Case History No. 9.14. Santa Clara Valley, California, U.S.A., by Joseph F. Poland, U.S. Geological Survey, Sacramento, California

9.14.1 INTRODUCTION

Land subsidence in the central part of the Santa Clara Valley--beneath the southern part of San Francisco Bay and extending to the southern edge of San Jose--was first recognized in 1932-33. Releveling of a line of first-order levels established by the National Geodetic Survey in 1912 showed about 1.2 m of subsidence in downtown San Jose in 1933. The subsiding area extends southward about 40 km from Redwood City and Niles past San Jose, has a maximum width of 22 km, and includes about 750 km^2. As shown by Figure 9.14.1, most of this central area experienced 0.3 to 2.4 m (1 to 8 feet) of subsidence from 1934 to 1967.

9.14.2 GEOLOGY

The Santa Clara Valley is a structural trough extending 110 km southeast from San Francisco. The valley is bounded on the southwest by the Santa Cruz Mountains and the San Andreas fault and on the northeast by the Diablo Range and the Hayward fault. The consolidated bedrock bordering the valley is shown as a single unit in Figure 9.14.1; it ranges in age from Cretaceous to Pliocene and consists largely of sedimentary rocks but includes areas of metamorphic and igneous rocks.

The fresh-water-bearing deposits forming the ground-water reservoir within the valley are chiefly of Quaternary age. They include (1) the semiconsolidated Santa Clara Formation and associated deposits of Pliocene and Pleistocene age and (2) the unconsolidated alluvial and bay deposits of Pleistocene and Holocene age. The Santa Clara Formation, which crops out on the southwest and northeast flanks of the valley, consists of poorly sorted conglomerate, sandstone, siltstone, and clay as much as 600 m thick in outcrop (Dibblee, 1966). Where exposed, this formation has a low transmissivity and yields only small to moderate quantities of water to wells (1 to 6 l/s)--rarely enough for irrigation purposes.

The unconsolidated alluvial and bay deposits of clay, silt, sand, and gravel overlie the Santa Clara Formation and associated deposits their upper surface forms the valley floor. They contain the most productive aquifers of the ground-water reservoir. Wells range in depth from 90 to 360 m. The deeper wells probably tap the upper part of the Santa Clara Formation although the contact with the overlying alluvium has not been distinguished in well logs. Well yields in the valley range from 20 to 160 l/s (Calif. Dept. Water Resources., 1967, pl. 6). The alluvial deposits are at least 460 m thick beneath central San Jose. However, the log of a well drilled to a depth of 468 m revealed a lack of water-bearing material below a depth of 300 M. Coarse-grained deposits predominate on the alluvial fans near the valley margins where the stream gradients are steeper. The proportion of clay and silt layers increases bayward. For example, a well-log section extending 20 km northward from Campbell to Alviso (Tolman and Poland, 1940, Figure 3) shows that to a depth of 150 m, the cumulative thickness of clay layers in the deposits increases from 25 per cent near Campbell to 80 per cent near Alviso.

In 1960, the U.S. Geological Survey drilled core holes to a depth of 305 m at the two centers of subsidence, in San Jose (well 16C6) and in Sunnyvale (well 24C7). (For location, see Figure 9.14.1.) The 305-m depth was chosen because it was the maximum depth of nearby water wells. Cores were tested in the laboratory for particle-size distribution, specific gravity of solids, dry unit weight, porosity and void ratio, hydraulic conductivity (normal and parallel to bedding), Atterberg limits, and one-dimensional consolidation and rebound (Johnson, Moston, and Morris, 1968).

X-ray diffraction studies of 20 samples from the two core holes indicate that montmorillonite composes about 70 per cent of the clay-mineral assemblage in these deposits. Other constituents are chlorite, 20 per cent, and illite, 5-10 per cent (Meade, 1967, p. 44).

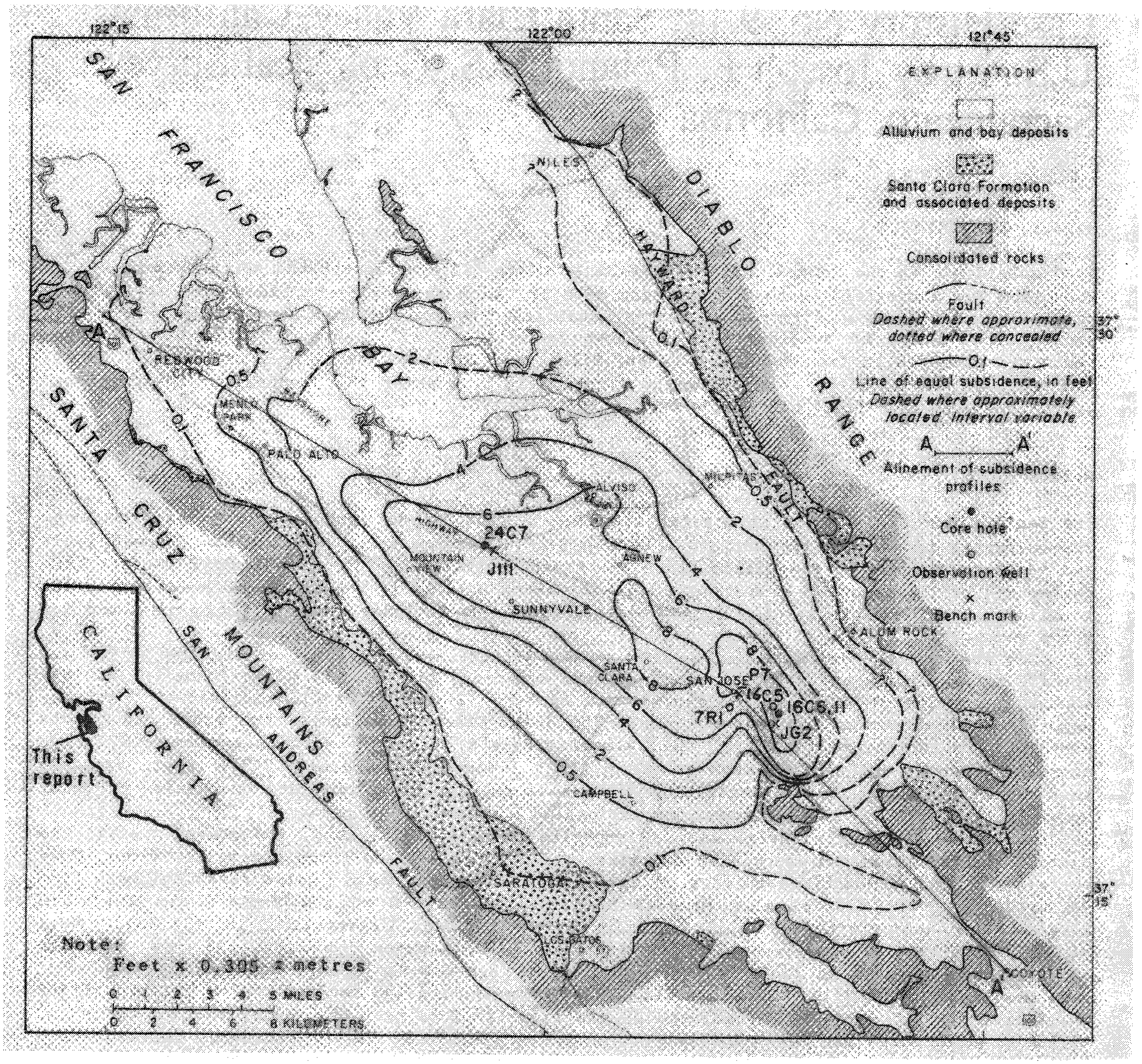

Figure 9.14.1 Land subsidence from 1.934 to 1967, Santa Clara Valley, California. Compiled from leveling of National Geodetic Survey in 1934 and 1967.

9.14.3 HYDROLOGY

In the central part of Figure 9.14.1 and below a depth of 50 to 60 m, ground water is confined. The extent of the confined aquifer system is defined roughly by the 0.6 m (2-ft) 1ine of equal subsidence in Figure 9.14.1. The area of confinement extends southward from beneath San Francisco Bay to San Jose, also west to Palo Alto and east to Milpitas. In the early years of development, wells as far south as San Jose and more than 60 m deep flowed (Clark, 1924, p.1. XV), demonstrating by their areal distribution a minimal extent of the confining sedments. The confined aquifer svstem is as much as 245 m thick. Around the valley margins, ground water is chiefly unconfined and most of the natural recharge to the ground-water reservoir percolates from stream channels in alluvial-fan deposits.

The confining member overlying the confined aquifer system has a thickness ranging from 45 to 60 m. Although predominantly composed of lenses and tongues of clay and silt, it contains some channel fillings and lenses of permeable sand and gravel. This confining member supports a shallow water table distinguished by an irregular surface. As of 1965-70, the shallow water table overlying much of the confined system was less than 10 m below the land surface (Webster, 1973). At least near the Bay, the shallow water table did not fluctuate appreciably during the period of prolonged artesian-head decline terminating in 1966.

The development of irrigated agriculture in the valley began about 1900 and expanded to a maximum about the end of World War II. After 1945, population pressures caused a great transition of land use from agricultural to urban and industrial development. Agricultural pumpage increased from about 50 hm^3 per year in 1915-20 to a maximum of 127 hm^3 per year in 1945-50 (1 cubic hectometre, hm^3, = 1 x $10^6 m^3$ = 810.7 acre-feet). By 1970-75 most of the orchards had been replaced by houses, and agricultural pumpage had decreased to 25 hm^3 per year. Municipal and industrial pumpage, on the other hand, increased from 27 hm^3 per year in 1940-45 to 162 hm^3 per year in 1970-75. Total pumpage (Figure 9.14.2, bottom graph) increased nearly fourfold from 1915-20 to 1960-65--from 60 to 222 hm^3 per year--but then decreased 19 per cent to 185 hm^3 by 1970-75, in response to a rapid increase in surface-water imports, discussed later.

The historical increase in withdrawal of ground water was a principal factor in causing a fairly continuous and severe 50-year decline of artesian head. In the spring of 1916, the artesian head in index well 7Rl in San Jose was 3.7 m above land surface (Figure 9.14.2); by the autumn of 1966 it was 55 m below land surface. The second major factor in this 50-year decline of 59 m was the negative trend of the local water supply. The upper line in Figure 9.14.2 is a plot of the cumulative departure, in per cent, of the seasonal rainfall at San Jose from the 50-year seasonal mean, 1897-98 to 1946-47 (Calif. State Water Resources Board, 1955, p. 26). The 50-year mean is 34.85 cm. Except for the 6-year wet period 1936-42, the departure in the 50

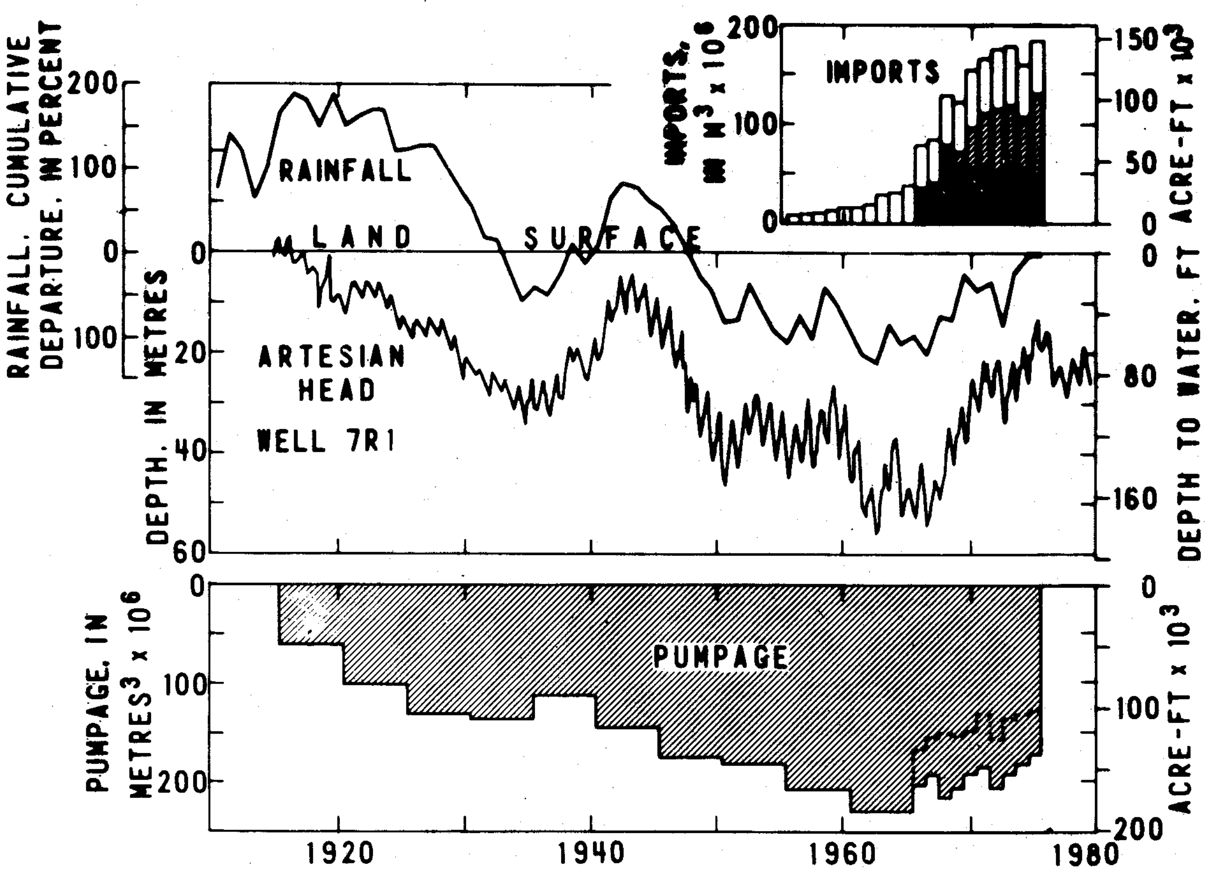

Figure 9.14.2 Artesian-head change in San Jose in response to rainfall, pumpage, and imports.

years 1916--66 was generally negative; the cumulative departure of 310 per cent from 1916 to 1966 represents a cumulative "deficiency" in rainfall of about 108 cm.

The 50-year decline in artesian head from 1916 to 1966 clearly was caused by the cumulative effect of generally deficient rainfall and runoff and a fourfold increase in withdrawals. The plot of artesian-head decline at index well 7R1 conforms in general with the cumulative departure of rainfall at San Jose.

9.14.4 LAND SUBSIDENCE

Land subsidence was first noted in 1932-33 when bench mark P7 in San Jose, established in 1912, was resurveyed and found to have subsided 1.2 m. As a result, a valleywide network of bench marks was established in 1934 (Poland and Green, 1962, Figure 3). The total length of survey lines comprising this bench-mark net was about 400 km. From 1934 to 1967 the National Geodetic Survey (formerly the U.S. Coast and Geodetic, Survey) resurveyed the network from "stable" bedrock ties a dozen times to determine changes in elevation of the bench marks; the latest full survey of the network was in 1967. In the 33 years 1934-67, subsidence along lines of benchmark control ranged from 0.3 to 1.2 m under the Bay to 2.4 m in San Jose (Figure 9.14.1). About 260 km^2 subsided more than 1 m. The subsidence record for bench mark P7 in central San Jose is plotted in Figure 9.14.3, together with the artesian head in nearby index well 7R1, taken from Figure 9.14.2. The black dots on the subsidence curve indicate times of bench-mark surveys. The fluctuations of artesian head represent the change in stress on the confined aquifer system; the subsidence is the resulting strain. Subsidence of bench mark P7 began about 1918 (note dotted inferred segment of subsidence plot representing the period 1912 to 1919) and reached 1.4 m in 1934. From 1938 to 1947 subsidence stopped, during a period of artesian-head recovery, in response to above-normal rainfall and recharge. (The natural recharge was supplemented by controlled percolation releases from newly constructed detention reservoirs on the larger streams.) Subsidence resumed in 1947 as a consequence of a rapidly declining artesian head due to deficient rainfall and increasing demand for ground water (Figure 9.14.2); it attained its fastest average rate in 1960-63 (0.22 m/year), in response to the rapid head decline of 1959-62 during a drought period (see Figure 9.14.2). By 1967 bench mark P7 had subsided 3.86 m.

Figure 9.14.4 shows land-subsidence profiles along line A-A′ from Redwood City to Coyote from 1912 through 1969 (for location, see Figure 9.14.1). The spring 1934 leveling was used as a reference base because this was the first complete leveling of the net. Note that from 1934 to 1967, maximum subsidence of 2.6 m was near bench mark W111, 4.8 km northwest of bench mark P7; also that from 1934 to 1960 the greatest subsidence along line A-A′ was 1.7 m, at bench mark

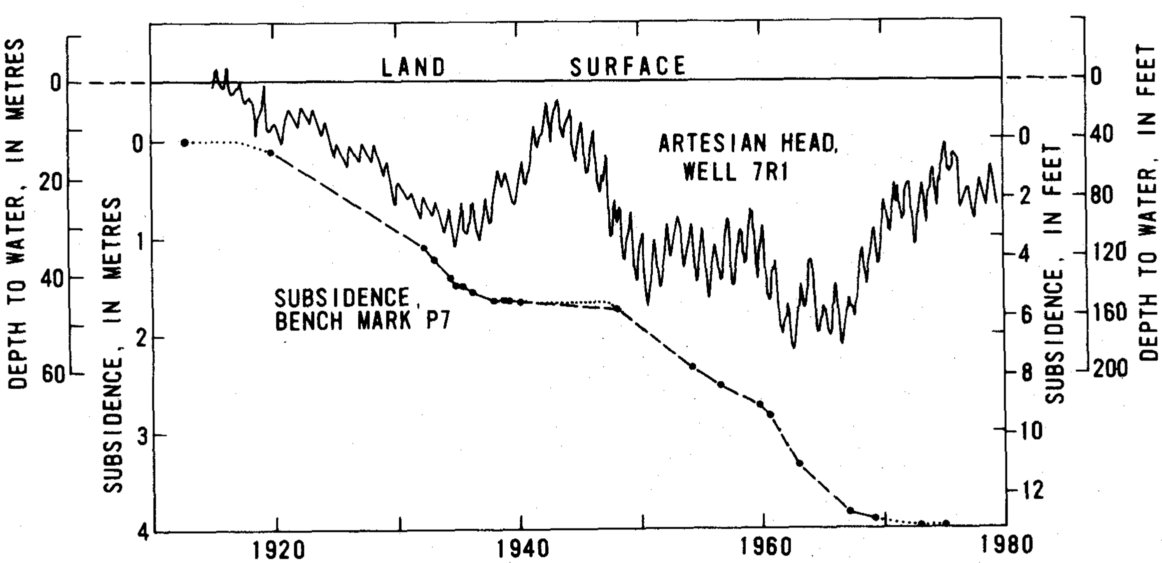

Figure 9.14.3 Artesian-head change and land subsidence, San Jose.

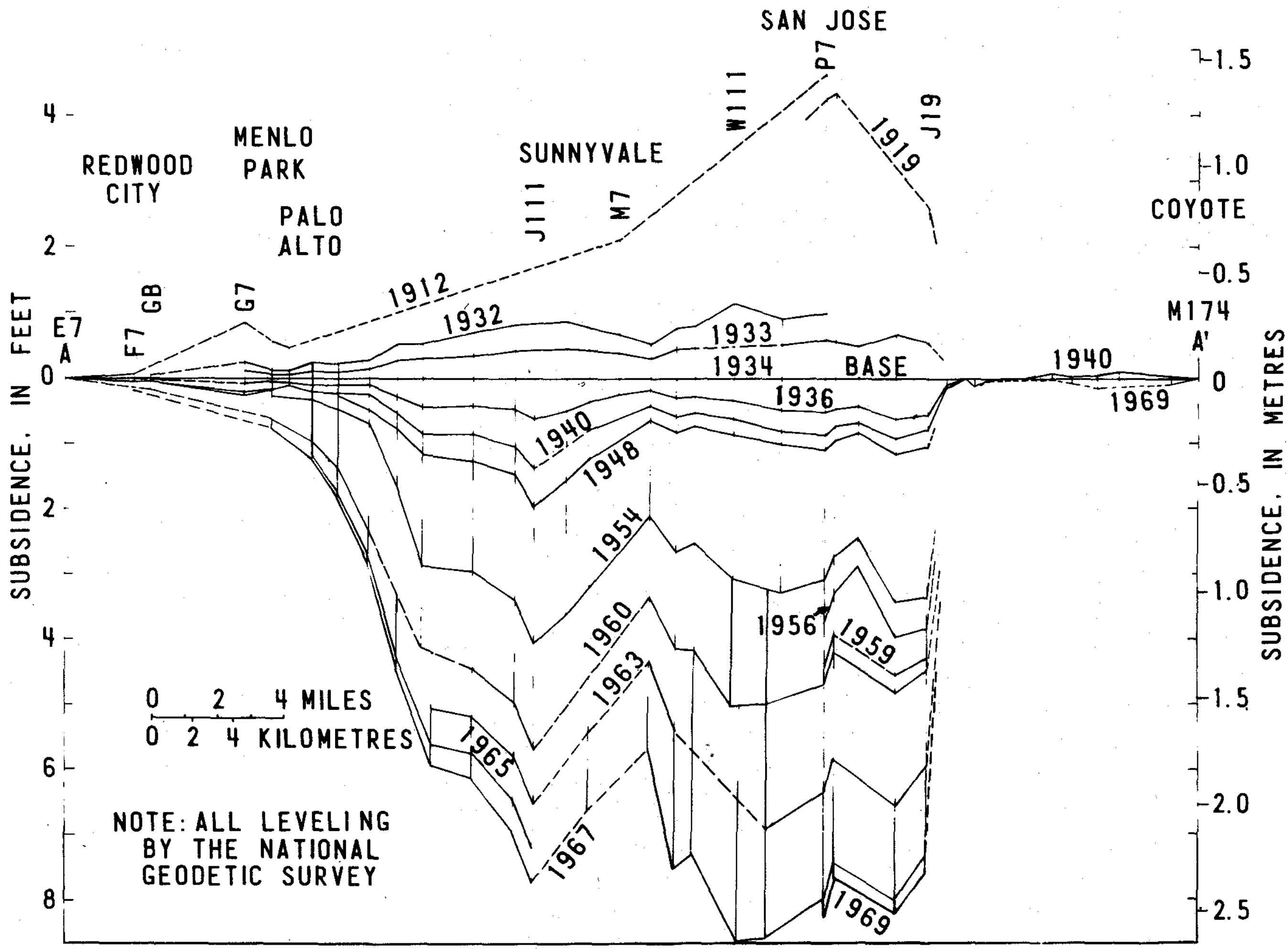

Figure 9.14.4 Profiles of land subsidence, Redwood City to Coyote, California, 1912-69.

J111 in Sunnyvale. Changes in the rate and magnitude of artesian-head decline doubtless have caused such geographic variations in subsidence rate and magnitude with time.

The volume of subsidence (pore-space reduction) planimetered from the 1934-67 subsidence map (Figure 9.14.1) was about 617 hm^3. If the ratio of the pre-1934 subsidence volume to the 1934-67 subsidence volume is assumed to be equal to the ratio of the pre-1934 subsidence of bench mark P7 to the 1934-67 subsidence of that bench mark, then the total subsidence volume from 1912 to 1967 is about 975 hm^3. Protrusion of well casings above the land surface and inundation of lands near the south end of San Francisco Bay also have furnished evidence of subsidence. Protrusion of well casings has been common in the subsiding area (Tolman, 1937, p. 345). Many of the casings gradually protruded 0.6-1 m above ground level but usually were cut off before protruding higher. This protrusion indicates that compaction of the deposits occurred in the depth interval above the bottom of the protruding casing. However, such protrusion often is accompanied by compression and rupture of the casing at depth and thus supplies only a minimal value of subsidence. In general, the deeper the compacting interval, the smaller will be the protrusion in proportion to the subsidence, because the frictional drag of the formation or the gravel-pack on the casing wall should increase proportionately with depth.

Although some horizontal movement doubtless has occurred in the subsidence area in association with the subsidence, no surveys or evidence of horizontal movement are known to the author.

The comparison of artesian-head change and subsidence from 1916 to 1967 (Figure 9.14.3) demonstrates beyond a reasonable doubt that the increase in effective stress resulting from the declining artesian head caused the compaction and the subsidence.

9.14.5 EXTENSOMETERS TO MEASURE COMPACTION

Extensometers (compaction recorders) were installed by the Geological Survey in 1960 in the cased core holes 305 m deep in San Jose (16C6) and in Sunnyvale (24C7) and in several unused water-supply wells. (For location, see Figure 9.14.1.) The purpose of this equipment was to measure the rate and magnitude of compaction occurring between the land surface and the well bottom. When first installed, the extensometer consisted of an anchor placed in the formation below the casing bottom, attached to a cable that passed over sheaves at the land surface and was counterweighted to maintain constant tension (Figure 2.5A). A recorder actuated by cable movement yields a time graph of the movement of land surface with respect to the anchor--the compaction or expansion of the deposits within that depth range. To reduce friction and increase the accuracy of measurement four of the extensometers were modified in 1972 by replacing the cable with a free-standing pipe of 3.8-cm diameter (Figure 2.5B) within the well casing of 10-cm diameter. The records obtained from these instruments show that the measured compaction to the depth of 305 m is nearly equal to the land subsidence as measured periodically by releveling of the bench-mark network. Thus, these instruments function as continuous subsidence monitors.

Figure 9.14.5 shows the measured compaction in the 305-m well in San Jose (well 16C6) and the compaction and artesian-head fluctuation in adjacent unused well 16C5 (depth 277 m) through 1975. The dashed line represents subsidence of adjacent bench mark JG2 as determined by periodic releveling from stable bench marks. Measured compaction of the confined aquifer system to the 305-m depth from July 1, 1960, to December 31, 1976, was 1.4 m.

9.14.6 MEASURES TAKEN TO CONTROL SUBSIDENCE

Local agencies have been working since the 1930’s to conserve water and to obtain water supplies adequate to stop the ground-water overdraft and raise the artesian head. Their program has involved (1) salvage of flood waters from local streams that would otherwise waste to the Bay and (2) importation of water from outside the valley. In 1935-36 five storage dams were built on local streams to provide detention reservoirs with combined storage capacity of about 62 hm^3 to retain floodwaters and permit controlled releases to increase streambed percolation (Hunt, 1940). The storage capacity of detention reservoirs was increased to 178 hm^3 in the early 1950’s (Calif. State Water Resources Board, 1955, p. 51).

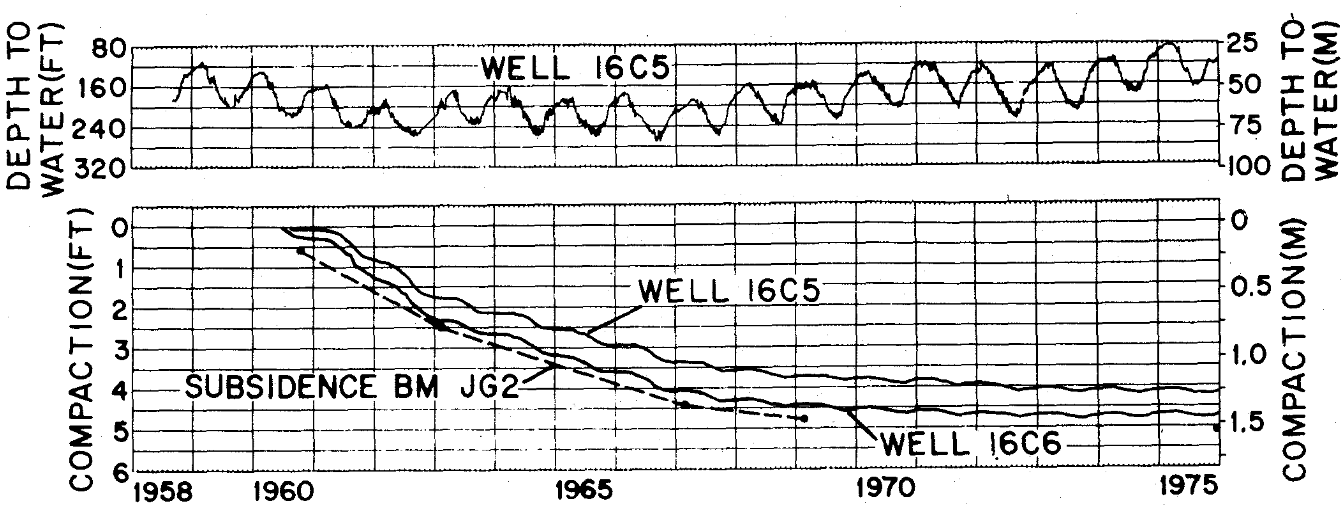

Figure 9.14.5 Measured water-level change, compaction, and subsidence in San Jose.

By 1960, sharply declining water levels furnished evidence that local resources were not adequate to supply present and future water needs. Steps were taken to increase water imports to the County. The import of surface water to Santa Clara County began about 1940 when San Francisco commenced selling water imported from the Sierra Nevada to several municipalities. This import increased to 15 hm^3 in 1960 and to 54 hm^3 by 1975 (see blank segments of yearly bars, upper right graph, Figure 9.14.2). Surface water imported from the Central Valley through the State's South Bay Aqueduct first became available in 1965; by 1974-75, the aqueduct import was 128 hm^3 (see cross-hatched plus diagonally ruled segments of yearly bars, upper right graph, Figure 9.14.2). As a result, total imports to Santa Clara County increased five-fold from 1964-65 to 1974-75--from 37 to 183 hm^3 per year.

The recovery of water level since 1967 has been dramatic. By 1975, the spring high water level at index well 7R1 (Figure 9.14.2) was 32 m above that of 1967, and about equal to the level in this well in 1925. This major recovery of head was due primarily to the fivefold increase in imports from the Central Valley. Two other favorable factors were the above-normal rainfall and the decreased pumpage (Figure 9.14.2).

The average seasonal rainfall at San Jose was 13 per cent above normal in the period 1966-75. The cumulative departure graph (Figure 9.14.2) indicates an increase of 120 per cent or a cumulative excess of about 41 cm above normal in the 9-year period.

The average yearly pumpage of ground water, which had reached its peak of 228 hm^3 in 1960-65, decreased to 185 hm^3 in 1970-75. A principal reason for this 19-per cent decrease was a use tax levied on ground-water pumpage since 1964. In 1977, for example, the ground-water tax was levied at $8.50 per unit (1 acre-ft. or 1234 m^3) for ground water extracted for agricultural purposes and at $34 per unit for ground water extracted for other uses. The energy cost to the consumer for pumping ground water in the Santa Clara Valley at 1977 prices was $10 to $15 per unit. Thus, the average total cost for ground water pumped for agricultural purposes was about $20 per unit and for other uses was about $45 per unit. The price for surface water delivered in lieu of extraction was $14 per unit for water used for agriculture and $39.50 per unit for water used for other purposes. The economic advantage of buying surface water, where available, is obvious.

Recharge to the ground-water reservoir from regulated local runoff released to stream channels and percolation ponds has been augmented since 1965 by water from the South Bay Aqueduct that could not be delivered directly to the user. The quantity diverted to recharge areas (cross-hatched segment of yearly bars, upper right graph, Figure (9.14.2) in the 10 years to 1975 averaged about 50 hm^3 per year and represents 56 per cent of the total import from the South Bay Aqueduct.

The marked decrease in rate of subsidence in response to the dramatic head recovery from 1967 to 1975 is demonstrated graphically by the compaction records from the two deep extensometers in San Jose and Sunnyvale (Figure 9.14.6). The rate of measured compaction in well 16C6 in San Jose decreased from about 30 cm per year in 1961 to 7.3 cm in 1967 and to 0.3 cm in 1973. Net expansion (land-surface rebound) of 0.6 cm occurred in 1974. In Sunnyvale, compaction of the sediments above the 305-m anchor in well 24C7 decreased from about 15 cm per year in 1961 to 1.2 cm in 1973; net expansion of 0.5 cm and 1.1 cm occurred in 1974 and 1975, respectively. Very deficient rainfall in 1975-76 and in 1976-77 virtually eliminated runoff and recharge from local sources, and water levels started to decline once more in 1976. In response, compaction and subsidence resumed once again. In San Jose at well 16C6, compaction in 1976 was 3.5 cm, about equal to that in 1968; in Sunnyvale, compaction was 1.6 cm.

9.14.7 COMPRESSIBILITY AND STORAGE PARAMETERS

Compressibility characteristics of fine-grained compressible layers (aquitards) can be obtained by making one-dimensional consolidation tests of "undisturbed" cores in the laboratory. As one phase of the research on compaction of the aquifer system, laboratory consolidation tests were made on 21 selected fine-grained cores from the two core holes. These tests were made in the Earth Laboratory of the United States Bureau of Reclamation at Denver, Colorado. Parameters tested included the compression index, C_c, a measure of the nonlinear compressibility of the sample, and the coefficient of consolidation, C_v, a measure of the time rate of consolidation. Complete results of these laboratory tests have been published (Johnson and others, 1968, Tables 8 and 9 and Figure 21). The 21 samples tested spanned a depth range from 43 to 292 m below land surface. The range of the compression index, C_c, was small compared to the range in the San Joaquin Valley: the maximum value was 0.33, the minimum 0.13, and the mean was 0.24. Of the 21 samples, 15 had C_c values falling between 0.20 and 0.30. This suggests that the nonlinear

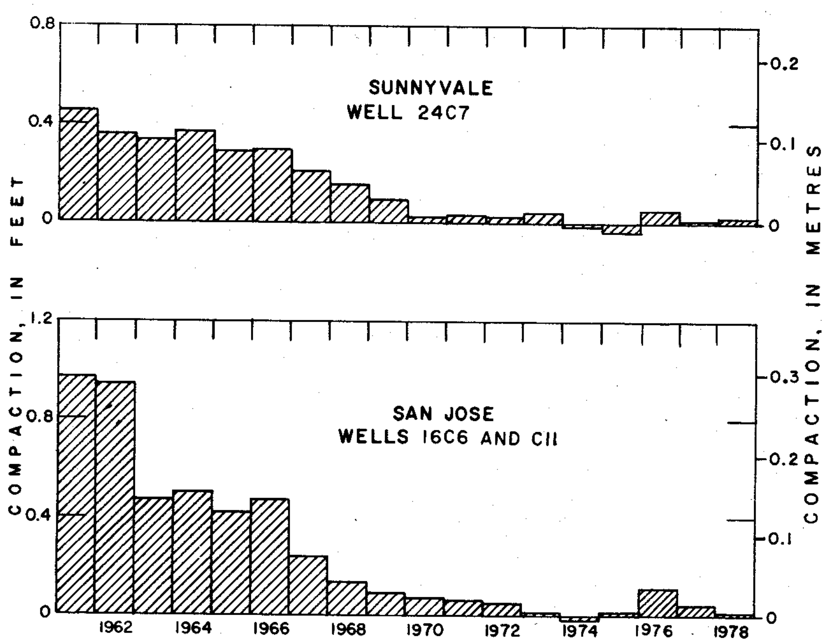

Figure 9.14.6 Measured annual compaction to 305-m (1,000-ft) depth.

compressibility characteristics of the aquitards in the confined aquifer system do not vary widely.

The plot of void ratio against the log of load (effective stress), known as the e-log p plot, can be used to obtain a graphic plot of compressibility versus effective stress. Such a graph can be used to estimate ultimate compaction due to a step increase in effective stress. This procedure applied to the laboratory consolidation tests at the Sunnyvale and San Jose core holes produced estimates of ultimate compaction that were only about one-third to one-half the values obtained by summing field measurements of compaction to date with residual compaction estimated from a one-dimensional simulation of the field observations (Helm, 1976). The reason for this disparity is not known. Apparently the samples tested were not representative of the aquitards that contributed most to the observed compaction.

Subsidence represents pore-space reduction which occurs almost wholly in the fine-grained compressible aquitards. At well 16C6 in San Jose the confined aquifer system is 244 m thick, from 61 to 305 m below land surface. Based on study of the microlog, the confined system contained 38 aquitards with a combined thickness of 145 m. The mean porosity of 27 core samples, determined in the laboratory, was 37 per cent. The total subsidence to date at well 16C6 is about 4 m. A reduction of 4 m in the thickness of the confined system requires about 1.8 per cent reduction in the porosity of the aquitards--for example, from 37 to 35.2 per cent.

The subsidence/head-decline ratio is a useful parameter in subsidence studies. The ratio is a rough approximation of the response of the aquifer system to a given change in stress. At San Jose, referring to the plot of subsidence for bench mark P7 and the artesian-head change in well 7R1 (Figure 9.14.3), the artesian head declined from 6 m below land surface in 1918 (approximate preconsolidation stress) to 55 m below land surface in 1966, for a net change of 49 m. Subsidence at bench mark P7 from 1918-66 was about 3.84 m. This means that as of 1966 the empirical ratio is 3.84 m/49 m = 0.08. The ratio of ultimate subsidence to head decline must therefore be larger than 0.08 at this site. Artesian head as measured in a well casing represents a composite pore pressure of all aquifers in the confined system that are tapped by the observation well. If and when the pore pressures in fine-grained aquitards reach equilibrium with those in the adjacent aquifers, compaction will cease, and the ratio of ultimate subsidence to head decline will be a true measure of virgin compressibility for the entire interval being stressed. Such an ultimate value is analogous to a storage coefficient.

Helm (1977), by means of a one-dimensional simulation of the long-term field observations of subsidence at bench march P7 and artesian head at well 7RI, provided the parameters used for estimating the ultimate compaction (subsidence) resulting from a step change in head of 49 m;

the computed compaction is about 5.3 m. Thus, on the basis of Helm's parameter values, the ultimate subsidence/head-decline ratio would be 5.3 m/49 m = 0.11. If we divide the ratio by the thickness of compacting aquitards, 145 m, we obtain the virgin compressibility (for stress increase beyond preconsolidation stress) of the aquitards:

$$5.3 \text{ m}/(145 \text{ m} \times 49 \text{ m}) = 7.4 \times 10^{-4} \text{m}^{-1}$$

As the water levels in the San Jose area rose rapidly after 1967 (Figure 9.14.2), the stress-strain curves obtained from paired measurements of compaction and artesian head began to show seasonal expansion during the winter months when the water level was highest and the effective stress on the confined system was lowest. These stress-strain loops can be used to obtain the compressibility of the confined system in the recoverable or elastic range of stresses (less than preconsolidation stress). One example (Figure 9.14.7) shows the stress-compaction plot for a pair of wells in San Jose from 1967 through 1974. Compaction was measured in well 16C6,11, 305 m deep, and stress in nearby well 16C5. Depth to water is plotted increasing upward. Change in depth to water represents an average change in stress in all aquifers of the confined aquifer system tapped by well 16C5. The lower parts of the descending segments of the annual loops for the winters of 1967-68, 1969-70, and 1970-71 are approximately parallel, as shown by the dotted lines, indicating that the response is essentially elastic in both aquifers and aquitards when the depth to water is less than about 55 m. The heavy dashed line drawn parallel to the dotted lines represents the average slope of the segments in the range of stresses less than preconsolidation stress. The reciprocal of the slope of this line is the component of the storage coefficient attributable to elastic or recoverable deformation of the aquifer-system skeleton, S_{ke}, and equals 1.5×10^{-3}. The component of average specific storage due to elastic deformation, S_{ske}, equals $S_{ke}/244 \text{ m} = 6.15 \times 10^{-6}\text{m}^{-1}$, if stresses are expressed in metres of water, and if γ_w (the unit weight of water) = 1, the average elastic compressibility of the aquifer system skeleton, α_{ke}, is equal numerically to S_{ske}.

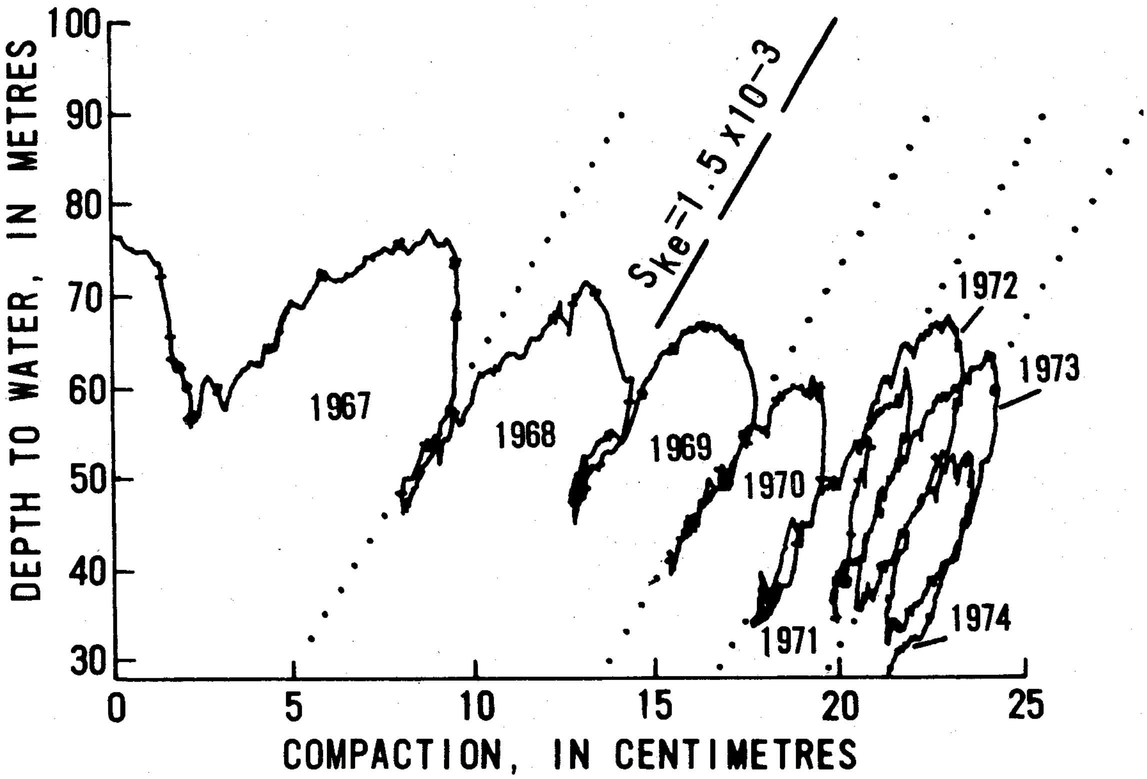

Figure 9.14.7 Stress change and compaction, San Jose site.

In these computations I have assumed that in the range of stresses less than preconsolidation stress, the compressibility of the aquitards and the aquifers is the same. Therefore, the full thickness of the confined aquifer system, 244 m, was used to derive the specific storage component, S_{ske}, in the elastic range of stress.

At these San Jose sites, then, the average compressibility of the aquitards in the virgin range of stress, 7.4×10^{-4} m^{-1}, is 120 times as large as the average compressibility of the confined aquifer system in the elastic range of stress, 6.15×10^{-6} m^{-1}. This great difference in response to stressing should be kept in mind when considering use of aquifer tests to derive hydrologic parameters, as well as in appraisal of subsidence potential.

9.14.8 ECONOMIC AND SOCIAL IMPACTS

Subsidence has created several major problems. Lands adjacent to San Francisco Bay have sunk as much as 2.4 m since 1912, requiring construction and repeated raising of levees to restrain landward movement of the saline bay water onto 44 km2 of land below high-tide level in 1967. Also, flood-control levees have been built and maintained near the bayward ends of the depressed stream channels. About $9 million of public funds had been spent to 1974 on such flood-control levees to correct for subsidence effects, according to Lloyd Fowler, former Chief Engineer of the Santa Clara Valley Water District. In addition, a major salt company has spent an unknown but substantial amount maintaining levees on 78 km2 of salt ponds to counter as much as 2.4 m of subsidence. Several hundred water-well casings have failed in vertical compression, due to compaction of the sediments. The cost of repair or replacement of such damaged wells has been estimated as at least $4 million (Roll, 1967). Including funds spent on maintaining the salt-pond levees, establishing and resurveying the bench-mark net, repairing railroads, roads, and bridges, replacing or increasing the size of storm and sanitary sewers, and making private engineering surveys, the direct costs of subsidence must have been at least 35 million dollars to date.

A major earthquake could cause failure of the bay-margin levees, resulting in the flooding of areas presently below sea level. The levees were constructed of locally derived weak materials and were designed only to retain salt-pond water under static conditions (Rogers and Williams, 1974). The potential for such an earthquake poses a continuing threat to flooding of the estimated 44 km^2 (4400 hectares) of land standing below high tide level as of 1967. Such a threat must have reduced the value of this land very substantially compared to the value if it all still stood above mean sea level as it did in 1912. This decrease in land value should be included in the gross costs of subsidence.

9.14.9 LEGAL ASPECTS

The successful management of a highly variable water supply to achieve a balance with an ever-increasing demand for water in Santa Clara County (not shown on map) has been remarkable for several reasons. First, maximum development of local water supplies and importation of water from two sources have momentarily brought supply and demand into balance. Secondly, by building up the ground-water storage in the recharge area, and thus the artesian head in the confined system, land subsidence was stopped, at least temporarily, by 1973. Thirdly, all this has been accomplished by bond issues, revenue from taxes, and water charges, thus avoiding a drawn-out expensive legal adjudication of the ground-water supply such as occurred in southern California, in the Raymond Basin (Pasadena vs. Alhambra, 1949).

9.14.10 CONCLUSIONS

Both the cause of subsidence and the means of its control are known. The evidence given here proves that the subsidence is caused by decline of the artesian head and the resulting increase in effective overburden load or grain-to-grain stress on the water-bearing beds in the confined system. The sediments compact under the increasing stress and the land surface sinks. Most of the compaction occurs in the fine-grained clayey beds (aquitards) which are the most compressible but have low permeability. Therefore, the escape of water from these slow draining aquitards (decay of excess pore pressure) and the increase in effective stress are slow and time-dependent, but the ultimate compaction is large and chiefly permanent.

The subsidence has been stopped by raising the artesian head in the aquifers until it equaled or exceeded the maximum pore pressures in the aquitards. The compaction and water-level records being obtained by the Geological Survey indicate that if the artesian head can be maintained 3 to 6 m above the levels of 1971-73, subsidence will not recur. On the other hand, subsidence will recommence if artesian head is drawn down as much as 6 to 9 m below the 1971-73 levels.

9.14-11 EPILOGUE

Recently the Santa Clara Valley Water District was given Historical Landmark status by the American Society of Civil Engineers for its major contributions to the development of the region. It was acknowledged that the district’s system is "the first and only instance of a major water supply being developed in a single ground-water basin involving the control of numerous independent tributaries to effectuate almost optimal conservation of practically all of the sources of water flowing into the basin."

9.14.12 REFERENCES

CALIFORNIA DEPARTMENT OF WATER RESOURCES. 1967. Evaluation of ground-water resources, South Bay: Calif. Dept. Water Resources Bull. No. 118-1, Appendix A, Geology, 153 p.

CALIFORNIA STATE WATER RESOURCES BOARD. 1955. Santa Clara Valley Investigation: Calif. State Water Resources Board Bull. No. 7, 154 p.

CLARK, W. 0. 1924. Ground water in Santa Clara Valley, Calif.: U.S. Geol. Survey Water-Supply Paper 519, 207 p.

DIBBLEE, T. W. 1966. Geologic map of the Palo Alto 15-minute quadrangle, California: Calif. Div. Mines and Geology, Map sheet 8.

HUNT, G. W. 1940. Description and results of operation of the Santa Clara Valley Water Conservation Districts project: Am. Geophys. Union Trans., pt. 1, p. 13-22.

HELM, D. C. 1977. Estimating parameters of compacting fine-grained interbeds within a confined aquifer system by a one-dimensional simulation of field observations: Internat. Symposium on Land Subsidence, 2d, Anaheim, Calif., Dec. 1976, Proc., p. 145-156.

JOHNSON, A. I., MOSTON, R. P., and MORRIS, D. A. 1968. Physical and hydrologic properties of water-bearing deposits in subsiding areas in central California: U.S. Geol. Survey Prof. Paper 497-A, 71 p.

MEADE, R. H. 1967. Petrology of sediments underlying areas of land subsidence in central California: U.S. Geol. Survey Prof. Paper 497-C, 83 p.

PASADENA v. ALHAMBRA (33 Cal. 2d 908 207 Pac. 2d 17) 1949; certiorari denied (339 U.S. 937) 1950.

POLAND, J. F. 1969. Land subsidence and aquifer-system compaction, Santa Clara Valley, California, USA, in Tison, L. J., ed., Land Subsidence, Vol. 2: Internat. Assoc. Sci. Hydrology, Pub. 88, p. 285-292.

_________. 1977. Land subsidence stopped by artesian-head recovery, Santa Clara Valley, California.: Internat. Symposium on Land Subsidence, 2d, Anaheim Calif., Dec. 1976, Proc., p. 124-132 (I.A.H.S., Pub. 121).

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.

ROGERS, T. H., and Williams, J. W. 1974. Potential seismic hazards in Santa Clara County, Calif.: Calif. Div. Mines and Geology, Special Report 107, 39 p. 6 pl.

ROLL, J. R. 1967. Effect of subsidence on well fields: Am. Water Works Assoc. Jour., v. 59, no. 1, p. 80-88.

TOLMAN, C. P. 1937. Ground Water: New York, McGraw-Hill Book Co., 593 p., lst ed.

TOLMAN, C. P., 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., p. 23-35.

WEBSTER, D. A. 1973. Map showing areas bordering the southern part of San Francisco Bay where a high water table may adversely affect land use: U.S. Geol. Survey Misc. Field Studies Map MF 530.