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# SUBSIDENCE OF LAND CAUSED BY 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, which accompanies land subsidence, has damaged many engineered structures and poses limitations to land use in subsiding areas.

B. Selected References


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associated with land subsidence in the United States.

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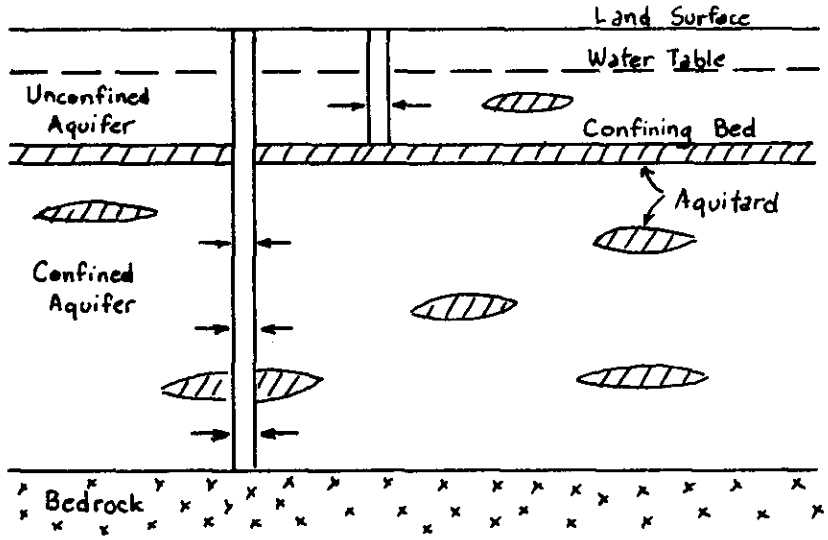
II. Cause of Land Subsidence

A. Idealized Aquifer System




1. Subsidence-prone areas are underlain by unconsolidated (nonlithified) sediments that consist of alternating layers of sand, silt, and clay. These layers make up an <u>aquifer system</u>.

   a. When the water at the top of an aquifer system is at atmospheric pressure, the aquifer system is <u>unconfined</u>.

   b. When the water at the top of an aquifer system is under pressure greater than atmospheric pressure, the aquifer system is confined.

2. When ground water is pumped from an aquifer system, water flows laterally in the sand layers to the pumping wells.
3. Clay and silt layers do not readily transmit water and hence behave as barriers to rapid movement of ground. Given sufficient time, sometimes measured in years or decades, significant quantities of water may drain from these clay and silt layers into the sand beds and flow to the pumping wells.
   a. Clay and silt beds are called aquitards.
   b. Laterally extensive aquitards that are particularly slow in transmitting water form confining beds. These beds compartmentalize aquifers so that pumping from one aquifer may have negligible effects on vertically adjacent aquifers.

B. Subsidence Mechanism

1. 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.

2. Clay and silt beds, that is, aquitards, in aquifer systems commonly are very compressible and will compact (decrease of pore volume) when the weight of the overlying sediments is transferred to the intergranular skeletons.

   a. Compaction is essentially irreversible. Water-level recoveries will not cause the clay and silt beds to expand to their original thickness.

b. Compaction may lag years behind water-level declines measured in sand beds because it may take years for water to drain out of aquitards.

3. As an aquitard compacts, the sediment and land surface above the aquitard move vertically downward. The land subsidence equals the amount of compaction because the lateral extent of aquitards typically is much greater than their depth.

4. Confined aquifers compact more than unconfined aquifers given equal declines of water level.

III. Subsidence Areas

A. Subsidence Areas in the United States

1. More than 15 areas in the United States have subsided because of ground-water withdrawal. Most of these areas occur in the Gulf Coast and in valleys in the western United States.

2. Affected 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.

3. Land subsidence affects both rural and urban areas.

B. Characteristics of Subsidence Areas

1. Subsidence-prone areas in general are topographically flat and are underlain by thick geologically youthful sediments (less than 5 million years old) that were deposited by a variety of geologic agents including streams, lakes, and oceans.

2. Deposits beneath areas prone to

subsidence are those that have significant quantities of clays and silts and have had relatively simple geologic histories.

IV. Subsidence Detection

1. Subsidence usually is first detected on the basis of resurveys of preexisting networks of bench mark in an area and before it is of practical consequence.

   a. Survey techniques and equipment are required that are more precise than those used for common land surveys.

   b. Such precise surveys are routinely performed by government agencies either to establish or maintain geodetic control networks for construction purposes. Coverage of the subsidence area, however, usually is incomplete.

   c. Costs of these precise geodetic surveys range from $125 to $570 per kilometer ($201 to $917 per mile) depending on the desired precision.

2. Subsidence also can be detected by specially instrumented wells, called borehole extensometers, which measure the compaction within the aquifer system.

3. Practical effects from changes in slope of the land surface from differential subsidence may become apparent when the magnitude of subsidence becomes large enough.

V. Effects

A. Loss of Surface Elevation

1. Lowering of the land surface is of greatest concern near bodies of surface water, particularly oceans and lakes, because of the potential for inundation and the increased hazard from tidal flooding.

   a. Damages and loss of property values associated with such flooding in the Houston-Galveston, Texas, area from 1969 to 1974 are estimated to have exceeded $31.7 million per year.

b. Aggregate direct costs from land subsidence on the south end of San Francisco Bay, California, exceeded $15 million.

2. Waste disposal facilities in coastal areas are particularly vulnerable.

B. Tilting of the Land Surface

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

2. Continuous regrading of fields under irrigation for growing crops may be required.

C. Well Damage

1. Well casings may fail because of shortening of the casing within the compacting part of the aquifer system.

2. Such collapse may destroy or reduce the productivity of a well, thereby necessitating its replacement.

D. Ground Failure

1. Renewed aseismic movement of geologic faults accompany land subsidence in some areas. Fault scarps as long as 16 km (10 mi) and as high as 1 m (3 ft) have formed. Damage to engineered structures, particularly residences and other buildings, commonly is devastating from these faults.

2. Tension cracks as long as 3.5 km (2.2 mi) and as deep as 25 m (82 ft) accompany land subsidence in many arid areas.

3. In undeveloped areas, faults and tension cracks impose restrictions on future land use.

E. Decreased Storage Capacity of Aquifer System

1. Water obtained from clay and silt beds during their compaction is "mined" water

because the compaction process is irreversible.

2. 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

1. The weight of the water removed from the clay and silt beds during their compaction represents a permanent unloading of the Earth's crust. When weight reductions are large, the Earth's crust beneath the aquifer system may begin to move slowly upward in response to the decreased weight on it.

2. In seismically active areas, earthquakes might be triggered by such movements.

VI. Assigning Responsibilities

A. Technical Evaluation

1. In order to identify parties

responsible for 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.

2. In general, detailed subsurface information will be required as will modeling of the ground-water system.
3. It is technically feasible to identify both elements.

B. Scientific Expertise

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

VII. Control of Subsidence

A. Subsidence can be halted by stopping water-level declines. This usually requires controlling ground-water pumpage to an amount equal to or less than the natural rate of recharge.

B. Complete cessation of pumping is not required.

C. Subsidence has been institutionally controlled in two U.S. areas.

1. In the Houston-Galveston, Texas, area, a special district was authorized based on State constitutional authority to conserve natural resources. The district regulates pumping by awarding permits for major water wells.

2. In the Santa Clara Valley, California, control of subsidence was a collateral benefit of the effort to stop ground-water overdraft. A tax was imposed on ground-water pumpage that removed the economic incentive to use ground water.

VIII. Prediction of Subsidence

A. Active Subsidence Areas

1. The reliability of subsidence prediction in areas which

already have experienced subsidence depends on the amount of information available on subsurface geology and water-level and survey data.

2. Given an adequate historical record of the relation between subsidence and water-level declines and the reliability of predictions of water-level declines, subsidence can be accurately forecast.
3. Caution must be used when predictions are based on historical water-level declines which have been small, 30 m (100 ft) or less. Subsidence per unit water-level decline commonly increases when a threshold value of water-level decline is exceeded.

B. Areas of Proposed Ground-Water Development

1. Prediction of subsidence in areas without previous ground-water development can be made by either:

a. Comparison with nearby developed areas with similar subsurface geology, or

b. Testing of representative core samples obtained by drilling.

2. Predictions by either of these techniques generally are imprecise and permit only qualitative assessments of potential subsidence.