CHAPTER 24

Water Aquifer Subsidence

INTRODUCTION

The following review of the global problem associated with subsidence due to withdrawal of fresh groundwater shows that in all cases the sediments are of Miocene age or younger. Compaction occurs due to fluid (water) depletion (1) of the fine-grained clay/silt aquitards (that are interbedded with sand/gravel aquifers), and (2) of aquifers. Subsidence is caused by grain rearrangement and compaction when the overburden load is transferred from water to the grain-to-grain contacts. Little information is recorded on the fracture systems generated by the fluid withdrawal and its effect on the generation of fractures.

China

Land subsidence in China occurs in cities and industrial complexes located along the coastal plains of eastern China, and in the alluvial plains along the big rivers. Young sediments (Miocene age and younger) are unconsolidated and interspersed with aquitards of fine-grained clay and shale. Unregulated withdrawal of water from these areas resulted in subsidence that was noted in the early 1960s. Before the land subsidence could create severe environmental problems, studies of the rates and amounts of water withdrawal (together with the evaluations of the mechanisms of compaction and recharge of the various reservoirs) led to the development of control measures. Inasmuch as the majority of water withdrawal took place during the summer months (for industrial usage and cooling) several regulations were imposed:

1. Water production for industrial purposes was limited to the summer months only; this, in itself, reduced the rate of land subsidence considerably.
2. During the winter months, the wells are used for artificial recharge of the aquifers using surface water that is trapped and injected.
3. Injection of cold surface waters into deeper fresh-water aquifers. This cools the groundwater and makes it suitable as industrial cooling water in the summer months.

These regulations, as well as restrictions on rates of withdrawal, have allowed the continued use of the groundwater aquifers for municipal and industrial purposes with control of land subsidence (Guangxiao and Yiaogi, 1984). (Also see Donaldson and Chilingarian, 1997.)

Tokyo, Japan

The great cities of Japan (e.g., Tokyo) are located on coastal plains where the subsurface aquifers are composed of Miocene age, or younger, unconsolidated sands with interspersed layers of clay and shale. Therefore, it is not surprising that Japan has experienced land subsidence in some 50 areas, in and around its most important cities, due to water production at rates exceeding the rates of recharge. In some areas, excessive rates of water withdrawal led to salinification of the aquifers from the incursion of seawater and increased pumping costs due to decrease of permeability around the production wells as compaction of the reservoir rocks took place (see Donaldson and Chilingarian, 1997). A computer program for estimating the loss of porosity and permeability, as a function of distance from the producing wells where compaction is taking place, was presented by Chilingarian et al. in 1995.

Venice, Italy

The subsurface beneath Venice is a system composed of six sand aquifers separated by clay/silt layers, one above the other. Withdrawal of water from this system leads to rapid subsidence as the overburden stress is transferred from the fluid to the grain-to-grain contacts. The pressure difference established across the aquitards leads to slow (diffusion controlled) compaction of the clay/silt layers. As industrial withdrawal of water increased in the 1950s and 1960s, the piezometric levels under the industrial zone declined from 7 m above to 16 m below the surface. This water level decline was transferred to the area under Venice as a drop in piezometric level to about 7 m below the surface, resulting in rates of subsidence of 5 mm/y in areas within the city; this translates to 9 cm of subsidence in the city by 1970. It was estimated that a 1 m lowering of the piezometric level under the city causes subsidence of 2 cm. About 70% of the total subsidence occurred in the period from 1952 to 1969 during industrial expansion that was accompanied by increases in water withdrawal (Carbognin et al., 1976, Carbognin and Gatto, 1984; Brighenti et al., 1995). Measures taken after 1969, however, ended the subsidence and resulted in a 2 cm rebound.

Mexico City, Mexico

The portion of Mexico City that underwent subsidence due to water production is underlain by a thick bed of clay (80% montmorillonite), mixed with fine-grained sand and silt, ranging up to 50 m in thickness. The fresh-water aquifer is a thick stratum of sand and gravel, up to 50 m in thickness. The permeability of the aquifer is very high, delivering 350 m^3/hr of water. Records indicate that the first water well was installed in 1860 and water production increased throughout the city as the need for municipal water increased with increasing development and population growth. Quantitative measurements of the amount and rate of subsidence have been made since 1891 and the effects of subsidence on structures in the city were noticed by 1920. It was not until 1948, however, that subsidence within the city was attributed to withdrawal of groundwater for municipal and industrial use. The estimated subsidence in the older part of the city, from 1891 (when the first well was installed) to 1973, was about 8.5 meters. Research has shown that 75% of the subsidence occurred in the overlying clay layer and the other 25% within the aquifer (see Vega, 1976, 1984; Donaldson and Chiligarian, 1997).

Taipei City, Taiwan

Land subsidence occurred in Taipei City, Taiwan, from 1955 to 1975 creating a bowl-shaped depression with a depth of about 1.2 m on the east side of the city. A mandated reduction of the amount and rate of water withdrawal in 1974 gradually reduced this rate of subsidence. The depression shifted to the west side as pumping was moved to the western border, where the rate of subsidence reached 14 cm per year. Subsidence occurred in both areas because of reduction of the piezometric head, principally in the Linkou Formation at a depth of 50 to 100 m, which is composed of gravel, sand, and clay. The Linkou Formation is overlain by the Sungshan Formation composed principally of clay, silt, and fine sand under a layer of alluvial beds. Most of the compaction is occurring in the Linkou Formation with probable time-delayed compaction in the Sungshan Formation (Wu, 1976).

Bangkok, Thailand

Land subsidence due to water production has occurred to some extent in Bangkok, Thailand. Bangkok, however, cannot tolerate a great deal of surface subsidence because the average ground elevation above mean sea level is only 1.0–1.5 m and the average ground water table is only 1–2 m below the surface in areas outside of the pumped zones. The top sedimentary layer is a gray marine clay about 30 m thick (Bangkok clay), which is followed by sequences of unconsolidated sands and gravel, separated by thick layers of clay, down to a fractured basement rock more than 1,000 m deep. Water production is generally from the Nakhon Luang aquifer at 150 m depth and the Nonthaburi aquifer at a depth of 200 m, which have very high transmissibility, in the order of 50–125 m^3/hr-m (Piancharoen, 1976). The Phrapradaeng aquifer below the Bangkok clay has been generally abandoned because of saltwater incursion.

Bergado et al. (1984) reported that the Asian Institute of Technology campus, just north of Bangkok, experienced subsidence as evidenced by cracks in buildings, concrete structures, and roads due to differential vertical movement. Compaction was taking place at a depth of 200 m from pumping near the campus (see Brand and Balasubramaniam, 1976; Yamamoto, 1984; Donaldson and Chilingarian, 1997).

Orange County, California, United States

Subsidence occurred near the coast in Orange County, California, from compaction of sands within the aquifer from which fresh water was withdrawn. The principal cause of subsidence is attributed to compaction and shrinkage of organic peat deposits lying on top of the aquifer at a shallow depth of about 20 m and ranging in thickness up to about 60 m. Decline of the piezometric level caused invasion of saline water from the coastal aquifers. When the chloride ion level began to rise, a hydraulic barrier to seawater incursion was installed (Fairchild and Wiebe, 1976).

Santa Clara Valley, California, United States

Land subsidence in the Santa Clara Valley was first recognized in 1932. The area that underwent subsidence ranges from the southern end of San Francisco Bay to the city of San Jose (about 40 km). The Santa Clara valley is a trough located between the Hayward Fault on the east and the San Andreas Fault on the west forming a confined aquifer system. Subsidence reached 8 m at the center between the cities of Santa Clara and San Jose until arrested in 1965 by (1) a decrease of pumping rates, (2) the importation of water from rivers, and (3) a recharge of the aquifer from impounded local rain water runoff. Compaction of the aquifer and associated inclusions of clay/silt lenses was responsible for the surface subsidence, which has been stabilized by maintaining the piezometric level at 1972 levels using prudent pumping rates (Poland, 1984).

San Joaquin Valley, California, United States

The greatest area of land subsidence in California is the San Joaquin Valley, which occupies the southern two-thirds of the Central Valley. The fluvial deposits of lenticular layers of sand, gravel, and silt are interspersed with deposits of lacustrine origin. The eastern side of the valley consists of deposits from major streams, which form a series of commingled alluvial fans made up of coarse deposits of sand and gravel between layers of clay and silt. All of the deposits are younger than Miocene age.

There are two principal freshwater-bearing aquifers divided by a bed of clay ranging to 40 m in thickness: (1) the upper zone that extends from the surface to depths of 275 m, and (2) the lower water zone with a thickness range of 60 to 600 m. During World War II the rate of water production was increased from about 4,000 hectare-m to more than 12,000 hectare-m by 1966, keeping pace with the rapidly expanding agricultural enterprises in the valley. During this period the piezometric level declined by 60 to 180 m in the region. A combination of three types of subsidence, in response to the piezometric level decline, resulted in the spectacular amount of decline that occurred over a large area. Subsidence up to 10 m occurred along a narrow trough west of Fresno and extending 140 km south. Other areas throughout the valley subsided 1 to 4 m during the period of increased water withdrawal (Donaldson and Chilingarian, 1997).

Subsidence was attributed to: (1) hydro-compaction when water for irrigation was applied to moisture-deficient, near-surface deposits; (2) compaction of the aquifer system, which includes major compaction of the fine-grained clay/silt sediments and compaction of the aquifer sands, as the piezometric level was decreased, transferring vertical stress to the grain-to-grain contacts; and (3) compaction due to hydrocarbon production in some areas. After 1966, subsidence was stopped when large imports of surface water from the north, west, and south sides of the valley were used for irrigation in place of groundwater (Prokopovich, 1976; Poland et al., 1984).

Houston, Texas, United States

High rates of water withdrawal has led to subsidence of 2.3 m southeast of Houston (in the Pasadena City area) and about 0.5 m in the industrial area of Texas City south of Houston. It is estimated that the piezometric level in the principal aquifer declined by almost 100 m. The sand aquifers contain a large number of interbedded layers of clay, ranging up to 6 m in thickness, which retard vertical movement of water and cause large vertical differences in water pressure. Major amounts of compaction occur in the fine-grained clay bodies. The subsidence has caused inundation of homes across the bay (in Baytown) and there is speculation that future hurricane tides may cause considerable damage in the south Houston area (Gabrysch, 1976).