

LAND SUBSIDENCE DUE TO WITHDRAWAL OF FLUIDS*

J. F. POLAND AND G. H. DAVIS

U. S. Geological Survey, Sacramento, California, and Washington, D. C.

ABSTRACT

Land-surface subsidence due to the withdrawal of fluids by man has become relatively common in the United States since 1940 and has been described at several other places throughout the world. This paper reviews the known examples of appreciable land subsidence caused by fluid withdrawal. Those related to exploitation of oil and gas fields include Goose Creek, Texas; Wilmington, California; Lake Maracaibo, Venezuela; Niigata, Japan; and the Po Delta in Italy. The areas of major subsidence related to ground-water withdrawal include areas in Japan; Mexico City, Mexico; and Texas, Arizona, Nevada, and California. The areas of greatest extent and maximum subsidence are in California.

The principles involved in the compaction of sediments and of aquifer systems, basically the increase in effective stress, are examined briefly, together with their application to subsidence problems involving head decline both under water table and confined conditions. The amount of compaction that a confined aquifer system will experience is a function of compressibility. Other factors that influence compaction (and, in part, compressibility) include particle size and shape, clay mineralogy, geochemistry of pore water in the clayey beds and of the water in contiguous aquifers, and secondary compression.

Land subsidence has caused great damage in some areas. At several of these places, subsidence problems are being alleviated in one or more of several ways; these include (1) cessation of withdrawal and (2) increase or restoration of reservoir pressure by reduction in production rate, artificial recharge, or repressuring by injection of water. The greatest subsidence control measures are being taken at Wilmington, California, where subsidence that had reached 27 feet at the center now is nearly stopped; in addition, significant rebound has occurred.

CONTENTS

TEXT

	Page
Introduction	190
General statement	190
Development of concepts	191
Application to subsidence	193

* Published with the approval of the Director, U. S. Geological Survey, Washington, D. C.

Subsidence of oil and gas fields	199
General statement	199
Goose Creek oil field, Texas	199
Wilmington, California	200
Lake Maracaibo, Venezuela	214
Niigata, Japan	216
Po Delta, Italy	218
Subsidence due to ground-water withdrawal	221
General statement	221
Areas on Honshu, Japan	222
Introductory comment	222
Osaka area	222
London, England	223
Mexico City, Mexico	224
Savannah, Georgia	230
Houston-Galveston area, Texas	231
Denver, Colorado	235
Eloy-Picacho area, Arizona	235
Las Vegas, Nevada	237
Areas in California	238
Introductory comment	238
San Joaquin Valley	239
Santa Clara Valley	252
Summary	262
References cited	264
Subject index to references cited	269

FIGURES

Figure	Page
1. Pressure diagram for water-table lowering	194
2. Pressure diagram for unconfined and confined aquifer with head reduction in confined aquifer only	195
3. Pressure diagram for unconfined and confined aquifer with lowering of water table and head reduction in confined aquifer equal	196
4. Subsidence, 1917-1925 and 1924-1925, at Goose Creek oil field, Harris County, Texas	200
5. Geologic section <i>A-B</i> at Wilmington oil field, California	203
6. Structure contour map at Wilmington oil field, California	204
7. Subsidence rate at center of subsidence at Wilmington oil field, California	205
8. Oil production and subsidence rate at Wilmington oil field, California	206
9. Casing collar surveys of typical well in Wilmington oil field, California	208
10. Subsidence from 1928 to August 1962 and location of selected bench marks at Long Beach Harbor area, California	211
11. Change in elevation of bench marks, line 1, Long Beach Harbor area, California	213
12. Change in elevation of bench marks, line 2, Long Beach Harbor area, California	213
13. Change in elevation of bench marks, line 3, Long Beach Harbor area, California	213
14. Bolivar coastal fields and reservoirs (stippled) of Lake Maracaibo area, Venezuela	215
15. Maximum cumulative compaction <i>versus</i> time for reservoirs in Bolivar coastal fields, Venezuela	216
16. Outline map of Honshu, Japan, showing areas of subsidence due to withdrawal of fluids	217
17. Subsidence from August 1957 to February 1958 in the Niigata area, Japan	217
18. Cumulative subsidence, 1898-1959, of three bench marks in the Niigata area, Japan, and production of natural gas since 1947	218
19. Map showing rate of subsidence, 1950-1951 to 1956, of Po Delta, Italy	219

20. Piezometric surface, 1936, of chalk aquifer beneath the London Clay in London, England	223
21. Lines of equal subsidence, 1865-1931, London, England	224
22. Subsidence, 1891-1959, of Mexico City, Mexico	225
23. Subsidence, 1898-1956, of four bench marks in Mexico City, Mexico	228
24. Subsidence, 1952-1957, of Mexico City, Mexico	229
25. Decline of artesian pressure and subsidence, 1933-1955, Savannah area, Georgia	231
26. Profile of land subsidence and decline of artesian pressure, 1933-1955, Savannah area, Georgia	232
27. Subsidence, in feet, 1943-1954, of the land surface in upper Gulf Coast area, Texas	234
28. Profiles of land-surface subsidence in upper Gulf Coast area, Texas	235
29. Subsidence of bench marks compared with decline of artesian pressure in nearby wells, upper Gulf Coast area, Texas	236
30. Subsidence profile, 1935 to 1949-1950, showing local subsidence as differentiated from regional effects across Las Vegas Valley, Nevada	238
31. Areas of land subsidence in California	239
32. Relationship of subsidence to ground-water occurrence and pumping draft, 1957, in San Joaquin Valley, California	241
33. Land subsidence due to artesian-head decline, 1943-1959, Los Banos-Kettleman City area, California	243
34. Land subsidence, 1955-1957, in Los Banos-Kettleman City area, California	244
35. Change in altitude at bench mark southwest of Five Points, California, and change in artesian head in nearby wells	246
36. Map showing generalized land subsidence and decline in artesian head, 1943-1953, Los Banos-Kettleman City area, California	247
37. Profiles of land subsidence and decline in artesian head along Fresno-Coalinga road northeast to Five Points, California	248
38. Diagram of compaction-recorder installation	249
39. Graph showing measured subsidence, compaction, and water-level change near Huron, California	250
40. Compaction rates near Oro Loma, California, as measured by three compaction recorders	251
41. Land subsidence, 1948-1954, in Tulare-Wasco area, California	253
42. Land subsidence, 1954-1957, in Tulare-Wasco area, California	254
43. Subsidence and change in water level near Delano, California	255
44. Land subsidence, 1959-1962, in Arvin-Maricopa area of San Joaquin Valley, California	256
45. Land subsidence, 1934-1960, in Santa Clara Valley, California	257
46. Change in altitude at bench mark P7 in San Jose, California, and change in artesian head in nearby well	258
47. Map showing network of level lines in San Jose subsidence area, Santa Clara Valley, California	259
48. Profiles of land subsidence, 1912-1963, Redwood City to Coyote, California	260
49. Measured compaction in wells 6S/2W-24C4, 24C3, and 24C7; water-level change; and subsidence of bench mark J 111 Reset, in Sunnyvale, California	261

PLATES

Plate	Following page
1. Subsidence, 1928-1962, of Long Beach area, California	232
2. Failure of surface structures	
3. Failure of surface structures	
4. Flooding by the ocean	
5. Remedial measures to keep sea from subsiding lands	
6. Protrusion of two well casings in northern part of Mexico City, Mexico	
7. Protruding well casings in Las Vegas, Nevada	

TABLES

Table	Page
1. Sediments of Los Angeles-Long Beach harbor area	202
2. Rebound to 1963 of seven bench marks in Wilmington oil field that recovered from 6 to 15 per cent of their initial subsidence	212

INTRODUCTION

GENERAL STATEMENT

Principal causes of land-surface subsidence are removal of solids or fluids from beneath the land surface, either naturally or artificially; solution; oxidation; compaction of soil or sediments under surface loading, vibration, or wetting; and tectonic movement. This paper discusses subsidence believed to have been caused chiefly, if not wholly, by fluid withdrawal by man. The geologic setting of subsidence is discussed in a companion paper by Alice Allen (this volume), and subsidence due to the application of water (wetting) is described by Ben E. Lofgren (this volume).

The two types of fluid withdrawal by man that have caused noticeable subsidence under favorable geologic conditions are (1) the withdrawal of oil, gas, and associated water and (2) the withdrawal of ground water. The withdrawal of steam for geothermal power has caused subsidence; also, the withdrawal of brines, reportedly, has caused subsidence.

Regardless of the nature of the fluid removed, the principles involved are the same; therefore, the separation of subsidence phenomena due to fluid withdrawal into those caused by exploitation of oil and gas fields and those caused by pumping of ground water may seem highly arbitrary. On the other hand, there are marked differences in the character and dimensions of the two types of reservoirs and in the magnitude of man-made stresses involved. Oil and gas commonly are produced from rocks that are older, at greater depth, more consolidated, and have lower permeability and porosity than most ground-water reservoir rocks. Also, oil and gas come from fields of relatively small extent, mostly from 1 to 50 square miles; whereas ground-water reservoirs may be many hundreds of square miles in area. Fluid pressures in deep oil- or gas-producing zones in a fully exploited field may be reduced as much as 2000–4000 pounds per square inch, from initial hydrostatic to approximately atmospheric pressure. Rarely has the fluid pressure in a ground-water reservoir been reduced more than 200 pounds per square inch (about 460 feet). One of the extreme declines of artesian head in the United States has been in the Chicago area where drawdown of head in the principal confined aquifer of Cambrian and Ordovician age has exceeded 600 feet since 1864 (Walton and Walker, 1961, p. 3366).

Fuller (1908, p. 33) was the first to theorize that withdrawal of fluids and decrease of fluid pressure cause sinking of the land surface (because of the removal of the hydrostatic support). The first published descriptions of subsidence, by Minor (1925) and Pratt and Johnson (1926) were for the Goose Creek oil field in Texas. The first specific observation of subsidence due to ground-water withdrawal—that in the Santa Clara Valley in California—was published in

1933 (Rappleye). Most of the major subsidences described in this paper have developed as a result of intensified withdrawal of fluid resources during and since the second World War in order to satisfy the needs of the burgeoning world population. Thus, most of the problems and damage due to subsidence have developed in the past two decades; these have spurred several intensive investigations of causes and possible remedial measures. Still more intensive and widespread exploiting of fluid resources, especially ground water, in the future will multiply the incidence of subsidence. Therefore, it appears particularly appropriate at this time to summarize available information on subsidence due to fluid withdrawal.

DEVELOPMENT OF CONCEPTS

Compaction of sediments and reduction in pore space resulting from increase in depth of burial and consequent increase in overburden load is a natural geologic process long recognized qualitatively by geologists. Sorby (1908) made the first substantial quantitative contribution showing the relationship between gravitational pressure and decrease in volume and porosity of sediments. Later investigators, notably Athy (1930), Hedberg (1926; 1936), and Engelhardt (1960) have supplied considerable quantitative evidence on the reduction of porosity with increasing depth by studying cores from depths as great as 6000 feet (10,000 feet for Engelhardt's study). Athy's study was based on measured bulk densities of a large number of samples from shales of Paleozoic age in Oklahoma; Hedberg's study was on Tertiary shales in Venezuela; and Engelhardt's study was on clay rocks from the Jurassic of northwestern Germany and the Tertiary of the Po Basin in Italy. Dickinson (1953, p. 427) supplied depth-density relationships for Tertiary sediments of the Gulf Coast in Louisiana to depths of 15,000 feet. Much of Dickinson's information, however, was from areas where abnormally high fluid pressures occur and, hence, where porosity reduction with depth has not been as great as in sediments where fluid pressures are normal. Rubey and Hubbert (1959, p. 175) showed a comparison of the depth-porosity relationship for the sediments of Athy, Hedberg, and Dickinson.

Meinzer (Meinzer and Hard, 1925, p. 91) recognized that an artesian aquifer (the Dakota Sandstone) was compressed when the artesian head was decreased. He stated (p. 92) that the overburden pressure of all beds above the confined Dakota aquifer was supported partly by the fluid pressure at the top of the Dakota and partly by the sandstone itself (intergranular pressure). He concluded that the grain-to-grain load on the Dakota aquifer at Ellendale, North Dakota, had increased about 50 per cent because of the decline of artesian head.

Meinzer (1928) discussed the compressibility and elasticity of artesian aquifers in detail. He cited evidence for compressibility and elasticity derived from laboratory tests and from field evidence for confined aquifers and for large artesian basins, notably the Dakota artesian basin. He concluded (p. 289):

. . . artesian aquifers are apparently all more or less compressible and elastic though they differ widely in the degree and relative importance of these properties. In general the properties of compressibility and elasticity are of the most consequence in aquifers that have low permeability, slow recharge, and high

head. In many aquifers these properties are evidently important in supplying water not only by permanent reduction of storage but also by temporary reduction that is replenished when the wells are shut down or during the season of minimum use.

He recognized that water withdrawn from storage was released both by compression of the aquifer and by expansion of the water and that reduction of storage—compression—may be permanent (inelastic) as well as elastic. In the same year Russell (1928, p. 148) estimated that the subsidence of the land surface in eastern South Dakota due to the artesian-head decline was at least 2 inches. He based this estimate on the computed quantity of water pumped from the Dakota Sandstone in eastern South Dakota in 15 years, which was equal to a layer of water 2 inches thick; therefore, he inferred that the area must have subsided 2 inches.

In 1940, Jacob postulated that when water is removed from and pressure is decreased in an elastic artesian aquifer, stored water is derived from expansion of the confined water, compression of the aquifer, and compression of the adjacent and included clay beds. He concluded that the third source is probably the chief one in the usual case, and he stated (p. 574), “. . . because of the low permeability of the clays (or shales) there is a time lag between the lowering of pressure within the aquifer and the appearance of that part of the water which is derived from storage in those clays (or shales).” He defined the coefficient of storage in terms of the three sources of water.

$$S = \gamma_w nm \left[\frac{1}{E_w} + \frac{b}{nE_s} + c\beta_c \right] \quad (1)$$

where S is the coefficient of storage; γ_w is the unit weight of water (0.434 pound/inch²/foot); n is the porosity of the aquifer; m is the thickness of the aquifer, in feet; E_w is the bulk modulus of elasticity of the water (3×10^5 pounds/inch²); b is the proportion of the plane of contact between the aquifer and the confining layer over which the hydrostatic pressure is effective (unity for an aquifer composed of uncemented granular material)¹; E_s is the modulus of elasticity of the aquifer matrix; β_c is the modulus of compressibility of clay beds; and c is a dimensionless quantity that depends largely on the thickness, configuration, and distribution of the intercalated clay beds.

Subsequently, Lohman (1961) derived an equation for determining the amount of *elastic* compression of artesian aquifers from known declines in artesian pressure and known hydrologic properties of the aquifers. Lohman's equation is in the form

$$\Delta m = \Delta p (S/\gamma_w - nm\beta) \quad (2)$$

in which Δm is the reduction in thickness of the aquifer (amount of elastic compression), in feet; Δp is the reduction in artesian pressure, in pounds/foot²; and

¹ As Jacob (1940) noted, “. . . there is no aquifer which is bounded sharply by an absolutely impervious confining bed. The factor b merely represents a concept introduced to facilitate mathematical treatment of the problem.” Also, see Hubbert and Rubey (1959, p. 132–137).

β is the reciprocal of E_w , the value of β being 3.3×10^{-6} inch²/pound. The other terms are as defined for equation (1). Lohman's equation (2) affords a means of evaluating the second component of equation (1), $\gamma_w mb/E_s$, when E_s is not known.

Poland (1961) showed that in highly compressible aquifer systems where the ratio of subsidence to head decline may be as much as 0.05–0.10, the stored water released by compaction of the clayey beds (element 3 of equation 1) may be as much as 50 times as great as the water released by elastic expansion of the water and elastic compression of the aquifer (elements 1 and 2 of equation 1). Thus, in effect, Jacob's (1940) conclusion that the third source of stored water probably is the chief one is verified for all subsiding areas where the ratio of subsidence to head decline appreciably exceeds the coefficient of storage derived from short-term pumping tests.

In the field of soil mechanics, Terzaghi (1925a; 1925b) developed the theory of primary consolidation that has served as the basis for solution of most practical soil mechanics and settlement problems in the past three decades. For a summary of the theory of consolidation, the reader is referred to Terzaghi and Peck (1948, p. 233–242) or to Taylor (1948, p. 225–238). In deriving his consolidation theory, Terzaghi made several simplifying assumptions, which Taylor (1948, p. 226) and Leonards (1962, p. 141) have summarized. Leonards (1962) made a comprehensive review of the engineering properties of soils that includes about 300 references, and he discussed the causes of difficulties that have developed between predictions made from the Terzaghi theory and observations of the time rate of consolidation both in the field and during laboratory tests.

In developing his theory in 1925, Terzaghi also elucidated the basic principle of effective stress that

$$p = p' + u_w \quad (3)$$

where p is total stress (total overburden load or geostatic pressure); p' is effective stress (effective overburden pressure or grain-to-grain load); and u_w is neutral stress (fluid or pore pressure). This was the same year that Meinzer (Meinzer and Hard, 1925) recognized the principle of effective stress in compression of artesian aquifers.

Utilizing studies made by many investigators of clay technology and soil mechanics in the past decade (1953–1962)—a period when advance in understanding and concepts was very rapid—Mitchell (1962) analyzed the components of pore-water pressure in clays and concluded (p. 162–163):

. . . a pore pressure measurement reflects interparticle repulsive pressures and water absorptive forces as well as purely hydrostatic pressures arising from mechanical effects. . . . In spite of these additional forces, the effective stress principle and information obtained through pore water pressure measurements correlate well with observed behavior of many fine-grained soils.

APPLICATION TO SUBSIDENCE

Ground water occurs both under unconfined (water table) and confined conditions; oil and gas occur under confined conditions; and commercial saline brines

usually are in confined aquifers. Thus, it is of interest to analyze the stresses involved both in lowering of the water table and of the pressure head in a confined aquifer. In applying the principle of effective stress to this analysis, pressure diagrams are useful (see Figs. 1, 2; equation [3]).² The geostatic pressure (total pressure) p of sediments and water equals the unit weight of moist sediments above the water table γ_m times their thickness, plus the unit weight of saturated sediments below the water table γ times their thickness; that is, under initial conditions for both figures, at depth $z_1 + z_2$,

$$p = z_1\gamma_m + z_2\gamma, \quad (4)$$

or

$$p = z_{11}\gamma_s(1 - n) + n_w\gamma_w + z_2[\gamma_s - n(\gamma_s - \gamma_w)] \quad (5)$$

and

$$u_w = z_2\gamma_w. \quad (6)$$

The effective (intergranular) pressure is

$$p' = z_1\gamma_m + z_2\gamma' \quad (7)$$

where $\gamma' = \gamma - \gamma_w$, the submerged unit weight of the sediments. (Notation: γ = unit weight of saturated sediments; γ_m = unit weight of moist sediments above the water table; γ_s = unit weight of solid constituents; γ_w = unit weight of water; γ' = submerged unit weight of sediments; n = porosity; n_w = moisture

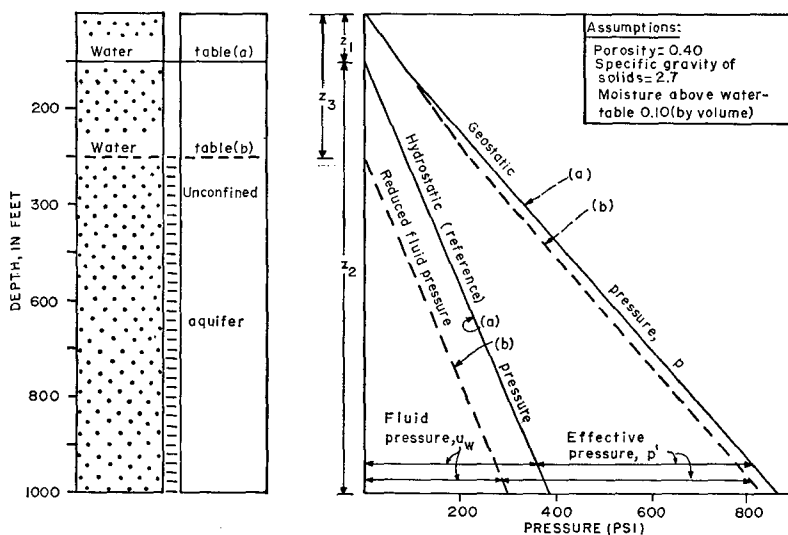


Figure 1. Pressure diagram for water-table lowering.

² For conversion from English to metric units or *vice versa*, Terzaghi and Peck (1948, p. xi) pointed out the closely approximate relationship,

$1 \text{ kg/cm}^2 \approx 1 \text{ ton/foot}^2 \approx 1 \text{ atmosphere} = 34 \text{ feet of water} = 15 \text{ pounds/inches}^2$.

above water table in per cent of total volume; p = geostatic pressure; u_w = fluid (neutral) pressure; u = excess pore pressure; and p' = effective intergranular pressure.)

For the water-table conditions of Figure 1, lowering the water table from a to b reduces the geostatic pressure in interval $a-b$ where the increase in effective pressure per unit of thickness may be expressed

$$\Delta p' = \gamma_w(1 - n + n_w), \quad (8)$$

and at all points below depth z_3

$$\Delta p' = \gamma_w(1 - n + n_w)(z_3 - z_1). \quad (9)$$

(In equation (8), $\gamma_w(1 - n)$ represents the buoyant force that is removed when the water table falls. This buoyant force is equal to the weight of the water displaced by the solid constituents.)

Lowering of the artesian head in a confined aquifer (Fig. 2) does not change the geostatic pressure, except for the removal of water by expansion which is disregarded in this diagram. The increase in effective pressure in the confined aquifer system (Fig. 2) due to lowering of head from a to b equals the reduction in fluid pressure or

$$\Delta p' = \gamma_w(z_3 - z_1). \quad (10)$$

Thus, the increase in effective pressure due to water-table lowering is less than that for artesian-head lowering by a factor of $1 - n + n_w$. If $n = 0.40$ and $n_w = 0.10$, the water-table lowering increases p' by only 0.7 the value for an artesian-head lowering of equal magnitude. Because all deposits are compressible

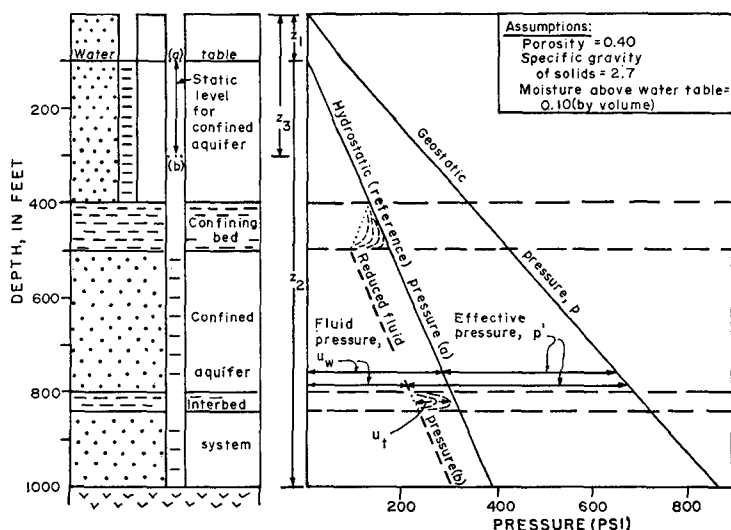


Figure 2. Pressure diagram for unconfined and confined aquifer with head reduction in confined aquifer only.

to some degree, it is concluded that lowering of the water table must cause compaction and subsidence. By nature, unconfined sediments, however, are relatively coarse-grained, granular, and permeable—and hence of low compressibility compared to clayey sediments. Subsidence, therefore, ordinarily is small and may not be detectable even by precise leveling techniques.

In the case of an unconfined aquifer overlying a confined aquifer system, when both undergo equal reduction of hydrostatic head (Fig. 3), the lowering of the water table in the unconfined aquifer reduces the geostatic pressure on the confined system. Thus, the increase in effective stress and the resulting compaction of the confined system is not as great as it would have been if the overlying water table had remained constant. Note that in this special case, the change in geostatic pressure and in effective stress in both aquifers would not be affected by the removal of the confining bed.

A lowering of artesian pressure in a confined aquifer system³ causes an equivalent increase in grain-to-grain pressure on the aquifer skeleton. The magnitude of the resulting compaction (compression) is dependent on the compressibility of the sediments. Confined aquifer systems often contain many fine-grained interbeds of silty clay, clay, or shale and are bounded by fine-grained confining beds. In unconsolidated sediments especially, these fine-grained elements normally are highly compressible compared to the coarse-grained aquifer elements; therefore, many confined aquifer systems are highly compressible. Pore pressure adjustment in the coarse-grained elements (aquifers) will be instantaneous, but these aquifers will not compress appreciably unless the sand contains several per

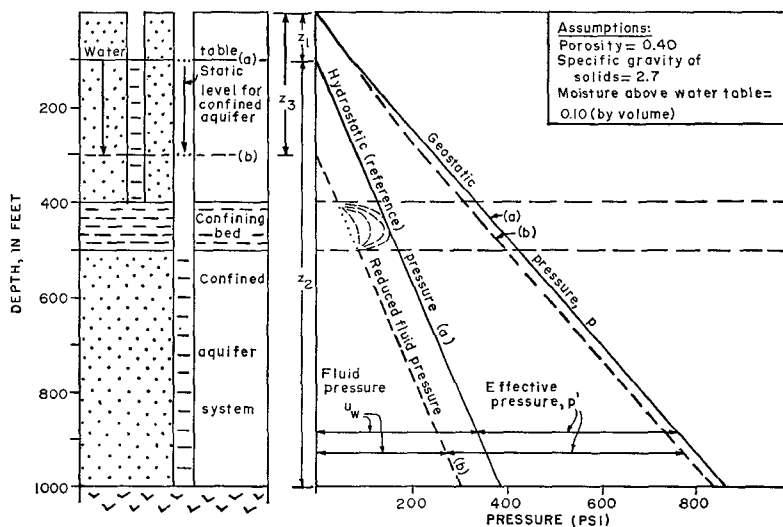


Figure 3. Pressure diagram for unconfined and confined aquifer with lowering of water table and head reduction in confined aquifer equal.

³ In this paper, the term aquifer system is used to mean not only the permeable aquifer or aquifers but also any included or adjacent fine-grained deposits of low permeability that have hydraulic continuity with the aquifers.

cent of mica. (In tests reported by Terzaghi and Peck [1948, p. 57, fig. 19] a mixture of 90 per cent sand and 10 per cent mica tested in the load range 0–100 kg/cm² was more compressible than a soft Detroit clay.) On the other hand, the pore pressure adjustment in the clayey interbeds and confining beds (aquitards) will be slow because of their low permeability. Full dissipation of excess pore pressure may require many years or tens of years. The pattern of excess pore-pressure decay is illustrated diagrammatically in Figure 2. At any time during the period of decay, the magnitude of the residual excess pore pressure, u , determines the magnitude of increase in effective pressure.

According to the principle of effective stress and Terzaghi's theory of consolidation, the compaction (compression) of the aquitards will be proportional to the magnitude of pore pressure decrease and will continue until hydrodynamic equilibrium (steady-state flow) is attained (*see* dotted fluid pressure lines of Fig. 2).⁴ As indicated later, compaction may continue after this condition is attained because of secondary compression (Leonards, 1962, p. 142), which is not considered in Terzaghi's theory.

In settlement problems for engineering structures, soil mechanics engineers commonly make one-dimensional consolidation tests on "undisturbed" samples and apply the results of the e -log p plot to the solution;⁵ this plot also can be used to estimate the overconsolidation (preconsolidation) or underconsolidation (Leonards, 1962, p. 150–156; Skempton, 1944, p. 131).

Leonards (1962, p. 171–172) summarized some of the problems that develop in the use of one-dimensional compression and flow theory in making estimates of rate of settlement of structures (*also see* Skempton, 1944; Rutledge, 1944). These same problems are encountered in analysis of compaction of aquifer systems when the same methods are applied.

The amount of compaction that a confined aquifer system will experience is a function of the compressibility of the sediments within the range of change in effective pressure (artesian-head decline) and the magnitude of that change. The compressibility decreases with reduction in porosity or void ratio (accompanying increasing depth of burial). The amount of compaction is also a function of the thickness and vertical permeability of the clayey (compactible) beds and of the time the head decline has existed in the permeable beds. Other factors influencing the compaction of clayey sediments are: (1) particle size, which has an inverse relationship to pore volume for a given effective pressure and also controls the permeability and, thus, the rate of excess pore pressure decay; (2) clay mineralogy (montmorillonite clay minerals are the most compressible [Waidelich, 1958] partly because of their small colloidal particle size which results in a large surface area as compared to the much larger plates of illite and kaolinite; thus, montmorillonite has greater initial pore volume and greater compressibility under

⁴ The stresses involved in the reduction of fluid pressure in sediments can also be analyzed by means of the seepage-force relationship (Taylor, 1948, p. 132–133, 200–204).

⁵ *See* Terzaghi and Peck (1948, p. 524–528) for analysis of settlement due to lowering the water table and due to pumping below a confining clay stratum; *see* Taylor (1948, p. 273–275) for intergranular pressure distribution in a clay bed for (1) the simple hydrostatic case, (2) the partial consolidation case, and (3) the artesian case; and *see* Gibbs (1953) for a brief description of theory and an example of settlement analysis.

a given load); (3) geochemistry of the pore water in the clayey beds, which affects the clay structure (Leonards, 1962, p. 85–107), and geochemistry of the water in contiguous aquifers, which may develop osmotic pressures across the clay membranes (the geochemistry of the pore solution of sediments has been discussed recently in a thought-provoking chapter by Engelhardt [1961, p. 189–204]); (4) physico-chemical factors (Rosenqvist, 1962) and the effect of adsorbed water (Martin, 1962); and (5) the fact that after excess pore pressures are dissipated and primary consolidation is completed, secondary compression (consolidation) may occur (Leonards, 1962, p. 142); this secondary compression is of considerable importance in the compaction of certain Mexico City clays (Zeevaert, 1957).

In a review of factors affecting the removal of water and the rearrangement of particles in clayey sediments under pressure, Meade (1964, p. 20B) stated that these factors are complex functions of particle size, clay minerals and associated ions, interstitial electrolytic concentration, acidity, temperature, and the arrangement of particles at the onset of compaction.

In areas where land subsidence is caused by compaction due to fluid-pressure decline, according to the effective stress theory, increasing the pore pressure at any time sufficiently to equal the maximum excess pore pressure should cause the compaction (and subsidence) due to primary consolidation to cease immediately.⁶ This principle has been used in repressuring operations at the Wilmington oil field in California to stop the subsidence. Increase of fluid pressure beyond this value should cause some expansion of the sediments, but unless the compaction had been wholly elastic, the initial porosity could not be restored.

A rebound or unloading test made as part of the one-dimensional consolidation test furnishes semiquantitative data on the magnitude of elastic rebound of a clayey sediment. Thus, consolidation and rebound tests on the same samples, if those samples are representative of the compacting sediments, should furnish guide lines for predicting the expansion of deposits when pore pressures are increased above residual excess pore pressures if all other conditions remain equal, especially the condition that the chemical character of the injected water be the same as that of the native pore water. The greatest unknown in such predictions is the magnitude of the excess pore pressure, which is difficult and expensive to determine even within 30 feet of land surface, let alone at 5000 feet of depth. The empirical solution is to increase pore pressures until subsidence stops and so conclude that the repressured pore pressure equals or exceeds the former maximum excess pore pressure.

⁶ See Hubbert and Rubey (1959, p. 136) for description of an experiment by Terzaghi in which a cake of clay was immersed in water to which pressure was applied. No measurable compaction was produced, showing that the fluid pressure within the clay increased immediately to equal the external fluid pressure. The water entering the clay to cause this increase in pressure was only the small quantity necessary to compensate for the elastic compression of the pore water.

SUBSIDENCE OF OIL AND GAS FIELDS

GENERAL STATEMENT

Major subsidence of three oil fields has been reported in the literature. These are Goose Creek oil field in Texas; the Wilmington oil field in the harbor area of Los Angeles and Long Beach, California; and oil fields on the shore of Lake Maracaibo in Venezuela. Although the Lake Maracaibo subsidence has been known since the early thirties (Kugler, 1933, p. 758, discussion, p. 769), little has been published on that subsidence. Each of these subsiding areas is at sea level, and the subsidence was obvious because of submergence of the land surface. Although local subsidence of as much as 40 feet occurred within the Sour Lake field, Hardin County, Texas in 1929 (Carpenter and Spencer, 1940, p. 4), this subsidence was attributed to solution of salt and development of a cavity.

Minor subsidence has been noted at several California oil fields, such as Venice-Playa del Rey (Grant, 1944, p. 136) and Long Beach (Signal Hill), Huntington Beach, and Santa Fe Springs (Gilluly and Grant, 1949, p. 525-527). Undoubtedly, many oil fields away from the ocean or other large water bodies have subsided as much as several feet, but without repeated precise leveling such subsidence may pass unnoticed.

Gas fields at Niigata, Japan, and in the Po Delta, Italy, experienced rapid subsidence in the late fifties. The Niigata field is at sea level, and the Po Delta field borders the sea. Many other gas fields above sea level and not subject to inundation probably have experienced subsidence, but with no marked deleterious effects; thus, they have not been publicized.

GOOSE CREEK OIL FIELD, TEXAS

The subsidence of Goose Creek oil field in Harris County, Texas, was the first subsidence due to fluid withdrawal described in the literature (Minor, 1925; Pratt and Johnson, 1926; Pratt, 1927; Snider, 1927). According to Pratt and Johnson (1926), development of the field began in 1917. By 1918, Gaillard Peninsula, which was at the mouth of Goose Creek and overlay part of the oil field, began to subside and soon was covered by the waters of San Jacinto Bay. The maximum subsidence, shown by periodic leveling, was more than 3 feet by 1925, and the area affected was about 2.5 miles long by 1.5 miles wide and conformed with the approximate limit of the producing oil wells (Fig. 4). No change in elevation of the land surface had occurred outside the affected area. Cracks developed at the north edge of the oil field, and by 1925, recurrent movement on these small faults had dropped the ground surface on the oil field (south) side as much as 16 inches. Similar faults developed on Hogg Island along the south edge of the field, and downward displacement of 3-12 inches occurred on the north side of these faults.

The State of Texas claimed title to the lands submerged by the subsidence and sought to recover the value of oil and gas removed subsequent to submergence. The court, however, decided in favor of the defendants, accepting their contention that the subsidence was caused by an act of man, namely the removal of

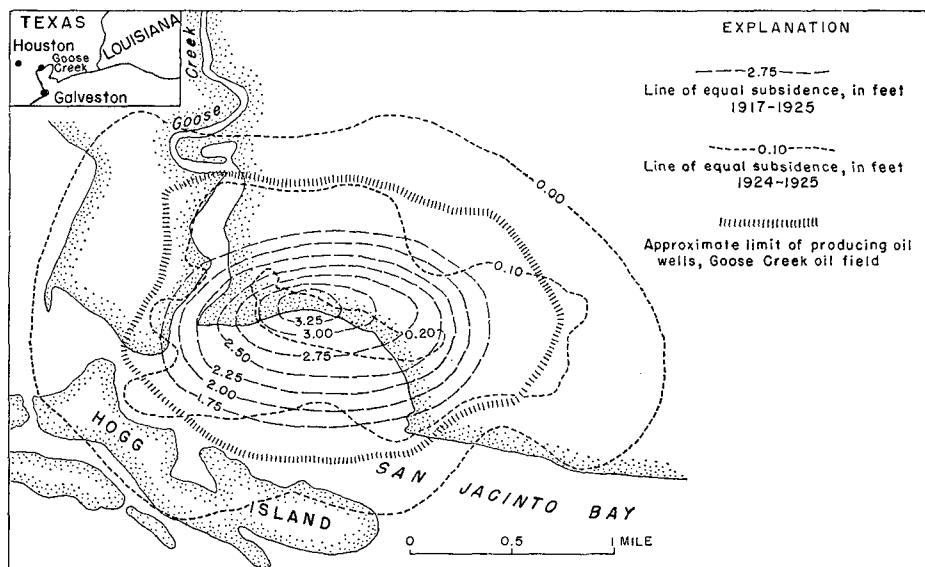


Figure 4. Subsidence, 1917-1925 and 1924-1925, at Goose Creek oil field, Harris County, Texas. (Generalized after Pratt and Johnson, 1926, Fig. 7.)

large volumes of oil, gas, water, and sand. If the subsidence had been shown to be a natural process, presumably, title to the submerged lands and the underlying oil would have passed to the State of Texas.

The oil at Goose Creek is withdrawn chiefly from lenticular deposits of relatively unconsolidated sand and clay of Oligocene to Pliocene age between depths of 700 and 4500 feet. The structure in the beds of Miocene and younger age is a gentle dome; the Oligocene sediments, beneath an unconformity, are intensely faulted. The volume of oil, gas (at 1000 pounds per square inch), water, and sand extracted from 1917-1926 exceeded 100 million barrels, about five times the calculated subsidence volume. The original reservoir pressures of 1000-1200 pounds per square inch had been reduced to atmospheric pressure by 1926.

Pratt and Johnson (1926) concluded that the subsidence was due to extraction of oil, water, gas, and sand because the area of subsidence corresponded with the area of extraction, because the time of subsidence and extraction corresponded, and because continued extraction was accompanied by continued subsidence.

WILMINGTON, CALIFORNIA

A spectacular and costly land subsidence, first noticeable in 1940 and 1941, has occurred at the Wilmington oil field in the harbor area of Los Angeles and Long Beach, California. By August 1962, the subsidence had increased to 27 feet at its center and included an area of about 25 square miles that had subsided 2 feet or more (Pl. 1). Much of the subsiding area initially was only 5-10 feet above sea level and is intensively industrialized, containing many costly

structures, such as port facilities, industrial plants, oil wells, pipe lines, and a major naval shipyard.

The subsidence at the Wilmington oil field is particularly noteworthy for three reasons: (1) the vertical settlement of 27 feet at the center is the greatest subsidence due to fluid withdrawal known to have occurred to date anywhere in the world; (2) many fields yielding oil from deposits of similar age and from an equivalent depth range, of approximately similar lithology, and with comparable decrease in fluid pressure have *not* experienced subsidence of more than a few feet; and (3) corrective remedial action taken since 1958 by repressuring of the oil zones had stopped the subsidence in much of the field by the end of 1962.

The first major published reports describing the subsidence (Harris and Harlow, 1947; Gilluly and Grant, 1949), both based on consulting reports made in 1945, concluded that it was caused primarily by the decrease in fluid pressure in the oil zones, due to removal of oil, gas, and water, which increased the grain-to-grain load and caused compaction. Those reports have been followed by many others, chiefly of the consulting type and reproduced in relatively few copies. To the authors' knowledge, these subsequent reports have concurred with the findings of the initial reports on the primary cause, which has been proven incontrovertibly by the results of the periodic casing collar logs and the repressuring briefly discussed later in this paper.

Geology. The Los Angeles-Long Beach harbor area is underlain by sediments of Recent to Miocene age about 6000 feet thick that unconformably overlie a basement schist of pre-Tertiary age. The age, thickness, and physical character of these sediments are summarized in Table 1, which is modified from Winterburn (1943).

The base of the deposits containing fresh water is approximately at 2000 feet—the base of the upper division of the Pico Formation. The underlying deposits contain saline water.

Seven productive oil zones have been developed. As Figure 5 shows, they extend from a depth of about 2500 feet to 6000 feet, which is from about 600 feet below the top of the Repetto Formation (of former usage) to the basement schist.

The Wilmington field is a gently arched anticlinal fold plunging to the northwest. Five main faults that trend roughly north and south and terminate at the top of the Repetto Formation divide the oil field into six structural blocks. Figure 6 shows the position of these faults at the top of the Ranger zone and the operators' numbered designation of the structural blocks. The faults divide the oil zones into semiseparate pools because of the barrier effect to movement of fluids although the effectiveness of the faults as barriers is reported to be highly variable. The per cent of sand in the several zones ranges from 23 to 70; the average porosity ranges from 24 to 34 per cent; and the weighted average permeability ranges from 100 to 1000 millidarcys (Murray-Aaron and Pheil, 1948, p. 11).

Development of the field. Oil production began in 1936 (Bartosh, 1938, p. 1052), reached a peak average rate of about 140,000 barrels a day in 1951, and declined to about 70,000 barrels a day by 1959. By March 1962, however, production increased to 82,000 barrels per day, due to the repressuring by water flood. Cumula-

TABLE 1. SEDIMENTS OF THE LOS ANGELES-LONG BEACH HARBOR AREA
(*Modified from Winterburn [1943]*)

Age	Formation	Thickness	Lithology and remarks
Recent	Unnamed } San Pedro }	1000 ±	Fresh-water sands, gravels, and clays
Pleistocene			
Pliocene	Upper part of Pico	800 ±	Alternating sands and siltstones
Pliocene	Middle part of Pico	0-200	Sands and siltstones
----- Unconformity -----			
Pliocene	Repetto (of former usage)	875-1150	Gray and green shales, siltstones, and sands at top, grading to interbedded grayish brown shales and fine-grained sands toward bottom.
----- Unconformity -----			
Miocene	Puente	4100 ±	Hard brown shales and sands; sands are fine and unconsolidated at top, becoming firmer and coarser grained toward bottom. Top part contains layers of laminated diatomaceous shale.
----- Unconformity -----			
Pre-Tertiary	Basement		Schist

tive production through December 1962 was 913 million barrels of oil, 484 million barrels of water, and 832 million MCF of gas (data from Long Beach Harbor Dept.; gas volume at atmospheric pressure; MCF = 1000 cu feet). The developed productive area is about 10 square miles (Fig. 6), but an undeveloped part of the field extends several miles to the southeast beneath the harbor.

Initial reservoir pressures in the oil zones were about equal to the hydrostatic pressure of a column of ocean water extending from sea level to the individual zone (Gilluly and Grant, 1949, p. 502). Fluid pressures in the oil zones ranged from about 1100 pounds per square inch for the Tar zone to 2600 pounds per square inch for the "237" zone. Gilluly and Grant (1949, Figs. 18, 19) showed the maximum pressure reduction to January 1945 in the Terminal and "Tar-Ranger" zones of 1100 pounds per square inch (*also see* Harris and Harlow, 1947, p. 1205). By 1960, bottom-hole pressures in the four upper zones had been drawn down locally to as little as 150-300 pounds per square inch.

Land subsidence. The subsidence of the Wilmington oil field began in 1937 (Gilluly and Grant, 1949, p. 464, 479) but was first definitely recognized in the summer of 1941 when the U. S. Coast and Geodetic Survey releveled lines between San Pedro and Long Beach that had been run in 1933-1934. Subsidence along Seaside Boulevard was 0.2 foot at the west boundary of Long Beach and reached a maximum of 1.3 feet at the east end of Terminal Island. Subsequent leveling by the U. S. Coast and Geodetic Survey in 1945 (July) indicated an increase in maximum subsidence to 4.2 feet and in 1946 (March), to at least 4.5 feet. Subsidence maps based on this control have been published by Gilluly and Grant (1949, Figs. 3, 4, 5).

Because of the problems caused by the accelerating subsidence, the Long Beach Harbor Department established almost 300 bench marks in 1945, and



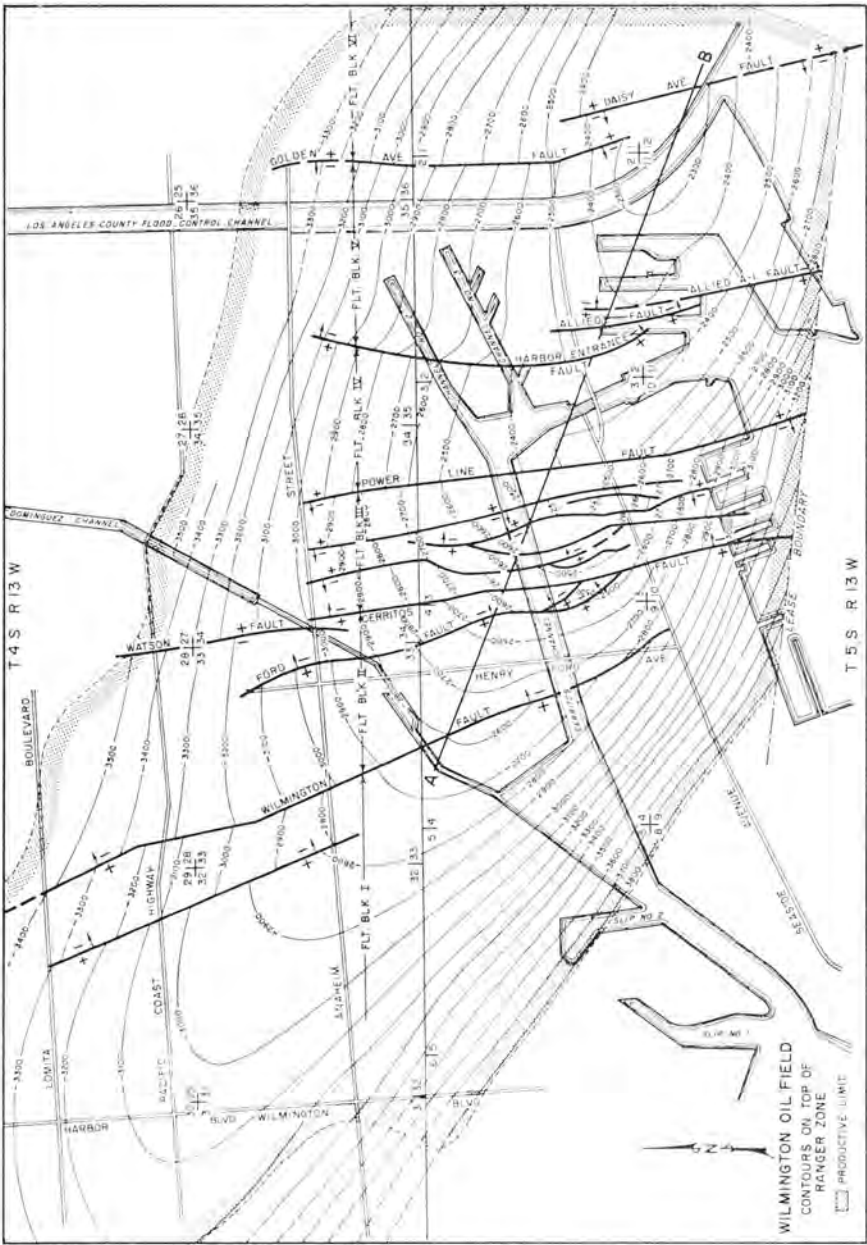


Figure 6. Structure contour map at Wilmington oil field, California. (After California Division of Oil and Gas, 1961, p. 684.)

since 1946, the Department has made level surveys to these marks every 3 months. In 1948, the U. S. Navy began quarterly surveys on a net of bench marks on the Naval base on Terminal Island; these surveys have been continued to date. The data from these surveys have been utilized by the Long Beach Harbor Department in preparing maps each year showing total and annual subsidence. These surveys are the basis for the lines of equal subsidence on Plate 1 and Figure 10.

Figure 7 shows the yearly rate of subsidence from 1947 to 1962 at bench mark 8772 at the east end of Terminal Island. The rate increased rapidly from 1 foot a year early in 1947 to 2.37 feet a year in November 1951. Since 1951, the rate has decreased about 0.2 foot per year on the average, except for disturbances associated with two local earthquakes that relieved stress and caused a temporary increase in the subsidence rate. From August 1961 to August 1962, this bench mark subsided 0.4 foot, and by August 1962, the annual rate was less than 0.3 foot per year. The oil withdrawal from the Wilmington field reached its maximum rate of 140,000 barrels a day in 1951, the year of maximum subsidence.

Figure 8 shows the general correlation between subsidence and oil production, both in time and rate. Note the time lag, however, between maximum oil production and maximum subsidence. Other graphs showing the correlation have been presented by Miller and Somerton (1955, Figs. 3, 4).

The volume of subsidence from 1928 to August 1962 for the entire Wilmington field (beyond the extent shown on Pl. 1 and Fig. 10) within the 2-foot subsidence line is 3.07 billion feet³ or 550 million barrels. Neglecting the gas, the volume of oil and water produced to December 1962 is 1397 million barrels (data from Long Beach Harbor Dept.); thus, the volume of subsidence within the 2-foot sub-

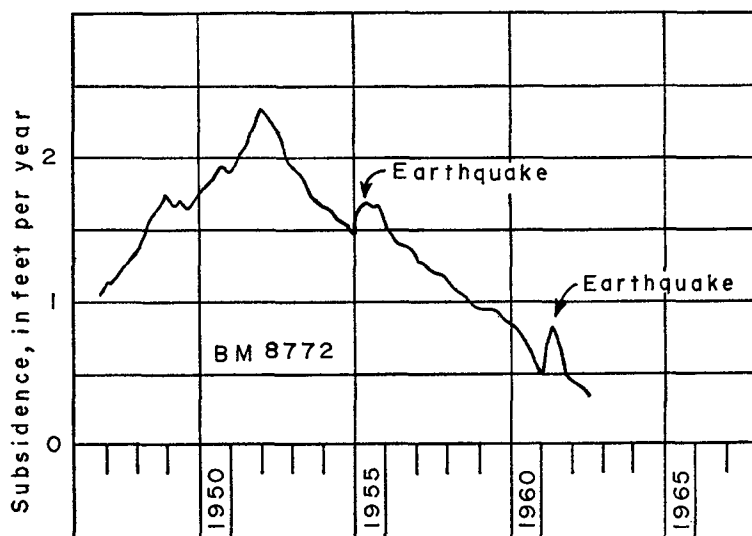


Figure 7. Subsidence rate at center of subsidence at Wilmington oil field, California. For location of BM 8772, see Figure 10. (Data from Long Beach Harbor Department.)

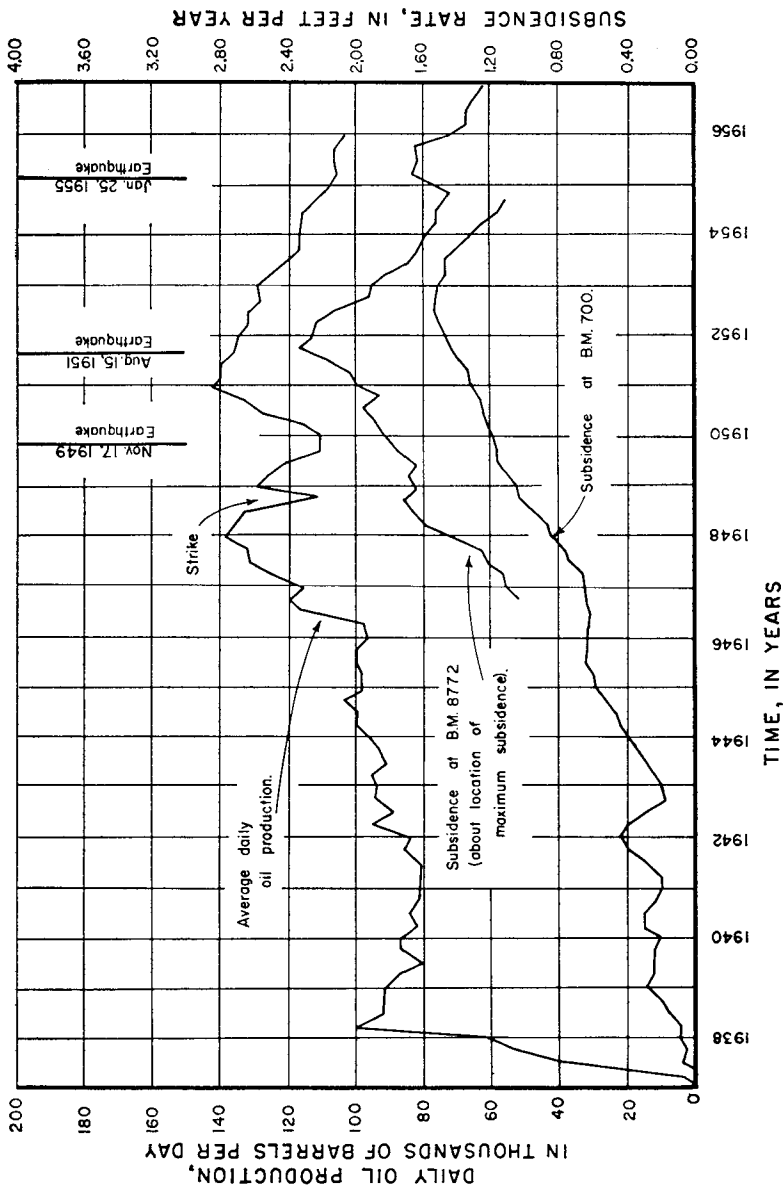


Figure 8. Oil production and subsidence rate at Wilmington oil field, California. (After Steinbrugge and Bush, 1958, Fig. 2; based on Long Beach Harbor Department drawing HD-4110-2.)

sidence line is equivalent to 39 per cent of the oil and water (at atmospheric pressure) removed. The volume of subsidence outside the 2-foot subsidence line is not known.

The Stanford Research Institute (1949, Unpub., Rept. to Harbor Subsidence Committee, 294 p.) recommended running of periodic casing collar logs in order to determine the depth range and magnitude of compaction of the sediments. These logs are obtained by electro-magnetic measurements of the distance between casing collars; they can be used to determine change in length of the individual joints of casing since the casing was placed in the well. At that time, the length of each joint was measured with a steel tape (casing tally made). They also indicate the depth range, rate, and magnitude of compaction of the sediments if it is assumed that the casing or cement at any point moves in exact accord with the contiguous sediments. In general, the evidence from casing collar logs *versus* depth and magnitude of fluid pressure reduction supports this assumption. Casing collar surveys made prior to 1952 indicate that almost all of the compaction was occurring in the Tar, Ranger, and Upper Terminal oil zones, which produced most of the oil and gas (Frame, 1952, p. 11, referring to statements of McCann and Wilts, *op. cit.*).

Casing collar surveys rerun several times since 1949 in individual wells clearly reveal the depth range, rate, and magnitude of compaction of the oil zones (Fig. 9). For the typical well shown, the increasing compaction from 1949 to 1960 is a striking demonstration that the subsidence is caused by compaction of the oil zones. The total compaction of the Tar, Ranger, and Upper Terminal zones from 1945 to 1960 was 17.60 feet, according to the casing collar survey. Some of the casing lengths above a depth of 2200 feet apparently were in tension as of 1960, but not as noticeably as in 1958.

Radioactive marker bullets have been placed in the formation outside several well casings and have been resurveyed periodically to determine changes in thickness of formation. Results from these surveys are much less definitive than the casing collar surveys and are subject to considerably greater error (Stanford Research Institute, 1949, unpub.).

Gilluly and Grant (1949) attributed the subsidence of the Wilmington field to the compaction of the oil-bearing sands; whereas Harris and Harlow (1947) concluded that the subsidence was caused by compaction of the shales in the oil zones. As pointed out by Poland and others (1959, p. 143):

The publication of these two conflicting concepts on the mechanics of land subsidence emphasizes the need for careful research to resolve the relatively unexplored question of whether subsidence of the land surface associated with the withdrawal of large quantities of fluid is caused primarily by compaction of the permeable reservoir beds or of the relatively impermeable but porous silt, clay, and shale members which are interbedded with or confine the permeable beds, and which, in effect, are a part of the reservoir system.

Comparison of casing collar surveys with the electric log of the well surveyed should help in revealing the lithology of the most compactible sediments. Unfortunately, the electric log of the well for which casing deformation is shown on

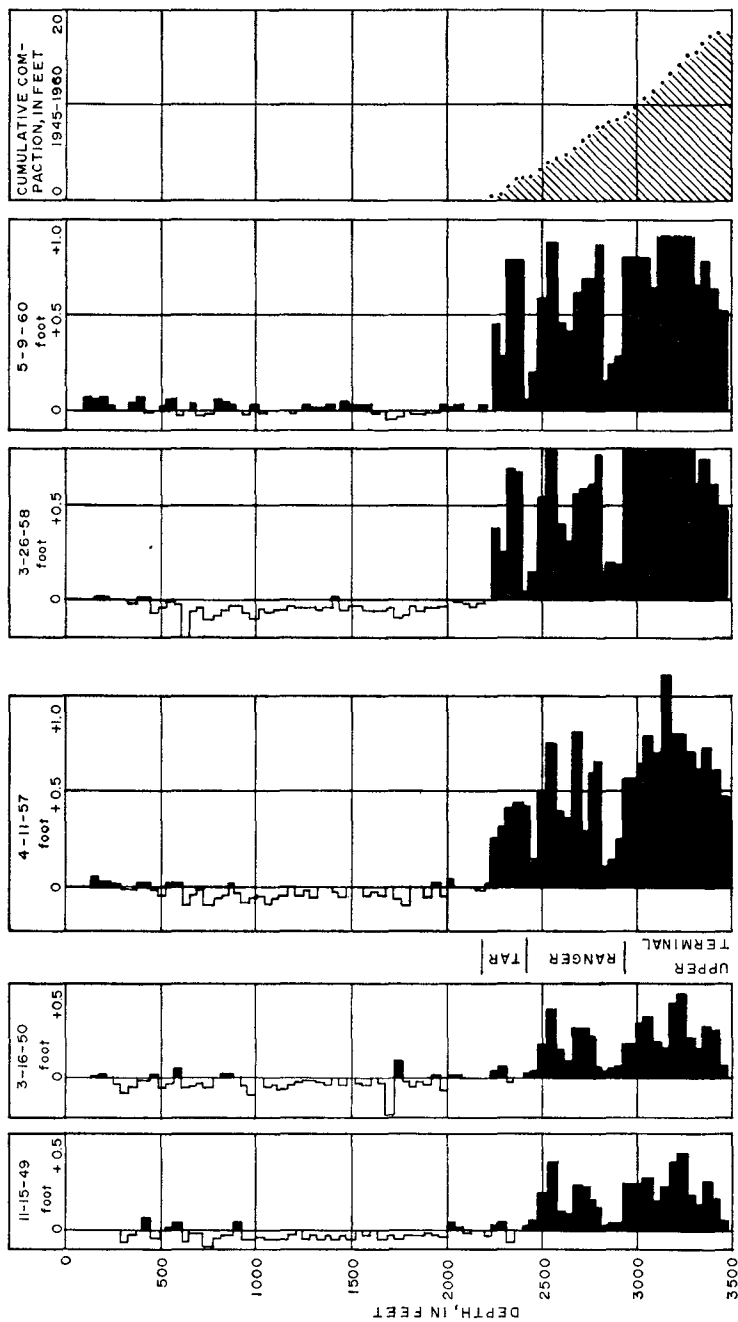


Figure 9. Casing collar surveys of typical well in Wilmington oil field, California. Survey on date indicated compared to casing tally of 9-26-45; elongation due to tension shown to left of zero reference; shortening due to compression shown to right (shaded); length of casing joints 41-44 feet in general. (Data courtesy of Long Beach Harbor Department.)

Figure 9 does not differentiate the sediments in the compacting oil zones sufficiently to relate changes in lithology with the variation in compaction shown by the casing collar surveys. The electric log, therefore, was not included on Figure 9. Comparative plots for other wells, however, may furnish a definitive answer. The authors of this paper surmise that most of the compaction has occurred in the siltstone interbeds (texture silty clay to clayey silt) so prevalent in the Wilmington oil zones. This surmise is based, in part, on the results of consolidation tests on samples of sand and siltstones (silt and silty clay texture) from the Wilmington oil zones.

Horizontal movement. The vertical subsidence has been accompanied by horizontal movement directed inward toward the center of subsidence. This horizontal movement has been measured by surveys of a triangulation network of the Los Angeles County Engineer's office. In 1951, when subsidence at the center was 16 feet, horizontal movement since 1937 had been as much as 6.2 feet (Grant, 1954, Fig. 1). By 1962, some points on the east end of Terminal Island had moved as much as 9 feet, according to the Long Beach Harbor Department.

Grant (1954) pointed out that the Terminal zones (upper and lower) have contributed most to the compaction and subsidence and that the overlying sediments, about 3000 feet thick, can be compared to a plate or prism deformed by gravity, acting on a compacting foundation beneath. Specifying certain simplifying assumptions, he used the analogy of a horizontal beam of uniform rectangular cross section with built-in ends deformed by a point load or a uniformly distributed load. All points on or in the beam, except along the neutral plane and at the center of the sag, are rotated and will move horizontally. All points on the upper surface of the beam are displaced toward the center, and those on the base are displaced outward. At the upper surface of the beam, this bending results in compression in the central part between the two inflection points and tension in the marginal areas. In the subsidence area, failure of structures at land surface by compression in the central area and failure by tension in the marginal area has been a common occurrence, indicating that the strains developed in the analog, in general, represent the observed strains.

Grant also demonstrated by analogy to a deformed beam that the shearing stresses are a maximum at the inflection points and in the neutral plane of the subsiding overburden plate. Shearing rupture of several hundred oil-well casings in the Wilmington field has occurred about halfway between the land surface and the top of the Upper Terminal zone, at depths between 1500 and 1700 feet (Frame, 1952, p. 5).

In addition to the shearing rupture of casings at a depth of about 1600 feet, deformation of the tubing and the oil string has been observed in many wells (Stanford Research Institute, 1949, unpub.).

In a mathematical analysis of the subsidence at Wilmington, G. D. McCann and C. H. Wilts (1951, unpub., Rept. to Long Beach Board of Harbor Commissioners, 117 p.) found that a "tension center" model fitted the available field data on vertical and horizontal motion to reasonable accuracy. They concluded that a "thick plate" model similar to Grant's analogy could not be described mathematically by a three-dimensional semi-infinite elastic model. As another

kind of approximation, however, a "vertical pincers" model was studied, but they found that this model did not fit the field data.

The compressional and tensional stresses and the horizontal movements caused by the bending of the sedimentary plate overlying the compacting oil zones have resulted in failure of many surface structures (Shoemaker, 1955; Shoemaker and Thorley, 1955; Neel, 1957). Sheared bridge columns of a lift bridge (Pl. 2) and buckled railroad tracks and pipe lines (Pl. 3) are representative examples.

Remedial measures. Extensive remedial measures have been necessary to keep the sea from invading the subsiding lands and structures (Pl. 4; *also see* Shoemaker, 1955; Coxe, 1949). These measures have been chiefly in the form of construction of levees, retaining walls, fill, and raising of structures (Pl. 5). Methods of repairing the sheared, deformed, or collapsed oil-well casings have been described by Frame (1952) and Allen (1959). The cost of remedial work to maintain structures and equipment in operating condition and to repair the several hundred ruptured oil wells had exceeded \$100 million by 1962. This remedial work was passive although it was necessary in order to keep facilities operating; it did not reduce the subsidence or eliminate the cause.

Repressuring. Estimates of ultimate subsidence of 30–45 feet made in the middle 1950's spurred joint constructive action directed toward active remedial work. Findings of consulting reports in 1957 that repressuring of the oil zones by water injection would not only control subsidence but also increase oil recovery by about one half billion barrels furnished both a method and economic justification. Many difficult legal, economic, and engineering problems had to be overcome before water injection could be done on a field scale. Probably the greatest of these was unitization of the 117 producers (Anonymous, 1959b). By concerted action, most of these problems have been solved, and repressuring, which had been initiated on a pilot scale in 1953 by the City of Long Beach, was undertaken on a large scale in 1958.

Injection water is obtained from supply wells tapping shallow aquifers. In large part, it has essentially the composition of ocean water and in general is chemically compatible with the oil-zone waters. It is treated chemically to inhibit corrosion and prevent bacterial growth. Then, it is injected into the oil zones at casing-head pressures ranging from 850 to 2000 pounds per square inch (Anonymous, 1960). By August 1960, the rate of repressuring was 370,000 barrels per day through 136 injection wells; by October 1962, the rate had increased to about 530,000 barrels per day through 203 injection wells, and total injection had been about 575 million barrels. All oil zones in fault blocks 3 and 4 and several of the zones in each of the other four fault blocks were being repressured. The Long Beach Harbor Department has estimated that a total of 300 injection wells and an injection rate of at least 1 million barrels per day will eventually be required. The estimated cost of the repressuring installations is about \$30 million (Anonymous, 1959a).

Effects of repressuring on subsidence. The initial repressuring was concentrated largely in the southern part of the field for the purpose of slowing down and arresting subsidence in the waterfront area. In order to show the effect of repressuring on subsidence, the relative change of elevation has been plotted for

bench marks along three north trending lines, shown on Figure 10. Line 1 is across Terminal Island; line 2 extends from the Navy Mole across Pier E; and line 3 is along Pier A.

Intensive repressuring near the south end of line 1 began in August 1959 and reached the planned maximum rate in February 1960 (in the upper four oil zones). Bench marks 364 north to 851 R showed a decrease in subsidence rate within 3 months after repressuring was begun (Fig. 11). By January 1960, subsidence had been stopped inland beyond bench mark P 615. As of May 1963, subsidence of the northern two bench marks on line 1 had been slowed but not yet stopped.

Repressuring near Pier E (line 2) began in August 1958. Bench marks M 22 north to 1533 showed an immediate decrease in subsidence rate (Fig. 12). By the end of 1961, subsidence had been arrested north to bench mark 1189, and by August 1962, all the bench marks, except 1353, had stopped subsiding.

Repressuring near Pier A was started in June 1958 in the two Terminal zones. Within 2 months, subsidence of the southern four bench marks of line 3 (Fig.

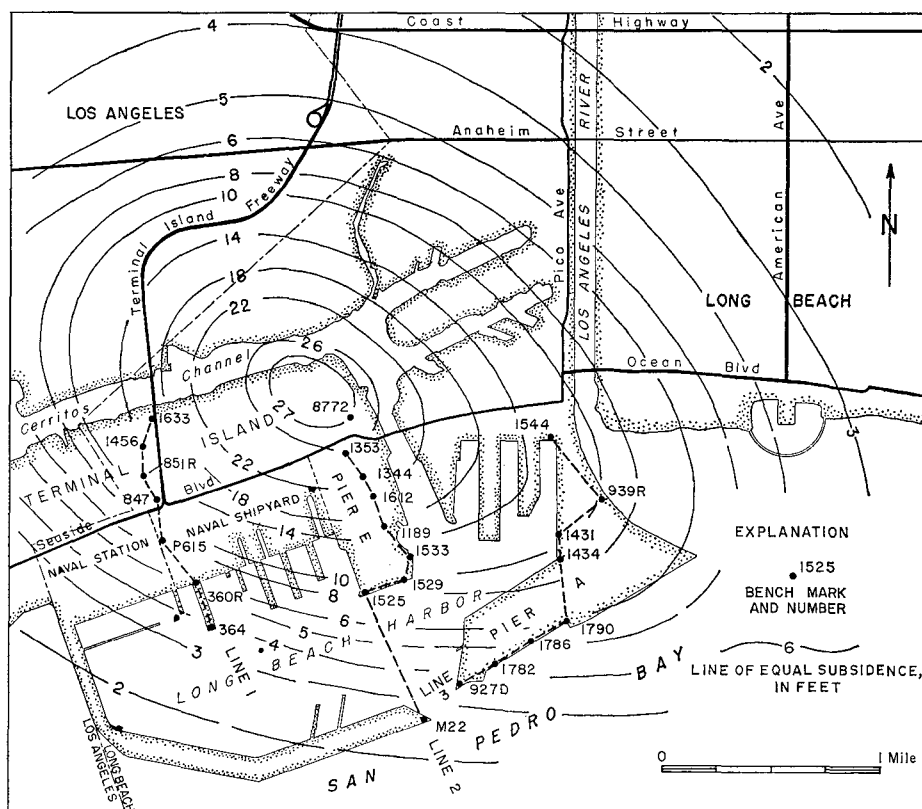


Figure 10. Subsidence from 1928 to August 1962 and location of selected bench marks at Long Beach Harbor area, California. (*Lines of equal subsidence from Long Beach Harbor Department.*)

13) was stopped, and the rate of subsidence was decreased north to bench mark 1431. By August 1962, subsidence had been stopped at all bench marks on the line.

The bench marks at the southern end of each line have experienced appreciable rebound. Table 2 shows the approximate rebound to May (or August) 1963 of seven bench marks that have recovered from 6 to 15 per cent of their initial subsidence. The maximum rebound has been 0.54 foot at bench mark 1790 (line 3), equivalent to about 9 per cent of the over-all subsidence at that place.

Results of consolidation and rebound tests of cores of silt and silty claystone from the Ranger, Upper Terminal, and Lower Terminal zones suggest that if fluid pressures were restored to initial pressure, the rebound of these fine-grained interbeds might range between 15 and 27 per cent for the individual zones. However, these figures are only suggestive, because only one test from each zone was examined. Furthermore, these zones are 30–60 per cent sand (Murray-Aaron and Pfeil, 1948, p. 11). The sand will not compact as much as the fine-grained interbeds for a given increase in grain-to-grain load. Although the *percentage of rebound* of the sand compared to its compaction would be greater than that of the silty beds, the *magnitude of sand rebound* probably would not be as great as that of the silty beds; therefore, the over-all rebound of the oil zones for full pressure restoration might be lower than is suggested by the rebound tests reported here.

Local subsidence and rebound of Terminal Island. Late in 1940, the U. S. Navy began construction of a graving dock near the east end of Terminal Island in fine-grained clayey sediments. The excavation, which was 65 feet deep and about 1000 feet long, was dewatered during the construction period by means of well points.

The underlying Gaspar aquifer, which occurs from about 80 to 160 feet below the land surface, had an artesian head standing about at sea level (5 feet below

TABLE 2. REBOUND TO 1963 OF SEVEN BENCH MARKS IN
WILMINGTON OIL FIELD THAT RECOVERED FROM 6 TO 15 PER CENT
OF THEIR INITIAL SUBSIDENCE

Bench mark	Approximate subsidence* (feet)	Rebound to May 1963 (feet)	Rebound in per cent of subsidence
<i>Line 1</i>			
364	4.0	0.49†	12
360R	5.7	.40†	7
<i>Line 2</i>			
M 22	2.7	.40†	15
1525	8.0	.45†	6
<i>Line 3</i>			
927D	3.7	.39	11
1786	5.3	.53	10
1790	6.0	.54	9

* Interpolated from map of subsidence, 1928–1960

† Rebound to August 1963

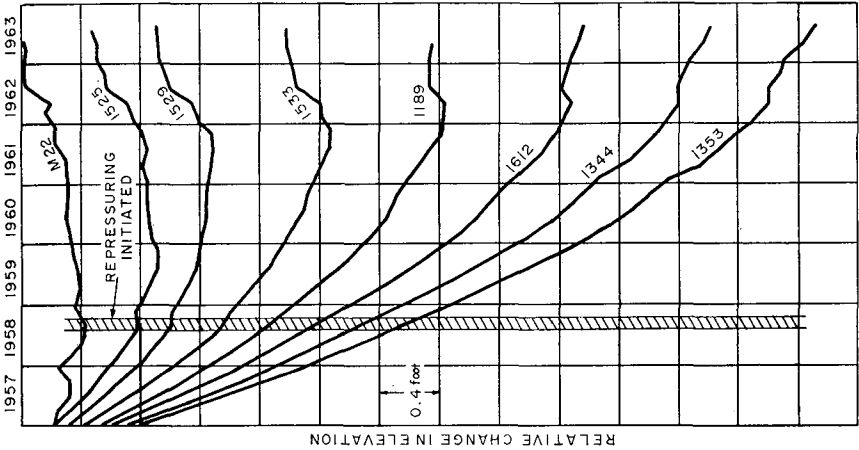


Figure 11. Change in elevation of bench marks, line 1, Long Beach Harbor area, California.

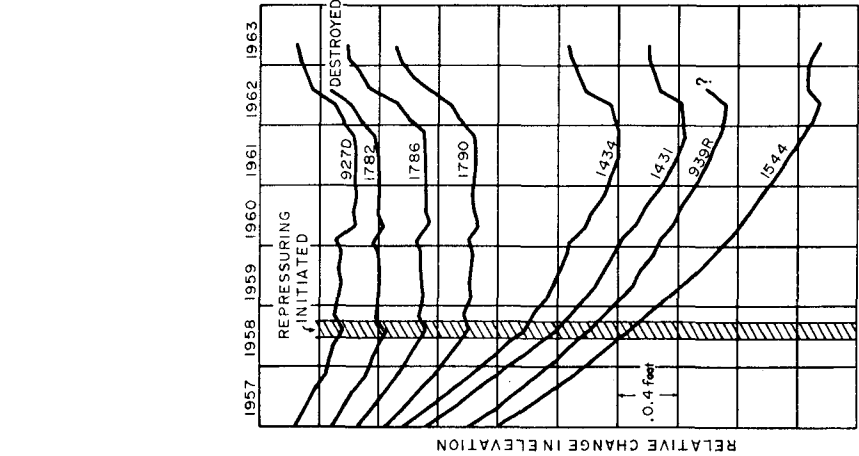


Figure 12. Change in elevation of bench marks, line 2, Long Beach Harbor area, California.

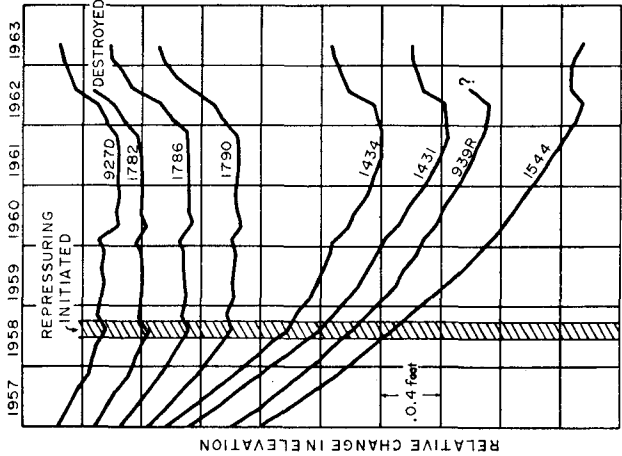


Figure 13. Change in elevation of bench marks, line 3, Long Beach Harbor area, California.

land surface). In order to prevent uplift and blowouts during construction, the artesian head in this aquifer was reduced below the bottom of the excavation by pumping water from 36 gravel envelope wells tapping the Gaspar zone. Grant (1944, p. 149-154) and Gilluly and Grant (1949, p. 494-497) described the dewatering, the effect on water levels in nearby wells, and the local subsidence and rebound of the land surface. The dewatering was started on June 27, 1941, and reached a maximum withdrawal rate of about 35,000 gallons per minute during August. Pumping operations ceased on April 4, 1942, after the removal of about 26,000 acre-feet of water from the Gaspar zone in 9 months. The maximum recorded subsidence was at bench mark 43, 1650 feet from the center of the graving dock. Subsidence of bench mark 43 was 0.50 foot relative to bench mark 18, which is about 3500 feet from the center of the graving dock. As described by Gilluly and Grant (1949, p. 497), substantial rebound of bench-mark altitudes coincided with recovery of water level in observation wells during the reduced pumping rates of the latter part of the dewatering operation and immediately after cessation of pumping. The rebound of bench marks ranged from 14 to 78 per cent with an average rebound of about 42 per cent. From these facts, Gilluly and Grant concluded that one half or more of this subsidence due to the drawdown of the piezometric level of the Gaspar zone was attributable to mineral-grain rearrangement, and the remainder was the result of elastic compression. It is of interest to note that the bench marks that underwent the largest subsidence had the smallest percentage of rebound.

This experience at Terminal Island is of particular interest because it is the only known documented example of subsidence *and significant partial recovery* of the land surface as a result of drawdown and recovery of artesian head in a fresh-water-bearing zone.

Acknowledgment. The authors wish to acknowledge the courtesy of the Long Beach Harbor Department and of the U. S. Navy in supplying unpublished data that were of great assistance in preparing this brief description of the Wilmington subsidence.

LAKE MARACAIBO, VENEZUELA

Kugler (1933) first reported subsidence of oil fields along the eastern shore of Lake Maracaibo, Venezuela. In 1935, Collins described a seawall built in 1932 on the east shore of Lake Maracaibo to protect an extensive oil-field development from flooding. According to Collins (1935, p. 405), a drainage program was begun in 1923, coincident with the start of oil-field development, to drain the swamps and marshes adjacent to the village of Lagunillas on the lake shore. Several years later, the shore was sinking 1 foot a year. To protect the oil fields on land, a continuous wall almost 3 miles long was built using reinforced concrete sheetpiles.

Although various aspects of the subsidence have been under study at the University of Illinois and elsewhere for a number of years, no papers describing the subsidence have come to the attention of the authors. A paper by D. J. L. Kennedy (1961, Ph. D. thesis, University of Illinois, 251 p.), however, which reports on a study of well-casing failures associated with compaction of oil-pro-

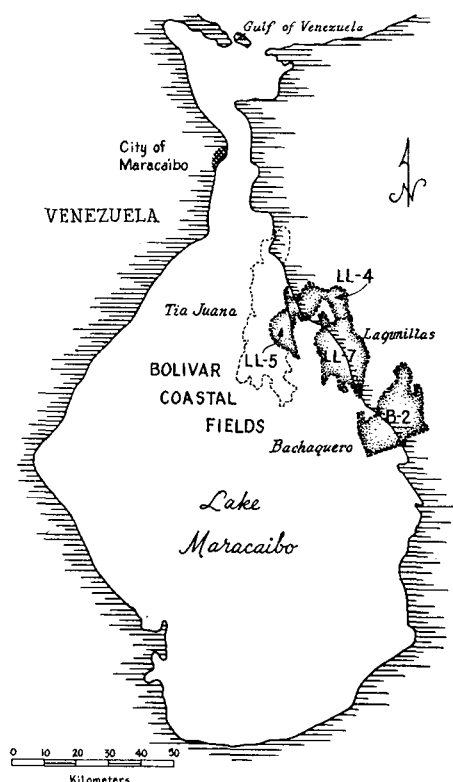


Figure 14. Bolivar coastal fields and reservoirs (stippled) of Lake Maracaibo area, Venezuela. (After Kennedy, 1961, Ph.D. thesis, University of Illinois, Figs. 1 and 2.)

Maximum cumulative compaction for the several reservoirs is plotted against time on Figure 15. The greatest compaction (subsidence) shown is for the LL-7 reservoir of the Lagunillas field—340 cm (about 11 feet) from 1926 to March 1954. The rate of subsidence was decreasing noticeably in the early fifties, but the reduction in reservoir pressure during this compaction period is not given. In the B-2 reservoir (Bachaquero field), compaction of 140 cm (4.6 feet) is indicated from 1938 to 1958. Initial reservoir pressure at the top of the Miocene sands was about 1800 pounds per square inch. When reservoir pressure had been reduced to 1000 pounds per square inch (decrease of 800 pounds per square inch), only about 20 cm of compaction had occurred, but reduction of pressure from 1000 to about 830 pounds per square inch was accompanied by 120 cm of additional compaction. Kennedy pointed out the implication from the theory of consolidation that the compacting beds in the B-2 reservoir may have been subjected to a pressure in their past history about 800 pounds per square inch greater than that existing when oil was first withdrawn.

As a result of the detailed study of liner or casing damage, Kennedy (1961, Ph.D. thesis, p. 104) concluded that the major cause of damage is the compac-

ducing strata in the eastern-shore fields, furnishes some information on the subsidence.

Oil was discovered in 1917 in the so-called Bolivar Coastal Fields on the northeast shore of Lake Maracaibo. Figure 14 shows the three main oil fields of this area. Much of the oil is produced from off-shore wells. The Tia Juana and Lagunillas fields were discovered in 1926, and the Bachaquero field was discovered in 1930. According to Kennedy (1961, Ph.D. thesis, p. 1), much of the oil has been produced from interbedded sands, hard clays, and silts of Miocene age, and the decrease in reservoir fluid pressure has caused compaction of these unconsolidated strata. He stated further (p. 18) that:

Evidence indicates that the consolidation of the shale layers within the producing stratum due to the increase in effective pressure is the chief cause of the subsidence; however, the compaction of the sands may contribute a considerable amount to the subsidence.

He concluded that, in general, the greatest subsidence coincides with the greatest pressure decline and with the thickest Miocene producing zones.

tion of the producing strata because "casing damage occurs almost exclusively within the producing stratum or can be attributed to movements in the producing interval."

NIIGATA, JAPAN

In the Niigata area on the northwest coast of the island of Honshu, Japan (Fig. 16), large quantities of saline ground water containing dissolved methane gas are pumped from wells as much as 1000 m deep, tapping relatively unconsolidated sediments of Cenozoic age. These sediments are primary coarse—sand, sandstone, and conglomerate, with pebble layers—but include three to four interbedded clay layers as much as 60 m thick. About 210 million cu m (7.3 billion feet³) of methane were produced in 1958, 60 per cent of the natural gas production in Japan. As a result, many chemical plants have been built to utilize the gas.

Subsidence of the Niigata harbor area became noticeable by 1955, and by 1958, much of the port area, which initially was only 1–2 m above sea level, had been

damaged by inundation from the sea. Because of the serious situation, several reports have been prepared (Committee for Investigation of Earth Level Subsidence in Niigata, 1958; 1960; Aki, 1959) which are the source of this description.

First-order level surveys have been made in Niigata and its vicinity by the Japan Geographical Survey Institute in 1898, 1930, 1951, 1955, and 1957, and leveling has been at about 6-month intervals since 1957. Subsidence from August 1957 to February 1958, as defined by the leveling, is shown on Figure 17. The area of productive gas wells shown by the stipple pattern, coincides in general with the area of subsidence. The subsidence of 20 cm at the harbor mouth in 6 months indicates an annual rate of 40 cm or about 1.3 feet. By 1959, the annual rate had increased to 50 cm (1.6 feet) a year.

Long-term graphs of elevation change for three bench marks are shown on Figure 18 (for location, see Fig. 17). Although these bench marks are not in the area of most intensive subsidence, their graphs are representative of the subsidence trend. They show a slow subsidence of about one half a centimeter per year from 1898 to 1952 and a rapid acceleration since 1955. The cause of the slow subsidence prior to 1952 is not explained. Natural gas production, shown by the dashed line in Figure 18, began about 1947 and increased rapidly

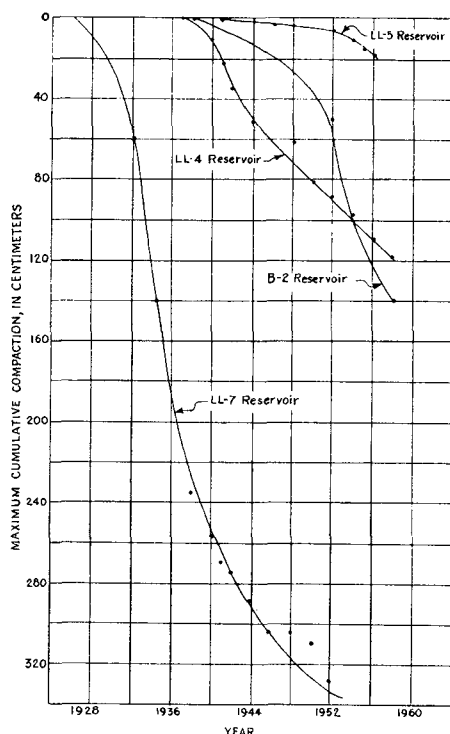


Figure 15. Maximum cumulative compaction *versus* time for reservoirs in Bolivar coastal fields, Venezuela. (After Kennedy, 1961, Ph. D. thesis, University of Illinois, Fig. 18.)



Figure 16. Outline map of Honshu, Japan, showing areas of subsidence due to withdrawal of fluids.

in the fifties. The volume of gas-bearing water pumped reportedly has been about equal to the volume of gas (atmospheric pressure) recovered.

Because of the coincidence in time and place of the increase in rate of subsidence and of fluid withdrawal, Japanese investigators concluded that the cause of the accelerated subsidence is the withdrawal of the water and gas. This withdrawal has decreased the fluid pressure in the gas-bearing zones and has caused compaction of the sediments.

The rate and distribution of compaction in depth is being observed by means of 12 novel compaction recording wells, ranging in depth from 20 to 1190 m, installed in 1958–1959. These compaction recording wells consist of two concentric pipes installed in drilled holes. The inner pipe is anchored on a bottom foundation and is protected

from lateral earth pressure by the outer pipe to provide for free vertical movement. In the deeper installations, the diameter of the outer pipe is about 14

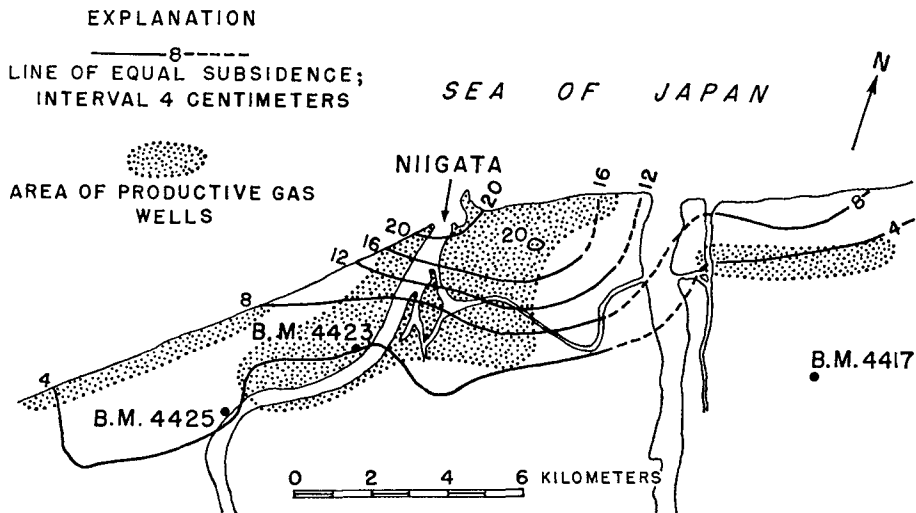


Figure 17. Subsidence from August 1957 to February 1958 in the Niigata area, Japan. (Modified from Committee for Investigation of Earth Level Subsidence in Niigata, 1958, Fig. 19; 1960, Fig. 2.)

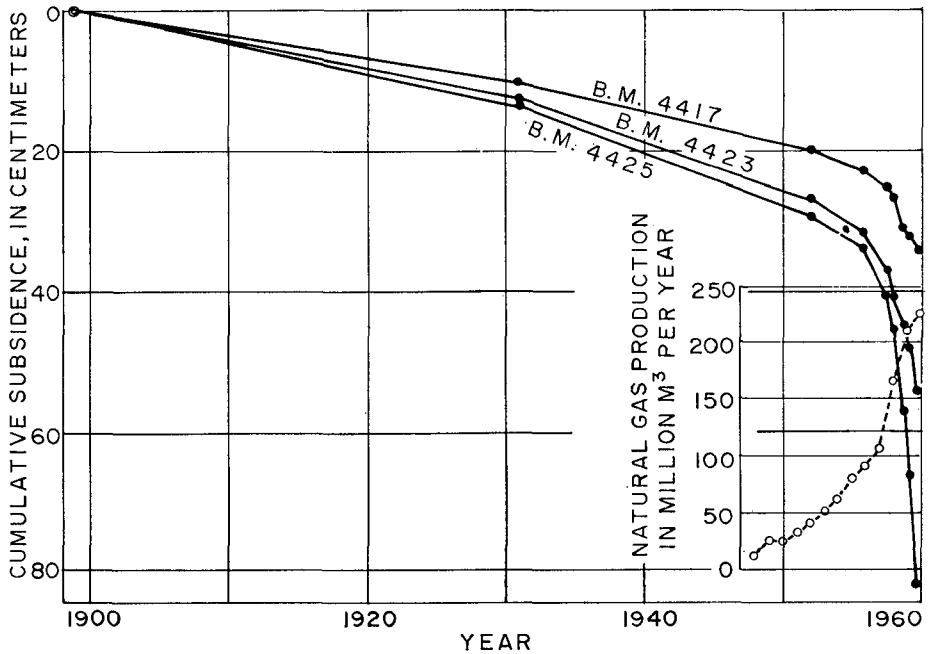


Figure 18. Cumulative subsidence, 1898–1959, of three bench marks in the Niigata area, Japan, and production of natural gas since 1947. (*Modified from Committee for Investigation of Earth Level Subsidence in Niigata, 1960, Figs. 3-1 and 7.*)

cm and that of the inner pipe about 7 cm. Centering devices are attached to the inner pipe at 40- or 50-m intervals. A lever system magnifies protrusion of the inner pipe at land surface as much as 20 times when compaction occurs. Wells of several depths have been installed at a single site to provide information on the distribution of compaction with depth. Preliminary results in mid-1959 after 1 year of operation indicated compaction of about 20 cm per year between depths of 300 and 610 m—equal to about 40 per cent of total subsidence at that place for the year.

Protection of the port and the industrial plants from inundation by the sea is very difficult because there is no impermeable stratum at shallow depth to restrain underflow beneath dikes. Drainage is being accomplished by costly pumping. Stopping the gas production would destroy the chemical industry. According to Professor Jiro Makiyama (June 1962, written commun.), the subsidence was being retarded by means of controlled withdrawal and repressuring by injection of water through wells.

PO DELTA, ITALY

The Po Delta, on the Adriatic coast in northeastern Italy, subsided from various causes at a slow average rate of 1–3 mm a year from about 1890–1950, based on precise leveling by the Institute of Military Geography. Releveling in

1956, however, revealed a great increase in the rate of subsidence after 1950. As Figure 19 shows, the average annual subsidence from 1950–1951 to 1956 was a maximum of about 30 cm (1 foot) a year at the River Po, 16 km west of the coast. The shape of the subsiding area was oval, and the 5-cm-per-year subsidence line included an area about 20 km wide (north–south) by 40 km long, extending west from the coast. Flooding and damage caused by the subsidence has led to large expenditures for remedial work, such as construction and raising of levees and reclamation of flooded lands.

Methane gas is produced from this area in large quantities and is an important industrial resource. Commissions have been formed to study the causes of subsidence, and many papers have been published citing causes contributing to the subsidence. Suggested causes include compaction under natural overburden

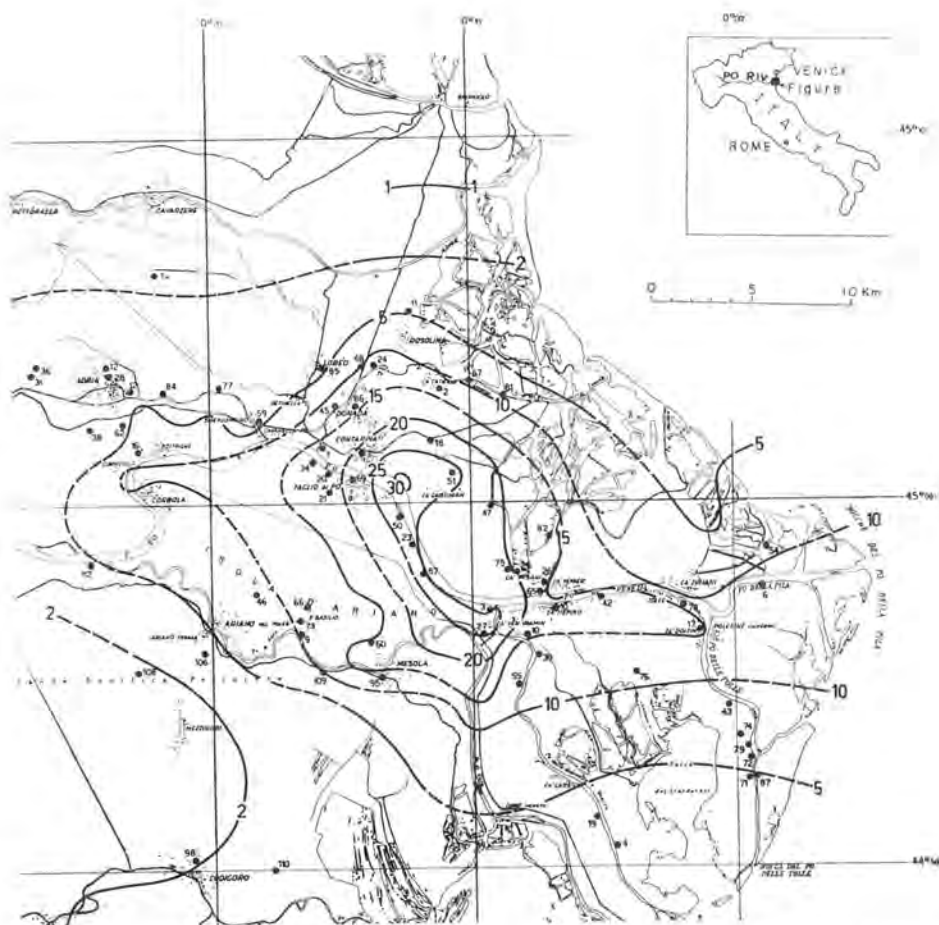


Figure 19. Map showing rate of subsidence, 1950–1951 to 1956, of Po Delta, Italy. Lines of equal subsidence in centimeters per year. Numbered black dots indicate centers of methane production. (After Puppo, 1957, Fig. 6.)

load, tectonic adjustment, rising sea level, and drying out of reclaimed lands (some of which contain peat beds). This discussion is based on information from a few of these papers for which translations are available. (The authors wish to acknowledge the assistance of Professor Francisco Penta of the University of Rome in supplying a number of pertinent papers on the subsidence; also that of R. E. Miller for translation of some of the papers.) These include papers by Boaga and others (1957); Puppo (1957); Dal Piaz (1959); Storer (1959); and Gortani (1961). An extensive bibliography relating to geology and elevation changes in the Po Delta region and to analysis of geodetic data is given by Dal Piaz (1959, p. 71-76).

The Po River delta (Venetian Po) has been built up very rapidly in Quaternary time. This has resulted in a thickness of 1000 m or more of relatively unconsolidated Quaternary deposits over most of the Delta—in synclinal areas, the thickness exceeds 2000 m (Dal Piaz, 1959). The deposits are chiefly marine (littoral with some lagoonal layers), sandy, and highly calcareous, but they contain some clay layers. According to Dal Piaz (1959, p. 450), Selli has distinguished five well-defined methane-bearing horizons. The gas accumulations are related to gentle undulations in the Quaternary strata or to breaks in the monoclinical dip. Methane also is produced from underlying deposits of Pliocene and Miocene age, but apparently, the major production is from the beds of Quaternary age. The saline and brackish waters in the methane layers have a chemical composition qualitatively similar to sea water.

The methane development began in 1938, and by 1956, gas production from the Delta area was at least 200 million m³ (about 7 billion feet³) a year. The ratio of gas to water is about 1 to 1. This methane is of great value to the economy of the region.

The rate of subsidence, which accelerated so sharply from 1951 to 1956, continued to increase after 1956. According to Gortani (1961), the area included between the lines of 20-25 cm of annual sinking increased from 8000 hectares (19,800 acres) in 1957-1958 to 17,000 hectares (42,000 acres) in 1959.

Analysis of the relationship between withdrawal of methane-bearing water and the subsidence did not lead to a clear cause and effect conclusion (Puppo, 1957); nevertheless, the costs of attempting to protect the subsiding lands from flooding became so great (about \$33 million in 1960) that it was decided to carry out a crucial experiment—stop all the gas and water removal in an experimental area of 10,000 hectares (24,700 acres), including the area of most rapid subsidence. According to Gortani (1961), pumping in this area, which had been about 50 million m³ (40,000 acre-feet) of water a year was stopped on February 20, 1960. Special bench-mark surveys were made every 3 months, and fluid levels in wells were measured weekly.

After 6 months of shutdown, several instructive developments could be reported. The piezometric level recovered rapidly in the closed-in area, and in general, the deeper the aquifer the greater the pressure recovery (as much as 15 m in 4 months). The bench-mark releveing showed that the maximum subsidence from February 20 to August 20, 1960, was 7.4 cm (annual rate about 15 cm). The rate of subsidence for bench marks in the area of no pumping decreased

noticeably after February 20; whereas, for those outside, it continued unchanged (Gortani, 1961, Fig. 12).

A well 714 m deep near the center of subsidence was filled with concrete and used to record compaction. During the period of record, the observed sinking of the land surface with reference to the top of the concrete-filled casing indicated that the compaction of the deposits within the well depth was equal to the subsidence.

The results of the experimental shutdown of wells supported the conclusion that the extraction of the methane waters is the principal cause of the rapid sinking of the Po Delta (Gortani, 1961, p. 13). It was proposed to extend the shutdown over all the Delta area, which would stop the annual extraction of 250 million m³ (200,000 acre-feet) of water from more than 850 gas wells yielding at least 200 million m³ (about 7 billion feet³) of methane. The revoking of mineral rights is being considered (Anonymous, 1961). Thus, the great cost and difficulty of protecting the sinking area from the sea and from the river floods may close down a major industry. This closure poses economic and social problems as well as legislative problems relating to indemnity for losses suffered.

SUBSIDENCE DUE TO GROUND-WATER WITHDRAWAL

GENERAL STATEMENT

For many years, major subsidence of the land surface has been observed in certain areas of intensive ground-water withdrawal. Areas of major subsidence in California are the San Jose area in the Santa Clara Valley and the Los Banos-Kettleman City, Tulare-Wasco, and Arvin-Maricopa areas in the San Joaquin Valley. Elsewhere, the best-known subsidences are in Mexico City, Mexico, and in the Houston-Galveston area of Texas. Minor subsidence related to ground-water withdrawal has occurred in several places in addition to those described in this paper. All of these areas are underlain by confined aquifers, and in all, the artesian head has been drawn down at least several tens of feet by heavy withdrawal. Doubtless, subsidence has occurred in many other ground-water basins where artesian head of compressible confined aquifers has been drawn down 50–100 feet or more, but it has gone undetected because of lack of repeated leveling.

On the other hand, subsidence is known to be small or negligible in some confined aquifer systems that have experienced head decline of 100 feet or more. For example, in Memphis, Tennessee, the artesian-head decline in confined aquifers of Eocene age has been 100 feet or more since 1886, yet subsidence, as shown by repeated levelings, has been negligible (G. H. Davis, Aug. 27, 1962, written commun.). Presumably, the lack of subsidence at Memphis is explained by the state of preconsolidation, the clay-mineral assemblage, which is probably dominantly kaolin-type (Griffin, 1962), and the lithology of the aquifers—these are the elements that determine the compressibility of the system within the range of increase in grain-to-grain load experienced. One of the principal aquifers is a well-sorted clean fine-to-medium quartz sand; the other contains several fine-grained interbeds (Criner and Armstrong, 1958).

AREAS ON HONSHU, JAPAN

Introductory Comment

On the island of Honshu, Japan, appreciable subsidence due to pumping of ground water for industrial use is reported in three harbor areas on the south coast at Osaka, Nagoya, and Tokyo (Fig. 16). Drawdown of the artesian head in confined aquifers reportedly has caused compaction of clayey beds to depths of about 100 m. At Tokyo and Osaka, the position of the compacting beds has been determined by establishing depth-bench-mark tubes in the aquifers and observing the rate of protrusion of the tubes at land surface (Aki, 1959, p. 4). Maximum subsidence is about 4 m at Tokyo (Naomi Miyabe, July 1, 1965, oral commun.) and about 3 m at Osaka (Jiro Makiyama, May 24, 1960, oral commun.) Apparently, plans are underway to reduce the local pumping by importing water by pipe line to these industrial areas in order to control the subsidence.

Osaka Area

Subsidence at Osaka City was first noted in 1885.⁷ From 1885–1928, the maximum rate of subsidence was almost constant, 0.5–1.3 cm per year; total subsidence in this period was 30–60 cm. In 1928, the rate of pumping of ground water was about 3 million gallons a day; pumping then increased rapidly to a maximum of 50 million gallons a day by 1942. Following the destruction of factories during the war years, pumping decreased to 30 million gallons a day by 1945. The rate of subsidence also increased in the period from 1928 to 1943, averaging 7–12 cm per year, and maximum subsidence in this 15-year period was at least 130 cm. After 1943, subsidence almost ceased for a few years in response to decreased pumping and a recovery of about 10 m in artesian pressure, but renewed increase in pumping after 1948 caused renewed subsidence. Maximum subsidence at Osaka to 1951 was about 2 m. The area of subsidence centering at Osaka City was about 280 sq km.

Large buildings, which have foundations set in the “Osaka foundation rock layer” at depths of 40–80 m, have risen with respect to land surface. Also, casings of deep wells extending to depths of 100–270 m have protruded above land surface. Both of these phenomena indicate compaction of beds above the foundation rock layer.

The Disaster Science Laboratory (Brashears, 1955, personal commun.) concluded from a study of subsidence from 1938 to 1942 that about 50 per cent of the subsidence was due to compaction in the top 30 m and that about 90 per cent was caused by compaction in the top 180 m. The rate of subsidence correlated with the change in water level, and the sudden acceleration of subsidence after 1928 was attributed to compaction of clay zones due to reduction of pressure in confined aquifers.

⁷ This description of subsidence at Osaka is from notes supplied by M. L. Brashears in personal communication of September 7, 1955, and is based on material from the Committee of Harbor Engineering Investigation in Osaka Bay.

LONDON, ENGLAND

Land subsidence at London is substantiated by records dating back almost a century. Longfield (1932) first called attention to local subsidence at London, which is superimposed on regional tilting movement that affects much of southern England. On the basis of precise leveling of 1865, 1895, 1914, and 1932, he reported settlements of as much as 1 foot, the maximum being slightly in excess of 1 foot at the Bank of England in the City of London.

Wilson and Grace (1942) re-examined Longfield's data in the light of soil mechanics theory. Using consolidation test results of samples of London Clay, they computed the theoretical subsidence that should have occurred due to decline in artesian head in the underlying chalk aquifer and underdrainage of the London Clay.

The London Clay is fairly continuous throughout the London area and ranges in thickness from 0 to 300 feet. Decline in head began about 1820 when the original artesian head in the chalk aquifer was as much as +30 feet O.D. (*Ordinance Datum*; approximate mean sea level). The head had declined about 25 feet by 1843, and by 1936, the water levels in wells tapping the chalk were -100 to -300 feet O.D. in much of the London area (Fig. 20).

Ignoring bench marks on heavy buildings, such as the Bank of England, which

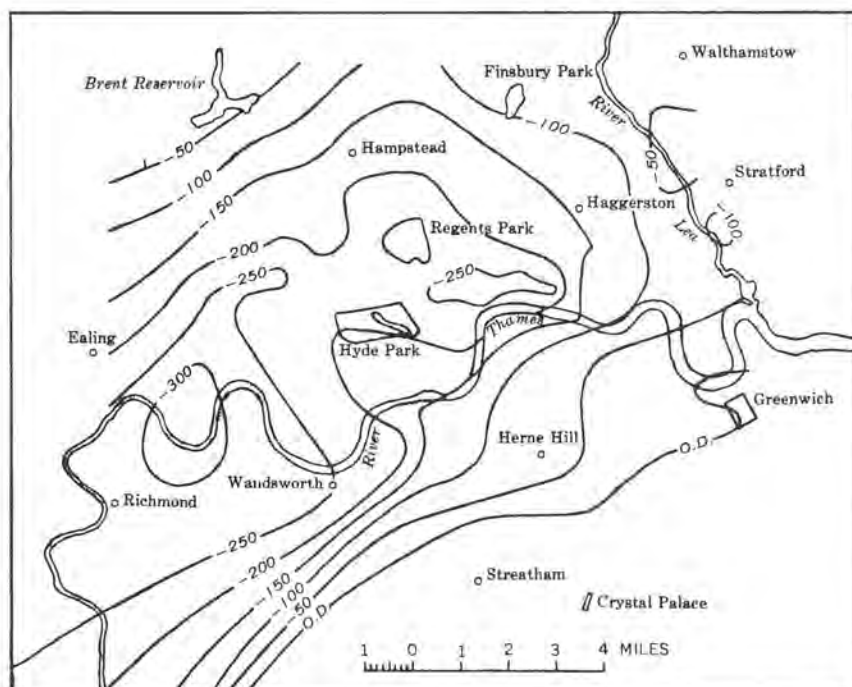


Figure 20. Piezometric surface, 1936, of chalk aquifer beneath the London Clay in London, England. Contour interval 50 feet, datum approximately mean sea level. (After Wilson and Grace, 1942.)

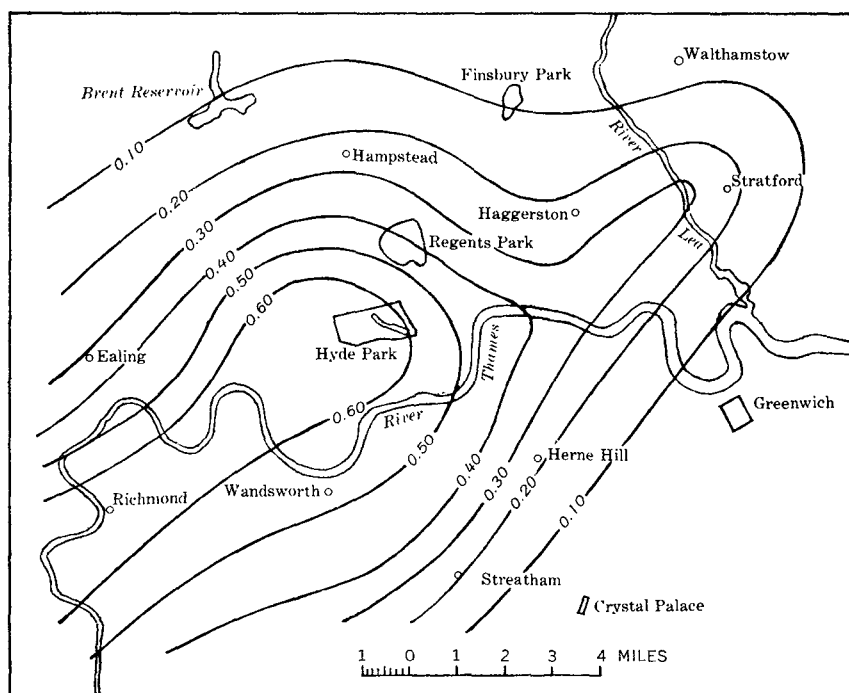


Figure 21. Lines of equal subsidence, 1865–1931, London, England. Interval 0.1 foot. (After Wilson and Grace, 1942.)

were believed to have settled partly because of the load of the building, Wilson and Grace presented contours of subsidence for several periods. These contours indicate that during the period 1865–1931 the subsidence was 0.2–0.6 foot throughout much of London (Fig. 21). Extrapolation back to the initiation of the increase in effective pressure (decline of head) suggests a maximum subsidence due to decline in head of about 0.7 foot.

MEXICO CITY, MEXICO

Mexico City is in southeastern Mexico, in the west central part of the Valley of Mexico, a closed basin at an elevation of about 7500 feet surrounded by high mountains. The relatively flat part of the valley underlain by alluvial deposits is about 100 km long (north–south) and 15–40 km wide (Mooser, 1961, unnumbered geologic map). Many small rivers flow into the valley, and under natural conditions, the rivers formed a series of shallow lakes, the largest of which was Lake Texcoco.

Roberto Gayol (1929) presented the first specific evidence on the subsidence of Mexico City and pointed out the need for continuing observation. By 1959, subsidence exceeded 4 m (13 feet) beneath all the old city (extent of city in 1891) and was as much as 7.5 m (25 feet) in the northeast part (Fig. 22). This great and long-continued sinking has caused many problems in water transport, drainage, and in the construction of buildings and other engineering structures in

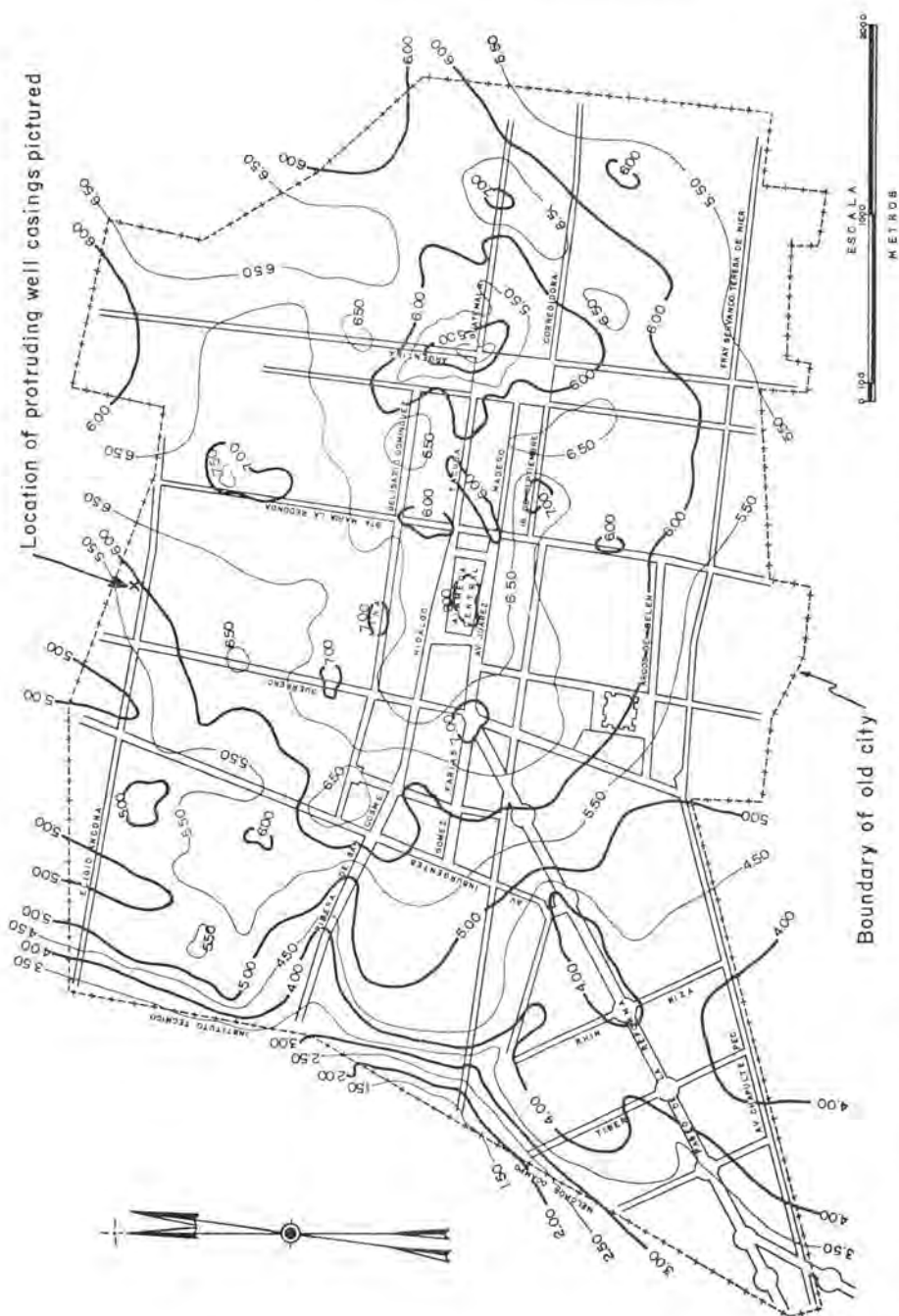


Figure 22. Subsidence, 1891-1959, of Mexico City, Mexico. Lines of equal subsidence in meters. (*After* Comisión Hidrológica de la Cuenca del Valle de México, 1961, p. 47.)

the heart of a great and growing city; consequently, this subsidence has been studied more intensively in its soil-mechanics aspects than has any other subsidence due to ground-water withdrawal.

Geology. At the end of the Cretaceous Period, crustal deformation of the Cretaceous limestone was accompanied by intensive volcanic activity, which has continued to Recent time but at a decreasing rate. The volcanic sequence has been andesite, rhyolite, and finally basalt. Only 2000 years ago, a basaltic lava flow drove the inhabitants from the valley (Zeevaert, 1949, Ph.D. thesis, University of Illinois, p. 20, 26).

In late Pliocene time and during most of the Pleistocene Epoch, inflowing streams brought coarse andesitic detritus into the valley. Logs of water wells show that sand and gravel containing some interbeds of clayey silt occur almost continuously from a depth of 50–60 m to more than 500 m. They constitute the highly productive aquifer underlying Mexico City (Zeevaert, 1949, Ph.D. thesis). This aquifer is overlain chiefly by soft fine-grained lake deposits of late Pleistocene age—volcanic ash and water-transported sediments.

The depositional units from the land surface to the top of the productive aquifer at about a depth of 50 m vary in thickness from place to place in the city. However, their character and thickness can be generalized as follows: artificial fill and water-laid silt and sand from the land surface to a depth of 6 m; then an upper soft bentonitic and diatomaceous silty clay about 30 m thick; then a coarse cemented sandy bed about 5 m thick; and then a second bentonitic silty clay 5–10 m thick, stiffer than the upper clay bed. Both of the bentonitic clay beds are highly compressible.

Marsal and Mazari (1959) in their monograph on “The Subsoil of Mexico City” gave detailed descriptions and graphs of the physical and engineering properties of these highly compressible bentonitic silty clays. Tables and graphs showing bench-mark elevations and subsidence, logs of bore holes and engineering properties of materials, and graphs of change in pressure in many hundreds of piezometer installations have been published by the Comision Hidrologica de la Cuenca del Valle de México (1953; 1958; and 1961).

In the upper bentonitic clay, the natural water content ranges from 200 to as much as 500 per cent of the solids by weight, depending on location and loading history. The average value is about 300 per cent. The void ratio ranges from about 5 to 9; the average value is about 7. Thus, the porosity of this upper clay ranges from 84 to 90 per cent; the average is about 88 per cent.

In the lower bentonitic clay, the natural water content is 200–300 per cent by weight. The void ratio generally is 4–5, indicating an average porosity of about 82 per cent. In spite of the very high water content and void ratio of these bentonitic clays, Zeevaert (1953b, p. 983) reported that their shearing strength and rigidity is comparable with other clays having water contents as low as 30 per cent.

The clay mineralogy of the bentonitic clay beds is highly complex and has been studied by several methods. From examination of several hundred samples by the electron microscope, Marsal and Mazari (1959, p. 86) concluded that the proportions of clay minerals are about as follows: 80 per cent montmorillonite, 14

per cent kaolinite, 4 per cent beidellite, and about 2 per cent of the illite group.

Hydrology. Until the last few years, most of the water supply for Mexico City has been obtained from wells within the city. As early as 1854, 140 artesian wells had been constructed. According to Loehnberg (1958), water was supplied from 3000 privately owned wells 30–100 m (100–325 feet) deep and from about 220 municipal wells 100–300 m (325–1000 feet) deep in 1957. Private wells yielded about 2.5 m³/second (90 cubic feet per second), and municipal wells yielded about 6.5 m³/second (230 cubic feet per second). This discharge of these wells far exceeded the natural recharge. The great increase in demand for water was a result of the rapid increase in population, which grew from about one half million in 1895 to 1 million in 1922 and to 5 million people by 1960.

The artesian head in deep wells initially was a few feet above the land surface, but by 1959, the pressure at 50 m depth (at the top of the main aquifer) had decreased 20–35 m (65–110 feet) (Comision Hidrologica de la Cuenca del Valle de México, 1961, p. 338).

The water table stands 1–2 m below the land surface beneath much of the old city, and its level has not changed appreciably throughout the historic record.

Land subsidence. Local subsidence first occurred owing to loading by the large Aztec structures and later by Spanish buildings. The principal subsidence, however, began in the late 1800's as a result of development of artesian water, the consequent decline of artesian head, and the increase in effective stress.

Figure 23 illustrates the trend of subsidence in the center of the old city. Between 1898 and 1938, subsidence was not defined by leveling; it probably was not uniform, but the average rate was about 4 cm per year (Marsal, and others, 1952, p. 3). The rate of subsidence increased sharply in 1938 and again in 1948, presumably as a result of increased withdrawal from municipal wells beginning in those years. From 1938 to 1948, the rate of sinking was about 15 cm per year; from 1948 to 1952, the rate increased to 30 cm (1 foot) per year in the central part of the city and to 50 cm per year locally (Marsal and Sainz-Ortiz, 1956, p. 3). After 1952, the rate decreased slightly to about 25 cm per year. The total subsidence of the four bench marks from 1898 to 1956 was 5–7 m (16–23 feet).

Figure 22 shows the magnitude and distribution of subsidence in the old city from 1891 to 1959 as determined by leveling. Maximum subsidence was 7.5 m (25 feet), and subsidence exceeded 4 m (13 feet) in all but the western edge of the old city.

From 1952 to 1957, subsidence was about 1 m on the average (Fig. 24) although it reached 1.5 m at a few centers, possibly areas of large building load. Thus, in this period, the average subsidence was about 0.2 m a year. In some areas of recent urbanization, beyond the extent of the old city shown in Figures 22 and 24, subsidence in the fifties occurred at a more rapid rate, but maps are not available to show the full areal extent and magnitude of the subsidence.

Protrusion of well casings is a common occurrence in the subsiding area and is a graphic demonstration of the decrease in thickness (compaction) of the sediments within the casing depth. The amount of protrusion is not an absolute measure of compaction above the casing bottom because the casing may shorten. The

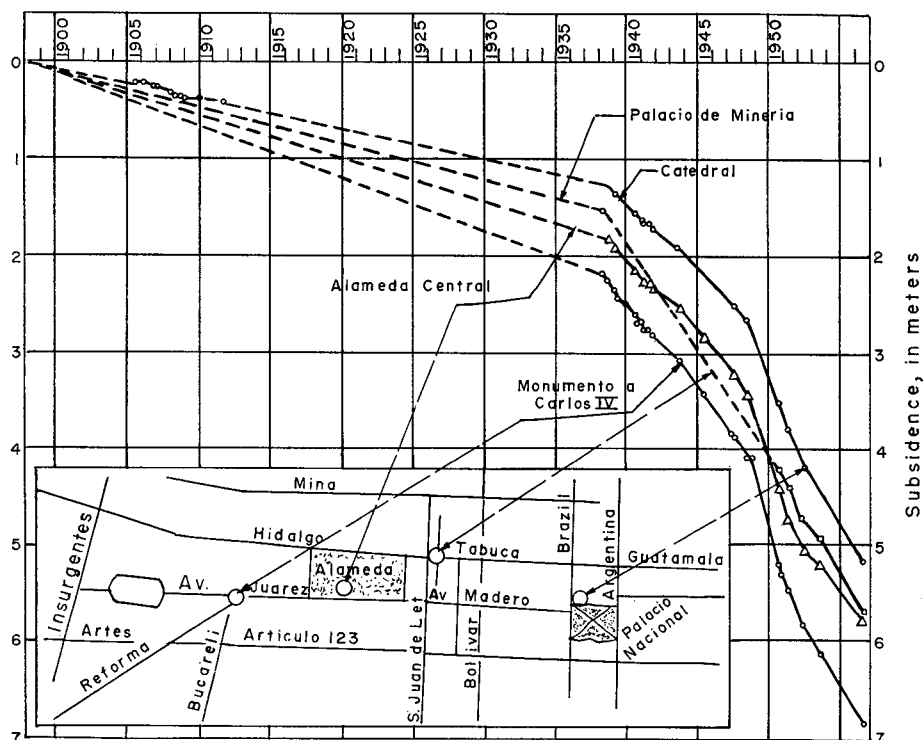


Figure 23. Subsidence, 1898–1956, of four bench marks in Mexico City, Mexico. (Modified from Marsal and Mazari, 1959, Fig. XI-5.)

protrusion does supply, however, a minimum value of compaction in that depth interval. The protruding casings shown in Plate 6 (see Figure 22 for location) indicate that at least 5.45 m of the subsidence at this site between 1923 and 1954 resulted from compaction of the deposits above a depth of about 100 m. Total subsidence at this site from 1891 to 1959 was on the order of 6 m (Fig. 22); thus, the protrusion indicates that here most of the subsidence has resulted from compaction of the deposits within the first 100 m below land surface.

Cause of the subsidence. Dr. Nabor Carrillo (1948) was the first to relate the subsidence of Mexico City to the theory of consolidation and the increase in effective stress caused by the decline in artesian pressure. With the benefit of the great amount of data obtained in the next decade, the causes of the subsidence have been examined in much greater detail by Marsal and Mazari (1959, p. 373–412). Zeevaert (1957) demonstrated that in addition to the primary consolidation caused by the reduction in excess pore pressures, secondary compression is an important aspect of the subsidence.

Investigators of the subsidence in the Mexico City area agree that the principal cause of the regional subsidence is the reduction in artesian pressure that has occurred—most rapidly since 1938. The increase in effective stress has been almost instantaneous in the coarse aquifer system below a depth of 50 m. A steep downward hydraulic gradient has developed in the fine-grained beds in the upper

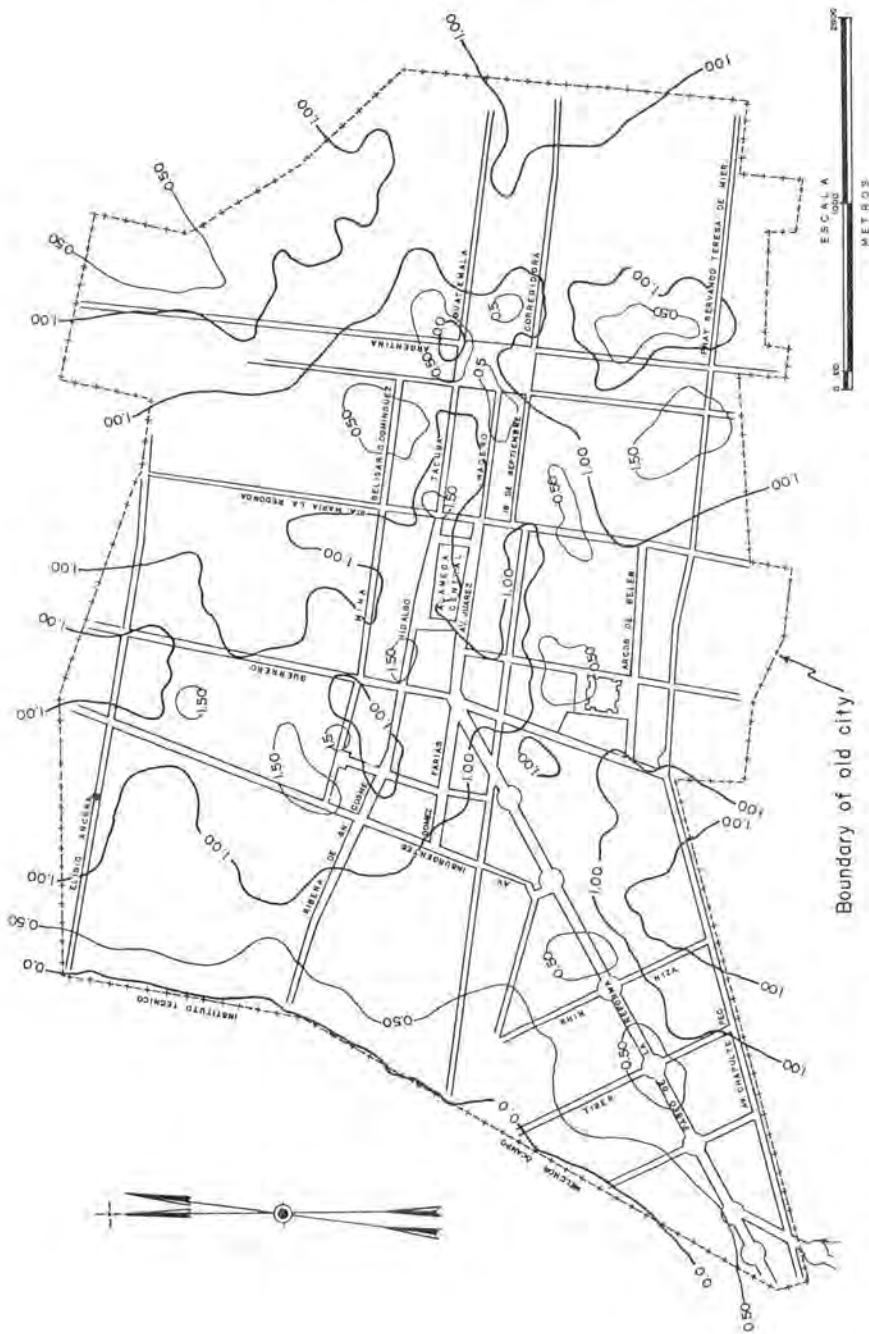


Figure 24. Subsidence, 1952-1957, of Mexico City, Mexico. Lines of equal subsidence in meters. (*After* Comisión Hidrológica de la Cuenca del Valle de México, 1961, p. 49.)

50 m, but the pore pressure decay has been retarded by the low permeability of the silty clay beds. Consolidation can occur only as fast as the excess pore pressure is reduced, and the rate at which this can occur is a function of the permeability and thickness of the beds.

Estimates of the proportion of subsidence caused by compaction of the upper 50 m of deposits that include the two bentonitic clay beds range from about two-thirds to 85 per cent, depending partly on location and the increase in effective stress (Zeevaert, 1953a). Evidence from the protruding casings of Plate 6 suggests that at some places, at least, the compaction of the top 100 m of sediment is about equal to the subsidence.

Recognizing that the artesian-head decline can be stopped only by reducing the local ground-water draft, comprehensive plans have been made for importing water to the city. Since 1952, several new projects have been completed to bring water into the city, and others are under construction. In addition, reservoirs and recharge wells have been constructed for the purpose of injecting flood waters into the aquifer system. According to Quintero (1958), 13 recharge wells have been installed since 1953, and others are planned.

Acknowledgment. The authors acknowledge the assistance of Mr. Jose A. daCosta of the Geological Survey in translation of the paper by Marsal, and others (1952). The authors also wish to thank Messrs. R. J. Marsal, I. Sainz-Ortiz, and Leonardo Zeevaert for supplying several publications.

SAVANNAH, GEORGIA

Davis and others (1963) reported land subsidence of as much as 200 mm at Savannah, Georgia, due to decline of artesian pressure in a limestone aquifer. Precise leveling in 1918, 1933, 1935, and 1955 by the U. S. Coast and Geodetic Survey indicated maximum subsidence of bench marks of about 100 mm. Most of the subsidence occurred during the period 1933–1955. Pumpage increased from 23 million gallons per day in 1933 to 57 million gallons per day in 1955, and decline of artesian head was about 40 feet in the 37 years before 1933 and about 100 feet in the 22 years after 1933. A close correlation was noted between subsidence, pumpage, and decline of artesian head.

During the period 1933–1955, subsidence exceeding 20 mm occurred in an area of 50 square miles including the city of Savannah and extending 5 miles to the north and west. As shown on Figure 25, the subsidence corresponded closely in areal extent to the area of greatest decline of artesian pressure during the same period.

Figure 26 shows the relationship between land subsidence and decline of artesian pressure, 1933–1955, along a profile extending from 10 miles north of Savannah through the city to the Atlantic Ocean 16 miles east.

The ratio of subsidence to decline of artesian pressure at Savannah of 0.0033 suggests that the maximum subsidence may have been about 200 mm from 1918 to 1955 in the area of greatest decline of pressure. The maximum rate of subsidence recorded by a bench mark was 40 mm during the 10-year period 1945–1955 at a point about 2 miles south of downtown Savannah.

Unlike the sediments of many other subsiding areas, the principal artesian

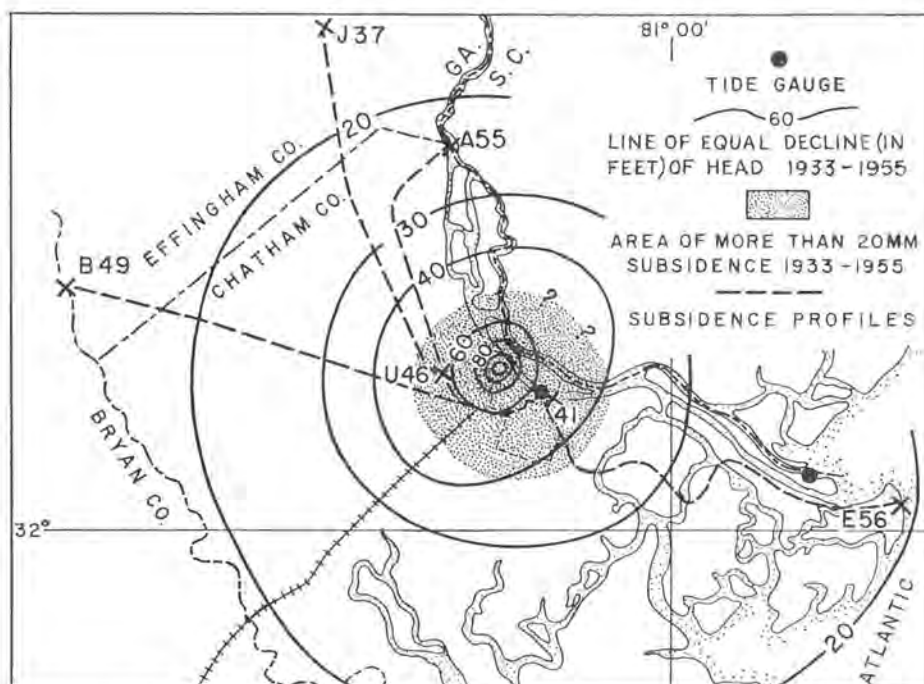


Figure 25. Decline of artesian pressure and subsidence, 1933-1955, Savannah area, Georgia. (After Davis and others, 1963.)

aquifer at Savannah, in which the pressure has declined, is a limestone sequence. The aquifer ranges in age from middle Eocene to Miocene and includes the Gosport Sand (middle Eocene), the Ocala Limestone (late Eocene), undifferentiated limestone of Oligocene age, and the Tampa Limestone (early Miocene). The Ocala Limestone makes up substantially more than half of the sequence. The principal aquifer is confined below by marl and limestone of the Lisbon Formation (middle Eocene) and above by silty deposits of the Hawthorn Formation (Miocene); it consists chiefly of soft, granular, commonly highly porous limestone but includes also beds of sand, marl, and sandy, clayey, cherty, and dolomitic limestone.

Davis and others (1963) concluded that the subsidence is due to compaction of the principal artesian aquifer in response to decline in artesian pressure and that the compaction probably occurs chiefly in the soft limestone and in the interbedded clay and marl, which may be highly compressible. The ratio of subsidence to decline in head has been about 1 to 300, that is, about 100 mm subsidence to 100 feet of head decline.

HOUSTON-GALVESTON AREA, TEXAS

Land subsidence due to withdrawal of ground water and petroleum has been known in the upper Gulf Coast area of Texas for many years. The subsidence of the Goose Creek oil field on Galveston Bay was reported as early as 1926 and

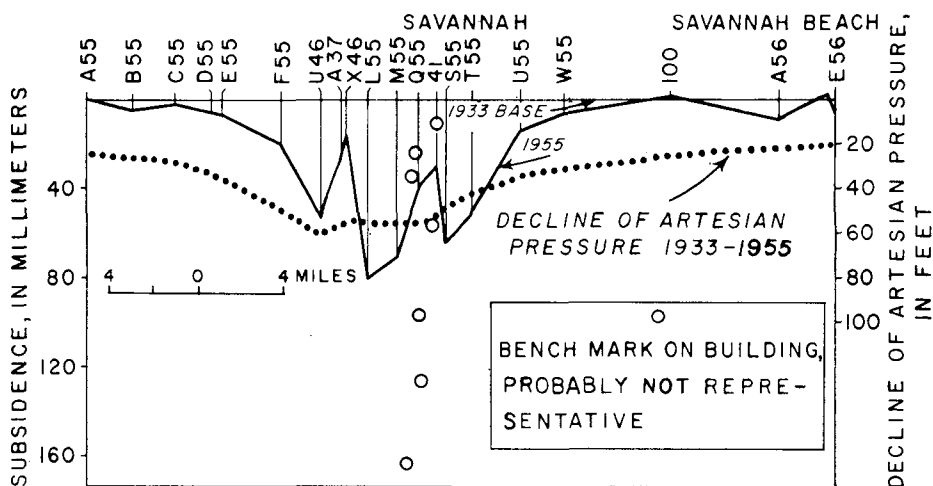


Figure 26. Profile of land subsidence and decline of artesian pressure, 1933-1955, Savannah area, Georgia. (After Davis and others, 1963.)

has been discussed previously in this paper. Winslow and Doyel (1954) in a paper given before the American Society of Civil Engineers reported on additional leveling results and suggested means for alleviating the subsidence in the Houston area. Winslow and Wood (1959) described subsidence throughout an area of 7200 square miles of coastal Texas, including Houston, that extends from Freeport to Port Arthur and 90 miles inland. The following summary has been prepared from those papers.

Geology. The upper Gulf Coast of Texas is underlain by unconsolidated sand and clay strata of Tertiary and Quaternary age that dip and generally thicken toward the Gulf. Accordingly, the strata crop out in bands that parallel the coast; inland they contain fresh water, but most contain salt water within a short distance of the shore. From the top down, the units penetrated by water wells are: the Beaumont Clay (Pleistocene), which ranges in thickness from zero a few miles northwest of Houston to 900 feet at Galveston and includes the Alta Loma Sand of Rose (1943), about 250 feet thick at Galveston; the Lissie Formation (Pleistocene), which thickens from 900 feet at Houston to 1500 feet at Galveston; the Willis Sand (Pliocene[?]), which thickens from 500 feet at Houston to 700 feet at Galveston; the Goliad Sand (Pliocene); and the Lagarto Clay (Miocene[?]).

The Beaumont Clay is the principal confining bed at and coastward from Houston. Although the Beaumont consists largely of calcareous clay, it includes a few beds of fine sand which are the principal water-yielding units at Texas City and in the Beaumont-Port Arthur area. The Alta Loma Sand (Rose, 1943) is the principal aquifer at Galveston, and the Lissie and Willis form the principal aquifer at Houston where they have a combined thickness of 2200 feet.

A recent X-ray diffraction study of the clay-size fraction of fine-grained samples from a core hole at Clear Lake, Harris County, indicates a clay-mineral assemblage of montmorillonite, illite, chlorite, and kaolinite. Montmorillonite is



SUBSIDENCE, 1928-1962, OF LONG BEACH AREA, CALIFORNIA

The subsidence in upper right is due to fluid withdrawal from Long Beach (Signal Hill) oil field. The major subsidence in foreground is due to withdrawal from Wilmington oil field. (Photograph and lines of equal subsidence, in feet, courtesy of Long Beach Harbor Department)



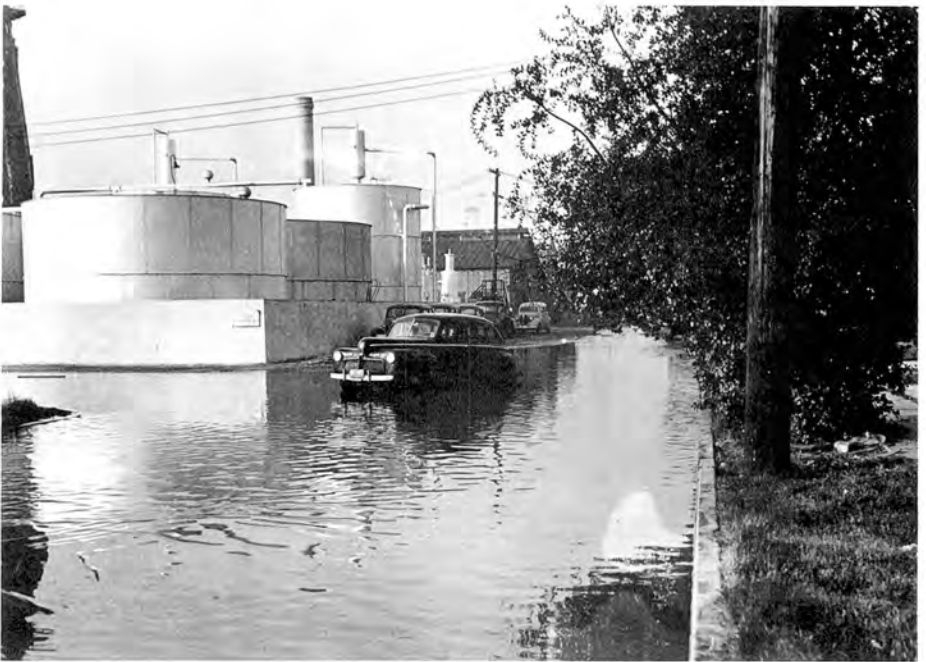
FAILURE OF SURFACE STRUCTURES

A shows lift bridge damaged by horizontal movements. *B* shows sheared bridge columns.
(Photographs by Long Beach Harbor Department)



FAILURE OF SURFACE STRUCTURES

A shows buckled railroad track. *B* shows buckled pipe line. (Photographs by Long Beach Harbor Department)



FLOODING BY THE OCEAN
A shows municipal wharf awash at high tide. *B* shows flooding of streets by tidewater.
(Photographs by Long Beach Harbor Department)



REMEDIAL MEASURES TO KEEP SEA FROM SUBSIDING LANDS

A shows waterfront at drydock No. 1, looking northeast past retaining wall; Long Beach Naval Shipyard; and, in middle distance, Southern California Edison Company steamplant, which is at center of subsidence. B shows southeast corner of Naval Shipyard. Note oil wells in distance; Long Beach levee, Pier E; concrete retaining wall restraining ocean waters; and working level of shipyard in foreground. (*Photographs by U. S. Navy*)

POLAND AND DAVIS, PLATE 5

Geological Society of America

Reviews in Engineering Geology II



PROTRUSION OF TWO WELL CASINGS IN NORTHERN PART OF MEXICO CITY, MEXICO

Wells were drilled about 1923, probably 100 m deep, and pictures were taken in 1954. Casing to left protrudes 5.45 m; casing to right protrudes 4.50 m. (*Pictures courtesy Ing. R. Marsal*)



PROTRUDING WELL CASINGS IN LAS VEGAS, NEVADA

A shows Well 4 at north end of Las Vegas Valley Water District well field. Note that part of the concrete foundation has remained fixed to well casing as the land surface subsided. B shows west tank well in North Las Vegas; protrusion is about 27 inches plus 9 inches that has been cut off. (Total about 3 feet). (*Photographs by U. S. Geological Survey, February 7, 1963*)

POLAND AND DAVIS, PLATE 7

Geological Society of America

Reviews in Engineering Geology II

the principal constituent (Corliss and Meade, 1964). The eight cores were taken from an 800-foot section of the Beaumont Clay and the upper part of the Lissie Formation.

Hydrology. Most supplies of industrial, municipal, and irrigation water in the upper Gulf Coast area are drawn from ground water. The pumpage as of 1956 was 200 million gallons per day in the Houston-Baytown district, 23 million gallons per day in the Texas City-Galveston district, and 6 million gallons per day at Freeport. Large additional unestimated withdrawals were made for irrigation.

The heavy pumping has resulted in substantial regional decline of artesian head and very large drawdown cones around the centers of pumping; for example, at Houston, where the head originally was about 65–75 feet above sea level, it had been reduced to as low as 260 feet below sea level in 1961 (Anders and Naftel, 1962, Fig. 12). As much as 100 feet of the decline occurred between 1943 and 1951. Winslow and Wood (1959) reported that the head in the Alta Loma at Galveston had declined 150 feet since 1898.

Land subsidence. The long-continued decline in artesian head has resulted in subsidence of the land surface throughout much of the upper Gulf Coast of Texas. Interest in the problem became active when leveling by the U. S. Coast and Geodetic Survey in 1951 indicated as much as 1.35 feet of subsidence at Houston since 1943. Lockwood (1954) reported that the maximum subsidence in the Houston district was 3.25 feet as of 1953 at Pasadena and that the greatest subsidence in the upper Gulf Coast area was at Texas City where subsidence was on the order of 4 feet as of 1954.

The entire level network of the U. S. Coast and Geodetic Survey in the upper Gulf Coast was readjusted in 1957, including leveling of 1905–1906, 1918, 1932–1933, 1935–1936, 1942–1943, 1951, and 1953–1954. This is the basis for subsidence shown in Figures 27 and 28 which are reproduced from Winslow and Wood (1959). Leveling by the U. S. Coast and Geodetic Survey indicates that maximum subsidence from 1905 to 1954 at a bench mark in Houston was 2.7 feet (Fig. 28); however, this probably is far less than the actual maximum because as shown on Figure 27, there was as much as 2.5 feet of subsidence at Houston between 1943 and 1954. Releveling in 1958–1959 indicates an additional foot of subsidence in the Pasadena-Baytown area since 1954 (Anders and Naftel, 1962, p. 24; *see also* Small, 1960, Figs. 5, 14). Maximum subsidence determined by the 1958–1959 releveling was 3.9 feet about 12 miles east of Houston (Small, 1963, p. 4).

Interpretation of subsidence in the Texas Gulf Coast is complicated somewhat by the effects of oil production at salt-dome oil fields. For example, Winslow and Doyel (1954) noted that the greatest subsidence in the Houston area was at South Houston where production of oil and gas has resulted in a pressure decline in the producing zone equivalent to a decline of 820 feet in artesian head. Presumably, at least part of the subsidence there is due to production of oil and gas.

The sharpest land-surface declines in the upper Gulf Coast area have been reported from the Texas City-Galveston area (*see* Figs. 27, 28). Private leveling reported by Lockwood (1954) indicated as much as 4 feet of subsidence at Texas City. The maximum at bench marks of the U. S. Coast and Geodetic

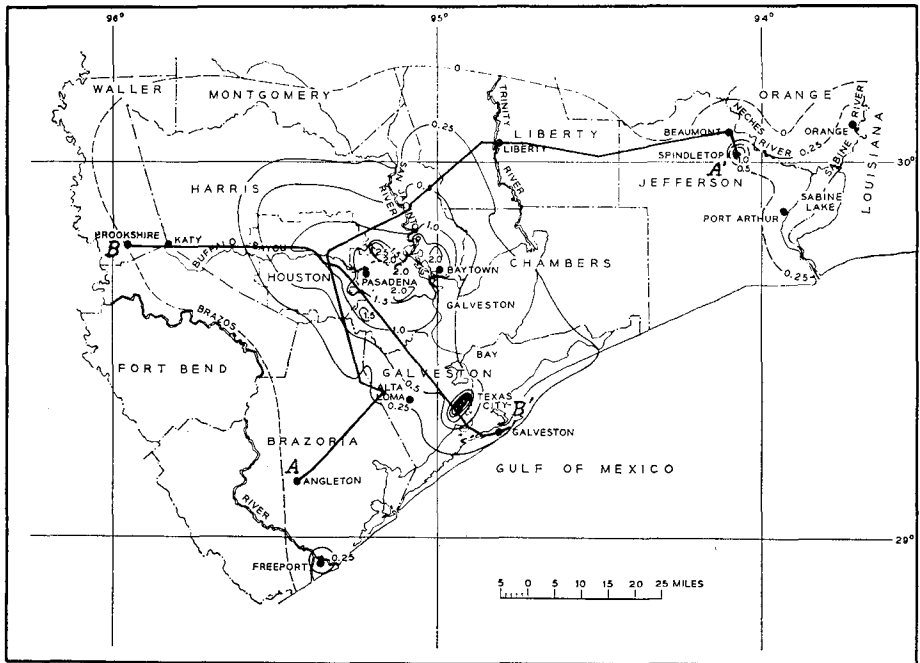


Figure 27. Subsidence, in feet, 1943-1954, of the land surface in upper Gulf Coast area, Texas. Subsidence shown in east part of area is for 1918-1955. (Modified from Winslow and Wood, 1959, Fig. 3; published with permission of the Society of Mining Engineers.)

Survey from 1943 to 1951 was 2.64 feet. The readjustment of 1957 indicated a maximum at Texas City of 3.5 feet between 1905 and 1954 along the U. S. Coast and Geodetic Survey level line.

Comparison of leveling of 1918 and 1955 indicated more than 0.25 foot of subsidence throughout much of the Beaumont-Port Arthur-Orange area with a localized maximum of about 1 foot near the Spindletop oil field.

At Freeport, subsidence of as much as 0.5 foot occurred from 1943 to 1951, presumably due to concentrated withdrawal of ground water from shallow sands for industrial use.

Relationship of decline in head and pumpage to subsidence. Comparison of decline in artesian pressure and subsidence shown on Figure 29 indicates a ratio of about 1 foot of subsidence to 100 feet of head decline. The consistency of the ratio indicates that the compaction (consolidation) characteristics of the deposits tapped by all four wells are equal. This is remarkable, considering that well 326 is 25 miles updip from well B-40 and taps older deposits. In the Texas City-Galveston area, where fine materials make up a greater part of the section, the ratio would be larger.

A comparison of the volume of land subsidence in the Houston-Baytown district for 1943-1951 with pumpage during the same period indicates that approximately 22 per cent of the 114×10^{10} gallons of water pumped was yielded by compaction of the sediments (Winslow and Wood, 1959, p. 1034).

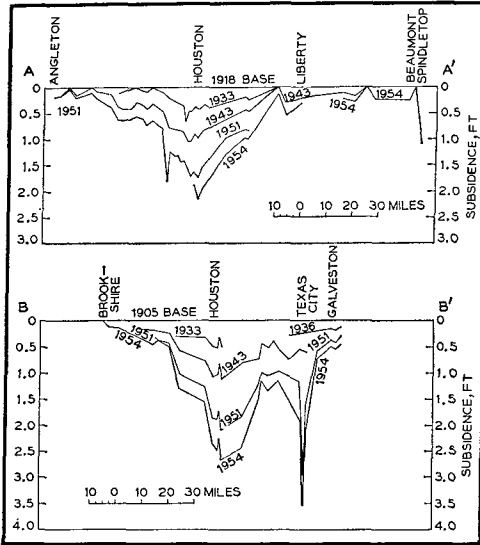


Figure 28. Profiles of land-surface subsidence in upper Gulf Coast area, Texas. Location of profiles shown on Figure 27. (After Winslow and Wood, 1959, Fig. 2; published with permission of the Society of Mining Engineers.)

tap three principal water-bearing zones: (1) an upper unit of alluvial deposits as much as 2500 feet thick; (2) a middle unit (the Laramie Formation) of Late Cretaceous age consisting of 200–500 feet of brackish-water deposits, chiefly silty shale, coal, and silty sandstone; and (3) marine deposits (the Fox Hills Sandstone) of Late Cretaceous age consisting of sandstone, shale, siltstone, and a little coal.

The first artesian wells were drilled at Denver in 1883; by 1896, 400 artesian wells were in use. By 1890, the head had decreased to a point where most artesian wells ceased flowing. In 1960, about 3000 artesian wells were in use in the Denver artesian basin; the pumpage ranged from 20 to 50 million gallons per day from 1951 to 1961. Chase (1962, written commun.) estimated the total withdrawal since 1883 at about 300 billion gallons or 900,000 acre-feet.

Lohman (1961, p. B48) computed the subsidence in the Denver metropolitan area, due to the *elastic* compression of the artesian aquifer system, to be about 0.25 foot. The total subsidence includes permanent compaction of the associated clay beds which in most areas of major subsidence is much larger than the elastic compression.

ELOY-PICACHO AREA, ARIZONA

Robinson and Peterson (1962) reported land subsidence of as much as 3.6 feet due to withdrawal of ground water in the Eloy-Picacho area about 50 miles northwest of Tucson, Arizona.

Precise leveling by the U. S. Coast and Geodetic Survey in 1905, 1934, 1948–1949, 1952, and 1960 indicates a maximum cumulative subsidence of 3.6 feet along

DENVER, COLORADO

Preliminary results of the investigations in the Denver artesian basin, Colorado (G. H. Chase, U. S. Geological Survey, January 1962, written commun.) indicate that as much as $1\frac{1}{4}$ feet of land subsidence has taken place near Denver.

Precise leveling by the U. S. Coast and Geodetic Survey in 1899–1903, 1929, 1938–1939, and 1954–1956 indicates subsidence of almost 1 foot in an area of sharp decline of artesian head centering on Denver and extending about 10 miles out from Denver. Within this area, the artesian head has declined as much as 600 feet since 1890.

Artesian aquifers underlie about 6000 square miles of the Denver artesian basin and extend to depths as great as 2500 feet. Artesian wells

a level line that parallels the main line of the Southern Pacific Railroad. Almost all the subsidence has occurred since 1934 and has been most widespread and rapid in the period 1952–1960. As of 1960, cumulative subsidence in excess of 2 feet had occurred along 8 miles of level lines centering at Eloy.

In the Eloy-Picacho area, unconsolidated alluvial deposits occur to a depth of 500–600 feet and are underlain by fine-grained sediments—locally called lake-bed sediments—that are as much as 800 feet thick; the fine-grained deposits are underlain by coarse materials. The older wells were 500–700 feet deep and tapped the upper alluvial deposits. Beginning about 1952, wells were drilled into or through the fine-grained sediments to depths of as much as 2000 feet.

Intensive pumpage of ground water for irrigation began in 1936. In 1937, the pumpage was 64,000 acre-feet and increased rapidly during and after World War II to 360,000 acre-feet in 1948; it totaled 300,000 acre-feet in 1952 and 330,000 acre-feet in 1960. This intensive pumpage has resulted in a general decline of water levels in wells of 100–200 feet below the head prior to development.

A definite relationship of subsidence to decline in head is indicated by the fact that (1) there was virtually no subsidence in the period 1905–1934 before pumping of ground water for irrigation began, and (2) the point of maximum subsidence has shifted southeastward in each leveling since 1948–1949, which is in agreement with a similar shift in the center of the pumping depression (Robinson and Peterson, 1962).

As stated, subsidence was negligible in the period 1905–1934 and probably for several years after 1934. The leveling of 1948–1949 indicated maximum subsidence since 1934 of 0.4 foot about $2\frac{1}{2}$ miles northwest of Eloy. The maximum for the period 1948–1949 to 1952 was 1.3 feet at a bench mark about 1 mile northwest of Eloy. By 1960, the point of maximum subsidence had shifted to 2 miles southeast of Eloy where slightly more than 3 feet of settlement was recorded for the period 1952–1960.

Numerous linear open fissures or earth cracks have been observed around the margins of the Eloy-Picacho area, and some workers (*see* Heindl and Feth, 1955) have suggested a relationship of the cracks to subsidence of the valley fill. Fissuring was observed, however, as early as 1927, some years before the beginning of pumping for irrigation (Robinson and Peterson, 1962, p. 4) and at least a decade before the beginning of substantial land subsidence in the valley as

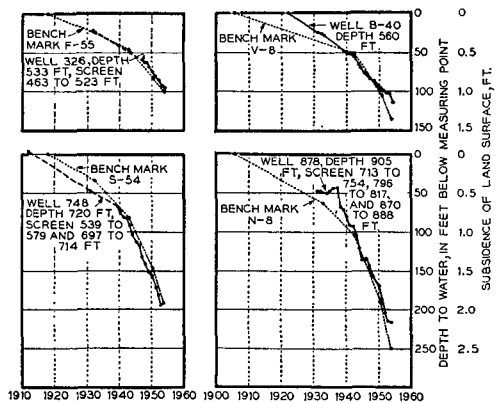


Figure 29. Subsidence of bench marks compared with decline of artesian pressure in nearby wells, upper Gulf Coast area, Texas. (After Winslow and Wood, 1959, Fig. 5; published with permission of the Society of Mining Engineers.)

indicated by precise leveling. Accordingly, the relationship of fissuring to land subsidence is somewhat tenuous. Moreover, Robinson and Peterson (1962) noted that the trend and location of the fissures conforms generally to Bouguer anomaly highs mapped in a gravity survey of the area, which suggests structural control of the fissuring.

LAS VEGAS, NEVADA

Subsidence due to withdrawal of ground water in the Las Vegas area was first reported by Maxey and Jameson (1948, p. 70) who noted that comparison of leveling of 1915 with that of 1935, both by the U. S. Coast and Geodetic Survey, indicated settlement of as much as 3 inches at Las Vegas. Leveling in 1940–1941 as control to determine the effects of loading by the water of Lake Mead, impounded by Hoover Dam, was reported on by Carder and Small (1948). This leveling indicated an additional 3 inches of subsidence at Las Vegas during the period 1935 to 1940–1941.

Longwell (1960), as part of a comprehensive survey of Lake Mead, analyzed and interpreted leveling done near the Lake in 1935, 1940–1941, and 1949–1950. He noted a broad basinlike subsidence centered on Lake Mead, which had a closure of 70 mm in the period 1940–1941 to 1949–1950; he attributed this to loading by the water of the Lake. He also noted a regional tilt to the southwest in the period 1940–1941 to 1949–1950 that affected the entire Lake Mead-Las Vegas area. Superimposed on the wider pattern of change was a sharply localized subsidence at Las Vegas which Longwell ascribed to withdrawal of artesian water. The maximum subsidence at Las Vegas recorded from 1935 to 1940–1941 was 100 mm; the maximum for the period 1935 to 1949–1950 was 350 mm.

G. T. Malmberg (1962, unpub. U. S. Geol. Survey open-file rept., Available water supply of the Las Vegas ground-water basin, Nevada) has prepared profiles across the Las Vegas Valley, which differentiate the local subsidence due to decline of artesian pressure from the broader effects due to loading by Lake Mead and the regional tilt. One of these profiles is reproduced as Figure 30.

In the area of sharp subsidence near Las Vegas, much of the production of ground water is from aquifers in alluvial deposits of late Tertiary and Quaternary age confined beneath an extensive blue clay that is believed to be of lacustrine origin (Maxey and Jameson, 1948, p. 68). Substantial decline of artesian head has been noted in the deep aquifers. The maximum subsidence along the line of profile in Las Vegas was about 300 mm, of which almost two-thirds was ascribed to effects of ground-water withdrawal.

In 1963, the U. S. Coast and Geodetic Survey releveled part of the net of first-order level lines surrounding Lake Mead, at the request of the U. S. Bureau of Reclamation. The unadjusted field results of this releveled indicated that maximum subsidence of bench marks at Las Vegas had increased 1.3 feet since 1950 and 2.2 feet (660 mm) since 1935 (Small, 1963, p. 4). These bench marks are about 1.5 miles from the heaviest withdrawal; therefore, it is to be expected that maximum subsidence in the well field has been greater than 2.2 feet since 1935.

Protrusion of casings as much as 3 feet above the land surface has been observed (*see* Pl. 7).

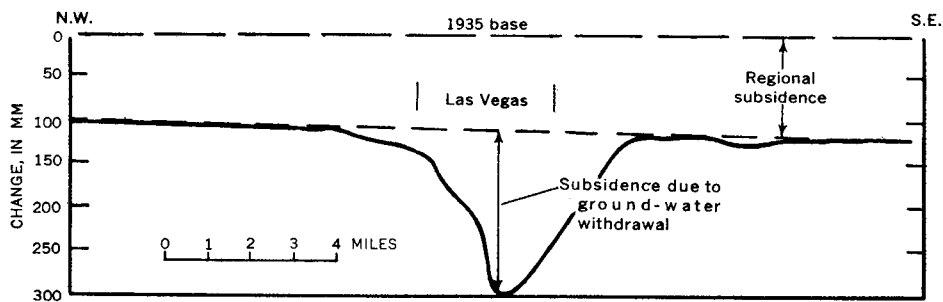


Figure 30. Subsidence profile, 1935 to 1949-1950, showing local subsidence as differentiated from regional effects across Las Vegas Valley, Nevada. Area above dashed line represents regional effect and that below, the local subsidence. (After Malmberg, 1962, U. S. Geological Survey open-file report.)

AREAS IN CALIFORNIA

Introductory Comment

Development of ground water has been intensive in California. Most of the water is withdrawn for irrigation although ground water is also pumped extensively for domestic and industrial supply. In 1955, about 13 million acre-feet of ground water was pumped for irrigation from ground-water basins in California, slightly more than one-third of the total pumpage for irrigation in the United States.

The ground-water withdrawals in California are chiefly from intermontane basins in which the valley fill of late Tertiary and Quaternary age is chiefly alluvial deposits but also, in places, is of lacustrine and shallow marine origin. In many of the basins, the water bodies tapped are semiconfined or confined below depths ranging from 100 to 600 feet, and, thus, much of the withdrawal is from confined aquifer systems.

The intensive and long-continued pumping has drawn down water levels more than 100 feet in many of the basins—maximum drawdown of 400-500 feet has been on the west side and in the southern end of the San Joaquin Valley. Thus, in California, substantial lowering of water level has occurred in young, unconsolidated, compressible deposits that contain extensive semiconfined to confined aquifer systems. It is not surprising, therefore, that land subsidence due to ground-water withdrawal has developed in many areas. Subsidence in all areas shown on Figure 31, except for those in the Wilmington oil field and in the Sacramento-San Joaquin Delta, is due to ground-water withdrawal and decline of artesian head. Subsidence in most of these areas has been described briefly by Poland (1958). About 11,000 square miles (7 million acres) of land in California is irrigated, and nearly two-thirds of this is irrigated wholly or in part by ground water. Of this 11,000 square miles, at least 30 per cent has subsided 1 foot or more due to artesian-head decline. Doubtless, many other areas in addition to those shown on Figure 31 have subsided at least a few tenths of a foot, but leveling control is not available to define the magnitude and extent of subsidence in most of these.

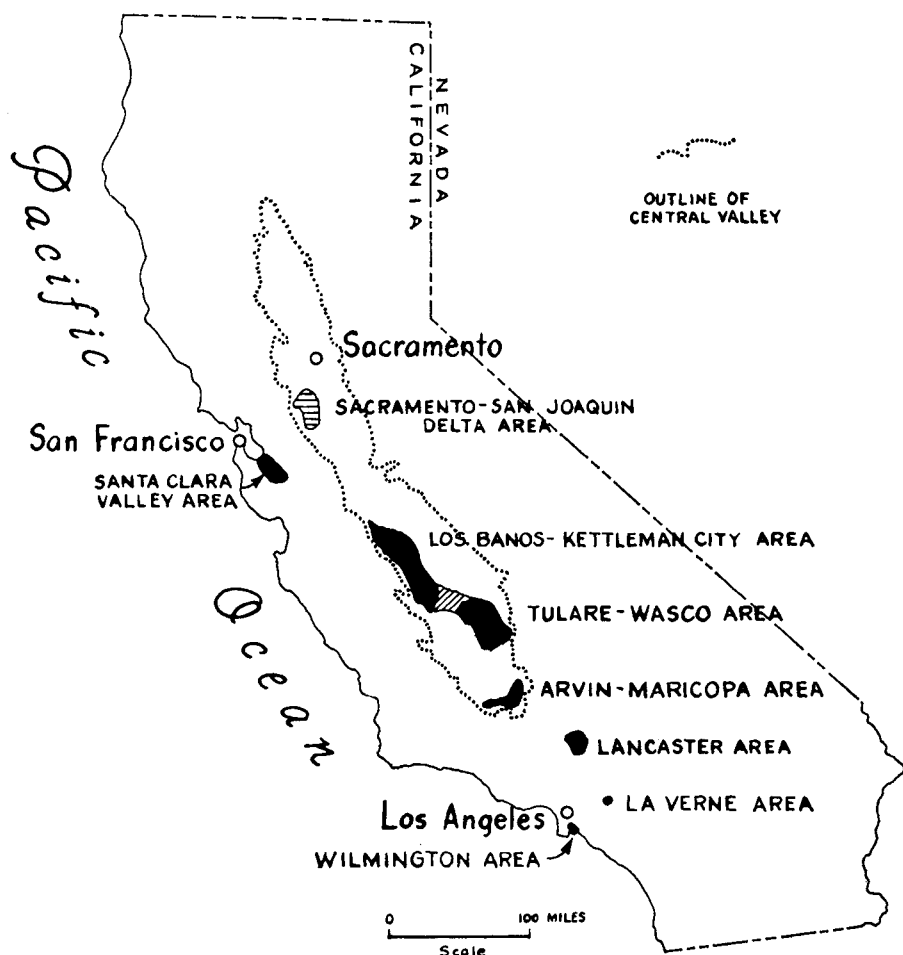


Figure 31. Areas of land subsidence in California. Major subsidence due to fluid withdrawal shown in black; subsidence in Delta caused by oxidation of peat.

The following description is limited to the major subsiding areas—in the San Joaquin Valley and the Santa Clara Valley south of San Francisco. The peat lands in the Sacramento-San Joaquin Delta have subsided as much as 15 feet in the last century as a result of drainage (lowering of the water table) for cultivation (Poland, 1958, p. 1774-1775). The primary cause of this subsidence, however, is oxidation of the peat (Weir, 1950), rather than compaction of an aquifer system due to increase in effective overburden load. The subsidence of peat lands is discussed by Alice Allen elsewhere in this Review Volume.

San Joaquin Valley

In the San Joaquin Valley, about 3000 square miles or 30 per cent of the valley floor is subsiding. The three principal subsiding areas are the Los Banos-Kettle-

man City area, the Tulare-Wasco area, and the Arvin-Maricopa area (Fig. 31). Maximum rates of subsidence in these areas range from 0.5 foot to 1.5 feet a year. Lands between the Los Banos-Kettleman City area and the Tulare-Wasco area are also subsiding but at a lesser rate. The areas of appreciable subsidence coincide generally with the areas in which ground water is withdrawn chiefly from confined aquifers (Fig. 32). No subsidence has been observed in areas where pumping is wholly from unconfined aquifers. In all of the subsiding areas, montmorillonite composes about 70 per cent of the clay-mineral assemblage and from 5 to 25 per cent of the sediments sampled (R. H. Meade, June 1963, written commun.).

Land subsidence in the San Joaquin Valley was first noted in 1935 when I. H. Althouse, a consulting engineer, called attention to the possibility of land subsidence near Delano (Ingerson, 1941, p. 40). The subsidence in the Delano (Tulare-Wasco) area was first described in print by Ingerson (1941, p. 40-42) who presented a map and profiles of land subsidence based on comparison of leveling of 1902, 1930, and 1940.

Releveling by the U. S. Coast and Geodetic Survey in 1943 of bench marks established in 1935 in the Los Banos-Kettleman City area indicated subsidence of as much as 3 feet. Nevertheless, this subsidence did not cause serious concern until after completion of the Delta-Mendota Canal by the U. S. Bureau of Reclamation in 1951. This large canal, which transports exchange water from the Sacramento-San Joaquin Delta to the San Joaquin River, has been subject to as much as 5.2 feet of differential subsidence from 1953 to 1963. Shortly after completion of the canal, it became evident that should land subsidence continue unabated, the canal soon would require remedial work in affected areas.

Because of the threat to the Delta-Mendota Canal and in order to assist in planning other major canals and engineering works that were proposed for construction in the subsiding areas, an "Inter-Agency Committee on Land Subsidence in the San Joaquin Valley" composed of interested federal, state, and private agencies was formed in December 1954 to plan and co-ordinate studies of subsidence. As one result of the interagency planning, an intensive investigation of land subsidence in the San Joaquin Valley was begun by the U. S. Geological Survey in 1956 in cooperation with the California Department of Water Resources. The objectives were to determine extent, rate, and causes of the subsidence; to develop criteria for estimating subsidence; and to suggest methods for alleviation or control.

These areas of active and substantial land subsidence offer an unexcelled opportunity to study the compaction of sediments. Not only are the aquifer systems compacting at a rate that is susceptible to field measurement, but, equally important, the forces causing this compaction can be determined quantitatively in much of the subsiding area. For this reason, the Geological Survey in 1956 began a companion Federally financed research project directed toward determining the principles controlling the deformation (compaction or expansion) of aquifer systems resulting from change in grain-to-grain load, caused chiefly by change in internal fluid pressure.

The summary of subsidence in the San Joaquin Valley presented here has

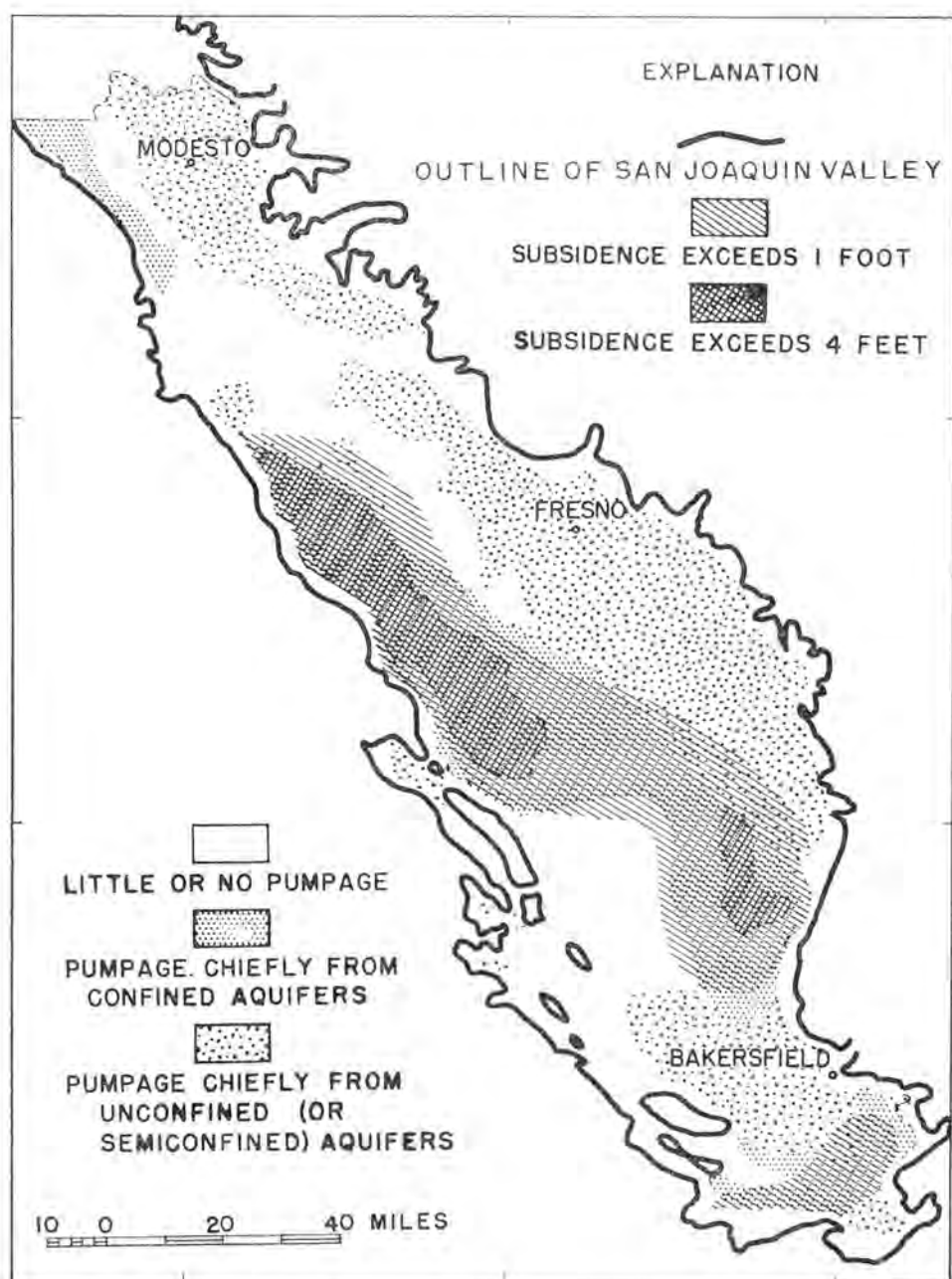


Figure 32. Relationship of subsidence to ground-water occurrence and pumping draft, 1957, in San Joaquin Valley, California.

drawn information from all of these investigations and from the releveling of the U. S. Coast and Geodetic Survey.

Subsidence in the two principal areas, the Los Banos-Kettleman City and Tulare-Wasco areas, was described briefly by Poland and Davis (1956) and more completely in a progress report by the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley (1958); both reports concluded that the decline of artesian head is a major cause of the subsidence. In a small part of the Los Banos-Kettleman City area and in part of the Arvin-Maricopa area, near-surface subsidence or hydrocompaction due to wetting of moisture-deficient deposits above the water table is an important contributor to total subsidence. This type of land subsidence due to the application of water is described by B. E. Lofgren elsewhere in this Review Volume.

Los Banos-Kettleman City Area. This area is of major importance in a discussion of subsidence in the San Joaquin Valley.

Geology: The Los Banos-Kettleman City area of 1500 square miles includes the western slope of the San Joaquin Valley extending from Los Banos in Merced County southeasterly 90 miles to the dry bed of Tulare Lake in Kings County near Kettleman City (*see* Fig. 33). The eastern boundary is the trough of the valley, marked by the San Joaquin River, Fresno Slough, and the Kings River. Fresh-water-bearing deposits tapped by wells in this area are unconsolidated, are of Recent to Pliocene age, and extend to depths ranging from 900 to more than 3000 feet below land surface. They can be divided into three units: (1) an upper unit of silt, clay, sand, and minor amounts of sandy gravel, chiefly alluvial-fan deposits, that extends to depths of 200–800 feet; (2) a relatively impervious diatomaceous clay of lacustrine origin, the Corcoran Clay Member of the Tulare Formation (Pliocene and Pleistocene), that ranges from a featheredge to 120 feet thick and underlies almost all the area; and (3) a lower unit of silt, clay, sand, and minor amounts of sandy gravel, chiefly alluvial-fan deposits but including some strata of lacustrine origin. This lower fresh-water-bearing unit commonly is 600–1500 feet thick but locally is as much as 3000 feet thick; it is underlain by brackish or saline water. The one consistent and outstanding feature of the mineralogy of the deposits, as revealed by detailed petrographic examination of core samples, is that the predominant clay mineral is montmorillonite (Meade, 1961, p. D-89).

Hydrology: A body of semiconfined water occupies most of the upper unit; the depth to water in this upper water-bearing zone ranges from 10 to 300 feet below the land surface. The ground water in the lower unit is confined by the Corcoran Clay Member of the Tulare Formation and, hence, is under artesian pressure.

Ground water pumped from some 1500 irrigation wells is the chief supply for irrigation in the area. Development of ground water for irrigation began during World War I and increased at a modest rate during the 1920's and 1930's; however, during and following World War II, annual pumpage for irrigation in the part of this area south of the Fresno-Merced County line (Fig. 33) increased almost fivefold, from 280,000 acre-feet in 1941 to 1,300,000 acre-feet in 1959.

Most of the ground water pumped is from the confined aquifer system of the

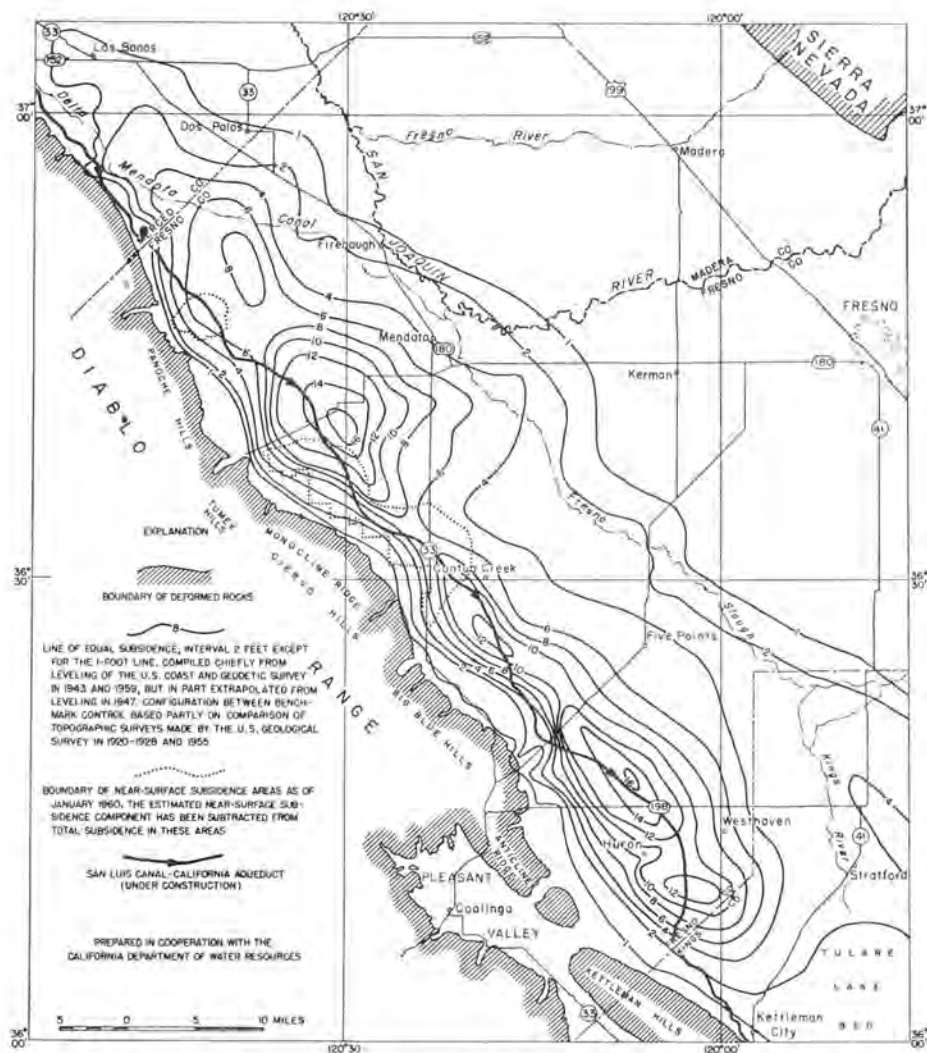


Figure 33. Land subsidence due to artesian-head decline, 1943-1959, Los Banos-Kettleman City area, California. (Base from U. S. Geological Survey Central Valley map, 1:250,000-1958; compiled by W. B. Bull.)

lower zone. Because of the intensive pumpage and small recharge, the artesian head in this lower zone has been reduced more than 100 feet in an area of about 1400 square miles in the past 40 years, and as much as 400 feet locally. The water table in the upper zone has not changed greatly from its initial position, although during the past few years the water table has risen in parts of the area where irrigation return is greatest. On the other hand, in the lower part of the upper zone, the head in confined aquifers has been drawn down as much as 100-200 feet at some places.

Land subsidence: Leveling by the U. S. Coast and Geodetic Survey in the Los Banos-Kettleman City area was begun in 1933 and was followed by releveing and new leveling at several periods to 1955 when a network of level lines was established to define the extent and rate of subsidence. This network was releveled in 1957-1958, 1959-1960, and 1963. This leveling is the basis for the subsidence from 1943 to 1959 shown on Figure 33 and from 1955 to 1957 (about 26 months) shown on Figure 34. The subsidence shown on Figure 33 represents that part resulting from compaction of the aquifer systems below the water table. The estimated near-surface subsidence component (the hydrocompaction above the water table; see paper by Lofgren in this Review Volume) has been subtracted from total subsidence in the pertinent areas. On the other hand, the near-surface subsidence component has not been subtracted from total subsidence shown on Figure 34 (1955-1957). Maximum subsidence from 1943 to 1959 (Fig. 33) was 16 feet, southwest of Mendota in the north and near Huron to the south.

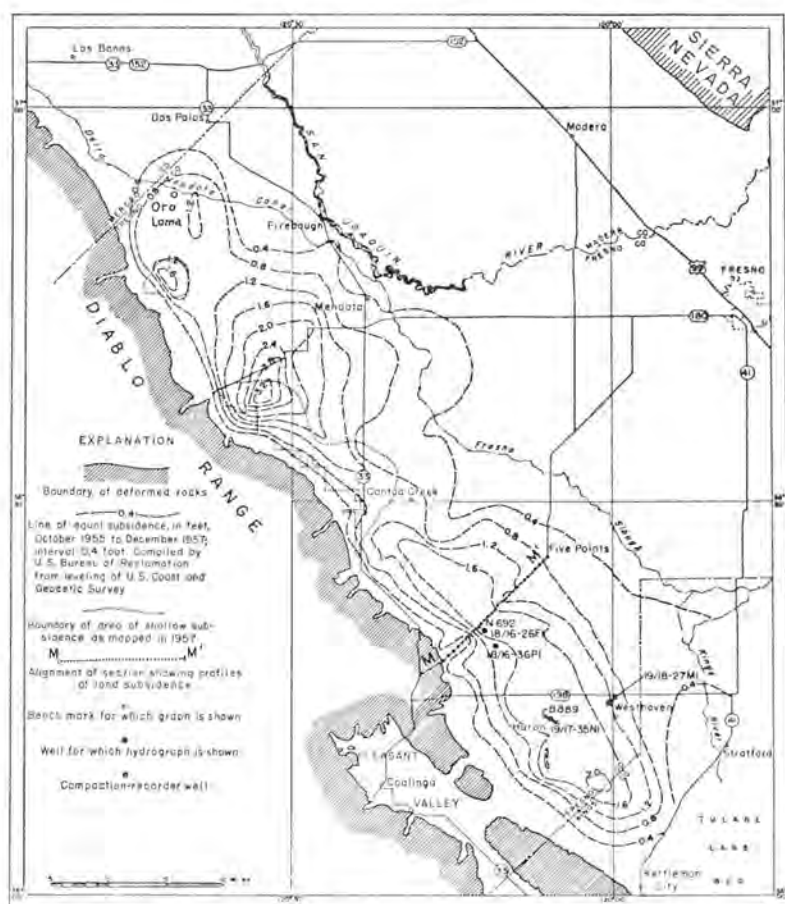


Figure 34. Land subsidence, 1955-1957, in Los Banos-Kettleman City area, California.

As of February 1963, maximum subsidence was 23 feet, southwest of Mendota, based on change in elevation of the land surface since the early topographic mapping of 1922–1932. Since 1955, the maximum rate of subsidence has been about 1.5 feet per year.

The joint San Luis Canal of the U. S. Bureau of Reclamation and California Aqueduct of the State is now under construction; it will have a design capacity of 13,100 cfs at the head, at San Luis Dam west of Los Banos, decreasing to 7000 cfs at Kettleman City. This canal will pass through about 70 miles of the subsiding ground, roughly along the center of the subsidence trough (*see* Fig. 33). The construction gradient of the canal is about 0.2 foot per mile. Thus, rapid land subsidence poses serious problems in construction and maintenance of this great canal.

Relationship of decline in head and pumpage to subsidence: The graph of the altitude of a bench mark southwest of Five Points and of the artesian head in two nearby wells (Fig. 35; for location *see* Fig. 34), is a typical illustration of the relationship of head decline to subsidence. The graph of subsidence agrees closely with the hydrograph at the 1 to 20 ratio of the plot. Before 1947, both graphs were relatively flat; after 1947, when intensive pumping began, both accelerated at about the same slope.

The ratio of subsidence to artesian head decline, which is a measure of the compressibility of the compacting deposits, ranges widely in the Los Banos–Kettleman City area—from 1:100 near the margins to 1:12 in the northern area of intensive subsidence west of Mendota.

The areal relationship of subsidence to artesian-head decline is demonstrated on Figure 36. Gross pumpage of ground water from 1943 to 1953 south of the Merced–Fresno County line has been estimated as 6.9 million acre-feet (Davis and Poland, 1957, p. 432). The net withdrawal of ground water (pumpage minus irrigation return) in this period is estimated to have been about 4 million acre-feet, and the volume of subsidence caused by compaction of the confined aquifer system in this same area was about 2 million acre-feet (Poland, 1960, p. 333). Thus, about one half the net withdrawal (water permanently withdrawn) represents water squeezed out of the aquifer system by compaction of the deposits. Most of the reduction in pore space would be permanent if the compaction is caused by consolidation of the silty clay interbeds and confining beds and is chiefly irreversible, as appears likely from several lines of evidence not here cited. If the artesian head was maintained at the 1953 position until subsidence had ceased, then restored to its 1943 position, and then drawn down in 10 years through the same decline that occurred from 1943 to 1953, additional compaction of these preconsolidated deposits should not be appreciable; thus, the water yielded would be about 2 million acre-feet less than that withdrawn in the 1943–1953 period. Studies evaluating water supply should consider this water yielded from compaction as a nonreplenishable resource.

Areal comparison of subsidence to change in artesian head is also illustrated on Figure 37. The slopes of the subsidence and head-decline profiles (drawn with a 1:17 vertical scale ratio) agree reasonably well except that the troughs of maximum subsidence are 2–3 miles east of the troughs of head decline. Both have

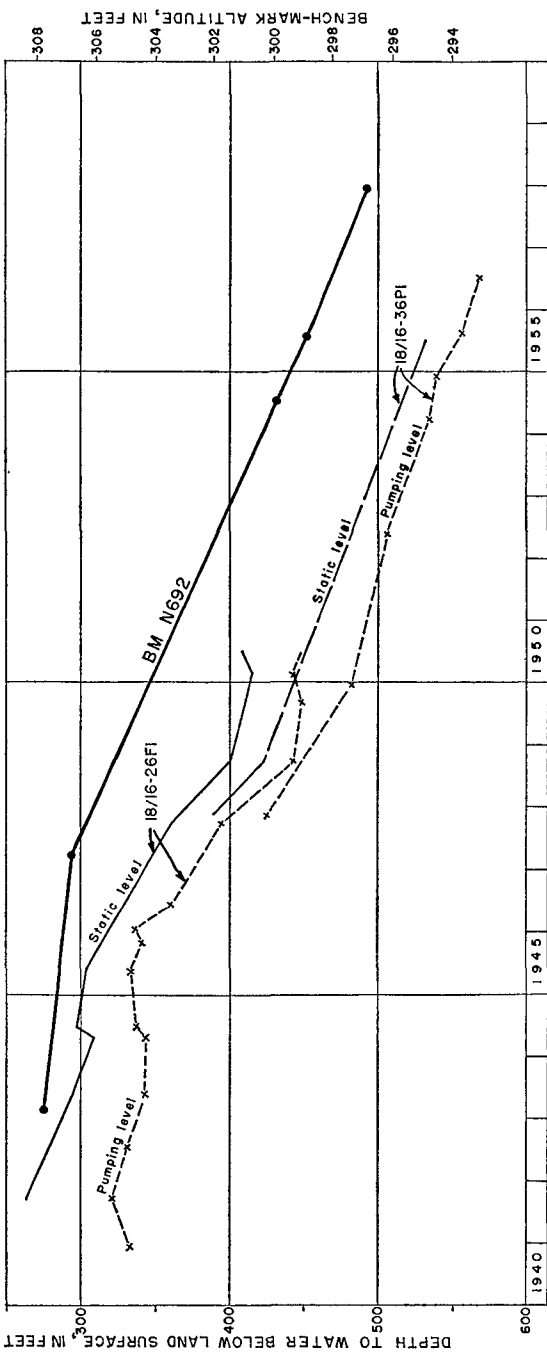


Figure 35. Change in altitude at bench mark southwest of Five Points, California, and change in artesian head in nearby wells. Location shown on Figure 34. (After Inter-Agency Committee, 1958, Pl. 42.)

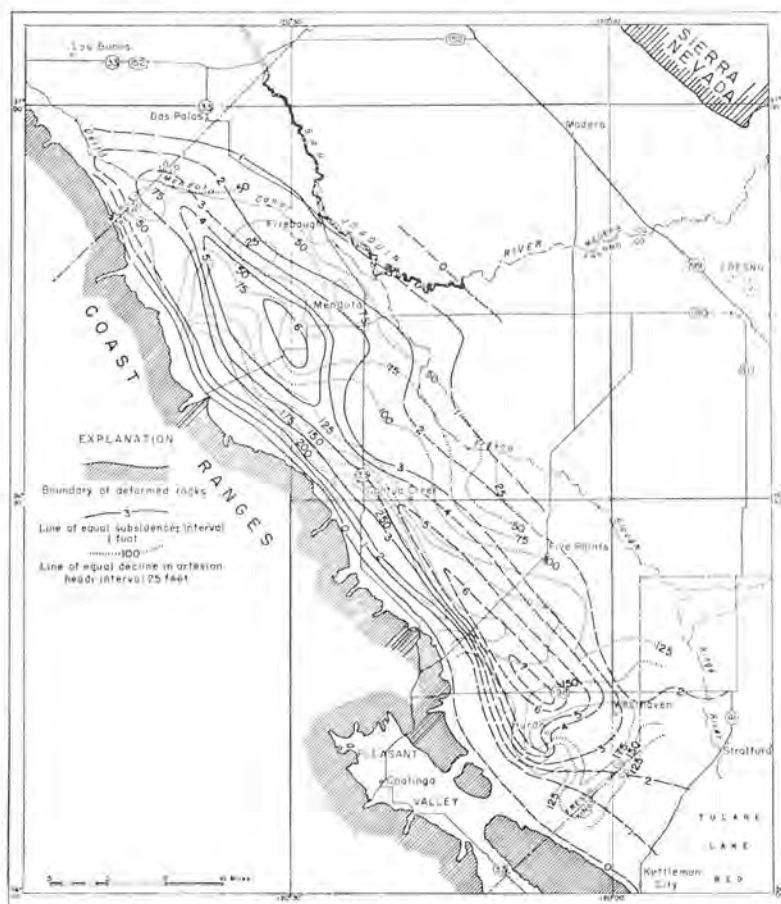


Figure 36. Map showing generalized land subsidence and decline in artesian head, 1943–1953, Los Banos-Kettleman City area, California. (After Inter-Agency Committee, 1958, Pl. 36.)

been migrating westward as the area of concentrated pumping has been extended toward the foothills. Characteristically, the subsidence tends to lag behind the artesian-head decline both in time and in its westward migration.

The total volume of subsidence within the 1-foot subsidence line of Figure 33 (1943–1959) is 5.2 million acre-feet (± 10 per cent). For the part of the Los Banos-Kettleman City area within Fresno and Kings Counties, the volume of subsidence from 1943 to 1959 was 4.5 million acre-feet; and the volume of ground water pumped was 15.7 million acre-feet (± 10 per cent). Thus, the volume of subsidence in the Fresno and Kings Counties part of the project area in the 17 years was equal to 29 per cent of the gross pumpage.

Using the compaction of the confined aquifer system in the Los Banos-Kettleman City area as an example, Poland (1961) evaluated the several components of the coefficient of storage. He demonstrated that in such an area, the component of the coefficient of storage derived from compaction of the clayey inter-

beds and confining beds may be 50 times as great as the components of the coefficient of storage due to water released by elastic expansion of the water and elastic compression of the aquifer.

Cause of subsidence: Comparison of subsidence of bench marks and decline of artesian head shows a close correspondence, both in areal extent and in time.

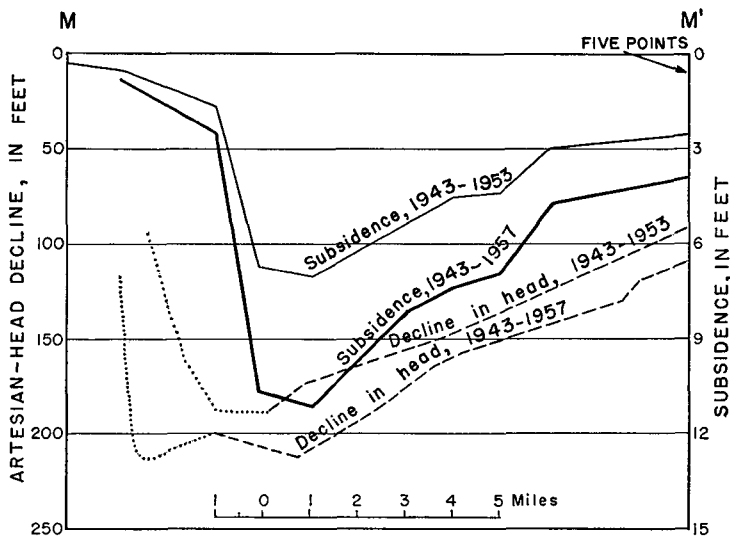


Figure 37. Profiles of land subsidence and decline in artesian head along Fresno-Coalinga road northeast to Five Points, California. Location of line M-M' shown on Figure 34.

The ratio of subsidence to decline of head, however, differs considerably, even locally. The causes of these differences appear to be chiefly geologic—such factors as differences in mineral composition, sorting, degree of consolidation, degree of cementation, and degree of confinement of the deposits. Moreover, the ratio of subsidence to decline in head is known to change with time. This effect appears to be due in part to time lag in compaction, which is related to slow movement of water out of fine-grained deposits of low permeability.

In order to find out how much of the subsidence is caused by compaction of the deposits tapped by water wells, the Geological Survey established depth bench marks and compaction recorders in several unused wells and cased core holes; Lofgren (1961) described the compaction-recorder installation (Fig. 38). The assembly consists of a heavy weight emplaced in the formation below the bottom of a well casing, with an attached cable extending to land surface and counterweighted to maintain constant tension. The amount of cable rising above the land surface as subsidence occurs is measured by a continuous recorder.

A compaction recorder of this type was installed in well 19/17-35N1, 2030 feet deep near Huron in 1955. Subsidence of nearby bench mark B 889 was determined by periodic leveling of the U. S. Coast and Geodetic Survey. Figure 39 shows the correlation between subsidence of the surface bench mark, vertical compaction within the well depth, and fluctuation of artesian

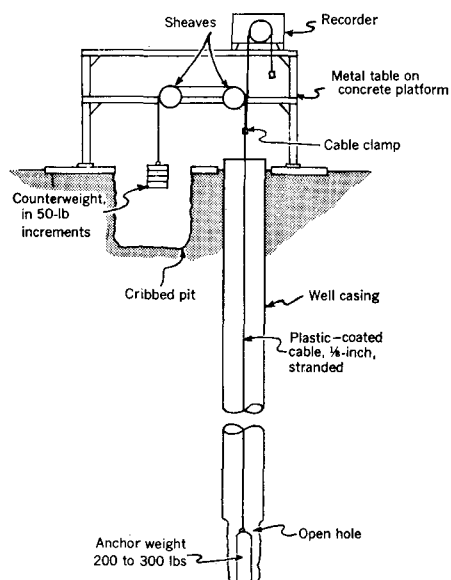


Figure 38. Diagram of compaction-recorder installation.

head in well 19/18-27M1 (for location, *see* Fig. 34). In the 4.8 years of record illustrated, measured compaction was 3.8 feet, subsidence of the land surface was 4.6 feet, and decline of artesian head was about 40 feet. The measured compaction equalled 82 per cent of the subsidence, suggesting that 18 per cent (0.8 foot) of compaction occurred below 2030 feet. This is reasonable because some nearby wells withdraw water from greater depth. Note that the compaction is seasonal and highly sensitive to change in effective stress as defined by change in artesian head. Compaction is greatest during periods of rapid decline of head; recovery of head results in a decrease or cessation of compaction.

In another compaction-recorder installation near Cantua Creek, the measured compaction in a 2000-foot core hole from February 1960 to March 1963 was 3.37 feet and the subsidence measured by leveling was 3.45 feet; thus, compaction to 2000 feet was 98 per cent of total subsidence. An intensively pumped irrigation well about 1/4 mile away is 2700 feet deep, suggesting that about 2 per cent of the subsidence may be caused by compaction of more consolidated deposits below 2000 feet. On the other hand, the instrumental accuracy of the compaction measurements probably is no better than 98 per cent. In any case, the subsidence near Cantua Creek has been demonstrated to be caused by compaction of deposits within the depth tapped by water wells. Tectonic activity is eliminated as a possible cause of appreciable subsidence at this place.

At several locations, compaction recorders have been installed in two or more closely spaced wells of different depths so that the compaction occurring in different depth intervals can be computed. For example, a triple installation at the Delta-Mendota Canal near Oro Loma (Fig. 40A) records compaction between land surface and depths of 350, 500, and 1000 feet. By comparing measurements of compaction from the several recorders, the magnitude and rate of compaction in each depth zone can be obtained. Figure 40B shows the measured compaction for two 1-year periods, converted to unit compaction per foot of thickness per year.

From November 1, 1961, to November 1, 1962, the depth zone 0-350 feet compacted 0.008 foot (0.23×10^{-4} feet/foot/year), the zone 350-500 feet compacted 0.008 foot (0.53×10^{-4} feet/foot/year), and the depth zone 500-1000 feet compacted 0.23 foot (4.6×10^{-4} feet/foot/year). The total compaction measured by the 1000-foot recorder in the year was 0.25 foot. About 92 per cent of this measured compaction occurred in the confined aquifer system below the Cor-

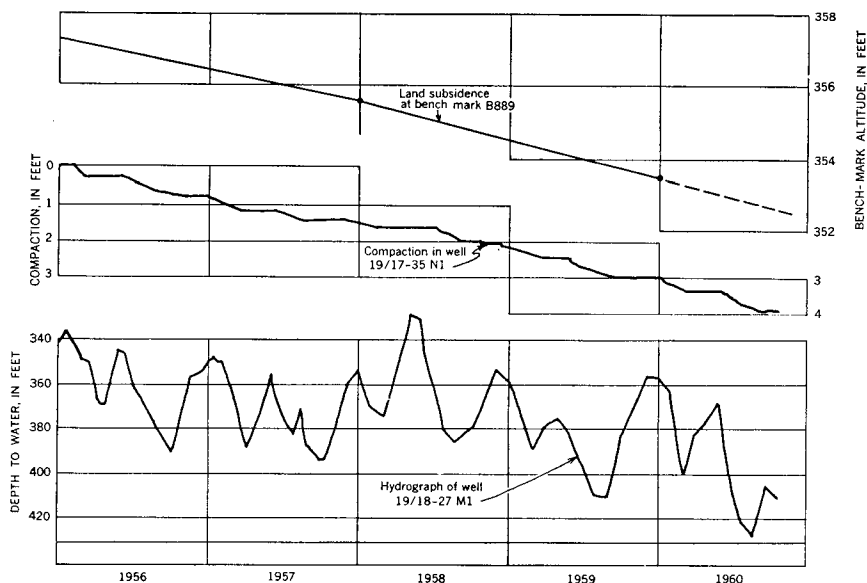


Figure 39. Graph showing measured subsidence, compaction, and water-level change near Huron, California. (After Lofgren, 1961, Fig. 24.2.)

coran Clay Member of the Tulare Formation; but the measured compaction equalled only about 70 per cent of the subsidence of a nearby surface bench mark in the same period; hence, 30 per cent of the subsidence was caused by compaction of deposits below the 1000-foot depth.

Results of one-dimensional consolidation tests made on core samples of the aquifer system and the observed decline in artesian head were utilized by Gibbs (1959) to compute compaction (and subsidence) occurring at the 1000-foot Oro Loma core hole (near well 16H2, Fig. 40A) and at several other core holes. By refining Gibbs' method, and based on more complete hydrologic data, Miller (1961) made a more detailed computation of compaction at the Oro Loma core hole. He computed that the compaction of the aquifer system below the Corcoran Clay Member of the Tulare Formation as of 1959, due to artesian-head decline between 1937 and 1959, was 7.5 feet, compared to land subsidence of 7.8 feet (by leveling). Residual computed compaction estimated to occur after 1959, attributed to slow decay of excess pore pressure in the thick confining clayey beds and thinner interbeds of low permeability, was 0.8 foot. He estimated that additional compaction of the overlying Corcoran Clay Member would continue at a rate of about 0.01 foot a year for many tens of years if the artesian head were stabilized at the 1959 level.

Tulare-Wasco Area. The Tulare-Wasco (Delano) area (Fig. 31) is on the east side of the San Joaquin Valley chiefly in Tulare County but extending into northern Kern County. Subsidence has been noted in an area 45 miles long by 30 miles wide. Before the construction of the Friant-Kern Canal by the U. S. Bureau of Reclamation, from which the first water was delivered in 1950, the

area was irrigated chiefly by ground water. Despite large imports of surface water since 1951, ground water still is the main supply for much of the area and elsewhere is pumped to supplement the imported supply.

Ground water in the Tulare-Wasco area occurs under conditions that are similar in many respects to those of the Los Banos-Kettleman City area. The Corcoran Clay Member of the Tulare Formation is known to extend southeastward beneath Tulare Lake bed into the Tulare-Wasco area where it is the principal confining member. Thus, in the western part of this area, a threefold subdivision of the fresh-water-bearing deposits is possible similar to that of the Los Banos-Kettleman City area. In the eastern part (in general, east of U. S. Highway 99), the Corcoran is missing, and the deposits are semiconfined to the depths reached by most water wells (500–1000 feet).

Water levels in the Tulare-Wasco area have declined substantially since 1905. For example, at Delano, the altitude of the water level was about 285 feet above sea level in 1905, and in 1921, it was about 275 feet, but by 1952, the water table had declined to 190 feet, and the head in the confined deposits was about 160 feet above sea level. Because of importation of water through the Friant-Kern Canal, however, the combined influence of decreased pumping and increased replenishment resulted in recovery of head of as much as 110 feet near Delano by 1958.

The distribution and rate of land subsidence in the Tulare-Wasco area cor-

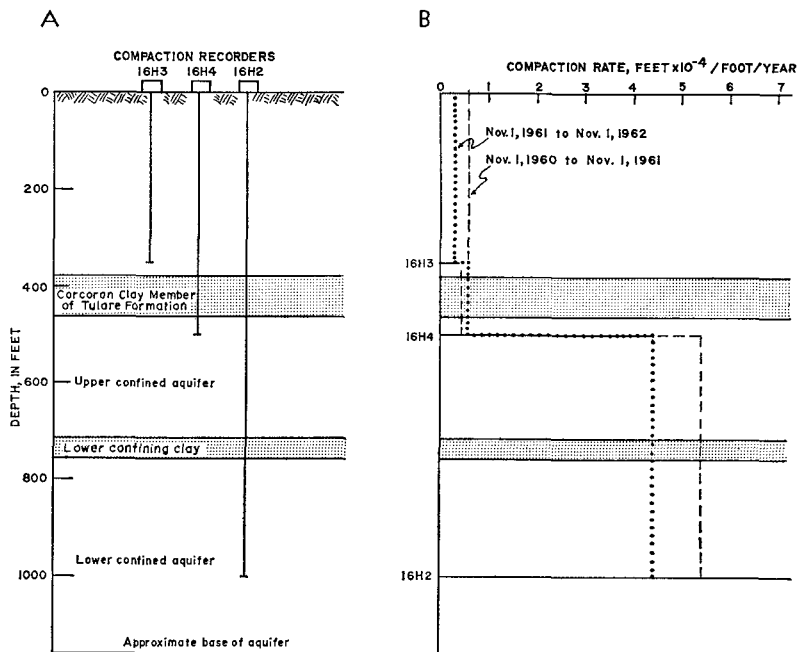


Figure 40. Compaction rates near Oro Loma, California, as measured by three compaction recorders. *A* shows relationship of multiple recorders to hydrologic units. *B* shows measured compaction rate of deposits in three depth zones.

relate in general with the decline in water level. Comparison of topographic maps of 1926 and 1954 indicated maximum subsidence of 12 feet 4 miles north of Delano. In 1948, the U. S. Coast and Geodetic Survey established a network of bench marks designed to give reasonably close vertical control in the area of known subsidence. Releveling of these bench marks in 1954 indicated more than 4 feet of subsidence between Earlimart and Pixley and west of Richgrove during the 6 years (Fig. 41). The area enclosed by the 1-foot subsidence line is about 450 square miles. In striking contrast, subsidence from 1954 to 1957 exceeded 0.6 foot only in an area of 80 square miles near Earlimart and Pixley (Fig. 42) still supplied solely by pumping from wells. Subsidence had virtually ceased in areas irrigated with water imported through the Friant-Kern Canal (shaded on Figure 42).

The reason for the decrease in subsidence is clearly demonstrated by Figure 43. The hydrographs of the two deep wells show the sharp recovery of water level after 1951 in response to the water deliveries from the Friant-Kern Canal. The surface bench marks, which had subsided continuously to 1954, remained nearly stable from 1954 to 1957. The recovery of water level had decreased the effective stress of the overburden load sufficiently so that compaction of the aquifer system virtually ceased by 1954.

Arvin-Maricopa Area. At least 400 square miles of irrigated land in the Arvin-Maricopa area at the southern end of the San Joaquin Valley is subsiding at rates up to 0.5 foot per year (Fig. 44). Most of the subsidence is related directly to the downward trend of water levels in semiconfined and confined aquifers (Lofgren, 1963). Most wells tap unconsolidated alluvial and lacustrine deposits to depths of 800–1200 feet. Accelerated pumping of ground water for irrigation, chiefly since 1940, has caused water levels to fall 5–15 feet a year and as much as 400 feet since 1929.

Leveling by the U. S. Coast and Geodetic Survey began in 1926, and a level net to define the subsidence area was established in 1957 and releveled in 1959 and 1962. This leveling indicated maximum subsidence of at least 6 feet from 1942 to 1962, 15 miles south of Bakersfield (Lofgren, 1963, Fig. 47.4).

The ratio of subsidence to head decline in this area currently is on the order of 1:60 to 1:120; it is lower than in the subsiding areas to the north, and suggests that the unit compressibility of the aquifer system is less. Compaction of the aquifer system due to head decline is the principal cause of subsidence, but near-surface subsidence related to the wetting of moisture-deficient deposits is prevalent in the southern part of the area, and tectonic readjustment may be a contributory cause on the south flank near Wheeler Ridge. This composite subsidence is a serious engineering problem in the construction of the California Aqueduct which is soon to be built through many miles of the subsiding area.

Santa Clara Valley

Land subsidence in the central part of the Santa Clara Valley, beneath the southern part of San Francisco Bay and south past San Jose, has been recognized for 30 years (Rappleye, 1933; Tibbetts, 1933). It was first noted when releveling in 1932–1933 of a line of first-order levels established by the U. S.

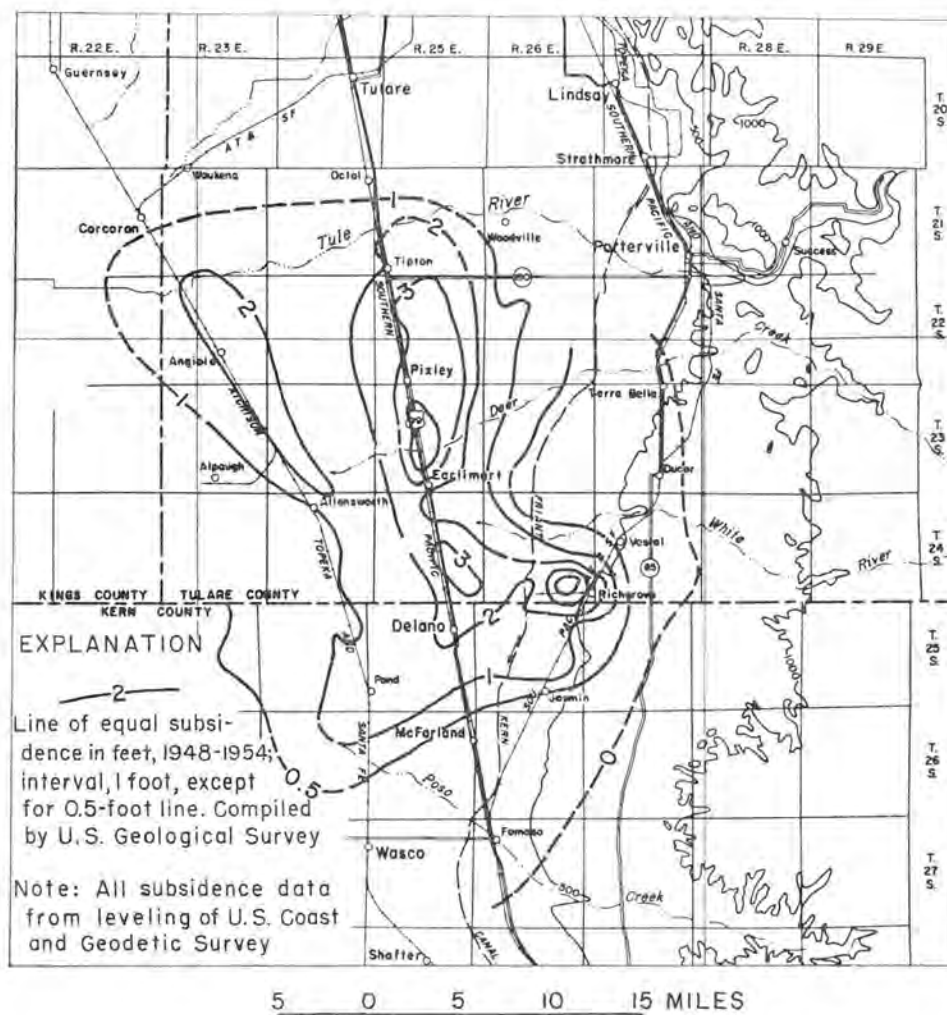
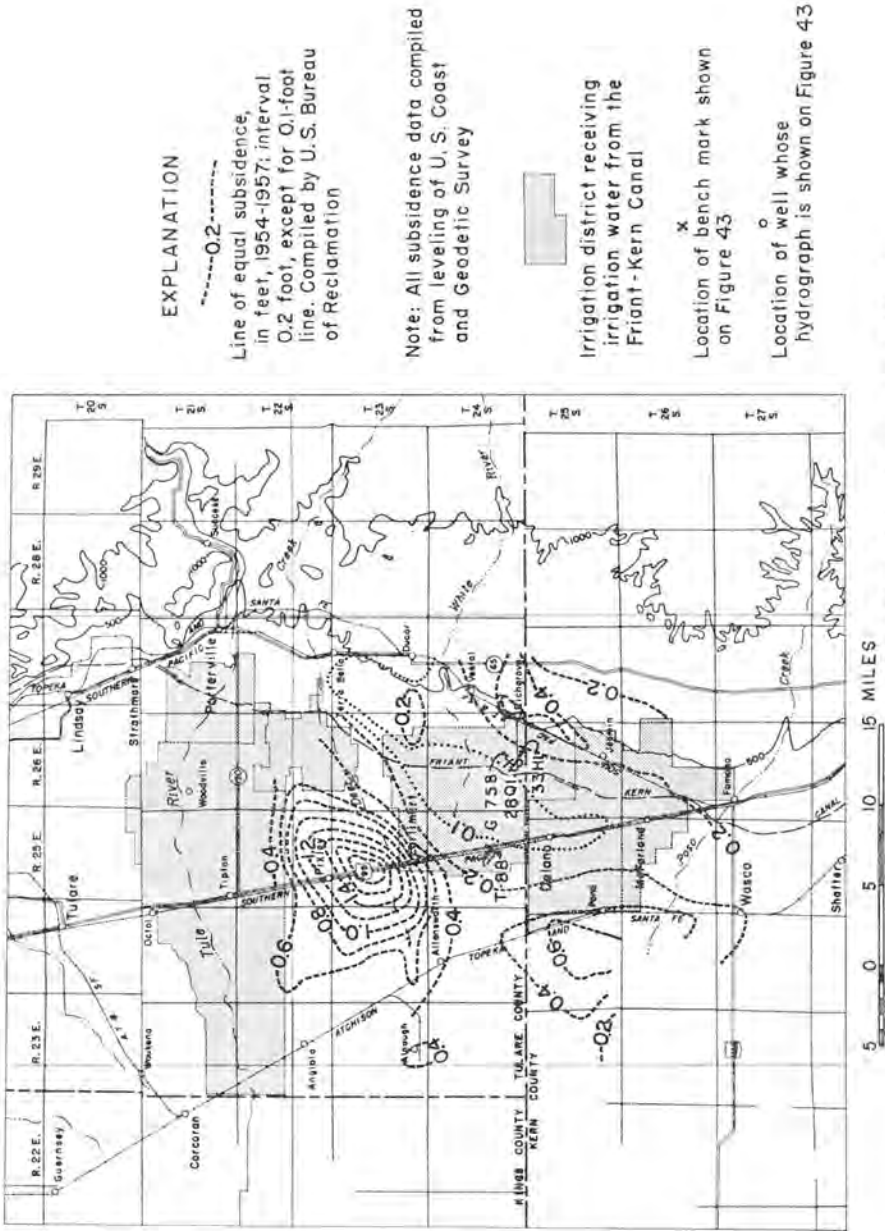


Figure 41. Land subsidence, 1948-1954, in Tulare-Wasco area, California.

Coast and Geodetic Survey in 1912 showed about 4 feet of subsidence at San Jose (Tolman and Poland, 1940, p. 29). Tolman and Poland described the subsidence to 1939 and concluded that decline in artesian head due to intensive and continued ground-water withdrawal was the principal cause. Poland and Green (1962) reported on the subsidence through 1954 and confirmed the earlier conclusions concerning the principal cause of subsidence.

The subsiding area extends southward about 25 miles from Redwood City and Niles to and beyond San Jose, has a maximum width of about 13 miles, and includes about 250 square miles (Fig. 45). The following summary is chiefly from the cited reports, from subsequent investigation of the subsidence by J. H. Green of the Geological Survey from 1958 through 1962, and from later leveling of the U. S. Coast and Geodetic Survey.



Geology. The Santa Clara Valley is a structural trough, bounded on the southwest by the Santa Cruz Mountains and on the northeast by the Diablo Range. Consolidated bedrock forms the floor and sides of the trough. Overlying this bedrock are the fresh-water-bearing deposits, which are the semiconsolidated Santa Clara Formation of Pliocene and Pleistocene age and the unconsolidated alluvial and bay deposits of Pleistocene and Recent age. The contact between

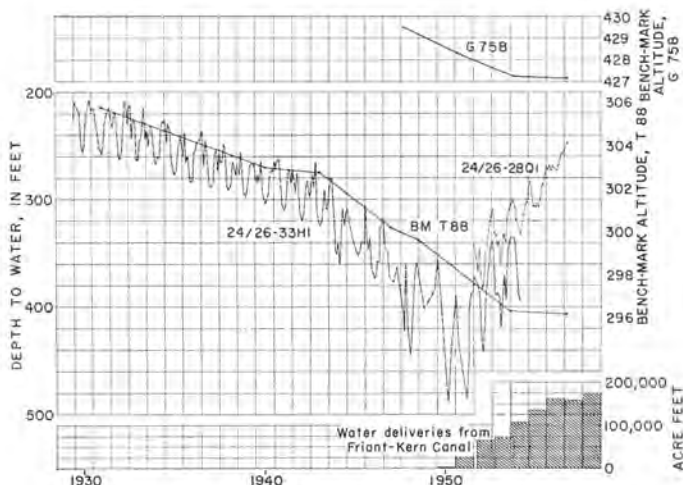


Figure 43. Subsidence and change in water level near Delano, California. Location shown on Figure 42.

these deposits cannot be recognized in well logs. Fresh water is obtained from wells that tap these alluvial and bay deposits and underlying deposits of the Santa Clara Formation; these deposits have a combined thickness of more than 1000 feet and possibly as much as 1500–2000 feet. Water wells range in depth from 200 to 1000 feet. Beneath the valley floor, the deeper wells probably tap the upper part of the Santa Clara Formation.

Where it is exposed around the valley margin, the Santa Clara Formation consists of semiconsolidated conglomerate, sandstone, siltstone, and claystone. These deposits, where they are tapped by wells in and near the outcrop area, have a low transmissibility and, at most places, do not yield enough water for irrigation wells.

The unconsolidated alluvial and bay deposits of clay, silt, sand, and gravel contain the most productive aquifers of the ground-water reservoir. Layers and tongues of silt and clay in the alluvial deposits are irregular but extensive, and they confine the ground water in the coarser lenses and tongues of sand and gravel. Thus, artesian conditions prevail beneath most of the valley, and initially, wells flowed near San Francisco Bay and south to San Jose (Clark, 1924).

Studies of samples from two 1000-foot core holes at the centers of subsidence in Sunnyvale and San Jose indicate that montmorillonite composes about 70 per cent of the clay-mineral assemblage in these deposits (R. H. Meade, June 1963, written commun.).

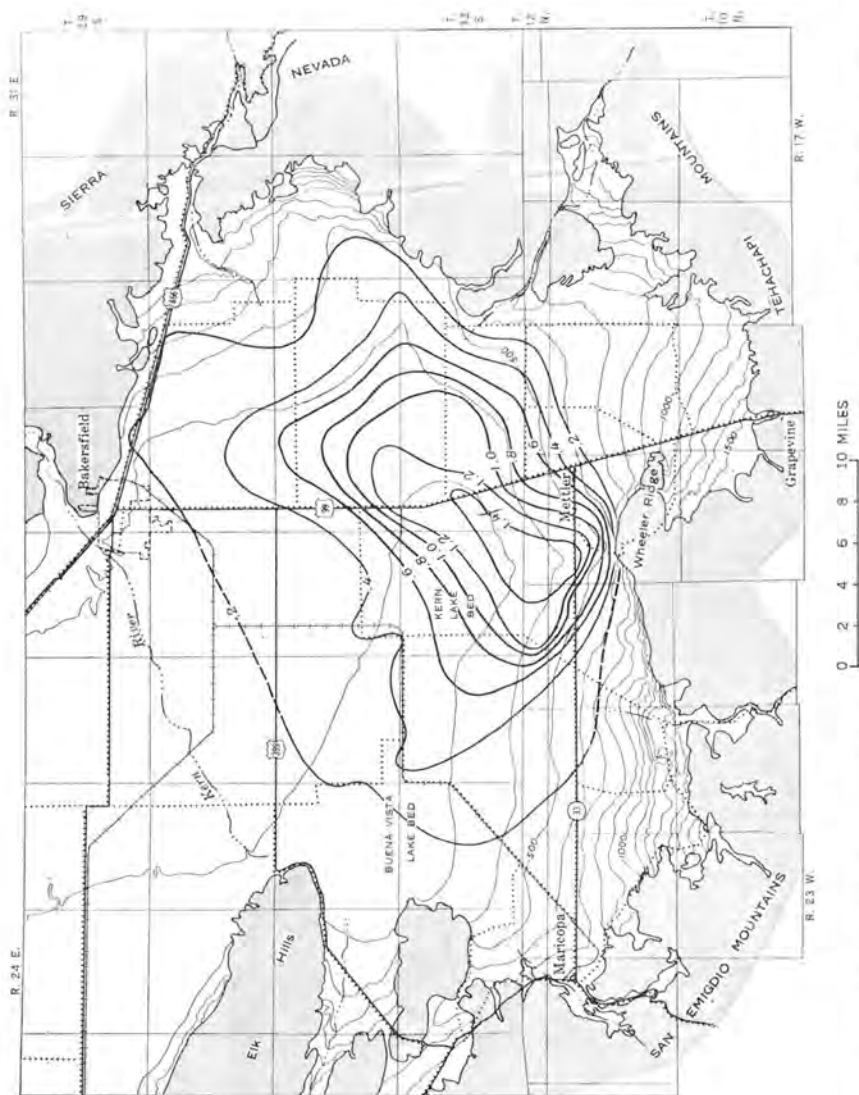


Figure 44. Land subsidence, 1959-1962, in Arvin-Maricopa area of San Joaquin Valley, California. Heavy contours are line of equal subsidence, in feet; shaded areas are deformed rocks bordering the valley. (After Lofgren, 1963, Fig. 47.7.)

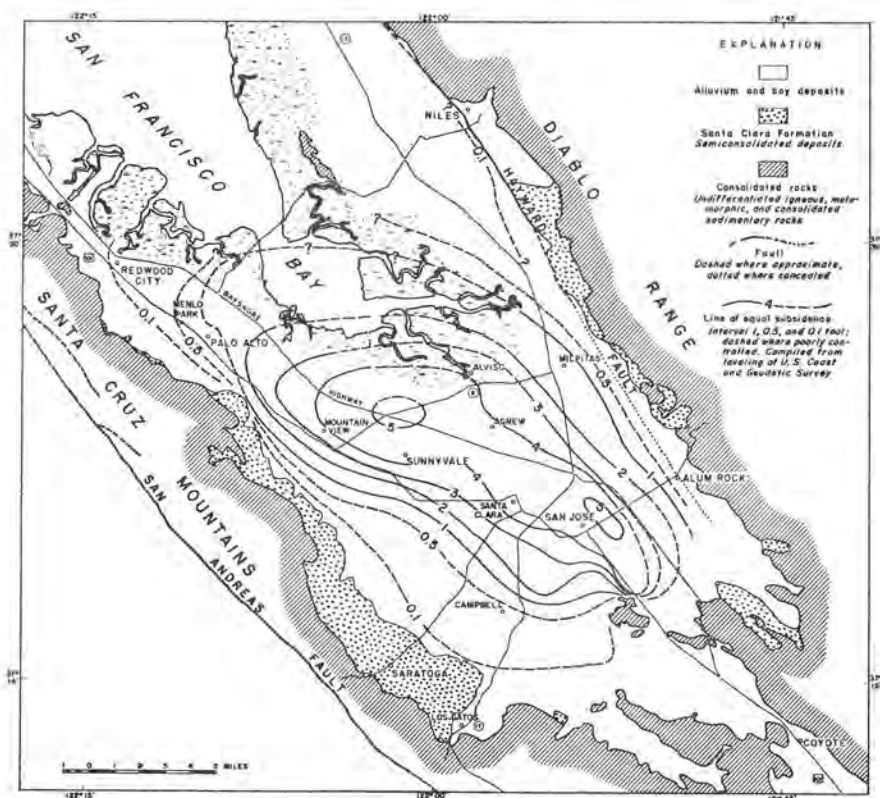


Figure 45. Land subsidence, 1934-1960, in Santa Clara Valley, California. (Compiled by J. H. Green.)

Hydrology. Development of ground water for irrigation began about 1900, and by 1934, about all irrigable land was under irrigation (Hunt, 1940, p. 14). Prior to 1942, pumpage for domestic and industrial use was small compared to irrigation draft, but with the rapid urbanization of the area during and since World War II, it has increased rapidly. Average pumpage in the fifties for all purposes has been about 200,000 acre-feet a year.

The intensive pumping of ground water has drawn down water levels throughout the valley. The hydrograph for well 7S/1E-7R1 in San Jose (Fig. 46) illustrates the change in water levels in the artesian area. The artesian head in this well, which was above the land surface in 1915, declined about 100 feet by 1934, recovered about 75 feet by 1943 during a period of above-normal rainfall, and then declined about 140 feet by 1962.

Land subsidence. The subsidence in the Santa Clara Valley has been well defined in time and magnitude by leveling of the U. S. Coast and Geodetic Survey. The level net established by that agency in 1933 (Fig. 47), which is tied to bedrock at several places, was completely leveled for the first time in 1934, was re-leveled seven times from November 1934 to April 1940, and again in 1948, 1954, and 1960; a partial releveing of the net from Palo Alto to bedrock south of San

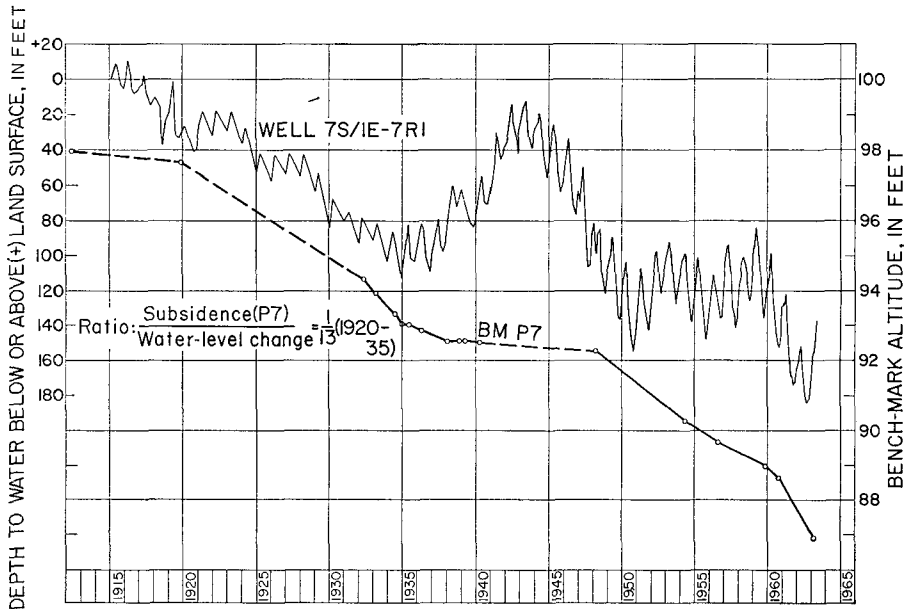


Figure 46. Change in altitude at bench mark P7 in San Jose, California, and change in artesian head in nearby well.

Jose was done in February 1963. The U. S. Coast and Geodetic Survey (1956) has published a compilation of adjusted elevations for all bench marks in the network through the 1954 leveling. Subsidence from 1934 to 1960 (Fig. 45) was a maximum of 5 feet at centers in San Jose and near Sunnyvale.

The longest record of subsidence is at bench mark P7 at the Hall of Records in San Jose (Fig. 46); from 1912 to February 1963, this bench mark subsided 11 feet. The rate of subsidence was greatest during periods of rapid decline in artesian head (*see* hydrograph for nearby well 7S/1E-7R1); the maximum rate was 0.73 foot per year from October 1960 to February 1963.

Profiles of land subsidence extending southeast near Redwood City to Coyote (Fig. 45) for 10 levelings between 1912 and 1963 (Fig. 48) indicate that maximum subsidence along the profiles occurred at bench mark P7 in San Jose although from 1934 to 1963, subsidence at bench mark J111 Reset in Sunnyvale (7 feet) was about equal to the maximum in San Jose (at bench mark B149).

Cause of subsidence. Within the artesian area (area of confined water), there is general correlation in time and rate of the subsidence and of the artesian-head decline as Figure 46 illustrates. Around the margins of the valley, however, where the deposits are mostly sand and gravel and are chiefly unconfined, substantial decline of the water table has not caused appreciable subsidence (Poland and Green, 1962, Fig. 12). These facts are positive evidence that the principal cause of the subsidence is the decline in artesian head and the corresponding increase in the grain-to-grain load on the aquifer system.

Quantitative comparison of land subsidence and compaction of the water-



Figure 47. Map showing network of level lines in San Jose subsidence area, Santa Clara Valley, California. (Modified after U. S. Coast and Geodetic Survey; numbers identify level lines according to 1956 tabulation.)

bearing deposits tapped by wells has been obtained. In 1960, the Geological Survey installed compaction recorders in two core holes drilled at the centers of subsidence in Sunnyvale and San Jose. The purpose of the equipment was to measure the rate and magnitude of compaction occurring between the land surface and the bottom of the test well. The equipment is similar to that installed in the San Joaquin Valley (Fig. 38). Figure 49 shows the compaction measured in the Sunnyvale core hole and in two shallower companion test wells. The core hole (24C7) was drilled to a depth of 1000 feet, which is the maximum depth of water wells in the area, and measured compaction in this well from October 1960 to February 1963 was 0.83 foot. Subsidence of the land surface at nearby bench mark J111 Reset during the same period, based on relevelings of the U. S. Coast and Geodetic Survey, was 0.82 foot. Thus, the land subsidence at this site is demonstrated to be equal to the compaction of the water-bearing deposits within the depth tapped by water wells, and the decline in artesian head is proved to

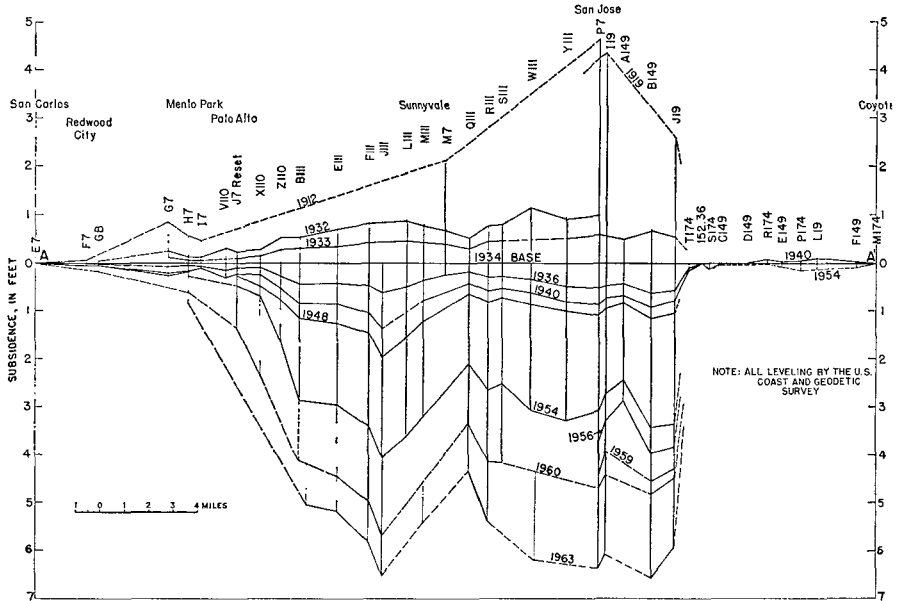


Figure 48. Profiles of land subsidence, 1912-1963, Redwood City to Coyote, California.

be the sole cause of the subsidence. Comparison of measured compaction in the other 1000-foot core hole in San Jose with subsidence of a nearby bench mark in the same period confirms this conclusion.

Green (1962) utilized results of consolidation and other laboratory tests on cores from the Sunnyvale and San Jose core holes to compute the compaction of the water-bearing deposits that theoretically should have occurred under the known change in artesian head from 1915 to 1960. The computed compaction agreed reasonably closely with the observed subsidence in the same period.

Protrusion of well casings has been common in the sinking area (Tolman, 1937, p. 344-345 and Figure 122). Many of the casings rose 2-3 feet above the land surface but usually were cut off before rising higher. This protrusion registers compaction between the land surface and the bottom of the casing but often is accompanied by compression and rupture of the casing and thus supplies only a minimum value for subsidence, not an absolute measure.

Relationship of subsidence to head decline. As a part of a study of the subsidence by the Geological Survey, J. H. Green (July 1962, written commun.) utilized subsidence and water-level change maps for the period 1948-1960 to map the ratio of subsidence to head decline in that period. The ratio increased from zero in the water-table areas around the valley margin to 0.10 in a central reach of the artesian area, extending from eastern San Jose to Sunnyvale. Thus, in this central reach, 1 foot of subsidence occurred for each 10 feet of water-level decline in the 12-year period. The ratio of subsidence at bench mark P7 to head decline at nearby well 7S/1E-7R1 (Fig. 46) was 0.08. From 1920 to 1935, when both subsidence and head decline were occurring at almost uniform rates, the ratio at P7 was also about 1:13 or 0.08.

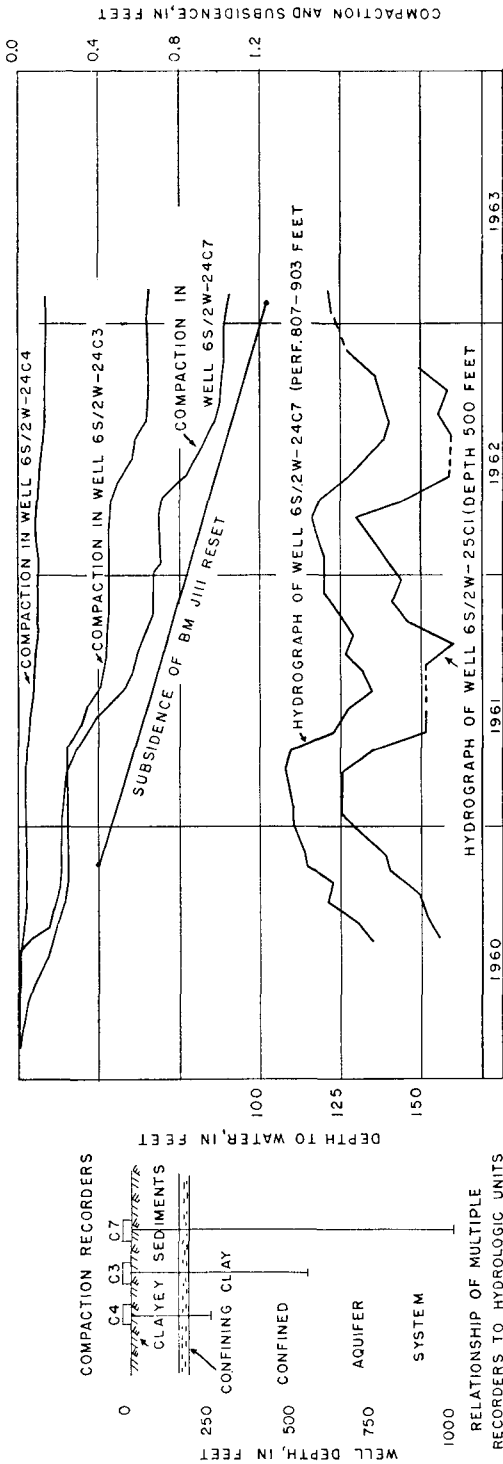


Figure 49. Measured compaction in wells 6S/2W-24C4, 24C3, and 24C7; water-level change; and subsidence of bench mark J111 Reset, in Sunnyvale, California.

Time lag in compaction, which affects the ratio of subsidence to head decline, is demonstrated clearly in Figure 46. From 1952 through 1958, the average artesian head was about uniform; however, bench mark P7 continued to subside throughout that 7-year period at only a slightly decreasing rate. The hydrograph registers the head change in the coarse permeable segments of the aquifer system; increase in effective stress in these segments occurs simultaneously with the head decline and is equal in magnitude. In the clay interbeds and confining beds (aquitards), however, the low permeability retards the escape of water, the reduction of pore pressure, and the compaction. Evidently, substantial excess pore pressures still existed in the aquitards in 1958 because the rate of compaction from 1956 through 1959 was two-thirds as great as from 1948 to 1954. This suggests that decay of excess pore pressure in the aquitards to approximate equilibrium with pore pressure in the aquifers would require many tens of years. Obviously, this time lag affects the ratio of subsidence to head decline; for example, if the average artesian head of 1952–1958 were maintained uniformly to 1970, the ratio of subsidence to head decline at this site for the 1948–1970 period would be substantially larger than the ratio obtained for the 1948–1960 period.

The volume of subsidence represented by the lines of equal subsidence from 1934 to 1960 (Fig. 45) is about 330,000 acre-feet (J. H. Green, January 1963, written commun.). This represents reduction in the pore volume of the groundwater reservoir, but the reduction has been principally in the fine-grained compressible clayey layers; therefore, it should not affect the storage capacity of the coarser grained sand and gravel aquifers appreciably. On the other hand, the quantity of water squeezed out of the aquifer system by permanent compaction is water available only once and thus is a nonreplenishable resource.

The extent to which the land surface would recover in response to substantial recovery of artesian head is not known. The artesian head at well 7S/1E-7R1 recovered about 75 feet from 1934 to 1943 (Fig. 46). Relevelings between 1934 and 1940 showed cessation of subsidence at bench mark P7 but no recovery. Leveling control was not available thereafter until 1948; thus, minor recovery of land surface may have occurred by 1943. Based on study of laboratory consolidation and rebound tests made on fine-grained clayey samples from the core holes, however, it is concluded that if initial artesian head were restored and the recharge water were chemically compatible with the water in the aquifers, recovery of the land surface would not be more than a few per cent of the total subsidence that has occurred.

SUMMARY

(1) Decrease in hydrostatic pressure in confined systems, such as oil and gas zones or artesian aquifers, results in increased grain-to-grain load on the sediments. The sediments compact in response to the added load, and the land surface subsides.

(2) Damage from subsidence and compaction has totaled hundreds of millions of dollars throughout the world and takes many forms. In tidal areas, flooding by sea water has been a major problem. Changing gradients have seriously af-

affected the capacity of canals, drains, and sewers, and even the channel capacity of streams has been changed materially. Structural failure of buildings, pipe lines, railroads, and other engineering structures at the land surface has occurred due to tensional or compressional stresses caused by flexure of the sediments. Compaction and flexure of sediments at depth have caused extensive damage by compressional or shear failure of oil- and water-well casings. In compressible aquifers, such as micaceous sand, the loss of ground-water storage capacity through compaction is a subtle but, in part, a permanent damage.

(3) Subsidence of the surface can be measured by precise leveling from stable reference points and, in tidal areas, by observing the change with respect to sea level. Compaction at depth can be measured by the use of anchored cables or pipes and by surveys in wells of reference points, such as casing collars and radioactive markers. Protrusion of well casings indicates that compaction has occurred but supplies only a minimum value for subsidence, not an absolute measure.

(4) The ratio of subsidence to head change depends upon the thickness and lithologic character of the compacting sediments. Chief controlling factors are the number, thickness, compressibility, and permeability of fine-grained interbeds and confining beds, clay mineralogy, geochemistry of pore fluids in aquifers and aquitards, initial porosity, previous loading history, and cementation. The most compressible materials are loosely consolidated, clayey sediments of Tertiary and Quaternary age, particularly those of volcanic provenance, that contain montmorillonite as the predominant clay mineral. In subsidence areas overlying these sediments, the range in ratio where known is about 0.01–0.2. The only known marked exceptions are at London and Savannah where water is produced from soft marine carbonate sediments associated with clays. In both of these areas, the ratio of subsidence to head decline is relatively small (less than 0.005).

(5) Continuous measurements of compaction indicate quick response to pressure changes in many areas although, commonly, some residual compaction or lag due to slow drainage of clays may continue long after the pressure decline has ceased.

(6) If artesian head declines over a period of years, then recovers and declines again, compaction will not recur until a previous pressure low is exceeded, provided all residual compaction from the previous drawdown phase has been completed (excess pore pressure has decayed).

(7) In a confined aquifer system, if the overlying water table remains unchanged, increase in effective pressure is equal in magnitude to the decrease of artesian pressure, and the sediments will compact in accord with this increase in stress. If the artesian pressure is wholly depleted and drawdown is continued, the fluid is yielded by dewatering of the sediments. Once the pressure at the top of the aquifer system (base of upper confining bed) declines to atmospheric pressure, further decline in fluid level will cause compaction at a decreased rate; this is in accord with the effective stress increase under water-table (unconfined) conditions, which is due to loss of buoyancy.

(8) Subsidence problems have been or are being alleviated in several ways: (1) cessation of withdrawal of petroleum, gas, or water due to depletion of the supply, legal action, or replacement with substitute supply; (2) increase or restoration of reservoir pressure due to reduction in production rate or to increase in recharge (water); (3) repressuring by injection of water. The last method has been highly successful in the Wilmington, California, oil field where it has stopped subsidence and has caused some rebound of the land surface.

REFERENCES CITED

- Aki, Kooichi, 1959, Notes on the investigation of earth level subsidence in Niigata, Japan: Japan Nat. Res. Bur., Sci. Technology Board, 27 p.
- Allen, Dennis, 1959, Wilmington subsidence problems: Houston, Tex., *World Oil*, v. 149, no. 2, p. 86-88
- Anders, R. B., and Naftel, W. L., 1962, Pumpage of ground water and fluctuation of water levels in the Houston district and the Baytown-La Porte area, Texas, 1957-1961: Texas Water Comm. Bull. 6211, 52 p.
- Anonymous, 1959a, Water buoys land that sank as oil was removed: *Eng. News-Rec.*, v. 163, no. 20, p. 26-27
- 1959b, Wilmington unitization is moving fast: Tulsa, Okla., *Oil and Gas Jour.*, v. 57, no. 18, p. 94-95
- 1960, The world's largest water flood: *Western Oil and Refining Mag.*, v. 57, no. 1, 8 p.
- 1961, Chiusi definitivamente I pozzi metaniferi del Polesine e del Delta Padano [Closing of gas wells in the Po Delta]: *Riv. Mineraria Siciliana*, no. 67, Gennaio-Febbraio, p. 42-43
- Athy, L. F., 1930, Density, porosity, and compaction of sedimentary rocks: *Am. Assoc. Petroleum Geologists Bull.*, v. 14, no. 1, p. 1-24
- Bartosh, E. J., 1938, Wilmington oil field, Los Angeles County, California: *Am. Assoc. Petroleum Geologists Bull.*, v. 22, no. 8, p. 1048-1079
- Boaga, G., Morelli, C., Puppo, A., and Selli, R., 1957, Necessari chiarimenti sui fenomeni di affondamento della zona del Delta Padano [Clarification of the phenomenon of subsidence of the Po Delta area]: Padova, Italy, Officine Grafiche Stediv, p. 5-15
- California Division of Oil and Gas, 1961, California oil and gas fields maps and data sheets—Part 2, Los Angeles-Ventura basins and central coastal regions: San Francisco, California Div. Oil and Gas, p. 495-913
- Carder, D. S., and Small, J. B., 1948, Level divergences, seismic activity, and reservoir loading in the Lake Mead area, Nevada and Arizona: *Am. Geophys. Union Trans.*, v. 29, no. 6, p. 767-771
- Carpenter, C. B., and Spencer, G. B., 1940, Measurements of compressibility of consolidated oil-bearing sandstones: U. S. Bur. Mines Rept. Inv. 3540, 20 p.
- Carrillo, Nabor, 1948, Influence of artesian wells in the sinking of Mexico City: Rotterdam, Internat. Conf. Soil Mech. and Found. Eng., 2nd, Proc., v. 7, p. 156-159
- Clark, W. O., 1924, Ground water in Santa Clara Valley, California: U. S. Geol. Survey Water-Supply Paper 519, 209 p.
- Collins, J. J., 1935, New type seawall built for subsiding lake shore in Venezuela: *Eng. News-Rec.*, v. 114, no. 3, p. 405-408
- Comision Hidrologica de la Cuenca del Valle de México, 1953, Recopilacion de datos del Valle de México, hasta el año de 1953 [Compilation of data on the Valley of Mexico to 1953]: Secretaria de Recursos Hidraulicos, Comision Hidrologica de la Cuenca del Valle de México, Bol. Mecanica de Suelos, no. 1, 217 p.
- 1958, Recopilacion de datos del Valle de México, 1953-1956 [Compilation of data for the Valley of Mexico, 1953-1956]: Secretaria de Recursos Hidraulicos, Comision Hidrologica de la Cuenca del Valle de México, Bol. Mecanica de Suelos, no. 2, 337 p.
- 1961, Boletin de Mecanica de Suelos, no. 3, June 1956-June 1959: Secretaria de Recursos Hidraulicos, Oficina de Estudios Especiales, 344 p.
- Committee for Investigation of Earth Level Subsidence in Niigata, 1958, On subsidence of the earth level in the Niigata area, Report Number 1: Niigata, Japan, Bureau of 1st Harbor Construction, Ministry of Transportation, 50 p.

- 1960, Subsidence of Niigata area: Niigata, Japan, Bureau of 1st Harbor Construction, Ministry of Transportation, 1 p.
- Corliss, J. B., and Meade, R. H., 1964, Clay minerals from an area of land subsidence in the Houston-Galveston Bay area, Texas: U. S. Geol. Survey Prof. Paper 501-C, p. C79-C81
- Coxe, L. C., 1949, Long Beach Naval Shipyard endangered by subsidence: *Civil Eng.*, v. 19, no. 11, p. 44-47, 90
- Criner, J. H., Jr., and Armstrong, C. A., 1958, Ground-water supply of the Memphis area [Tennessee, Arkansas, and Mississippi]: U. S. Geol. Survey Circ. 408, 20 p.
- Dal Piaz, G., 1959, Il bacino Quaternario Polesano-Ferrarese e i suoi giacimenti gassiferi [The Quaternary Polesano-Ferrarese basin and its gas-bearing layers], in *Atti del Convegno di Milano su I Giacimenti Gassiferi dell'Europa Occidentale*, Milan 1957: Rome, Accademia Nazionale dei Lincei, v. 1, p. 433-474
- Davis, G. H., and Poland, J. F., 1957, Ground-water conditions in the Mendota-Huron area, Fresno and Kings Counties, California: U. S. Geol. Survey Water-Supply Paper 1360-G, p. 409-588
- Davis, G. H., Small, J. B., and Counts, H. B., 1963, Land subsidence related to decline of artesian pressure in the Ocala Limestone at Savannah, Georgia, p. 1-8 in Trask, P. D. and Kiersch, G. A., *Editors*, Engineering Geology Case Histories, Number 4: Geol. Soc. America, 57 p.
- Dickinson, George, 1953, Geological aspects of abnormal reservoir pressures in Gulf Coast Louisiana: *Am. Assoc. Petroleum Geologists Bull.*, v. 37, no. 2, p. 410-432
- Engelhardt, Wolf von, 1960, Der porenraum der sedimente [The pore space of sediments]: Berlin, Springer Verlag, 207 p.
- 1961, Zum chemismus der porenlösung der sedimente [On the chemistry of the pore solution of sediments]: Uppsala [Sweden], Univ. Geol. Inst. Bull., v. 40, p. 189-204
- Frame, R. G., 1952, Earthquake damage, its cause and prevention in the Wilmington oil field, in *Summary of Operations, California Oil Fields*: California Dept. Nat. Res., Div. Oil and Gas, v. 38, no. 1, p. 5-15
- Fuller, M. L., 1908, Summary of the controlling factors of artesian flows: U. S. Geol. Survey Bull. 319, 44 p.
- Gayol, Roberto, 1929, Breves apuntes relativos a las obras de Saneamiento y Desagüe de la Capital de la República de las que, del mismo género, necesita con grande urgencia: Mexico, D. F., *Rev. Mexicana de Ingeniería y Arquitectura*, v. 7
- Gibbs, H. J., 1953, Estimating foundation settlement by one-dimensional consolidation tests: Denver, Colo., U. S. Bur. Reclamation, Eng. Mon. no. 13, 24 p.
- 1959, a laboratory testing study of land subsidence: Denver, Colo., U. S. Bur. Reclamation, Earth Lab. Rept. No. EM-564, 10 p.
- Gilluly, James, and Grant, U. S., 1949, Subsidence in the Long Beach Harbor area, California: *Geol. Soc. America Bull.*, v. 60, p. 461-530
- Gortani, M., 1961, L'estrazione delle acque Metanifere e il Delta Padano (Extraction of methane waters and the Po Delta): *Natura e Montagna*, ser. 2, v. 1, no. 1, p. 4-13
- Grant, U. S., 1944, Subsidence and elevation in the Los Angeles Region, p. 129-158 in *Science in the University*, by members of the faculties of the University of California: Berkeley and Los Angeles, California Univ. Press, 332 p.
- 1954, Subsidence of the Wilmington oil field, California, p. 19-24 in Jahns, R. H., *Editor*, *Geology of Southern California*: California Dept. Nat. Res., Div. Mines Bull. 170, 700 p.
- Green, J. H., 1962, Compaction of the aquifer system and land subsidence in the Santa Clara Valley, California: U. S. Geol. Survey Prof. Paper 450-D, art. 172, p. D175-D178
- Griffin, G. M., 1962, Regional clay-mineral facies—Products of weathering intensity and current distribution in the northeastern Gulf of Mexico: *Geol. Soc. America Bull.*, v. 73, p. 737-768
- Harris, F. M., and Harlow, E. H., 1947, Subsidence of the Terminal Island-Long Beach area, California: *Am. Soc. Civil Engineers Proc.*, v. 73, no. 8, p. 1197-1218
- Hedberg, H. D., 1926, The effect of gravitational compaction on the structure of sedimentary rocks: *Am. Assoc. Petroleum Geologists Bull.*, v. 10, p. 1035-1072
- 1936, Gravitational compaction of clays and shales: *Am. Jour. Sci.*, 5th ser., no. 31, p. 241-287
- Heindl, L. A., and Feth, J. H., 1955, Discussion of Symposium on Land Erosion, "Piping," by Joel E. Fletcher, Karl Harris, H. B. Peterson, and V. N. Chandler: *Am. Geophys. Union Trans.*, v. 36, no. 2, p. 342-345
- Hubbert, M. K., and Rubey, W. W., 1959, Role of fluid pressure in mechanics of overthrust

- faulting, I. Mechanics of fluid-filled porous solids and its application to overthrust faulting: *Geol. Soc. America Bull.*, v. 70, p. 115-166
- Hunt, G. W., 1940, Description and results of operation of the Santa Clara Valley Water Conservation District's project: *Am. Geophys. Union Trans.*, pt. 1, p. 13-22
- Ingerson, I. M., 1941, The hydrology of the southern San Joaquin Valley, California, and its relation to important water supplies: *Am. Geophys. Union Trans.*, pt. 1, p. 20-45
- Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1958, Progress report on land-subsidence investigations in the San Joaquin Valley, California, through 1957: Sacramento, Calif., Inter-Agency Comm. on Land Subsidence in the San Joaquin Valley, 160 p.
- Jacob, C. E., 1940, On the flow of water in an elastic artesian aquifer: *Am. Geophys. Union Trans.*, pt. 2, p. 574-586
- Kugler, H. G., 1933, Contribution to the knowledge of sedimentary volcanism in Trinidad (with discussion): *Inst. Petroleum Technologists Jour.*, v. 19, p. 743-772
- Leonards, G. A., 1962, Engineering properties of soils, p. 66-240 in Leonards, G. A., *Editor*, *Foundation Engineering*: New York, McGraw-Hill Book Co., 1136 p.
- Lockwood, M. G., 1954, Ground subsides in Houston area: *Civil Eng.*, v. 24, p. 370-372
- Loehnerberg, Alfred, 1958, Aspects of the sinking of Mexico City and proposed countermeasures: *Am. Water Works Assoc. Jour.*, v. 50, no. 3, p. 432-440
- Lofgren, B. E., 1961, Measurement of compaction of aquifer systems in areas of land subsidence: U. S. Geol. Survey Prof. Paper 424-B, art. 24, p. B49-B52
- 1963, Land subsidence in the Arvin-Maricopa area, California: U. S. Geol. Survey Prof. Paper 475-B, art. 47, p. B171-B175
- Lohman, S. W., 1961, Compression of elastic artesian aquifers: U. S. Geol. Survey Prof. Paper 424-B, art. 23, p. B47-B49
- Longfield, T. E., 1932, The subsidence of London: Ordnance Survey, Prof. Papers, new ser., no. 14
- Longwell, C. R., 1960, Interpretation of the leveling data, in *Comprehensive survey of sedimentation in Lake Mead 1948-1949*: U. S. Geol. Survey Prof. Paper 295, p. 33-38
- Marsal, R. J., and Mazari, Marcos, 1959, El subsuelo de la Ciudad de México: Parte A, Estratigrafía y propiedades; Parte B, Hundimiento general; Parte C, Comportamiento de las cimentaciones: Universidad Nacional Autónoma de México, Contribucion del Instituto de Ingenieria al Primer Congreso Panamericano de Mecanica de Suelos y Cimentaciones, 614 p.
- Marsal, R. J., and Sainz-Ortiz, I., 1956, Breve descripción del hundimiento de la Ciudad de México [Short description of the sinking of Mexico City]: *Bol. Soc. Geol. Mexicana*, p. 1-11
- Marsal, R. J., Hiriart, Fernando, and Sandoval, L. Raúl, 1952, Hundimiento de la Ciudad de México, observaciones y estudios analíticos [Sinking of the City of Mexico, observations and analytical studies]: *Ingenieros Civiles Asociados, S. A. de C. V., Serie B Ingenieria Experimental*, no. 3, 26 p.
- Martin, R. T., 1962, Adsorbed water on clay: A review, p. 28-70 in Swineford, Ada, *Editor*, *Clays and clay minerals*: New York, Pergamon Press, 614 p.
- Maxey, G. B., and Jameson, C. H., 1948, Geology and water resources of Las Vegas, Pahrump, and Indian Spring Valleys, Clark and Nye Counties, Nevada: *Nevada Water Res. Bull.* 5, 121 p.
- Meade, R. H., 1961, Compaction of montmorillonite-rich sediments in western Fresno County, California: U. S. Geol. Survey Prof. Paper 424-D, art. 324, p. D89-D92
- 1964, Removal of water and rearrangement of particles during the compaction of clayey sediments—Review: U. S. Geol. Survey Prof. Paper 497-B, 23 p.
- Meinzer, O. E., 1928, Compressibility and elasticity of artesian aquifers: *Econ. Geology*, v. 23, no. 3, p. 263-291
- Meinzer, O. E., and Hard, H. A., 1925, The artesian-water supply of the Dakota sandstone in North Dakota with special reference to the Edgeley quadrangle: U. S. Geol. Survey Water-Supply Paper 520-E, p. 73-95
- Miller, F. G., and Somerton, W. H., 1955, Operators eye heroic measures to halt Wilmington sinking: *Oil and Gas Jour.*, Dec. 19, v. 54, no. 33, 7 p.
- Miller, R. E., 1961, Compaction of an aquifer system computed from consolidation tests and decline in head: U. S. Geol. Survey Prof. Paper 424-B, art. 26, p. B54-B58
- Minor, H. E., 1925, Goose Creek oil field, Harris County, Texas: *Am. Assoc. Petroleum Geologists Bull.*, v. 9, no. 2, p. 286-297
- Mitchell, J. K., 1962, Components of pore water pressure and their engineering significance,

- p. 162–184 in Swineford, Ada, *Editor*, Clays and clay minerals: New York, Pergamon Press, 614 p.
- Mooser, Federico**, 1961, Informe sobre la geología de la cuenca del Valle de México y zonas colindantes [Report on the geology of the Valley of Mexico and adjacent area]: Comisión Hidrológica de la Cuenca del Valle de México, Oficina de Estudios Especiales, 38 p.
- Murray-Aaron, E. R., and Pfeil, A. W.**, 1948, Recent developments in the Wilmington oil fields, in Summary of Operations, California oil fields: California Dept. Nat. Res., Div. Oil and Gas, v. 34, no. 2, p. 5–13
- Neel, Charles H.**, 1957, Surface subsidence and remedial measures at the Long Beach Naval Shipyard, Long Beach, California: Rept. to Long Beach Naval Shipyard, 90 p.
- Poland, J. F.**, 1958, Land subsidence due to ground-water development: Am. Soc. Civil Engineers Proc., Jour. Irrigation and Drainage Div., Paper 1774, v. 84, no. IR3, 11 p.
- 1960, Land subsidence in the San Joaquin Valley, California, and its effect on estimates of ground-water resources: Internat. Assoc. Sci. Hydrology, Comm. Subterranean Waters, Pub. No. 52, p. 324–335
- 1961, The coefficient of storage in a region of major subsidence caused by compaction of an aquifer system: U. S. Geol. Survey Prof. Paper 424-B, art. 25, p. B52–B54
- Poland, J. F., and Davis, G. H.**, 1956, Subsidence of the land surface in the Tulare-Wasco (Delano) and Los Banos-Kettleman City areas, San Joaquin Valley, California: Am. Geophys. Union Trans., v. 37, no. 3, p. 287–296
- Poland, J. F., and Green, J. H.**, 1962, Subsidence in the Santa Clara Valley, California—A progress report: U. S. Geol. Survey Water-Supply Paper 1619-C, 16 p.
- Poland, J. F., Garrett, A. A., and Sinnott, Allen**, 1959, Geology, hydrology, and chemical character of ground waters in the Torrance-Santa Monica area, California: U. S. Geol. Survey Water-Supply Paper 1461, p. 142–146
- Pratt, W. E.**, 1927, Some questions on the cause of the subsidence of the surface in the Goose Creek field, Texas: Am. Assoc. Petroleum Geologists Bull., v. 11, no. 8, p. 887–889
- Pratt, W. E., and Johnson, D. W.**, 1926, Local subsidence of the Goose Creek field: Jour. Geology, v. 34, no. 7, p. 577–590
- Puppo, A.**, 1957, L'estrazione delle acque metanifere nel territorio del Delta Padano e l'affondamento del suolo [The production of methane in the area of the Po Delta and the subsidence of the ground]: Metano, Petrolio, e Nuove Energie, v. XI, no. 11, p. 1–12
- Quintero, Andres Garcia**, 1958, Recharge wells in Mexico City, Mexico: The Texas Engineer, v. 28, no. 2, p. 6–10
- Rappleye, H. S.**, 1933, Recent areal subsidence found in releveling: Eng. News-Rec., v. 110, p. 848
- Robinson, G. M., and Peterson, D. E.**, 1962, Notes on earth fissures in southern Arizona: U. S. Geol. Survey Circ. 466, 7 p.
- Rose, N. A.**, 1943, Ground water and relation of geology to its occurrence in Houston district, Texas: Am. Assoc. Petroleum Geologists Bull., v. 27, no. 8, p. 1081–1101
- Rosenqvist, I. Th.**, 1962, The influence of physico-chemical factors upon the mechanical properties of clays, p. 12–27 in Swineford, Ada, *Editor*, Clays and clay minerals: New York, Pergamon Press, 614 p.
- Rubey, W. W., and Hubbert, M. K.**, 1959, Role of fluid pressure in mechanics of overthrust faulting. II. Overthrust belt in geosynclinal area of western Wyoming in light of fluid-pressure hypothesis: Geol. Soc. America Bull., v. 70, p. 167–206
- Russell, W. L.**, 1928, The origin of artesian pressure: Econ. Geology, v. 23, no. 2, p. 132–157
- Rutledge, P. C.**, 1944, Relation of undisturbed sampling to laboratory testing (with discussion): Am. Soc. Civil Engineers Trans., Paper 2229, p. 1155–1216
- Shoemaker, R. R.**, 1955, Protection of subsiding waterfront properties: Am. Soc. Civil Engineers Proc., v. 81, no. 805, p. 805-1–805-24
- Shoemaker, R. R., and Thorley, T. J.**, 1955, Problems of ground subsidence: Am. Water Works Assoc. Jour., v. 47, no. 4, p. 412–418
- Skempton, A. W.**, 1944, Notes on the compressibility of clays: Geol. Soc. London Quart. Jour., v. C, p. 119–135
- Small, J. B.**, 1960, Subsidence in the Texas Gulf Coast area: Washington, D. C., U. S. Coast and Geod. Survey, 26 p.
- 1963, Interim report on vertical crustal movement in the United States: Washington, D. C., U. S. Coast and Geod. Survey, 14 p.
- Snider, L. C.**, 1927, A suggested explanation of the surface subsidence in the Goose Creek oil and gas field [Texas]: Am. Assoc. Petroleum Geologists, v. 11, no. 7, p. 729–745

- Sorby, H. C., 1908, On the application of quantitative methods to the study of the structure and history of rocks: *Geol. Soc. London Quart. Jour.*, v. 64, p. 171-232
- Steinbrugge, K. V., and Bush, V. R., 1958. Subsidence in Long Beach-Terminal Island-Wilmington, California: San Francisco, Pacific Fire Rating Bur., 38 p.
- Storer, D., 1959, Constipamento dei sedimenti argillosi nel Bacino Padano [Compaction of argillaceous sediments in the Po Basin], in *Atti del Convegno di Milano su I Giacimenti Gassiferi dell'Europa Occidentale*, Milan 1957: Rome, Academia Nazionale dei Lincei, v. 2, p. 519-544
- Taylor, D. W., 1948, *Fundamentals of Soil Mechanics*: New York, John Wiley and Sons, Inc., 700 p.
- Terzaghi, Karl, 1925a, *Erdbaumechanik auf Bodenphysikalischer Grundlage*: Wein, Deuticke, 399 p.
- 1925b, Principles of soil mechanics: IV, Settlement and consolidation of clay: *Eng. News-Rec.*, p. 874-878
- Terzaghi, Karl, and Peck, R. B., 1948, *Soil mechanics in engineering practice*: New York, John Wiley and Sons, Inc., 566 p.
- Tibbetts, F. H., 1933, Areal subsidence: *Eng. News-Rec.*, v. 3, p. 204
- Tolman, C. F., 1937, *Ground Water*: New York, McGraw-Hill Book Co., p. 341-345
- Tolman, C. F., and Poland, J. F., 1940, Ground-water, salt-water infiltration, and ground-surface recession in Santa Clara Valley, Santa Clara County, California: *Am. Geophys. Union Trans.*, pt. 1, p. 23-34
- U. S. Coast and Geodetic Survey, 1956, San Jose area, California, 1912-1954 leveling (190A Calif.): Washington, D. C., U. S. Coast & Geod. Survey, 42 p.
- Waidelich, W. C., 1958, Influence of liquid and clay mineral type on consolidation of clay-liquid systems, in *Water and its conduction in soils*: Washington, D. C., Natl. Research Council, Highway Research Board Spec. Rept. 40., p. 24-42
- Walton, W. C., and Walker, W. H., 1961, Evaluating wells and aquifers by analytical methods: *Jour. Geophys. Research*, v. 66, no. 10, p. 3359-3370
- Weir, W. W., 1950, Subsidence of peat lands of the Sacramento-San Joaquin Delta, California: *Hilgardia*, California Univ. Agr. Expt. Sta., v. 20, no. 3, p. 37-56
- Wilson, Guthlac, and Grace, Henry, 1942, The settlement of London due to underdrainage of the London Clay: *Jour. Inst. Civil Eng.*, v. 19, no. 2, paper no. 5294, p. 100-127
- Winslow, A. G., and Doyel, W. W., 1954, Land-surface subsidence and its relation to the withdrawal of ground water in the Houston-Galveston region, Texas: *Econ. Geology*, v. 49, no. 4, p. 413-422
- Winslow, A. G., and Wood, L. A., 1959, Relation of land subsidence to ground-water withdrawals in the upper Gulf Coast region, Texas: *Mining Eng.*, v. 11, no. 10, p. 1030-1034
- Winterburn, Read, 1943, Wilmington oil field: California Div. Mines and Geology Bull. 118, p. 301-305
- Zeevaert, Leonardo, 1953a, Pore pressure measurements to investigate the main source of surface subsidence in Mexico City: Switzerland, 3rd Internat. Conf. on Soil Mech. and Found. Eng. Proc., v. 2, p. 299-304
- 1953b, Outline on the stratigraphical and mechanical characteristics of the unconsolidated sedimentary deposits in the basin of the Valley of Mexico: *Actes, 4th Internat. Congrès du Quaternaire*, v. 2, p. 976-987
- 1957, Consolidation of Mexico City volcanic clay, p. 18-32, in *Conference on soils for engineering purposes*: Am. Soc. Testing and Materials Spec. Tech. Pub. 232, 501 p.

SUBJECT INDEX TO REFERENCES CITED

Development of concepts and application to subsidence.

Athy, 1930; Dickinson, 1953; Engelhardt, 1960, 1961; Fuller, 1908; Gibbs, 1953; Hedberg, 1926, 1936; Hubbert and Rubey, 1959; Jacob, 1940; Leonards, 1962; Lohman, 1961; Martin, 1962; Meade, 1964; Meinzer, 1928; Meinzer and Hard, 1925; Mitchell, 1962; Poland, 1961; Rosenqvist, 1962; Rubey and Hubbert, 1959; Russell, 1928; Rutledge, 1944; Skempton, 1944; Sorby, 1908; Taylor, 1948; Terzaghi, 1925a, 1925b; Terzaghi and Peck, 1948; Waidehch, 1958; Walton and Walker, 1961; Zeevaert, 1957

Subsidence of oil and gas fields.

California, Wilmington: Allen, 1959; Anonymous, 1959a, 1959b, 1960; Bartosh, 1938; California Division Oil and Gas, 1961; Coxe, 1949; Frame, 1952; Gilluly and Grant, 1949; Grant, 1944, 1954; Harris and Harlow, 1947; Miller and Somerton, 1955; Murray-Aaron and Pfeil, 1948; Neel, 1957; Poland, Garrett, and Sinnott, 1959; Shoemaker, 1955; Shoemaker and Thorley, 1955; Steinbrugge and Bush, 1958; Winterburn, 1943

Italy, Po Delta: Anonymous, 1961; Boaga, Morelli, Puppo, and Selli, 1957; Dal Piaz, 1959; Gortani, 1961; Puppo, 1957; Storer, 1959

Japan, Niigata: Aki, 1959; Committee for Investigation of Earth Level Subsidence in Niigata, 1958, 1960

Texas, Goose Creek Oil Field: Minor, 1925; Pratt, 1927; Pratt and Johnson, 1926; Snider, 1927

Venezuela, Lake Maracaibo: Collins, 1935; Kugler, 1933

Subsidence due to ground-water withdrawal.

Arizona, Eloy-Picacho area: Heindl and Feth, 1955; Robinson and Peterson, 1962

California

San Joaquin Valley: Davis and Poland, 1957; Gibbs, 1959; Ingerson, 1941; Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1958; Lofgren, 1961, 1963; Meade, 1961; Miller, 1961; Poland, 1960, 1961; Poland and Davis, 1956

Santa Clara Valley: Clark, 1924; Green, 1962; Hunt, 1940; Poland and Green, 1962; Rappleye, 1933; Tibbetts, 1933; Tolman, 1937; Tolman and Poland, 1940; U. S. Coast and Geodetic Survey, 1956

Colorado, Denver: Lohman, 1961

England, London: Longfield, 1932; Wilson and Grace, 1942

Georgia, Savannah: Davis, Small, and Counts, 1963

Japan, Honshu: Aki, 1959

Mexico, Mexico City: Carillo, 1948; Comision Hidrologica de la Cuenca del Valle de Mexico, 1953, 1958, 1961; Gayol, 1929; Loehnberg, 1958; Marsal, Hiriart, and Sandoval, 1952; Marsal and Mazari, 1959; Marsal and Sainz-Ortiz, 1956; Mooser, 1961; Quintero, 1958; Zeevaert, 1953a, 1953b, 1957

Nevada, Las Vegas: Carder and Small, 1948; Longwell, 1960; Maxey and Jameson, 1948; Small, 1963

Texas, Upper Gulf Coast area: Anders and Naftel, 1962; Corliss and Meade, 1964; Lockwood, 1954; Rose, 1943; Small, 1960, 1963; Winslow and Doyel, 1954; Winslow and Wood, 1959

Reviews in Engineering Geology

LAND SUBSIDENCE DUE TO WITHDRAWAL OF FLUIDS

J. F. Poland and G. H. Davis

Reviews in Engineering Geology 1969;2;187-270

doi: 10.1130/REG2-p187

Email alerting services

click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article

Subscribe

click www.gsapubs.org/subscriptions/ to subscribe to Reviews in Engineering Geology

Permission request

click <http://www.geosociety.org/pubs/copyrt.htm#gsa> to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes
