The Effect of Artesian-Pressure Decline on Confined Aquifer Systems and its Relation to Land Subsidence

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By J. H. GREEN

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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An appraisal of the relation of compaction of confined aquifer systems to porosity and the coefficient of storage

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THE EFFECT OF ARTESIAN-PRESSURE DECLINE ON CONFINED AQUIFER SYSTEMS AND ITS RELATION TO LAND SUBSIDENCE

By J. H. Green

ABSTRACT

Ground water in the Southwestern United States is derived chiefly from unconsolidated to semiconsolidated alluvial deposits. Where these deposits contain confined water, they may be susceptible to compaction and related land-surface subsidence, if artesian pressures are reduced.

Compaction of artesian-aquifer systems can be estimated from core tests if the artesian-pressure decline is known. Compaction occurs chiefly in the finer grained deposits; porosity decrease is greater near the top of the confined aquifer than near the bottom.

Because most of the compaction of these aquifer systems is permanent, the storage coefficient during the initial decline of artesian pressure greatly exceeds the storage coefficient during a subsequent pressure decline through the same depth range, after an intervening period of pressure recovery.

INTRODUCTION

Throughout the Southwestern United States, ground-water resources are derived chiefly from unconsolidated and semiconsolidated alluvial sediments. Owing to the nature of alluvial deposition, the ground-water reservoir is likely to contain one or more extensive and thick fine-grained beds that confine or partially confine underlying aquifers and form a confined aquifer system.

If artesian pressure is reduced, the resultant increase of grain-to-grain load in the aquifer system may cause compaction of deposits and an equal subsidence of the overlying land surface. The subsidence at any given location is related to the subsurface lithology and to the magnitude and duration of pressure decline, and it appears to be mostly inelastic and permanent. Careful releveling of surface bench marks is adequate to detect subsidence of tenths of a foot.

Figure 1 shows the areas of California where land subsidence is known to have resulted from the lowering of artesian pressure.

FIGURE 1.—Areas of land subsidence (solid black) in California caused by decreased artesian pressure. Dotted line outlines Central Valley.

Eight core holes have been drilled in California to study the causes of aquifer compaction and land-surface subsidence: four in the Los Banos-Kettleman City area, two in the Tulare-Wasco area, and two in the Santa Clara Valley (fig. 1). The core holes are from 760 to 2,200 feet deep, and most pentrate the full thickness of sediments tapped by wells in the artesian-aquifer systems.

Core samples for laboratory testing were taken at predetermined intervals. Tests included consolidation characteristics, physical and hydrologic properties, and petrographic analysis. The consolidation testing, from which data were gathered for this report, was done by the Earth Laboratory of the U.S. Bureau of Reclamation, Denver, Colo.

AQUIFER COMPACTION

Analysis of consolidation-test data and the known artesian-pressure decline in the same locality provide a means for computing aquifer compaction and land-surface subsidence. The method of computing aquifer compaction from consolidation tests and artesian-pressure decline has been described by Miller (1961). The following two examples illustrate the correspondence between actual land-surface subsidence and the computed aquifer-system compaction in the Santa Clara Valley, described in more detail elsewhere (Green, 1962).

Figure 2 shows the computed compaction and actual subsidence at core hole 7S/1E–16C6 and the hydrograph of a nearby water well. A comparison of actual subsidence to the water-level change shows that aquifer compaction was most pronounced at times when artesian pressure was declining and was lower than in any prior period. Compaction progressed rapidly between 1915 and 1934 and between 1948 and 1960.

From 1948 to 1951, rapid artesian-pressure decline at core hole 7S/1E–16C6 was accompanied by a rapid rate of subsidence. After 1951, the artesian pressure fluctuated widely but continued a slow decline. The lack of bench-mark leveling in 1951 prevents a short-term analysis of pressure change and subsidence. However, compaction computations indicate a quick response of subsidence to pressure decline, and the sinking of bench mark A149 from 1948 to 1960 probably is more irregular than is shown in figure 2.

Subsidence stopped or slowed considerably when artesian pressure (either rising or falling) was above the prior low (fig. 2). Between the middle 1930's and 1943, when artesian pressure was increasing, subsidence was extremely slow compared to the period before 1934, and may have ceased entirely by 1940. The subsidence net was not releveled between 1940 and 1948, and the change in elevation of bench mark A149 in that critical period is not known. However, the cessation of subsidence by 1940 and the subsidence of 0.16 foot between 1940 and 1948, interpreted in relation to artesian-pressure change, suggest stability from 1940 to 1947 and the renewal of subsidence in 1947. This interpretation would imply that compaction of the aquifer system was complete for the artesian pressure and grain-to-grain load of 1940, and did not resume until the piezometric surface was drawn down below the 1940 level (in 1947).

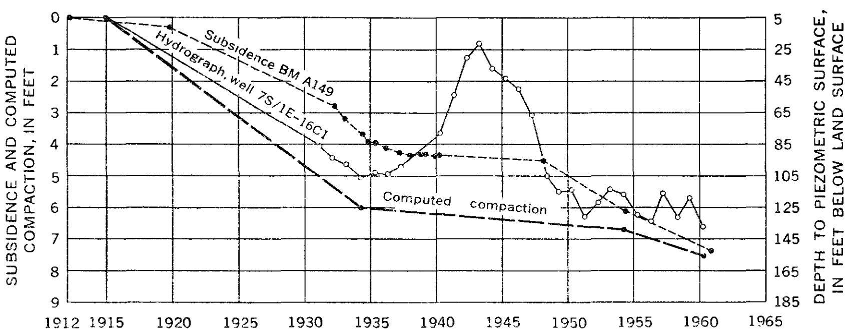

FIGURE 2.—Computed compaction and actual subsidence at core hole 7S/1E–16C6 and hydrograph of nearby water well.

Computed compaction for the 45-year period between 1915 and 1960 was 7.56 feet and the actual subsidence was 7.42 feet; computed compaction agrees closely with actual subsidence.

Figure 3 shows the computed compaction and actual subsidence at core hole 6S/2W–24C7 and a hydrograph of a nearby water well.

A definite period of time is required for fine-grained sediments to compact and adjust completely to increased loading conditions. According to Terzaghi (1943), the time required for complete adjustment is proportional to the square of the thickness of the compacting layer. In beds of silty clay and clay, the rate of compaction depends upon the rate at which water can be squeezed from the pore spaces. Thick clay beds may require hundreds of years to adjust, but thinner beds may need only a few tens of years or less. Because consolidation tests for core hole 24C7 indicated a large amount of lagging long-term compaction, figure 3 also shows a plot of computed compaction less lag. Residual compaction (and the resultant subsidence lag) is the potential compaction remaining in the consolidating sediments at any given time after the effective stress (grain-to-grain load) has been increased. In figure 3, compaction lag is represented by the vertical distance between the lines showing "computed compaction, less lag" and "computed compaction, total."

Computed compaction, less lag, for the 1915–60 period was 10.95 feet and the actual subsidence was 10.98 feet. (This degree of agreement should not be expected for all subsidence computations, but a reasonable approximation should be within 30 percent of the actual amount.) In both core holes, compaction as computed over long periods is more reliable than compaction computed for short periods. The longer periods allow more time for the accumulated residual compaction to occur. The relation of actual subsidence to the hydrograph shown in figure 3 is about the same as that shown in figure 2 for core hole 7S/1E–16C6.

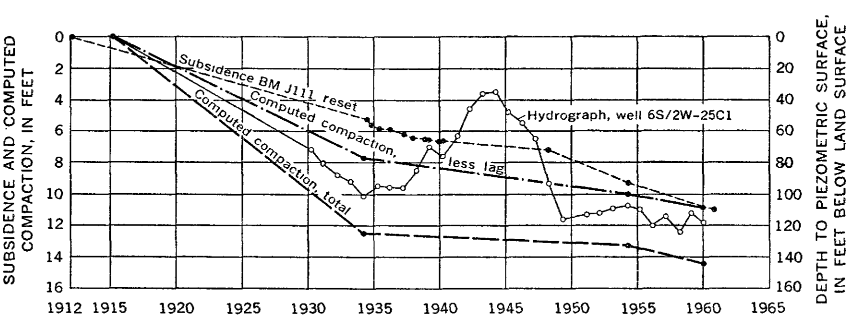

FIGURE 3.—Computed compaction and actual subsidence at core hole 6S/2W–24C7 and hydrograph of nearby water well.

It is concluded that laboratory consolidation tests and known artesian-pressure declines can be used to estimate aquifer compaction and the resultant land-surface subsidence.

EFFECTS OF COMPACTION ON ARTESIAN-AQUIFER SYSTEMS

As aquifer systems are reduced in volume by compaction due to artesian-pressure decline they undergo changes that influence their ability to store water: Porosity is reduced, and, if the aquifer system experiences more than a single stage of artesian-pressure decline through the same range, the storage coefficient during the first decline greatly exceeds that during subsequent declines.

POROSITY

When unconsolidated granular deposits are subjected to increased effective stress, rearrangement and deformation of mineral grains reduces the volume of the voids. The result is a porosity decrease in each compacting zone in the aquifer system.

The consolidation-test data and known artesian-pressure declines permit estimation of porosities at selected magnitudes of pressure decline. For compaction and porosity computations, the aquifer system is divided into relatively uniform lithologic zones by use of an electric log. Each zone is represented by the consolidation-test sample considered to be most typical of that zone. Consolidation-test results are plotted by the testing laboratory as graphs of void ratio versus load (load plotted on logarithmic scale). From these graphs, void ratio may be read directly for any value of applied load, or for any effective load on any part of the aquifer system. The approximate porosity decrease of any zone is computed from the relationship:

$$\Delta n=\frac{e_1}{1+e_1}-\frac{e_2}{1+e_2}$$

where Δn=porosity change,

e_1=void ratio prior to load change, and

e_2=void ratio after load change.

The average porosity decrease of the aquifer system undergoing compaction is the weighted average of the porosity decreases for all compacting zones.

Figure 4 shows a typical plot of void ratio versus log load and illustrates the method of computing Δn. Void ratio for a particular effective stress ("load" in fig. 4) can be determined more accurately by replotting the straight line segment of the curve on arithmetic

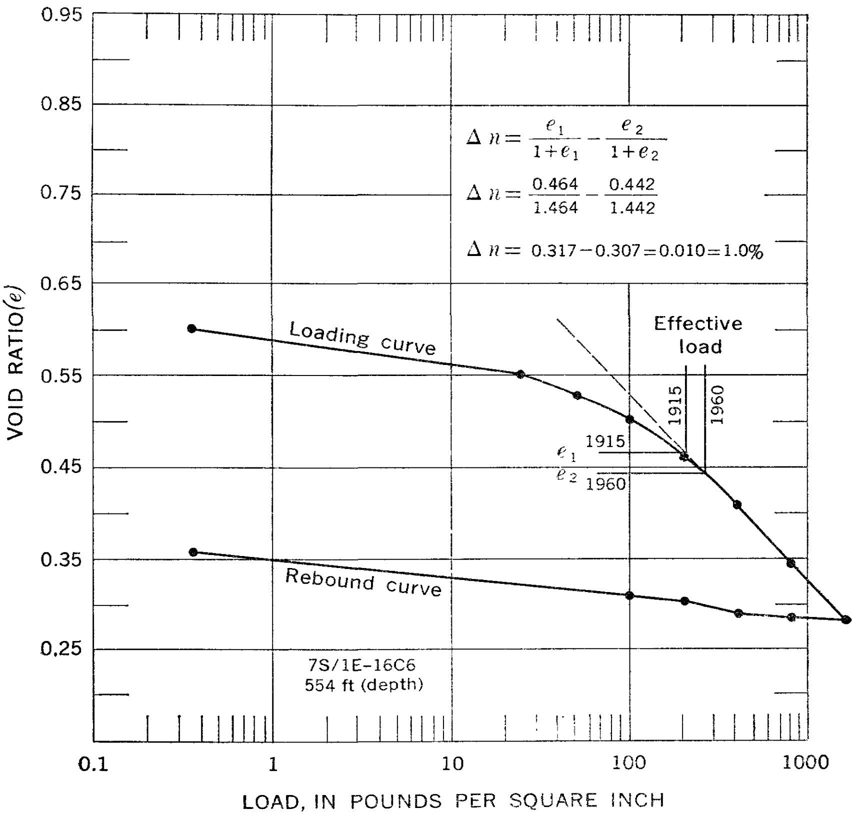

FIGURE 4.—One-dimensional consolidation and rebound curves and method of computing Δn from effective load and void ratio.

coordinates to a larger scale. However, when the void ratio (or porosity) of a compacting zone several tens of feet thick is estimated from a laboratory consolidation test on one sample about 1 inch thick, the accuracy of the estimate is dependent on how representative the sample is of the entire zone. Obviously, in alluvial deposits, the estimate for the whole zone is only a rough approximation, and the reader should keep this in mind.

Table 1 shows the porosity decrease from 1915 to 1960 in compacting zones in core hole 7S/1E–16C6 in the Santa Clara Valley (fig. 1), as computed from the laboratory consolidation tests and the change in artesian pressure. Because compaction occurs chiefly in the fine-grained sediments and is small to negligible in the sand and gravel zones, porosity decrease is shown only for the silt and clay zones. Porosity decrease ranges almost uniformly downward from 1.5 percent in the 245 to 335-foot zone to 0.2 to 0.3 percent near the bottom of the core hole. Average porosity decrease for all compacting zones is 0.9 percent. The analysis shows that decrease is greater in the upper zones than in the lower.

TABLE 1.—*Porosity decrease, in percent, in core hole 7S/1E–16C6, computed from typical consolidation curves*

Zone depth (feet)	Porosity		
	1915	1960	Decrease
245–335	35.1	33.6	1.5
335–390	30.4	29.1	1.3
390–420	34.4	33.2	1.2
420–435	31.8	30.7	1.1
435–475			
475–580	31.7	30.7	1.0
580–670			
670–750	32.6	31.9	.7
750–785			
785–815	25.9	25.4	.5
815–865	31.3	30.7	.6
865–895	34.4	34.2	.2
895–930	30.9	30.4	.5
930–1,000	34.3	34.0	.3
Weighted average	32.5	31.6	.9

Computations based on soil mechanics theory indicated that most compaction at core hole 7S/1E–16C6 would occur within a few years after the reduction of artesian pressures and that residual compaction would be minor. Therefore, porosity decreases in table 1 are considered as approximate actual values for the period from 1915 to 1960.

Table 2 shows porosity decrease from 1915 to 1960 in compacting zones in core hole 6S/2W–24C7, also in the Santa Clara Valley. Again, porosity decrease is greatest at shallow depth and least near the bottom. At this core hole, computations based on data from the time-consolidation curves indicated an appreciable amount of residual compaction. The average porosity decrease of 1.2 percent for the compacting section represents the porosity decrease at a future time, if and when all residual compaction, due to the 1915–60 pressure decline, is accomplished.

TABLE 2.—*Porosity decrease, in percent, in core hole 6S/2W–24C7, computed from typical consolidation curves*

Zone depth (feet)	Porosity		
	1915	1960	Decrease
185–215	35.9	34.1	1.8
215–415	37.8	35.9	1.9
415–550	32.7	31.5	1.2
550–680	37.0	36.1	.9
680–800	37.9	37.0	.9
800–905	37.2	36.4	.8
905–1,000	37.5	36.9	.6
Weighted average	36.7	35.5	1.2

Tables 3 and 4 show computed porosity decrease in core holes 16/15–34N1, in the Los Banos-Kettleman City area, and 23/25–16N1, in the Tulare-Wasco area. These areas are in the San Joaquin Valley, Calif. (fig. 1). Here also, compaction of the artesian-aquifer system reduces porosities more at shallow depth than near the bottom. At these locations, compaction computations (R. E. Miller and B. E. Lofgren, written communication, 1961) indicate that residual compaction is minor. Porosity decreases shown in tables 3 and 4 are considered actual values for the periods shown.

TABLE 3.—*Porosity decrease, in percent, in core hole 16/15–34N1, computed from typical consolidation curves*

Zone depth (feet)	Porosity		
	1905	1955	Decrease
637–700	48.4	47.2	1.2
700–750	33.7	32.4	1.3
750–772	40.6	39.4	1.2
772–795	---	---	---
795–842	40.8	39.6	1.2
842–895	33.0	31.9	1.1
895–907	40.4	39.3	1.1
907–940	32.8	31.7	1.1
940–980	42.0	40.7	1.3
980–1,130	---	---	---
1,130–1,200	30.5	29.6	.9
1,200–1,375	40.6	40.3	.3
1,375–1,465	31.9	31.0	.9
1,465–1,549	35.0	34.4	.6
1,549–1,720	39.2	38.7	.5
Weighted average	37.5	36.7	.8

TABLE 4.—*Porosity decrease, in percent, at core hole 23/25–16N1, computed from typical consolidation curves*

Zone depth (feet)	1905	1961	Decrease
296–330	43.2	40.5	2.7
330–363	43.5	40.8	2.7
363–420	---	---	---
420–615	41.9	39.8	2.1
615–660	40.8	38.7	2.1
660–673	39.4	37.5	1.9
673–707	40.1	38.3	1.8
707–760	39.0	37.1	1.9
Weighted average	41.5	39.4	2.1

Consolidation tests (fig. 4) show that the relation of void ratio to load, on a semilogarithmic plot, is approximately linear after the preconsolidation load is exceeded. As loading progresses, more load is required to produce an equal decrease in void ratio and in porosity. Sediments near the bottom of the section, which have been under greater natural overburden load than those near the top, would require a greater change in effective load to produce uniform porosity decrease throughout the compacting aquifer system. Where residual compaction is not a factor, porosity reduction is greatest near the top of the compacting aquifer system, because decreased artesian pressure causes a uniform increase of effective grain-to-grain load on the entire column of compacting sediments.

The rebound curve in figure 4 indicates an increase of void ratio, and consequent increase of porosity, when the sample is unloaded. When samples are taken from loaded conditions at depth, field effective stress is removed and they expand.

Laboratory porosity determinations made at, or near, atmospheric pressure reflect the unloading effect and indicate higher porosities than exist in the sediments at depth. Table 5 shows a comparison of porosities for individual depth zones of relatively uniform lithology determined by two methods: (1) from the void ratio of a representative sample loaded in a consolidometer, and (2) from averages of porosity values for samples at one or more depths in the zone, tested at atmospheric pressure. In every case the average porosity for the samples tested at atmospheric pressure is higher than that for the sample tested under load. The average difference for the two methods is 5.1 percent for the 17 zones listed in table 5.

The above comparison shows a need for all porosity determinations to be adjusted to pressures equal to those of the natural field conditions by means of consolidation-test data.

TABLE 5.—*Porosities, in percent, of samples from core holes in the Santa Clara Valley*

Zone depth (feet)	Porosity: From consolidation tests [1]	Porosity: From samples tested at atmospheric pressure [2]	Difference (percent)
Core hole 6S/2W-24C7			
185-215	34.1	38.8	4.7
215-415	35.9	38.1	2.2
415-550	31.5	38.8	7.3
550-680	36.1	36.6	.5
680-800	37.0	40.3	3.3
800-905	36.4	38.1	1.7
905-1,000	36.9	42.5	5.6
Core hole 7S/1E-16C6			
245-335	33.6	39.4	5.8
335-390	29.1	36.2	7.1
390-420	33.2	43.0	9.8
420-435	30.7	35.7	5.0
475-580	30.7	33.1	2.4
670-750	31.9	33.2	1.3
785-815	25.4	39.0	13.6
815-865	30.7	36.0	5.3
895-930	30.4	34.8	4.4
930-1,000	34.0	40.8	6.0

[1] Porosity as of 1960 from field effective stress and consolidation curves, Earth Laboratory, U.S. Bur. Reclamation.
[2] Average porosity of zone from samples tested at Denver Hydrologic Laboratory, U.S. Geol. Survey.

GROUND-WATER STORAGE

The amount of compaction of the aquifer system represents an equivalent reduction in pore space and in stored water. The volume of land subsidence caused by compaction, both inelastic and elastic, is equal to the volume of pore-space reduction. Therefore, the magnitude of land subsidence at any locality can be used to determine the approximate coefficient of storage. Although the gross storage coefficient, S, equals S_w+S_c, the volume of water produced by water expansion, S_w, can be ignored in highly compressible aquifer systems because this volume is negligible compared to that produced by porosity reduction. At any locality, the component of storage derived from compaction of the artesian aquifer, S_c is equal to the amount of land subsidence (feet of water produced) divided by the reduction of artesian head, in feet (Poland, 1961, p. 53).

In the Santa Clara Valley, two periods of large-scale reduction of artesian pressure have occurred since 1915. The magnitude of subsidence near the two core holes is known for both these periods. Analysis of subsidence and artesian-pressure reduction indicates that the storage coefficient of the aquifer system was much greater during the first drawdown period (1915–34) than during the second drawdown period.

Figure 2 shows that about 100 feet of artesian-head decline at core hole 7S/1E–16C6 produced about 3.7 feet of subsidence between 1912 and 1934. The indicated coefficient of storage, S_c, for the first drawdown phase is about 0.04. Between 1934 and 1943 the artesian head nearly recovered to its original level. The second drawdown phase, through the same range of pressure, began in 1943, and the artesian head declined about 85 feet, to the 1934 level, by 1948. During this period, land-surface subsidence was only about 0.09 foot. The indicated coefficient of storage, S_c, for the second drawdown phase is about 0.001. The coefficient of storage during the first drawdown phase exceeded that of the second by a ratio of about 40 to 1. Furthermore, the coefficient of storage, S_c, during the second drawdown phase has decreased to the same order of magnitude as the coefficient of storage obtained from a short-term pumping test.

Figure 3 shows that about 100 feet of artesian-head decline at core hole 6S/2W–24C7 produced about 5.3 feet of subsidence between 1912 and 1934. The indicated coefficient of storage for the first drawdown phase is about 0.05. Between 1934 and 1944, the artesian head recovered about 65 feet above the 1934 level. The second drawdown phase, through the same range of pressure, began in 1944, and the artesian head declined about 65 feet, to the 1934 level, by 1948. During this period, land-surface subsidence was only about 0.29 foot. The indicated coefficient of storage for the second drawdown phase is about 0.004. The coefficient of storage during the first drawdown phase exceeded that of the second by a ratio of 13 to 1.

Residual compaction (that due to the first drawdown phase, but not yet accomplished by 1944) at core hole 6S/2W-24C7 was part of the total compaction between 1944 and 1948 and caused the indicated storage coefficient for that period to be much larger than it would have been if the second drawdown phase had occurred after residual compaction had been completed.

If all compaction (and subsidence) were elastic, the land surface would subside during periods of artesian-head decline and rebound an equal amount if head recovered to the initial level. The coefficient of storage would be the same for each repetition of drawdown through the same range of head decline. However, because the compaction is almost wholly inelastic and rebound is negligible, the coefficient of storage for the first drawdown phase greatly exceeds that of the second.

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