I Introduction, by Working Group 8.4, International Hydrological Programme

1.1 BACKGROUND INFORMATION

The increasing exploitation of ground water, especially in basins filled with unconsolidated alluvial, lacustrine, or shallow marine deposits, has as one of its consequences the sinking or settlement of the land surface--land subsidence (see Glossary, Appendix D).

The occurrence of major land subsidence due to the withdrawal of ground water is relatively common in highly developed areas. Case studies on land subsidence and on remedial measures taken will be useful for developing areas facing similar problems in the future.

The problems of land subsidence were included in the programme of the International Hydrological Decade. During the Decade the major action with respect to land subsidence was the organization of the International Symposium on Land Subsidence held in Tokyo in 1969. The subject has also been retained under the framework of the International Hydrological Programme and included in the work plan for the first phase of the Programme (1975-1980) as IHP subproject 8.4.

In April 1975, the Intergovernmental Council for the International Hydrological Programme, at its first session in Paris, established a Working Group for coordination of IHP subproject 8.4, "Investigation on land subsidence due to ground-water exploitation." The Working Group members are listed below. In addition, A. I. Johnson, Vice President of the International Association of Hydrological Sciences, was the designated liaison from that international organization.

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1.2 PURPOSE AND SCOPE OF GUIDEBOOK

The group was asked to prepare a guidebook on subsidence due to ground-water withdrawal, paying particular attention to measures to control and arrest subsidence, the use of artificial recharge, and the repressuring of aquifers. The goal was to produce a guidebook that will serve as a guide to engineers, geologists, and hydrologists faced with the problem of land subsidence, particularly in developing countries. They may be asked to answer the questions of whether land subsidence is occurring, if so, where and at what rate, the cause or causes, and what can be done to stop it or at least slow it down. The guidebook should be of assistance in planning and undertaking the field studies.

The first session of the Working Group was held in December 1976 in connection with the Second IAHS-UNESCO International Symposium on Land Subsidence in Anaheim, California. At that meeting the group drafted the general outline of the guidebook and decided on the distribution of work.

The guidebook is organized in two parts. Part I is a manual of seven chapters on the occurrence, measurement, mechanics, prediction, and control of land subsidence due to groundwater withdrawal. It has been prepared as a joint effort of the Working Group members.

Part II is a series of invited case histories of land subsidence due to ground-water withdrawal, prepared by individual authors. The first chapter in Part II (Chapter 8) is a brief discussion of other types of land subsidence written by Ms. Alice Allen. Subsidence may occur from many other causes than withdrawal of ground water. Some occurrences are due to natural causes and some are the work of man. Anyone investigating subsidence due to ground-water withdrawal should have at least an elementary knowledge of other types of subsidence and the geologic environments in which they are likely to occur. Although the present discussion by Ms. Allen is brief, it contains 62 references, which should prove very helpful to the reader who wishes to learn more about any particular subsidence process.

The second chapter in Part II (Chapter 9) consists of 15 case histories of subsidence due to ground-water withdrawal, prepared by individual authors. These case histories cover a wide range of conditions and magnitudes of subsidence. Of the occurrences described, 12 are areas of ground-water withdrawal for use and 3 represent conditions where ground water is withdrawn as a step in obtaining a resource. These are Latrobe Valley, Australia (withdrawal to permit mining brown coal), Niigata, Japan (withdrawal to obtain natural gas), and Wairakei, New Zealand (withdrawal of hot water for geothermal power).

1.3 OCCURRENCE OF SUBSIDENCE

The chief source of information on areas of land subsidence due to ground-water withdrawal is the Questionnaire on Land-Subsidence Occurrence, Research, and Remedial Work that was distributed worldwide in 1975-78 by A. I. Johnson, then President of the International Commission of Subsurface Water of IAHS. The results of this survey are being compiled for publication by UNESCO and IAHS. Other sources of data are (1) the 15 case histories in Part II of this casebook, (2) the Proceedings of the lst International Symposium on Land Subsidence held in Tokyo, Japan, in September 1969, and (3) the Proceedings of the 2nd International Symposium on Land Subsidence held in Anaheim, California, in December 1976.

Table 1.1, based on the information listed above, summarizes information on 42 subsidence areas worldwide, of which 18 are in the United States and 10 are in Japan (Figure 1-1). Actually, Japan has the largest number of subsiding areas of any country. According to Yamamoto (1977, p. 9 and Figure 2), the number of subsiding areas in Japan has reached 40 and is still increasing. Most of the subsidence is due to ground-water withdrawal from thickly populated topographically low areas bordering the ocean. Only the 10 chief subsidence areas in Japan due to ground-water withdrawal are reported in Table 1.1 and shown in Figure 1.1. All of these border the ocean.

In terms of vertical magnitude, the subsiding areas listed in Table 1.1 range from reported minor casing protrusion in Bangkok, Thailand, and 0.15 m of subsidence in Venice, Italy, to 15 m in the Cheshire district of Great Britain where rock salt has been mined by solution since Roman times. As a result of man-induced sinkhole development in carbonate terrane in Alabama, we even have a reported maximum of 37 m. The areal extent of subsidence, worldwide, ranges from 10 km^2 in the San Jacinto Valley to 13,500 km^2 in the San Joaquin Valley, both in California (USA).

Figure 1.2 shows the geographic location of the 17 areas in the United States (exclusive of the Alabama sinkhole area) on a map of conterminous United States. Subsidence of the land surface in the 17 areas ranges from 0.3 m at Savannah, Georgia to 9 m. on the west side of the San Joaquin Valley (Los Banos-Kettleman City area) in California (Figure 1.3). Subsidence exceeding 1 metre occurs in four States: Texas, Arizona, Nevada, and California. The areal extent ranges from 10 km^2 in San Jacinto Valley, California, to 13,500 km^2 in the San Joaquin Valley. California is the State ranking number one for the dubious honor of having the largest area of subsidence --about 16,000 km^2. Close behind is Texas with 12,000 km^2; and Arizona is third with 2,700 km^2.

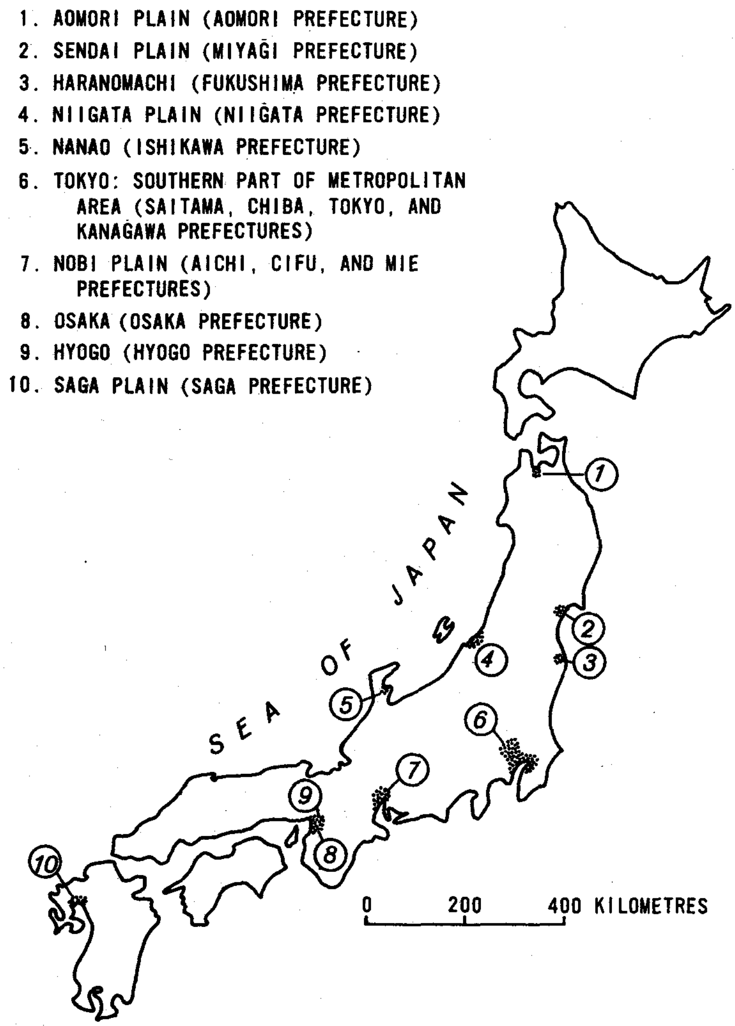

Figure 1.1 Chief subsidence areas in Japan.

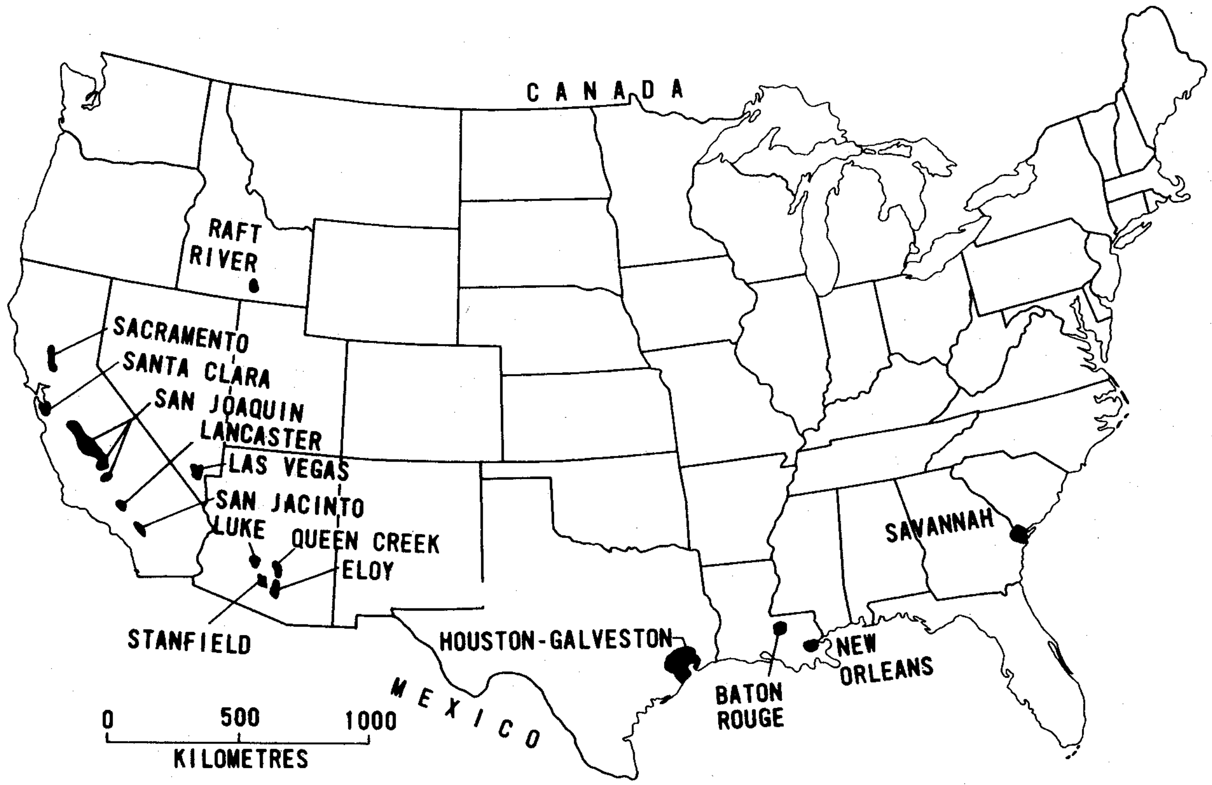

Figure 1.2 Areas of land subsidence from ground-water withdrawal, USA.

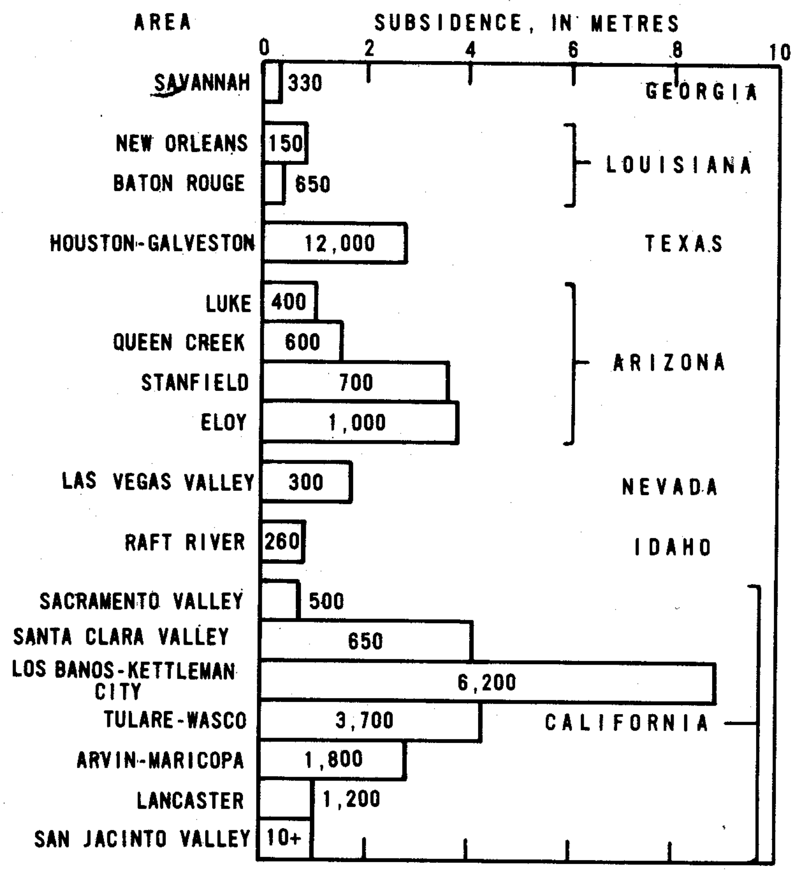

Figure 1.3 Magnitude of land subsidence from ground-water withdrawal, USA (number in column represents area in square kilometres).

Table 1.1. Areas of land subsidence due to ground-water withdrawal

Location	Depositional environment and age	Depth range of compacting beds (m)	Maximum subsidence (m)	Area of subsidence (km^2)	Time of principal occurrence	Remedial or protective measures taken	Principal reference(s)
Australia:							
Latrobe Valley.	Lacustrine and fluviatile; early Tertiary.	10-300	1.6 (1977)	100 (>0.2 m)	1961-78	Reduction in artesian ground-water pressures, necessary for mining coal. Restrictions placed on building in critical area.	Gloe (1977); Gloe, Guidebook, Ch. 9.1.
China:							
Shanghai.	Alternating fresh-water and marine; Quaternary.	3-300	2.63 (1965)	121	1921-65	Restricted use of ground water; artificial recharge by injection of treated river water into wells; adjustment of pumping pattern.	Shanghai Hydrogeological Team (1973); Luxiang and Manfang, Guidebook, Ch. 9.2.
Taipei Basin.	do.	10-240	1.9 (1974)	235	1955-74	In 1968, legal action taken to limit ground-water pumpage.	Hwang and Wu (1969); Wu (1977).
Great Britain:							
London.	London Clay of Eocene age overlying chalk aquifer of Cretaceous age.	50-100	0.35 (1976)	450	1865-1932	None.	Longfield (1932); Wilson and Grace (1942); Water Resources Board (1972).
Cheshire district.	Sandstone, marl, and rock salt; Triassic.	100-300	15 (1977)	1,500	1533-1977	Reduced pumping of brine; installed flexible foundations; regraded railways roads, canals.	Howell and Jenkins (1977); Collins (1971).
Hungary:							
Debrecen.	Fluviatile; Quaternary.	50-250	0.42 (1975)	390	1920-75	None.	Orlóczi (1969); Miskolczi (1967); Szekely (1975).
Visonta.	Fluviatile and swampy; late Cenozoic.	20-100	0.5 (1975)	40	1961-75	None.	Kesserü (1970); Kesserü (1972).
Italy:							
Po Delta.	Alluvial, lagoonal, and shallow marine; Quaternary.	100-600	3.2	2,600	1951-66	Pumping of gas-bearing water stopped by legal action.	Schrefler, Lewis, and Norris (1977); Zambon (1967); Caputo, et al (1970).
Ravenna.	Alluvial, lacustrine, and shallow marine; Neozoic.	80-500	1.20 (1977)	about 600	1955-77	None (project plans underway).	Bertoni, et al (1973); Carbognin, et al (1978); Guidebook, Ch. 9.15.
Venezia.	Alluvial, lacustrine, and shallow marine; Neozoic.	70-350	0.15 (1976)	about 400	1952-70	A 70-percent shutdown of active artesian wells including some principal ones, and construction of two river-fed aqueducts supplying mainly the industrial zone.	Gambolati and Freeze (1973); Gambolati, et al (1974); Carbognin, et al (1977) (reprinted in Guidebook as Ch. 9.3).
Japan:							
Aomori.	Alluvial and lacustrine; late Cenozoic.	0-600	0.45 (1977)	65	1958-78	Reduced withdrawal of ground water by regulation	Aomori Pref. (1974).
Sendai.	Alluvial and shallow marine; late Cenozoic.	0-300	0.57 (1977)	90	1966-78	As above and introducing water from river	
Haranomachi. City.	Alluvial and shallow marine; late Cenozoic.	100-200	2	25	1965-78+	Regulation of ground water withdrawal; constructed multipurpose dams and water-supply systems	IAHS questionnaire.
Nanao.	Alluvial and shallow marine; late Cenozoic.	0-200	0.53 (1977)	80	1972-78	Reduced withdrawal of ground water by regulation	Murakami and Takahashi (1969)

Tokyo, including Chiba, Saitama, and Kanagawa Prefectures.	Alluvial and shallow marine; late Cenozoic.	0-400 and *800-2,000	4.59 (1975)	3,420	1918-78+	Built reservoirs and canals to import surface water-from R. Tone and reduce ground-water withdrawal	Miyabe (1962); Aoki and Miyabe (1969); Ishii, et al (1977); Yamamoto, Guide book, Ch. 9.4.
Niigata	Shallow marine and marine; late Cenozoic.	0-1,000	2.65 (1965)	430	1957-78+	Reduced withdrawal of gas-bearing water by regulation; since 1973, all gas water reinjected into reservoirs.	Takeuchi et al (1969); Aoki (1977); Yamamoto, Guidebook, Ch. 9.7.
Nobi (Aichi, Gifu, and Mie Prefectures.	Alluvial and lacustrine; late Cenozoic.	0-300	1.53 (1970)	1,140	1932-78+	Diverted Aichi irrigation water and constructed dam; reduced ground-water withdrawal by regulation.	Kuwahara, et al (1977); Yamamoto, Guidebook, Ch. 9.6.
Osaka.	Alluvial and lacustrine; Quaternary.	0-400	2.88 (1970)	630	1935-70	Imported surface water from R. Yodo and reduced ground-water withdrawal.	Murayama (1969); Ikebe, et al (1970); Nakamachi (1977); Editorial Comm. (1969); Yamamoto, Guidebook, Ch. 9.5.
Hyogo.	do.	0-200	2.84 (1960)	100	1932-70	do.	
Saga.	Alluvial and shallow marine; Quaternary.	0-200	1.20 (1977)	300	1957-78+	Imported surface water; dam under construction.	Kumai, et al (1969).
México:							
México city.	Alluvial, lacustrine; Quaternary and Tertiary.	0-50	9(1978)	about 225	1891-1978	Holding withdrawal constant and undertaking delivery of surface water into the valley of Mexico to diminish and eventually eliminate ground-water overdraft.	Marsal y Mazari (1959); CHCVM (1953-1970); CAVM (1975); Figueroa-Vega, Guidebook, Ch. 9.8.
New Zealand:							
Wairakei.	Volcanic flows and breccias; Pleistocene.	250-800	6-7 (1975)	30	1952-78	None.	Stilwell, Hall, and Tawhai (1975); Bixley, Guidebook, Ch. 9.9.
South Africa:							
Far West Rand.	Dolomite Series, Paleozoic, and weathered overburden.	30-200 for overburden; 30-1,200 for dolomite.	9(overburden)	?	1959-75	Artificial recharge of dolomitic compartments with ground water pumped from mines.	Bezuidenhout and Enslin (1969); Enslin, et al (1977).
Thailand:							
Bangkok.	Alluvial and shallow marine; Quaternary.	0-200	Well casing protrusion reported.	?	1978-	None.	Piancharoen (1977); Brand and Balasubramaniam (1977); Yamamoto, Guidebook, Ch. 9.10.
United States:							
Alabama:	Carbonate terrane; unconsolidated deposits on bedrock.	10-100	37(?)	4,000 manmade sinkholes, 1-1,000 m in diameter.	1900-75	Removal of surface water; bridging of railroads and highways; removal of unconsolidated deposits.	Newton (1977); Newton, Guide book, Ch. 9.11.
Arizona**:							
Luke area.	Alluvial and lacustrine; Cenozoic	50-350	1(1967)	400	1950(?)-1978	Damaged well casings repaired	Laney, Raymond, and Winikka (1978).
Queen Creek area.	do.	50-350	1.5 (1976)	600	1950(?)-1978	Constructing major aqueduct to import Colorado River water and reducing overdraft.	Winikka and Wold (1977); Schumann (1914).

Table 1.1. Areas of land subsidence due to ground-water withdrawal--Continued

Location	Depositional environment and age	Depth range of compacting beds (m)	Maximum subsidence (m)	Area of subsidence (km^2)	Time of principal occurrence	Remedial or protective measures taken	Principal reference(s)
United States--Continued:							
Arizona--Continued:							
Stanfield area.	Alluvial and lacustrine; Cenozoic.	50-350	3.6 (1977)	700	1950(?)-78	Well casings repaired.	
Eloy area.	do.	50-350	3.8 (1977)	1,000	1950(?)-78	Well casings, highway, and railroad repaired.	Schumann and Poland (1969).
California							
Sacramento Valley.	Alluvial and fluviatile; late Cenozoic.	30-300	0.7	500	1955-78+	None.	Lofgren and Ireland (1973).
Santa Clara Valley.	Alluvial and shallow marine; late Cenozoic.	50-330	4.1 (1975)	650	1918-70	Built detention dams; increased local recharge; built levees; imported water; many damaged well casings repaired or wells replaced.	Poland (1977); Poland, Guidebook, Ch. 9.14.
San Joaquin Valley							
Los Banos-Kettleman City area.	Alluvial and lacustrine; late Cenozoic.	60-900	9.0 (1977)	6,200	1930-75	Built dams and canals to import surface water and reduce ground-water withdrawal. Repaired many well casings damaged by compressive stresses.	Poland, Lofgren, Ireland, and Pugh (1975); Bull (1975); Poland and Lofgren, Guidebook, Ch. 9.13.
Tulare-Wasco area.	Alluvial, lacustrine, and shallow marine; late Cenozoic.	60-700	4.3 (1970)	3,680	1930-70	do.	Lofgren and Klausing (1969); Poland and others (1975).
Arvin-Maricopa area.	Alluvial and lacustrine; late Cenozoic.	60-500	2.8 (1970)	1,800	1940-70	do.	Lofgren (1975); Poland and others (1975).
Lancaster area.	Alluvial and lacustrine; late Cenozoic.	60-300	1+ (1976)	1,200	1955-78	Damaged well casings repaired.	Lewis and Miller (1968); McMillan (1973).
San Jacinto Valley.	Alluvial; late Cenozoic.	60-300	1+ (1974)	10+	1950-75+	None.	Lofgren (1976).
Georgia:							
Savannah area.	Marine; Tertiary.	50-150	0.3	330	1933-75+	None.	Davis, Counts, and Holdahl (1977).
Idaho:							
Raft River.	Alluvial; late Cenozoic.	50-300	10.8 (1975)	260	1960-75+	None.	Lofgren (1975).
Louisiana:							
Baton Rouge.	Fluviatile and shallow marine; late Cenozoic.	120-900	0.38 (1976)	650+	1935-76+	None.	Davis and Rollo (1969); Wintz, Kazmann, and Smith (1970); Smith and Kazmann (1978).
New Orleans.	Fluviatile and shallow marine; Quaternary(?).	150-260	0.8 (1975)	150	1940-75+	None.	Rollo (1966); Kazmann and Heath (1968).
Nevada:							
Las Vegas.	Alluvial; late Cenozoic.	60-300	1-1.7 (1972)	300	1935-75+	Moved well field away from fine-grained deposits; imported Colorado River water.	Malmberg (1964); Kindling (1971).
Texas:							
Houston-Galveston area.	Fluviatile and shallow marine; late Cenozoic.	60-900	2.75 (1973)	12,000 >15 cm	1943-78	Built reservoirs and importing surface water to reduce overdraft; Subsidence Control District created.	Gabrysch and Bonnet (1975); Gabrysch, Guidebook, Ch. 9.12.

*Extraction of natural gas.
**Data chiefly from questionnaires for IAHS completed by Carl Winikka, January 1978.

1.4 GEOLOGICAL ENVIRONMENTS OF OCCURRENCE

Subsidence due to ground-water withdrawal develops principally under two contrasting environments and mechanics. One environment is that of carbonate rocks overlain by unconsolidated deposits, or old sinkholes filled with unconsolidated deposits, that receive buoyant support from the ground-water body. When the water table is lowered, the buoyant support removed, and the hydraulic gradient increased, the unconsolidated material may move downward into openings in the underlying carbonate rocks, sometimes causing catastrophic collapses of the roof. In Alabama, according to J. G. Newton (1977 and Chapter 9.11), an estimated 4,000 man-induced sinkholes have formed since 1900 in contrast to less than 50 natural collapses. In the United States manmade sinkhole occurrence is common in carbonate terranes from Florida to Pennsylvania, numbering many thousands. The individual sinkhole area is small, however, the diameter usually ranging from 1 to 100 m (Stringfield and Rapp, 1977). Carbonate terrane susceptible to sinkhole formation when the water table is lowered occurs in many parts of the world. In populated areas the formation of sinkholes can produce a variety of problems related to the maintenance of manmade structures and the pollution of water supplies. Newton discusses some of these problems in Chapter 9.11. The overall subject is broad and beyond the scope of this guidebook.

The other environment and by far the most extensive occurrence is that of young unconsolidated or semiconsolidated clastic sediments of high porosity laid down in alluvial, lacustrine, or shallow marine environments. Almost all the subsiding areas included in Table 1.1 are underlain by semiconfined or confined aquifer systems containing aquifers of sand and/or gravel of high permeability and low compressibility, interbedded with clayey aquitards of low vertical permeability and high compressibility under virgin stresses. All the compacting deposits were normally loaded, or approximately so, before man applied stresses exceeding preconsolidation stress. These aquifer systems compact in response to increased effective stress caused by artesian-head decline in the coarse-grained aquifers and time-dependent pore-pressure reduction in the fine-grained compressible aquitards, causing land-surface subsidence.

Of the principal clay minerals--montmorillonite, illite, and kaolinite--montmorillonite is the most compressible. Montmorillonite is the predominant clay mineral in the compacting aquifer systems in southwestern United States--California (Meade, 1967), south-central Arizona (Poland, 1968), and Texas (Corliss and Meade, 1964)--also in Mexico City (Marsal and Mazari, 1959). Montmorillonite comprises 60 to 80 per cent of the clay-mineral assemblage in each of these areas. Illite is the chief clay mineral in the Taipei basin (Hwang and Wu, 1969), and in the Quaternary deposits in Tokyo (Tokyo Metropolitan Govt., 1969).

Another occurrence of subsidence due to ground-water withdrawal that is not represented in Table 1.1 has developed at many sites in Sweden and Norway and probably in other glaciated areas of similar geologic and hydrologic environments. According to Broms, Fredriksson, and Carlsson (1977), most of the bedrock in Sweden is crystalline rock, favorable for construction of underground structures, especially tunnels, because of high strength and because loose and weathered parts have been removed by the glaciation. After the latest glaciation, clay and silt were deposited on a thin layer of till or sand and gravel resting on the bedrock surface, especially in bedrock depressions that commonly are indicative of tectonic zones deepened by the ice. The areas covered with clay are small but the urban regions are mostly in these areas. Deep tunnels cutting through tectonic zones act as drains, lowering the pore-water pressure first in the pervious bottom layers (confined aquifers), and then gradually (over a period of years) in the overlying clay layer. Broms and others (1977) describe damages cause by this type of subsidence and steps that can be taken to mitigate or prevent the subsidence. They can be summarized as follows:

1. Before the construction of a tunnel, by avoiding areas which can be affected by subsidence;

2. During the construction, by pregrouting;

3. After the construction, by grouting, in order to reduce the leakage or by artificial infiltration of water to maintain the pore pressure in the compressible layers.

Moreover it is often possible to decrease the subsidence in soft clays by preloading. It is also possible to preload the compressible layers in advance by temporarily lowering the groundwater level by pumping from deep wells.

1.5 PROBLEMS AND REMEDIAL STEPS

Principal problems caused by the subsidences listed in Table 1.1 are (1) differential changes in elevation and gradient of stream channels, drains, and water-transport structures, (2) failure of water-well casings due to compressive stresses generated by compaction of aquifer systems, (3) tidal encroachment in lowland coastal areas, and (4) in areas of intensive subsidence, development of tensional or compressional strain in engineering structures. Additional details on problems are discussed in the case histories of Chapter 9.

Remedial or protective measures of some sort have been taken in 10 of the 15 case-history areas and 30 of the 42 areas listed in Table 1.1. The various steps that have been taken to control or ameliorate subsidence will be discussed in Chapter 7. The methods employed and the results attained should be of interest to anyone facing a subsidence problem due to water-level decline from overpumping. In Part I of this guidebook, frequent reference will be made to pertinent case histories.

1.6 ACKNOWLEDGMENTS

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