, 1950)	Circlar sinkholes 15-30 m diam; funnel shaped	Pleistocene "White Silts" on Thompson River Terraces	Dry silt	Nearly horizontal passageways up to 1 m high; at temporary water table	Gulleys; terrace front
Eastern Oregon (Parker and other, 1964)	"Pseudokarst" (resembles karst topography in limestone areas)	Altered tuff and volcanic ash	Dry tuff and ash	Eroded cavern complex 200 m long with 4 levels	Hanging valley walls
Chuska Mountains NW New Mexico (Wright, 1964)	Pleistocene depressions containing intermittent lakes	Uncemented eolian sandstone	Cemented sandstone strata	Inferred but not observed; process inactive at present	Steep mountain escarpments
Zuni Dam, New Mexico (Eckel, 1939)	Cracking and subsidence of abutments, 1909, 1936	Sand bed 1-2.5 m thick; underlain by clay	Basalt flow, jointed	Through joints in basalt, water under head flushed out sand, creating large voids	Cliff below dam
Memphis, Tennessee (Terzaghi, 1931)	Subsidence of building and strip of land 200 m long; bluff subsided 18 m over 2 1/2 month period	Bed of uniform, rounded, fine quartz sand, 14 m thick	Fairly stiff clay	Inferred channel eroded along under side of sand, leaving cavity which collapsed	Mississippi River bluff
Minneapolis-St. Paul, Minnesota (Schwartz, 1936; Soper, 1915)	A few sinkholes; not all tunnels broken through to surface	Poorly cemented St. Peter sandstone (Ordovician)	Platteville limestone	Caves developed in friable sandstone, probably more than a kilometre long in places	River gorges
Attala County, Mississippi (Parks, 1963)	Caves and sinkholes near hilltops and heads of gullies	Thin deposits of leached silt	Quartzitic sandstone, fractured	Through cracks in quartzitic bed, water washes out silt forming tunnels 6+ m long and caves 1+ m high	Heads of gullies

The material that forms the roof of tunnels at some localities is a different, and more competent, material than that in the eroded horizon. In other localities, the material forming the roof and the eroded horizon are the same (i.e. loess, altered volcanics), but the competency of the roof is dependent on cohesion in a dry condition provided by montmorillonitic clay bonding. Such cohesion is lost upon saturation as the component particles become disaggregated when wet.

Cases of underground mechanical erosion are difficult to identify. At least part of the process must be inferred in the absence of direct observation. Tunnel development is concealed below ground and may only be disclosed by the apparently sudden collapse at the surface. The collapse is the last step in a long continued process in which sediments are eroded grain by grain and transported to the outlet. Accumulations of transported sediments are rarely observed because the silt and sand grains either become incorporated in the colluvium below the outlet on a valley wall, or are washed down into cavities or excavations in the bedrock.

8.4 LATERAL FLOW AS A SUBSIDENCE MECHANISM

Lateral flow of subsurface materials as a cause of subsidence is uncommon but not unknown. Examples have been reported both under natural geologic conditions and under loading by man’s activities (Allen, 1969). Common earth materials susceptible to plastic flow are salt, gypsum, clay, and clay shale.

Geologic examples of subsidence by salt flowage are rim synclines surrounding salt domes in coastal Texas and Louisiana (Nettleton, 1934; Ritz, 1936) and broad synclines associated with salt tectonics in the Paradox Basin in Utah and Colorado (Cater, 1954). Where the Green and Colorado Rivers have cut deep canyons well down into the formation overlying salt and gypsum in Utah, the removal of load has permitted salt and gypsum to flow laterally, resulting in very local folds and graben (Baker, 1933).

Flowage of shale has produced a geologic subsidence feature termed "cambering" in the Jurassic iron ore locality in east-central England (Hollingworth and Taylor, 1951). Cambering occurs in deeply dissected areas in which a competent rock such as ironstone or limestone overlies Lower Jurassic clay shale. Lateral flowage of clay shale toward the valley axes has lowered the overlying competent rock as much as 30 m; in places the lowering has been intensified by subsurface erosion along the shale-ironstone contact and by sliding of the ironstone on the shale surface.

On thick glacial clay deposits in the Great Lakes region of North America, lateral flowage has been induced beneath stockpiles of ore, resulting in slight-lowering of the ground surface and increasing the distance between ore-retaining walls over a few decades by nearly 2 m (Terzaghi, 1953).

8.5 COMPACTION AS A CAUSE OF SUBSIDENCE

A common cause of ground-surface subsidence is reduction in the volume of low-density sedimentary deposits that accompanies the process of compaction, in which particles become more closely packed and the amount of pore space is reduced. Compaction may be induced by loading, by drainage, by vibration, by extraction of pore fluids, and under certain conditions by the application of water. Compaction occurs both naturally and by man’s manipulation.

The amount of subsidence effected by compaction is a function of the relative amount of pore space in the material as originally deposited, the effectiveness of the compacting mechanism, and the thickness of the deposit undergoing compaction. Natural deposits of unusually high initial porosity include modern delta deposits, terrigenous mudflows, undisturbed loess, and peat.

8.5.1 Loading

The effects of natural loading are most apparent where great thicknesses of fine-grained sediments accumulate rapidly. The process of compaction is accompanied by contemporary subsidence. On the modern Mississippi River delta, 300 to 500 million tons of sediment is deposited each year. Fisk and others (1954) found that levee deposits on the lower delta had subsided 6 m and interdistributary marsh deposits, 8.5m.

At New York’s La Guardia Airport, the natural compaction of an 18-m thickness of saturated organic silt and clay deposits was accelerated by artificial loading (Engineering News Record, 1949; Kyle, 1951). Half the airport was reclaimed from Flushing Bay by placing 7.5 m of fill over the saturated sediments. After 25 years of operation, parts of the filled area had subsided

2.5 m, with further subsidence anticipated (Halmos, 1962). Protection from tide waters is furnished by a dike around three sides of the airport, which was built on soil stabilized by sand drains that extend 20 m below sea level.

8.5.2 Drainage

In low-lying areas, lowering of the water table by artificial drainage stimulates compaction of sediments with accompanying subsidence of the surface. Compaction rates have much more than academic significance in areas such as the polders of the Netherlands where vast regions have been reclaimed from the sea by building dikes and installing pumps. Bennema and others (1954) found that clay deposits containing 30 to 35 per cent of a minus 2-micrometre fraction compressed to about half their original thickness after reclamation over a 100-year period. Sediments with about 20 per cent fine fraction compressed about 25 per cent; compaction of sand layers was negligible.

Drainage of peat areas can be expected to result in subsidence for two reasons. Peat is commonly underlain by, and frequently interbedded with, fine sediments that are susceptible to compaction when drained. In addition, peat has certain physical and chemical characteristics that lead to extreme volume changes upon drying (Highway Research Board, 1954; MacFarlane, 1959; Stephens and Speir, 1969). Peat has a water-holding capacity ranging from 300 to 3,000 per cent.

Its bulk density is extremely low--about 960 kg/m^3 when wet and 64 kg/m^3 when dry. Particle specific gravity is also low--between 1.0 and 2.0. Furthermore, peat undergoes irreversible biochemical changes on drying that reduce volume. The largest peat areas in the United States that have been subsiding following reclamation for agricultural development are the Florida Everglades (Stephens and Speir, 1969) and the delta area at the confluence of the Sacramento and San Joaquin Rivers in California (Weir, 1950). In the Chikuho coalfield in Japan, subsidence in areas underlain by thick peat and organic clay deposits was attributed to their compaction in response to the lowering of ground-water levels during mining operations (Noguchi, Takahashi, and Tokumitsu, 1969).

8.5.3 Vibration

Sedimentary materials may be compacted by vibration under natural conditions during earthquakes. Buildings on saturated alluvium or uncompacted fill may subside or settle differentially in response to earthquake vibrations or, if the foundations are tied to a lower stable stratum, the buildings may appear to rise as the surrounding sediments subside by compaction.

A variety of manmade sources of vibration have been cited by Terzaghi and Peck (1967) as having produced subsidence by compaction of underlying earth materials. These sources of vibration include heavy rock-crushing equipment, turbogenerators, truck traffic, an elevated railway, pile driving and blasting. At sites of structures to be built on saturated sand, future subsidence may be forestalled by the vibroflotation process of foundation treatment. Giant vibrators fitted with jets are lowered to the desired depth and withdrawn slowly, resulting in cylinders of compacted sand (Sowers and Sowers, 1961). Loose foundation materials may also be densified by buried charges of explosives (Lyman, 1942). Underground nuclear explosions in unconsolidated materials are characterized by craters on the ground surface (Drell, 1978).

8.5.4 Extraction of pore fluids

Of all causes of land subsidence, both natural and those induced by man’s activities, subsidence associated with extracting fluids from subsurface formations is best understood. Many areas of subsidence caused by pumping of artesian water, oil, and gas have been identified, surface and subsurface changes have been monitored, and corrective measures have been devised. A decade ago the topic of "Land Subsidence Due to Fluid Withdrawal" was reviewed by Poland and Davis (1969). Current progress in identifying and coping with subsidence caused by withdrawing ground water in many parts of the world is reported in the case histories comprising Chapter 9 of this volume.

8.5.5 Hydrocompaction

Certain materials of unusually low density deposited in areas of low rainfall undergo significant compaction when they become thoroughly wetted. The process, termed "hydrocompaction," produces rapid and irregular subsidence of the ground surface, ranging from 1 to nearly 5 m. Reclamation projects that import and distribute irrigation water in dry areas underlain by loess and by mudflow deposits have encountered subsidence problems. It is thought that clay bonding of the particles is responsible for maintaining open textures while the deposits are in a dry condition, and for rapid disaggregation and volume loss when immersed in water (Bull, 1964). Surface subsidence resulted from wetting without the addition of surcharge load at many sites; at others, a combination of water infiltration and surface loading was required. A review of the phenomenon of hydrocompaction by Lofgren (1969) describes the process and associated subsidence occurrences in the United States, Europe, and Asia.

8.6 TECTONIC SUBSIDENCE

Large areas of measurable downward displacement have been associated with a few earthquakes of large magnitude. The 1959 Hegben Lake earthquake in Montana produced an asymmetrical subsided area 69 by 22 km, in which the maximum subsidence was 6.6 m (Myers and Hamilton, 1964). During the 1960 series of earthquakes in Chile, subsidence of 1 to 1.5 m was reported to have affected a coastal area 600 by 30 km (Weishcet, 1963). The 1964 Alaska earthquake produced an asymmetrical downwarped area 800 by 160 km. Tectonic subsidence, which ranged up to 2.3 m, was augmented in many places by compaction of unconsolidated materials (Plafker, 1965).

8.6.1 Discussion

The state-of-the-art in land-subsidence analysis progresses unevenly because the degree of understanding of various subsidence mechanisms varies. Most study has been directed to subsidence related to man’s engineering activities. This is facilitated by availability of data on quantities of subsurface material removed (or injected), on rates and duration of extraction operations, and on changes in ground-water levels. Natural processes are not as easily quantified.

A case of land subsidence is necessarily the integrated surface expression of whatever processes may be active at that site, whether natural or manmade, or both. A working hypothesis as to the mechanism or combination of mechanisms operative at the specific site is requisite for designing control measures. The complexity of subsidence mechanisms and their interaction requires cooperative effort among different disciplines, both in collecting physical evidence and in developing the rationale for the processes involved. The hydrologic sciences have been, and will continue to be, significant contributors to land subsidence investigations.

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