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LAND-SURFACE SUBSIDENCE AT SEABROOK, TEXAS

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations 76-31

REPORTS SECTION
COPY

Prepared in cooperation with the U.S. Army Corps of Engineers

1975

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.
4. Title and Subtitle LAND-SURFACE SUBSIDENCE AT SEABROOK, TEXAS			5. Report Date October 1976 6.
7. Author(s) R. K. Gabrysch and C. W. Bonnet			8. Performing Organization Rept. No. WRI/NTIS 76-31
9. Performing Organization Name and Address U.S. Geological Survey, Water Resources Division Federal Building, 300 E. Eighth Street Austin, TX 78701			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address U.S. Geological Survey, Water Resources Division Federal Building, 300 E. Eighth Street Austin, TX 78701			13. Type of Report & Period Covered Final 14.

15. Supplementary Notes

16. Abstracts Removal of water, oil, and gas from the subsurface in Harris and Galveston Counties, Texas, has caused a decline in fluid pressures, which in turn has resulted in subsidence of the land surface. Subsidence of the land surface at Seabrook is due principally to the removal of water. Significant subsidence of the land surface probably began after 1920, and a minimum of about 3.3 feet (1.0 m) and a maximum of about 4.3 feet (1.3 m) of subsidence had occurred at Seabrook by 1973.

Probable future subsidence was calculated by two different methods for each of two different loading situations. In the first loading situation, case I, the artesian heads in the Alta Loma Sand (Rose, 1943) and Evangeline aquifer would continue to decline at the respective rates of 8 feet (2.4 m) per year and 7 feet (2.1 m) per year until 1980 and then cease. In the second loading situation, case II, the artesian heads in the Alta Loma Sand and Evangeline aquifer would continue to decline at rates of 8 and 7 feet (2.4 and 2.1 m) per year until 1990 and then cease.

17. Key Words and Document Analysis. 17a. Descriptors

*Subsidence, land-surface subsidence, compaction, artesian pressures, water-level declines

17b. Identifiers/Open-Ended Terms

Harris County, Texas; Galveston County, Texas

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
No restriction on distribution.	UNCLASSIFIED	60
	20. Security Class (This Page) UNCLASSIFIED	22. Price

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LAND-SURFACE SUBSIDENCE AT SEABROOK, TEXAS

By

R. K. Gabrysch and C. W. Bonnet

ABSTRACT

Removal of water, oil, and gas from the subsurface in Harris and Galveston Counties, Texas, has caused a decline in fluid pressures, which in turn has resulted in subsidence of the land surface. Subsidence of the land surface at Seabrook, due principally to the removal of water, is becoming critical because much of the area is now subject to inundation by high tides.

Production of ground water within the city limits of Seabrook is small, but pumping in adjacent areas has caused artesian-head declines in the Evangeline and Chicot aquifers of as much as 200 and 240 feet (61 and 73 m), respectively. Significant subsidence of the land surface probably began after 1920, and a minimum of about 3.3 feet (1.0 m) and a maximum of about 4.3 feet (1.3 m) of subsidence had occurred at Seabrook by 1973.

Probable future subsidence was calculated by two different methods for each of two different loading situations. In the first loading situation, case I, the artesian heads in the Alta Loma Sand (Rose, 1943) and Evangeline aquifer would continue to decline at the respective rates of 8 feet (2.4 m) per year and 7 feet (2.1 m) per year until 1980 and then cease. In the second loading situation, case II, the artesian heads in the Alta Loma Sand and Evangeline aquifer would continue to decline at rates of 8 and 7 feet (2.4 and 2.1 m) per year until 1990 and then cease.

Calculations using the consolidation theory of soil mechanics did not result in satisfactory agreement between predicted and measured subsidence; therefore, calculations using field records of subsidence and artesian-head decline were used. These calculations indicated an ultimate subsidence of 7.6 feet (2.3 m) under the conditions of case I and 9.9 feet (3.0 m) under the conditions of case II.

To halt subsidence in the near future, artesian heads need to be increased, either by a decrease in pumping or by artificially recharging the aquifers. Planned decreases in ground-water use in the southern part of Harris County and in the northern part of Galveston County would result in increases in artesian heads in the Alta Loma Sand and the Evangeline aquifer of as much as 35 and 20 feet (11 and 6 m), respectively, before 1980. These increases in artesian heads should cause the rate of land-surface subsidence to decrease substantially in the more critical areas.

INTRODUCTION

The pumping of vast quantities of ground water to meet increasing demands for municipal supply, industrial use, and irrigation has caused significant declines in artesian heads in parts of Harris and Galveston Counties, Texas. The declines in artesian heads have in turn caused critical subsidence of the land surface in parts of the area. One such area of critical land-surface subsidence is in the vicinity of Seabrook in the southeastern part of Harris County (fig. 1).

The land surface in this area has subsided more than 3 feet (1 m) since development of ground water began, and parts of the area are subject to inundation by seawater. Driveways and streets along the waterfront are flooded regularly by normal high tides, and unusually high tides, such as those produced by Hurricane Carla in 1961, flood everything at an altitude less than about 14 feet (4 m) above mean sea level.

Objectives

At the request of the U.S. Army Corps of Engineers, the U.S. Geological Survey began an investigation in September 1972 of land-surface subsidence in the area of Seabrook. The objectives of this investigation are:

1. To determine the amount of land-surface subsidence due to the withdrawal of subsurface fluids.
2. To determine the rates of subsidence and the relation of subsidence to the declines in artesian heads.
3. To predict the declines in artesian heads during the next 50 years.
4. To predict the rate of subsidence caused by fluid withdrawals.
5. To predict the maximum amount of subsidence to be expected during the next 50 years.

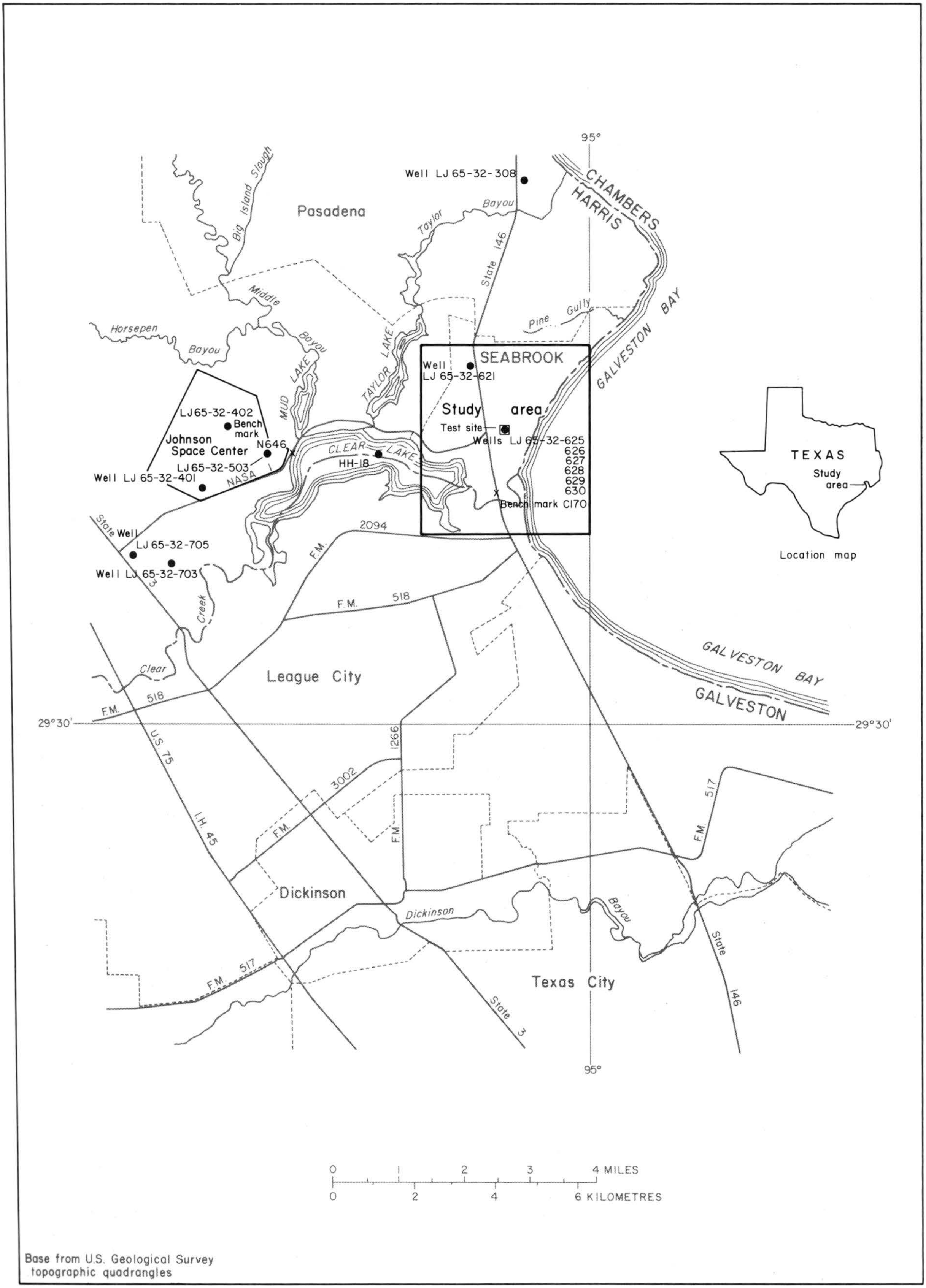


FIGURE 1.-Locations of test wells and and the test site in the Seabrook study area

Metric Conversions

For those readers interested in using the metric system, metric equivalents of English units of measurements are given in parentheses. The English units used in this report may be converted to metric units by the following conversion factors:

From		Multiply by	To obtain	
Unit	Abbreviation		Unit	Abbreviation
feet	--	0.3048	metres	m
$feet^{-1}$	ft^{-1}	3.2808	$metres^{-1}$	m^{-1}
miles	--	1.609	kilometres	km
million gallons per day	million gal/d	.04381	cubic metres per second	m^3/s
pounds per square inch	lb/in^2	.07031	kilograms per square centimetre	kg/cm^2
tons per square foot	ton/ft^2	.9765	kilograms per square centimetre	kg/cm^2

To convert centimetres per second (cm/s), as given in table 3, to inches per second (in/s), multiply by 0.3937.

To convert square centimetres per second (cm^2/s), as given in table 3, to square inches per second (in^2/s), multiply by 0.1550.

Acknowledgments

The authors gratefully acknowledge the assistance of Mr. Baker Birdwell, Birdwell's Water Well Service, for his cooperation in drilling and sampling. The city of Seabrook through Mr. Don Badeaux, Water Superintendent, provided the site for test drilling and installation of monitoring equipment.

CAUSES OF SUBSIDENCE

The primary cause of land-surface subsidence in the Seabrook area is the decline in artesian head due to ground-water pumping. Pumping within the limits of Seabrook is relatively small, about 0.6 million gal/d (0.03 m^3/s) in 1972, but withdrawals of ground water from areas adjacent to Seabrook are sizable. Seabrook is in the extreme southeastern part of Harris County and is part of the NASA (National Aeronautical and Space Administration) area (fig. 2), as described by Gabrysch (1971), in which pumping increased from about 1.6 million gal/d (0/07 m^3/s) in 1960 to about 7.3 million gal/d (0.32 m^3/s) in 1967 and to 18.4 million gal/d (0.80 m^3/s) in 1972.

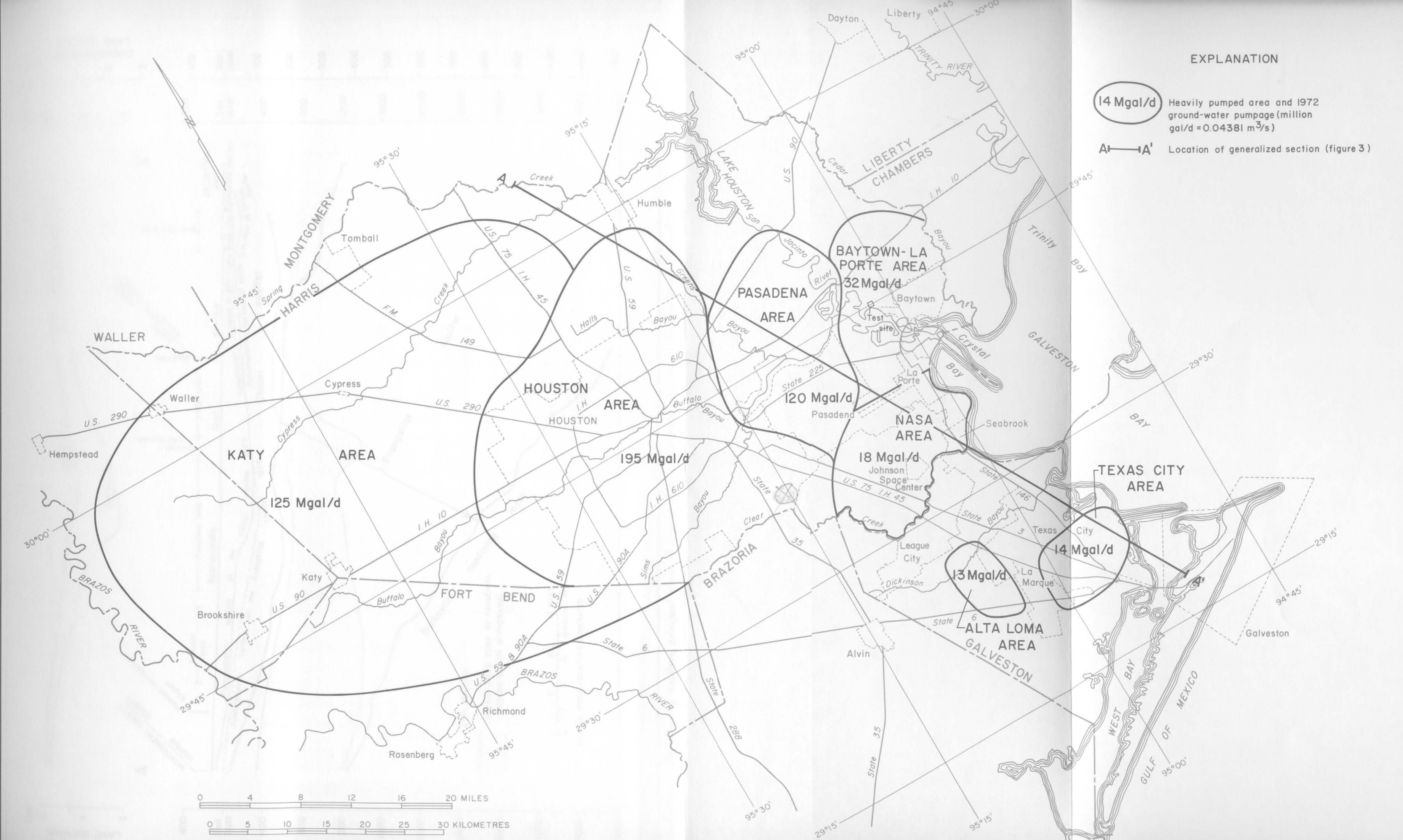
The principal areas of ground-water pumping and the average rates of withdrawal in 1972 for the region surrounding the area of Seabrook are shown on figure 2.

Most of the ground-water withdrawals in Galveston County and in the southern one-half of Harris County are from wells completed in the lower unit of the Chicot aquifer (Alta Loma Sand of Rose, 1943; hereafter referred to as the Alta Loma Sand). The declines in artesian heads at Seabrook are greatly affected by ground-water pumping in the Baytown and Pasadena areas to the north and in the Alta Loma area to the southwest. The decline in artesian head in the Evangeline aquifer at Seabrook is due to pumping at Pasadena and elsewhere in Harris and adjoining countries.

Figure 3 shows the depths and thicknesses of the aquifers, the principal zones of withdrawal, the altitudes of the potentiometric surfaces, and subsidence along a line A-A' (fig. 2) from about 40 miles (64 km) northwest to about 20 miles (32 km) southeast of the study area. In the Seabrook study area, the Chicot aquifer extends from the land surface to a depth of about 650 feet (198 m), and the Evangeline aquifer extends from the base of the Chicot to a depth of about 3,800 feet (1,158 m).

The pressure declines are illustrated by the hydrographs of wells near Seabrook (fig. 4). Locations of wells are shown on figure 1. Wells LJ 65-32-703 and LJ 65-32-705 are located near Webster west of Seabrook, and wells LJ 65-32-308 and LJ 65-32-621 are north of Seabrook.

The rates of decline, as indicated by the hydrographs of wells LJ 65-32-703 and 705, were about 5.2 feet (1.6 m) per year between 1937 and 1955, about 2.2 feet (0.7 m) per year between 1955 and 1964, about 6 feet (1.8 m) per year between 1964 and 1969, and about 8.3 feet (2.5 m) per year between 1969 and 1973. The amount of decline for these periods was affected by pumping at Webster and Alta Loma as well as elsewhere in Harris and Galveston Counties.



Base from Texas Highway Department

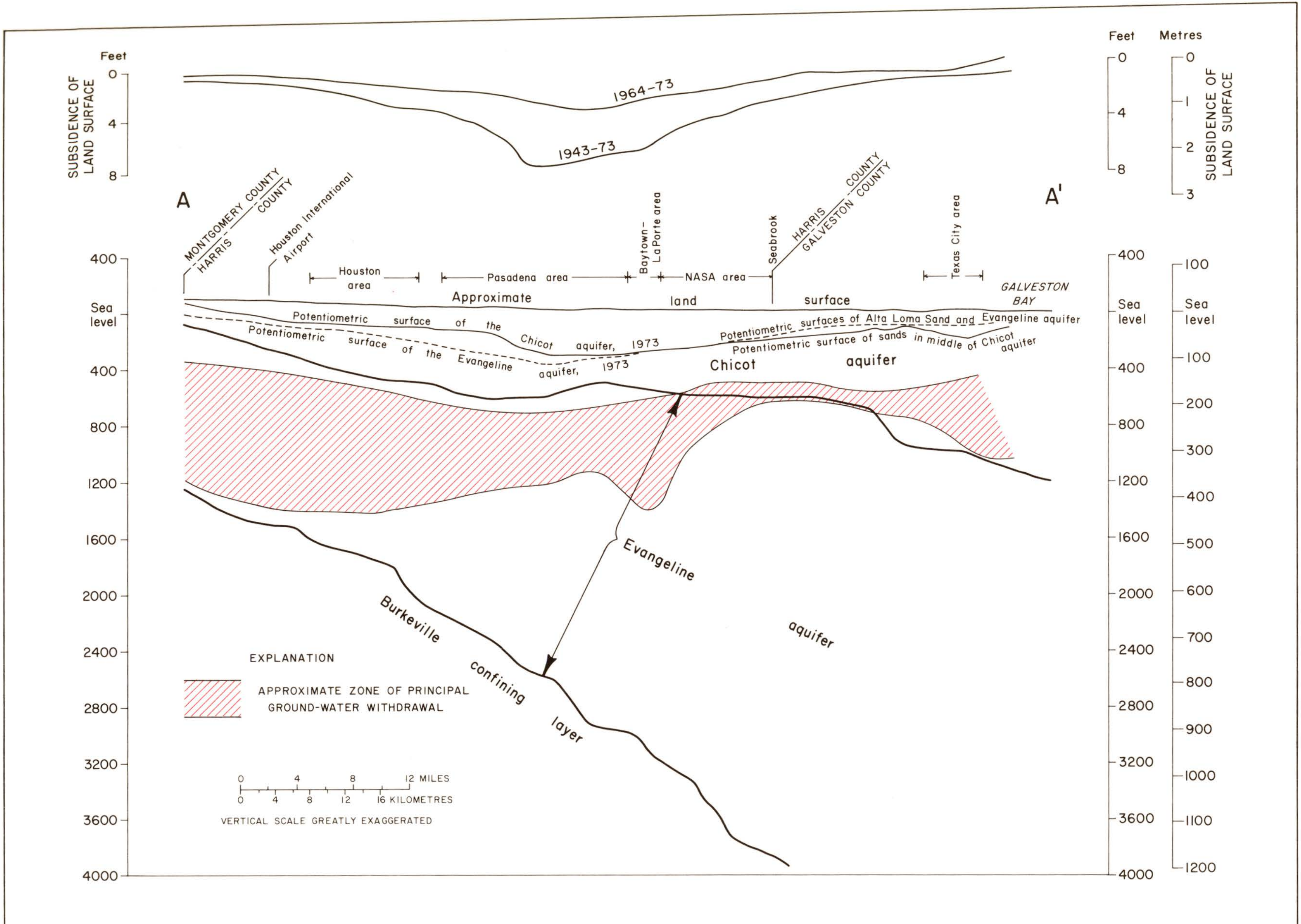
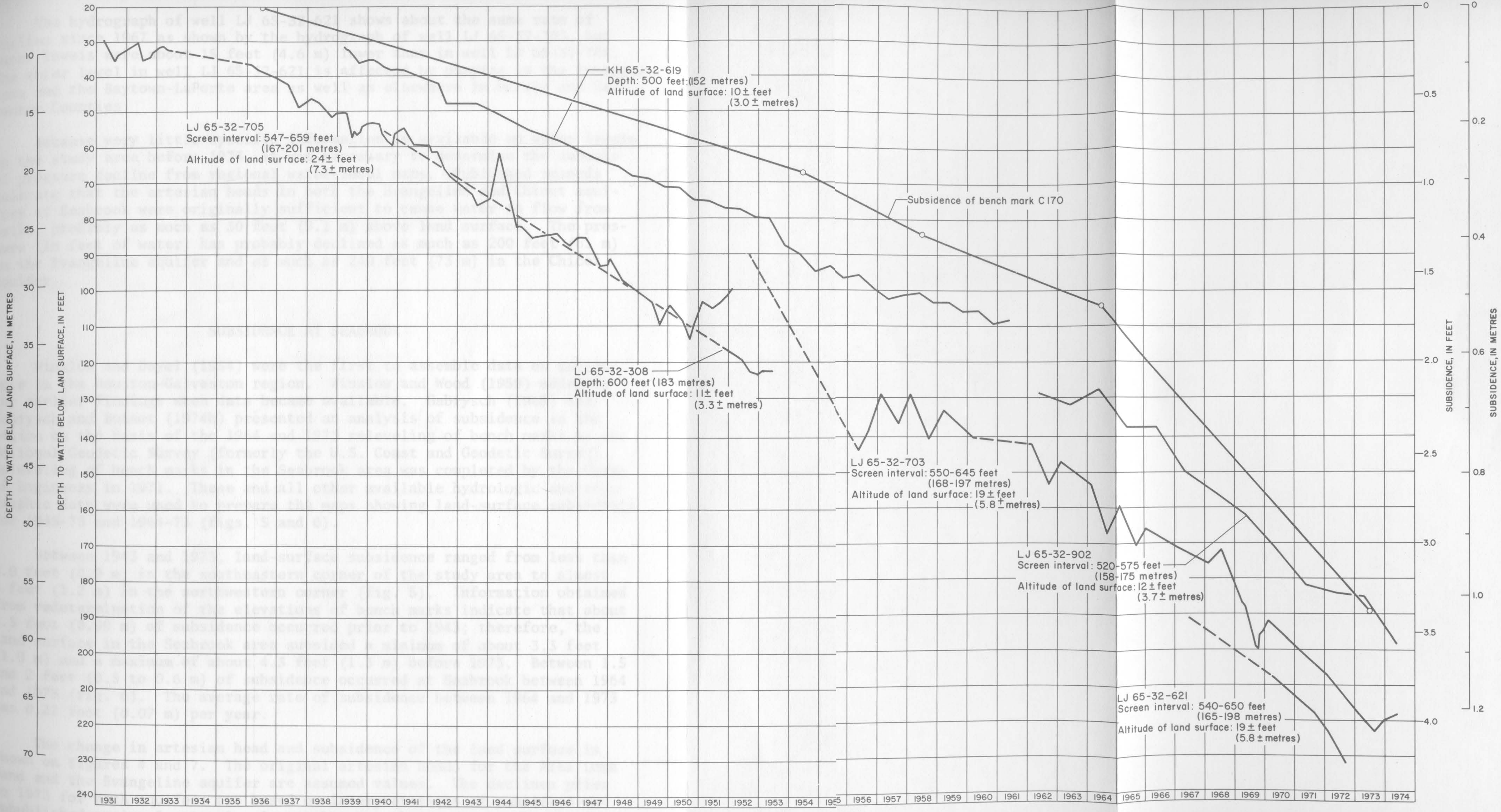


FIGURE 3.-Hydrologic profile showing aquifers, principal zones of ground-water withdrawal, altitudes of the potentiometric surfaces, and land-surface subsidence



KH 65-32-619
Depth: 500 feet (152 metres)
Altitude of land surface: 10± feet (3.0± metres)
LJ 65-32-705
Screen interval: 547-659 feet (167-201 metres)
Altitude of land surface: 24± feet (7.3± metres)
Subsidence of bench mark C170
LJ 65-32-308
Depth: 600 feet (183 metres)
Altitude of land surface: 11± feet (3.3± metres)
LJ 65-32-703
Screen interval: 550-645 feet (168-197 metres)
Altitude of land surface: 19± feet (5.8± metres)
LJ 65-32-902
Screen interval: 520-575 feet (158-175 metres)
Altitude of land surface: 12± feet (3.7± metres)
LJ 65-32-621
Screen interval: 540-650 feet (165-198 metres)
Altitude of land surface: 19± feet (5.8± metres)
DEPTH TO WATER BELOW LAND SURFACE, IN METRES
DEPTH TO WATER BELOW LAND SURFACE, IN FEET
SUBSIDENCE, IN FEET
SUBSIDENCE, IN METRES
1931 1932 1933 1934 1935 1936 1937 1938 1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974

The hydrograph of well LJ 65-32-621 shows about the same rate of decline since 1967 as shown by the hydrograph of well LJ 65-32-703, but water levels were about 15 feet (4.6 m) lower than in well LJ 65-32-703. The water level in well LJ 65-32-621 is affected by pumping in the Pasadena area and the Baytown-LaPorte area as well as elsewhere in Harris and Galveston Counties.

Because very little specific information is available on water levels in the study area before 1973, it was necessary to determine the amounts of pressure decline from regional water-level maps. Published records indicate that the artesian heads in both the Evangeline and Chicot aquifers at Seabrook were originally sufficient to cause water to flow from wells, probably as much as 30 feet (9.1 m) above land surface. The pressure (in feet of water) has probably declined as much as 200 feet (61 m) in the Evangeline aquifer and as much as 240 feet (73 m) in the Chicot aquifer.

SUBSIDENCE AT SEABROOK

Winslow and Doyel (1954) were the first to assemble data on subsidence in the Houston-Galveston region. Winslow and Wood (1959) added to the earlier findings when data became available. Gabrysch (1969) and Gabrysch and Bonnet (1974b) presented an analysis of subsidence in the region on the basis of the 1964 and 1973 releveling of bench marks by the National Geodetic Survey (formerly the U.S. Coast and Geodetic Survey). Releveling of bench marks in the Seabrook area was completed by the Corps of Engineers in 1971. These and all other available hydrologic and topographic data were used to prepare the maps showing land-surface subsidence for 1943-73 and 1964-73 (figs. 5 and 6).

Between 1943 and 1973, land-surface subsidence ranged from less than 3.0 feet (0.9 m) in the southeastern corner of the study area to almost 4 feet (1.2 m) in the northwestern corner (fig. 5). Information obtained from redetermination of the elevations of bench marks indicate that about 0.3 foot (0.09 m) of subsidence occurred prior to 1943; therefore, the land surface in the Seabrook area subsided a minimum of about 3.3 feet (1.0 m) and a maximum of about 4.3 feet (1.3 m) before 1973. Between 1.5 and 2 feet (0.5 to 0.6 m) of subsidence occurred at Seabrook between 1964 and 1973 (fig. 6). The average rate of subsidence between 1964 and 1973 was 0.22 foot (0.07 m) per year.

The change in artesian head and subsidence of the land surface is shown on figures 4 and 7. The original artesian heads for the Alta Loma Sand and the Evangeline aquifer are assumed values. The declines prior to 1973 for both aquifers are based on interpretations of published and unpublished regional water-level maps because there are no suitable observation wells in the area.

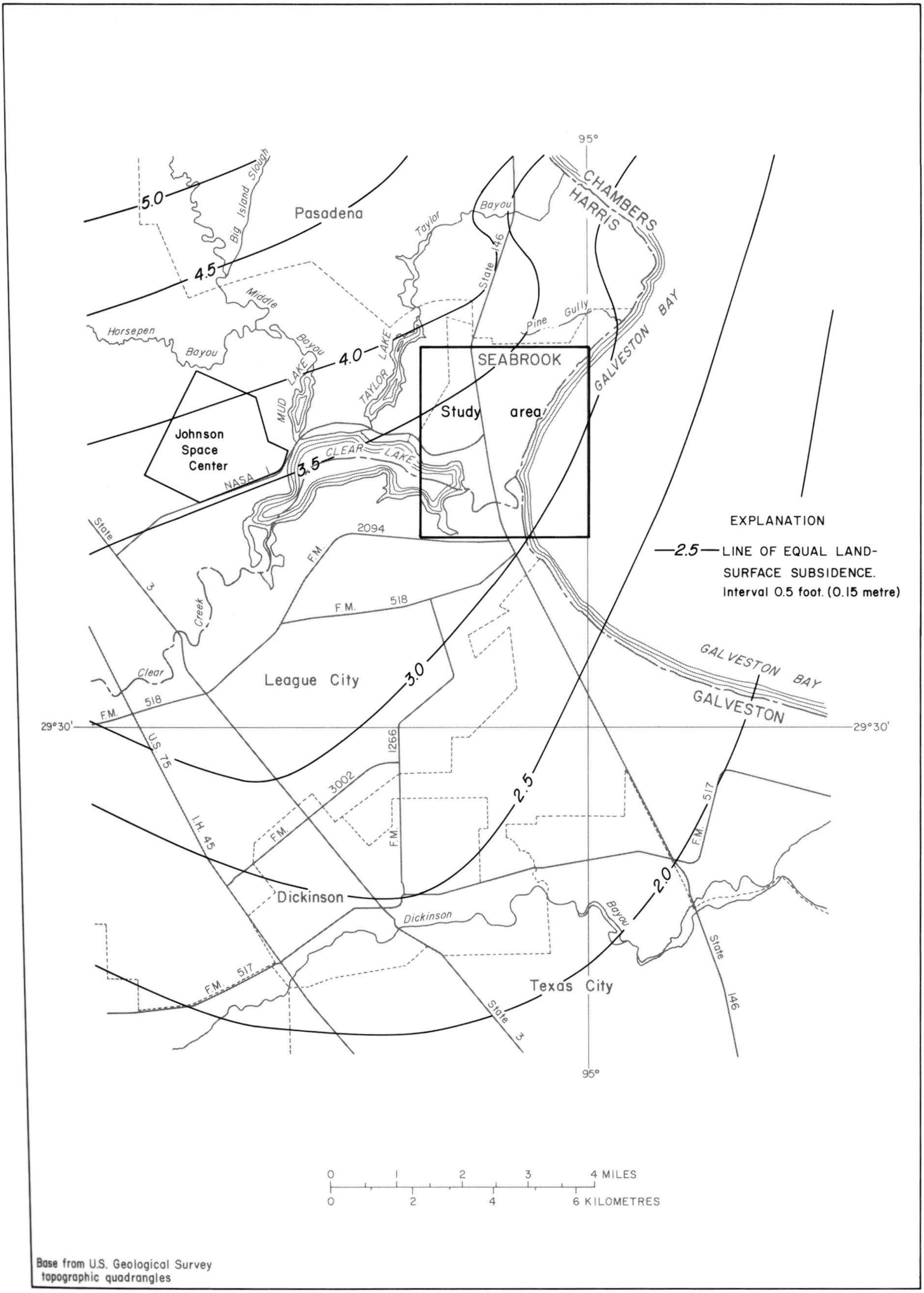


FIGURE 5.-Approximate subsidence of the land surface, 1943-73

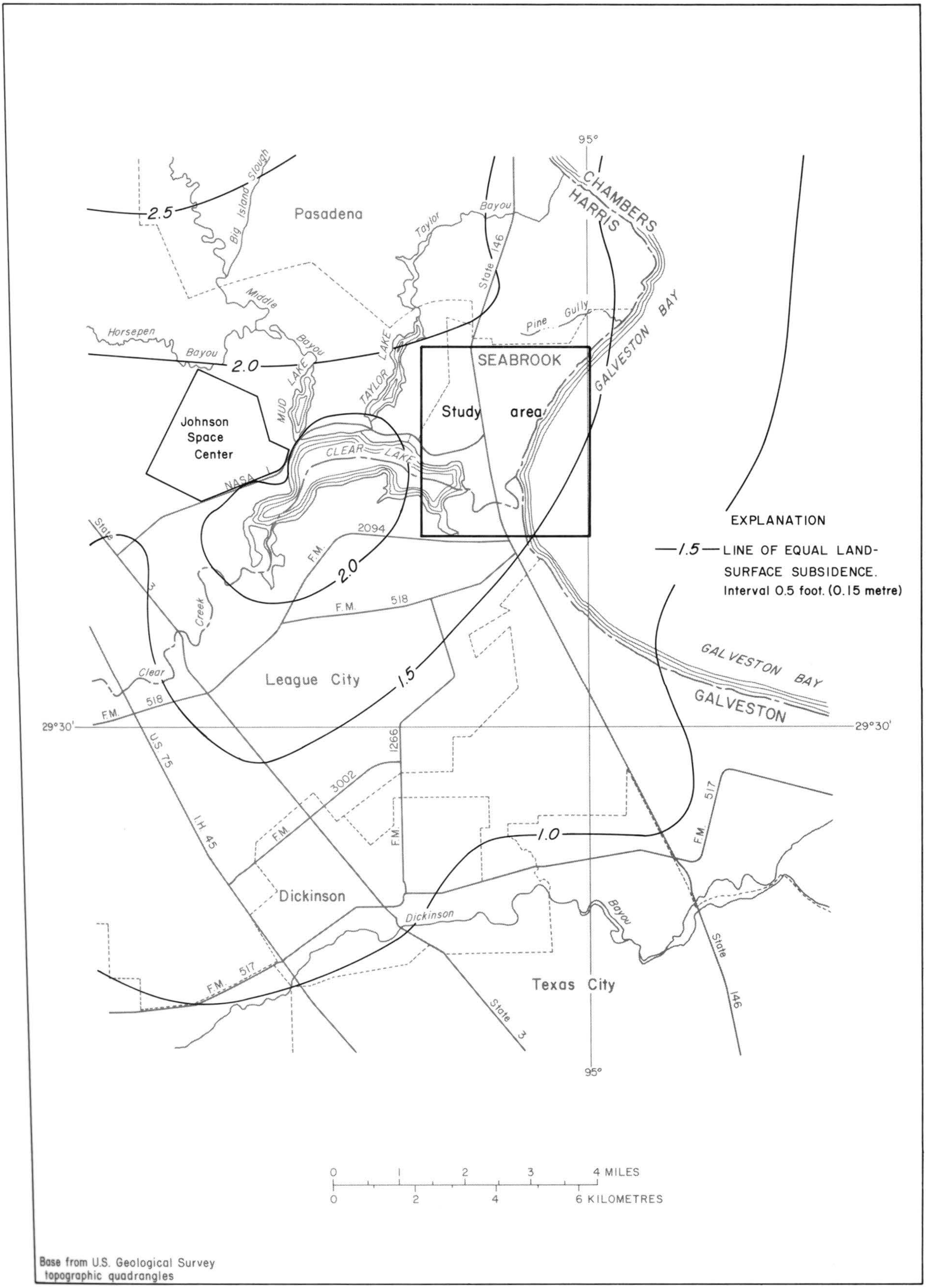


FIGURE 6.-Approximate subsidence of the land surface, 1964-73

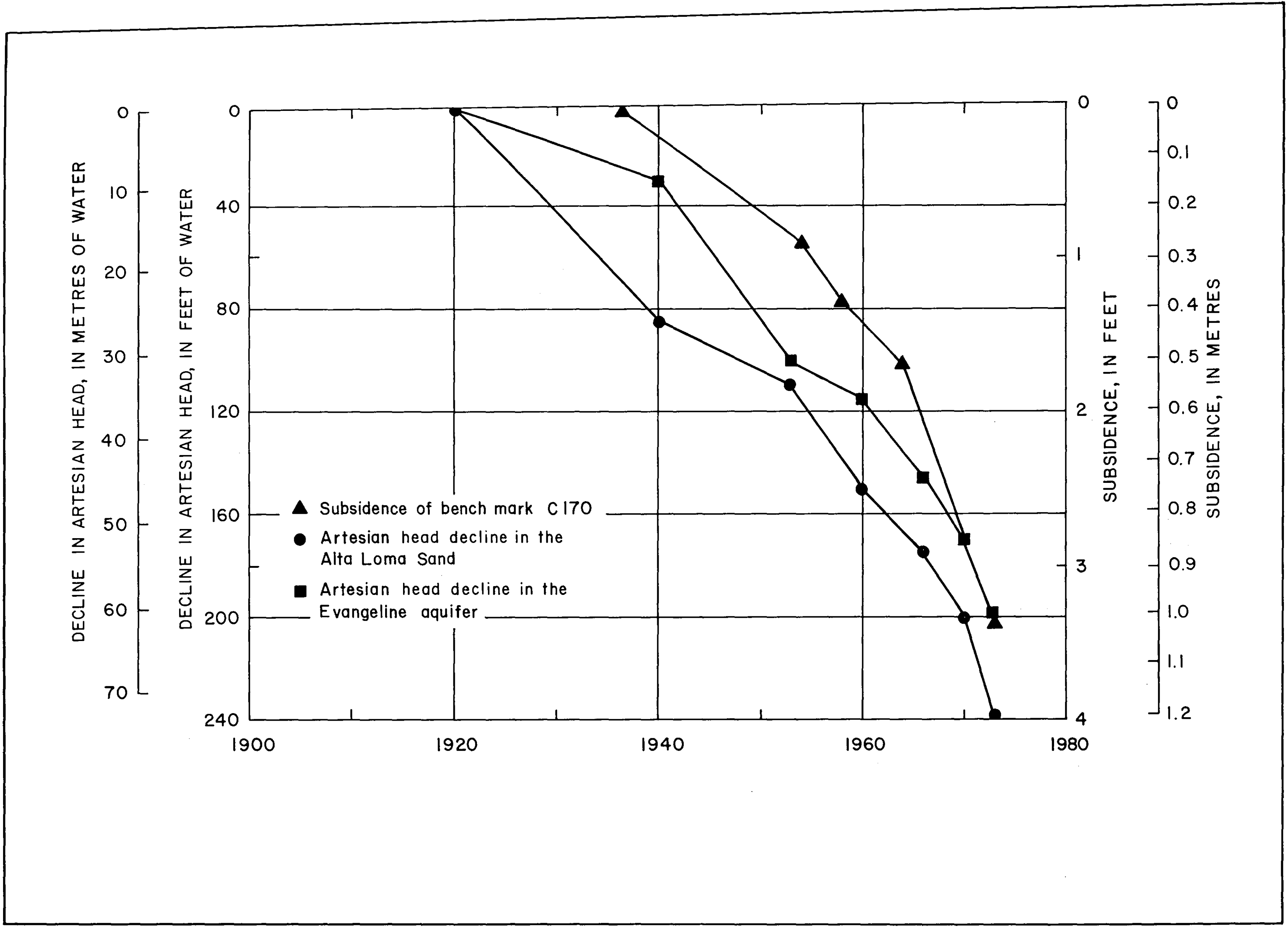


FIGURE 7.-Land-surface subsidence and artesian-head decline at Seabrook

The reader is cautioned that care must be exercised in the projection of subsidence curves on the basis of pressure declines only, because the ratio of subsidence to the decline of water levels in wells is not constant in time or uniform in space. For example, Gabrysch (1969, fig. 10) showed a range of 0.5 foot (0.15 m) to more than 2.5 feet (0.76 m) of subsidence per 100 feet (30.5 m) of water-level decline in the Houston-Galveston region. The variation in the ratio is caused primarily by the difference in total clay thickness, individual clay-bed thickness, and clay characteristics. The depth of the overburden and the amount of load to which the material has been previously subjected must also be considered.

DATA COLLECTION AND ANALYSIS

This study of land-surface subsidence required the collection and analysis of data from boreholes; therefore, it was necessary to select a drilling and monitoring site in the study area where instrumentation could be protected from vandalism. The site selected is in a fenced water-plant yard, 1.1 miles (1.8 km) north of the mouth of Clear Lake (fig. 1). A total of six wells (LJ 65-32-625 - 630, fig. 1) was drilled by conventional rotary-drilling methods at this site.

The depths of the wells are 150, 300, 920, 1,308, 1,360, and 1,381 feet (46, 91, 280, 399, 414, and 421 m). Water levels are measured in all six wells. A borehole extensometer was installed in well LJ 65-32-627 to monitor compaction of the material between land surface and a depth of 1,381 feet (421 m). Records of compaction at this site for July 1973-August 1974 and at three other sites in the Houston-Galveston region are shown on figure 8. The record at the test site is not sufficient to relate the amount of compaction to total subsidence.

At the Johnson Space Center (fig. 9), about 55 percent of the subsidence between 1964 and 1973 was due to compaction between the land surface and a depth of 750 feet (229 m). Most of the subsidence at Seabrook is due to compaction of shallow clays (less than 1,500 feet or 457 m deep). Therefore, the extensometer record should be valuable for estimating subsidence on a continuing basis. Drillers' logs, chemical analyses of water samples, water-level measurements, and well-completion records for these wells are given in a separate report (Naftel, Vaught, and Fleming, 1975).

Electrical logs run in well LJ 65-32-626 at the monitoring site and at nearby wells were used to determine the thickness of the clay beds. Figure 10 shows the logs of a well at the site and at a nearby well used in the interpretation. On the basis of these logs, the clays from the land surface to a depth of 2,000 feet (610 m) were grouped into 54 layers (table 4). The clay beds in the layers ranged in thickness from 1 foot (0.3 m) to 24 feet (7.3 m); 32 of the beds were less than 10 feet (3.0 m) thick. Some compaction probably occurs in the Evangeline aquifer in the depth interval 2,000-3,800 feet (610-1,158 m), but it was considered negligible, and clay beds in the interval were not analyzed.

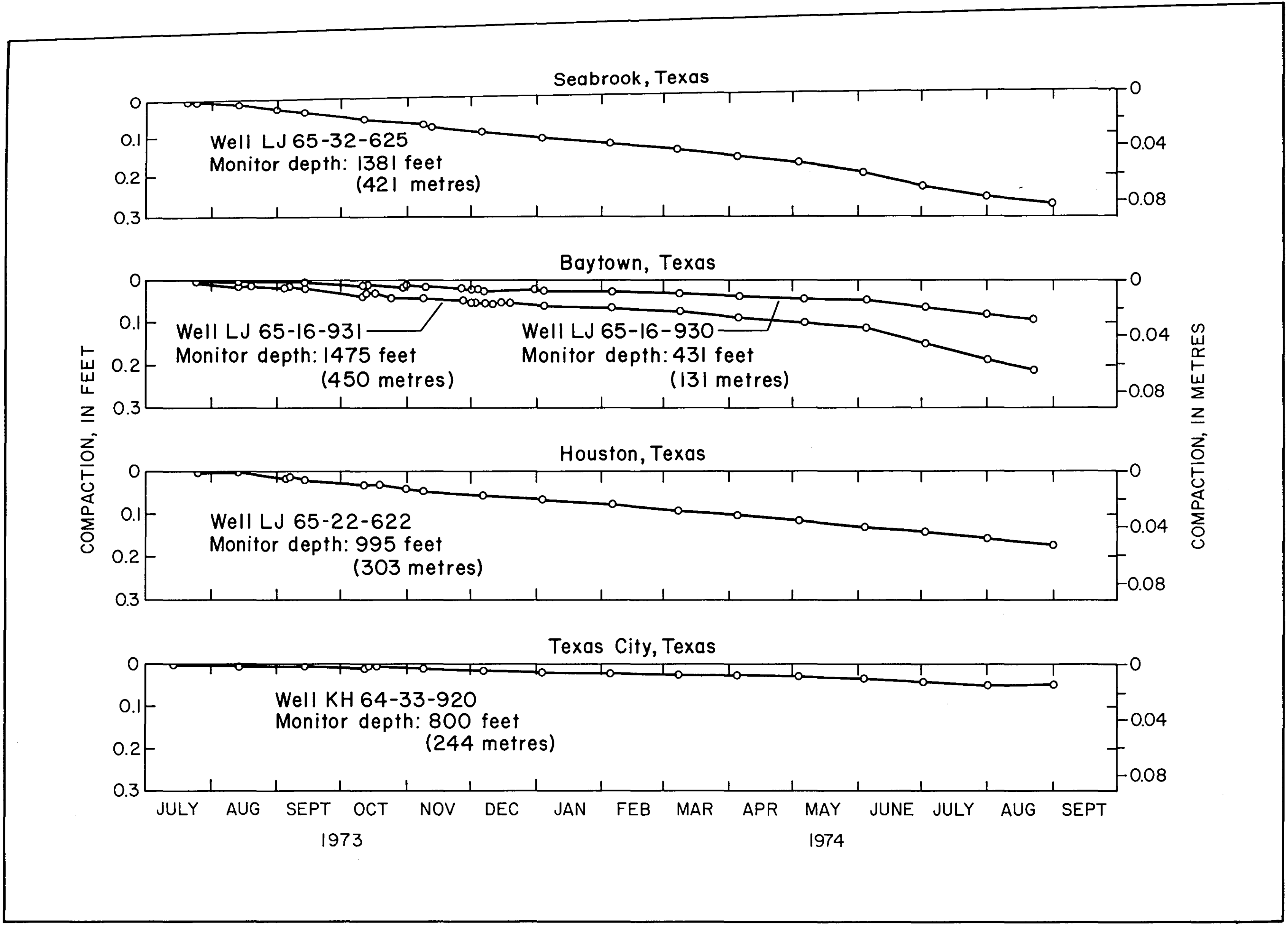


FIGURE 8.-Measured compaction in the Houston-Galveston region, July 1973-August 1974

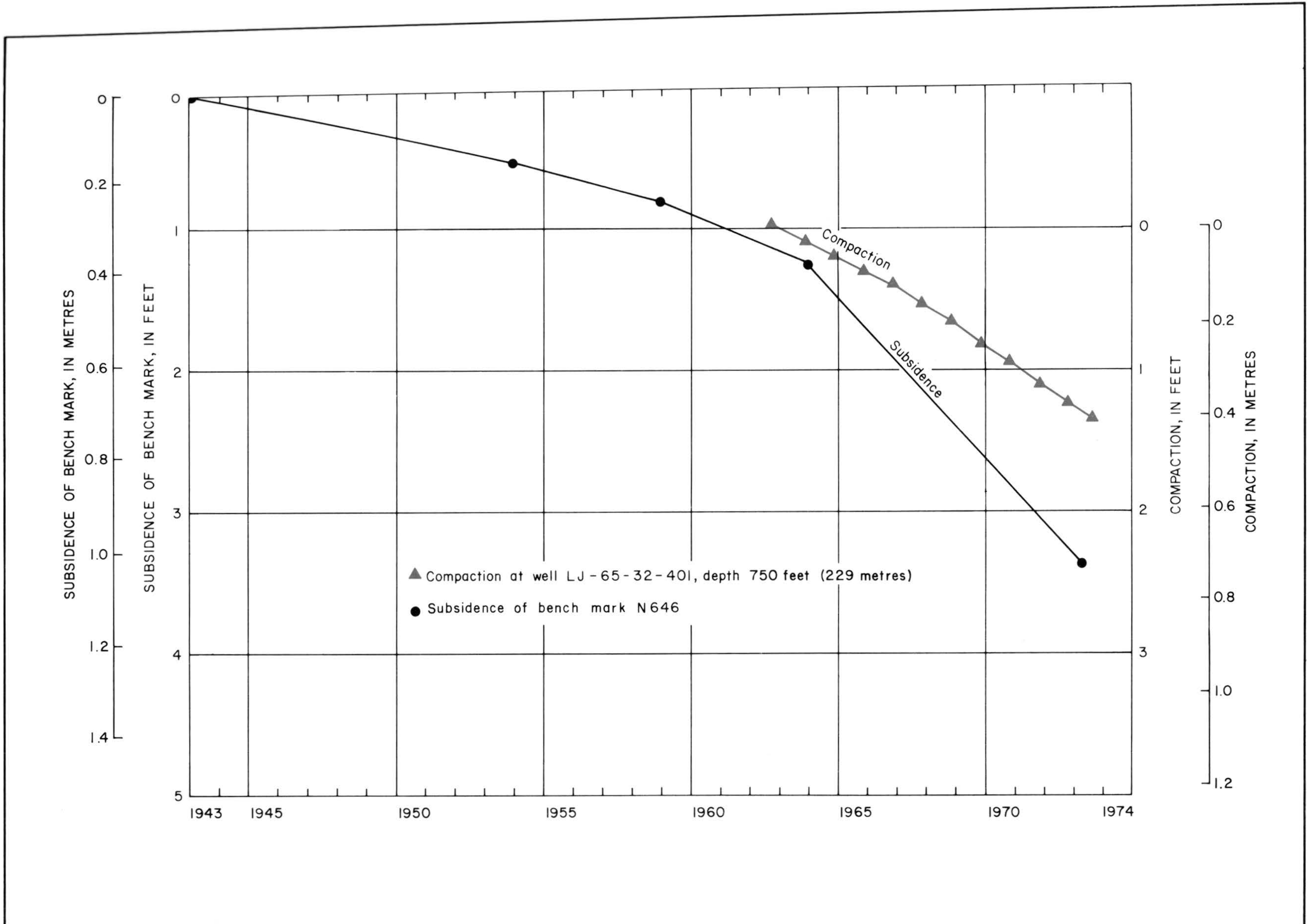
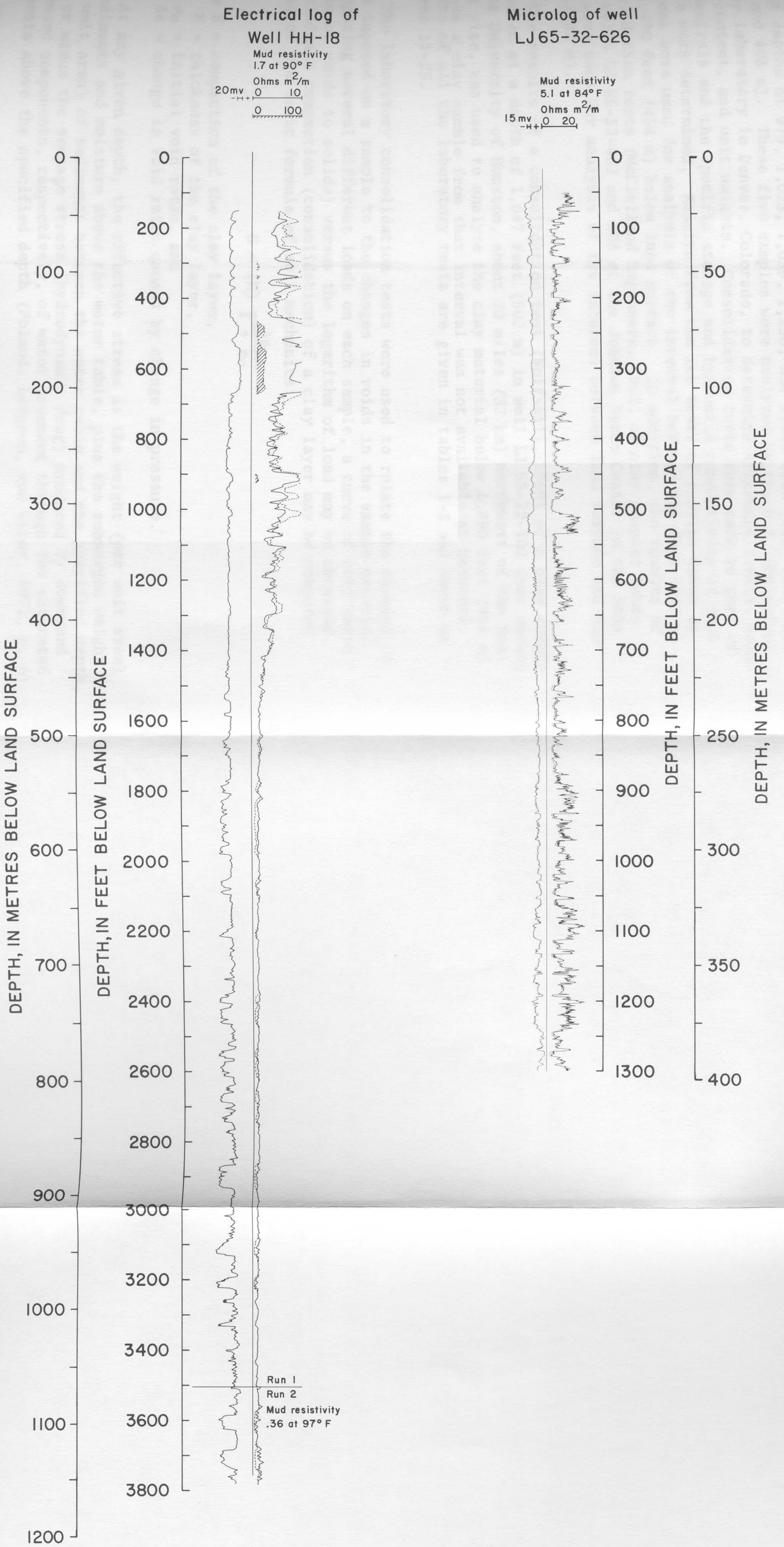


FIGURE 9.-Measured compaction and subsidence at the Johnson Space Center



RE 10.-Electrical logs of wells in the study area

Because compaction of the subsurface material is dependent in part on the characteristics of the fine grained material (chiefly clay) that is being compacted, undisturbed clay samples were collected in well LJ 65-32-627 at depths of 979, 1,023, 1,059, 1,250, and 1,340 feet (298, 312, 323, 381, and 408 m). These five samples were analyzed by the U.S. Geological Survey laboratory in Denver, Colorado, to determine Atterburg limits, moisture content, and unit weights. Consolidation tests were made as part of the analysis and the specific storage and hydraulic conductivity of each sample were determined. Results from the lab tests of samples taken at Seabrook were used for analysis of the interval between 926 feet (282 m) and 1,490 feet (454 m) below land surface. In addition, the results of consolidation tests (McClelland Engineers, 1962) of clay samples taken from wells LJ 65-32-402 and 503 at the Johnson Space Center in the NASA area were used for analysis of the interval between land surface and 926 feet (282 m).

The results of a consolidation test (Wolfskill, 1960) of a clay sample collected at a depth of 1,647 feet (502 m) in well LJ 65-22-102 (not shown) at the University of Houston, about 20 miles (32 km) northwest of the Seabrook site, was used to analyze the clay material below 1,490 feet (454 m) because a clay sample from that interval was not available at Seabrook. Results of all the laboratory tests are given in tables 1-3 and shown on figures 11-25.

The laboratory consolidation tests were used to relate the changes in loads imposed on a sample to the changes in voids in the sample material. By imposing several different loads on each sample, a curve of void ratio (ratio of voids to solids) versus the logarithm of load may be obtained. The ultimate compaction (consolidation) of a clay layer may be computed by use of the basic formula of soil mechanics:

$$S = (H) \frac{\Delta e}{1 + e_o}$$

where S = compaction of the clay layer,
H = thickness of the clay layer,
e_0 = initial void ratio, and
Δe = change in void ratio caused by change in pressure.

At any given depth, the effective stress is the weight (per unit area) of sediments and moisture above the water table, plus the submerged weight (per unit area) of sediments between the water table and the specified depth, plus or minus the seepage stress (hydrodynamic drag) produced by downward or upward components, respectively, of water movement through the saturated sediments above the specified depth (Poland, Lofgren, and Riley, 1972, p. 6).

The effective loads (stress) on the clay layers at Seabrook were calculated by using soil weights as determined in the laboratory and artesian heads as determined from individual measurements and as interpreted from regional water-level maps. The effective loads in 1973 were based on pressure measurements at the test site. The calculated effective load at Seabrook is shown on figure 26.

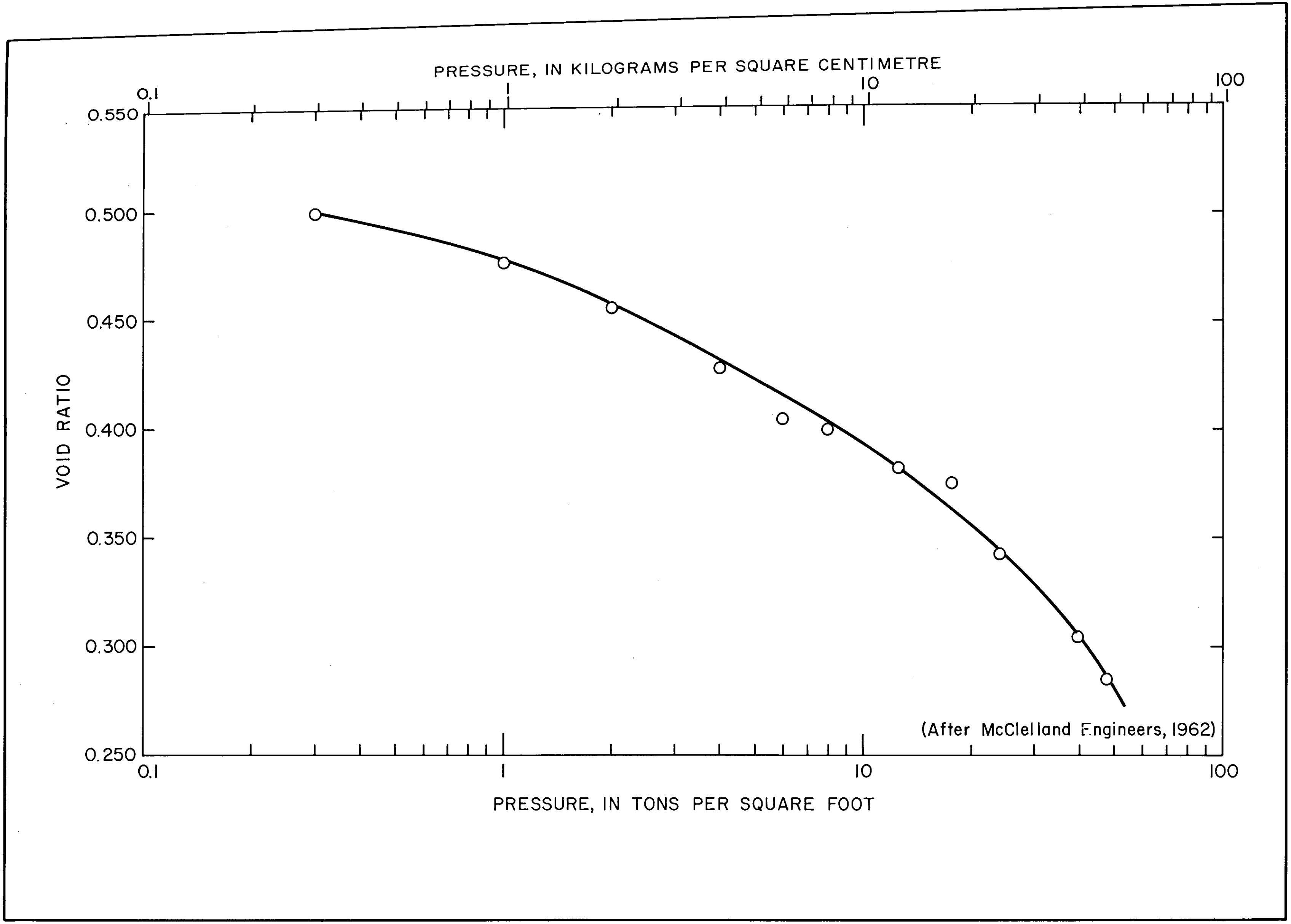


FIGURE 11.-Relation between void ratio and applied pressure for clay sample from a depth of 131 feet (40 m), well LJ 65-32-503

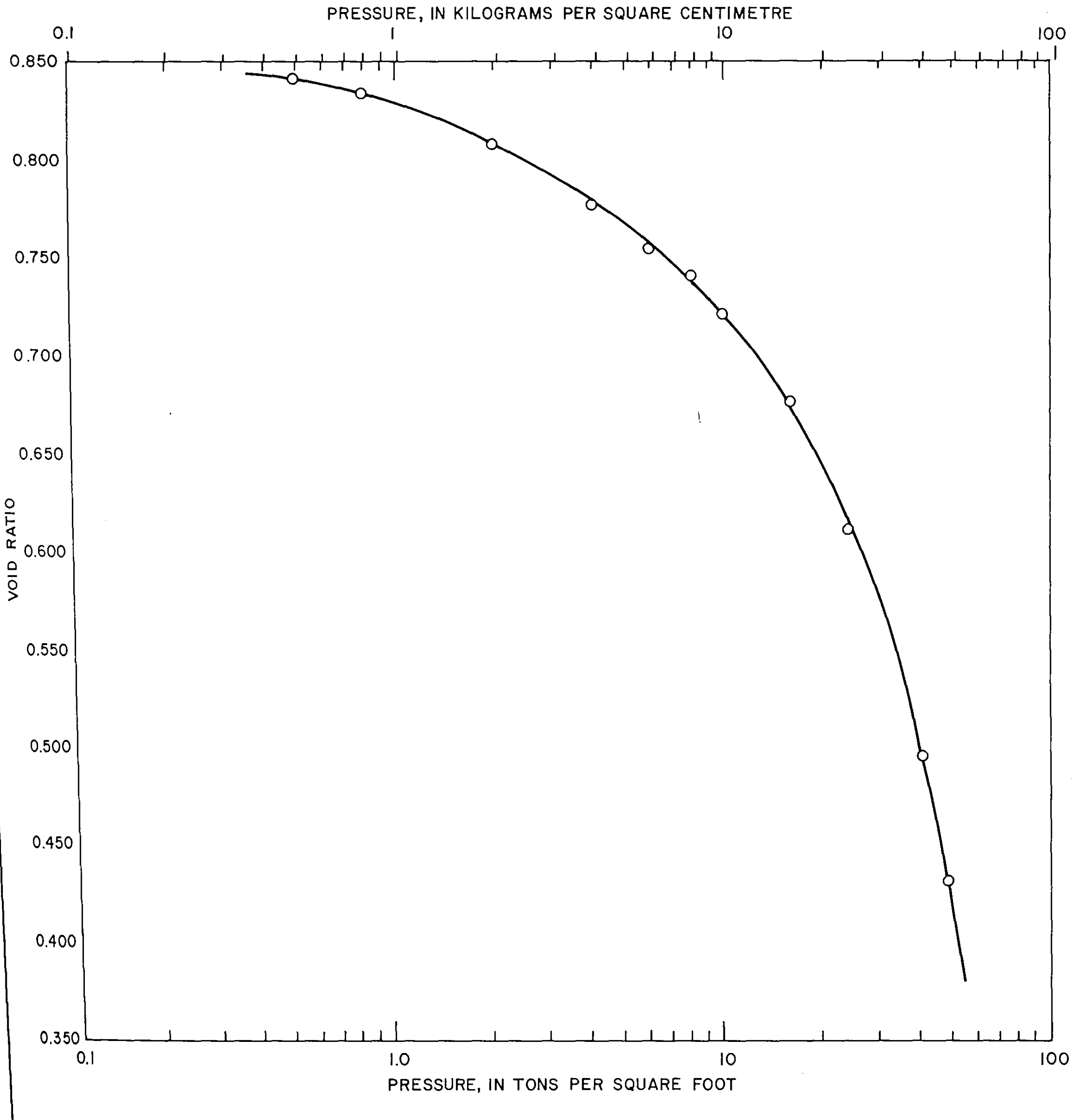


FIGURE 12.-Relation between void ratio and applied pressure for a clay sample from a depth of 221 feet (67 m), well LJ 65-32-503

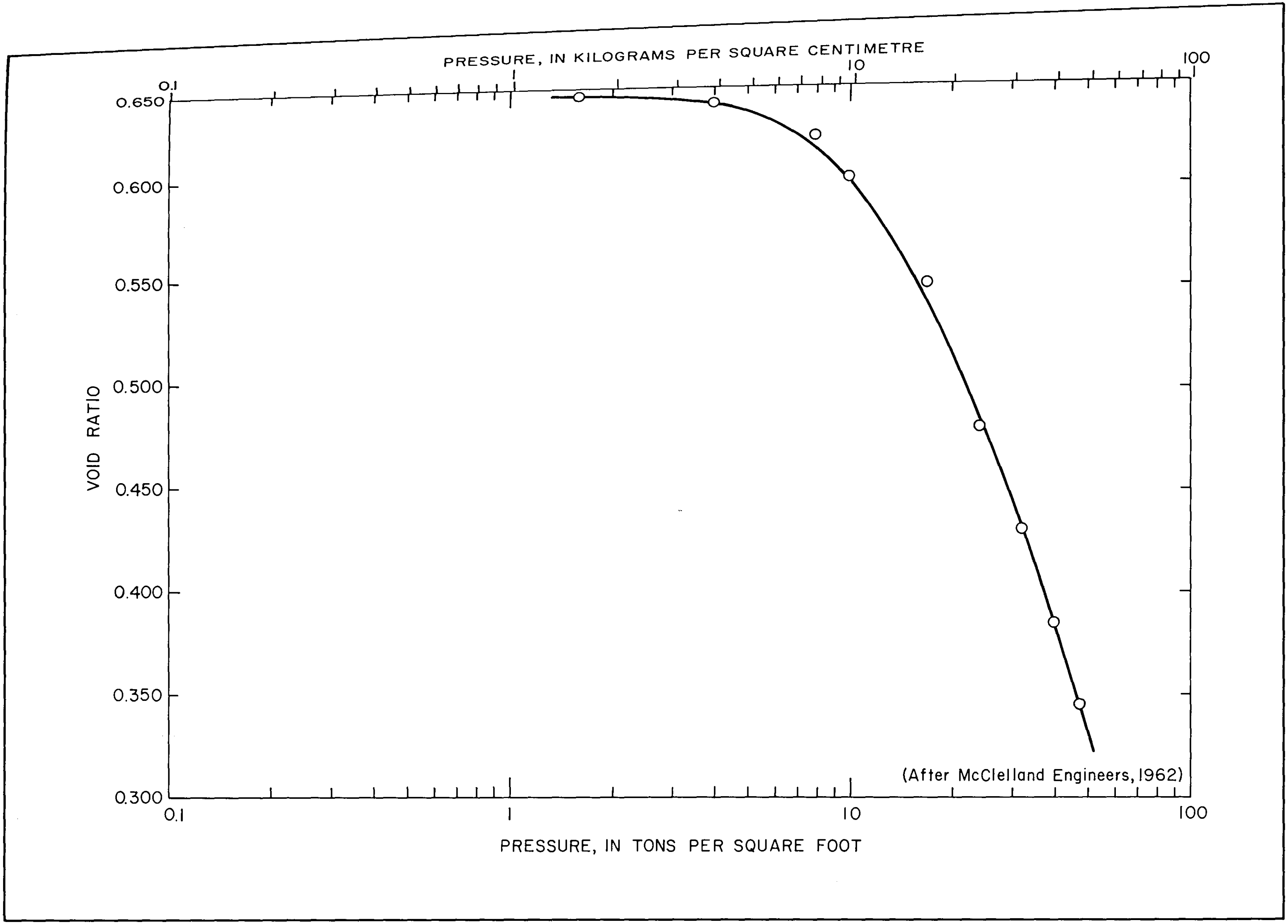


FIGURE 13.-Relation between void ratio and applied pressure for clay sample from a depth of 312 feet (95 m), well LJ 65-32-503

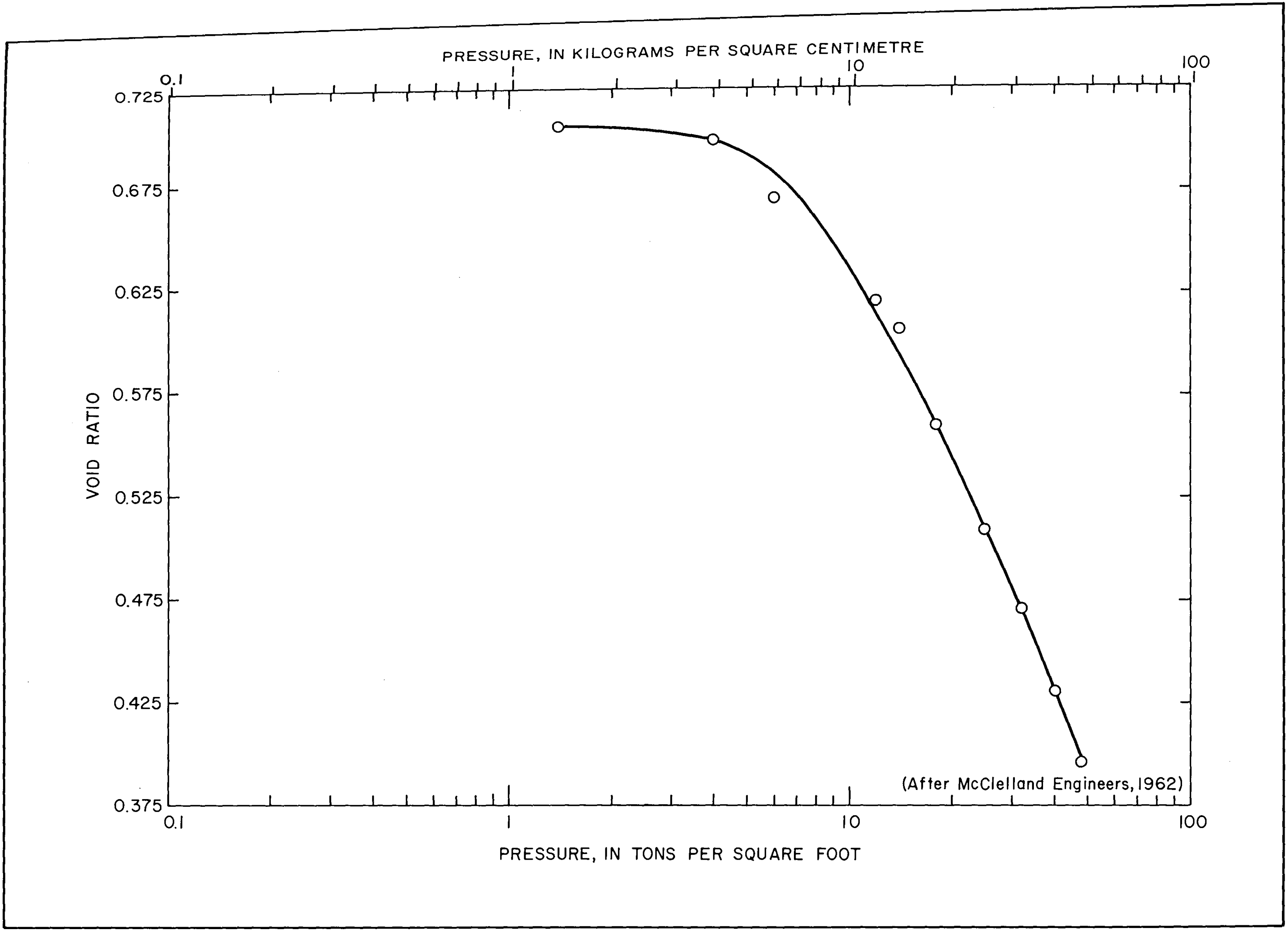


FIGURE 14.-Relation between void ratio and applied pressure for clay sample from a depth of 412 feet (126 m), well LJ 65-32-503

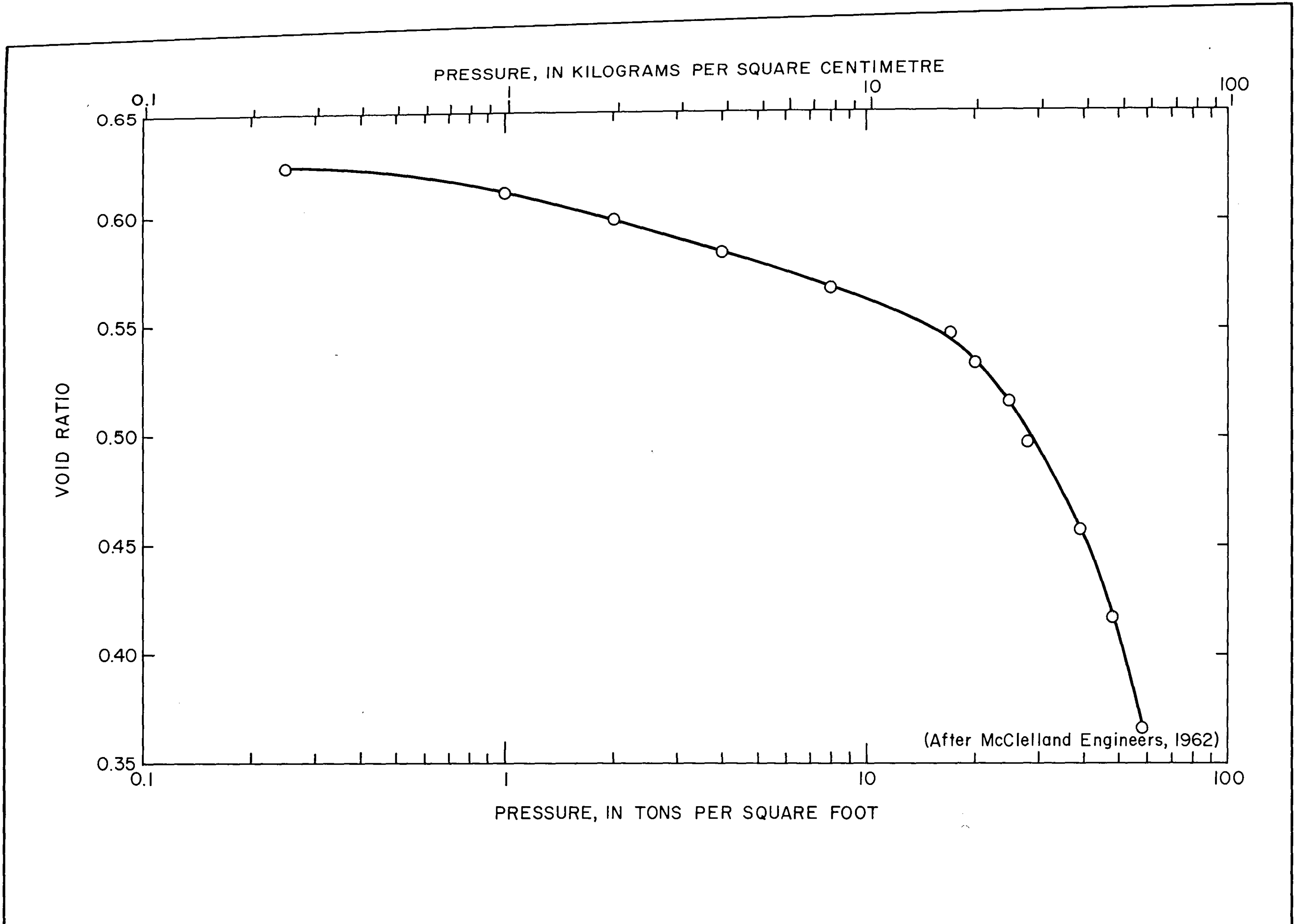


FIGURE 15.-Relation between void ratio and applied pressure for clay sample from a depth of 510 feet (155 m), well LJ 65-32-503

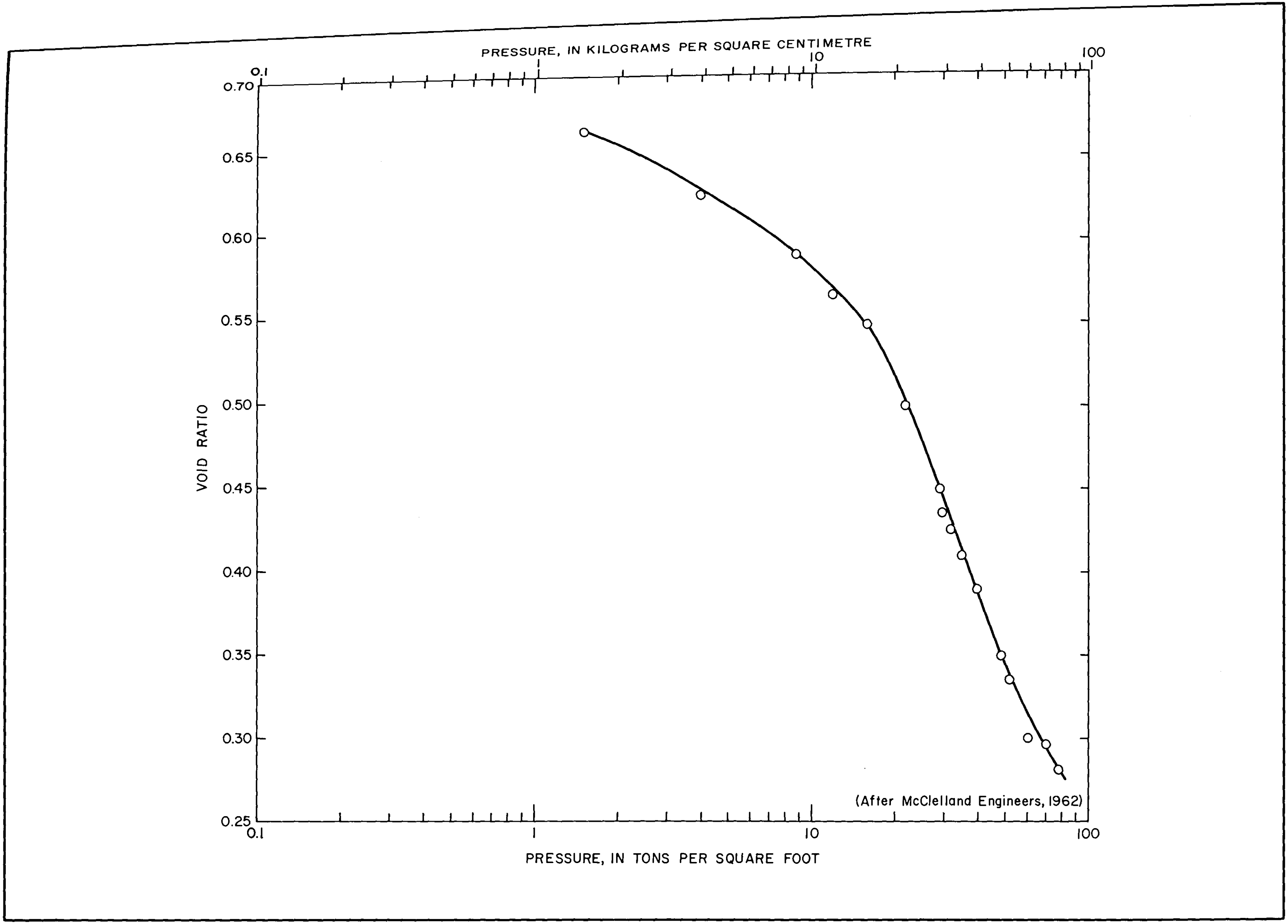


FIGURE 16.-Relation between void ratio and applied pressure for clay sample from a depth of 682 feet (208 m), well LJ 65-32-402

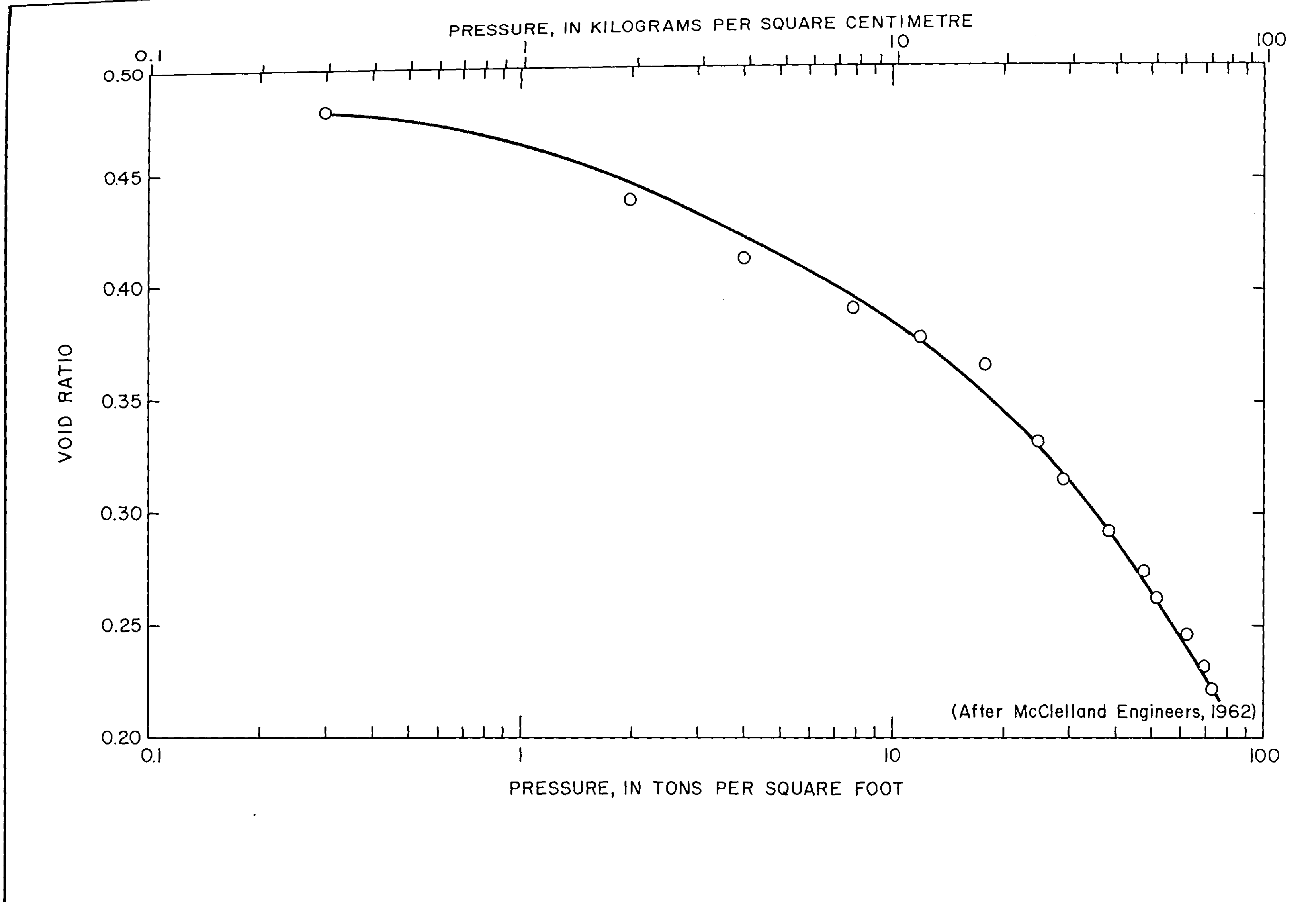


FIGURE 17.-Relation between void ratio and applied pressure for clay sample from a depth of 737 feet (225 m), well LJ 65-32-503

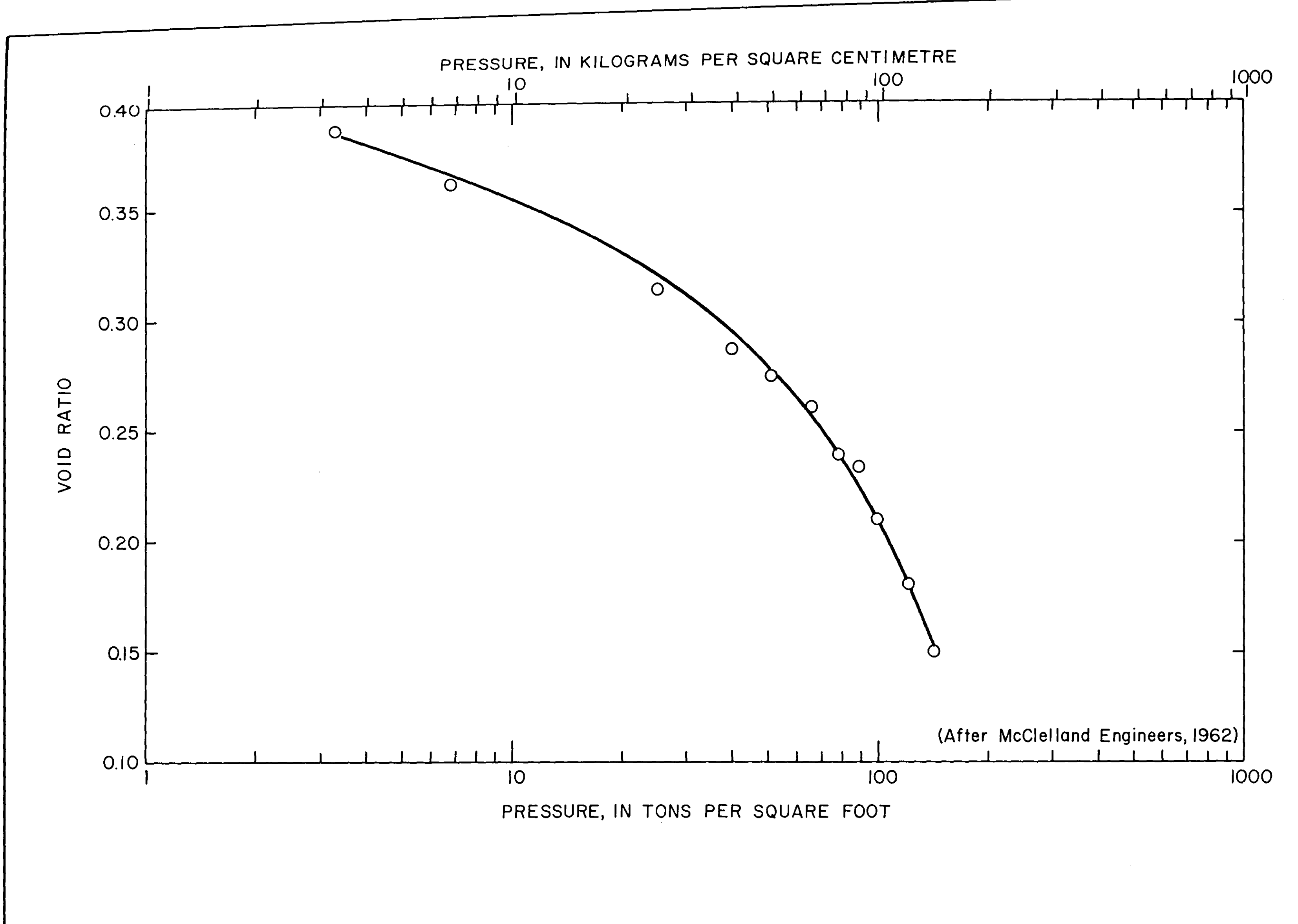


FIGURE 18.-Relation between void ratio and applied pressure for clay sample from a depth of 818 feet (249 m), well LJ 65-32-402

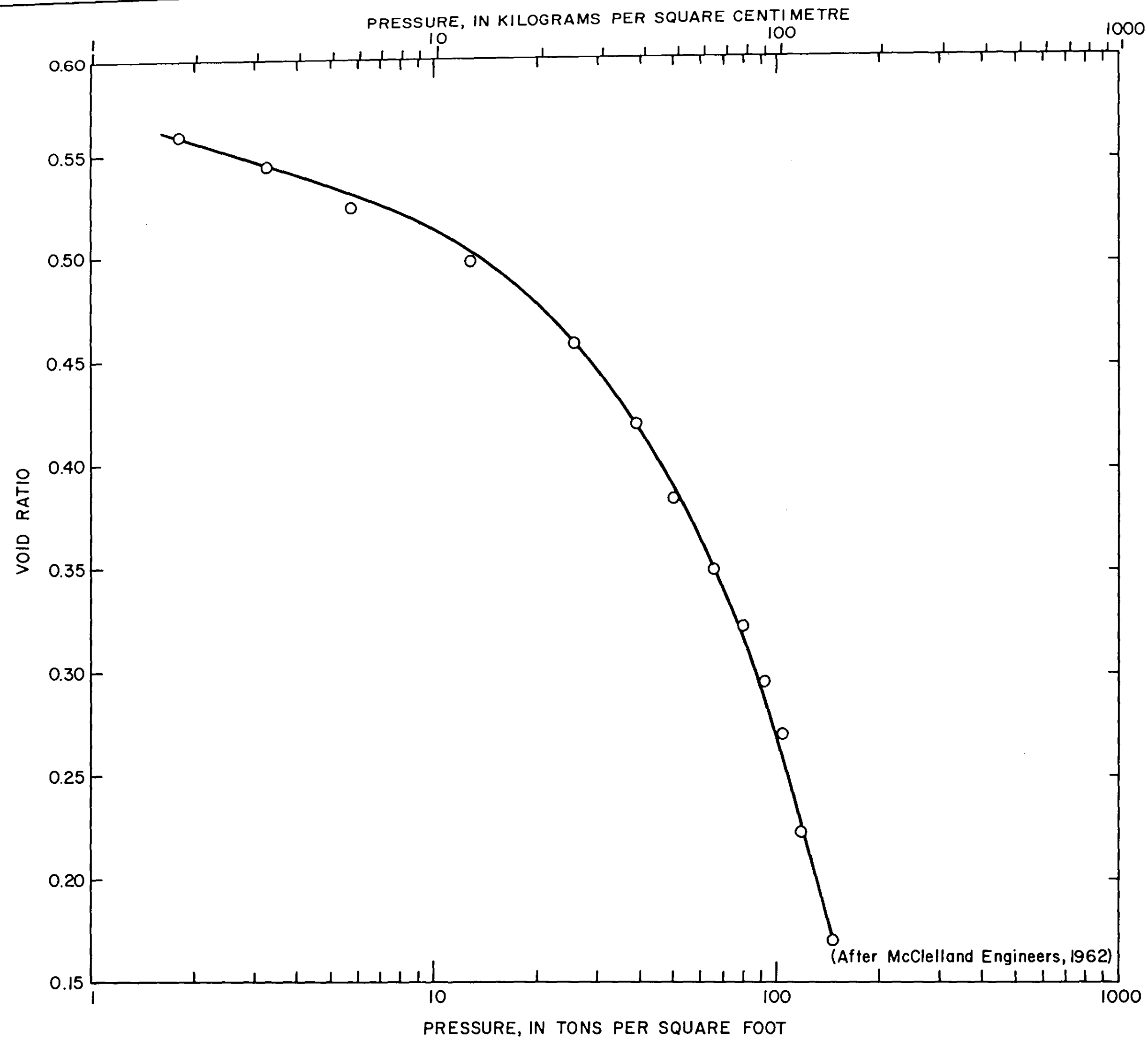


FIGURE 19.-Relation between void ratio and applied pressure for clay sample from a depth of 874 feet (266 m), well LJ 65-32-503

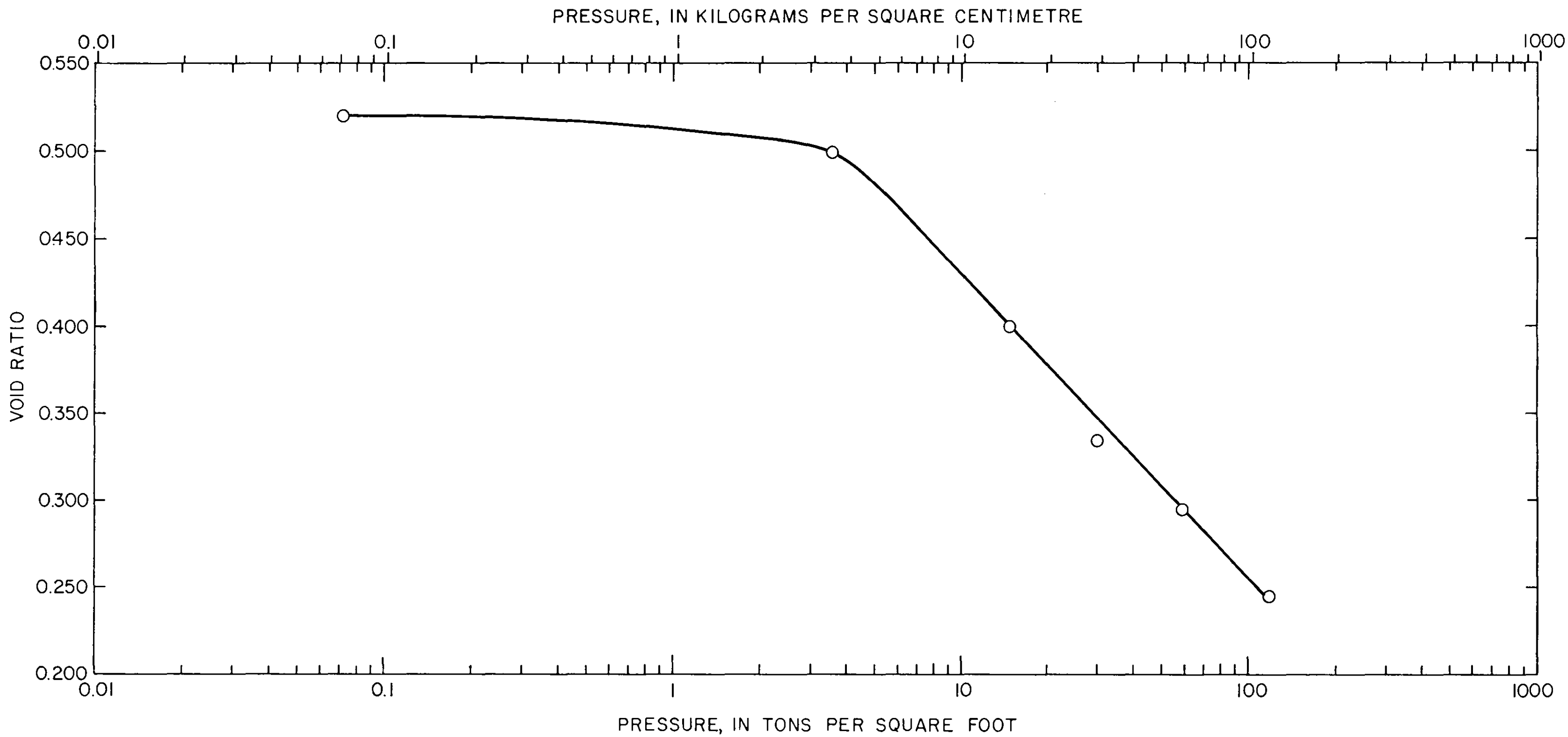


FIGURE 20.-Relation between void ratio and applied pressure for clay sample from a depth of 979 feet (298 m), well LJ 65-32-627

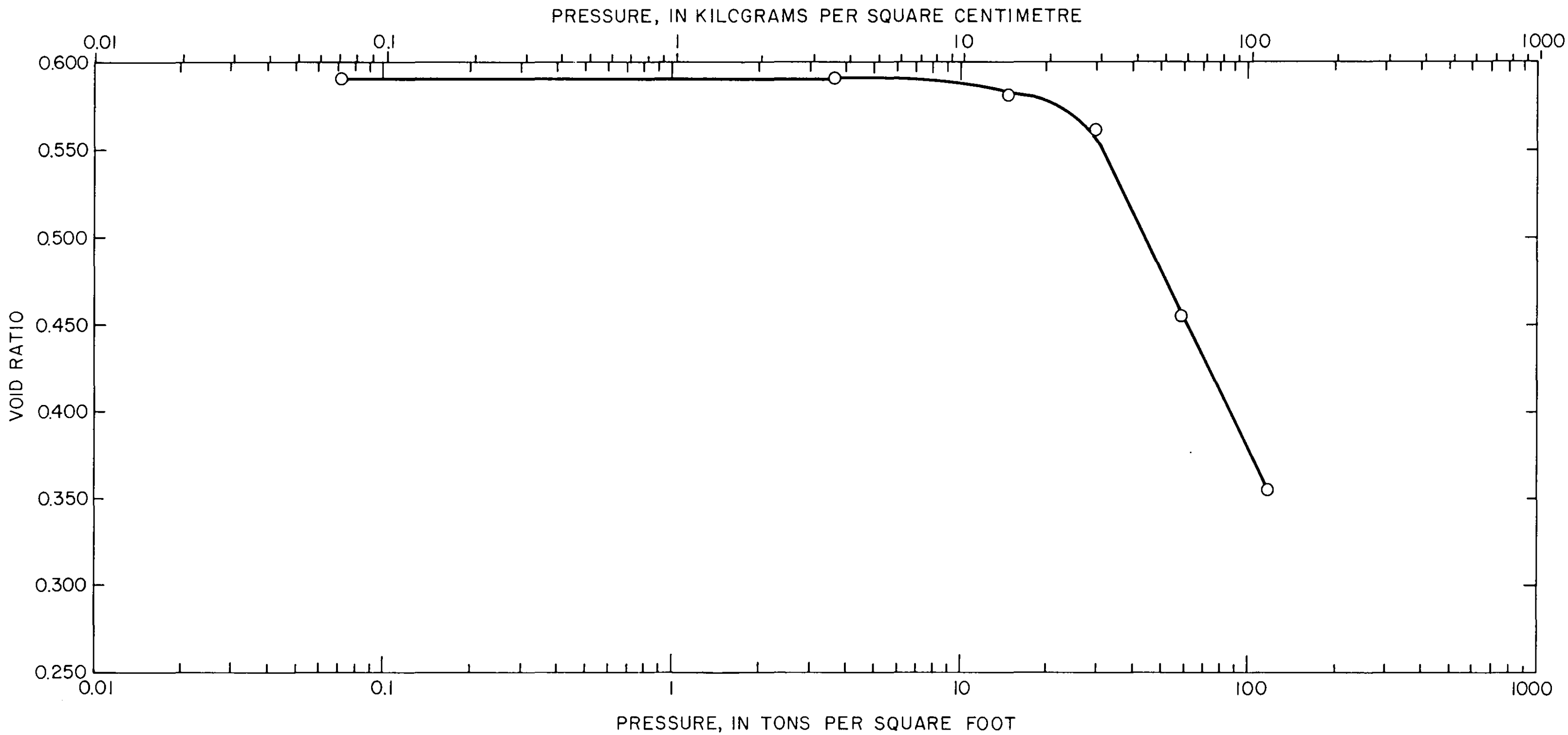


FIGURE 21.-Relation between void ratio and applied pressure for clay sample from a depth of 1,023 feet (312 m), well LJ 65-32-627

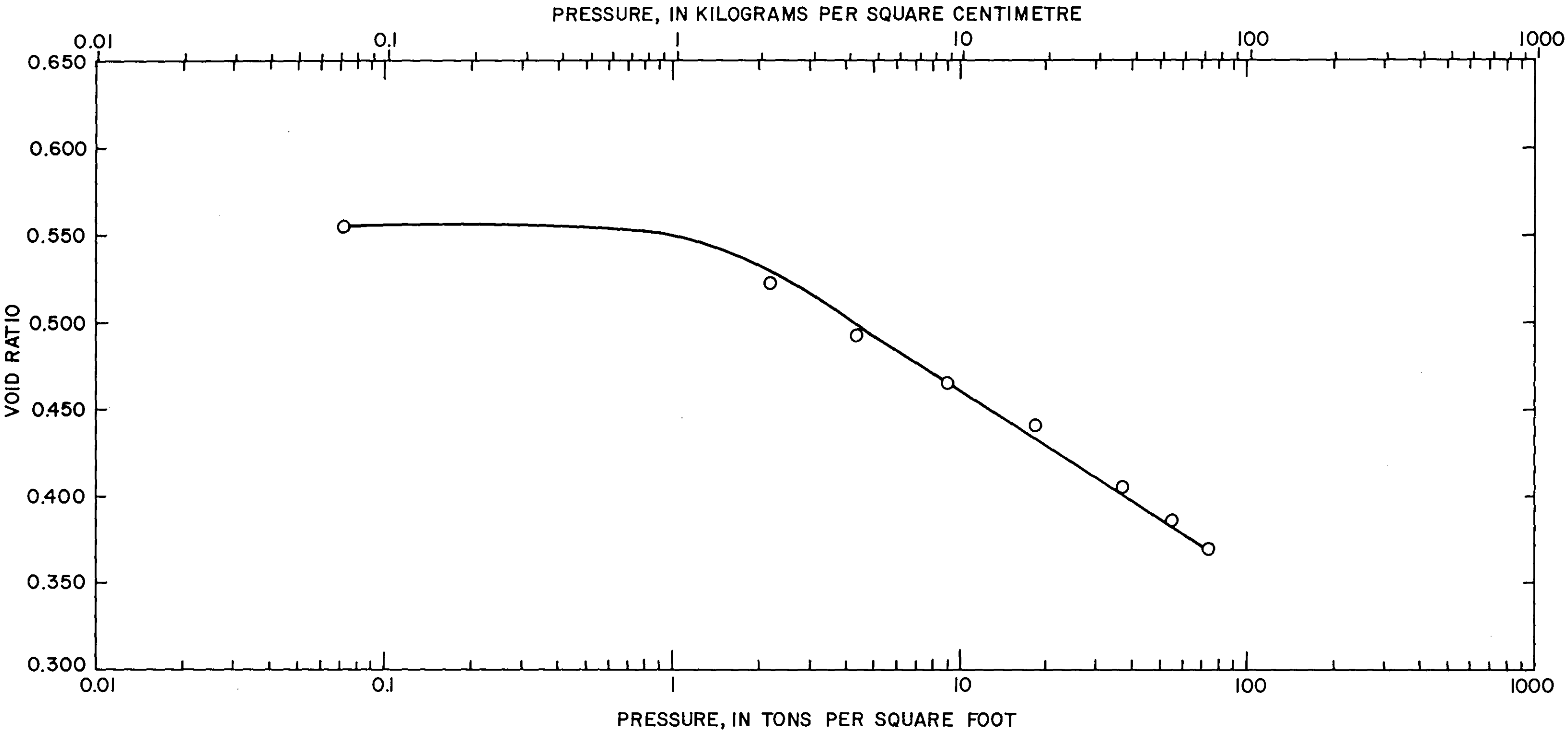


FIGURE 22.-Relation between void ratio and applied pressure for clay sample from a depth of 1,059 feet (323m), well LJ 65-32-627

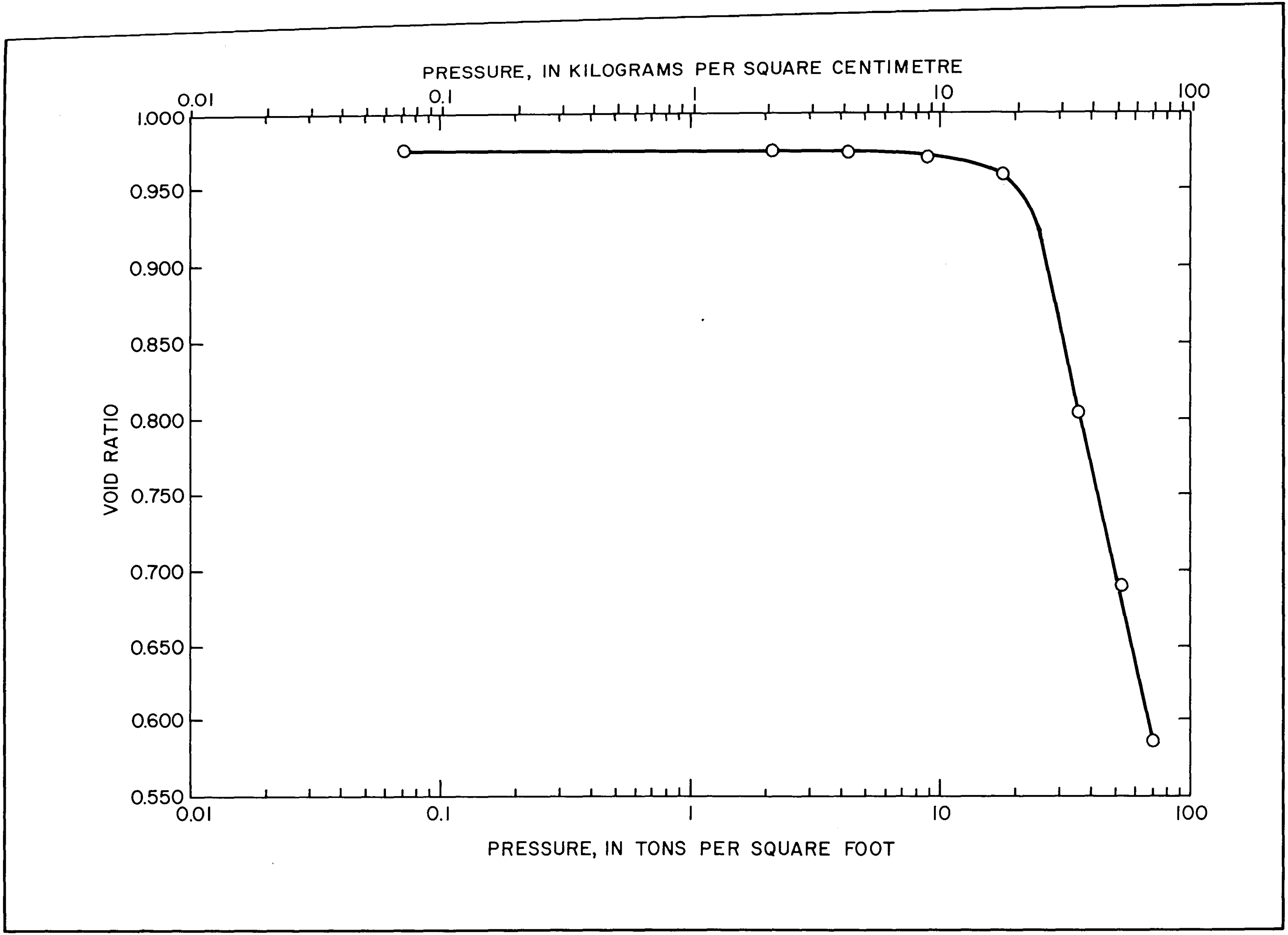


FIGURE 23.-Relation between void ratio and applied pressure for clay sample from a depth of 1,250 feet (381 m), well LJ 65-32-627

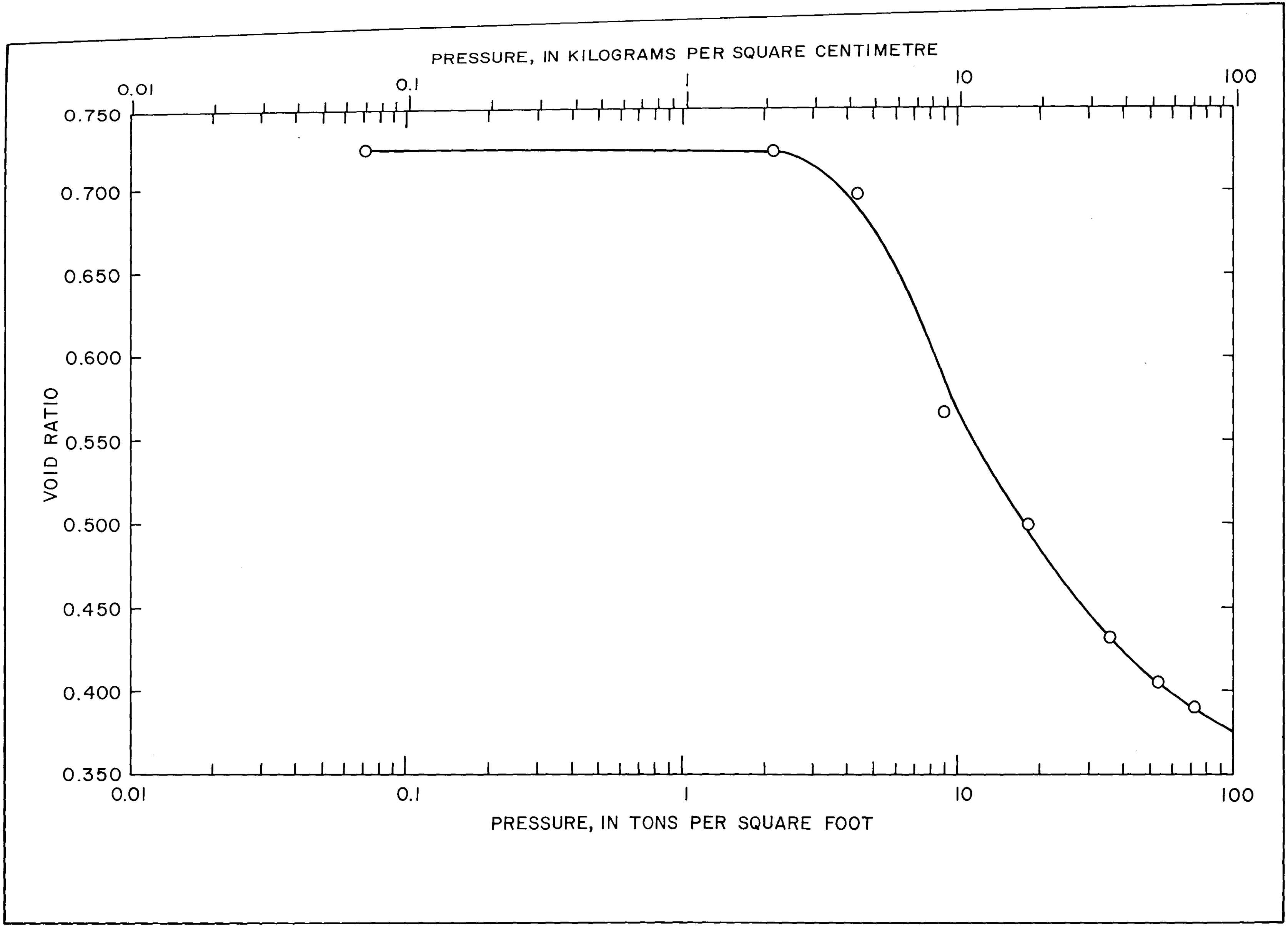


FIGURE 24.-Relation between void ratio and applied pressure for clay sample from a depth of 1,340 feet (408 m), well LJ 65-32-627

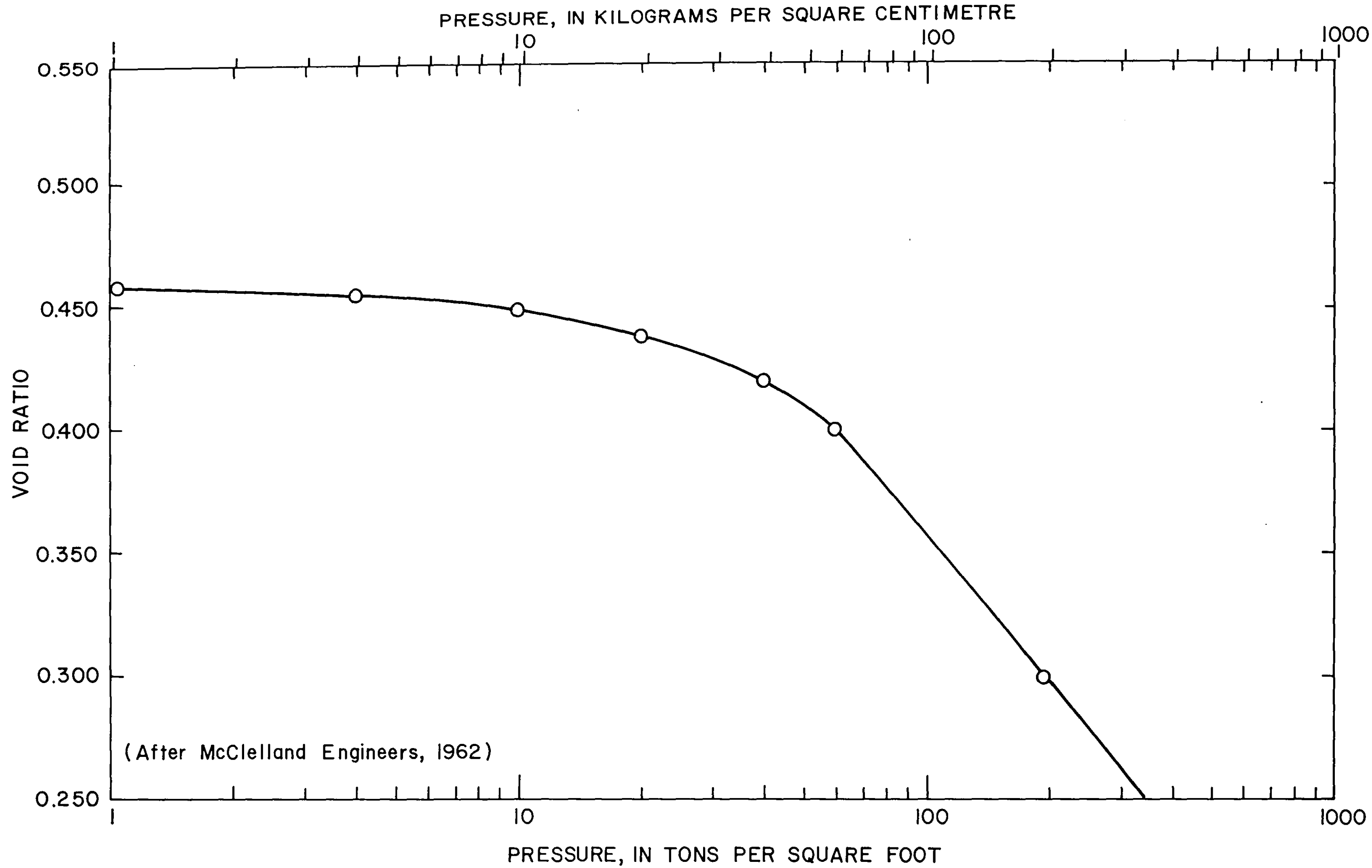


FIGURE 25.-Relation between void ratio and applied pressure for clay sample from a depth of 1,647 feet (502 m), well LJ 65-22-102

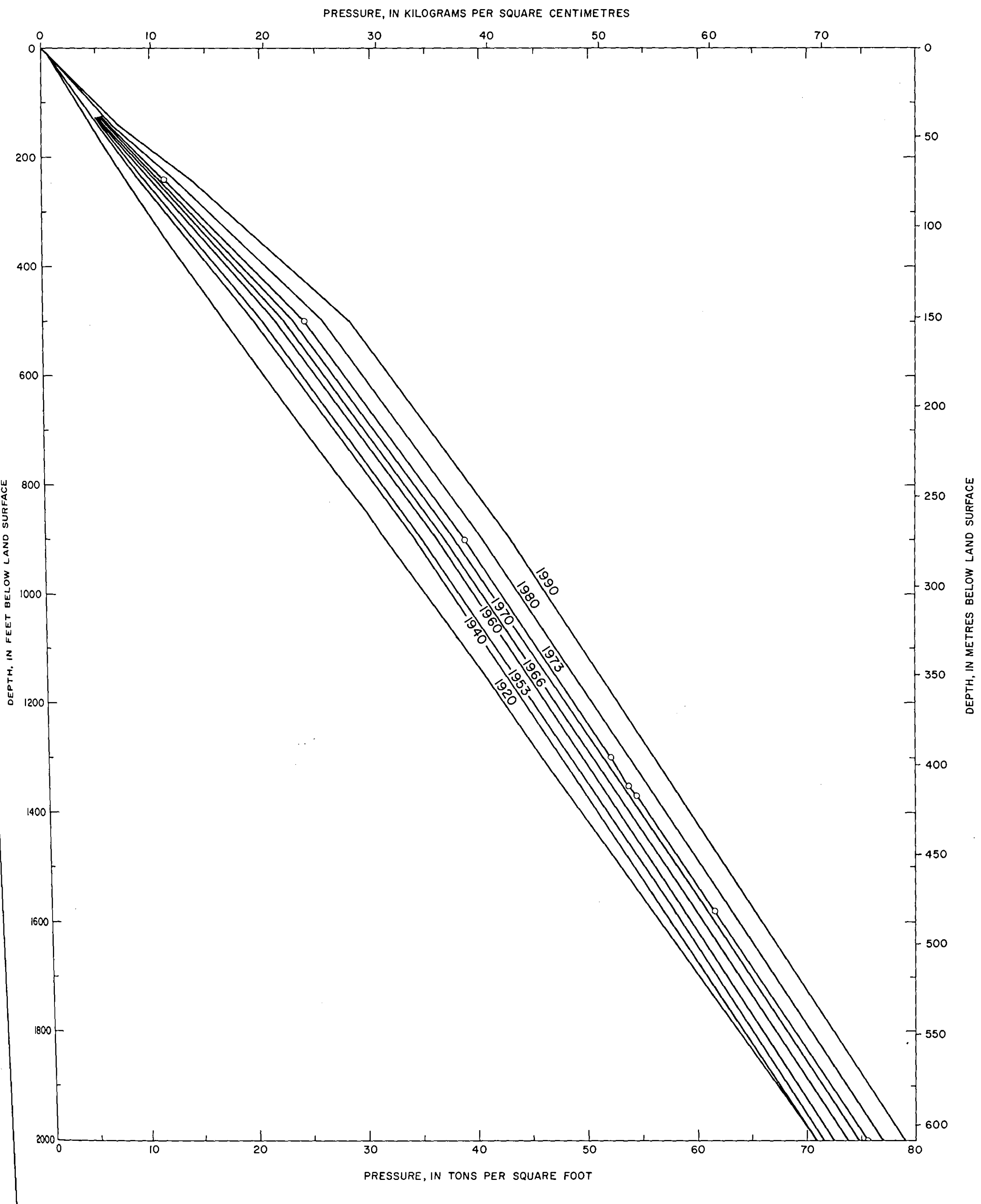


FIGURE 26. Effective load at Seabrook for depths between 0 and 2000 feet (0 and 610 m)

By using the void ratio-loading curve, the loading due to declines in artesian heads, and the preceding formula, each clay layer was analyzed for its change in thickness according to the procedure outlined by Terzaghi and Peck (1948) and by Taylor (1948). The compaction of all clay layers was then summed to determine ultimate subsidence. It was assumed that the properties of a particular sample as determined in the laboratory represented the properties of all clay layers in a depth interval from midway between the nearest samples above and below.

The time lag between loading and ultimate consolidation is dependent upon the thickness and permeability of the clay bed. The degree of consolidation at any time was determined with the aid of the formula from basic soil mechanics theory:

$$T = \frac{c_v}{(H/2)^2} t$$

where T = dimensionless time factor,
c_v = coefficient of consolidation from consolidation test,
t = time period, and
H = thickness of the clay layer.

Using the dimensionless time factor, the degree of consolidation was obtained from the graph presented by Taylor (1948, fig. 10.10, p. 237). Corrections for incremental continuous loading rather than instantaneous loading were made according to the procedure outlined by Taylor (1948, p. 291).

The results of these calculations reflect compaction due to dissipation of excess pore pressure only. Riley (1969, p. 425), in his description of subsidence in California in which the hydrogeologic setting is similar to the Seabrook area, considers secondary, or nonhydrodynamic consolidation to be minor. Table 1 shows clay mineralogy of samples obtained at Baytown, Seabrook, Texas City, and California.

Standard laboratory tests of clays usually indicate secondary effects. In the standard method of testing, incremental loads, doubling the preceding load are added to the test specimen. Compared to field conditions, the loading is extremely rapid. Laboratory tests using gradually increasing loads (simulating field conditions) are being conducted at Lamar University by Dr. Andre P. Delflache. Early results indicate little, if any, nonhydrodynamic effects (A. P. Delflache, oral commun., August 1974). Therefore, in this report, secondary, or nonhydrodynamic consolidation is considered to be minor.

Gross approximations of the declines in artesian heads in the Alta Loma Sand and the Evangeline aquifer at the monitoring site were made from data on published and unpublished maps showing the altitudes of the potentiometric surfaces in 1940, 1953, 1960, 1966, and 1970. The potentiometric surface, which is defined by the levels to which water will rise in tightly cased wells, is a surface that represents the static head. Loading of the clay was estimated for the assumed original conditions, and changes in loading were computed from the maps showing changes in artesian heads.

The current (1973) loading profile is based on measurements in observation wells. The measurements made in July 1974, in the six wells at the test site were plotted against depth of the well (fig. 27). This illustration shows the wide variation in water levels in a particular area.

The following assumptions were used to predict the rate of subsidence and the maximum amount of subsidence:

1. The altitude of the potentiometric surface in 1920 was the same as the original surface in 1890 and no subsidence occurred before 1920. The land surface subsided about 0.3 foot (0.09 m) between 1906 and 1943 (Gabrysch and Bonnet, 1974b, fig. 10, p. 17).
2. Artesian-head declines in the Alta Loma Sand and Evangeline aquifer will continue at respective rates of 8 and 7 feet (2.4 and 2.1 m) per year until 1980. Thereafter, no further head declines will occur (case I).
3. Artesian-head declines in the Alta Loma Sand and Evangeline aquifer will continue at respective rates of 8 and 7 feet (2.4 and 2.1 m) per year until 1990. Thereafter, no further head declines will occur (case II).

Subsidence from 1920 to 1973 calculated by use of laboratory-determined characteristics and of leveling data is shown on figure 28. The measured subsidence was 3.3 feet (1.0 m), and the calculated subsidence was 9.3 feet (2.8 m). The gross error in the calculated values is clearly indicated by the difference in the two plots. The two major factors used in calculating subsidence are the consolidation characteristics of the clay material and the load to which the clays have been subjected. Errors in the determination of load are not likely to be nearly large enough to account for the difference between the measured and calculated subsidence shown by figure 28. The error is more likely due to nonrepresentative sampling of the clays. Regardless of the reason, use of another method of estimating subsidence is necessary.

The method adopted for prediction of subsidence relates average stress change determined from field records, measured subsidence, and clay thickness determined from electrical logs. The unit of compaction per unit clay thickness per unit stress change during a specific time period is the specific unit compaction in feet^{-1} (3.2808 m^{-1}).

Subsidence was determined for 1906-43, 1943-54, 1954-59, 1959-64, and 1964-73, and the change in stress was determined for approximately the same periods. Figure 29 shows the change in stress at Seabrook and the assumed change in stress used for prediction.

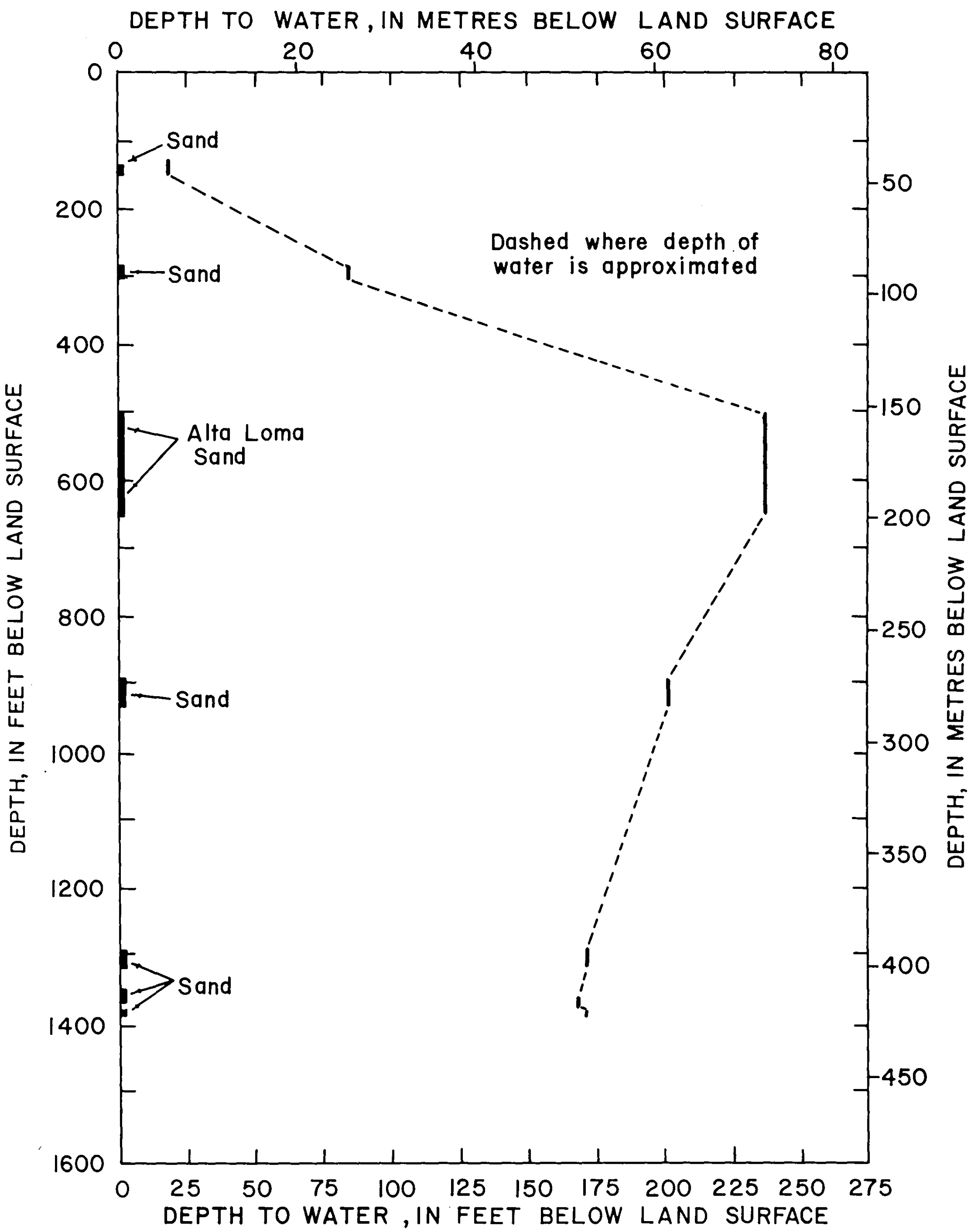


FIGURE 27.-Potentiometric profile at Seabrook, July 1974

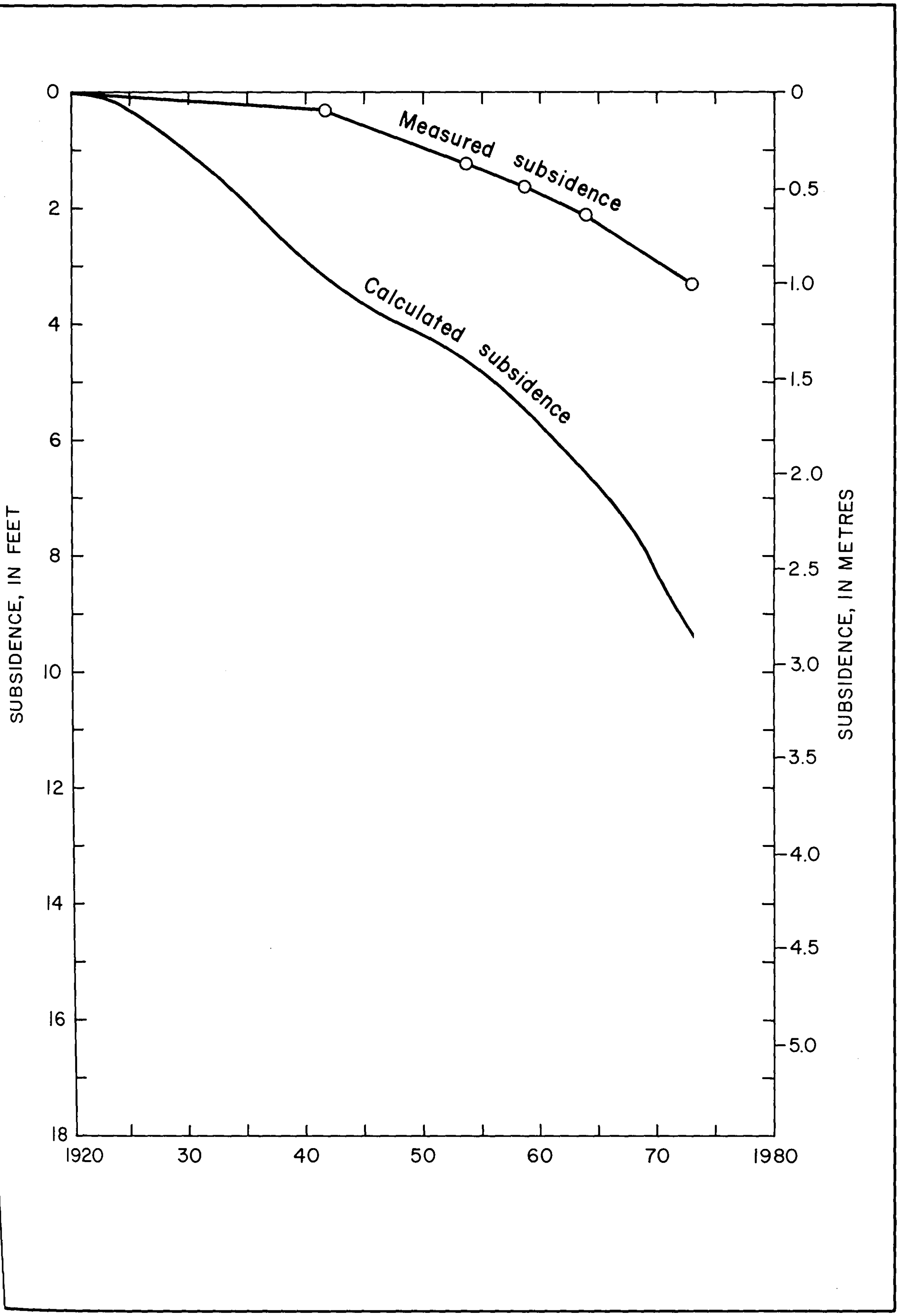


FIGURE 28.-Land-surface subsidence calculated on the basis of consolidation theory, 1920-73

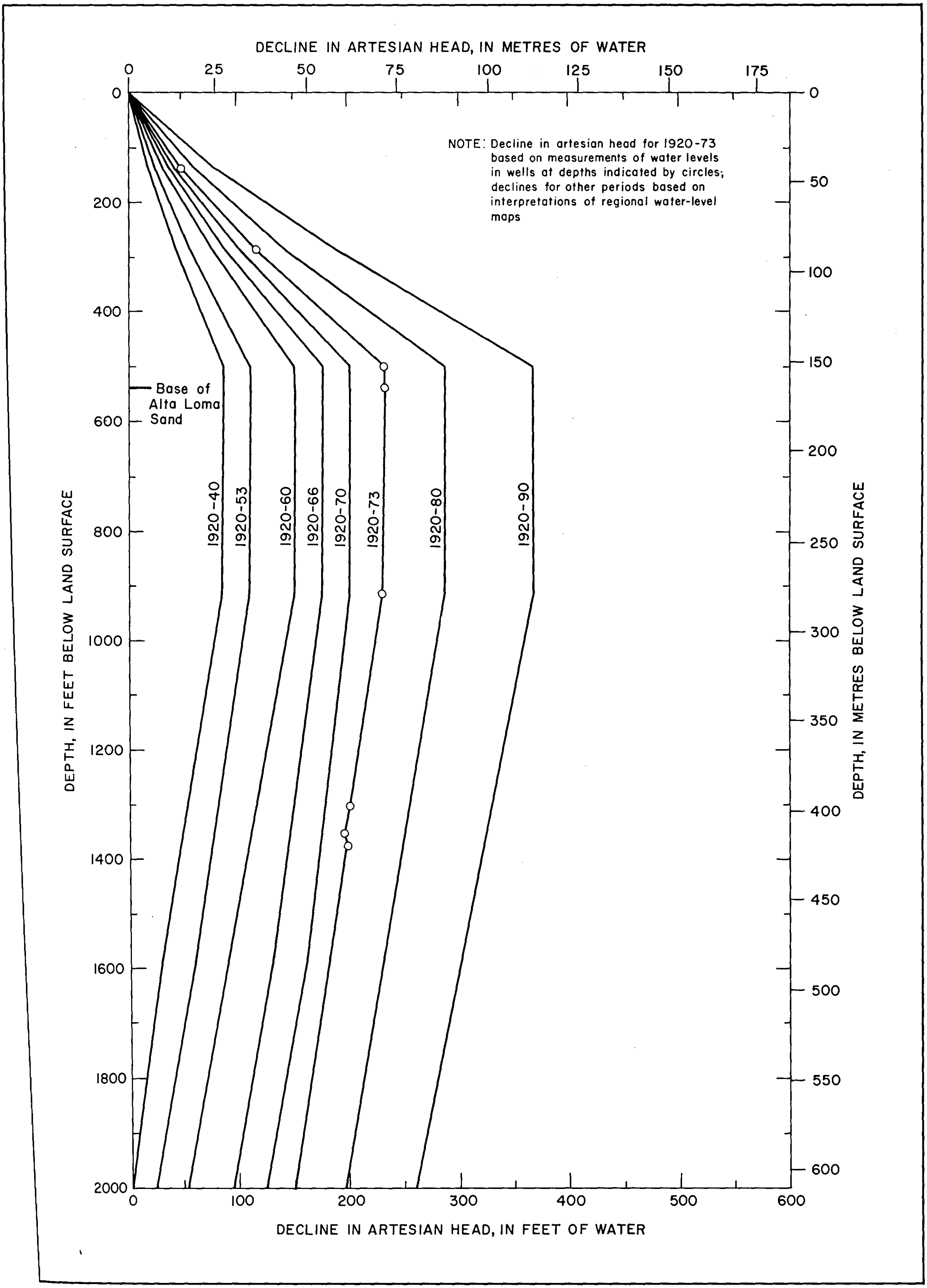


FIGURE 29.-Approximate decline in artesian head

Hydrographs of individual wells or potentiometric maps based on either single or multiscreened wells are not directly applicable to computations of subsidence. Figure 29 shows that the decrease in pressure in 1973 in the upper part of the Evangeline aquifer was about 230 feet (70 m) of water versus 150 feet (46 m) of water at a depth of 2,000 feet (610 m). Maps of the potentiometric surface in the Evangeline aquifer approximate the potentiometric surface at a depth of about 1,580 feet (482 m).

On the basis of the change in stress, a total thickness of 799 feet (243.5 m) of clay was determined for the site, and the measured subsidence and specific unit compaction for each of five periods was calculated. The calculated values for the periods of subsidence ranged from 7.5×10^{-6} to 4.9×10^{-5} ft^{-1} (2.46×10^{-5} to 1.6×10^{-4} m^{-1}) (see following table).

Period	Average stress change (feet of water)	Average annual stress change (feet/year)	Subsidence (feet)	Specific unit compaction (ft^{-1})
1906-43	50	1.4	0.3	7.50×10^{-6}
1943-54	23	2.1	.9	4.9×10^{-5}
1954-59	32	6.4	.4	1.6×10^{-5}
1959-64	13	2.6	.5	4.8×10^{-5}
1964-73	59	6.6	1.2	2.5×10^{-5}

The lowest value was for 1906-43, when the material was probably undergoing recompression. The range from 1.6×10^{-5} to 4.9×10^{-5} ft^{-1} (5.2×10^{-5} to 1.6×10^{-4} m^{-1}) appears to be related to the rate of stress change and the time necessary for drainage. Both of the high values are for periods of small changes in stress, and both of the low values are for periods of large changes in stress. The specific unit compaction for 1943-73 is 3.0×10^{-5} ft^{-1} (9.8×10^{-5} m^{-1}); the average specific unit compaction for the four periods is 3.5×10^{-5} ft^{-1} (1.1×10^{-4} m^{-1}).

The weighted average of the values determined by laboratory-consolidation tests of 15 cores from the Seabrook, Johnson Space Center, and University of Houston sites was 1.0×10^{-4} ft^{-1} (3.2×10^{-4} m^{-1}). The values were weighted according to the thickness of clay to which each applies. Once preconsolidation load (load to which the material had previously been subjected) has been exceeded, the amount of compaction that will occur with additional load may be as much as 100 times the compaction that occurred under a load range less than the preconsolidation load.

The value selected for predicting ultimate subsidence, 1.0×10^{-4} ft^{-1} (3.2×10^{-4} m^{-1}), was the average value derived from the laboratory tests of the cores. This value is probably high because the cores were obtained from the shallow, more compressible clays. However, field data indicate that the value should exceed 4.8×10^{-5} ft^{-1} (1.6×10^{-4} m^{-1}). At Seabrook, it is estimated that about 0.08 foot (0.024 m) of subsidence will occur for each foot of decline in mean artesian head after 1973.

The value selected for predicting subsidence from 1973 to 1980 and 1990 under the two assumed cases was 4.8×10^{-5} ft^{-1} (1.6×10^{-4} m^{-1}). For each foot of decline in artesian head, 0.038 foot (0.012 m) of subsidence will occur by the end of each period. The estimated average increase in stress through the compacting interval (using fig. 29) for 1973-80 is 44 feet (13.4 m). Ultimate subsidence expected due to this stress increase is 44 feet x 1.0×10^{-4} ft^{-1} x 799 feet = 3.5 feet (1.1 m). The subsidence expected by 1980 due to this increase in stress is 44 feet x 4.8×10^{-5} ft^{-1} x 799 feet = 1.7 feet (0.5 m).

Test data and calculations in the Baytown area (Gabrysch and Bonnet, 1974a) indicate that 80-85 percent of the expected subsidence due to hydrodynamic compaction caused by pressure decline to date has already occurred. Thus 15-20 percent of the subsidence might be expected due to pressure decline before 1973. If 3.3 feet (1.0 m) of subsidence has occurred at Seabrook between 1906 and 1973, another 0.8 foot (0.24 m) could be expected. Therefore, 4.3 feet (1.3 m) of additional subsidence could be expected under case I. By the same analysis, under the conditions of case II, additional subsidence of 6.6 feet (2.0 m) could be expected. The total subsidence would then be 7.6 feet (2.3 m) and 9.9 feet (3.0 m) under the conditions of case I and case II. Figure 30 shows the ranges in subsidence that could be expected under the two assumed cases of pressure decline if the present relation of compaction to increase in stress continues. Because of the complexity of the system and the many assumptions necessary, it should be stressed that the predicted subsidence is at best an approximation.

CORRECTIVE MEASURES

Subsidence of the land surface in the Seabrook area will continue until pore pressures in the clay beds reach equilibrium with the pressures in the adjacent sand beds. Therefore, even if artesian head is maintained at the 1973 level, compaction of the clay layers would continue, but at a decreasing rate. To establish equilibrium and thereby more quickly halt compaction, the artesian head in the sands must be raised to a value equal to the pore pressure in the adjacent clay beds.

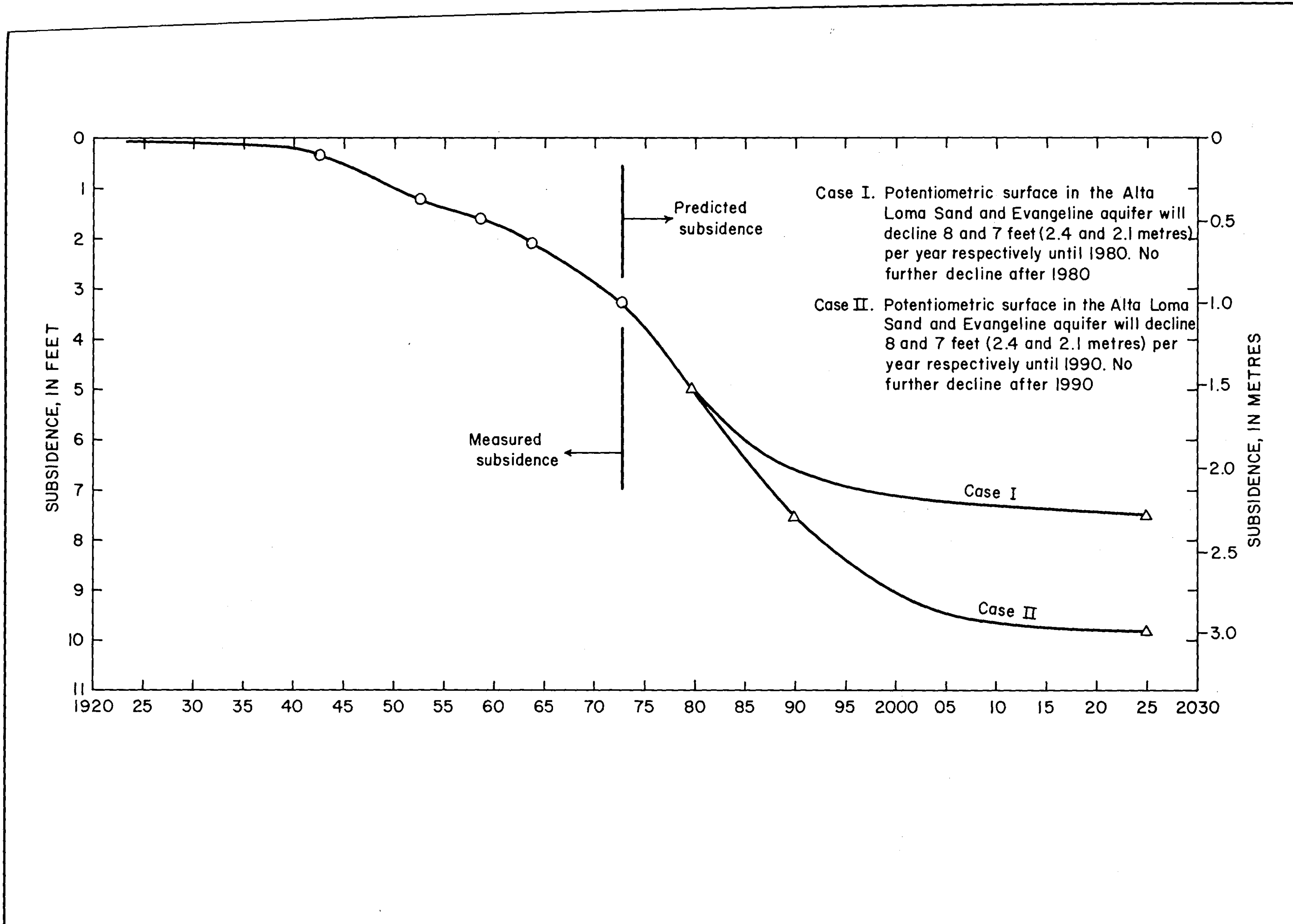


FIGURE 30.-Measured and predicted land-surface subsidence, 1920-2025

No data have been collected at Seabrook on the excess pore pressure in the clay, but the data collected at Baytown indicate that it is equivalent to as much as 135 feet (41.1 m) or 58 lb/in^2 (4.08 kg/cm^2) of head. However, malfunction of the pore-pressure measuring device leaves doubt as to the validity of this value. Other measurements at Baytown indicate that it is more likely that the pressure recovery need not be this great--possibly 60-70 feet (18.3-21.3 m) of water-level recovery would be sufficient to halt further subsidence.

Two methods of repressurizing are: (1) Decrease the rate of ground-water pumping in the area; and (2) artificially recharge the aquifer. Artificial recharge would require that the injected water be of a quality suitable for future use and be compatible with the native ground water and associated water-bearing material. Because of these requirements, any available surface water probably would need treatment before injection into the aquifer.

Although at least a dozen wells drilled for the disposal of liquid wastes are in operation in Harris and surrounding counties, no large-scale fresh-water injection is underway or planned. Additional fresh water is available from aquifers in other areas and from nearby lakes.

A decrease in pumpage would cause artesian heads to increase by natural means and is probably the most logical solution to the problem of artesian-head declines and land-surface subsidence.

PLANNED DEVELOPMENT AND SUBSIDENCE

Pumping of ground water in the Houston-Galveston region has continued to increase, and the rates of artesian-head decline and subsidence have accelerated. Subsidence will continue at a rate dependent on the decline in pressure resulting from ground-water pumping. Commitments for future use of about 166 million gal/d (7.3 m^3/s) of surface water from Lake Livingston have been received from 24 major ground-water users in the southern part of Harris County. Additionally, minor ground-water users have recently begun or firmly plan to use surface water.

The increased use of surface water will reduce the pumpage of ground water and will probably result in some recovery of artesian head. The city of Galveston began using surface water in August 1973 and has decreased ground-water withdrawals by about 6 million gal/d (0.3 m^3/s). Water levels in some wells in the Alta Loma area were about 15 feet (4.6 m) higher in February 1974 than in February 1973.

The actual or planned decrease in the withdrawal of ground water was programed in an analog model (Jorgensen, 1974) of the ground-water system of the Houston-Galveston region, and the results of the model study (Jorgensen and Gabrysch, 1974) indicate a rapid rise in artesian heads would occur in the southern part of Harris County. Within a few months, as much as 35 feet (10.7 m) of recovery could be expected in the altitude of the potentiometric surface in the Chicot aquifer and 20 feet (6.1 m) in the altitude of the potentiometric surface of the Evangeline aquifer at Seabrook. With recovery of artesian head in southern Harris and northern Galveston Counties, the rate of subsidence should decrease substantially in the more critical areas. However, unless increasing needs are met from surface-water sources or remote ground-water sources, the recovery would be short-lived, and subsidence would resume.

SUMMARY AND CONCLUSIONS

The pumping of ground water from the Chicot and Evangeline aquifers in Harris and Galveston Counties, Texas, has caused declines in artesian heads at Seabrook of as much as 240 feet (73 m) in the Chicot aquifer and 20 feet (61 m) in the Evangeline aquifer. The declines in artesian heads have in turn caused subsidence of the land surface. At Seabrook, the Chicot aquifer extends from land surface to a depth of about 650 feet (198 m) and the Evangeline aquifer extends from the base of the Chicot to a depth of about 3,800 feet (1,158 m). The rates of artesian-head decline in 1973 were 8 feet (2.4 m) per year in the Alta Loma Sand (basal sand of the Chicot aquifer) and 7 feet (2.1 m) per year in the Evangeline aquifer. A minimum of about 3.3 feet (1.0 m) and a maximum of about 4.3 feet (1.3 m) of subsidence occurred in the Seabrook area by 1973, of which about 0.3 foot (0.09 m) occurred before 1943 and between 1.5 and 2 feet (0.5 and 0.6 m) occurred between 1964 and 1973. The average rate of subsidence between 1964 and 1973 was 0.22 foot (0.07 m) per year.

Six wells were drilled at the test site at Seabrook to collect data on properties of the clays and on artesian heads in the sands. One well was completed as a borehole extensometer to monitor compaction of material between the land surface and a depth of 1,381 feet (421 m). The record from this extensometer is not sufficient to relate the amount of compaction to total subsidence.

Five clay cores obtained from one well drilled at Seabrook were tested to determine the characteristics of compressibility. These data, together with compressibility data on cores from sites at the Johnson Space Center and the University of Houston were used to compute subsidence by the Terzaghi theory of consolidation. The amount of subsidence computed by this method far exceeded the measured amount of subsidence. In 1973, subsidence as based on calculations by this method was 9.3 feet (2.8 m) as compared to measured subsidence of 3.3 feet (1.0 m); therefore, calculations were made by using field records of subsidence and artesian-head decline.

To predict future subsidence, it was assumed that artesian heads would decline at the 1973 rates until 1980 (case I) and until 1990 (case II). The specific storage as determined in the laboratory and the specific unit compaction as determined from field records were used to estimate the amount of subsidence resulting from the decline in artesian head between 1973 and 1980 and between 1973 and 1990. On the basis of laboratory tests of the clay cores, it is estimated that about 0.08 foot (0.024 m) of subsidence will ultimately occur at Seabrook for each foot of mean artesian-head decline after 1973.

The amount of subsidence that will occur during the periods of head decline is based on field records and is estimated to be 0.038 foot (0.012 m) per foot of mean artesian-head decline. Bench-mark level data indicated that 3.3 feet (1.0 m) of subsidence had occurred at the test site at Seabrook. Based on calculations of residual subsidence at Baytown, the expected residual subsidence at Seabrook due to head decline before 1973 was conservatively estimated to be 0.8 foot (0.24 m) or 20 percent of total subsidence. Additional subsidence expected under conditions of cases I and II are 4.3 feet (1.3 m) and 6.6 feet (2.0 m), respectively. The total subsidence would then be 7.6 feet (2.3 m) and 9.9 feet (3.0 m), respectively. Because of the complexity of the system and the many assumptions that must be made, the predicted subsidence should be considered as approximations.

Water from Lake Livingston will be available in the Houston-Galveston area in 1976. Planned usage of the surface water will allow a decrease in ground-water pumping and a recovery in artesian head of about 35 feet (10.7 m) in the Chicot aquifer and about 20 feet (6.1 m) in the Evangeline aquifer. As a result of the recovery, the rate of subsidence should decrease substantially in the Seabrook area.

Table 1.--Clay minerals in samples from Texas and California

Site	Number of samples	Clay minerals (percent)			
		Montmorillonite	Illite	Chlorite and kaolinite-type minerals	Mixed layer clay minerals
Seabrook[1/]	5	21	21	9	49
JSC[2/]	8	65	15	20	--
Baytown[1/]	4	40	10	24	26
Texas City[1/]	6	26	20	14	40
California[3/]	85	70	10	15	5

1/ Analysis by U.S. Geological Survey laboratory.
2/ Johnson Space Center; analysis by Corliss and Meade (1964).
3/ Los Banos-Kettleman City area; analysis reported by Mead (1967).

Table 2.--Physical properties of clay samples

Sample no. 1/	Sample depth (feet)	Specific gravity	Water content (percent)	Liquid limit (percent)	Plastic limit (percent)
1	131	2.69	15	33	14
2	221	2.60	32	91	26
3	312	2.62	30	83	24
4	412	2.68	28	82	25
5	510	2.74	20	38	24
6	682	2.65	24	60	19
7	737	2.68	18	65	19
8	818	2.64	16	42	15
9	874	2.70	17	53	15
10	979	2.66	18	30	14
11	1,023	2.66	28	27	13
12	1,059	2.70	18	30	13
13	1,250	2.71	23	47	20
14	1,340	2.69	16	37	15
15	1,647	2.74	47	--	--

1/ Samples 1-9 from Johnson Space Center tested by McClelland Engineers, Houston, Texas. Samples 10-14 from Seabrook tested by U.S. Geological Survey laboratory, Denver, Colorado; and sample 15 collected at the University of Houston and tested by Lyle A. Wolfskill.

Table 3.--Coefficients of consolidation and hydraulic conductivities of clay samples

Sample no.	Depth (feet)	Time - consolidation data: Load (ton/ft^2)	Coefficient of consolidation, c_v (cm^2/s)	Hydraulic conductivity, k (cm/s)
1/ 1	131	18	4.5×10^{-5}	--
1/ 2	221	6	2.2×10^{-4}	--
1/ 3	312	17	2.2×10^{-5}	--
1/ 4	412	24	3.4×10^{-5}	--
1/ 5	510	60	4.5×10^{-5}	--
6	682	--	--	--
1/ 7	737	28	7.5×10^{-6}	--
1/ 8	818	38	4.5×10^{-5}	--
1/ 9	874	38	2.8×10^{-4}	--
2/ 10	979	36.5	1.8×10^{-4}	2.4×10^{-10}
2/ 11	1,023	36.9	2.6×10^{-3}	4.6×10^{-9}
2/ 12	1,059	37.9	8.0×10^{-4}	6.4×10^{-10}
2/ 13	1,250	44.0	1.1×10^{-4}	4.2×10^{-10}
2/ 14	1,340	46.8	3.2×10^{-4}	2.7×10^{-10}
3/ 15	1,647	128	1.3×10^{-5}	--

1/ Load and c_v read from graphs, Plates A-1 to A-12, McClelland Engineers, 1962. Samples from JSC.

2/ Tested by U.S. Geological Survey laboratory, Denver, Colorado. Load approximates 1973 stress. Samples from Seabrook.

3/ Tested by Lyle A. Wolfskill. Samples from University of Houston.

Table 4.--Thickness of clay and maximum clay-bed thickness

Layer number	Depth interval (feet)	Clay thickness[1/] (feet)	Maximum clay-bed thickness (feet)
1	73-76	3	3
2	80-82	2	2
3	88-92	4	4
4	95-97	2	2
5	102-107	5	5
6	108-113	5	5
7	117-122	5	5
8	127-140	13	13
9	152-166	14	14
10	170-174	4	4
11	176-178	2	2
12	182-186	4	4
13	191-199	8	8
14	206-208	2	2
15	216-223	7	7
16	224-232	8	8
17	237-244	7	7
18	252-259	7	7
19	269-289	20	20
20	300-325	18	3
21	328-348	10	2
22	351-360	9	9

See footnote at end of table.

Table 4.--Thickness of clay and maximum clay-bed thickness--Continued

Layer number	Depth interval (feet)	Clay thickness1/ (feet)	Maximum clay-bed thickness (feet)
23	369-374	5	5
24	376-396	18	9
25	403-435	25	8
26	488-453	5	5
27	462-470	8	8
28	486-502	16	16
29	534-552	18	18
30	556-583	16	5
31	645-650	5	5
32	661-685	24	24
33	695-700	5	5
34	750-757	7	7
35	763-772	6	2
36	768-800	26	8
37	804-834	18	3
38	836-848	12	12
39	854-875	20	8
40	878-890	5	1
41	934-1,050	36	5
42	1,056-1,150	40	3
43	1,158-1,200	6	2
44	1,244-1,250	6	6

See footnote at end of table.

Table 4.--Thickness of clay and maximum clay-bed thickness--Continued

Layer number	Depth interval (feet)	Clay thickness[1/] (feet)	Maximum clay-bed thickness (feet)
45	1,253-1,256	3	3
46	1,261-1,268	10	2
47	1,272-1,316	16	16
48	1,324-1,350	22	18
49	1,430-1,445	15	15
50	1,452-1,490	20	5
51	1,493-1,530	27	13
52	1,509-1,530	15	8
53	1,558-1,660	85	20
54	1,680-2,000	100	7

1/ Clay thickness for layers 1-46 and 46-54 were determined from logs of well LJ 65-32-626 and well HH-18.

SELECTED REFERENCES

Allen, D. R., and Mayuga, M. N., 1969, The mechanics of compaction and rebound, Wilmington Oil Field, Long Beach, Calif., USA: Internat. symposium of land subsidence, Tokyo, Japan, 1969, Proc., p. 410-422.

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.

Gabrysch, R. K., 1969, Land-surface subsidence in the Houston-Galveston region, Texas: Internat. symposium on land subsidence, Tokyo, Japan, 1969, Proc., p. 43-54.

______1971, Development of ground water in the Houston district, Texas, 1966-69: Texas Water Devel. Board Rept. 152, 24 p.

Gabrysch, R. K., and Bonnet, C. W., 1974a, Land-surface subsidence in the area of Burnett, Scott, and Crystal Bays near Baytown, Texas: U.S. Geol. Survey Water-Resources Inv. 21-74, 48 p.

______1974b, Land-surface subsidence in the Houston-Galveston region, Texas: U.S. Geol. Survey open-file rept., 23 p.

Gabrysch, R. K., Bonnet, C. W., and Naftel, W. L., 1970, Records of water-level measurements in wells in Harris County, Texas, 1966-69: Texas Water Devel. Board Rept. 122, 67 p.

Gabrysch, R. K., Naftel, W. L., and McAdoo, G. D., 1969, Records of water-level measurements in observation wells in Harris County, Texas: Texas Water Devel. Board Rept. 122, 67 p.

Jorgensen, D. G., 1974, Analog-model studies of ground-water hydrology in the Houston district, Texas: U.S. Geol. Survey open-file rept., 80 p., 40 figs.

Jorgensen, D. G., and Gabrysch, R. K., 1974, Simulated water-level changes resulting from proposed changes in ground-water pumping in the Houston, Texas area: U.S. Geol. Survey open-file rept., 3 p.

McClelland Engineers, 1962, Study of probable subsidence, Manned Spacecraft Center, Clear Lake, Texas, in A study of land-surface subsidence conditions at the National Administrative Space Association site in the vicinity of Houston, Texas: Layne Texas Co., Inc., 12 p., 12 pl.

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.

Miller, R. E., 1961, Compaction of an aquifer system computed from consolidation tests and decline in artesian head: U.S. Geol. Survey Prof. Paper 424-B, p. 54-58.

Naftel, W. L., Vaught, Kenneth, and Fleming, Bobbie, 1975, Records of wells, drillers' logs, water-level measurements, and chemical analyses of ground water in Harris and Galveston Counties, Texas, 1970-74: U.S. Geol. Survey open-file rept., 173 p.

Poland, J. F., 1969, Status of present knowledge and needs for additional research on compaction of aquifer systems: Internat. symposium on land subsidence, Tokyo, Japan, 1969, Proc., p. 11-21.

Poland, J. F., and Davis, G. H., 1969, Land subsidence due to the withdrawal of fluids: Reviews in Engineering Geology II, Geol. Soc. America, Inc., p. 187-269.

Poland, J. F., Lofgren, B. E., and Riley, F. S., 1972, Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal: U.S. Geol. Survey Prof. Paper 2025, 9 p.

Pratt, W. E., and Johnson, D. W., 1926, Local subsidence of the Goose Creek Oil Field: The Jour. Geology, v. XXXIV, no. 7, pt. 1, p. 577-590.

Riley, F. S., 1969, Analysis of borehole extensometer data from Central Calif.: Internat. symposium on land subsidence, Tokyo, Japan, 1969, Proc., p. 423-431.

Rose, N. A., 1943, Progress report on the ground-water resources of the Texas City area, Texas: Texas Board of Water Engineers, U.S. Geol. Survey open-file rept., 45 p., 3 figs.

Taylor, D. W., 1948, Fundamentals of soil mechanics: New York, John Wiley and Sons, Inc., 703 p.

Terzaghi, Karl and Peck, Ralph, 1948, Soil mechanics in engineering practice: New York, John Wiley and Sons, Inc., 566 p.

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. Geol., 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., Oct., p. 1030-1034; Am. Inst. Mining, Metall., Petroleum Engineers, Trans., v. 214.

Wolfskill, L. A., 1960, The consolidation characteristics of undisturbed soil samples of deep formations and their application to problems of regional subsidence: Master of Science Thesis, Texas A & M University, College Station, 70 p.

Wood, L. A., and Gabrysch, R. K., 1965, An analog-model study of ground water in the Houston district, Texas, with a section on design, construction, and use of analog models, by E. P. Patten, Jr.: Texas Water Commission Bull. 6508, 103 p.