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OUTLINE

LAND SUBSIDENCE AND GROUND-WATER PUMPING

BY

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I. INTRODUCTION

A. Summary

Land subsidence is loss of elevation of the land surface. Although it can be caused by a variety of man-induced processes, the most areally extensive land subsidence in the United States has been caused by ground-water pumping from unconsolidated aquifer systems. Such pumping has caused a cumulative area of more than 22,000 km^2 (8500 mi^2), an area approximately the size of the State of New Jersey, to subside more than 30 cm (1 ft). The maximum subsidence exceeds 8.8 m (29 ft) which was observed in the San Joaquin Valley, California, from 1926 to 1972. Although effects from subsidence are most dramatic in coastal areas subject to flooding upon loss of elevation, regional differential subsidence has had a costly impact on the design and operation of canals and aqueducts in the western United States. In addition, rupture or failure of the ground has locally accompanied land subsidence, damaging many engineered structures and posing limitations to land use in subsiding areas.

B. Research Sources

1. Poland, J. F., and Davis, G. H., 1969, Land subsidence due to withdrawal of fluids in Varnes, D. V., and Kiersch, G., eds. Reviews in Engineering Geology, v. 2, Geological Society of America, pp. 187-269--This article describes the occurrence of subsidence on a world-wide basis and reviews the mechanisms of

subsidence.

2. Helm, D. C., 1976, One-dimensional simulation of aquifer system compaction near Pixley, California, 2. Stress-dependent parameters: Water Resources Research, v. 12, no. 3, pp. 375-391--This technical article describes and illustrates the precision of the best of the digital models available for predicting land subsidence.

3. Holzer, T. L., 1977, Ground failure in areas of subsidence due to ground-water decline in the United States in International Land Subsidence Symposium, 2nd, Anaheim, 1976, Proceedings: International Association of Scientific Hydrology, Publication No. 121, pp. 423-433--This article summarizes and describes the occurrence of ground failure associated with land subsidence in the United States.

4. Holzer, T. L., 1979, Elastic expansion of the lithosphere caused by ground-water depletion: Journal of Geophysical Research, v. 84, no. B9, pp. 4689-4698 --This article examines the potential for deep-seated crustal movements caused by ground-water mining.

5. Brah, W. J., and Jones, L. L., 1978, Institutional arrangements for effective groundwater management to halt land subsidence: Texas Water Resources Institute Technical Report No. 95, Texas A & M, 194 p.--This report evaluates the alternative arrangements of legal, economic, and political institutions that were

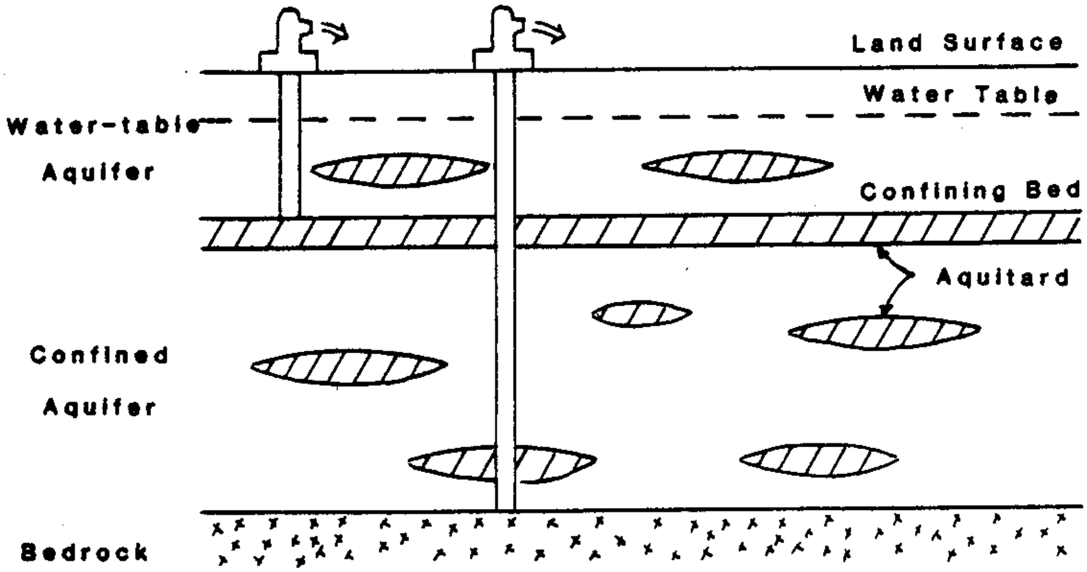
considered in order to arrest subsidence in the Houston-Galveston, Texas, area where subsidence of the coastal area was costing approximately $31.7 million per year by the 1970's.

6. Lucas, C. V., and James, L. B., 1977, Land subsidence and the California State Water Project in International Land Subsidence Symposium, 2nd, Anaheim, 1976, Proceedings: International Association of Scientific Hydrology, Publication No. 121, pp. 533-543--This nontechnical article describes the effect of land subsidence on the design of the California Aqueduct.

7. Poland, J. F., Lofgren, B. E., and Riley, F. S., 1972, Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal: U. S. Geological Survey Water-Supply Paper 2025, 9 p.--A well-written glossary of subsidence terms.

II. CAUSE OF LAND SUBSIDENCE

A. Idealized Aquifer System



Subsidence-prone areas typically are underlain by unconsolidated (nonlithified) sediments that consist of alternating layers of sand, silt, and clay. When ground-water is pumped from these sediments, the water is transmitted laterally to pumping wells in the sand layers. The fine-grained clay and silt layers behave as barriers to rapid movement of ground-water. Given sufficient time, sometimes measured in years or decades, these fine-grained layers may transmit significant quantities of water to the sand beds and ultimately to the pumping wells. The sand beds and clay and silt beds are called aquifers and aquitards, respectively. Laterally extensive aquitards that are particularly slow in transmitting water are called confining beds and compartmentalize the aquifer such that pumping from one aquifer may have negligible effect on adjacent aquifers.

B. Subsidence Mechanism

When water levels are lowered by ground-water pumping, the water pressure decreases in the pores of the sediments from which the ground-water is withdrawn. Because the water pressure in the pores helps support the weight of overlying sediments, the decrease of pore pressure causes more of the weight of the overlying sediments to be transferred to the intergranular skeleton of the sediments. At the depths encountered in aquifer systems, clay and silt beds, i.e., aquitards, often are very compressible and compact (decrease of pore volume) irreversibly as the weight of the overlying sediments is slowly transferred to the intergranular skeletons. Because the lateral extent of these beds typically is much greater than their depth, 100 percent of the compaction is transmitted to the land surface and is manifested as land subsidence.

III. SUBSIDING AREAS AND METHODS OF DETECTION

A. Subsiding Areas in the United States

More than 15 areas in the United States have experienced subsidence caused by ground-water withdrawal. Most of these areas occur in the Gulf Coast and in valleys in the western United States. The areas vary greatly in size ranging approximately from 100 to 10,000 km^2 (40 to 4,000 mi^2). The three largest areas of land subsidence are the

Houston-Galveston, Texas, area, the San Joaquin Valley, California, and south-central Arizona. Land subsidence affects both rural and urban areas.

B. Characteristics of Subsiding Areas

Subsidence-prone areas in general are topographically flat and are underlain by thick geologically youthful sediments (less than 5 million years old) deposited by a variety of geologic agents including streams, lakes, and oceans. The deposits most prone to subsidence are those that have significant amounts of clays and silts and have had relatively simple geologic histories. Deposits squeezed by tectonic forces or previously weighed down by sediments now eroded away, tend to be less compressible and not as subsidence prone.

C. Subsidence Detection

Subsidence usually is first detected before it is of practical consequence on the basis of resurveys of preexisting bench mark networks in an area. Survey techniques are required that are more precise than those used for common land surveys. Such precise surveys are routinely performed by many different government agencies. Subsidence also can be detected by specially instrumented wells designed to measure the compaction within the aquifer system.

IV. EFFECTS

A. Loss of Surface Elevation

Lowering of the land surface is of greatest concern near bodies of surface water, particularly oceans and lakes, because of the potential for of inundation and the increased hazard from tidal flooding. Costs associated with such flooding in the Houston-Galveston, Texas, area are estimated to exceed $30 million per year.

B. Tilting of the Land Surface

Differential subsidence can wreak havoc on the operation of water-conveyance structures dependent on gravity flow. Special studies and design are required for such structures in subsiding areas.

C. Well Damage

Compaction within the aquifer system can cause wells to fail by shortening their casing to the point of collapse. Such collapse typically destroys the productivity of the well, thereby necessitating its replacement.

D. Ground failure

Renewed aseismic movement of geologic faults and development of long tension cracks commonly accompany land subsidence. Fault scarps as long as 16 km (10 mi) and as high as 1 m (3 ft) have been observed. Damage to engineered structures, particularly residences and other buildings, commonly is devastating from these faults. In undeveloped areas, faults and tension cracks impose restrictions on future land use.

E. Decreased Storage Capacity of Aquifer System

Water obtained from clay and silt beds during their compaction is "mined" water because the compaction process is irreversible. In other words, the storage capacity of an aquifer system is permanently diminished by the compaction, so that less water will be available during any subsequent cycles of recharge and depletion.

F. Crustal Movements

The mass of the water removed from the clay and silt beds during their compaction represents a permanent unloading of the earth's crust. When mass losses are large, the earth's crust beneath the aquifer system may begin to move slowly upward in response to the decreased weight on it. In seismically active areas, earthquakes might be triggered by such movements.

V. ASSIGNING RESPONSIBILITIES

A. Technical Evaluation

In order to identify parties responsible for damages associated with land subsidence one must know what part of the aquifer system is compacting and which parties are responsible for the water-level declines in that part of the system. In general, detailed subsurface information will be required as will modelling of the ground-water system. It is technically feasible to identify both elements.

B. Scientific Expertise

In well-studied areas, government agencies may have already performed much of the analyses required for a technical evaluation. In less well-studied areas, geotechnical (soils engineering) or water-resource expertise is required for appropriate analyses.

VI. PREDICTION OF SUBSIDENCE

A. Active Subsidence Areas

The reliability of subsidence prediction in areas where it is ongoing depends on the amount of information available, particularly subsurface geology and water-level and leveling or survey data. Given adequate information and the future water-level declines, accurate predictions can be made.

B. Undeveloped Areas

Prediction of subsidence in areas of proposed ground-water development can be made by either (1) comparing them with nearby developed areas with similar subsurface geology or (2) geotechnical testing of representative core samples obtained by drilling. Predictions by either of these techniques generally are imprecise and permit only qualitative assessments of the subsidence potential.