Subsurface Temperatures and Moisture Contents In Six New Jersey Soils, 1954-1955

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● SUBSURFACE temperatures and moisture contents were measured in six New Jersey soils subjected to natural freeze-thaw conditions during the winter of 1954-1955. These soils, compacted in 9-foot square by 2-foot deep pits, were among a group of 30 soils being used for frost heave and bearing capacity loss studies at the Joint Highway Research Project, Rutgers University. For this purpose a 4-foot square by 6-inch thick concrete slab was poured on each soil. In the six soils considered in this report temperatures and moisture contents were measured daily at selected intervals of depth beneath the centers of the concrete slabs and beneath the soil shoulders at the edge of the slabs. Air temperature, ground-water temperature, ground-water elevation, and the relative vertical displacement of the concrete slabs resulting from frost heave were also measured. This report presents an analysis of the data obtained.

SOILS

The six soils used for the temperature and moisture study were selected from the available soils to represent a range of HRB classification groups, and, for convenience in instrumentation, to present a compact grouping in their existing positions at the field installation at Rutgers University. The soils, listed according to their assigned sample numbers, may be described thus: F-5 a sandy silt-clay mixture, derived from old glacial lake bed sediments; F-10 a mixture of coarse, medium and fine sands containing considerable gravel and some silt and clay—derived from gneissic glacial materials which have been reworked by water; F-13 a sandy gravel with considerable silt and clay, derived from basalt and diabase (gravel size is large; fragments are angular); F-15 a silt-clay mixture, derived primarily from underlying Triassic argillite; F-17 a mixture of coarse, medium and fine sands, derived from Coastal Plain sediments; F-24 a well-graded mixture of gravel, sands, silt and clay, derived from till containing much limestone.

A representative fraction of each sample was tested in the Soil Mechanics Laboratory for the determination of engineering properties. These are presented in Table 1. Grain size distribution curves are shown in Figure 1.

Several years previously the soils had been placed in the 9-foot square by 2-foot deep pits at the field installation. They were originally compacted in 6-inch layers by means of an air hammer. Recompaction of the soil surface developed field densities shown in Table 2. Measurement was by the sand cone method.

INSTRUMENTATION

For the measurement of subsurface soil temperatures and moisture contents the Fiberglas Soil-Moisture Instrument was selected (1, 2). This instrument, developed by E. A. Coleman at the California Forest and Range Experiment Station, consists of two basic parts: soil moisture units which are placed in the soil being studied and a meter unit used to measure the electrical resistance of the soil moisture units. The instrument was supplied by the Berkeley Division of Beckman Instruments, Inc.

Soil Moisture Unit

A fiberglas soil-moisture unit consists of two monel screen electrodes separated by and encased in a wrapping of fiberglas fabric. This electrode "sandwich" is mounted within a rigid monel case which is perforated to allow contact between the fiberglas and the soil. A Western Electric 7A thermistor is also enclosed in the case. Details of the

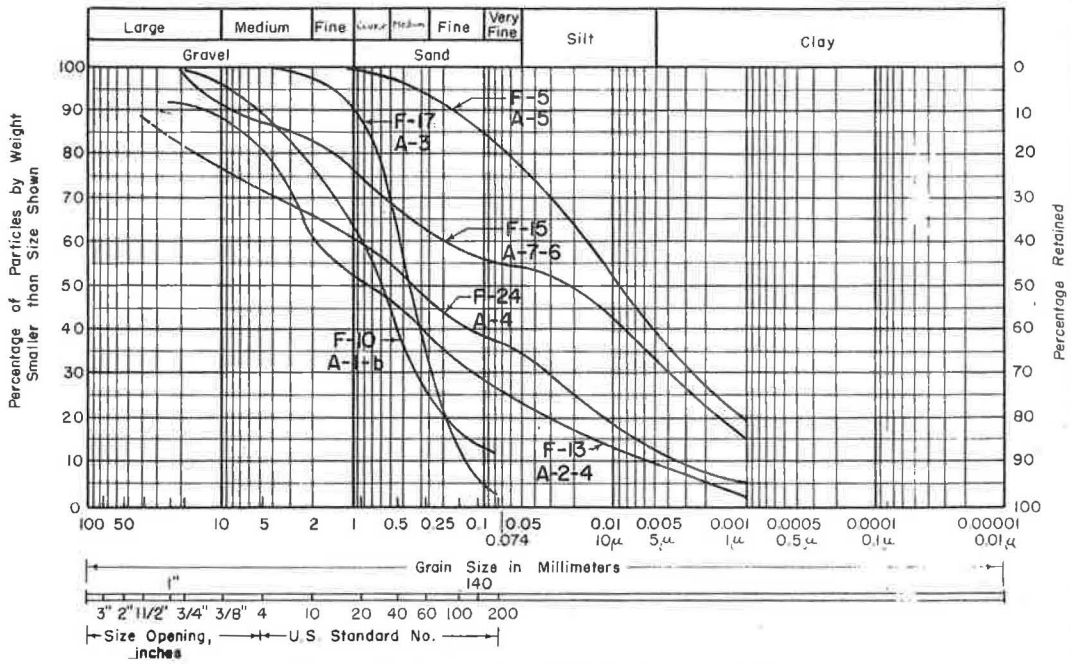

Figure 1. Grain size distribution curves.

soil moisture unit are shown in Figure 2.

When the unit is placed in soil the fiberglas readily absorbs or gives up moisture, so as to remain in a constant equilibrium of moisture content with the soil. The electrical resistance between the electrodes varies with the moisture content of the fiberglas. Thu after proper calibration the measured electrical resistance of the soil moisture unit indicates the moisture content of the soil in which it is placed. The resistance of the unit is also dependent upon temperature, hence the inclusion of a thermistor so that temperature can be measured and a proper correction applied to the indicated resistance.

Meter Unit

The instrument used for measuring soil moisture unit resistance is a self-powered alternating current ohmmeter. Alternating current of 90 cps is generated in the vacuum tube circuit of the instrument, passed through the soil moisture unit or thermistor and rectified for indication on a d-c microammeter.

Selection of Unit Spacing

As a result of previous subsurface temperature measurements in the six soils used for this study, underground cables and junction boxes were already in place at the field

TABLE 1

ENGINEERING SOIL PROPERTIES

Sample No.	Agronomic Name (as mapped 1917-27)	Soil Test Results: Sieve Analysis Percent Passing					Hyd Anal: Silt Sizes	Hyd Anal: Clay Sizes	Atterberg Test: LL	Atterberg Test: PI	Proctor: Max Dens	Proctor: Opt MC	Uniform Coef D_{60}/D_{10}	Eff Grain Size	HRB Classification: Sub-grade Group	HRB Classification: Group Index
		¾	4	10	40	200	%	%	%	%	pcf	%				
F-5	Whippany	100	100	100	98	83	43	37	41	7	100	22	50.0	--	A-5	8
F-10	Merrimac	100	90	77	41	11	--	--	NL	NP	125	9	11.4	.07	A-1-b	0
F-13	Montalto	91	80	58	46	28	9	19	32	9	114	17	360.0	.03	A-2-4	0
F-15	Lansdale	99	87	85	69	55	21	32	41	15	95	26	283.3	--	A-7-6	6
F-17	Lakewood	100	99	98	64	3	--	--	NL	NP	106	14	2.8	.15	A-3	0
F-24	Dover	82	72	66	54	37	20	14	31	9	112	16	400.0	.0025	A-4	0

installation. This equipment provided electrical circuits sufficient for placing 13 soil moisture units in each of the soils. Selected spacing of the units was at depths of 6, 10, 14, 18, 23 and 29 inches beneath the completed top surface of the concrete slab, and at depths of 2, 6, 14, 18, 23 and 29 inches beneath the soil shoulder which is flushed with the slab surface.

TABLE 2

FIELD DENSITIES

Soil No.	Dry Density	Percent of Proctor Density
	pcf	
F-5	98.8	98.8
F-10	111.9	89.6
F-13	101.2	88.9
F-15	88.9	93.5
F-17	104.0	98.2
F-24	104.3	93.3

Calibration

Thermistor resistance varies with temperature. The resistance of each thermistor falls within ± 10 percent of a standard resistance-temperature curve (Figure 3). Thermistor calibration is accomplished by measuring resistance at a known temperature. A thermistor coefficient is determined by dividing the standard resistance at this temperature by the measured resistance. When performing temperature measurements with a thermistor the measured resistance is multiplied by the coefficient and the corrected resistance referred to the standard curve for temperature determination. For convenience, a table was prepared showing the range of standard thermistor resistance for each 0.1 deg F. Soil moisture units were supplied with calibrated thermistors, the coefficients being engraved on the cases by the manufacturer.

As the electrode "sandwich" of the soil moisture unit is not standardized, it was necessary to calibrate each unit in the soil in which it was to be placed.

The laboratory method of calibration suggested by the manufacturer was followed with several modifications (2). Briefly, this method consists of packing each soil moisture unit with a small amount of its respective soil into a small container. The soil was saturated and dried slowly at room temperature, its moisture content being determined at intervals by weighing. Measurement of soil moisture unit resistance at respective intervals provided a calibration curve.

The manufacturer's instructions suggest several drying cycles before calibration and several during calibration. As anticipated, each drying cycle proved to be a lengthy process. As this study was dependent upon natural climatic conditions, the time available for calibration of the soil moisture units before installation in the field was limited. It was thus possible to perform only two drying cycles, both of which were used for calibration.

Calibration Details

Seventy-eight calibration boxes were made to allow simultaneous calibration of all soil units. Monel was used for resistance to corrosion and ease of fabrication. Details of a calibration box are shown in Figure 4. Each soil moisture unit and its calibration box were assigned code numbers and their weights recorded. Thirteen units were assigned to each soil.

Samples of each soil were prepared for calibration by removing all material retained on the No. 10 sieve and oven-drying. A small specimen of each soil was mixed with water to achieve respective optimum moisture content. Each specimen was then compacted in an empty calibration box by tamping with the end of a short length of

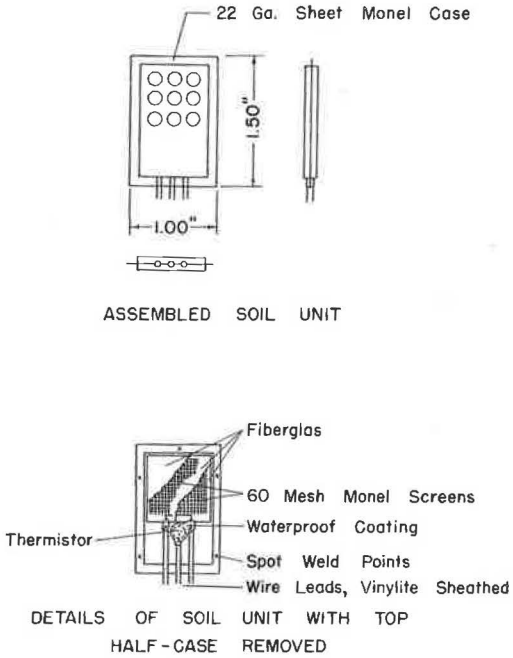

Figure 2. Fiberglas soil moisture unit.

½-in. square rod. To prevent distortion of the screened sides, the box was supported between the upright legs of pieces of 2- by 2-in. angle clamped to a steel plate. Densit determination of the compacted specimens showed that reasonable approximations of Proctor density could be achieved by this means of compaction.

The preparation of each soil moisture unit for calibration was achieved as follows: A 150-g specimen of the required soil was mixed thoroughly with sufficient water to bring it to optimum moisture content. The soil moisture unit was placed vertically in its respective calibration box, the wires at the top, and the soil compacted around it. The box was filled to within ¼ in. of its top. The remainder of the soil specimen was then oven-dried and weighed. Subtracting this weight from 150 g gave the weight of dry soil in the calibration box.

Six humidity chambers were prepared for the calibration process. Clear plastic cal covers 11 inches in diameter by 5 inches high were placed on plywood bases. Slots wer provided in the bases to allow passage of the soil moisture unit wires. In order to mai tain high humidity, a jar containing a wick and filled with a saturated solution of lead nitrate, $Pb(NO_3)_2$, was placed in each chamber.

Upon completion of preparation of the soil moisture units in the calibration boxes they were placed in shallow pans and sufficient distilled water added to cover the soil surface. After saturating overnight the boxes were allowed to drain briefly and placed in the humidity chambers for a 48-hour period. The covers of the chambers were then removed for a five-hour period to allow for evaporation of soil moisture. The covers were then replaced. At the end of a 19-hour period the electrical resistances of each soil moisture unit and thermistor were measured and the boxes removed from the humidity chambers and weighed. The calibration cycle of five hours' evaporation and 19 hours in the humidity chamber was continued until the soils no longer showed loss of moisture. This cycle was described by Kelley (3). His experiments show that for mos soils a 19-hour period in the humidity chamber is sufficient to allow the moisture content throughout the soil specimen to reach an equilibrium. The average moisture con-

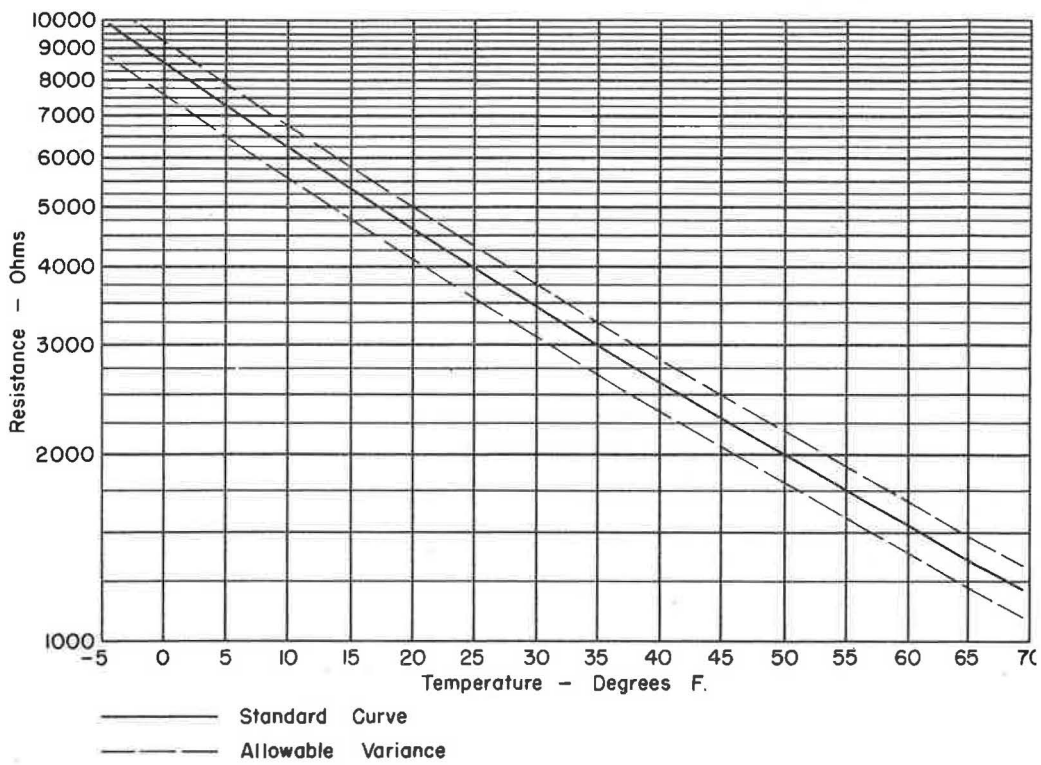

Figure 3. Temperature-resistance curve for 7-A and 17-A thermistors.

tent of the specimen determined by weighing is essentially the same as that of the soil at the center of the specimen in contact with the soil moisture unit.

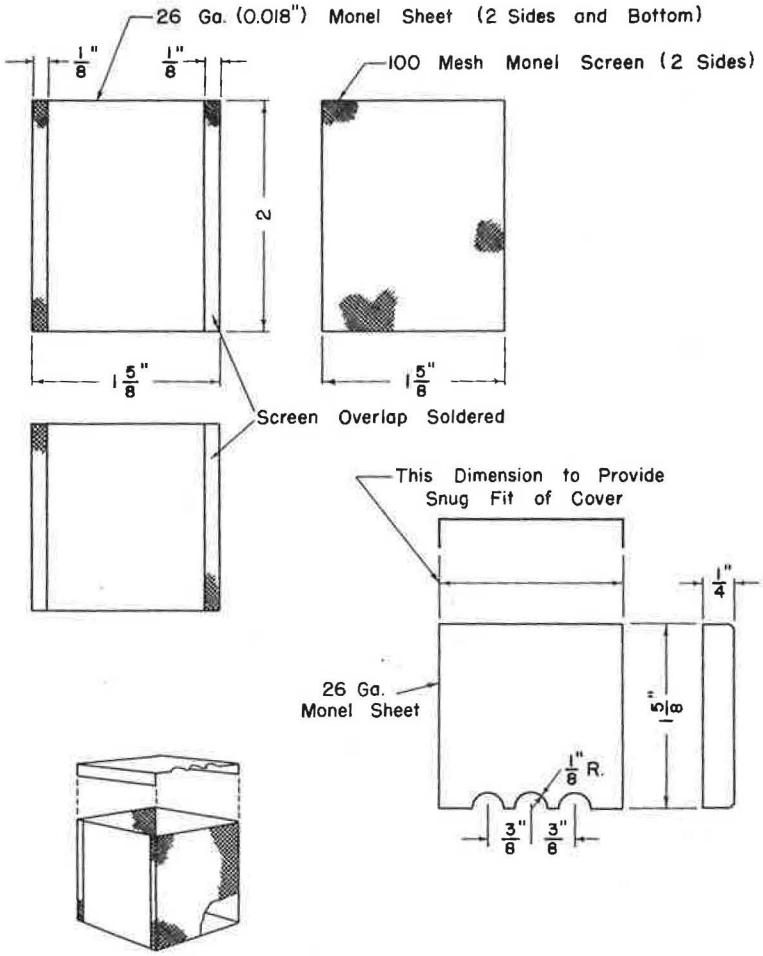

Figure 4. Calibration box for soil moisture unit.

Soil temperature was calculated from thermistor resistance and soil moisture unit resistance corrected to 60 deg F by means of a chart furnished by the manufacturer.

Weighing during each calibration interval determines the total amount of water in both the soil specimen and the soil moisture unit. The water within the soil moisture unit does not contribute to the moisture content of the soil specimen. Hence, the weight of this water must be determined and subtracted from the total in order to determine the moisture content of the soil specimen.

Calibration to determine the relationship between soil moisture unit resistance and the weight of water in the unit was performed on five units. The units were saturated with distilled water and left exposed for evaporation. Resistance and weight were determined at one-hour intervals. Resistance was corrected to 60 deg F. A plot of resistance vs. water in unit for each of the five soil moisture units indicated that the characteristics of the units were sufficiently similar to allow the use of an average curve based on these five units for the purpose of determining the weight of water in each of the other 78 soil moisture units during calibration.

Though distilled water was also used in the calibration of the 78 soil moisture units it was felt that materials from the soils might be dissolved with varied effects upon the resistance of the units. Investigation of these effects proceeded as follows: A small

amount of one of the soils was stirred into distilled water and allowed to settle. The clear water containing any solutes from the soil was poured off and used to saturate the five soil moisture units. The calibration process was repeated. The average curve of resistance vs water in moisture unit which resulted was decidedly different from that produced by the use of distilled water alone, resistance values being relatively lower.

The five soil moisture units were then washed thoroughly by flushing with distilled water to remove the soil solutes. The process was then repeated, using solutions from the remaining soils. An average calibration curve of soil moisture unit resistance vs weight of water in the soil moisture unit was then produced for each of the six soils. An example is shown in Figure 5.

During the calibration of the 78 soil moisture units these average curves were used in calculating the weight of water within each soil specimen for the purpose of moisture content determination. As previously mentioned, two drying cycles were performed.

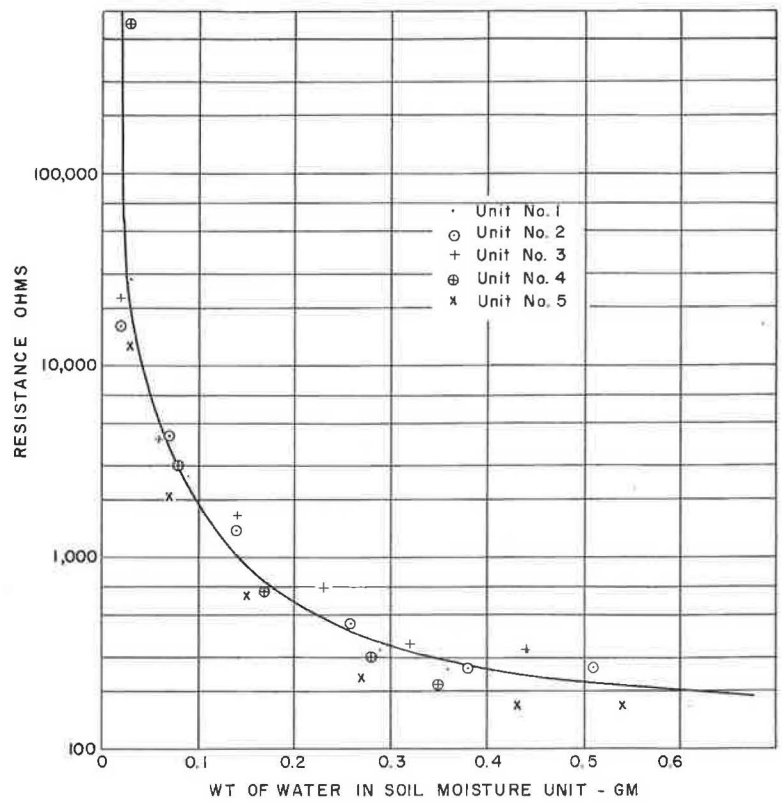

Figure 5. Relationship between soil moisture unit resistance and weight of water in unit. Resistance corrected to 60 deg. Units saturated with a solution of soil F-15.

Plots of resistance vs moisture content for each of the soil moisture units showed rathe close correlation between the points determined during each cycle. Similarity was note among the 13 curves developed for each soil. Considerable contrast was apparent, how ever, when the curves of each soil were compared with those of the others. Examples of calibration curves are shown in Figures 6 and 7.

Thermistor Calibration

Sensitivity of the a-c ohmmeter when measuring thermistor resistance was not sufficient to allow temperature determination to the desired accuracy of 0.1 deg F. During previous subsurface temperature studies a d-c Wheatstone bridge was found satisfactor

for thermistor resistance measurement. The soil moisture unit thermistors were recalibrated with this instrument. The units were immersed in circulating ice water at 32.0 deg F and their thermistor resistances measured. The resulting thermistor coefficients were thus determined to a greater accuracy than those supplied by the manufacturer, using the a-c ohmmeter.

Thermistor Preparation

Measurement of moisture content at the surface of the soil shoulders was considered impractical. To allow soil temperature measurement along at these points Western Electric 17-A thermistors were used. Their characteristics are similar to those of the 7-A thermistors, the same standard curve and method of calibration being applicable. The 17-A thermistors were prepared for field use as shown in Figure 8, a method which proved satisfactory in previous subsurface temperature studies.

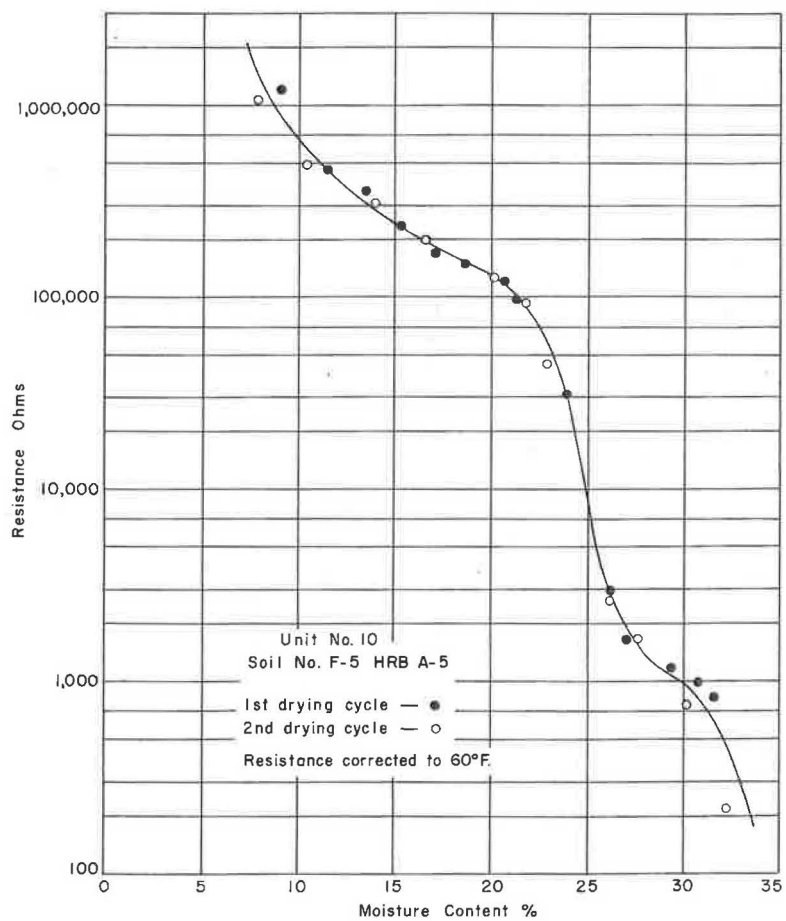

Figure 6. Soil moisture unit calibration curve.

Three groups of 17-A thermistors were also prepared for use in soil F-10. Two groups were intended for installation beneath the concrete slab and one beneath the soil shoulder at depths corresponding with the soil moisture units. These groups of thermistors and soil moisture units were all arranged in a single vertical plane for the purpose of determining the profile of frost penetration beneath the shoulder and slab.

INSTALLATION OF SOIL MOISTURE UNITS AND THERMISTORS

The soil moisture units and thermistors were arranged in groups according to the

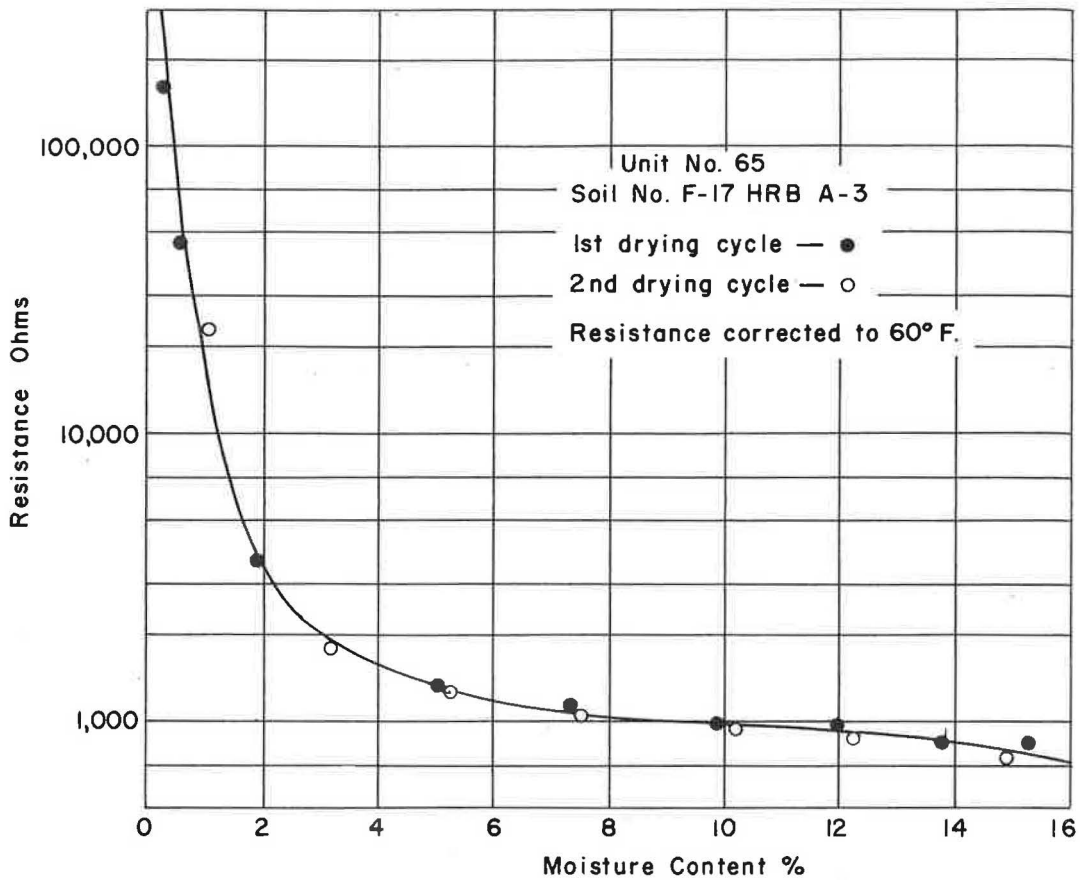

Figure 7. Soil moisture unit calibration curve.

soils in which they were calibrated. Their wire leads were cabled with nylon cord, the units being spaced according to their required depth of placement. The wire leads were lengthened where necessary to reach the existing junction boxes. All splices were carefully insulated with varnish and tape.

After leveling and compaction of the soils in the field, 8-inch diameter auger holes were placed at the proper positions for installation of the soil moisture units and thermistors. Shallow trenches were formed to carry the wire leads beneath the soil surface (Figure 9).

The prepared groups of soil moisture units and thermistors were then lowered into their respective holes and the soil replaced, each unit being carefully compacted in place at its respective depth. The wire leads were pulled into the junction boxes, the trenches filled and the soil surfaces smoothed. The soil moisture units and thermistors intended for installation in the top six inches of the soil shoulders were left exposed. Forms were set and the concrete slabs poured. Additional soil was then put in and compacted, building up the shoulders flush with the slab surfaces. The remaining soil moisture units and thermistors were placed at their respective depths. Completed soil installations are shown in Figures 10 and 11. After a two-day period to allow the soil moisture units to reach

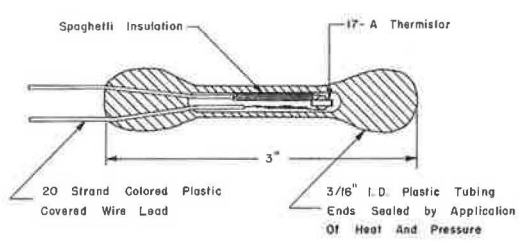

Figure 8. Section through a sealed thermistor unit.

equilibrium with the soil, measurements were started.

INSTRUMENTS

The instruments for measuring soil moisture unit and thermistor resistance were conveniently located in a small heated building. Permanent underground cables were used for the electrical circuits between the building and the soil installations (Figure 12). Within the building, circuits were connected to panel-mounted rotary selector switchs (Figure 13). By this means each soil moisture unit and thermistor could be connected in turn to its respective instrument. The resistances of the moisture elements of the soil moisture units were measured by means of the a-c ohmmeter. Resistances of all thermistors were measured with a Leeds and Northrup d-c Wheatstone bridge. For convenience in balancing the bridge a Brown Electronik Null Indicator was used. Power for this instrument and for lighting was supplied by a 600-watt gasoline generator set.

Figure 9. Groups of thermistors before installation in the soil.

CABLE RESISTANCE

The d-c resistances of all cable circuits were measured. The highest resistance determined for the longest cable, when added to the resistance of a thermistor, would change the temperature indication less than 0.1 deg F. Thus no correction was necessary.

When using the a-c ohmmeter for measuring soil moisture unit resistance, the apparent resistance of the cable resulting from the capacitance of the parallel wires must be considered. As suggested by the manufacturer, all cable circuits were opened at the junction boxes and their apparent resistances measured with the a-c ohmmeter. Six

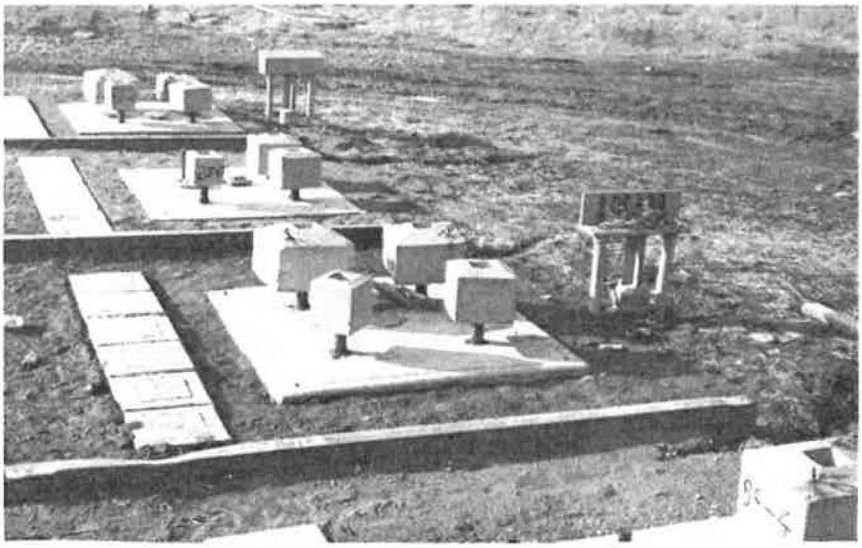

Figure 10. Completed soil installation.

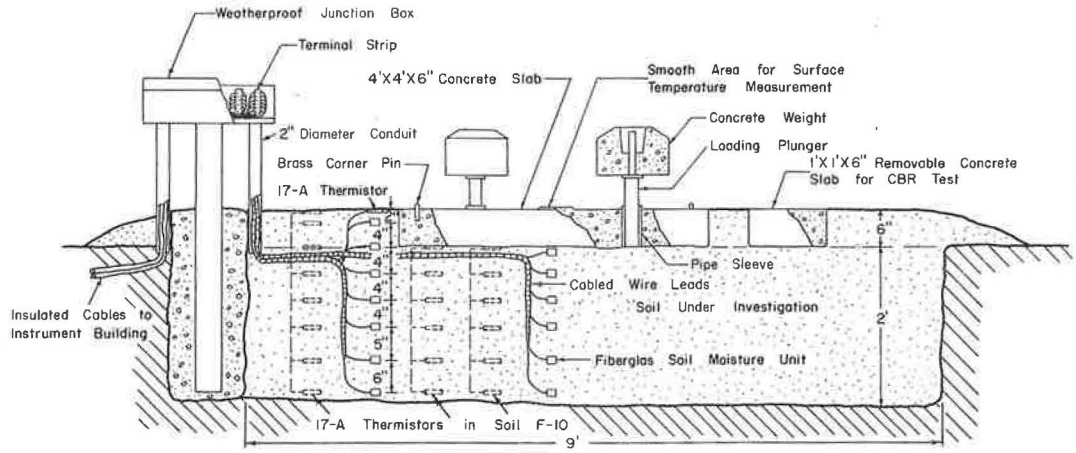

Figure 11. Soil installation equipped for subsurface soil temperature and moisture content determination.

correction curves were calculated to cover all circuits by means of the following expression (2):

$$\frac{1}{R(\text{soil unit})} = \frac{1}{R(\text{measured})} - \frac{1}{R(\text{cable})}$$

where R is resistance (Figure 14). The apparent resistance (reactance) of the cable is considered in parallel with the combined reactance and resistance of the soil moisture unit. Each measured soil moisture unit resistance was to be corrected by the use of

Figure 12. Preparation of soil installations. Wooden forms, completed slabs, installation of underground cables and the instrument building are shown.

the appropriate correction curve. During the period of winter study, however, it was found that all soil moisture resistances were so low, as a result of high soil moisture contents, that no corrections were necessary.

EQUIPMENT FOR OTHER DATA

Air Temperature

Maximum and minimum thermometers were mounted at elevations of 1 foot and 6 feet above the ground surface to determine daily air temperature range. A recording ther-

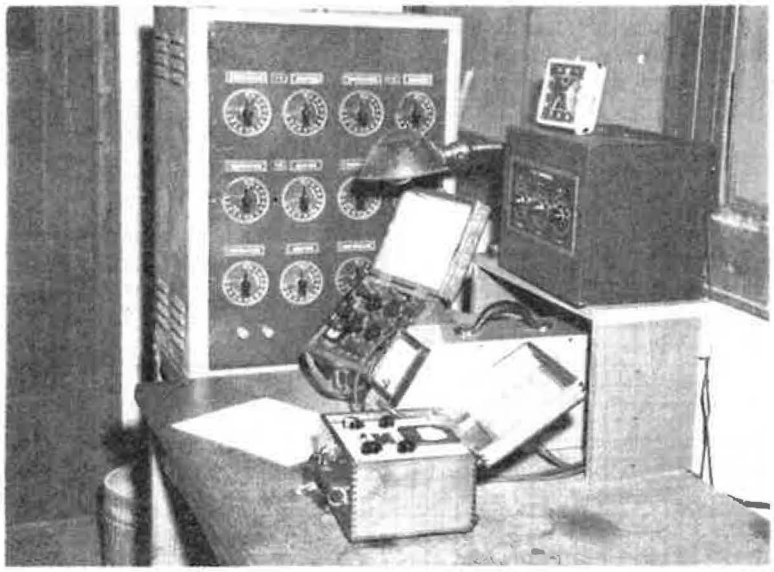

Figure 13. Instrument grouping for measuring subsurface soil temperatures and moisture contents.

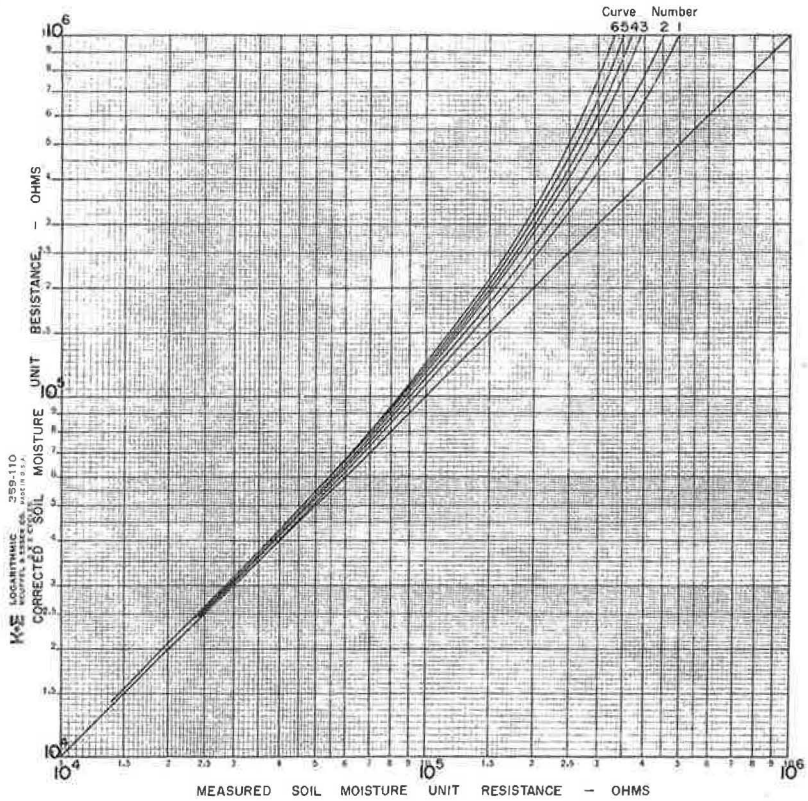

Figure 14. Correction curves for apparent cable resistance.

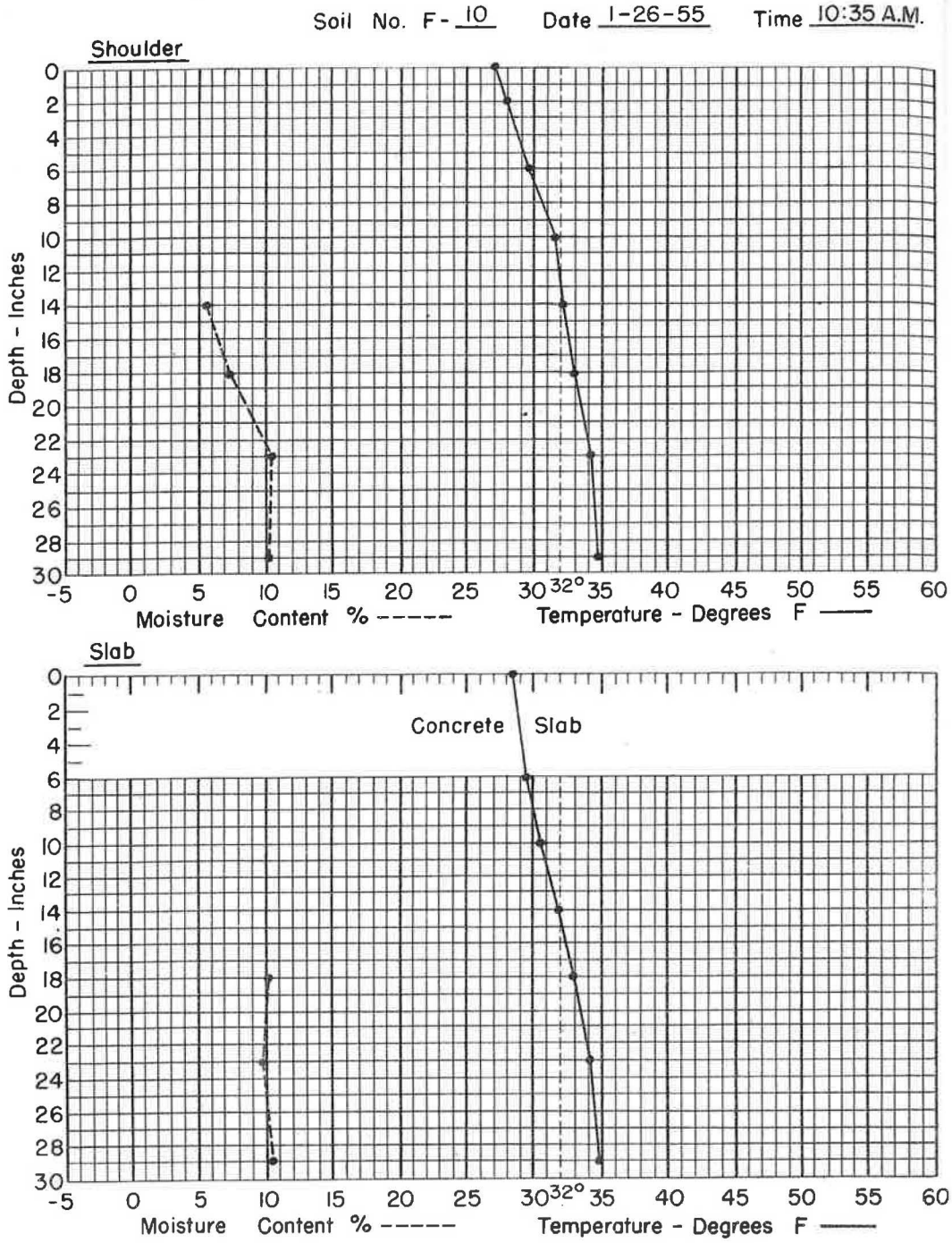

Figure 15. Subsurface soil temperature and moisture content.

mograph mounted at a 3-foot elevation was used to obtain a continuous record of air temperature.

Ground-Water Table

Three 20-foot deep wells were drilled at the field installation for the purpose of daily

determination of ground-water elevation and temperature. For protection and to afford a means of capping, the wells were lined with steel casing at the ground surface. Ground-water elevation was measured with a cloth tape and float. Each well was provided with a thermometer suspended 15 feet below the ground surface by a cord. The thermometers were drawn up for reading temperatures.

Soil Heave

The amount of soil heave upon freezing was indicated by fluctuations in elevation of the concrete slabs. Each slab was provided with brass pins at its corners for reference points in determining its elevation. Slab elevations were measured daily by means of a Lenker L. E. Vation rod and a Gurley Wye level permanently mounted within the instrument building.

METHODS OF OBSERVATION

Daily measurements of air temperature and ground water were started on December 1, 1954. After completion of the installation of the soil moisture units, thermistors and

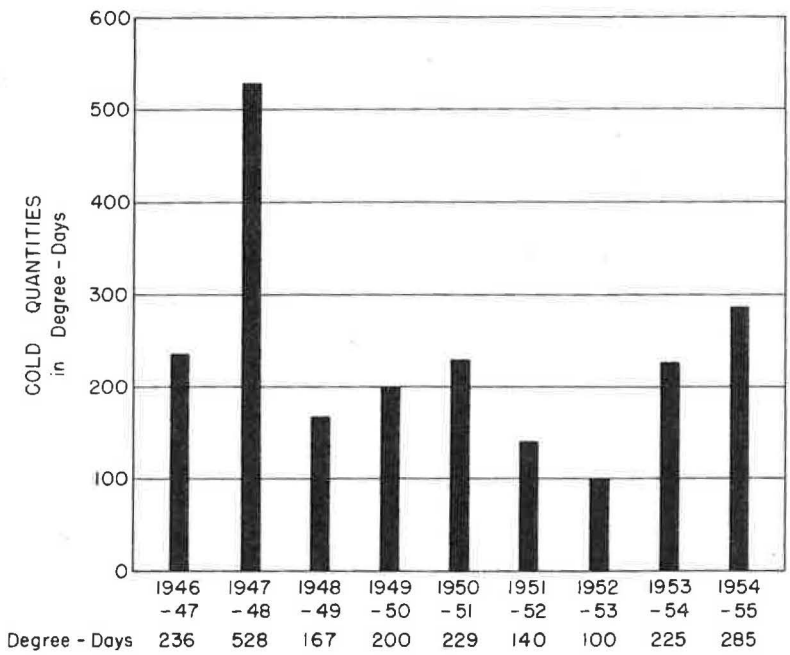

Figure 16. Cold quantities - New Brunswick Weather Station.

concrete slabs, daily subsurface temperature and moisture measurements and slab elevation measurements to the nearest 0.002 foot were started on December 28. Readings were made during the period from 9:00 to 11:00 a.m. each morning. All readings were continued until March 15, when frost activity had ceased. During the period of study the concrete slabs were cleared of snow when necessary to simulate highway conditions. Data were recorded on forms prepared for convenience in performing the calculations necessary for the determination of temperature, moisture content and relative soil heave.

ASSEMBLY OF DATA

Daily charts were prepared for each soil showing the relationship between soil depth, moisture content and temperature. An example is shown in Figure 15. From these

charts the daily depth of frost penetration beneath the slabs and shoulders was interpolated for each soil. For this purpose it was assumed that soil moisture freezes at 32 deg F and the depth of frost penetration coincides with the depth of the 32 deg isotherm.

For each of the six soils studied master charts were prepared for both the soil beneath the slab and the soil shoulder. These charts (Appendix A) show the relationship between time and the following factors:

Precipitation. Precipitation data, plotted as a bar graph, were obtained from the United States climatological data for the New Brunswick, N.J., weather station. The letter "s" above a bar in the precipitation graphs indicates snow.

Air Temperature Range. Maximum and minimum temperatures measured at the 1 foot elevation above the ground surface were used to determine daily air temperature range.

Slab Displacement. Daily slab displacements were plotted using initial slab elevations determined on December 29, 1954, as zero reference points.

Frost Penetration. The 32 deg isotherm was plotted as the depth of frost penetration, the cross-hatched area on the chart indicating frozen soil.

Soil Moisture Content. The soil moisture content indicated by each soil moisture unit was plotted as a separate curve. The discontinuity of these curves results from the soil moisture units freezing and becoming inoperative.

Depth of Ground-Water Table. Ground-water elevation data produced three curves showing respective depth to the ground-water table at the surface elevations of the three wells. These curves were interpolated where necessary to determine depth to ground-water curves for each soil, based on the respective elevation of the soil.

Ground-Water Temperature. The ground-water temperature curve was plotted from the average temperature determined in the three wells.

OBSERVATIONS

Climatic Conditions

A general evaluation, based upon temperature, of the severity of the winter of 1954-1955 was made by means of cold quantity determined by a degree-day method. To allow comparison with previous winters, U.S. Weather Bureau climatological data for the New Brunswick, N.J. weather station was used. The differences between the daily mean temperature and 32 deg F for the days that the mean was lower than 32 deg F was totaled for the period from September, 1954, to April, 1955. A cold quantity of 285 degree-days was obtained. By comparison, the winter of 1947-1948, a recent outstanding example

TABLE 3

MAJOR PERIOD OF FROST PENETRATION

Soil	Position	Date of Initial Frost Penetration	Date of Complete Thaw	Number of Days Frost Was in Soil
F-5	Slab	Jan 12	Feb 23	42
HRB A-5	Shoulder	Jan 7	Feb 26	50
F-10	Slab	Jan 7	Feb 21	45
HRB A-1-b	Shoulder	Jan 5	Feb 20	46
F-13	Slab	Jan 14	Feb 23	40
HRB A-2-4	Shoulder	Jan 8	Feb 28	51
F-15	Slab	Jan 15	Feb 26	42
HRB A-7-6	Shoulder	Jan 8	Feb 27	50
F-17	Slab	Jan 8	Feb 21	42
HRB A-3	Shoulder	Jan 7	Feb 20	44
F-24	Slab	Jan 14	Feb 26	43
HRB A-4	Shoulder	Jan 7	Feb 25	49

TABLE 4

MAXIMUM DEPTH OF FROST PENETRATION

Soil	Position	Max Depth of Frost Penetration		Date of Max Frost Penetration	
		Inches			
F-5	Slab	22		Feb 6	
HRB A-5	Shoulder		22		Feb 7
F-10	Slab	26		Feb 6	
HRB A-1-6	Shoulder		25.5		Feb 5
F-13	Slab	17		Feb 5	
HRB A-2-4	Shoulder		20		Feb 6
F-15	Slab	22		Feb 6	
HRB A-7-6	Shoulder		21		Feb 5,6
F-17	Slab	29		Feb 5,6,7	
HRB A-3	Shoulder		23		Feb 6
F-24	Slab	17		Feb 6	
HRB A-4	Shoulder		15.5		Feb 6

of severity from the viewpoint of resulting extensive frost damage to pavements, had a cold quantity of 528 degree-days (Figure 16). The winter of 1954-1955 may be considered medium severe.

During the entire month of January and first few days of February the mean daily air temperature remained below 32 deg F. The maximum daily air temperature remained below freezing from January 27 to January 31 and February 2 to February 3rd. Thirteen degrees below zero F, the lowest air temperature of the winter, was recorded on February 3rd. This entire period was characterized by an abnormally low amount of precipitation. January's precipitation was the lowest ever recorded by the weather bureau for that month in New Jersey.

Heavy rainfall on February 6 and 7 was accompanied by rising air temperatures. After more rain on February 11th the soils at the surfaces were thawed and appeared to be completely saturated. Air temperatures fell rapidly on February 12th, the maximum for that day and the following day remaining below freezing.

A general period of thaw began on February 17, the mean air temperature remaining above freezing until March 5th. During several days of this period the minimum air temperature was above 32 deg F. The final brief cold spell of the winter occurred between March 5 and 8th.

Ground-Water

An examination of precipitation and ground-water data shows that the primary factor controlling the elevation of the ground-water table is the presence or lack of precipitation. Each period of precipitation produced an immediate rise in ground-water elevation. A decided difference was noted between the effects of precipitation occuring as rain or as snow. The amounts of precipitation during all of the precipitation periods for the winter, when compared with resulting rises in ground-water elevation, indicated the following:

The average rise of ground-water elevation per tenth of an inch of rain was 1.7 inches A tenth of an inch of precipitation occuring as snow, however, produced an average ground-water rise of 6 inches. Apparently the melting of the snow allowed considerably more percolation and less runoff than would have resulted from an equal amount of rain. This statement, of course, does not consider the complex hydrologic conditions involved.

Slight rises in ground-water elevation were also noted during periods of thawing without the presence of precipitation. Precipitation, during periods when frost was in the

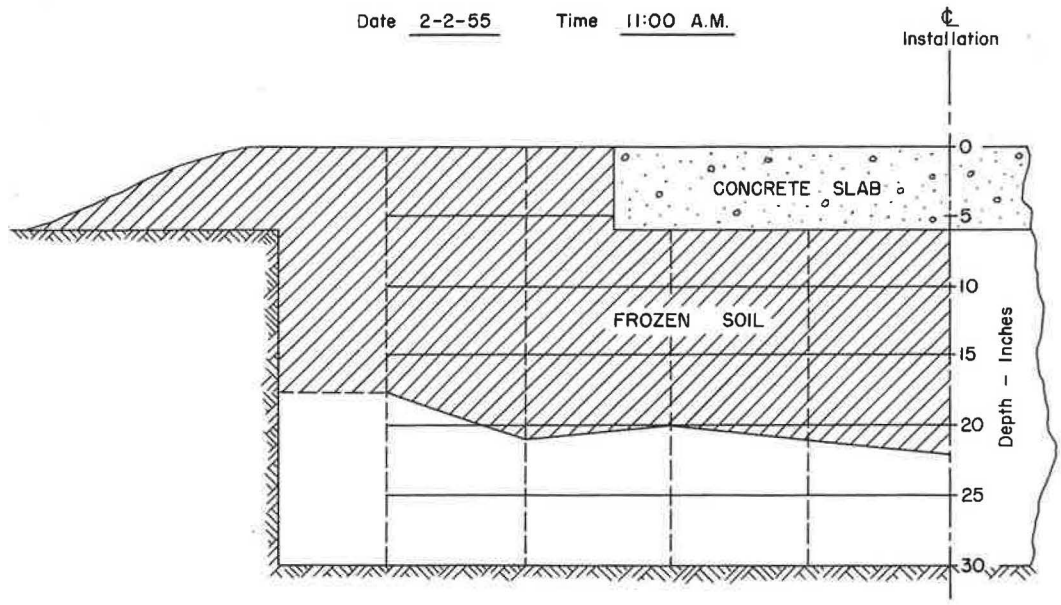

Figure 17. Profile of frost penetration in soil F-10, HRB A-1-b.

soil, still raised the ground-water elevation. Apparently the presence of frost did not prevent all percolation through the relatively porous structure of the surrounding soil at the field installation. It should be noted that the ground-water under consideration occurs in joints and fractured zones of shale.

The outstanding feature of ground-water conditions was the steady decline of elevation during the dry period of January and early February. By the end of this period the ground-water table had reached a depth of 69 inches below the ground surface, its maximum for the winter. A minimum depth of 14 inches was recorded following heavy rain in early March. Except during January the general depth to the ground-water table fluctuated between 20 and 30 inches.

During the winter the ground-water temperature fluctuated between 45 deg F and 53 deg F. In general, a steady decline occurred throughout the winter as a result of the cooling effect of freezing air temperatures. Precipitation produced noticeable variations in ground-water temperature, depending upon whether the temperature of the percolating water was higher or lower than that of the ground-water. Usually after rain or melting snow the ground-water temperature was lowered. An occasional increase was noted, however.

Frost Penetration

Observations indicated that prior to the completion of the soil installations there had been some frost in the soil. As a complete thaw was noted by December 29, 1954, this frost was not considered for evaluation.

The reaction of all of the soils was generally characterized by frost entering the soil early in January and remaining until late in February. Frost penetration proceeded at a reasonably steady rate in most of the soils during the extended cold period of January and early February. Superficial thawing was initiated by rising temperature and rain on February 7th. Varying amounts of frost remained continuously in all of the soils throughout several more freeze-thaw cycles until complete thawing in late February ended this major period of frost. A minor period of frost penetration was noted for all of the soils in early March. Frost occurred primarily in the soil shoulders at this time. The lengths of time of the major frost period for each soil are presented in Table 3.

It is noted that frost penetration occurred first in the soil shoulders. Soils F-10 and F-17, the granular materials, were the first to freeze both in the shoulders and beneath the concrete slabs. Complete thawing occurred first beneath the slabs. Again soils

TABLE 5

FROST PENETRATION DURING PERIOD FROM JANUARY 27 TO JANUARY 31

Soil	Position	Depth of Frost Penetration (Inches) Start of Period		End of Period		Amount of Penetration During Period	
						Inches	
F-5	Slab	14		18		4	
HRB A-5	Shoulder		15		18.5		3.5
F-10	Slab	14		22		8	
HRB A-1-b	Shoulder		13		21.5		8.5
F-13	Slab	8.5		13.8		5.3	
HRB A-2-4	Shoulder		13.2		17.3		4.1
F-15	Slab	11		14		3	
HRB A-7-6	Shoulder		13		16.5		3.5
F-17	Slab	17		25		8	
HRB A-3	Shoulder		12		20.4		8.4
F-24	Slab	8.6		13.4		4.8	
HRB A-4	Shoulder		8		13.4		5.4

F-10 and F-17 were the first to react. In each of the soils, frost was present in the shoulders longer than beneath the slabs. For soils F-10 and F-17 the difference between the lengths of these periods was considerably less than for the other soils.

The maximum depths of frost penetration for each of the soils are listed in Table 4. These were measured from the upper surfaces of the concrete slabs, which were flush with the soil shoulders.

It is noted that the maximum depth of frost penetration in all cases occurred just prior to the February 7 thaw, several days after the date of minimum air temperature. With the exception of F-13, all soils showed an equal or greater depth of frost penetration beneath the concrete slabs than in the shoulders, indicating that the thermal conductivity of a slab is greater than that of an equal thickness of soil. This may also be illustrated by an example of a frost profile determined by means of the additional thermistors installed in soil F-10 (Fig. 17).

The greatest depth of frost penetration occurred in the granular soils, F-17 and F-10, indicating a greater thermal conductivity than that of the finer-grained soils.

During the five-day period of continuous subfreezing temperatures from January 27 to January 31 all of the soils presented steady rates of frost penetration. The amounts of penetration during this period are listed in Table 5.

It can be observed from the frost penetration charts (Appendix A) that thawing occurs at both the top and bottom of the frozen soil layer.

As a means of comparing rates of thawing for the soils, depths of thaw from the surface to the remaining frozen soil on February 11 are listed in Table 6. Thawing on this date was the result of rising air temperature and rain. The frozen soils thawed primarily from the surface.

The rates of frost penetration and thaw-

TABLE 6

DEPTH OF THAWING INTO FROZEN SOIL ON FEBRUARY 11th

Soil	Depth of Thaw Beneath Slab	Beneath Shoulder
F-5 HRB A-5	9.5	5.5
F-10 HRB A-1-b	13.5	9.5
F-13 HRB A-2 4	11	6
F-15 HRB A-7-6	--[a]	5.5
F-17 HRB A-3	14.5	13.5
F-24 HRB A-4	8.5	6

[a] Thawing did not proceed beneath the base of the slab.

ing presented in Tables 5 and 6 further demonstrated the higher thermal conductivity of the granular soils. Of particular note is the observation that thawing in the soils proceeds more rapidly beneath the concrete slabs than beneath the shoulders.

Frost Heaving

For each soil the difference between its initial slab elevation and its maximum slab elevation reached during the winter was considered the maximum frost heave. These heaves are listed in Table 7. For convenience some frost penetration data are repeated.

The granular soils F-17 and F-10 experienced little heaving. The slight fluctuations of elevation of soil F-17 as shown by the frost heave charts (Appendix A) are insignificant. Soil F-10 also experienced insignificant heaving during the cold but dry period of January and early February. Slight heaving occurred during the cold spell starting on February 11th after heavy rains had raised the water table and moisture content of the soil.

Soils F-5, F-13 and F-15 experienced relatively moderate heaves. The rate of heave of each of these soils decreased steadily toward the end of January, whereupon the soils maintained a reasonably constant elevation until the thaws on February 10th and 11th. Rapid heaving was then noted in each of these soils during the cold spell starting on February 11th.

Soil F-24, a silty material, heaved the most of all 30 soils being studied for this purpose. It showed a relatively large and steady rate of heave until the February 7 thaw. The heaving which recurred on February 11 was of minor consequence when compared with the over-all reaction of this soil.

It is noted that maximum frost heave does not necessarily occur simultaneously with maximum depth of frost penetration. Undoubtedly the effect of increased moisture content following the early February rains caused some of the soils to experience maximum heaves at that time rather than at the time at which they were frozen to the greatest depth. Had the cold spell following these rains been of longer duration it is possible that the other soils might have experienced greater heaves at this time.

Soil Moisture Contents

In most instances operation of the fiberglas soil moisture units was considered to be satisfactory. It should be expected that, when present, the variance of soil moisture content with depth should be reasonably uniform, assuming, of course, that the soil is homogenous. An examination of the moisture content curve (Appendix A) shows in some instances erratic fluctuations of soil moisture content with depth rather than steady variations. It is suspected that this is a result of the placement of the soil moisture units in the soil. It is difficult to restore each unit to exactly the same conditions of soil contact and soil density under which it was calibrated. Soil moisture units placed in soil

TABLE 7

MAXIMUM FROST HEAVES

Soil	Max Frost Heave	Date of Max Heave	Date of Max Frost Penetration	Frost Heave at Time of Max Frost Penetration	Max Frost Penetration	Frost Penetration at Time of Max Heave
	feet			feet	inches	inches
F-5 HRB A-5	.041	Feb. 16	Feb. 6	.034	22	18
F-10 HRB A-1-b	.016	Feb. 14, 15	Feb. 6	.002	26	17
F-13 HRB A-2-4	.035	Feb. 14, 15, 16	Feb. 5	.027	17	12
F-15 HRB A-7-6	.045	Feb. 6	Feb. 6	.045	22	22
F-17 HRB A-3	.004	Feb. 4, 5	Feb. 5, 6, 7	.004	29	29
F-24 HRB A-4	.144	Feb. 6	Feb. 6	.144	17	17

F-17 (HRB A-3) seemed to be the worst offenders, probably because of the relatively small proportion of fines in this soil to afford good contact with the fiberglas element.

In general, it is estimated that the soil moisture units as used in this study have indicated soil moisture contents to an approximate accuracy of several percent.

When a soil moisture unit freezes its resistance increases sharply. An examination of moisture unit resistance and soil temperature data showed that the actual freezing temperatures of the soils were slightly lower than 32 deg F. Measurements were not taken at sufficiently close time intervals, however, for an accurate determination of their freezing points.

As the soil moisture units could not indicate the moisture content of frozen soil each moisture content curve is discontinuous during the periods when the soil at the corresponding depth was frozen.

In both soil F-10 and soil F-15 the shoulder moisture contents were approximately the same as the moisture contents beneath the slabs. In soil F-5 the slab moisture contents were significantly higher than the shoulder moisture contents. Soil F-13 showed slightly higher slab moisture contents than shoulder contents. In soils F-17 and F-24 shoulder moisture contents were slightly higher than slab moisture contents.

Four of the six soils showed increases of moisture content with depth. The approximate ranges are as follows:

Soil	Approximate Moisture Content Range	
F-5	33-34 percent beneath slab	25-20 percent beneath shoulder
F-10	8-12	
F-13	17-22	
F-15	27-30	

The moisture content of soil F-17 varied little with depth except in the proximity of the ground-water table when present. Normal approximate moisture contents were 3 to 5 percent. Moisture content of this soil at its lower depths when affected by the ground-water table was 16 percent.

Soil F-24 presented a rather uniform moisture content with depth, ranging from 21 to 23 percent.

During the dry period of January and early February moisture contents of all of the soils were reduced, the rate of reduction increasing toward the end of the period. In the early part of the period the greatest reduction in moisture content appeared near the soil surfaces in soils F-5, F-13, F-15 and F-24. Of course, it was possible to follow the moisture content trend in the upper soils only until they were frozen. F-10 and F-17, having relatively lower moisture contents than the other soils, showed less reduction of moisture content near the surface. Toward the end of the dry period the soil moisture contents at greater depths showed reduction. Of the finer-grained materials, F-13 showed the greatest reduction, approximately 5 percent. The moisture content of F-10 was reduced a relatively small amount. The moisture content at greater depths of F-17, however, experienced a sharp reduction of over 10 percent as the effect of the ground-water table was removed.

In general, immediately after the early February rains all of the measurable soil moisture contents returned to their approximate initial values. As thawing proceeded the remaining moisture contents were found to be at or slightly above initial values. A possible increase of soil moisture content as a result of thawing was masked by the simultaneous occurrence of rain.

All of the soils showed some fluctuation of moisture content resulting from precipitation. This effect was most noted near the surface. The sharp increase of moisture content for all soils at the beginning of the period of study is believed more a result of the replaced soil and soil moisture units reaching an equilibrium than a result of precipitation. The moisture content of soil F-17 showed the greatest sensitivity to precipitation. Considerable increases in moisture contents were apparent after rains. By means of the moisture content curves it was possible to trace this increase with depth as percolation resulted. Rapid decreases of moisture content shortly after rain show the free-draining properties of this material.

CONCLUSIONS

1. The Fiberglas soil moisture units as used in this study indicated soil moisture contents to an apparent accuracy of several percent. Soil moisture units placed in coarse-grained soils presented the most erratic performance.

2. Thermistors are reliable and convenient for measuring subsoil temperatures. They can be easily calibrated to an accuracy of 0.1 deg F.

3. The winter of 1954-1955 may be regarded as medium severe for New Jersey on a comparative basis of temperature. Coincident with the coldest part of the winter, however, was an extended period of abnormally low precipitation.

4. The elevation of the ground-water table shows a direct relationship to precipitation. Percolation from melting snow may be greater than from an equivalent amount of rain. Even when frost has penetrated to a considerable depth percolation may still be possible, probably as a result of porous soil structure. The ground-water temperature is controlled primarily by the effect of air temperature. Immediate minor fluctuations may result from percolation.

5. The greatest depth and rate of frost penetration occurs in the granular soils as a result of their relatively high thermal conductivity as compared with that of fine-grained soils. Because the thermal conductivity of a concrete slab is greater than that of an equal depth of soil, frost usually penetrates deeper beneath the slabs than through the shoulders. For the same reason, the soils thaw faster beneath the slabs. As a frozen layer of soil thaws from both top and bottom, this is of particular importance because the greater rate of thawing beneath pavement slabs may produce "pockets" of thawed soil at high moisture content from which the water cannot drain. Consequently, the soil bearing capacity is reduced because of the saturated state of the soil. This observation implies a drainage problem concerning base and subbase courses to be solved with particular reference to drainage from underneath the road pavement of water produced by the melting of frozen soil moisture.

6. The greatest depth of frost penetration does not necessarily occur at the same time as minimum air temperature.

7. The silty A-4 soils are most susceptible to frost heaving. The granular A-1-b and A-3 soils heave the least.

8. Maximum frost heaving does not necessarily occur simultaneously with the maximum depth of frost penetration.

9. Frost heaving is dependent upon soil moisture content resulting from precipitation or proximity to ground-water as well as upon the amount of frost penetration resulting from freezing temperatures.

10. Soil freezes at temperatures slightly lower than 32 deg F.

11. Fine-grained soils normally retain higher moisture contents than coarse-grained soils. Moisture contents usually increase with depth in a soil. The effect of increased soil moisture content resulting from precipitation and percolation is modified with depth.

12. There is a great need for the investigation of thermal properties of New Jersey soils.

13. There is also a great need for studying moisture migration in soils upon freezing.

ACKNOWLEDGMENT

The authors wish to express their appreciation to the New Jersey State Highway Department for having initiated the project which provided the material for this report, to the Joint Highway Research Committee and, in particular, to Chairman Allen C. Ely for their interest and advice, and to Dr. E.C. Easton, Dean of the College of Engineering, Rutgers University, for his support of a project of such potential value to the state as a whole.

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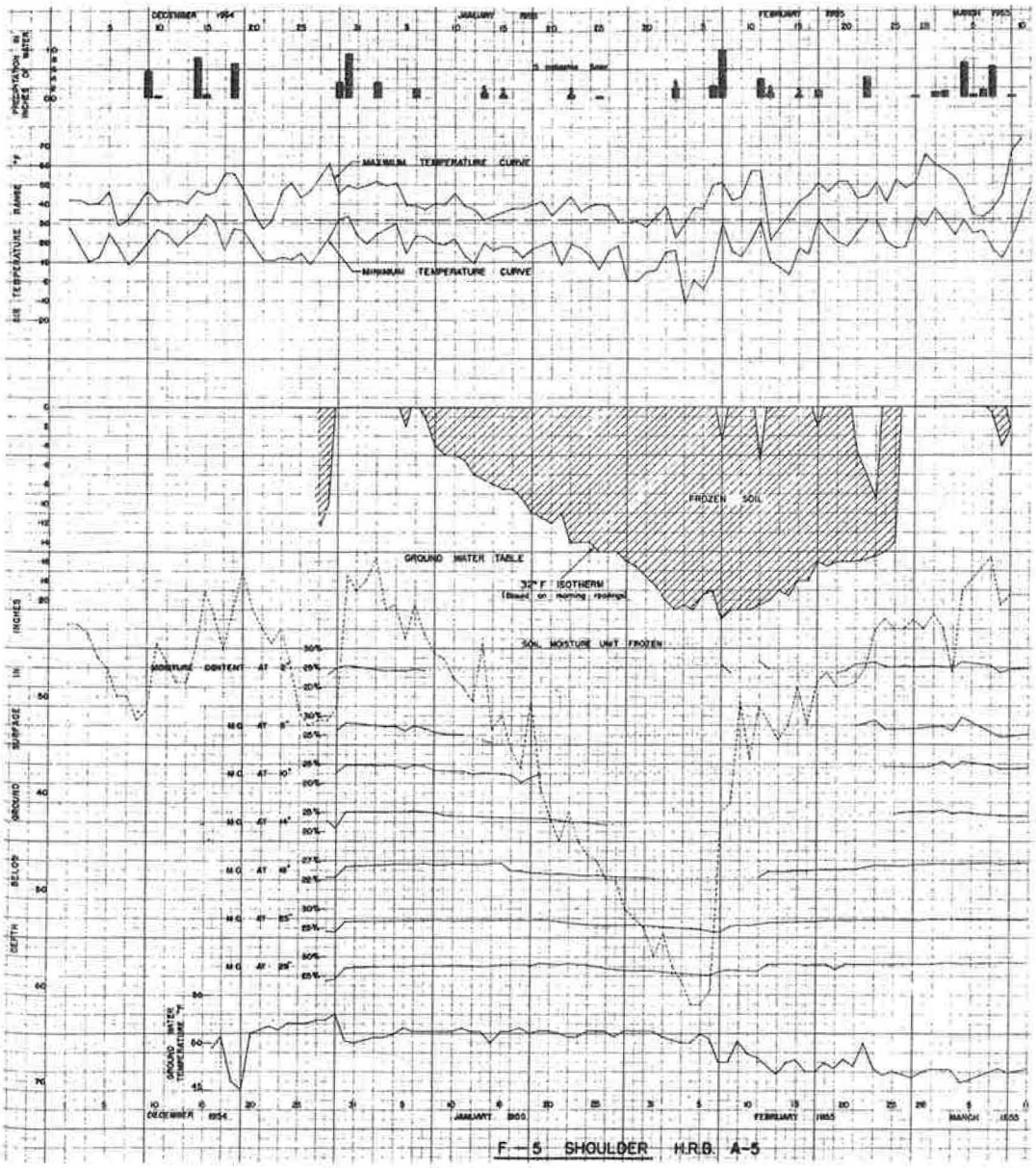
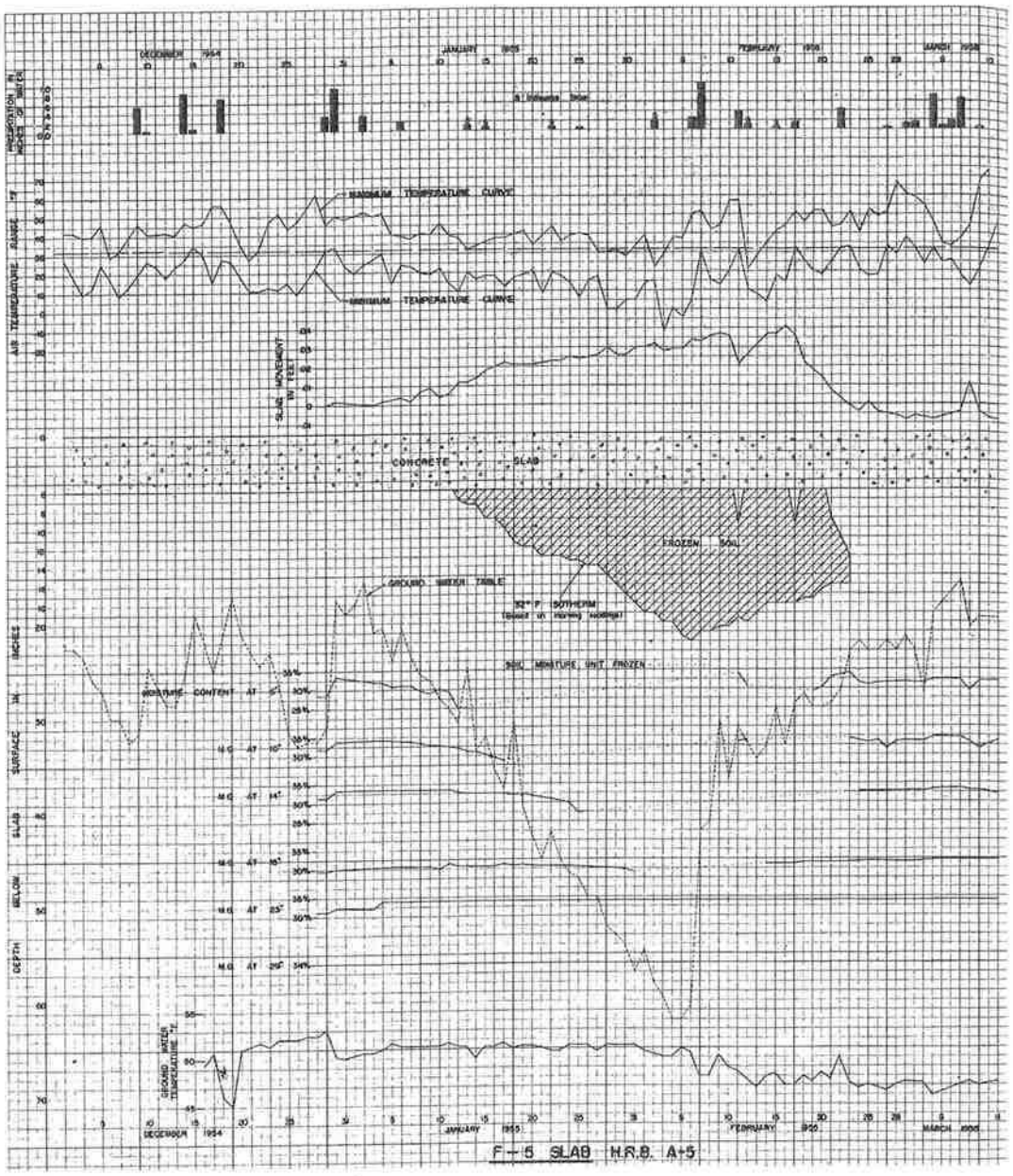
1. Colman, E.A., and Hendrix, T.M., "The Fiberglas Electrical Soil-Moisture Instrument," Soil Science, Vol 67, 1949, pp 425-438.

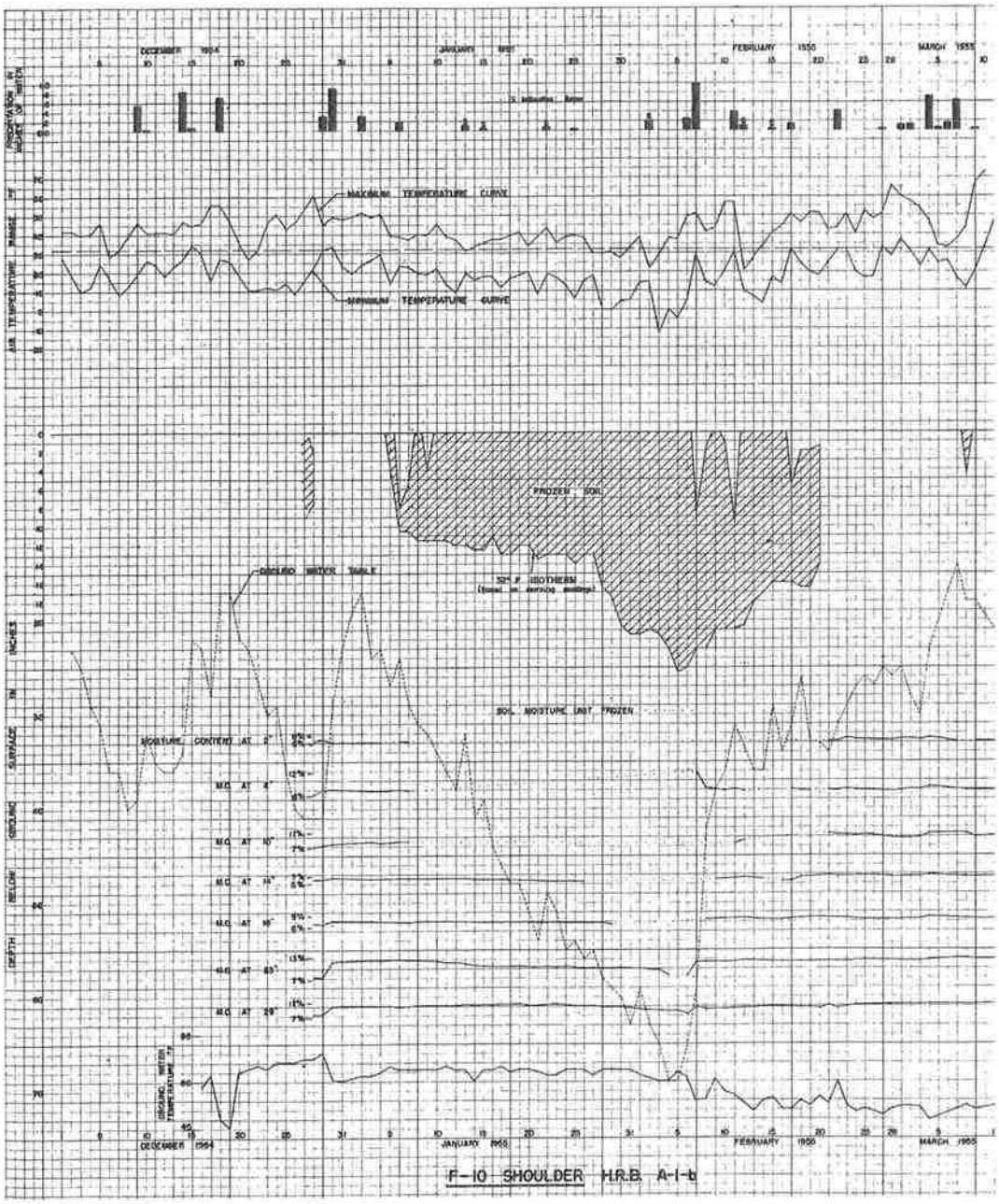
2. Colman, E. A., Manual of Instructions for Use of the Fiberglas Soil Moisture Instrument, California Forest and Range Experiment Station, Berkeley, Cal, 1947.
3. Kelley, O. J., "A Rapid Method of Calibrating Various Instruments for Measuring Soil Moisture in Situ," Soil Science, Vol 58, 1944, pp 433-440.

Appendix A

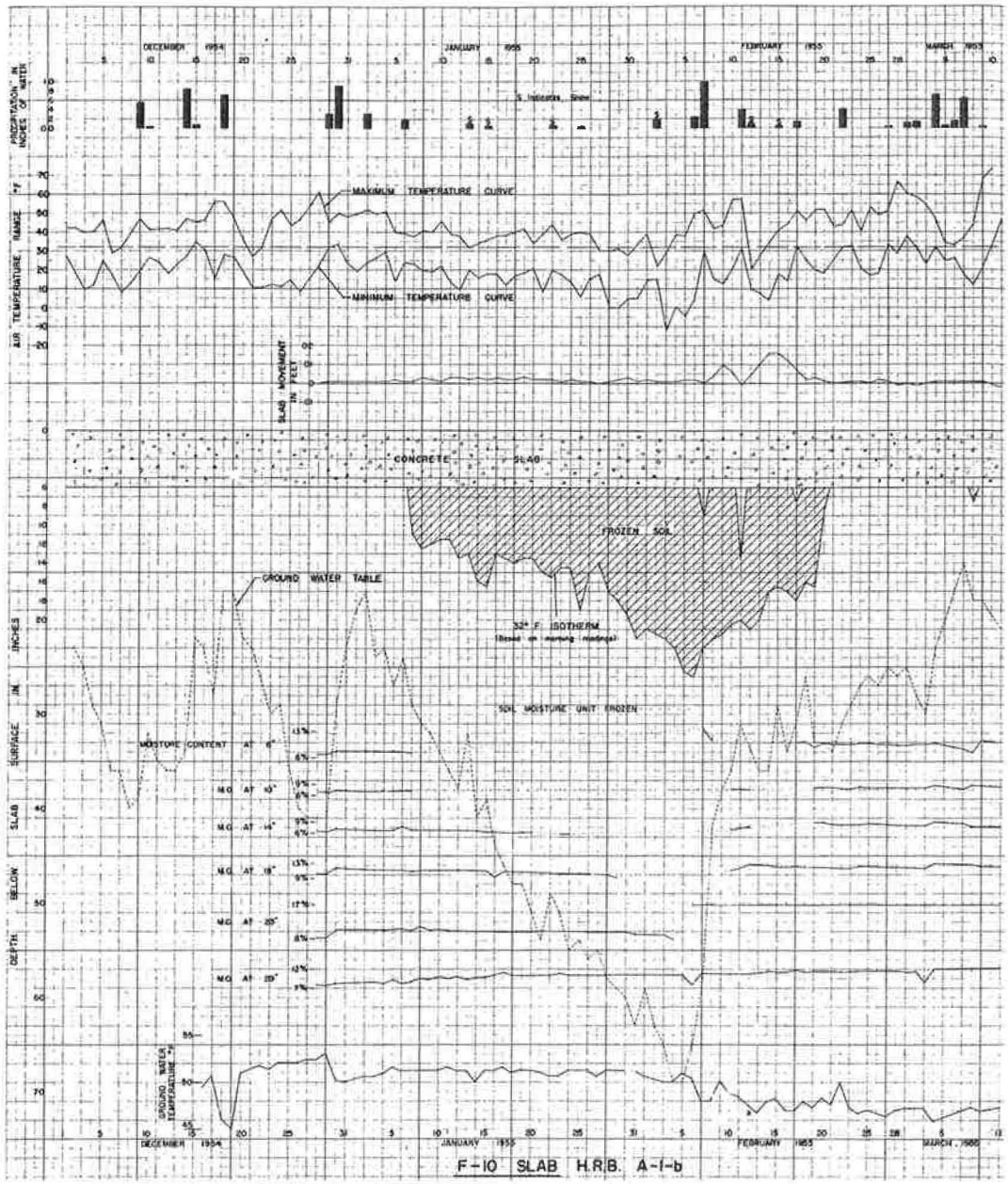
Curves showing precipitation, air temperature range, slab displacement (heave), frost penetration, soil moisture content, ground-water level and ground-water temperature for six New Jersey soils exposed to natural freeze-thaw conditions during the winter of 1954-1955.

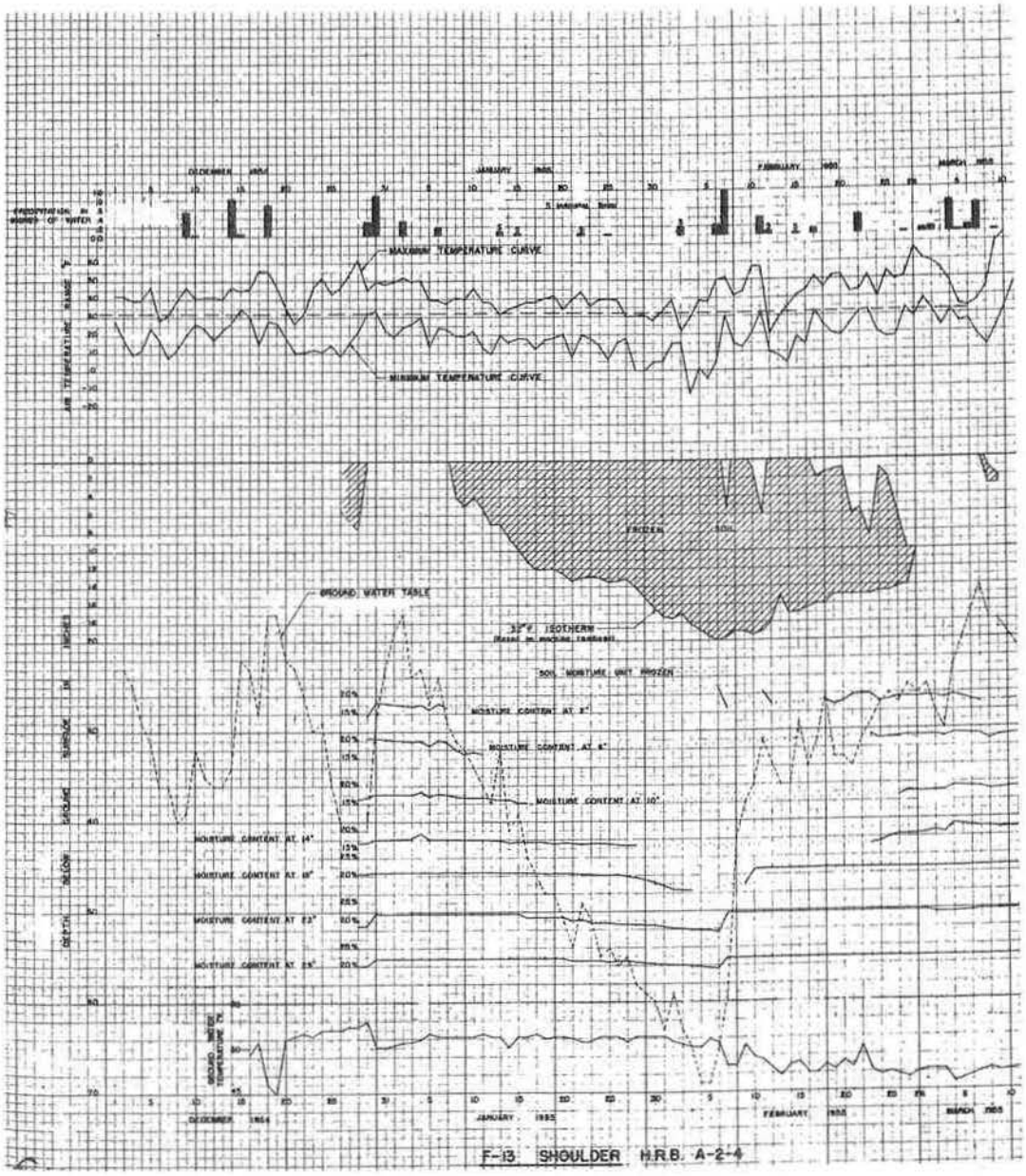



DECEMBER 1954
JANUARY 1955
FEBRUARY 1956
MARCH 1956
PRECIPITATION IN INCHES OF WATER
AIR TEMPERATURE RANGE °F
MAXIMUM TEMPERATURE CURVE
MINIMUM TEMPERATURE CURVE
SLAB MOVEMENT IN THOUSANDTHS
CONCRETE SLAB
FROZEN SOIL
GROUND WATER TABLE
32° F ISOTHERM
SOIL MOISTURE UNIT FROZEN
MOISTURE CONTENT AT 8"
AT 10"
AT 14"
AT 18"
AT 23"
AT 29"
DEPTH BELOW SURFACE IN INCHES
GROUND WATER TEMPERATURE °F
F-5 SLAB H.R.B. A-5

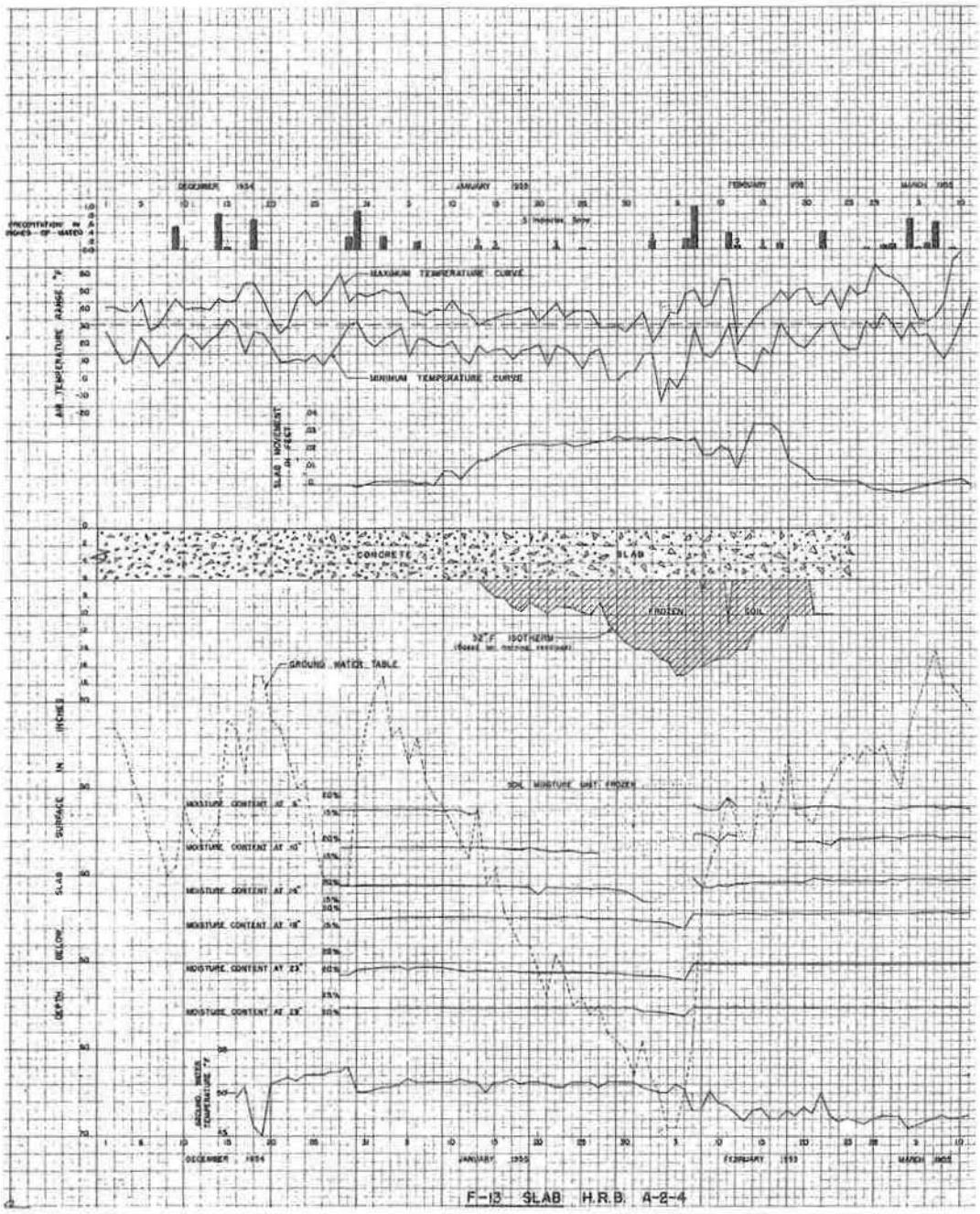


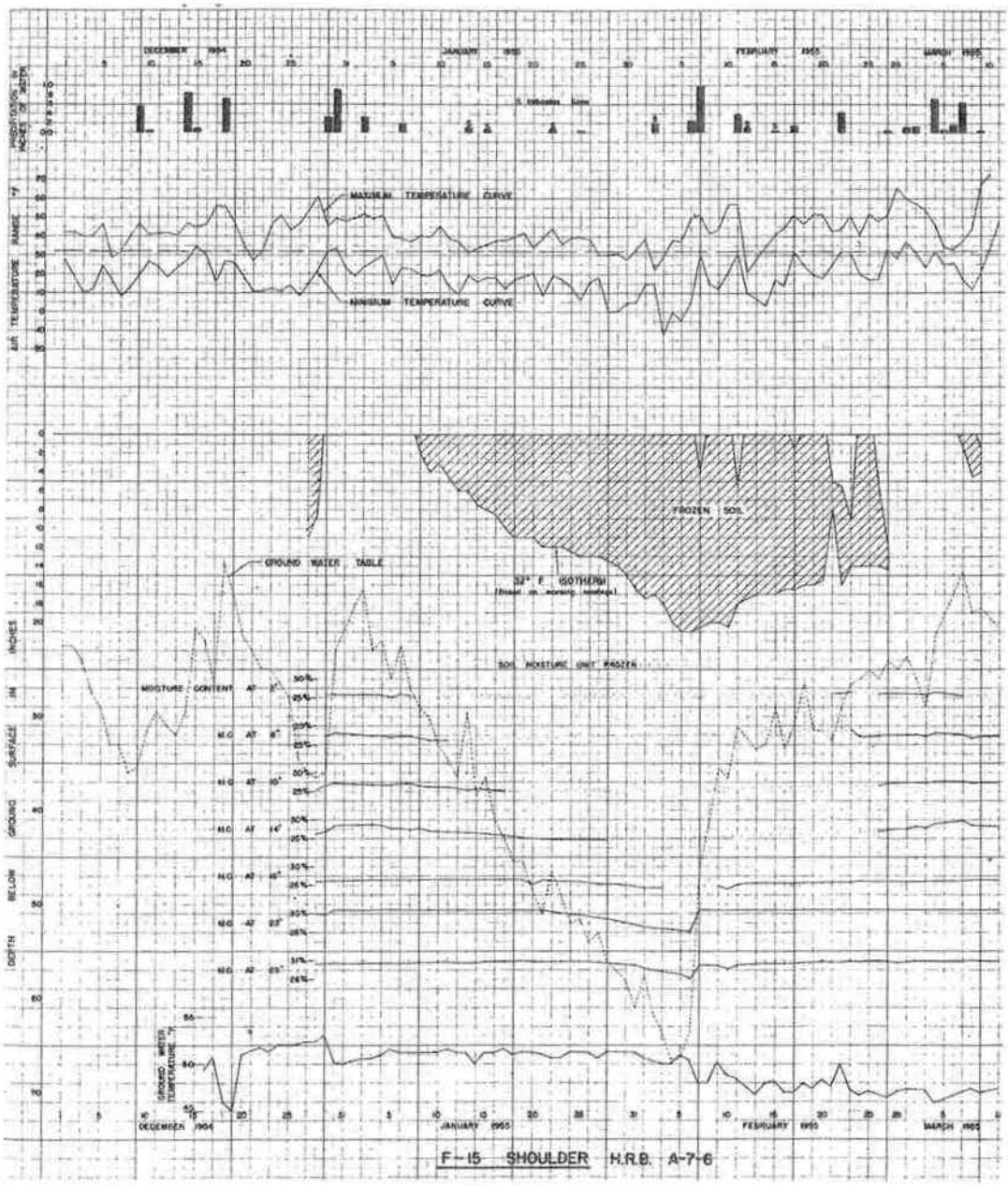
F-10 SHOULDER H.R.B. A-1-b


DECEMBER 1954
JANUARY 1955
FEBRUARY 1955
MARCH 1955
PRECIPITATION IN INCHES OF WATER
S Indicates Snow
AIR TEMPERATURE RANGE °F
MAXIMUM TEMPERATURE CURVE
MINIMUM TEMPERATURE CURVE
SLAB MOVEMENT IN FEET
CONCRETE SLAB
FROZEN SOIL
GROUND WATER TABLE
32° F ISOTHERM
(Based on morning readings)
SOIL MOISTURE UNIT FROZEN
SURFACE SLAB BELOW DEPTH IN INCHES
MOISTURE CONTENT AT 6"
M.C. AT 10"
M.C. AT 14"
M.C. AT 18"
M.C. AT 25"
M.C. AT 29"
GROUND WATER TEMPERATURE °F
F-10 SLAB H.R.B. A-1-b

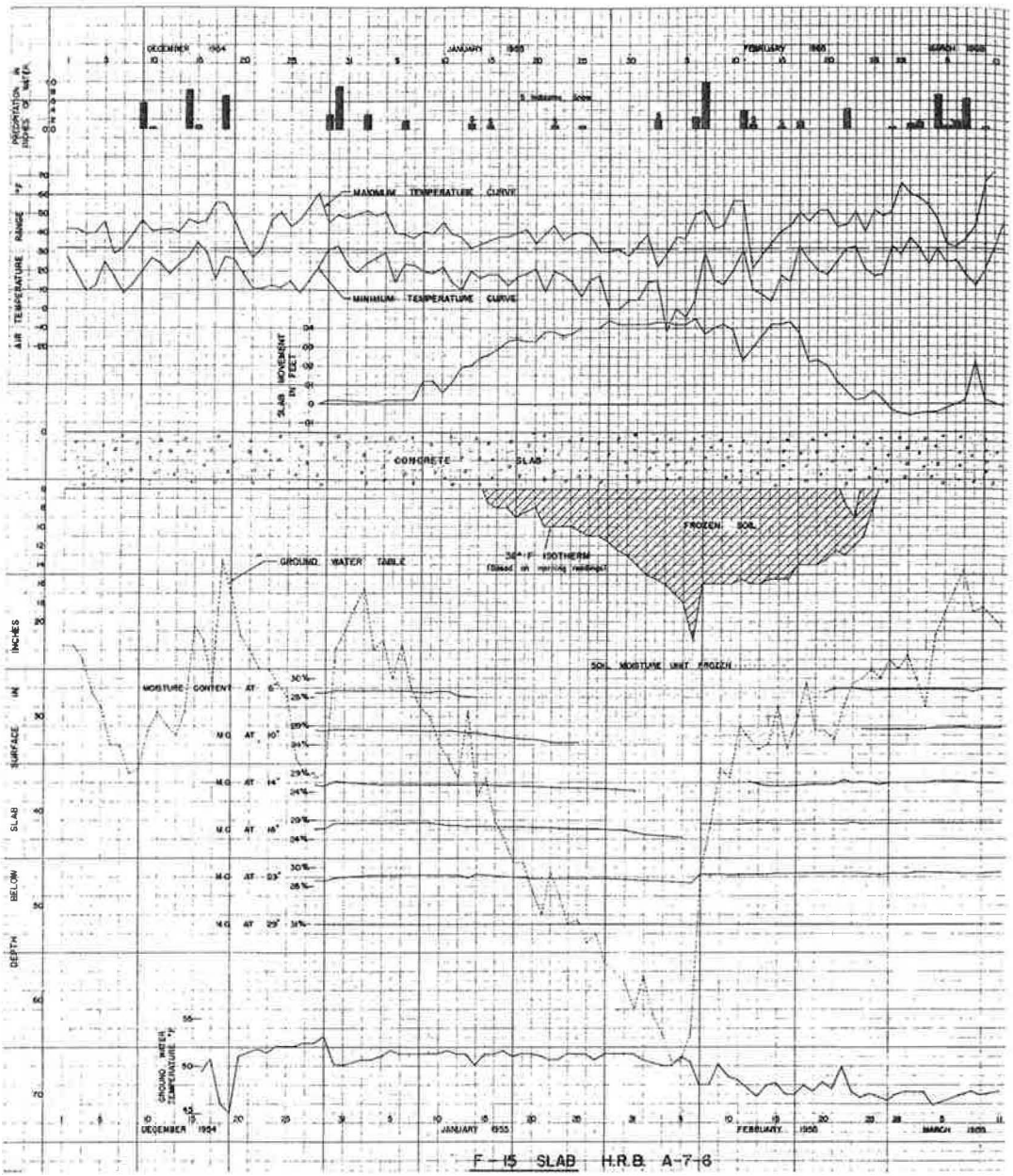


F-13 SHOULDER H.R.B. A-2-4

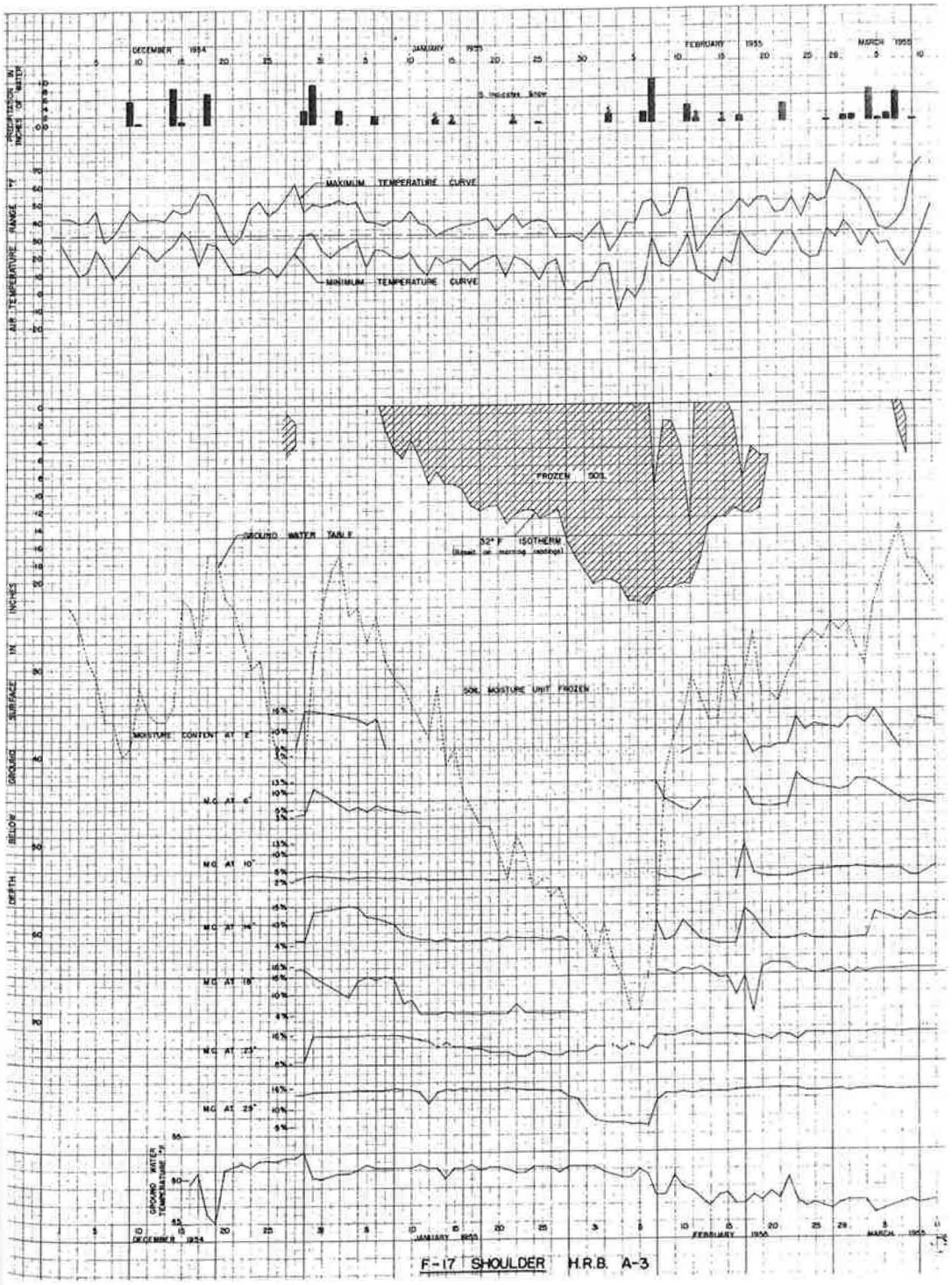

DECEMBER 1954
JANUARY 1955
FEBRUARY 1955
MARCH 1955
PRECIPITATION IN INCHES OF WATER
MAXIMUM TEMPERATURE CURVE
MINIMUM TEMPERATURE CURVE
AIR TEMPERATURE RANGE °F
SLAB MOVEMENT IN FEET
CONCRETE SLAB
FROZEN SOIL
32°F ISOTHERM
GROUND WATER TABLE
SOIL MOISTURE UNIT FROZEN
MOISTURE CONTENT AT 8"
MOISTURE CONTENT AT 10"
MOISTURE CONTENT AT 14"
MOISTURE CONTENT AT 18"
MOISTURE CONTENT AT 23"
MOISTURE CONTENT AT 28"
DEPTH BELOW SLAB SURFACE IN INCHES
GROUND WATER TEMPERATURE °F
F-13 SLAB H.R.B. A-2-4



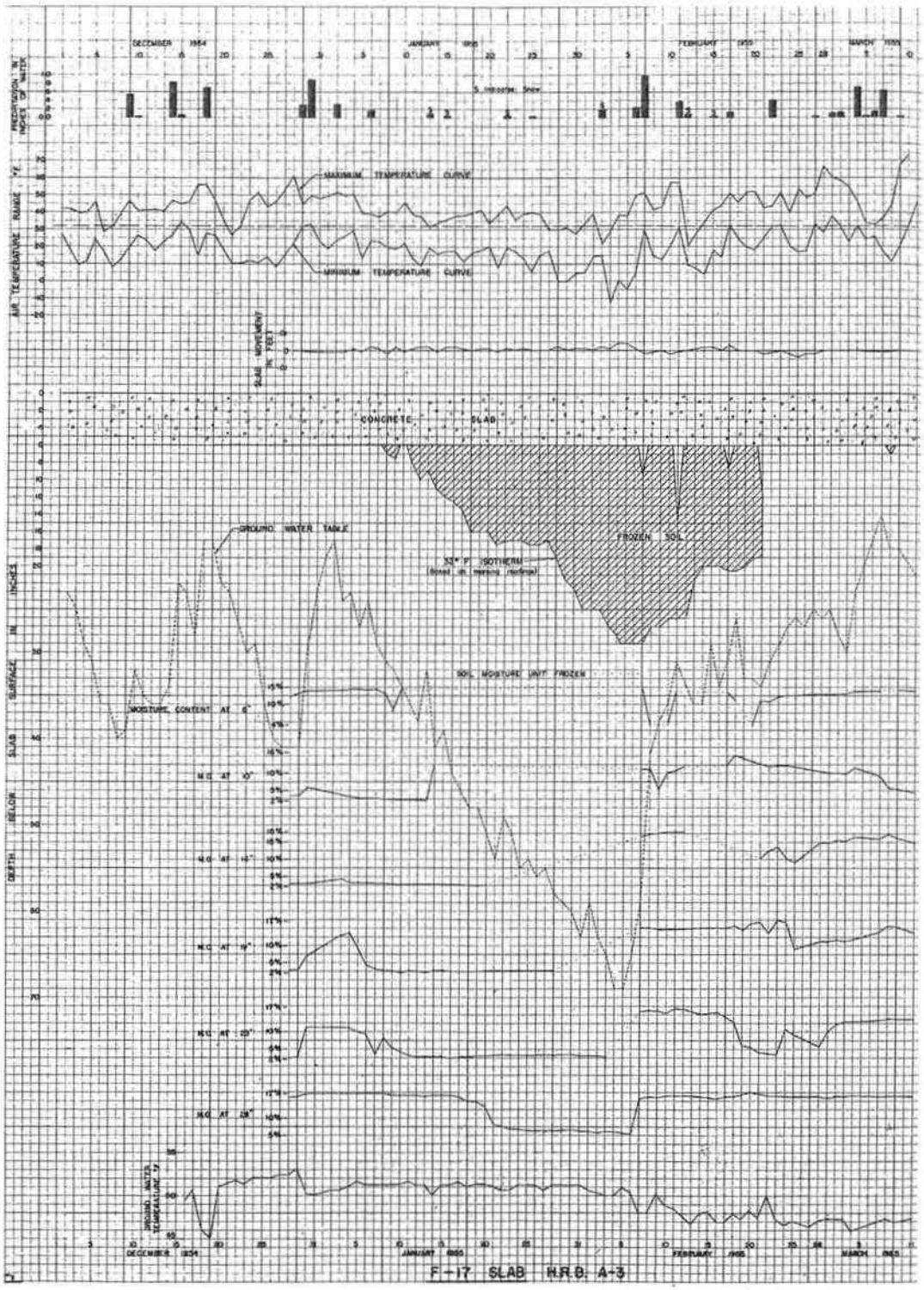
F-15 SHOULDER H.R.B. A-7-6



F-15 SLAB H.R.B. A-7-6



F-17 SHOULDER H.R.B. A-3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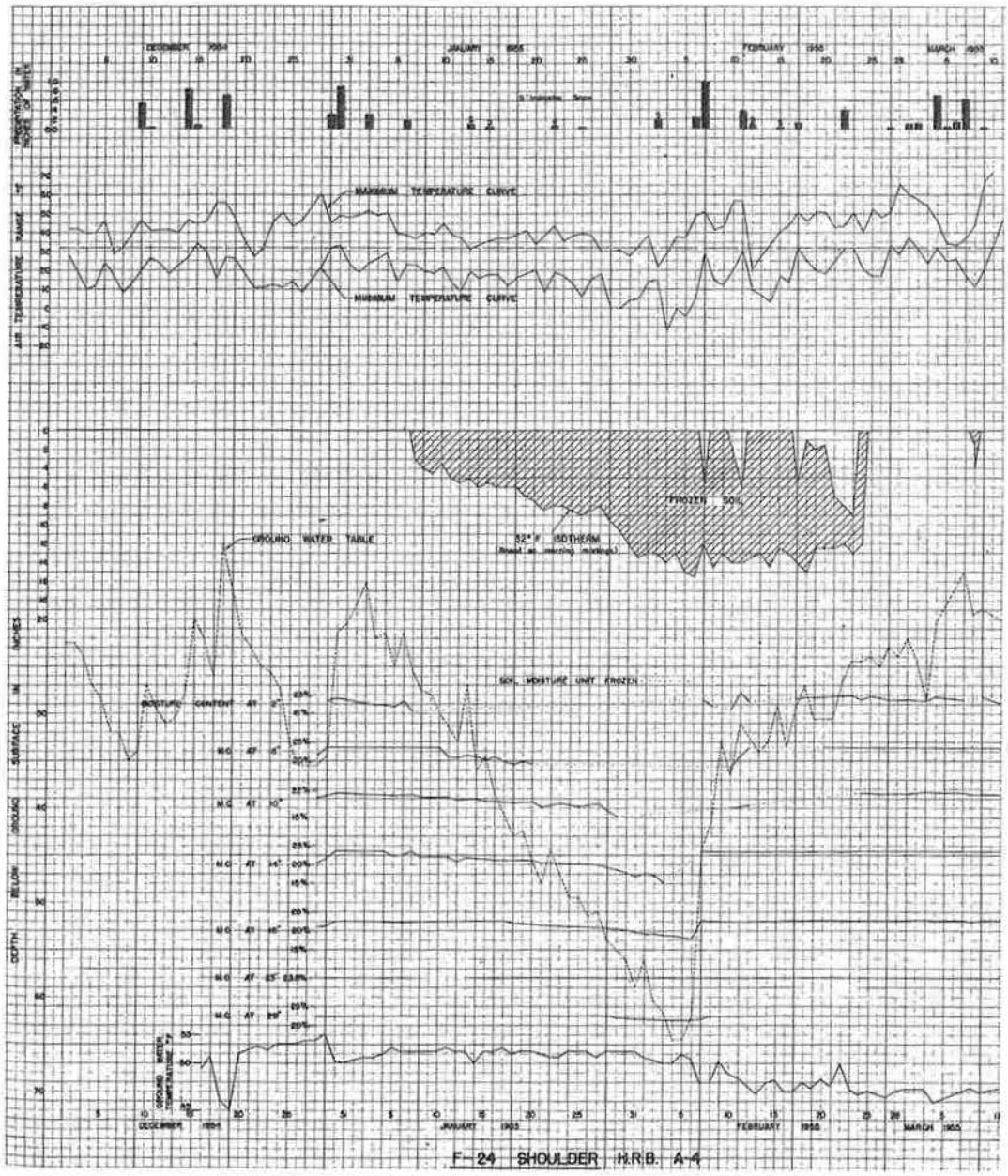
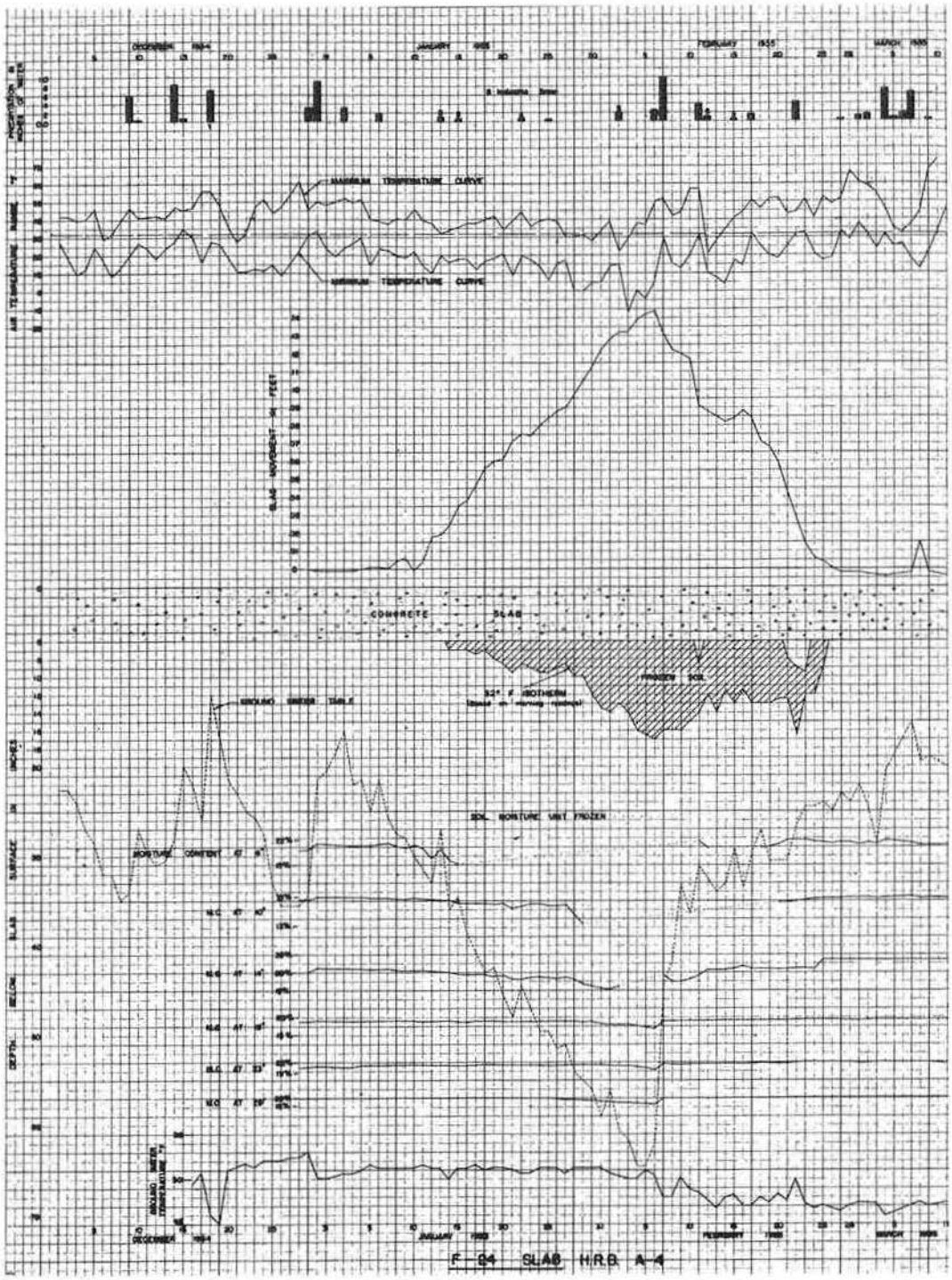
MARCH 1955
PRECIPITATION IN INCHES OF WATER
AIR TEMPERATURE RANGE °F.
MAXIMUM TEMPERATURE CURVE
MINIMUM TEMPERATURE CURVE
SLAB MOVEMENT IN FEET
CONCRETE SLAB
GROUND WATER TABLE
FROZEN SOIL
32° F ISOTHERM
SOIL MOISTURE UNIT FROZEN
MOISTURE CONTENT AT 6"
M.C. AT 10"
M.C. AT 13"
M.C. AT 19"
M.C. AT 25"
M.C. AT 28"
DEPTH BELOW SLAB SURFACE IN INCHES
GROUND WATER TEMPERATURE °F.
F-17 SLAB H.R.B. A-3



F-24 SHOULDER H.R.B. A-4


DECEMBER 1954
JANUARY 1955
FEBRUARY 1955
MARCH 1955
MAXIMUM TEMPERATURE CURVE
MINIMUM TEMPERATURE CURVE
SLAB MOVEMENT IN FEET
CONCRETE SLAB
FROZEN SOIL
32° F. ISOTHERM
GROUND WATER TABLE
SOIL MOISTURE VAST FROZEN
MOISTURE CONTENT AT 9"
MOISTURE CONTENT AT 14"
MOISTURE CONTENT AT 19"
MOISTURE CONTENT AT 24"
MOISTURE CONTENT AT 29"
MOISTURE CONTENT AT 34"
DEPTH BELOW SLAB SURFACE IN INCHES
AIR TEMPERATURE DEGREES F.
F-94 SLAB H.R.B. A-4