Land-Surface Tilting Near Wheeler Ridge, Southern San Joaquin Valley, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 497-G

Prepared in cooperation with the California Department of Water Resources

Land-Surface Tilting Near Wheeler Ridge, Southern San Joaquin Valley, California

By FRANCIS S. RILEY

MECHANICS OF AQUIFER SYSTEMS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 497-G

Prepared in cooperation with the California Department of Water Resources

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1970

UNITED STATES DEPARTMENT OF THE INTERIOR

WALTER J. HICKEL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 70 cents (paper cover)

CONTENTS

ILLUSTRATIONS

LAND-SURFACE TILTING NEAR WHEELER RIDGE, SOUTHERN SAN JOAQUIN VALLEY, CALIFORNIA

By FRANCIS S. RILEY

ABSTRACT

Two continuous-recording liquid-level tiltmeters and three associated borehole extensometers recorded tilt at land surface and compaction in the upper 150 feet of alluvial-fan deposits at the site of the future Wheeler Ridge pumping plant of the California Aqueduct. The location, at the southern end of the San Joaquin Valley, borders on a large bowl of active land subsidence caused by compaction of the confined aquifer system under the stress of artesian-head decline. It is in an area subject also to subsidence due to near-surface hydrocompaction of moisture-deficient fan deposits. Lastly, it is an area of potential tectonic movement related to the historically active White Wolf fault. The instrumentation was intended to record tilt and, so far as practicable, to identify and furnish magnitudes of tilt related to specific causes.

During the first summer of operation (1965), the tiltmeter, a one-directional instrument, showed an abrupt northwestward tilting toward the nearby valley areas of intense pumping and rapid artesian-head decline. The tilt record lagged the hydrograph by about 6 weeks, but this delay was not unreasonable in view of the time required for artesian-head change to migrate laterally through the aquifer system. The magnitude of the northwesterly summer tilt was 46 microradians, or roughly half the annual rate of tilting that had been postulated on the basis of repeated spirit leveling surveys between 1960 and 1965.

The second tiltmeter, a two-directional instrument, was not in operation during the 1965 pumping season; it began recording in October 1965 and recorded virtually stable conditions during the following autumn months. A very slow but steady background tilting (5 microradians per year in a direction about N. 55° E.) may be due to continuing uplift of the Wheeler Ridge anticline; Pleistocene gravels have been tilted 60° to the northeast only one-quarter mile south of the tiltmeter site.

From December 16, 1965, to March 2, 1966, water was pumped at about 500 gallons per minute into an infiltration pond 400 feet upslope from the tiltmeter site. The resulting hydrocompaction caused as much as 2.7 millimeters of differential settlement at the pumping-plant site, completely overwhelming the more subtle tilting due to deep-seated aquifer compaction during the 1966 pumping seasons. Differences in magnitude and timing between the responses of the tiltmeters and compaction sensors indicate that significant susceptibility to hydrocompaction existed at depths greater than 150 feet.

A special array of 24 bench marks installed within a radius of 2,400 feet from the pumping-plant site was leveled six times between August 1965 and September 1966. The areal pattern of tilting determined by the leveling agreed with the tiltmeter data in defining two principal periods of northward tilting per year; these periods coincided with the winter and summer irrigation seasons. In 1966 the total northward tilt was 42 microradians.

INTRODUCTION

From March 26, 1965, to September 19, 1966, the U.S. Geological Survey operated a recording tiltmeter station near Wheeler Ridge, 24 miles south of Bakersfield, Calif. This report describes the installation and discusses the data obtained.

STATEMENT OF THE PROBLEM

The site of the future Wheeler Ridge pumping plant of the California Aqueduct at the north base of Wheeler Ridge (lat 35°01′54″ N.; long 119°00′24″ W.) is near the southern margin of a large bowl of active land subsidence at the south end of the San Joaquin Valley. The extent and the magnitude of the subsidence from 1957 to 1965 are indicated by the lines of equal subsidence in figure 1. The principal cause of subsidence is compaction of the confined aquifer system between depths of about 300–1,500 feet, because of withdrawal of large quantities of ground water for irrigation (Lofgren, 1963, and oral commun., 1966). An additional contributing cause of subsidence along the southern border of the area is compaction of moisture-deficient low-density alluvial-fan deposits of Pleistocene and Holocene age through the action of percolating excess irrigation water. This process, known as hydrocompaction, occurs when highly porous, moderately clayey sediments lying above the water table are rewetted for the first time since deposition. The resulting weakening of intergranular clay bonds permits partial collapse of the sediments under the existing overburden load. (For a discussion of the process of hydrocompaction, see Bull, 1961, p. B187–189.)

Before the present investigation, test drilling by the California Department of Water Resources revealed that, at the pumping-plant site, the alluvial deposits

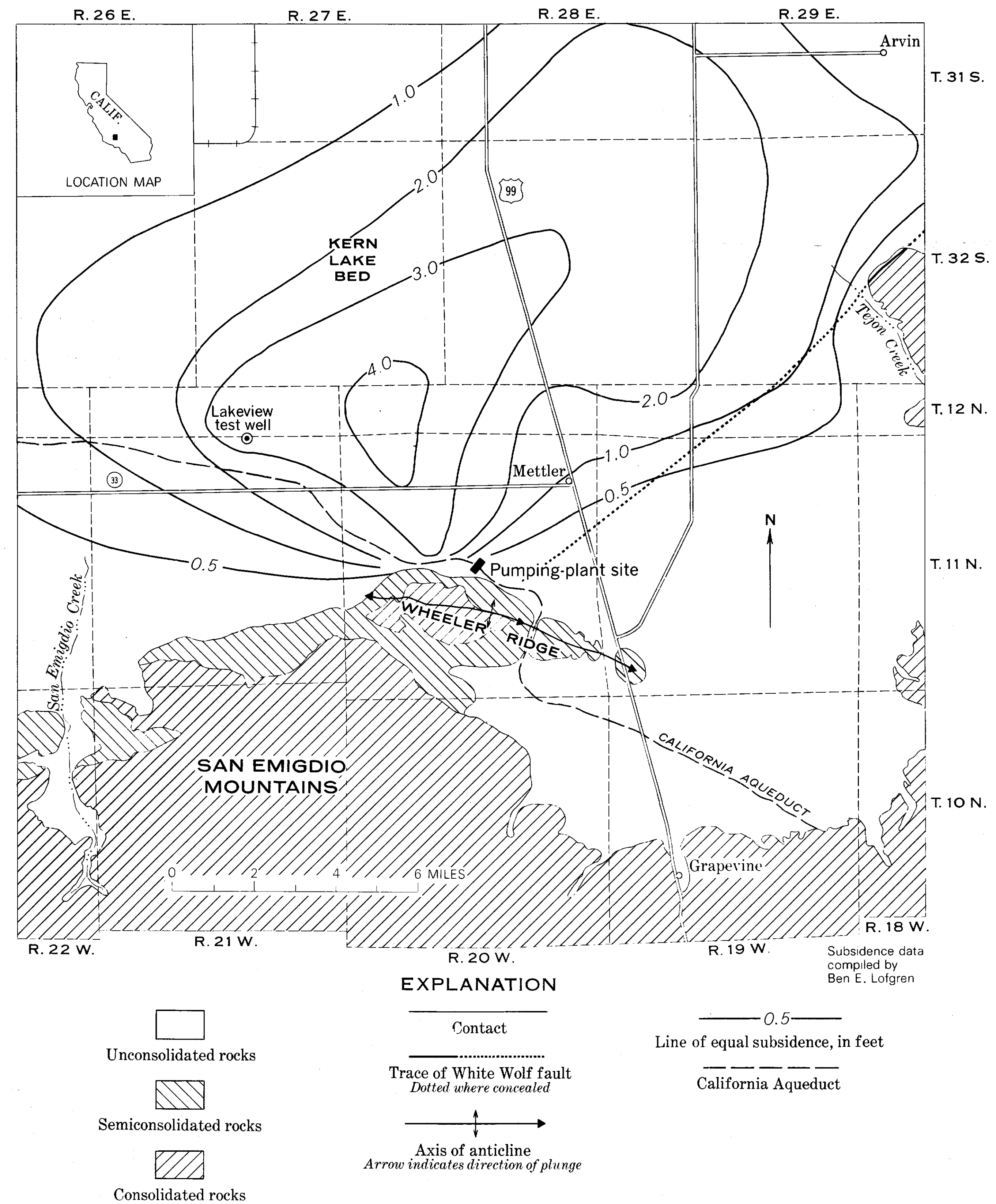

Figure 1.—Map of southern San Joaquin Valley, showing location of Wheeler Ridge pumping-plant site and lines of equal land subsidence, 1957–65.

were subject to hydrocompaction to a depth of at least 100 feet.

Analysis of data from repeated spirit leveling by the U.S. Coast and Geodetic Survey and the California Department of Water Resources indicated that particularly intense differential subsidence, or tilt, has occurred near the site of the Wheeler Range pumping plant, as is shown by the close spacing of the lines of equal subsidence in figure 1. Since 1960 the area apparently has been subject to valleyward (northward) tilting at an average rate of roughly 100 microradians per year (0.01 ft per 100 ft year), a movement which, if continued, would result in about half a foot of differential settlement across the 100-foot width of the plant in a 50-year period. However, because the nearest bench marks, A1053 and LS–8 (pl. 1), were 1,200 and 1,400 feet, respectively, from the site and did not closely bracket its location this estimate was considered uncertain. Furthermore, the leveling data did not provide any means of discriminating among several possible causes of tilting, namely, deep-seated aquifer compaction, near-surface hydrocompaction, removal of fluids from nearby oil fields, and tectonic movement associated with the historically active White Wolf fault and the very youthful Wheeler Ridge anticline.

PURPOSE AND SCOPE OF THE TILTMETER PROGRAM

The Wheeler Ridge pumping-plant site afforded the U.S. Geological Survey an opportunity to measure the magnitude and time distribution of tilt in an area of aquifer deformation and possible tectonic movement, to identify the possible causes of tilt, and to advance tiltmeter techniques. Furthermore, the California Department of Water Resources was concerned that possible tilting of the pumping-plant foundation over a 50-year period might cause mechanical problems and, for this reason, was willing to undertake the necessary preparation of the site. Accordingly, in March 1965, the Geological Survey installed a temporary continuous-recording one-directional tiltmeter on the center line of the pumping-plant site. Late in April, the equipment was converted to semipermanent status.

In October 1965, more comprehensive instrumentation was installed adjacent to the first tiltmeter. The new equipment, a two-directional tiltmeter linked to three ultrasensitive compaction sensors, was designed to determine the true direction and full magnitude of tilting and to distinguish between tilt of deep-seated origin and tilt due to differential hydrocompaction in the upper 150 feet of alluvial-fan deposits.

The instrumentation and data obtained through January 1966 were discussed briefly in a progress report (Riley, 1966). The instruments were operated through September 19, 1966, when they had to be removed to make way for excavation of the pumping-plant intake channel and bowl.

The present report describes the installation in some detail, discusses the principal problems, presents the basic data obtained, and relates the results to pertinent features of the hydrologic environment.

ACKNOWLEDGMENTS

The tiltmeters were installed and operated through June 1966 under the Mechanics of Aquifers project, which is a part of the Survey's nationwide, federally supported research program. Continuation of operations from July 1 to September 19, 1966, was made possible by financial cooperation between the Geological Survey and the California Department of Water Resources. The Department of Water Resources also furnished helpful advice in the design of the compaction sensors, was responsible for site preparation and construction of the compaction-sensor wells, and carried out a special program of precise spirit leveling. The writer wishes to acknowledge particularly the thoughtful assistance and unfailing cooperation of W. D. Fuqua and R. J. Akers, Project Geology Branch, Department of Water Resources, in planning the tiltmeter installation and coordinating the activities of the Department of Water Resources. Special thanks are also due Robert G. Pugh of the Mechanics of Aquifers project staff for his capable assistance in field operations and data reduction.

DESCRIPTION OF THE INSTRUMENTATION

Because of the unusual and, in some respects, unique aspects of the tiltmeters and compaction sensors employed in the Wheeler Ridge studies, the following description of the instrumentation is included to facilitate the understanding and interpretation of the results.

TILTMETER PRINCIPLES

The tiltmeters employed at the Wheeler Ridge station were of the liquid-level, or water-tube type, in which differential elevation changes between two (or more) points are measured by reference to a common liquid level. This principle is not new. Its modern employment in high-precision instruments extends back at least as far as the earth-tide investigations of Michelson (1914) and Michelson and Gale (1919). Various forms of the device have been developed by a number of workers, notably Egedal and Fjeldstad (1937), Hagiwara (1947), Eaton (1959), and Bonchkovsky and Skur'yat (1961).

The automatic recording tiltmeters used at Wheeler Ridge were developed by the author (Riley, 1962) from an earlier manually operated instrument described by Riley and Davis (1960). The instruments were originally intended for use primarily in geotechnical studies of relatively short duration, typically a few days or weeks. For this purpose the equipment should be reasonably portable, operable under widely varying ambient temperatures, and usable with minimum site preparation. The tiltmeter described in this report differs from other similar instruments chiefly in the electromechanical system used to obtain the continuous record of tilt and in the techniques employed to minimize and compensate for temperature effects.

The tiltmeter consists of a pair of cylindrical measuring pots, partly filled with liquid and connected by a length—usually 50–200 feet—of liquid-filled hose (fig. 2). A second hose connects the closed air spaces above the liquid surface in the pots. Minute changes in the relative elevations of the pots appear as reciprocal variations in the heights of the liquid columns in the pots. A float-actuated transducer in each pot converts the position of the liquid level above or below an adjustable arbitrary datum to an analogous electrical signal. The signals from both pots are fed to a dual-coil, center-zero, strip-chart recording milliameter, connected so that differential liquid-level changes resulting from ground tilting are electrically additive, whereas parallel fluctuations due to temperature-induced volume changes are mutually canceling. Thus, the strip-chart trace constitutes a continuous record of the changes in elevation of one pot with respect to the other. Sensitivity is adjustable to a maximum (limited by amplifier noise) of 1 millimicron of ground movement per millimeter of pen displacement (an amplification of 10^6), but no practical use has been found for this extreme level of sensitivity.

TILTMETER CONSTRUCTION

The basic design features of the tiltmeter measuring pot are illustrated in figures 3 and 4. The inner cylinder within which the liquid-level changes are measured is 3.375 inches in diameter and 5.000 inches high. It is surrounded by an outer cylinder which serves as a water jacket whose purpose is to promote uniform temperatures in the cylinder walls and to minimize rates of change in response to changing ambient temperatures. The cylinders are mounted on a heavy triangular base plate equipped with three adjustable legs which permit leveling the instrument and adjusting its

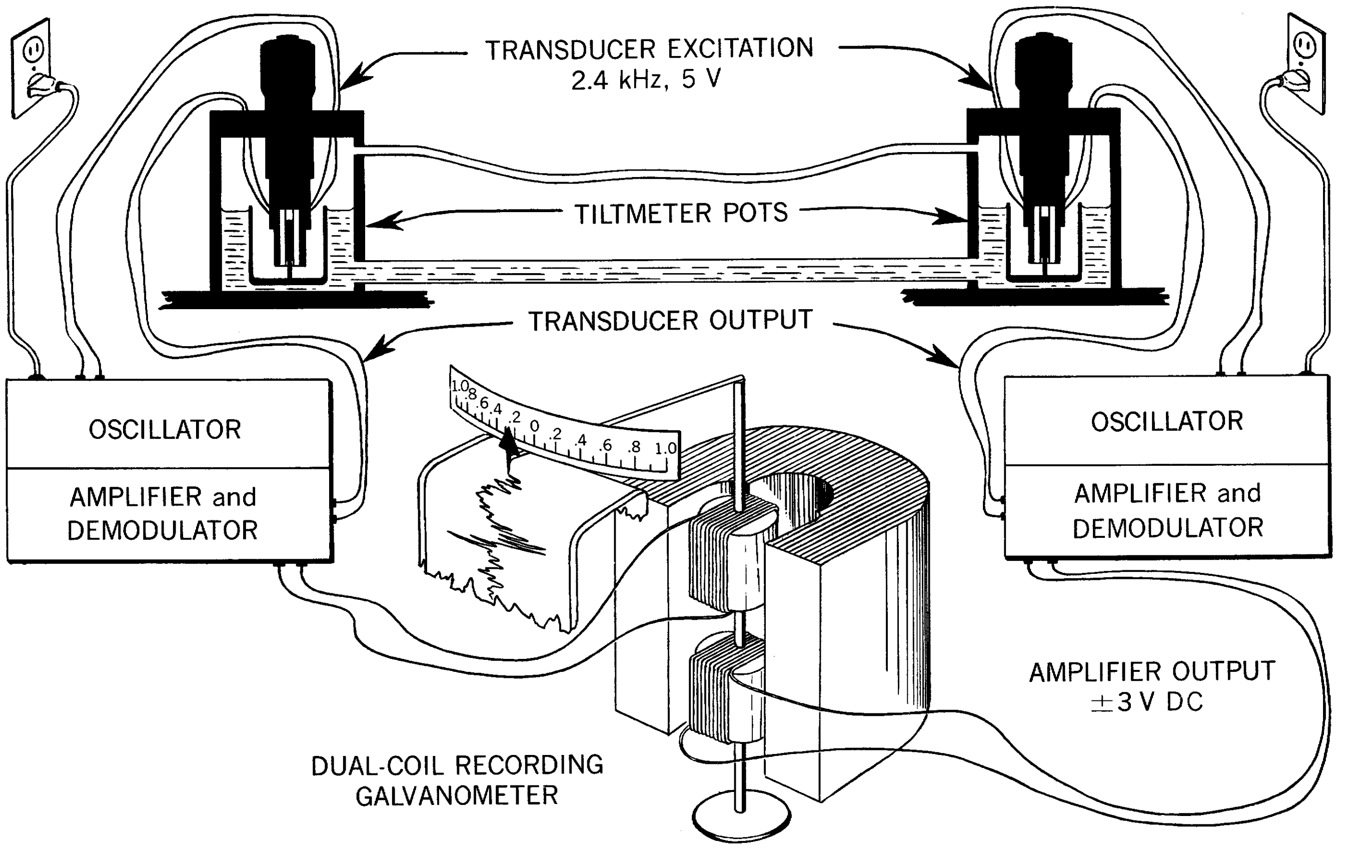

FIGURE 2.—Schematic diagram of recording tiltmeter.

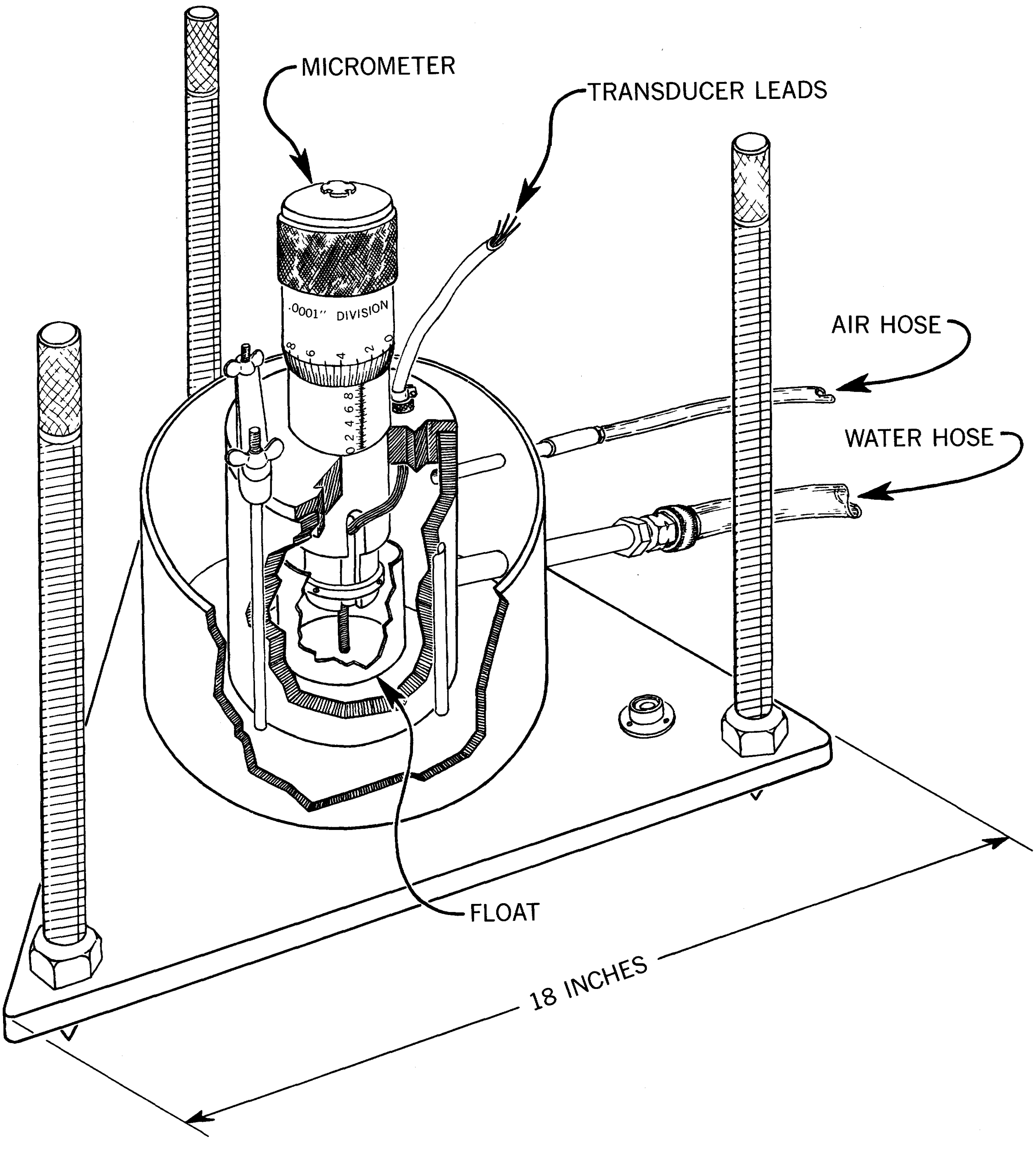

FIGURE 3.—Cutaway sketch of tiltmeter measuring pot.

height to accommodate varying foundation conditions. The measuring pots are fabricated entirely from stainless steel.

The transducer used to measure changes in liquid level is a linear variable differential transformer that converts vertical motion of its movable part into an analogous electrical signal. The transducer consists of two mechanically separate elements: one, the fixed or reference element, contains the transformer coils; the other, the moving element, is a small core of ferromag-

373-386 O - 70 - 2

netic material which is free to move vertically within the coil assembly (fig. 4). The reference element, or coil assembly, is clamped in an adjustable plunger mounted in the pot lid. The vertical position of the plunger and coil assembly can be precisely adjusted by means of the large micrometer.

The moving core is mounted in the center of an open-topped cylindrical float, which is weighted to sink close to the bottom of the pot. A Teflon washer at the bottom end of the core keeps it approximately centered within the bore of the coil assembly and also serves to center the float within the pot. As the transformer is relatively insensitive to radial movements of their outputs are equal in amplitude but opposite in phase, and consequently self-canceling. Energy transfer from the primary to the two secondary coils is governed by the vertical position of the core. When the core is perfectly centered vertically, the output voltage is zero and the transducer is said to be at null. If the core is raised, the output voltage in the upper secondary is increased, while that in the lower secondary is decreased; the difference appears as a net output signal. If the core is lowered, the converse occurs. The direction of departure from null is defined by the phase relationship (either 0° or 180°) between the output and excitation wave forms.

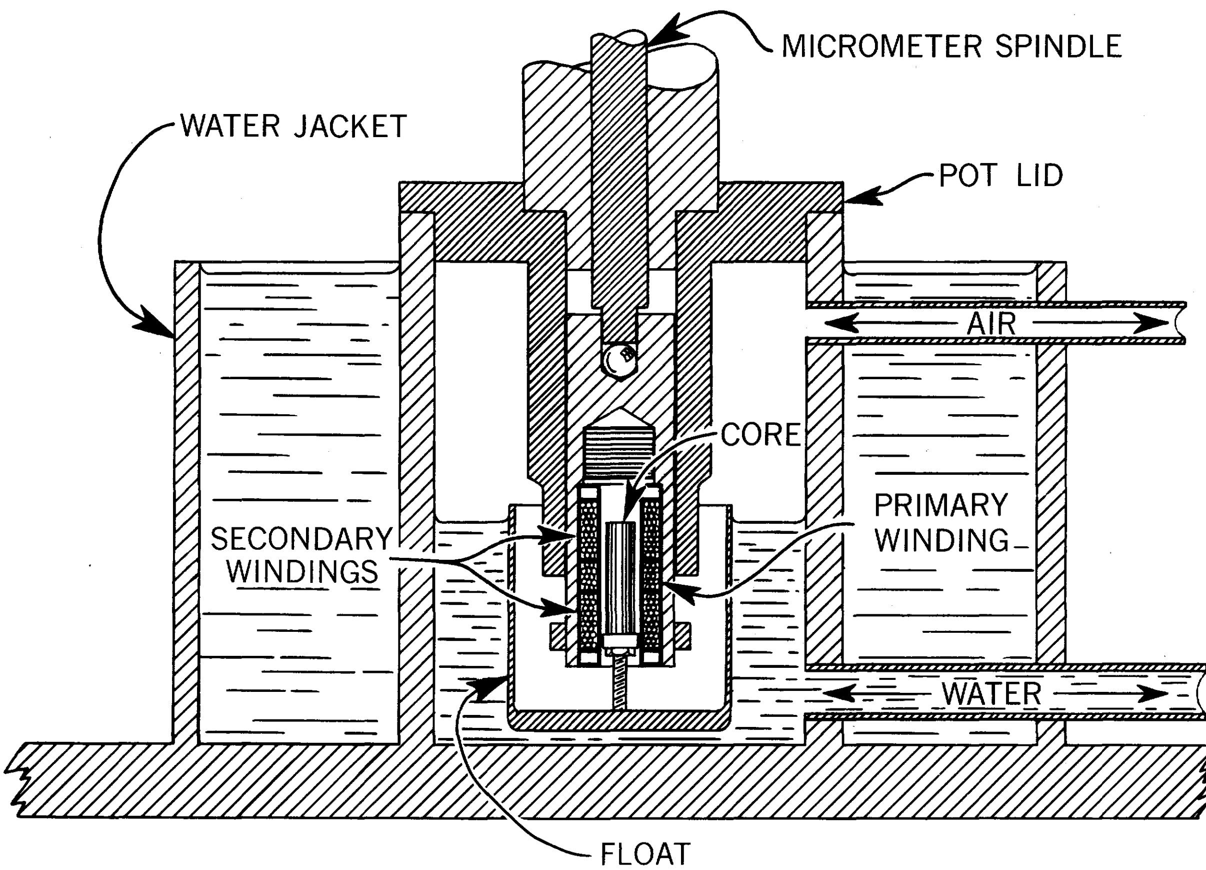

FIGURE 4.—Diagrammatic section of tiltmeter measuring pot, showing transducer mounting.

the core, it is possible to make the washer slightly smaller in diameter than the bore of the coil assembly, thereby effectively eliminating friction between the moving core and the fixed coils.

The transducer is excited by a 5-volt a-c electrical signal at 2.4 kilohertz; this signal is fed to the middle or primary coil of the transducer and is transferred by induction to the two secondary coils located above and below the primary. The secondary coils are wound and connected in series opposing so that, when energy is transferred into them equally from the primary coil,

Several features make the differential transformer particularly attractive as a linear-displacement transducer in this application. Paramount among these are the absence of friction between the moving and the fixed elements, and the negligibly small loading effects of the alternating-current field on the magnetic core. These properties enable the transducer to be actuated by extremely small buoyant forces applied to the float and therefore to respond to water-level changes of a few thousandths of a micron. Other advantages of the differential transformer are infinite resolution, extremely high sensitivity, good linearity, and acceptably low temperature sensitivity. Finally, the stable null point provides a recoverable instrument datum that is unaffected by amplifier drift or other possible malfunctions in downstream stages of the electronics.

A solid-state oscillator-amplifier (Sanborn Model 311) drives the primary winding of the differential transformer and also functions as the amplifier and phase-sensitive demodulator for the output signals from the secondary windings.

Each transducer is driven by its own oscillator-amplifier, and the d-c output (±3 volts) from each amplifier is fed to the dual-coil tilt recorder (Esterline-Angus Model AW, range ±1.0 milliampere), as illustrated schematically in figure 2. The amplifier outputs are direct electrical analogs of the heights of the floats above or below the transducer null points, and the difference between the outputs, measured by the dual-coil recorder, represents the differential elevation change of one measuring pot with respect to the other. It has been found useful to record also the output from each amplifier independently, as a check on the proper functioning of the entire system. For simplicity, these supplementary recorders are omitted from figure 2.

For the Wheeler Ridge installation, commercial power (120 volts, 60 hertz) was brought in from a nearby pole line. Regulated voltage was supplied to all electronic components by a servo-operated variable autotransformer that stabilized line voltage within ±1 volt.

The tiltmeter recorders at Wheeler Ridge were usually operated at a chart-drive rate of three-fourths of an inch per hour and a sensitivity of 200–300 microns for full-scale deflection. At those settings, the minimum detectable angular change was less than 0.1 microradian, or about 0.1 percent of the postulated annual tilt at the pumping-plant site. When accumulated tilting caused the pen to approach the edge of the recorder chart, the instrument datum was reset by adjusting the large reference micrometer (figs. 3 and 4), which, in turn, adjusted the height of the differential transformer. In this manner the record was shifted back toward the center of the chart, and a check was obtained on the instrument scale factor. Thus, the span of the recorder was offset by accurately determined increments; in cases of large accumulative tilt, the ultimate range and accuracy of the instrument is limited by the range and accuracy of the micrometers. The first tiltmeter installed at Wheeler Ridge had 1-inch micrometers divided every 0.0001 inch (2.54 microns). The second, a two-directional tiltmeter, had 25-millimeter micrometers bearing 2-micron divisions. With care, both types of micrometers can be read with a repeatability of plus or minus one-tenth of a scale division. The absolute accuracy of the micrometers, according to manufacturer's specifications, is one scale division.

Figure 5 provides a convenient graphic comparison between the English and metric units used in this report and also facilitates conversion from units of differential elevation change to angular units of tilt (microradians).

METHODS USED TO CONTROL TEMPERATURE EFFECTS

The principal source of error in tiltmeter measurements is change in temperature, which adversely affects the mechanical, fluid, and electronic components of the system. The part most sensitive to temperature change is the liquid-filled hose connecting the measuring pots. Transparent vinyl hoses of ⅝-inch inside diameter were used in order to facilitate checking for air bubbles. An experimentally determined solution of 31 percent methanol in distilled, de-aired water proved to have nearly the same expansivity as the hoses, within the range of temperatures usually encountered. Nevertheless, the hose lines, which normally are not buried, must be thermally ballasted and insulated to prevent severe short-term (period less than 30 minutes) instability due to solar heating. At Wheeler Ridge the ballasting was accomplished by covering both the liquid and air hoses with a flattened plastic tube about 8 inches wide, containing slightly less than one gallon of water per lineal foot. The tiltmeter hoses and ballast tube (as well as electrical power and signal cables) were enclosed in a wrap of foil-backed fiberglass batting which was, in turn, wrapped in plastic film, covered with a second layer of fiberglass batting, and finally covered with overlapping 4-foot lengths of 12-inch-diameter half-section steel culvert pipe. The large thermal mass contained within the insulation produced a nearly uniform and very slowly changing temperature environment for the hoses. In general, the diurnal temperature fluctuation in the hoses was 2°–4° Celsius, in contrast to a daily range of 40° or more on the unsheltered ground surface. Seasonally, the hose temperatures progressed slowly from a December low of 7°C to a June high of 38°C.

Although the insulation and ballast effectively minimized short-term instability throughout the period of operation, some inconvenience resulted from the fact that the plastic film enclosing the inner layer of insulation was not a sealed vapor barrier. Consequently, under appropriate conditions of temperature and humidity, moisture condensed on the ballast tube and eventually accumulated in amounts sufficient to saturate the fiberglass batting beneath the tube. As nearly as could be determined, this had no significant effect

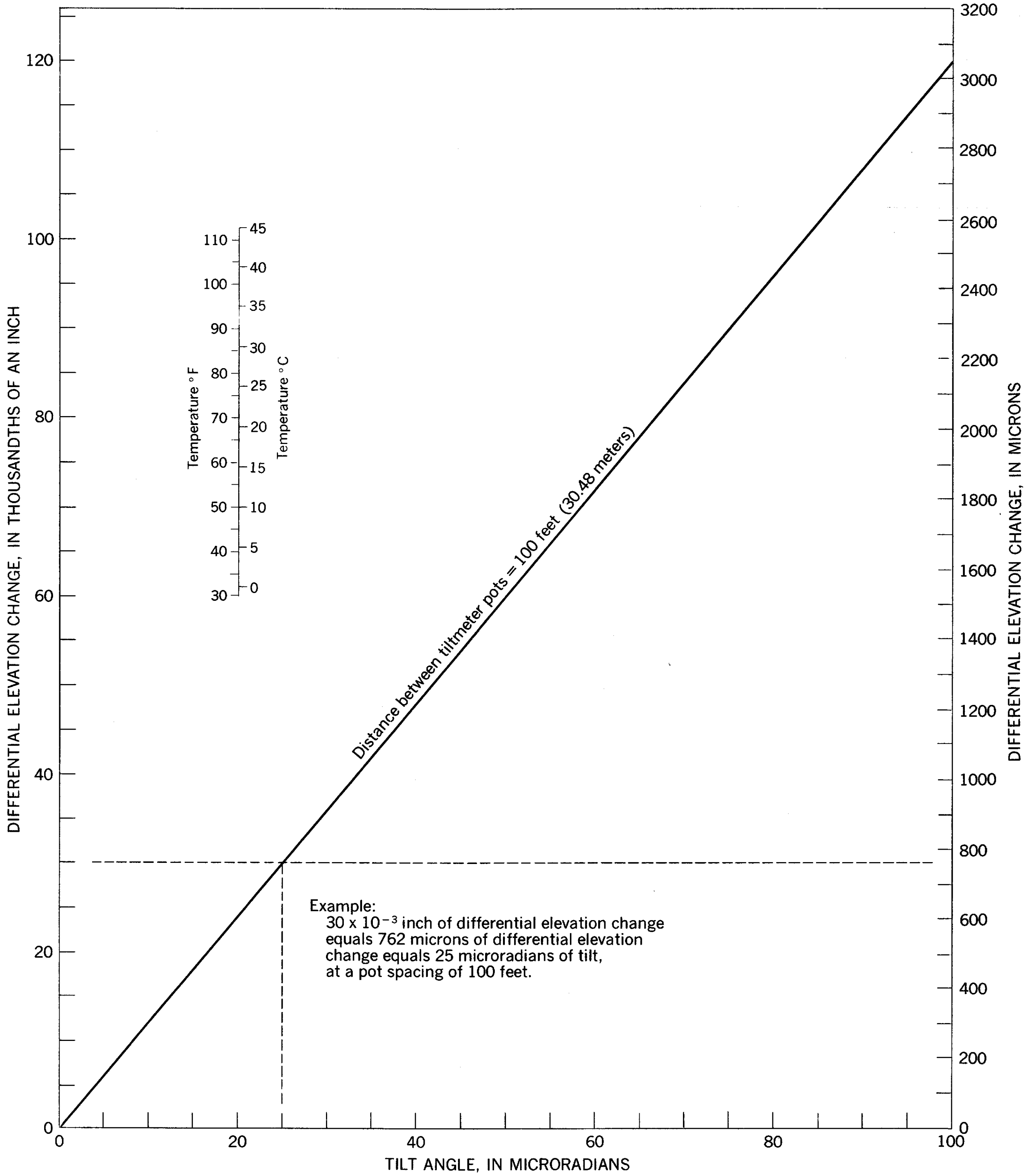

FIGURE 5.—Relationships of units of measurement used in this report.

on the functioning of the tiltmeters.

Despite the approximate equalization obtained between hose and fluid expansivities, operating convenience requires a means of adjusting the height of the liquid columns in the pots to achieve optimum operating levels and to compensate for the volume changes that accompany large temperature changes. Manual adjustment is provided by a micrometer-actuated ground-glass syringe connected to the midpoint of the hose line. Precisely metered volumes of liquid may be added or withdrawn from the tiltmeter system in order to test the response of the transducers and the hydrodynamic symmetry of the hose line about its midpoint. The latter test is especially important as a means of detecting a density trap or accumulation of bubbles at some point in the hose. Such a condition constitutes an impedance to flow through the hose and causes a lag or, in severe cases, a permanently attenuated response in the measuring pot on the obstructed side of the midpoint. An impedance is reflected in an offset of the tilt record, which may be temporary or permanent depending on the nature of the obstruction. During the operations at Wheeler Ridge, the correct functioning of the tiltmeters was routinely checked each time the instruments were serviced, by adding and subtracting fluid as described above.

In addition to the provision for manual adjustment of fluid volume, the tiltmeters were equipped with automatic volume controllers, which continuously compensated for temperature-induced changes in volume that would otherwise have driven the transducer systems off scale. The volume controller consists of a thermally insulated, liquid-filled expansion chamber which is connected to the midpoint of the hose and which contains an electrical heating element. Power input to the heating element is controlled by a transistorized servoamplifier that responds to the output from the transducer amplifier at one end (designated the "controlled" end) of the tiltmeter line. When the transducer core in the controlled pot is centered (at null), the output from its amplifier is zero, and the power input to the heater is maintained at a constant low level, sufficient to maintain the temperature in the expansion chamber about 10°C above the ambient air temperature. Heat input to the chamber equals heat loss through its walls, and no change in the volume of contained liquid occurs. If the liquid level in the controlled pot declines slightly, the servoamplifier responds by a greatly increased power input to the heater. Liquid in the chamber immediately expands into the hose and raises the level in the controlled pot to approximately its nominal operating point. Conversely, a rise in liquid level in the controlled pot causes a reduction in power input to the heating chamber so that its contained fluid cools, contracts, and withdraws water from the hose to correct the level in the pots. The net result of this arrangement is that liquid-level fluctuations due to temperature-induced changes in volume are almost entirely absorbed in the expansion chamber, and liquid-level changes due to tilting are forced to appear almost entirely in the uncontrolled pot at the other end of the hose line. At Wheeler Ridge, an expansion chamber of half-gallon capacity containing a 75-watt heater proved satisfactory for compensating 100 feet of hose line. For simplicity, the manual and automatic volume controllers have been omitted from figure 2.

The measuring pots and associated transducer amplifiers were shielded from abrupt temperature change in small insulating shelters made of rigid polyurethane foam panels, 3 inches thick. The daily fluctuation of air temperatures within the shelters did not usually exceed 2°C, and the daily fluctuation of liquid temperatures in the pots was about 1°. The seasonal fluctuation of temperatures inside the shelters was about 24°C for the air temperatures and 21°C for the pot temperatures.

The shelters for the first tiltmeter at Wheeler Ridge were equipped with heaters, circulating fans, and thermostats capable of maintaining temperatures constant within 0.1°. Their use was discontinued, however, when it became evident that small diurnal temperature fluctuations in the pots and amplifiers were of no significance at the tilt sensitivities being used. It was not considered feasible to maintain the shelters at the same temperature throughout the year, inasmuch as this would have necessitated a setting of about 55°C, which, during the winter, would have resulted in a temperature gradient of more than 30°C between the pots and the adjacent hose.

The use of cylindrical flat-bottomed floats, weighted to sink close to the bottoms of the pots, minimizes the sensitivity of the system to temperature-induced density changes in the fluid columns in the pots. Because the sides of the floats are vertical, only the hydrostatic uplift on their bottom surfaces influences their positions in the fluid columns. Identical floats require equal hydrostatic uplift and therefore come to rest on hydrostatic pressure surfaces having the same pressure value. That value (equal to the weight per unit area of the floats) is determined directly by the weight per unit area of liquid overlying the pressure surface and is not affected by thermally induced changes in the height of the liquid column above that surface.

Because of the lack of static shear strength in the liquid, the pressure surfaces under no-flow conditions must be horizontal; that is, they parallel the gravitational equipotential surfaces passing through the instrument. If the hose is perfectly level, all hydrostatic pressure surfaces in one end of the line will be continuous through the hose to the other end and will extend horizontally into the measuring pots at both ends. Thus, if the bottoms of the floats are opposite the hose-connection orifices and the hose line is level, floats resting on the same pressure surface will also rest on a single gravitational equipotential surface, regardless of density differences within the system.

Any departure of the hose from the horizontal will truncate some of the pressure surfaces against the top and bottom of the hose and thus will restrict the vertical range within which the floats can operate with assurance of remaining on the same equipotential surface. If the sum of the largest upward and downward departures from level exceeds the inside diameter of the hose, there will be no continuous pressure surface throughout the instrument. Given this circumstance plus a nonuniform temperature environment and an imperfect match between hose and fluid expansivities, thermally-induced changes in fluid volume can displace the hydrostatic-pressure surfaces differentially about either side of the low point in the hose line. The floats, although still resting on surfaces of the same pressure value, will no longer be on the same gravitational equipotential surface, and therefore will not define an accurate horizontal datum. For this reason the hose must be almost exactly level if temperature effects are to be avoided. Measures taken to insure horizontality of the hoses in the Wheeler Ridge tiltmeters are described in the following section entitled "The GS–I tiltmeter."

Within the constraints imposed by transducer mounting and operating requirements, the pots, lid assemblies, and floats were designed to minimize relative movements between the core and coils of the transducer caused by thermally-induced dimension changes. For example, if the temperature rises uniformly within the entire measuring pot, upward displacement of the pot lid and micrometer head by thermal expansion of the pot walls is largely compensated by downward expansion of the plunger within which the transducer coil assembly is clamped (fig. 4).

According to the manufacturer, the maximum thermal drift of the transducer amplifier output is 30 millivolts per 10°C, equivalent to only 0.15 microradian at the recording scale used.

A field test, in which the thermostat and heaters in one of the pot-amplifier shelters were used to create a step increase of 4.5°C in shelter-air temperature, produced no clearly discernible offset in the tilt record. In view of the low temperature sensitivity of the pot-transducer-amplifier systems and of the nearly parallel seasonal temperature fluctuations in the shelters, it is believed that errors due to temperature changes within the shelters were not significant at the recording scale used.

The long-term temperature insensitivity of the entire tiltmeter system is demonstrated by the record obtained; this is discussed more fully in the section entitled "Data from the GS–II tiltmeter."

THE GS–I TILTMETER

The first tiltmeter at Wheeler Ridge, herein designated GS–I, was laid out parallel to and about 25 feet southwest of the center line of the aqueduct and across the long axis of the pumping plant (pl. 1). The alinement selected (N. 35° W.) is approximately normal to the contours of the alluvial fan; therefore, considerable excavation was required to provide the level surface necessary for the instrument. A trench, about 12 feet wide, 120 feet long, and 7 feet deep at the uphill end, was prepared by the Department of Water Resources, and two rectangular concrete pads, 2 feet wide by 4 feet long by 0.3 foot thick, were poured at a center spacing of 101 feet to serve as pot foundations. To minimize moisture changes in the soil and changes in pad thickness after the initial cure, polyethylene film was used as a liner for the forms and cover for the fresh concrete.

A final hand leveling and grading of the surface on which the tiltmeter hose was to rest brought this line to within ±0.02 foot of a horizontal grade in order to minimize the possibility of differential-density traps developing in the hose under nonuniform temperature conditions.

Because the aluminum sheds intended to house the pots and recorders were not immediately available, small box covers were used for the pots and a truck was used to house the recorders. This installation, which began recording March 26, 1965, was damaged by storms and vandalism, so data were recorded only intermittently. The aluminum sheds were erected in mid-April, and during the remainder of the month the installation was upgraded to essentially final status. Useful data were recorded beginning May 1, 1965.

THE GS–II INSTALLATION

In June 1965, the Department of Water Resources asked the Survey to consider the installation of a two-directional tiltmeter at the pumping-plant site. Such an instrument would permit determination of the true direction and full magnitude of tilting at the site. Additionally, it was desired that an entirely new function be incorporated into this installation—that of distinguishing between deep-seated tilting and tilting due to differential compaction of the upper 150 feet of alluvial-fan deposits underlying the site. Because the pumping-plant foundation was to be set in an excavation 150 feet deep, only deep-seated tilting was of practical interest in evaluating the stability of the foundation. Furthermore, the near-surface fan deposits along the aqueduct alinement near the pumping plant were being prewetted and precompacted (under their own weight) by means of a series of infiltration ponds designed to produce virtually all potential hydrocompaction prior to aqueduct construction. If water from the ponds were to permeate the sediments beneath the tiltmeters, substantial hydrocompaction might be expected, making it impossible to extract data on deep-

FIGURE 6.—Aerial view southeastward along the aqueduct alinement, showing the pumping-plant site and tiltmeter station on the alluvial-fan surface that extends northward from the base of Wheeler Ridge. Rectangular infiltration ponds define the aqueduct alinement except at the site of the pumping plant and its intake channel. (Photographed May 1966.)

seated tilting from the tiltmeter records unless independent measurements of hydrocompaction were available.

The aerial photographs of the pumping-plant site (figs. 6 and 7) show the ponds on either side of the tiltmeter station. Each pond contained a set of gravel-filled infiltration wells (usually 6–12 wells which were about 80 feet deep) to hasten penetration of water. Typically, during several months of continuous infiltration at rates of a few hundred to more than 1,000 gallons per minute, the ponds subsided 2–6 feet, and an area of perceptible subsidence, accompanied by surface cracking, expanded to distances of 100–500 feet from the ponds as water moved downward and outward through the deposits. In figure 6, which is a view southeastward up the alluvial fan toward Wheeler Ridge, numerous concentric cracks may be seen surrounding the ponds in the foreground. In figure 7,

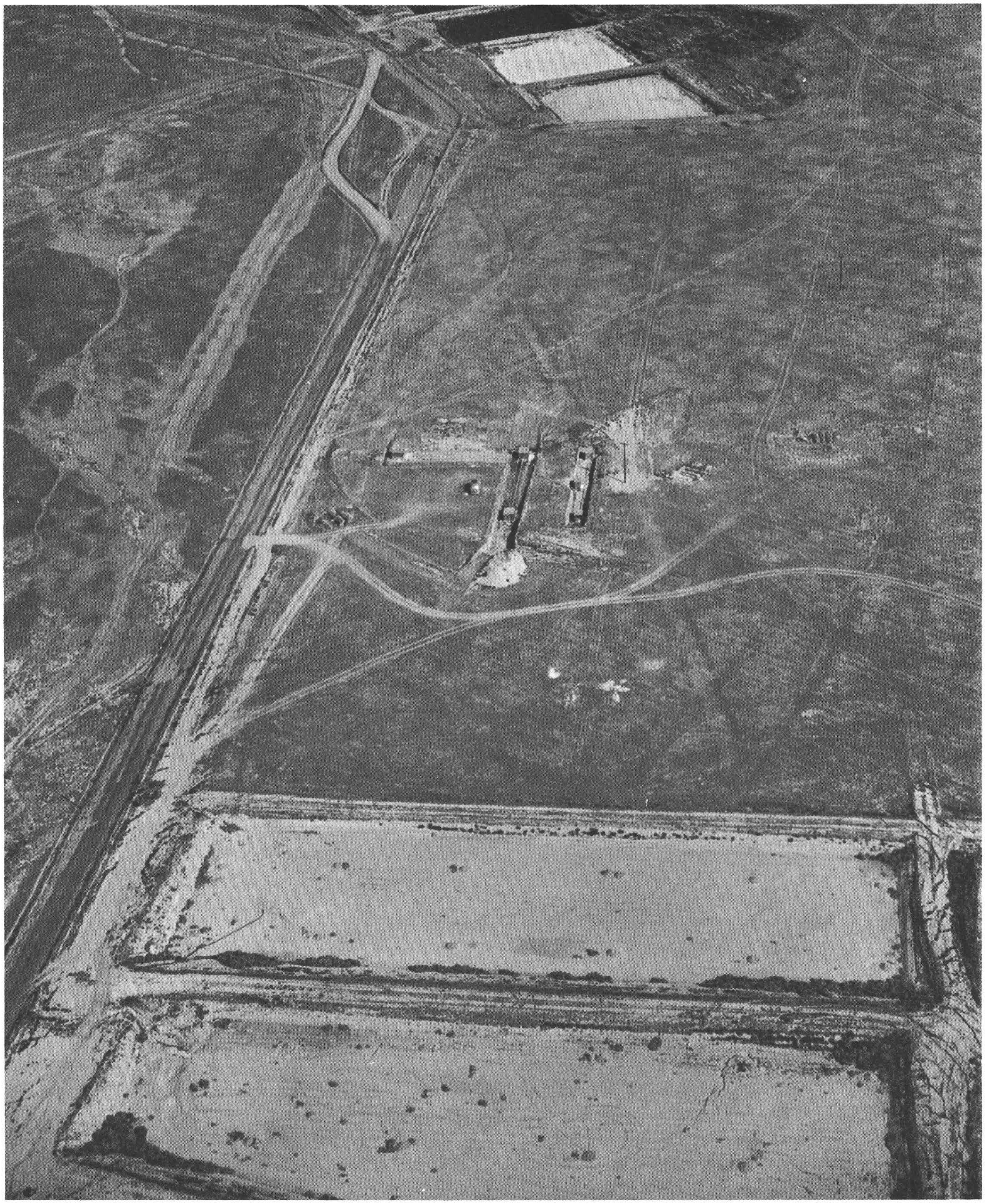

FIGURE 7.—Aerial view northwestward along the aqueduct alinement, showing infiltration ponds and the GS–I and GS–II tiltmeters. (Photographed May 1966.)

which is a northwestward view, cracks are visible in the banks of the uphill ponds (in the foreground) and are evidenced by arcuate lines of vegetation intersecting the unpaved road in the lower left part of the photograph. The trenches and aluminum sheds of the GS–I and GS–II tiltmeters are visible in the center of the photograph.

The basic elements of a design to accomplish the desired goals of the second tiltmeter installation were worked out in a series of meetings attended by F. S. Riley of the Geological Survey and A. L. O'Neill, W. D. Fuqua, R. J. Akers, and R. B. Hoffman of the Department of Water Resources. Fundamentally, the design provided for linking a two-directional tiltmeter—employing three interconnected measuring pots in an orthogonal isosceles array—to three compaction sensors installed in 150-foot dry wells. A compaction sensor is a borehole extensometer consisting of an invar tape suspended from the land surface and anchored to a subsurface bench mark at the bottom of the well; the tape is maintained at a constant tension by a counterweighted lever at the land surface and is electronically linked through a differential transformer to the reference micrometer of the adjacent tiltmeter pot. The output of the differential transformer is recorded for each of the three compaction sensors; these data can be used to subtract from the record of land-surface tilt any component due to differential compaction of the upper 150 feet of deposits beneath the three tiltmeter pots. Figure 8 is a simplified, diagrammatic sketch of this arrangement. There is no physical contact between the compaction sensor and the tiltmeter pot. If frictional contact between the invar tape and the well casing can be avoided, the resolution of the sensor is better than 1 micron.

Early in July, the decision was made to proceed with the final design and construction of the second installation, herein designated GS–II. It was agreed that the Department of Water Resources would be responsible for site preparation, including drilling the wells for the compaction sensors, and that the Geological Survey would be responsible for the design, acquisition, emplacement, and operation of the instrumentation.

Line 1 of the GS–II tiltmeter was laid out in a trench parallel to, and about 50 feet southwest of, the GS–I tiltmeter. Line 2 was laid out approximately along a contour at right angles to line 1 and extended southwestward from the northwest end of line 1 (pl. 1). Each line was 100 feet long. A single measuring pot at the intersection of the two lines was common to both. The hose lines were constructed, ballasted, and insulated identically to those at the GS–I tiltmeter.

The GS–II tiltmeter differed from the GS–I in the method of recording tilt. A dual-coil differential recorder was not used; instead three individual recorders were used to graph the liquid level in each pot independently, and the volume controller was connected directly to the central or common pot at the north corner of the layout. In this manner, the liquid level in the common pot was held nearly constant, while the northwest-southeast component of tilting was recorded directly by the southeast pot and the northeast-southwest component by the southwest pot.

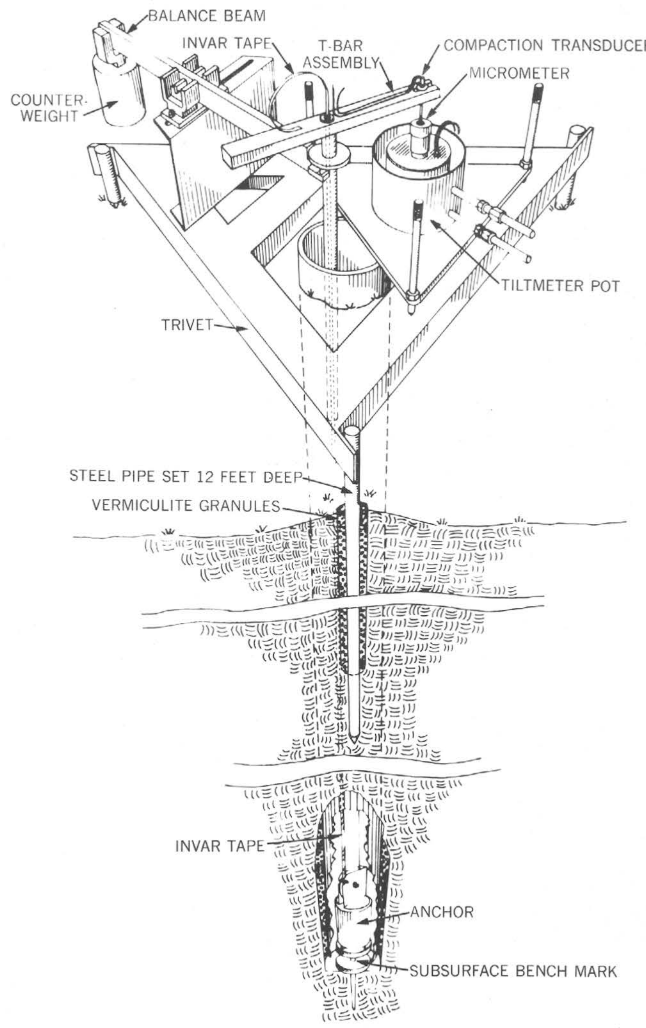

FIGURE 8.—Diagrammatic sketch of compaction sensor and tiltmeter foundation, GS–II installation.

A major difficulty in the construction of the compaction sensing system was the drilling of the 150-foot wells at the ends of the tiltmeter lines. Prime requirements for the wells were as follows: (1) they should be nearly plumb and of such diameter and straightness that the invar tape would not touch the well casing; (2) they should be drilled without wetting the deposits, because wetting would cause mechanical instability of the dry, highly compactible formation; (3) they should provide firm, stable foundations for the subsurface bench marks to be set in their bottoms; (4) they should be cased to prevent sloughing of formation materials against the tape and anchor; (5) to the extent feasible, the casings should be mechanically decoupled from the formation so that any compaction in the upper part of the deposits would not transmit a downward thrust through the casings to the bench-mark foundations; (6) the drilling should be done in such a way as to minimize temperature changes in the formation next to the well bore.

In consideration of the stringent requirements, it was decided to drill by the rotary method using compressed air to clear the cuttings from the hole. Because no reverse-rotary air rig was available, the air circulated down through the drillstem and up the annular space; with this arrangement the low velocity of the rising air limited the hole diameter to a maximum of 9 inches. This method was used with the first hole, but progress was exceedingly slow and the hole could not be held straight. The two remaining holes were drilled with a hydraulic rotary rig; highly viscous drilling mud composed of diesel fuel and bentonite was used to prevent wetting the adjacent sediments. When the holes reached 147 feet, the mud was bailed out and the last 3 feet were drilled dry, using compressed air. This method worked well. The holes were cased with thin-walled 6-inch ducting, and the annuli between casings and well bores were backfilled with commercial vermiculite insulating granules.

The subsurface bench marks, resembling huge double-headed scaffold nails (fig. 8), were attached to the end of the drill string and driven to refusal into the formation at the bottoms of the wells. The top of each bench mark, on which the tape anchor rested, was a machine-finished surface.

When the drilling was completed, only the central (northern) one of the three wells was entirely satisfactory in terms of straightness and plumbness. The southeastern well, which was drilled with air, was so crooked that a light lowered from the surface disappeared from view at a depth of about 100 feet. The southwestern well was less crooked, but the light disappeared in it, too, at a depth of about 130 feet. Because there were neither funds nor time for redrilling, the installations were completed in spite of the fact that friction between the invar tape and the well casing presumably would impair the operation of the southeastern and southwestern compaction sensors.

The tiltmeter pots and above-ground components of the compaction sensors were mounted on steel trivets which were welded to the tops of three steel piers. The piers consisted of 2-inch pipes about 12 feet long that had been driven into the bottoms of 3-inch holes drilled 9 feet deep at the corners of 52-inch equilateral triangles centered about each well (fig. 8). The annuli were backfilled with vermiculite. Figure 9 shows

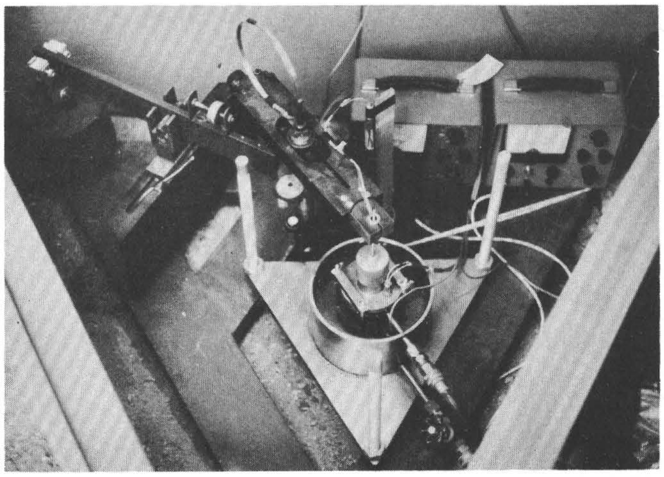

FIGURE 9.—Southwestern end of the GS–II tiltmeter (line 2). The lid of the insulating shelter has been removed, revealing the trivet, measuring pot, compaction-sensor components, and transducer amplifiers. (For identification of parts, see figure 8.)

a tiltmeter pot, compaction-sensor components, and transducer amplifiers mounted over the southwestern well and housed in a triangular insulating shelter made of foamed plastic.

The compaction-tape anchors were steel cylinders, 5½ inches in diameter and weighing about 75 pounds (fig. 8). To avoid overstressing the invar tapes, each anchor was lowered into position on a loop of steel cable which passed under the sheave attached to the top of the anchor. Subsequently, the lower end of the tape was attached to the cable, pulled down the well, and engaged in the latch at one end of the sheave bracket. This method of emplacement and attachment made it possible to position the anchor so that the lower end of the tape was near the "outside" of the inevitable bend in the well casing; thus, contact between tape and casing at the "inside" of the bend was avoided entirely in the nearly straight northwestern well and minimized in the other two.

With the same goal in view, the trivets and above-ground elements of the compaction sensors also were designed to permit maximum flexibility in positioning the tiltmeter pots and compaction equipment, so that the tapes could be brought out of the well at whatever position would minimize contact with the casings.

The upper end of each invar tape was clamped in the top of a T-bar assembly 4 feet long, which hung about 3 feet down into the well from a knife-edged yoke at one end of an equal-arm astatic balance beam (figs. 8 and 9). At the other end of the balance beam was suspended a counterweight that maintained the

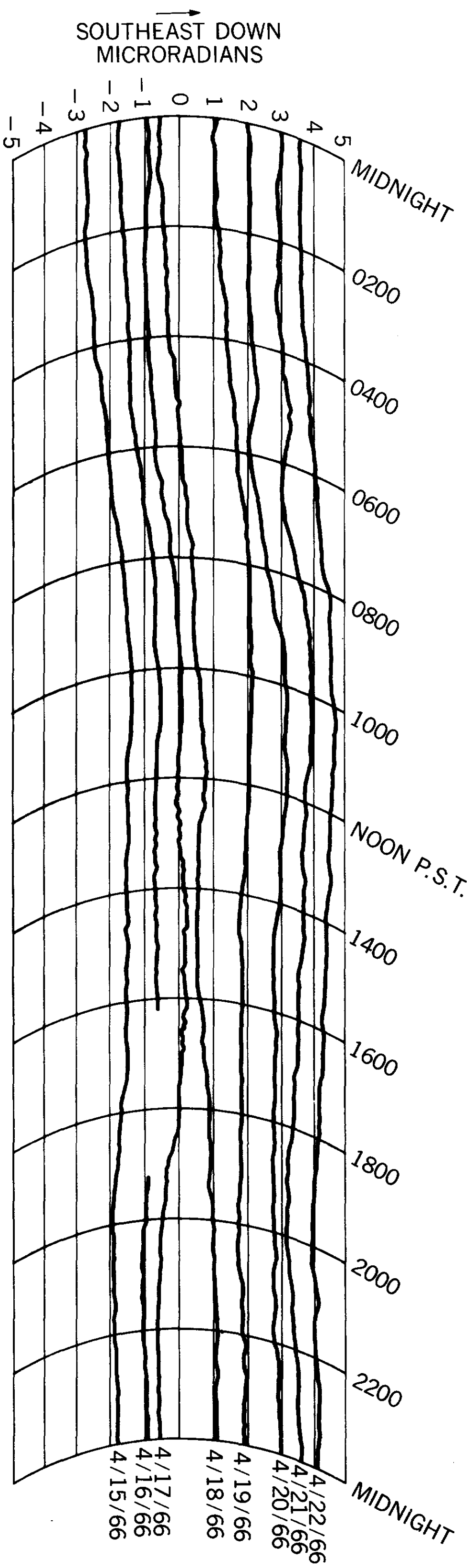

FIGURE 10.—Reproduction of 8 days of typical record, GS–I tiltmeter.

tape under the 20-pound tension specified by the manufacturer. The balance-beam support, or fulcrum, was bolted to the trivet. All suspensions were by hardened knife-edges and V-blocks of the type used in precision industrial balances.

At the down-hole end of the T-bar, the invar tape was centered between the ends of a pair of nylon set screws. With the tape under tension, the set screws restrained the T-bar from tipping on its yoke but did not appreciably restrict vertical movement between the tape and the bottom of the T-bar due to differential thermal expansion.

When compaction occurred within the upper 150 feet of sediments, the trivet at the land surface subsided, carrying down with it the tiltmeter pot and the fulcrum of the balance beam. The tape and T-bar, however, remained fixed with respect to the subsurface bench mark, and the compaction transducer sensed the lowering of the pot with respect to the fixed reference. To the observer at the surface, the effect was an apparent protrusion of the T-bar from the well, accompanied, of course, by a tipping of the balance beam.

THE TILT AND COMPACTION RECORDS

The primary concern in evaluating the stability of the pumping-plant site is the long-term accumulative tilting measured in tens of microradians. However, short-term oscillatory tilting of smaller amplitude is of interest in evaluating the response characteristics and reliability of the instrument systems. Accordingly, both aspects of the tilt and compaction records are discussed.

CHARACTERISTICS OF THE GS–I TILTMETER RECORD

Typical diurnal and other short-term fluctuations in the GS–I tiltmeter record are illustrated in figure 10, in which 8 days of record in April 1966 have been retraced on a single 24-hour length of recorder chart. The rapid and rather uniform southeasterly tilt that was occurring at the time separates the successive lines by about 1 microradian per day.

It is apparent that the daily record is characterized by a fairly smooth repetitive pattern, well displayed on April 15, 19, and 22, upon which are superimposed small shorter-term fluctuations of varying duration and amplitude. The diurnal pattern is a somewhat distorted sinusoidal oscillation which had a peak (maximum southeasterly tilt) at about 1000 Pacific Standard Time, a trough at about 2200, and an amplitude (double) of about 0.7 microradian. The cause of the diurnal fluctuation has not been extensively investigated. Instrumental error, perhaps of thermal origin, has not been ruled out, although the fluctuation does not coincide in phase with any of the temperature cycles that have been recorded in the tiltmeter system and does not vary in amplitude with daily and seasonal weather changes. The fluctuation may represent real tilting related to the diurnal temperature cycle.

The repetitive diurnal tilting cannot reasonably be attributed to tidal effects because it is about four times larger than the maximum theoretical earth tide and does not exhibit the strong semidiurnal component and regular progression characteristic of both earth tides and ocean-tide loading.

Some of the short-term fluctuations are readily identified when a cause-and-effect relationship can be observed as the record is being generated. Wind noise with an amplitude of 0.2–0.6 microradians is common during the summer, and the passage of small but vigorous whirlwinds, common on hot days, has been observed to cause "spikes" in the record of more than 3 microradians. Because the pot lids are not equipped with positive hermetic seals, it is not impossible that such large spikes were caused by the leakage of strong, transient barometric gradients into the pots. However, this probably is not a competent explanation for the more typical wind-induced fluctuations with "periods" of 3–15 minutes, because the very high impedance of the possible leakage paths, in contrast to the low impedance of the air line connecting the pots, minimizes the possibility of sustaining a significant internal air-pressure gradient between the pots.

The winter record was characteristically less noisy than the summer, except during major storms, when substantial tilts—as much as 3 microradians—were recorded over periods of several hours.

The inherent viscous damping properties of the hose-fluid system sharply attenuate the response to oscillations with frequencies higher than about 3 cycles per minute, with the result that the instrument is nearly immune to high-frequency noise from vehicular, seismic, or other sources. Longer-period seismic waves from major earthquakes as far away as Alaska, Chile, and Formosa were recorded on the Wheeler Ridge tiltmeters. The GS–I tiltmeter was approximately critically damped and had a time constant of about 20 seconds without being subject to "ringing" or overshoot. For comprehensive discussions of the dynamic characteristics of liquid-level tiltmeter systems see Eaton (1959) and Bonchkovsky and Skur'yat (1961).

Much of the GS–I record is characterized by a diurnal departure during the daylight hours from the typical sinusoidal fluctuation shown in figure 10. The departure consists of a rapid northwesterly tilting from about 1 hour after sunrise to about 1230 and moderately rapid southeasterly tilting from about 1230 to about 1 hour after sunset. The amplitude of the departure reached a maximum of about 7 microradians during June and July and a minimum of about 3 microradians in December and January. These diurnal and seasonal characteristics, together with the fact that the departure is subdued or almost absent on overcast days, suggest that it is directly related to the intensity of solar heating of the hose line, despite the fact that the fluctuation is not in phase with recorded temperature change in the hose. The mechanism by which solar heating of the hose may, under some circumstances, generate a spurious tilt is not fully understood. It may be caused by the development of density traps as the result of gradual segregation of warmer and cooler liquid in minor humps and sags in the hose. Experiment has shown that flushing the hose temporarily eliminates the spurious diurnal tilting but that it tends to build up again over a period of weeks.

CHARACTERISTICS OF THE GS–II COMPACTION RECORDS

Diurnal and other short-term fluctuations typically are of much smaller amplitude in the compaction records than in the tilt records. During the first 3 months of operation, when there were no nearby infiltration ponds in use to disturb the instruments, only two identifiable factors—temperature and barometric pressure—exerted significant influence on the compaction sensors.

The characteristics of the compaction records and their relation to temperature and barometric-pressure changes are illustrated in figure 11, in which 4 days of data in December 1965 have been replotted to convenient scales. This particular interval of record was selected because continuous records of temperature (in the northern instrument shelter) and barometric pressure were available and because significant barometric changes took place.

The generally downward trend of the compaction records in figure 11 is due to the seasonal cooling trend (fig. 14), which causes a substantial shortening of the instrument piers. A detailed discussion of the effects of ambient temperature changes on the compaction sensors is presented in a later section dealing with the long-term compaction records. Of interest here is the fact that the diurnal temperature cycle is not strongly reflected in the compaction records. Inasmuch as the transducer-amplifier system in the compaction sensor is identical with that in the tiltmeter, and any dimension changes in the tiltmeter pots would appear in the compaction record (fig. 8), the diurnal temperature response of the compaction sensors may be taken as the maximum limit for the temperature sensitivity of the electronic and mechanical elements of the tiltmeter system. Thus, the theoretically predicted low thermal sensitivity of the tiltmeter pots and transducer system is further confirmed by the compaction records.

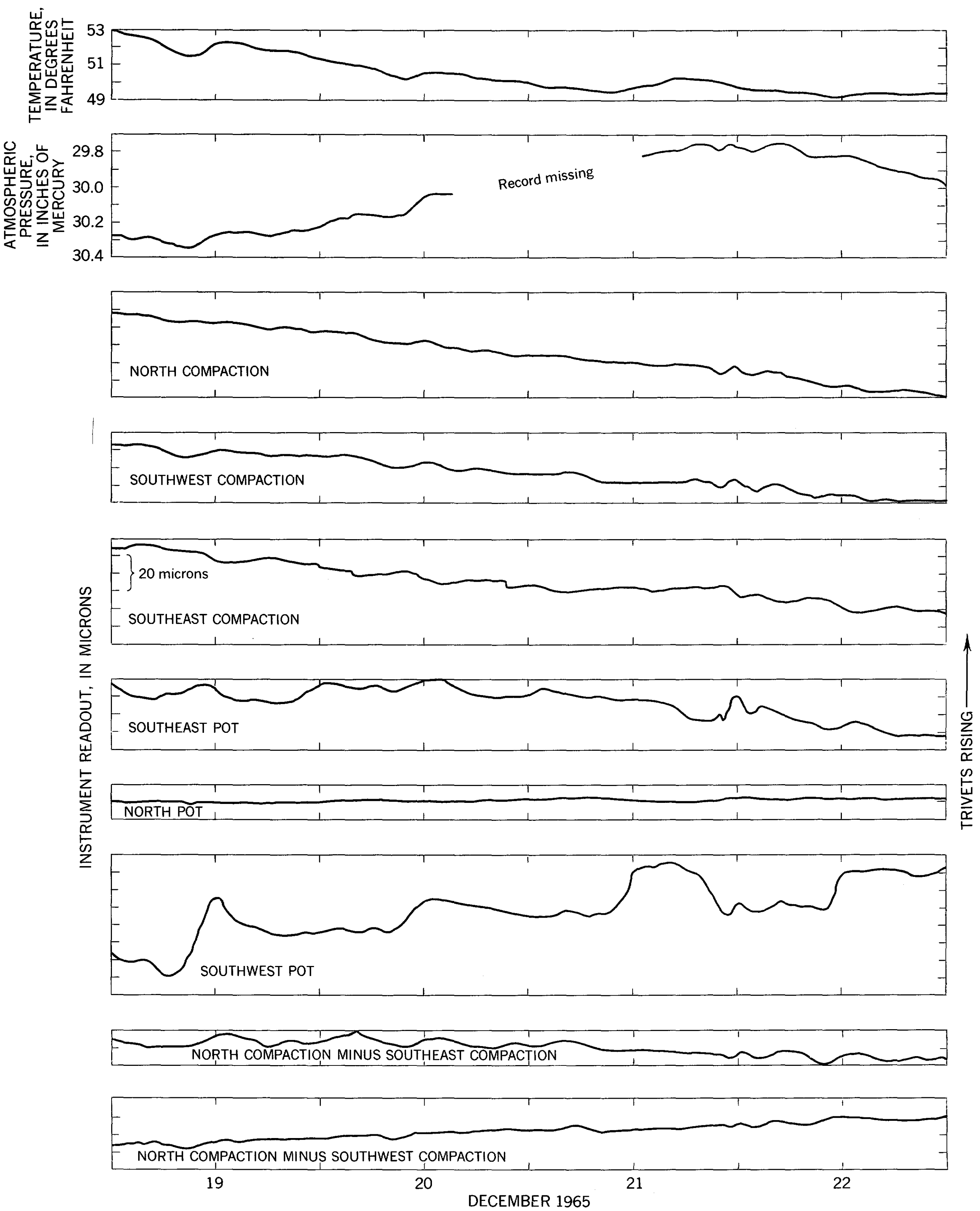

FIGURE 11.—Differential compaction, compaction, tilt, temperature, and barometric pressure at the GS–II installation, December 19–22, 1965.

Visual comparison of the barograph and compaction records demonstrates that the alluvial-fan deposits beneath the site experience measurable changes in thickness in response to variations in atmospheric loading. The relationship is, however, neither direct nor simple. Large, rather long-term barometric changes accompanying the passage of major weather systems have little or no effect, but small short-term fluctuations with rapid rates of change produce evident responses. For example, during the night of December 21–22, a distinctive series of barometric fluctuations caused definite but somewhat dissimilar responses in the three compaction records.

A thorough analysis of the barometric responses of the compaction sensors is not within the scope of this investigation. The records seem to suggest, however, that the observed effects are time-dependent, rate-sensitive processes, in which atmospheric loading constitutes an effective stress on the deposits only to the extent that pore-pressure changes in the intergranular air cannot keep pace with barometric -pressure changes at land surface. For example, in the case of an abrupt increase in barometric pressure, significant movement of air into the deposits would occur until the interstitial pressure was built up to equilibrium with the increased barometric pressure. During this interval of downward flow, the pressure dissipated in viscous drag against the soil grains is accumulative downward within the solid skeleton of the deposit and constitutes an effective stress tending to compact the deposits. As pressure equilibrium is approached, the flow and resultant seepage stress approach zero, and the soil column tends to rebound toward its normal thickness. On the other hand, large but gradual changes in barometric pressure produce low flow rates, small seepage stresses, and minimal strains within the soil column.

Under the circumstances postulated, the response of a column of unsaturated soil to a given rate of change of barometric pressure would be dependent primarily upon the vertical permeability, effective porosity, compressibility, thickness, and temperature of the deposits. All but the last two of these factors would be highly dependent on the lithology, mineralogy, and moisture content of the soil. Thus, at the Wheeler Ridge site, the exceedingly heterogeneous nature of the alluvial-fan deposits underlying the tiltmeter station should be expected to result in appreciable differences in both phase lag and amplitude among the responses of the three compaction sensors. This, indeed, seems to be the case.

CHARACTERISTICS OF THE GS–II TILTMETER RECORD

The diurnal and other short-term characteristics of the two-directional GS–II tiltmeter records are very similar to those of the GS–I record. Minor differences in dynamic response characteristics probably are due to the tripartite pot connections and certain differences in plumbing fittings. The "normal" diurnal fluctuation in both lines is nearly identical in shape but somewhat smaller in the GS–II than in the GS–I tiltmeter. A spurious diurnal tilting presumably related to solar heating of the hose is also observed, especially in line 2, which often indicates a northeastward departure from the true tilt record during the daylight hours.

Figure 11 illustrates, in addition to the compaction records, the records of liquid-level fluctuations in the three tiltmeter pots during the same 4-day period. The functioning of the automatic volume controller is demonstrated by the nearly straight-line record of the northern pot. The records for the southeastern and southwestern pots constitute approximations of the indicated tilt in those directions. (For precise tilt determination, the minor departures from null of the controlled northern record must be subtracted from each of the other two records.)

Comparison with the barograph record again indicates that atmospheric pressure changes are a principal source of the minor irregularities characteristic of the tilt records. Comparison is complicated by the fact that the tiltmeters show only the *differences* in barometric response among the instrument piers. Therefore, in figure 11 the tilt records are compared with derived curves of differential compaction obtained by subtracting the northern compaction record from each of the other two. The comparison demonstrates that the tiltmeters are recording differential compaction and expansion similar to, but of greater magnitude than, the fluctuations measured by the compaction sensors. Presumably, the greater magnitude and certain differences in phase may be taken to indicate that differential effects of short-term barometric fluctuations extend to depths considerably greater than the 150 feet measured by the compaction sensors.

The spurious daytime tilting indicated by the southwestern pot shows up very clearly in the record as humps that bear no relation to the differential-compaction graph.

SUMMARY OF TILT AND COMPACTION DATA

The long-term tilt and indicated compaction measured by all instruments throughout the life of the Wheeler Ridge installation are summarized in figure 12. This illustration was prepared by plotting for each day the 0600 hours point in the diurnal cycle of the tilt and compaction records. This procedure minimizes extraneous fluctuations due to thermal and barometric anomalies in the original records. Each graph was plotted in the original units of measurement—thousandths

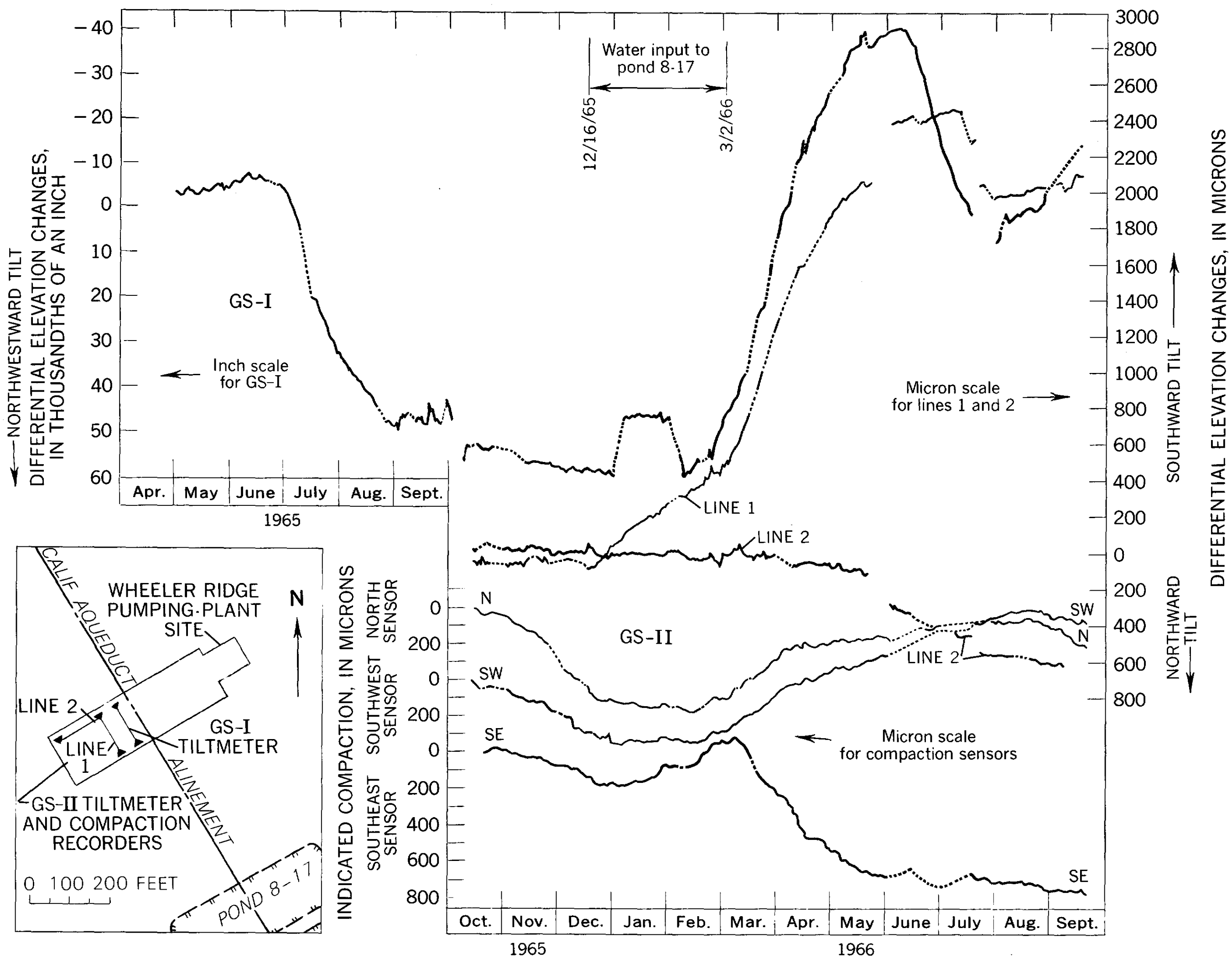

FIGURE 12.—Tiltmeter and compaction-sensor data, Wheeler Ridge, Calif.

of an inch for the GS–I tiltmeter, and microns for the GS–II tiltmeter and compaction sensors. The two vertical scales on the illustration are comparable within 1.6 percent. The resolution of the graphs as originally plotted is about 5 microns (2×10^{-4} inch) or roughly 0.2 microradians.

Data from GS–I tiltmeter

During its first 6 weeks of operation, the GS–I tiltmeter indicated almost stable conditions—small fluctuations of unknown origin superimposed upon a trend of slow southeastward tilting. From the middle of June 1965 until the end of August, however, a very rapid northwestward tilting was recorded, the northwestern pot subsiding a total of 55×10^{-3} inch (4.6×10^{-3} foot) with respect to the southeastern pot. This 2½-month interval corresponds approximately to the summer period of most intense ground-water pumping in the valley area immediately north of the site.

The nearest well for which detailed water-level data are available is the Geological Survey's Lakeview test well, 11N/21W–3B1, which is 6.4 miles west-northwest of the site, in an area of concentrated pumping. The well is equipped with water-level and compaction recorders. Its hydrograph (fig. 13) reflects the artesian head in the aquifers between the depths of 1,037 and 1,237 feet, which is the lower part of the principal producing zone. The artesian-head decline between April 26 and July 30, 1965, was 47 feet, and at the well, the resulting aquifer compaction between depths of about 300 and 1,477 feet was 0.25 foot during the same period (fig. 13).

The similarity between the shapes of the hydrograph and compaction graph (fig. 13) and the shape of the tilt record through the summer pumping season strongly suggests that the northwestward tilt is the result of differential aquifer compaction, although the tilt record lags the hydrograph by about 6 weeks. This

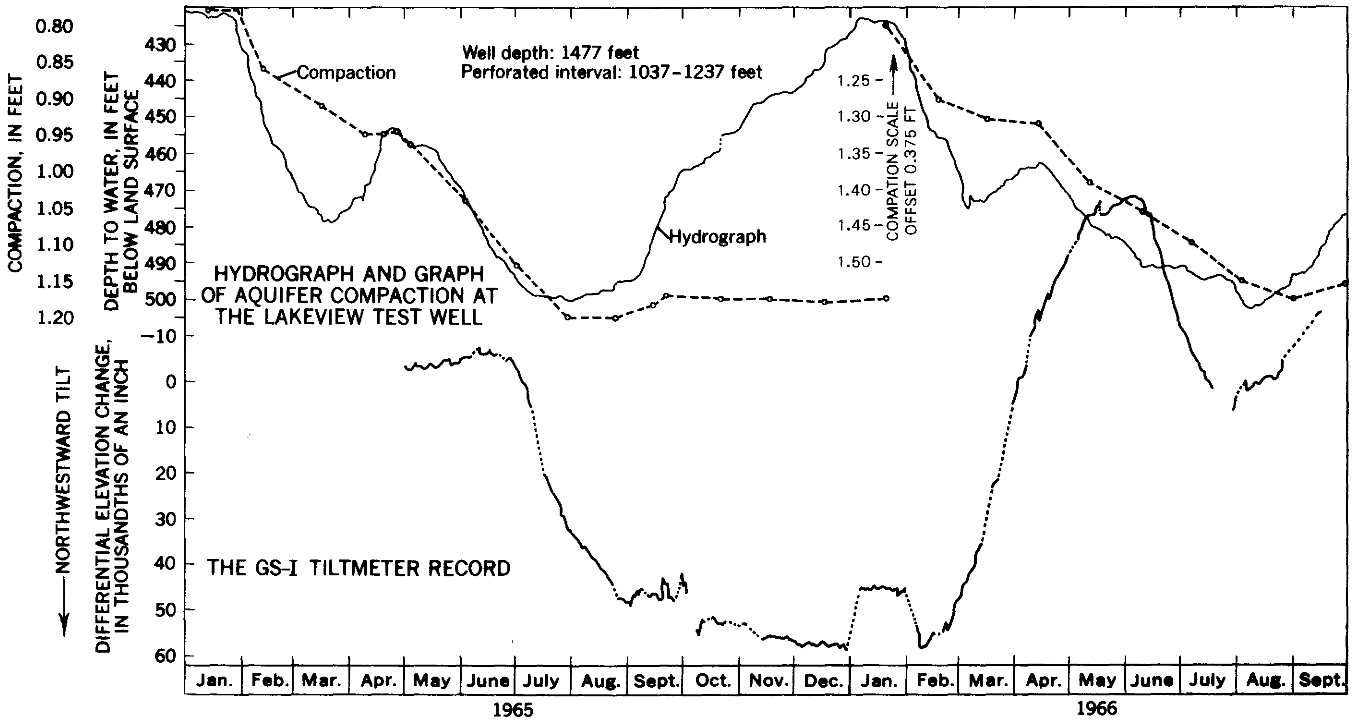

FIGURE 13.—The GS–I tiltmeter record and graph of aquifer compaction at well 11N/21W–3B1.

delay is not unreasonable if one considers the time required for significant head decline to migrate laterally from the areas of intensive pumping to the tiltmeter site. (The nearest irrigation well is almost a mile from the site.) Furthermore, local variations in agricultural practices may have produced appreciable time differences between the pumping effects recorded at the test well and those that occurred in the irrigated areas closest to the tiltmeter site.

The tilt recorded during the pumping season (55×10^{-3} inch or 46 microradians), if extrapolated northwestward toward the center of subsidence, would produce much more subsidence than actually occurred, about 1.55 feet at the Lakeview test well, for example, instead of the 0.25 foot that was recorded. This situation is in accord with the historical record of subsidence, which shows that differential subsidence, or tilt, has been particularly intense along the north base of Wheeler Ridge. (See fig. 1.) The intensification of tilting close to the ridge presumably is due to profound seasonal steepening of the ground-water pressure surface in that area and perhaps also to a local decrease in compressibility of the sediments adjacent to the ridge. Both factors would be likely corollaries of the inferred geologic structure beneath the pumping-plant site. Pleistocene gravels with a northeasterly dip of 60° crop out in the north flank of Wheeler Ridge a quarter of a mile south of the pumping-plant site, and presumably extend beneath the valley floor with dips diminishing rapidly northward. Because permeability across the bedding typically is much less than permeability parallel to the bedding, the dipping strata almost certainly constitute partial barriers to ground-water movement; such barriers would cause steep hydraulic gradients and delayed transmission of head declines from the areas of concentrated pumping to the north. It is also possible that the up-arching of older, more indurated sediments near Wheeler Ridge into the depth range of artesian-head decline has effectively thinned the aquifer system and reduced the compressibility of this zone on the north flank of the anticline.

Early in September 1965, ground-water pumping virtually ceased and artesian pressures began to recover rapidly. The compaction record from the Lakeview test well (fig. 13) suggests about 0.03 foot of expansion of the aquifer system at the onset of rapid recovery, followed by an interval of stability during the 4 succeeding months of water-level rise.

The tilt record shows minor fluctuations after the first of September, but no change comparable to that which occurred during the pumping season.

Early in October 1965, the failure of a differential transformer and certain mechanical problems necessitated partial dismantling of the GS–I tiltmeter. During reassembly it was not possible to recover precisely the preexisting instrument datum. At the time it was thought that the preexisting datum had been recovered within ±0.002 inch. However, the trend of the subsequent record suggests that the datum may have been offset by 0.004–0.008 inch in such a way as to indicate an erroneously large subsidence of the northwest pot.

During the heavy rains at the end of December, sufficient water seeped under the walls of the shelters to moisten the clayey soil surrounding and underlying the northwestern instrument pad at the GS–I tiltmeter. The moistened soil swelled rapidly and elevated the pad about 0.012 inch. Continuing cool, damp weather prevented significant drying of the soil during January 1966. At the end of January a storm flooded the southeastern pad and caused an apparently equal amount of soil swell there; this swelling returned the tilt record to its former trend line.

A rapid southeastward tilt began February 11 and continued through May, during which interval 98×10^{-3} inch of differential elevation change occurred. Evidence from the compaction records, discussed in a following section, indicates that the large southeastward tilt was caused by hydrocompaction of deposits beneath the southeastern pot foundation. The hydrocompaction resulted from lateral percolation of water from infiltration pond 8–17, 400 feet upslope. On June 10, the record reversed and began a rapid northwestward tilt which continued through July, totaling 47×10^{-3} inch of differential elevation change. Finally, from July 30 until the end of the record (September 16), irregular but moderately rapid southeastward tilting caused 22×10^{-3} inch of differential elevation change.

Although the northwestward tilting in June and July once again corresponds approximately to the period of most intensive draft on the ground-water reservoir, the correlation between the tilt record and the hydrograph at Lakeview is much less impressive in 1966 than it was in 1965. This problem is discussed further in the "Summary" of this report.

Data from GS–II tiltmeter

Data from line 1 and line 2 of the GS–II tiltmeter (fig. 12) show that the site was nearly stable from October through mid-December 1965. During that period the only consistent trend in the data was a slight northeastward tilting on line 2, which, in fact, continued until April 1966, at an average rate of 12 microns per month of differential elevation change. This observed trend seems to indicate that during the autumn period of no known aquifer or near-surface compaction,[1] the GS–II tiltmeter record suggested a continuing "background" tilting of about 5 microradians per year in a direction about N. 55° E. Tectonic tilting in that direction and of such a magnitude (0.5 ft per 100 ft per 1,000 yrs) would not be inconsistent with what is known of the recent activity of the White Wolf fault and of the Pleistocene origin of the Wheeler Ridge anticline (Dibblee, 1954, p. 26, 27).

The stability shown by line 1 from October through mid-December and by line 2 through mid-April is highly significant in that it clearly demonstrates the insensitivity of the tiltmeter system to seasonal temperature changes. From October to late December, the temperatures in the instrument shelters fell 17°C and the hose temperatures fell about 22°C. From late December to mid-April the shelter temperatures rose 15°C and the hose temperatures rose 22°C. These changes encompassed 70 percent of the total annual temperature fluctuations in the shelters and hoses, but produced no discernible response in the tiltmeter records.

On December 16, 1965, water was introduced into preconsolidation pond 8–17, 400 feet upslope from the southeast ends of the tiltmeters. On December 21, the graph of line 1 turned sharply upward, indicating that the southeastern pot was subsiding in relation to the other two. (In order to plot the northward tilting during the pumping season as a declining trend comparable to the hydrograph and compaction record in figure 13, an arbitrary plotting convention that causes the relative subsidence of the southeastern pot to appear on the graph as a rising trend was adopted in laying out figure 12.) Relative subsidence of the southeastern pot continued at an average rate of 11 microns per day through January 7. From January 7 to March 1, the southeastern pot subsided at a diminishing rate that averaged 6 microns per day. Differential subsidence of the southeastern pot relative to the north pot from December 21 to March 1 was about 500 microns. On March 1, the southeastern pot began an accelerated subsidence that rapidly attained a sustained maximum rate of 33 microns per day. On March 2, input of water to pond 8–17 ceased. The subsidence slowed in April, May, and June and finally ceased on July 6, after creating a total differential displacement of 2,530 microns since December 21.

Between July 11 and July 29, there was rapid relative subsidence of the northern pot in the amount of 490 microns, followed by a resumption of slow southeastward tilting.

Line 2 first departed from its well-established trend of very slow northeastward tilting (12 microns per month of relative subsidence of the northern pot) about April 1. Thereafter, northeastward tilting occurred at a more rapid rate; tilting accelerated notably in mid-May but gradually diminished through June, July, and August. Between April 1 and September 6, 1966, the northern pot subsided about 600 microns

[1] The compaction-sensor curves in figure 12 are strongly influenced by temperature, as will be discussed in detail in the next section.

with respect to the southwestern pot—a departure of about 500 microns from its previously established trend.

For both lines 1 and 2, the interval of record between June 3 and July 18, 1966, is shown disconnected from the rest of the plot because of some uncertainty as to the precise relationship of the instrument datum during this interval to that existing before and after. The uncertainty, which may be as much as 100 microns, derives from the fact that the differential transformer in the northern pot was damaged by prolonged immersion during the latter part of May because of leakage of a valve on the fluid-supply reservoir. The damage and resulting offset in the instrument datum were not noticed until mid-July, when the transformer failed entirely and had to be replaced.

Data from GS–II compaction sensors

The long-term records of the compaction sensors (fig. 12) are dominated by two kinds of fluctuations—a seasonal oscillation apparently due to the temperature cycle, and, in the case of the southeast sensor, a major downward departure from the temperature curve, due to hydrocompaction effects beneath the southeast trivet.

The relationship between temperature and indicated compaction is illustrated in figure 14; this figure shows the northern compaction record and the temperatures measured in the northern tiltmeter pot and at a depth of 7 feet in the northern compaction sensor well. The close correspondence between the temperature and compaction records suggests that thermal expansion and contraction of the piers, trivets, tiltmeter pots, and transducer mounts may account for the seasonal fluctuation in the compaction records. Calculations based on the observed temperature range of 22°C and handbook values of thermal-expansion coefficients yield an amplitude (double) of 130 microns for the seasonal dimension change in the above-ground components of the compaction sensor.

Very few data were obtained on temperatures of the piers, but temperatures were recorded regularly at 7, 16, and 40 feet below land surface in the north compaction-sensor well. The relationship between the amplitude of seasonal temperature fluctuation and depth in the wells was found to be approximately exponential. Because several spot checks indicated that the temperatures at depths of about 8 feet in the piers were generally comparable to those recorded at 7 feet in the wells, the assumption has been made that the observed exponential relationship can be extrapolated to the piers. On the basis of this assumption, the value calculated for the average seasonal temperature fluctuation for the 11 feet of buried pier is 13°C, and the resulting seasonal dimension change is about 500 microns. The total calculated dimension change for the piers plus the above-ground elements is therefore about 630 microns. This amount is offset to a minor degree by the thermal response of the invar tape, which for the entire length of tape does not exceed 30 microns. Thus, it can be estimated from the properties and dimensions of the materials and the observed temperature fluctuations that approximately 600 microns of fluctuation in the compaction record can be expected in response to the annual temperature cycle. This value compares favorably with the 570 microns of fluctuation (a minimum value) recorded by the northern sensor and the 750 microns recorded by the southwestern sensor.

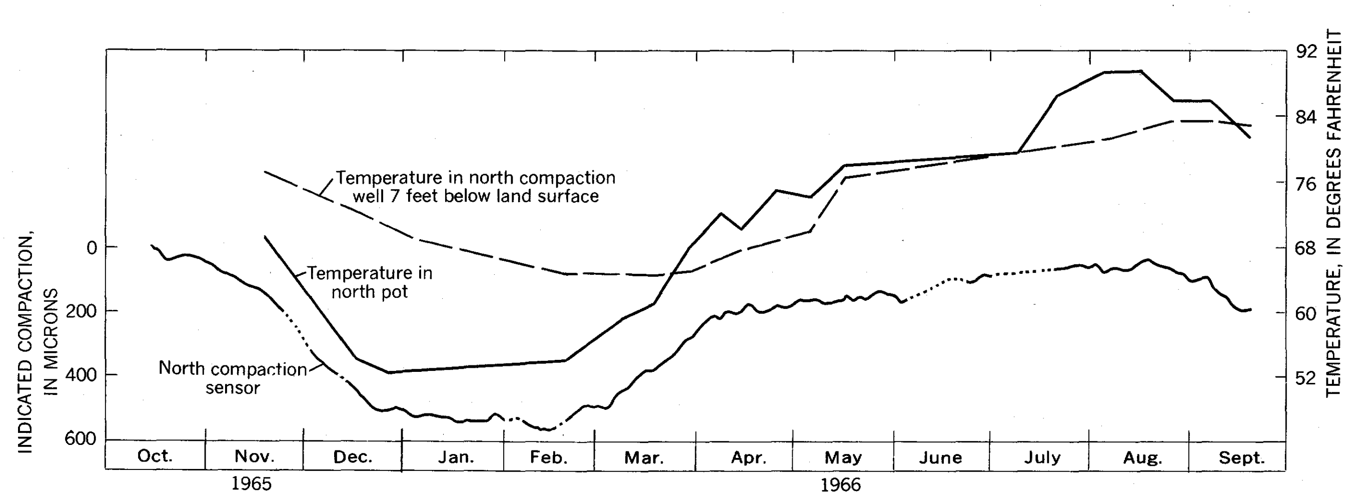

FIGURE 14.—Temperature changes and indicated compaction, northern compaction sensor.

Hindsight reveals that better temperature compensation of the compaction sensors could have been achieved if the invar tapes had been clamped at the bottom instead of at the top of the T-bar assembly.

(See fig. 8.) In the zone of maximum temperature fluctuation, this would have placed comparable materials (mostly steel pipe) in parallel, instead of invar in parallel with steel, which has a thermal expansion coefficient about 30 times that of the invar.

As far as can be determined, the indicated seasonal compaction and expansion recorded by the southwestern sensor during 11 months of operation are attributable almost entirely to thermally induced changes in dimension in the instrument and its piers.

If the southwestern compaction record is accepted as the standard curve of temperature response for all three instruments, it is evident that the first well-defined departure from this curve appears in the southeastern record early in January 1966 (fig. 12). At that time, an apparent expansion of the sediments beneath the southeastern trivet began, as shown by the rising trend of the record. Early in March, the rising trend was abruptly reversed and rapid compaction was recorded through May, followed by slow compaction during the remainder of the record.

The northern compaction record began a gradual but continuing downward departure from the temperature curve in April, indicating that real compaction began at that time. (See fig. 12.)

To minimize the effect of the temperature fluctuations and to facilitate a comparison of the compaction and tilt records, differential compaction plots (north minus southeast and north minus southwest) are presented in figure 15. The apparent northward tilting shown by the differential compaction curves during November and December results from the fact that the northern compaction sensor recorded substantially more indicated compaction during this period than did the other two (fig. 12). This excessive indicated compaction is not corroborated by the tiltmeter data and therefore cannot be attributed to changes in the near-surface elements of the equipment (piers, trivets, and measuring pots). It may simply reflect processes of thermal and mechanical stabilization of the sediments surrounding the subsurface bench marks, following the disturbance created by drilling. The same explanation may be invoked to account for the modest divergence of the differential compaction plots during November and December.

The downward trend of the north-minus-southeast graph (comparable to line 1 of the tiltmeter) during January and February suggests northwestward tilting at the time when line 1 of the tiltmeter was recording substantial southeastward tilting. Both phenomena are believed to be related to the influx of water to the sediments through pond 8–17, which was flooded continuously from December 16 to March 2. In a previous progress report (Riley, 1966), it was tentatively concluded, on the basis of data available through January 1966, that the initial southeastward tilt recorded by the GS–II tiltmeter was due to the loading effect of the large mass of water (about 2,900 tons per day) being added to the deposits beneath the pond. However, the lack of a comparable response from the GS–I tiltmeter casts considerable doubt on this interpretation. In the light of later data and an improved understanding of the response characteristics of the compaction sensors, the following alternative interpretation is suggested.

The principal movement of water from the infiltration pond and wells (80 ft deep) is presumed to have been downward toward the water table; before flooding of the pond began, the water table was at an unknown depth, but greater than 250 feet (W. D. Fuqua, oral commun., June 1965). The writer postulates that some of the percolating water encountered a narrow, highly permeable stringer of gravel filling a former channel cut in sediments of much lower permeability.[2] Moving along the channel as a perched ground-water body, this water was, in effect, "piped" downdip toward the tiltmeter site far ahead of the general advance of the wetted front surrounding the pond. Arriving beneath the southeastern end of the GS–II tiltmeter, at some depth appreciably greater than 150 feet, the water created a highly localized tongue of hydrocompaction whose gradual growth was recorded by the moderate southeastward tilting between December 21 and March 1. Because the hydrocompaction was initially restricted to a small body of sediment at considerable depth, its effect, in transmission to the surface, was spread laterally and attenuated vertically by the cohesiveness and resulting "beam strength" of the dry overlying deposits. Those deposits thus were placed in vertical tension above the region of actual compaction, and the subsurface bench mark subsided more than the trivet at land surface. Evidence tending to support this postulate is found in the approximately 200 microns of expansion recorded by the southeastern compaction sensor between January 10 and March 1 (figs. 12 and 15). The differential subsidence of the southeastern trivet as recorded by the tiltmeter was about 500 microns, so the total subsidence of the southeastern subsurface bench mark relative to the north trivet was about 700 microns.

Continuing growth of the bulb of wetted sediments beneath pond 8–17 evidently pushed the moisture front upward and outward past the southeastern subsurface bench mark on March 2, as is shown by the sharp inflection in the differential-compaction graph

[2] The existence of thin zones of very high permeability is demonstrated by the fact that intervals of severe mud loss were encountered in test holes drilled by the hydraulic rotary method immediately upslope from the tiltmeter site (W. D. Fuqua, oral commun., June 1965).

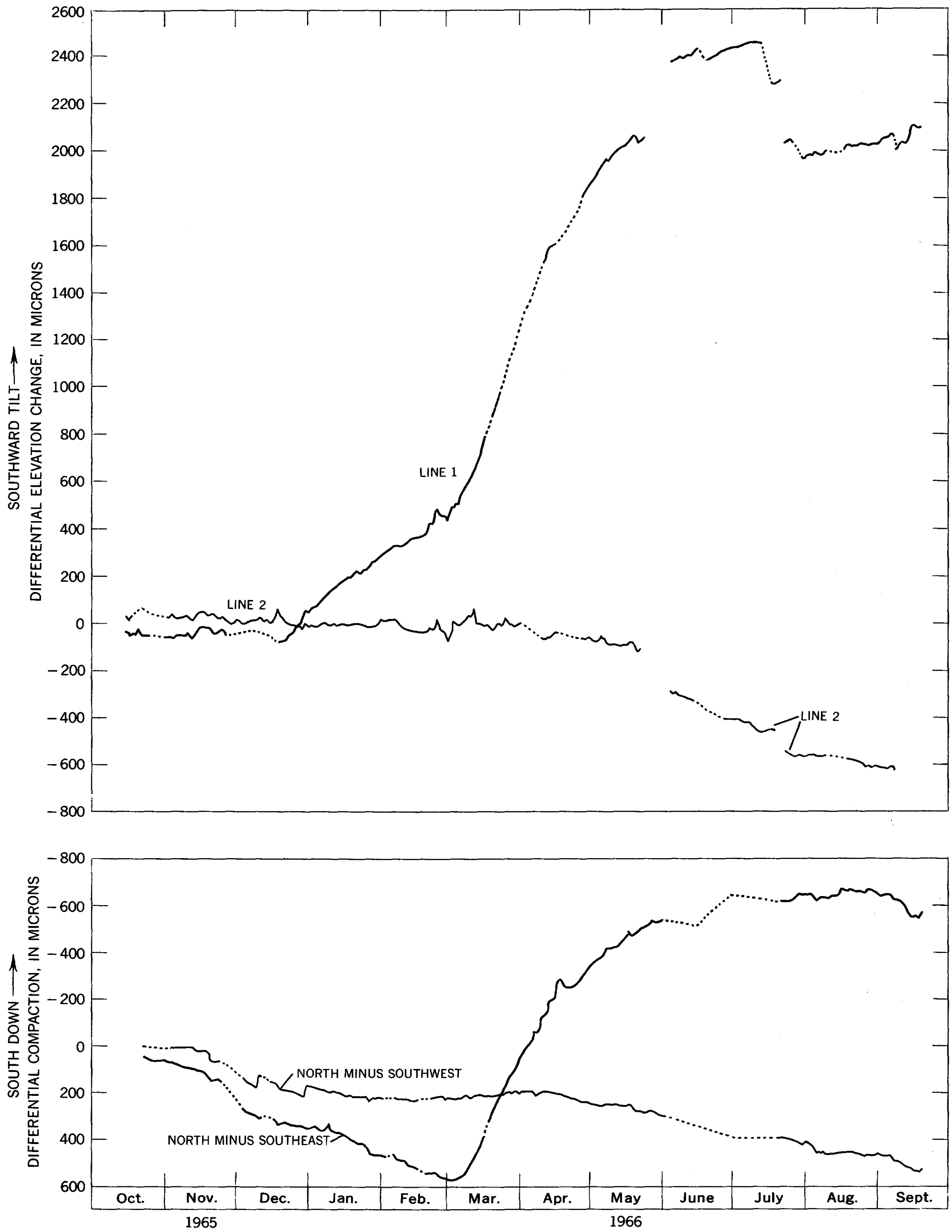

FIGURE 15.—Differential compaction and GS–II tiltmeter data.

(fig. 15). Thereafter, hydrocompaction between the subsurface bench marks and some unknown upper limit caused about 1,250 microns of differential compaction in the upper 150 feet of sediments. If, as previously stated, the indicated compaction record of the southwestern sensor (fig. 12) is taken as the standard temperature-response curve, then the total hydrocompaction between the southeastern trivet and its subsurface bench mark may be estimated at about 1,500 microns, on the basis of the departure of the indicated southeastern compaction record from the indicated southwestern compaction record, March to September 1966. (See fig. 12.)

The north-minus-southwest differential-compaction graph (fig. 15) shows no indication of hydrocompaction effects until mid-April. Thereafter, a fairly constant rate of compaction beneath the northern trivet is indicated, with a total of about 300 microns attained by the end of the record. This amount constitutes 60 percent of the northeastward tilting (500 microns) recorded on line 2 during the same period. A major, but indeterminate, part of the 200 microns of northeastward tilting that must be accounted for below the north subsurface bench mark probably is attributable to deep-seated differential aquifer compaction due to artesian-head decline.

During the period of rapid hydrocompaction (mid-December through June), line 1 of the tiltmeter recorded about 2,500 microns of differential subsidence beneath the southeastern trivet. Within the same period, the northern compaction sensor recorded about 200 microns of hydrocompaction. (See fig. 15.) Thus, the total subsidence of the southeastern trivet during this time was at least 2,700 microns. Data from spirit leveling (discussed in a following section) reveal that nearby areas outside the influence of hydrocompaction tilted toward the north during this period because of deep-seated aquifer compaction. This fact strongly suggests that the total hydrocompaction beneath the southeastern trivet was substantially more than 2,700 microns and that probably more than half of the total hydrocompaction occurred below 150 feet.

In the preceding discussion, the compaction data have been taken at face value as indicative of actual hydrocompaction at the point of measurement. In the strictest sense, this implicit conclusion must be regarded as an inference because, in the absence of an array of piezometers and soil-moisture probes, no direct information on the migration of water from pond 8–17 is available.

The small magnitude of compaction at the pumping-plant site (about 3 millimeters) in contrast to the 1,080 millimeters (3.54 feet) of subsidence that occurred at pond 8–17 suggests that only a minute percentage of the hydrocompactible deposits beneath the site was appreciably moistened. This, in turn, implies that only the outermost fringes of a highly irregular moisture front migrated through the sediments as far as the pumping-plant site.

Alternatively, it might be argued that the apparent hydrocompaction at the site was due wholly or in part to a lateral transmission of strain from the area within 200 feet of the pond where nearly all the subsidence occurred. This argument assumes that the deposits possess a fairly high degree of tensile strength and thus are able to transmit laterally part of the centripetal pondward rotation that affected the area immediately surrounding the pond.

No evidence of the required strength is available. On the contrary, the characteristic weakness of soils in tension is demonstrated by the numerous tension cracks that formed around the pond as the unwetted shallow deposits tipped toward the pond in response to differential hydrocompaction at greater depth. Cracks usually developed at radial intervals of 10–50 feet and had initial widths at the surface as small as 0.05 inch. Cracking had extended 215 feet from the pond by February 4, 1966, but not until mid-April did the cracks reach the maximum extent of 350 feet from the pond and 50 feet from the tiltmeters. The cracking demonstrates that the sediments could not withstand appreciable tensile strain and that stress was relieved by quasi-brittle failure rather than by plastic yielding. In addition, the cracks, extending down to unknown depths, served to isolate, at least partly, the area of major subsidence from outlying areas.

Additional evidence in favor of direct hydrocompaction rather than the strain-transmission hypothesis may be inferred from the spatial and temporal distribution of hydrocompaction effects around pond 8–17. Spirit-level surveys indicate that subsidence around the pond diminished very abruptly beyond about 150 feet from the pond's northwestern margin. This suggests that the bulb of complete or nearly complete saturation never expanded beyond that distance. The leveling data also show (1) that by January 6, 1966, subsidence at the pond was 95 percent of the value achieved by the end of the flooding on March 2 and (2) that by April 15, subsidence within 100 feet of the pond was 90 percent of that attained by September 1966. In contrast, the compaction sensors recorded no compaction before early March, and the tiltmeters had by mid-April recorded only 65–75 percent of their maximum southeastward tilt. It should also be noted that the infiltration rate had stabilized by mid-January at about 90,000 cubic feet per day. These facts suggest a slow but continuing lateral migration of capillary moisture beyond the limits of a bulb of saturation that had become essentially stabilized early in the hydrocompaction episode. The high degree of horizontal and vertical textural variability characteristic of the fan deposits insures a large range of capillary permeabilities, which in turn implies a highly irregular moisture front, characterized by increasing irregularity at increasing distances from the pond. This conceptual model of the hydrocompaction process provides, in the writer's opinion, the most reasonable explanation of the facts available and is the basis for the interpretive statements and conclusions presented in this report.

DATA FROM SPIRIT LEVELING

Before the present investigation, information on tilting in the immediate vicinity of the pumping-plant site was derived from a series of spirit-level surveys over bench marks A1053 and LS–8. (For locations of bench marks, see fig. 16.) The California Department of Water Resources surveyed the bench marks annually from 1960 through 1965 and the U.S. Coast and Geodetic Survey leveled through the area in 1960, 1964, and twice in early 1965.

The results of these surveys are plotted in figure 16, which shows the progressive subsidence of LS–8 with respect to A1053. LS–8, which is about 1,380 feet north of A1053, subsided at a nearly uniform rate (with respect to A1053) from 1960 through mid-1963, and at a somewhat reduced rate from mid-1963 through mid-1965. The northward tilting averaged 104 microradians per year (about 0.01 ft per 100 ft per yr) during the first period and 67 microradians per year during the second period. The average rate of northward tilt between April 1960 and August 1965 was about 90 microradians per year. No later data are usable because during September 1965, bench mark LS–8 was radically affected by hydrocompaction that was caused by the flooding of adjacent preconsolidation ponds.

Bench mark LS–8 was less than 40 feet from the edge of a field that was irrigated during the latter part of the 1950's and as recently as 1962. Therefore, the possibility of bench-mark subsidence due to near-surface hydrocompaction during this period must be considered in evaluating its history. For this purpose, the differential elevation changes of bench mark B1053 with respect to A1053 are also shown in figure 16. Bench mark B1053 was 1.0 mile due west of LS–8 in a comparable geologic setting. The nearest irrigation was half a mile to the north and east, so hydrocompaction at this location can be ruled out. The subsidence history of LS–8 closely approximates that of B1053 and shows no significant departure correlating with cessation of nearby irrigation in 1962. This fact indicates that local hydrocompaction did not affect LS–8 during the period shown.

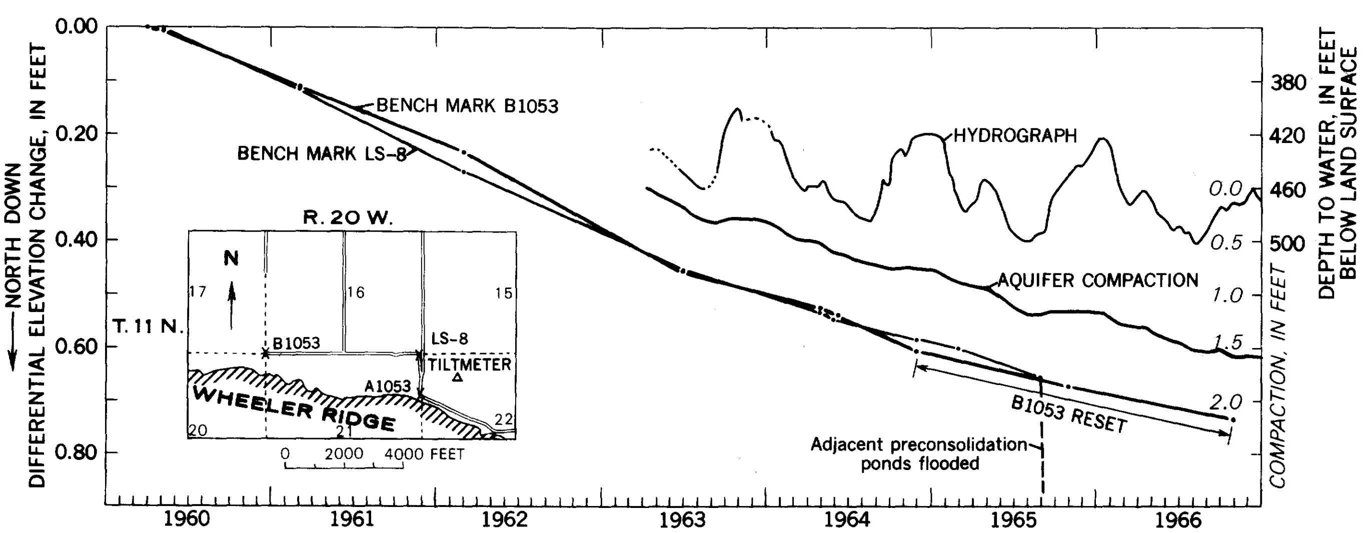

FIGURE 16.—Subsidence of bench marks LS–8 and B1053 with respect to bench mark A1053.

Data from the Lakeview test well (11N/21W–3B1), also plotted in figure 16, show continuing compaction of the confined aquifer system during the period of record (1963 through 1966). Although the compaction rate fluctuated in response to seasonal changes in head in the aquifer, the overall rate was approximately uniform, as was the subsidence rate of LS–8 and B1053 during this period.

In the light of the facts just presented, the tiltmeter data, and the detailed leveling data discussed in subsequent paragraphs, it is believed that the 1960–65 subsidence history of bench mark LS–8 is a reliable record of the effects of aquifer compaction at a point one-quarter mile northwest of the pumping-plant site.

For the period 1963–65, the due northward tilting near the pumping-plant site, as indicated by the subsidence of bench mark LS–8 relative to A1053, is approximately defined by the empirical relationship

$$T = 1.4C \times 10^2$$

where T is the angular tilt expressed in microradians and C is the compaction of the aquifer system, in feet, measured at the Lakeview test well.

During August 1965, after the seasonal character of the tilting had been demonstrated by the GS–I tiltmeter, the Department of Water Resources installed a special array of paired bench marks near the pumping-plant site (fig. *A* on pl. 1). Each pair consisted of a standard bench mark (brass cap in concrete pier) and an adjacent "deep-seated" pier of 1½-inch pipe set about 15 feet into the ground. Ten pairs were set along the aqueduct centerline between preconsolidation ponds 8–17 and 8–9. Twelve pairs were established along a line approximately normal to the aqueduct between preexisting bench marks A1053 and WR–18. The two lines intersected 380 feet northwest of the tiltmeter station.

On August 30, 1965, a crew from the Department of Water Resources leveled over the bench marks for the first time, using high-precision equipment and techniques. Subsequent releveling was done on October 6 and December 15, 1965, and on April 15, June 14, and September 13, 1966. The results of this work are presented on plate 1 in figures *B* and *C* as a series of tilt profiles, showing the changes in elevation of the deep-seated bench marks for each successive survey. The August 30, 1965, elevations were taken as the datum, and each profile represents the changes in elevations that have occurred since that date. All elevations are relative to bench mark A1053, which was the starting point of the surveys and was arbitrarily considered to be stable.

The profiles show very clearly both the regional northward tilting due to deep-seated aquifer compaction during the winter and summer irrigation seasons and the highly localized effects of hydrocompaction around ponds 8–17 and 8–9. There is also a small but well-defined northeastward tilting during the fall, comparable to that recorded by line 2 of the GS–II tiltmeter.

The resolution of apparent tilts along the two profiles into true tilts is shown by the vector diagram (fig. *D* on pl. 1) in which the lengths of the vectors are proportional to the angles of tilt in microradians. The vector for the period August 30–December 15, 1965, is based upon the estimated average slopes of the entire profiles. Vectors for subsequent intervals are based on bench marks A1053, 1016A, 1007A, and 1009A, which apparently are unaffected by hydrocompaction. The vectors should be regarded as approximate, because in some cases leveling errors of only 0.001 foot would produce large changes in their direction and length. For example, a total leveling error of 0.001 foot between bench marks A1053 and 1016A, 900 feet apart, would produce an angular error of 1.1 microradians. The same leveling error between 1007A and 1009A, 300 feet apart, would result in an angular error of 3.3 microradians.

It is evident from the vector diagram that between August 30, 1965, and September 13, 1966, the tilt history of the pumping-plant location (outside of hydrocompaction areas) was dominated by two major episodes of northward tilt, corresponding approximately to the winter and summer irrigation seasons. Between December 15, 1965, and April 15, 1966, the tilt was 21 microradians in the direction N. 2° E.; and between June 14 and September 13, 1966, the tilt was 15 microradians in the direction N. 9° W. The minor north-northwestward tilting (3 microradians) during the spring of 1966 is poorly controlled because of the small elevation change and short profile available and must be considered very approximate. The modest northeastward tilting (4.5 microradians) during the fall of 1965 is, on the other hand, well controlled by the long profile and probably is significant. As previously noted in the discussion of the tiltmeter data, this type of tilting may be of tectonic origin.

The total tilt from August 30, 1965, to September 13, 1966, as found by the addition of the vectors in figure *D* on plate 1, is 42 microradians in the direction N. 1° E.

The relative coarseness of the leveling data and the distances between the bench-mark grid and the tiltmeters preclude detailed comparisons between the two kinds of information. Nevertheless, a question naturally arises as to why northeasterly tilt on line 2 of GS–II was only 2 microradians during the winter irrigation period (December 15, 1965, to April 15, 1966), while tilting along profile *A–A′* between bench marks A1053 and 1016A was 14 microradians. No definitive explanation can be given for this seeming anomaly. However, examination of figures *B* and *C* on plate 1 demonstrates that a considerable degree of irregularity is characteristic of the tilt profiles. Some of the irregularity presumably is due to minor leveling errors, but substantial changes in slope, greater than the probable range of error, occur from place to place along the profiles. For example, between December 15, 1965, and April 15, 1966, the average tilt of the 2,020-foot profile segment between bench marks 1016A and 1022A, which includes the segment directly downslope from the tiltmeters, was only 3 microradians northeastward, while the segment A1053–1016A tilted 14 microradians, as noted above. Thus, the local irregularities in the leveling profiles and the rapid decrease in tilt with distance from the base of Wheeler Ridge indicate that small tilts measured over relatively short distances cannot be confidently extrapolated very far from the point of actual measurement.

SUMMARY

Two continuous-recording liquid-level tiltmeters were operated at land surface on the site of the future Wheeler Ridge pumping plant of the California Aqueduct. The location, at the southern end of the San Joaquin Valley, is at the margin of a large bowl of active land subsidence caused by compaction of the confined aquifer system under the stress of artesian-head decline; the site is also subject to subsidence due to hydrocompaction of moisture-deficient alluvial-fan deposits.

The first tiltmeter, designated GS–I, began recording in May 1965. Between mid-June and the end of August 1965, the GS–I tiltmeter recorded 46 microradians of valleyward tilting (0.0046 ft of differential elevation change between bases 100 ft apart). Between the end of April and the end of July, the Lakeview test-well installation recorded 47 feet of artesian-head decline and 0.25 foot of compaction in the artesian aquifer system. If a 6-week time lag is allowed for pumping effects to migrate laterally through the aquifer system, there is a very good apparent correlation between the record of the tiltmeter and the curves of head decline and aquifer compaction.

The GS–I tiltmeter, mounted on thin concrete pads, is known to have been sensitive to changes in soil moisture and soil temperature, but the large summertime deflection of the tilt record does not correlate with any major change in these factors, nor does it correlate with flooding of infiltration ponds, construction activity, or any other known phenomenon except artesian-head decline. Known major changes in soil moisture and temperature during the fall and winter produced much smaller deflections of the tilt record. Therefore, it is concluded that most, if not all, of the northwestward tilting recorded during the summer of 1965 is most reasonably attributable to differential aquifer-system compaction due to seasonal decline of artesian head.

Although the one-directional GS–I tiltmeter measured only the N. 35° W. component of tilting and almost certainly did not record the full magnitude of valleyward tilt, the 46 microradians of tilt recorded during the summer pumping season constitutes about half the average annual tilt that had been postulated on the basis of repeated spirit leveling between nearby bench marks during the period 1960–65. It is reasonable to expect that a roughly comparable amount of tilt would have been recorded during the other yearly pumping period, the pre-irrigation season of late winter and early spring, had the tiltmeter been in operation at that time.

The second tiltmeter, a two-directional instrument designated GS–II, began recording in October 1965, after the end of the summer pumping season. During the fall and early winter, it demonstrated that the site was essentially stable when artesian head was not being drawn down by pumping. The only significant long-term movement recorded during this period was a very slow background tilting of about 5 microradians per year in a direction about N. 55° E. This tilt may be of tectonic origin. The GS–II tiltmeter, mounted on piers set 9 feet deep, was relatively insensitive to changes in surficial soil conditions. The short-term irregularities in the tilt records may be largely attributable to differential responses of the subsurface materials to changes in atmospheric loading.

The three compaction sensors linked to the GS–II tiltmeter proved to be rather sensitive to temperature changes in the instrument piers. Nevertheless, the effects of hydrocompaction resulting from infiltration of water beneath preconsolidation pond 8–17 are clearly discernible in the records of the southeastern and northern compaction sensors. As far as can be determined, the major long-term fluctuations in the southwestern compaction record were due almost entirely to changes in temperature.

The southeastern compaction sensor recorded about 1,500 microns of hydrocompaction within the upper 150 feet of deposits. Comparison of the compaction and tilt records indicates that at least 2,700 microns of hydrocompaction occurred beneath the southeastern trivet and that at least 44 percent of the total hydrocompaction occurred below a depth of 150 feet. The amount of subsidence due to hydrocompaction beneath the pumping-plant site was too small (2.7 mm) to be, in itself, of practical engineering significance. It should be noted, however, that the site was at the extreme fringe of the moisture front surrounding infiltration pond 8–17 and that the percentage of moistened deposits beneath the pumping plant was probably very small. In view of the apparent susceptibility to hydrocompaction of the deposits below 150 feet, the possibility of substantial subsidence beneath the pumping plant, in the event of thorough wetting, cannot be ruled out.

The northern compaction sensor recorded about 300 microns of hydrocompaction between the northern trivet and the subsurface bench mark at 150 feet, while the tiltmeter was measuring 500 microns of northeastward tilt. Because of the evidence that hydrocompaction may occur at depths greater than 150 feet, it is impossible to determine from the tilt and compaction data how much of the 200 microns of northeastward tilting that must be accounted for beneath the subsur-

face bench mark is due to hydrocompaction and how much is due to deep-seated compaction of the artesian aquifer system.

Discrepancies among the tilt, compaction, and leveling data indicate that the irregular, prolonged, and unpredictable process of hydrocompaction increasingly influenced the data obtained at the site after December 21, 1965, and, by late April 1966, dominated the records from all instruments except the southwestern compaction sensor. As soon as hydrocompaction beneath the subsurface bench marks is indicated in the records, it becomes impossible to determine whether a given feature in the tilt record is attributable to hydrocompaction below the bench marks, mass loading, differential aquifer compaction, or tectonic movement. Furthermore, compaction in equal amounts beneath the subsurface bench marks at both ends of the tiltmeter line completely escapes detection by both the compaction sensors and the tiltmeter. For these reasons, the northward tilting recorded by the GS–I and GS–II tiltmeters during June and July 1966 cannot be definitely and quantitatively related to the summer head decline, although the effect of aquifer compaction is clearly demonstrated by the northward tilting of the bench-mark profiles outside the areas of hydrocompaction. For the same reasons, no firm interpretation can be made of the irregular southeastward tilting recorded during August and September 1966.

CONCLUSIONS

Interpretation of the mutually supporting data from the Lakeview test well and from the tiltmeters, compaction sensors, and spirit leveling at the Wheeler Ridge pumping-plant site leads to the following principal conclusions:

1. In the valley areas north of Wheeler Ridge, decline of artesian head during the winter and summer irrigation seasons causes two pulses per year of aquifer compaction, resulting in substantial annual land subsidence.
2. The cone of artesian-head decline evidently encounters a partial ground-water barrier and probably less compressible deposits as it expands seasonally into the steeply north-dipping strata on the flank of the Wheeler Ridge anticline. The resulting steep hydraulic (and compressibility?) gradients generate a narrow band of fairly intense differential subsidence, or tilt, along the north base of Wheeler Ridge, in the area of the pumping-plant site.
3. Tiltmeter data recorded during one episode of artesian-head decline in the summer of 1965 support the estimate based on repeated spirit-level surveys between 1960 and 1965 that as much as 100 microradians (0.01 ft per 100 ft) of northward tilting occurs annually. From August 1965 to September 1966, however, data from spirit leveling indicated only 42 microradians of northward tilt.
4. The tiltmeter data and the leveling indicate that nearly all the tilting is due to differential compaction of the artesian-aquifer system under the stress of seasonal pumping.
5. There is inconclusive evidence from both the tiltmeter and the leveling data that 5–10 percent of the observed northward tilting may be due to some other cause, possibly tectonic.
6. Pleistocene and Holocene alluvial-fan deposits beneath the pumping-plant site apparently are subject to at least a limited degree of hydrocompaction (collapse on wetting) to depths appreciably greater than 150 feet.
7. Hydrocompaction may proceed in a highly irregular manner as water moves downward and outward from the infiltration ponds through the heterogeneous alluvial-fan deposits.
8. The resulting bowl of local subsidence continues to expand for months after infiltration at the surface has ceased.

REFERENCES CITED

Bonchkovsky, V. F., and Skur'yat, A. N., 1961, The level variometer LV: Akad. Nauk SSSR, Izv. Geofiz. Ser., p. 79–90.

Bull, W. B., 1961, Causes and mechanics of near-surface subsidence in western Fresno County, California, *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–B, p. B187–B189.

Dibblee, T. W., 1954, Geology of the southeastern margin of the San Joaquin Valley, California, *in* Earthquakes in Kern County, California, during 1952: California Div. Mines Bull. 171, p. 23–34.

Eaton, J. P., 1959, A portable water-tube tiltmeter: Seismol. Soc. America Bull., v. 49, no. 4, p. 301–316.

Egedal, J., and Fjeldstad, J. E., 1937, Observations of tidal motions of the earth's crust made at the Geophysical Institute. Bergen: Geofys. Publikasjoner, v. 11, no. 14.

Hagiwara, T., 1947, Observations of changes in the inclination of the Earth's surface at Mt. Tsukuba: Earthquake Research Inst. Bull., Tokyo [Japan] Univ., v. 25, pts. 1–4, p. 27–32.

Lofgren, B. E., 1963, Land subsidence in the Arvin-Maricopa area, California, *in* Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 475–B, p. B171–B175.

Michelson, A. A., 1914, Preliminary results of measurements of the rigidity of the earth: Astrophys. Jour., v. 39, no. 2.

Michelson, A. A., and Gale, H. G., 1919, The rigidity of the Earth: Astrophys. Jour., v. 50, p. 330–345.

Riley, F. S., 1962, An automatic recording liquid-level tiltmeter [abs.]: Am. Geophys. Union Trans., v. 43, no. 4, p. 427.

——— 1966, Progress report on the U.S. Geological Survey tiltmeter station near Wheeler Ridge, California: U.S. Geol. Survey open-file report, 23 p., 7 figs.

Riley, F. S., and Davis, S. N., 1960, A tiltmeter to measure surface subsidence around a pumping artesian well [abs.]: Jour. Geophys. Research, v. 65, no. 5, p. 1637.

U. S. GOVERNMENT PRINTING OFFICE : 1970 O - 373-386