

PREDICTION OF FUTURE SUBSIDENCE ALONG DELTA-MENDOTA AND SAN LUIS CANALS, WESTERN SAN JOAQUIN VALLEY, CALIFORNIA

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ABSTRACT

About 120 miles of the Delta-Mendota and San Luis Canals, constructed by the Bureau of Reclamation, have been affected by subsidence caused by overdraft of ground water. When the Delta-Mendota Canal was completed in 1951, the subsidence was not recognized. From 1905 to 1951 piezometric ground-water levels along the alignment declined up to 200 feet. Canal deliveries stopped the overdraft, but continuing readjustment of pore pressures has caused some "residual subsidence" to continue at gradually diminishing rates. The subsidence has affected the downstream 35-40 miles of the canal, locally exceeding 6 feet from 1953 to 1966. Estimates of ultimate future subsidence, varying from traces to 3.6 feet, were derived from bench mark data treated as an exponential decay function.

About 80 miles of the San Luis Canal, constructed in 1963-67, are subsiding due to ground-water overdraft. From 1905 to 1962, piezometric levels along the alignment declined up to 470 feet, causing up to 18 feet of subsidence. Ultimate subsidence after 1963 was estimated using subsidence rates or piezometric decline-subsidence ratios and varied from traces to 15.2 feet (based on subsidence rates) or 10.4 feet (based on the ratios).

Hydrocompaction of low-density sediments above the water table occurs in two portions of the San Luis Canal. The phenomena may be related to freezing swelling and following freeze-drying of Pleistocene mudflows. Ultimate amounts of hydrocompaction ranging from traces to 20 feet were calculated from average dry densities of sediments and "ultimate" density values obtained in a few long-flooded areas.

RÉSUMÉ

Les canaux Delta-Mendota et de San Luis construits par le Bureau of Reclamation ont été affectés sur environ 120 milles par des affaissements provoqués par des pompages exagérés de l'eau souterraine. Quand le canal de Delta-Mendota fut achevé en 1951, on ignorait l'existence d'affaissements. De 1905 à 1951, les niveaux piézométriques le long de cet alignement tombèrent de 200 pieds. L'eau du canal arrêta l'action des pompages, mais le réajustement continu des pressions des pores a causé une continuation de l'action d'"affaissements résiduels" à des taux graduellement décroissants. Les affaissements ont affecté les 35-40 milles de la partie aval du canal, dépassant localement 6 pieds de 1953 à 1966. Une estimation des affaissements futurs, variant de traces à 3,6 pieds, a été déduite de l'examen de la descente de repères, traitée comme une fonction exponentielle décroissante.

Environ 80 milles du canal de San Luis, construit en 1963-67, s'affaissent sous l'action du retrait de l'eau souterraine. De 1905 à 1962, le niveau piézométrique le long de son alignement a déchu de 470 pieds, causant un affaissement de 18 pieds. L'affaissement futur après 1963 a été estimé en utilisant les taux d'affaissement ou les rapports entre la descente du niveau piézométrique et l'affaissement. Il varie de traces à 15,2 pieds (en utilisant les taux d'affaissements) ou 10,4 pieds (d'après les rapports dont question ci-dessus).

La compaction hydrique de sédiments de faible densité au-dessus du niveau phréatique se produit dans deux portions du Canal San Luis. Le phénomène peut être mis en relation avec le gonflement par congélation et le séchage des flots de boue congelés du Pleistocène. Pour l'avenir, la valeur de la compaction variant de traces à 15 pieds a été calculée des densités moyennes des sédiments secs et des densités "finales" obtenues dans une zone assez longuement inondée.

INTRODUCTION

Land subsidence due to irrigation overdraft of ground water and hydrocompaction related to wetting of porous, low-density sediments are serious geologic problems in several areas in the United States. Estimates of ultimate amounts of subsidence are important for design, construction, rehabilitation and operation of water conveyance projects in such

areas. This paper describes basic data, ideas, and methods of predictions which were recently used by the US Bureau of Reclamation in the San Joaquin Valley, California (fig. 1).

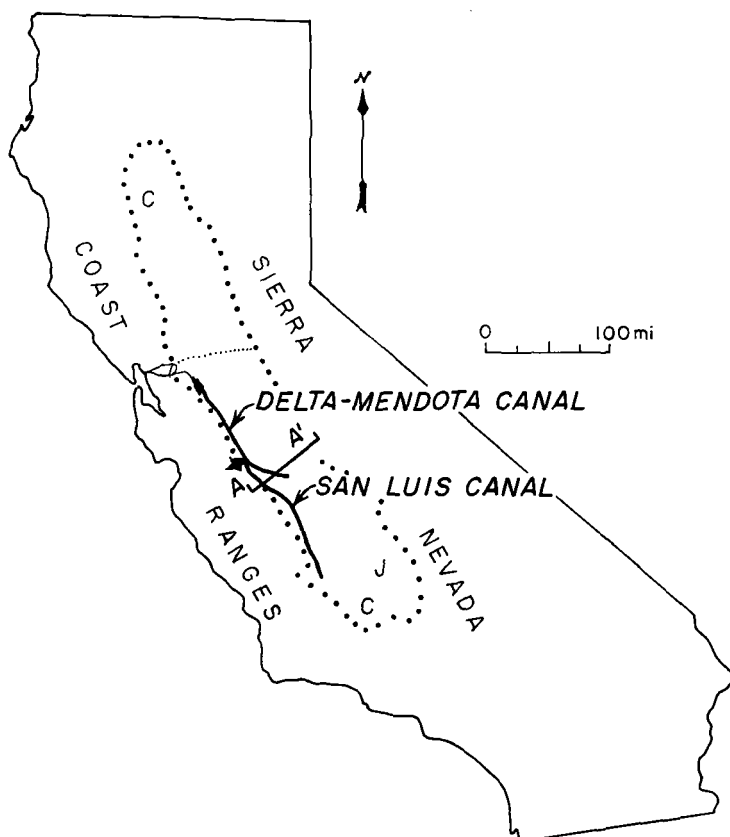


FIGURE 1. *State of California-location map*

C *Central Valley*

J *San Joaquin Valley*

A-A' *Geologic section shown on figure 2*

The valley is the southern portion of California's Central Valley and is one of the world's most productive agricultural areas. The climate is semiarid of Mediterranean type; modern farming requires intense irrigation. Artesian ground water has been used for irrigation since around 1900. Irrigated acreage and the overdraft of ground water expanded notably in the late 1940's causing an acceleration of land subsidence.

Importation of surface waters was pioneered by USBR in 1951 with the completion of the Delta-Mendota Canal (USBR, 1961). Additional water imports to the south were accomplished in 1967 by the completion of the San Luis Unit with a 101.5-mile-long canal (USBR, 1966). Some reaches of these canals are affected by subsidence. Methods of prediction of ultimate future subsidence along the canals are described below.

REGIONAL GEOLOGY AND GROUND WATER

The 250-mile-long San Joaquin Valley is a large, northwesterly trending syncline between the Coast Ranges and the Sierra Nevada (fig. 1, Bailey, 1966). The valley is 30 to 50 miles wide, and is filled with thick predominantly alluvial, Cenozoic clays, sands, and gravels, overlying more or less consolidated older, mostly marine sedimentary beds (fig. 2).

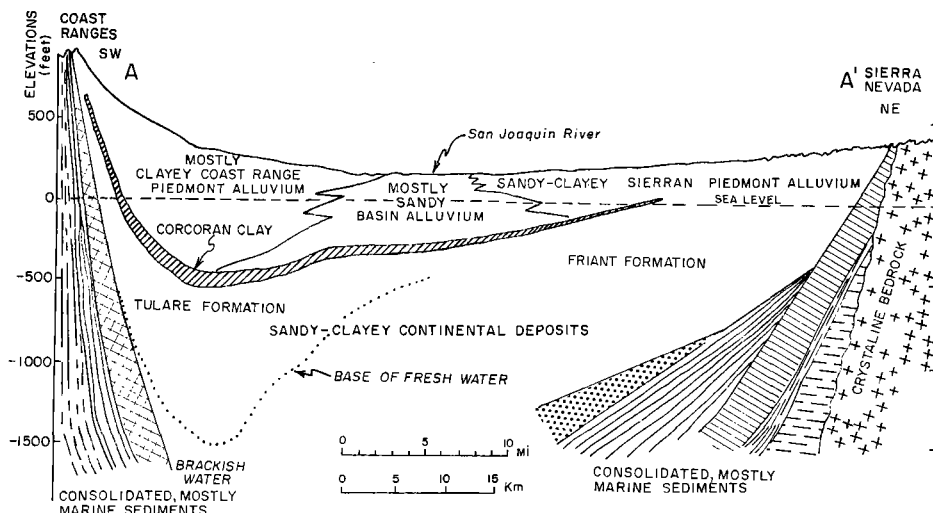


FIGURE 2. Diagrammatic geologic section across San Joaquin Valley looking northwesterly (for location see fig. 1)

The near surface deposits consist of eastern and western belts of piedmont alluvium separated by the central zone of river and lake deposits. The Coast Range piedmont consists of sandy-gravelly deposits in main fans and more clayey, coalescing interfan bodies deposited essentially by mudflows.

The most widespread bed in the upper continental portion of the valley fill is the Pleistocene Corcoran clay, a buried lacustrine bed (fig. 2, Frink and Kues, 1954). The clay creates confined ground-water conditions in the underlying fluvial beds which are the principal aquifers. A semiconfined ground-water body occurs in river sands above the Corcoran clay (fig. 2).

SUBSIDENCE—GENERAL DATA

Increases of irrigation pumping in the area and associated decreases of sub-Corcoran piezometric water levels resulted in increased effective load and corresponding compaction—"deep subsidence." The phenomenon was first recognized by the Bureau in 1951-52 and an "Interagency Committee" was initiated by the Bureau to study subsidence (Poland, 1958). Particularly comprehensive studies were made by U.S. Geological Survey.

The basic data for present studies were: (a) periodic levelings of numerous bench marks, (b) maps showing piezometric ground-water levels, and (c) a few observation holes with compaction recorders. The recorder data (fig. 3) indicate that most subsidence occurs in and below the Corcoran clay.

A comparison of topographic quadrangles surveyed in 1923-28 and 1926-33 failed to indicate any elevation changes caused by subsidence. However, subsidence was noted by releveling of a bench mark near Mendota in 1935. The early 1930's are therefore a probable time of the beginning of subsidence. Total subsidence in the area has locally exceeded 25 feet.

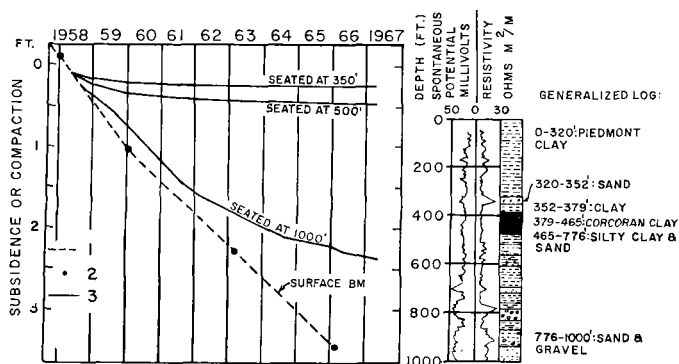


FIGURE 3. Subsidence of a surface bench mark and compaction of deposits to depths indicated, from compaction recorders, Delta-Mendota Canal near Ora Loma

Hydrocompaction is restricted mostly to the Little Panoche-Panoche and Panoche-Cantua interfans (fig. 4). Moisture contents and dry densities of clayey sediments prior to the irrigation were locally as low as 5 to 8 percent and 75 to 80 pounds/ft³. When wetted, these deposits compact as much as 12-15 feet, and produce tension cracking and sinkholes which damage canals, ditches, roads, buildings, etc. (fig. 5A, B, C).

The origin of the low-density sediments is uncertain: Present-day mudflows and near-surface (0 to 3 or 4 ft) piedmont deposits have high dry densities (about 95 pounds/ft³). Most of the piedmont alluvium was deposited during Pleistocene time. Hummocky soil surfaces and intra-formational, severely contorted bedding are common in the area and are very similar to typical permafrost features (Prokopovich 1969). Perhaps the origin of the low densities may be related to paleo-climates as follows: Pleistocene mudflows from the Coast Ranges were frozen in the valley. Expansion of water by freezing expanded the saturated sediments which were subsequently not melted but "freeze dried" in the semi-arid environment. Consequently, the low densities of the sediments were preserved. Sandy well-drained fan deposits were not expanded by freezing and became nonsubsiding terrains.

DELTA-MENDOTA CANAL—ESTIMATED SUBSIDENCE

The existence of subsidence in the area was not known during preconstruction and construction studies, but discrepancies between old and new levelings were consistently encountered in the downstream 35 to 40 miles. Numerous bench marks were established after completion of the canal in 1952-1953, when the subsidence was recognized by the Bureau. From 1953 to 1966 subsidence along 35-40 miles of the canal locally exceeded 6 feet (fig. 6) and canal lining, bridges, pipe crossings and other structures became more or less flooded (fig. 5E, F).

From 1905 (the earliest record) to 1953, sub-Corcoran piezometric levels along the canal declined as much as 200 feet causing up to 6 feet of subsidence. Canal deliveries ended the overdraft and, since 1953, piezometric levels below and above the Corcoran clay

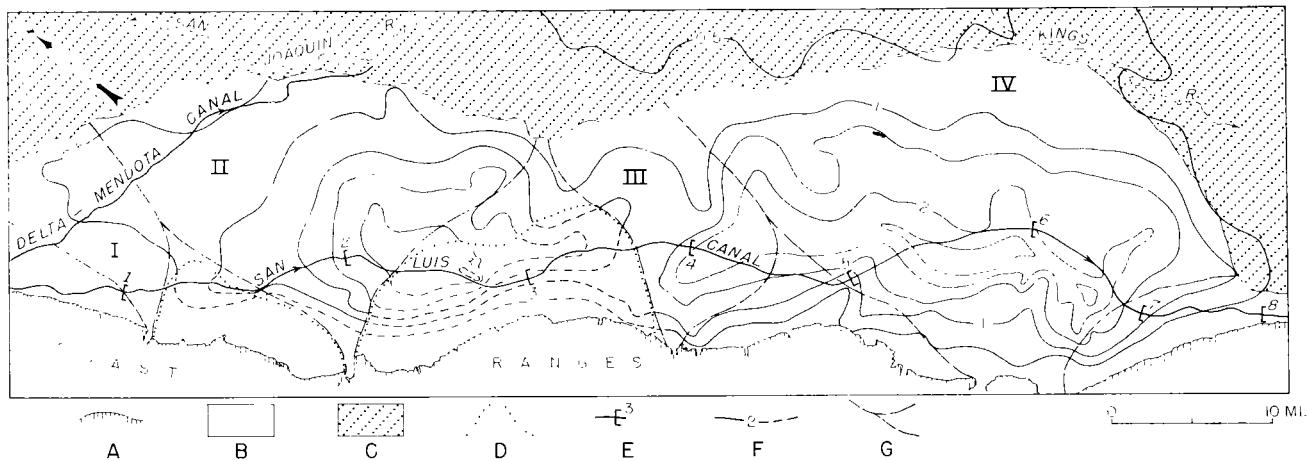


FIGURE 4. Geologic map of west-central San Joaquin Valley and land subsidence between 1963 and 1966. A. Edge of Coast Ranges; B. Piedmont Coast Range alluvium; C. River and lake alluvium; D. Boundary of areas affected by hydrocompaction; E. Canal check with number; F. Subsidence contour line, contour interval 1/2 ft; dashed where affected by hydrocompaction; G. Boundary of piedmont fans.

Major fans: I Little Panoche, II Panoche, III Cantua, IV Los Gatos-Zapato

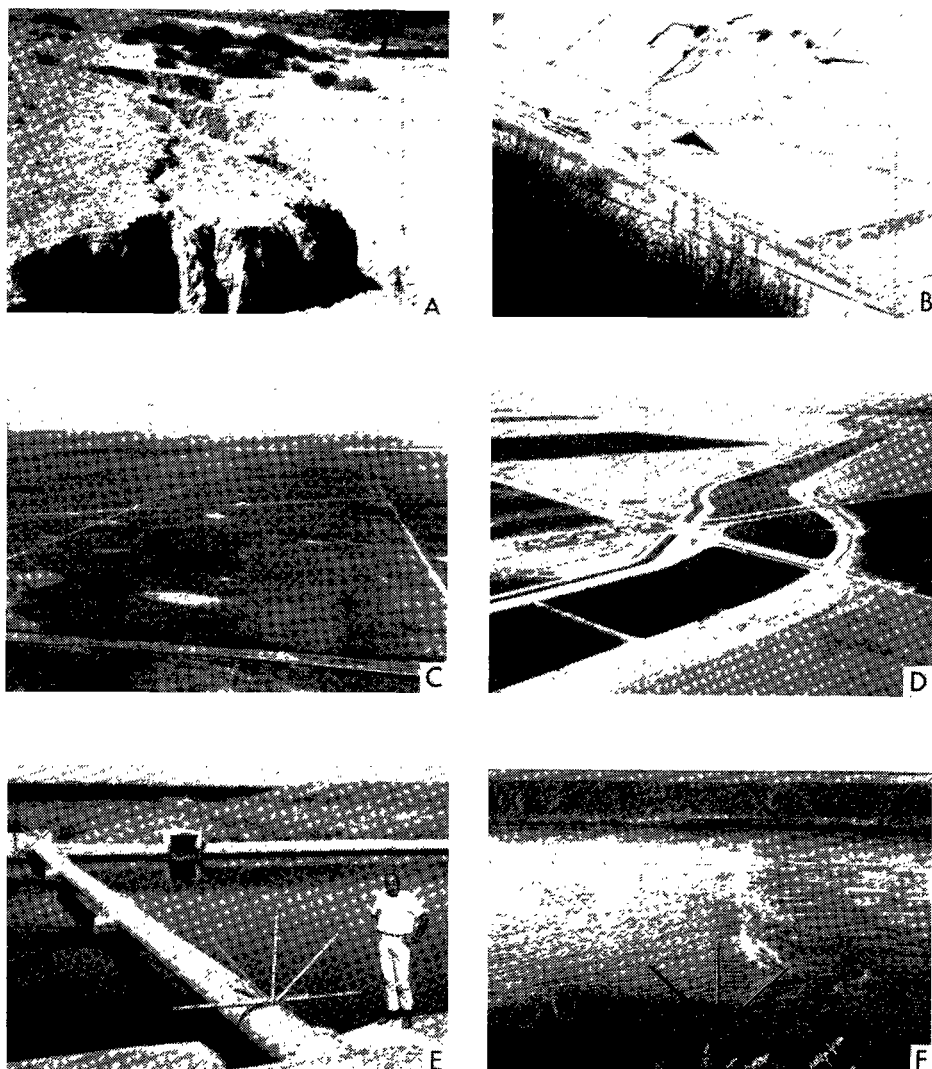


FIGURE 5A, B, C, D. *Hydrocompaction on Panoche-Cantua Interfan:*

- A. *Soil cracks caused by a nearby irrigation ditch;*
- B. *Damage to a test section of a canal at the State test site;*
- C. *Sinkholes created by irrigation in originally flat fields;*
- D. *Preconstruction flooding of San Luis Canal alignment.*

FIGURE 5E,F. *Land subsidence along Delta-Mendota Canal:*

- E. *Normal pipe crossing and concrete lining in stable area;*
- F. *Similar crossing in subsiding area.*

showed some fluctuation but have not progressively declined. Hence the postconstruction subsidence is a progressively diminishing residual action (fig. 7), caused by the gradual readjustment of pore pressures.

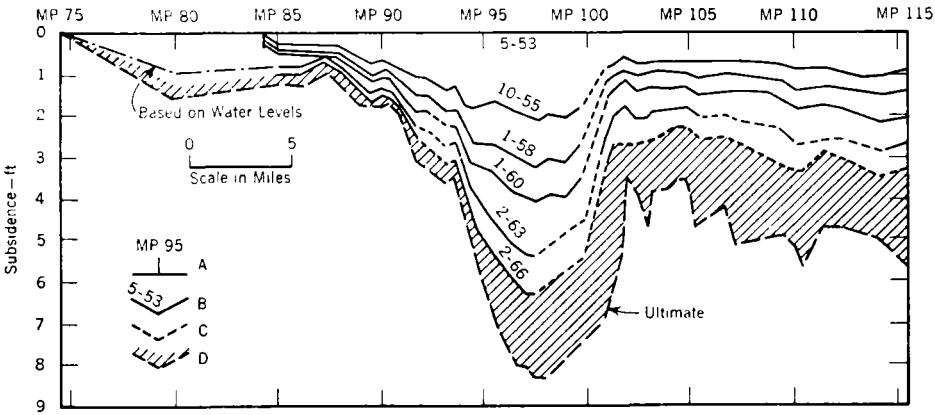


FIGURE 6. 1953-1966 and future land subsidence in downstream reaches of the Delta-Mendota Canal.
A. Mile post distance from intake;
B. Date of survey;
C. Interpolations to bridge data gaps;
D. Predicted ultimate subsidence

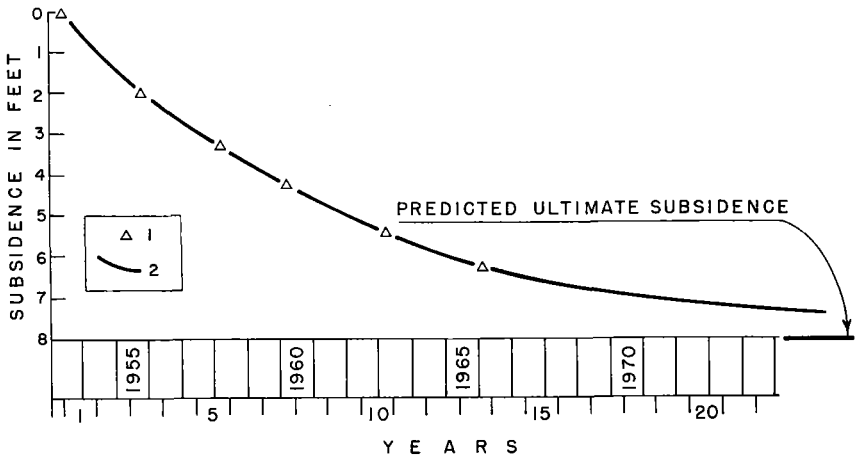


FIGURE 7. Typical graph of residual and calculated subsidence of the bench mark 96.61. 1. Measured values; 2. Calculated curve

Attempts were made to calculate ultimate subsidence using laboratory consolidometer tests of samples from a core hole at the canal (USBR 1956, 1959, Miller 1961). For the entire canal this method would require numerous holes and laboratory tests. It is also questionable how well 20-30 samples would represent a heterogeneous column of sediments several hundred feet thick.

Time-subsidence graphs of bench marks, influenced by residual subsidence, could be considered as "consolidation graphs" under a constant load. Rates of change in such

graphs appear to be proportional to the amount of uncompleted consolidation. This is characteristic, and suggests the use, of an exponential decay function with the following form (fig. 8): $Z - y = Ae^{Bt}$ in which $Z - y$ is uncompleted subsidence, y is recorded subsidence after 1953, t is time after 1953, A and B are unknown constants and Z is ultimate subsidence after 1953. With 3 data points from a bench mark graph the three unknowns including ultimate subsidence (Z) can be calculated (fig. 7).

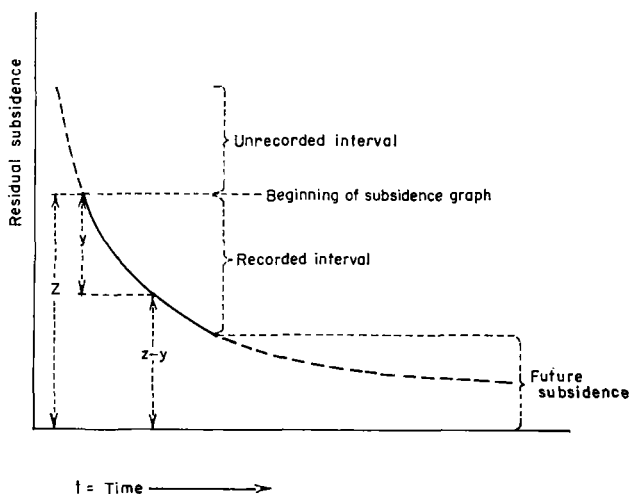


FIGURE 8. Exponential decay curve of residual subsidence

The calculated values of subsidence after January 1966 varied from traces to 3.6 feet (fig. 6). The validity of the approach was confirmed indirectly by correlation with recorded subsidence data (fig. 7). (Prokopovich and Herbert 1968). It was estimated that the residual subsidence (lag) will be virtually completed during the next 20-25 years.

SAN LUIS CANAL—ESTIMATED SUBSIDENCE

Land subsidence in the area was well known and studied prior to the canal construction. It affects about 80 miles of the alignment. From 1905 to 1962, piezometric levels along the alignment declined 300-470 feet (fig. 9) causing as much as 18 feet of subsidence (fig. 10). Historic subsidence piezometric decline ratios along the canal varied from 0.01 to 0.06.

Estimates of ultimate future subsidence were required for design of the canal. The first estimate was made in April 1961, using 1956-1958 and 1958-1960 subsidence maps and published 1:24,000 topographic quadrangles. It was assumed that subsidence would continue at the same rates until the end of ground-water overdraft which would occur in January 1968 with the completion of the canal and expected completion of the distribution system and that residual subsidence would continue with diminishing rates and would eventually total an amount equal to 5 years of subsidence at the same rates. Strip maps of the canal area were drawn showing estimated topography at the beginning and the end of construction (January 1963, January 1968) and under the assumed ultimate conditions. The next estimate was made in 1963 and was based on the same assumptions but

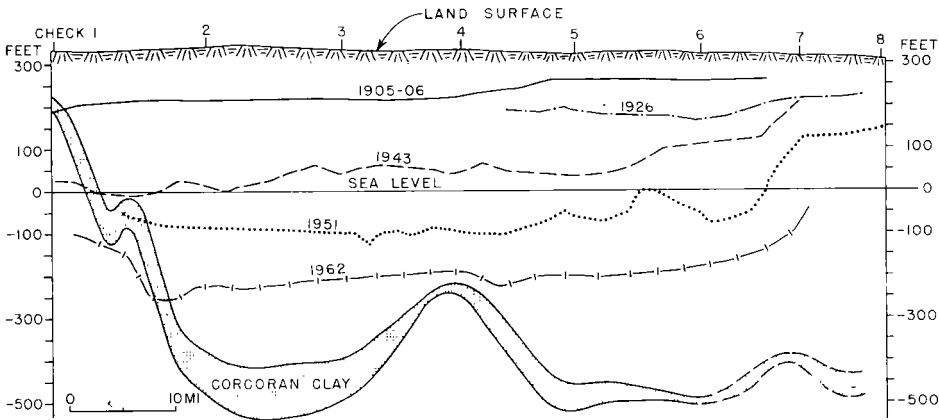


FIGURE 9. Historic decline of sub-Corcoran piezometric water levels along the San Luis Canal

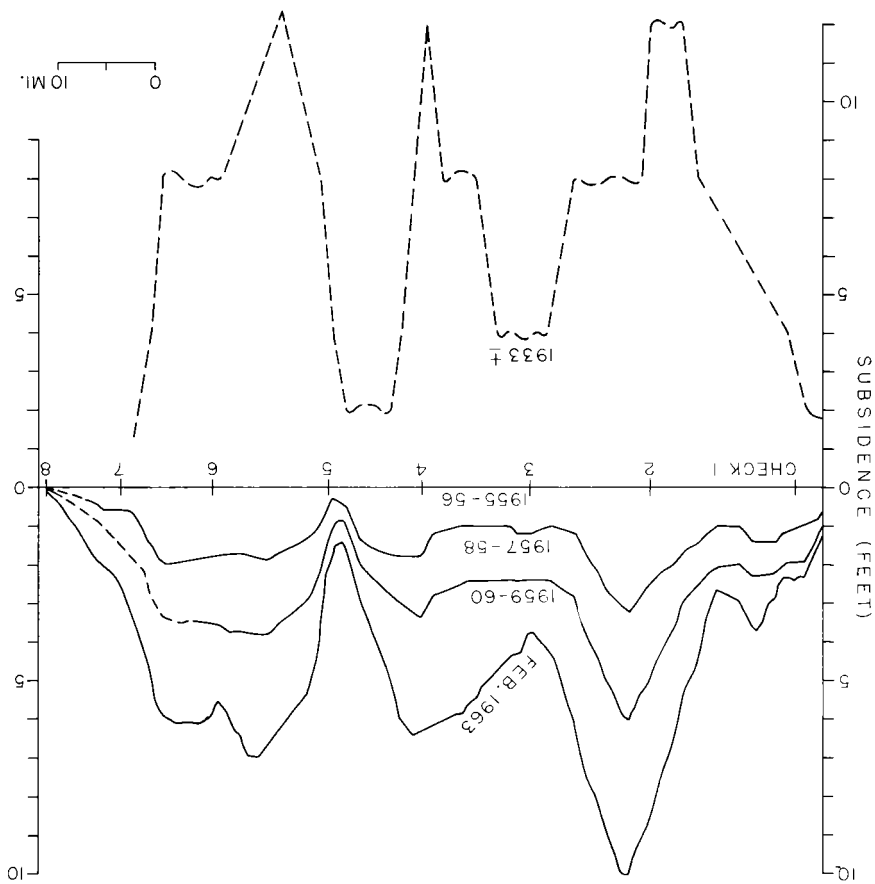


FIGURE 10. Historic subsidence along San Luis Canal alignment before construction (1933-1955/1956 data from topographic quadrangles)

using 1960-1963 subsidence rates. In areas affected by hydrocompaction, its magnitude was estimated graphically and was subtracted from the total subsidence rates. Residual subsidence was assumed to be equal to 10 percent of the total and was added to the estimates. Estimated ultimate values of subsidence after January 1963 ranged from traces to 15.2 feet and averaged 8 feet.

Somewhat smaller values, ranging from traces to 10.4 feet and averaging 5 feet, were derived from the piezometric decline data and piezometric decline-subsidence ratios. Use of the ratios, however, ignores the fact that essentially complete compaction of thick sedimentary sequence requires at least several decades. Subsidence-piezometric decline plottings are therefore HISTORIC rather than FUNCTIONAL graphs. An attempt is now being made to adjust San Luis subsidence-piezometric decline graphs using data obtained along Delta-Mendota Canal.

SAN LUIS CANAL—HYDROCOMPACTION

Hydrocompaction affected two reaches of the San Luis Canal, totaling about 20 miles, and 90 miles of the alignments of distribution pipelines. The area has received variable amounts of irrigation water and has been subjected to different amounts of hydrocompaction.

Estimates of remaining hydrocompaction along the canal were made using more than 2,000 dry density values from 120 test holes. Average densities from the holes were compared with "ultimate densities" from 14 holes in local areas which had been flooded for a long time and were believed to be completely hydrocompacted (Prokopovich 1962):

$$\Delta h = H - \frac{H \cdot d}{D}$$

where:

- Δh amount of compaction;
- H depth to ground water;
- d present average density, and
- D "ultimate density" for the same depth interval.

Estimates of future hydrocompaction ranged from traces to 20 feet. It is possible, however, that this method yielded too large values because of variable compaction during sampling with 3-inch diameter Shelby samplers.

To minimize the effects of hydrocompaction, 20 miles of the canal alignment were flooded prior to construction by a system of 128 preconsolidation ponds (Hall and Carlson 1965). Gravel-packed infiltration wells up to 125 feet deep were used in some areas to speed wetting at depth. The flooding was conducted for 12 to 18 months and resulted in up to 8 feet of settling. The total cost of the treatment (fig. 5D) was about \$4 million.

Various types of preconstruction treatment, including flooding of trenches, are under consideration for the distribution pipe-lines to be constructed in soils susceptible to hydrocompaction.

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DISCUSSION

Intervention by Mr. Herbert H. SCHUMANN (USA):

Question:

What are cost estimates for repairs caused by unpredicted additional subsidence along the San Luis Canal? (Note: The question deals with final remarks of the speaker about unpredicted excessive subsidence, which is not discussed in the published text.)

Answer of Mr. PROKOPONICH:

The estimates are not completed, but are in an order of several millions. In original predictions we faced two problems:

1. Bench marks along the alignment were very sparse and subsidence rates were obtained by an interpretation of subsidence contour maps.
2. Construction of distribution system was assumed to be completed in 1967. The system is still under construction.