REC-ERC-81-1

CLOSED-SYSTEM FREEZING OF SOILS IN LININGS AND EARTH EMBANKMENT DAMS

Engineering and Research Center

Water and Power Resources Service

March 1981

MS-230 (3-78)
Water and Power

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
REC-ERC-81-1		

4. TITLE AND SUBTITLE

Closed-System Freezing of Soils in Linings and Earth Embankment Dams

5. REPORT DATE

March 1981

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

Chester W. Jones

8. PERFORMING ORGANIZATION REPORT NO.

REC-ERC-81-1

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Water and Power Resources Service
Engineering and Research Center
Denver, Colorado 80225

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS

Same

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE

DIBR

15. SUPPLEMENTARY NOTES

Microfiche and/or hard copy available at the Engineering and Research Center, Denver, Colo.

Ed: LDP

16. ABSTRACT

A brief review of studies of closed-system freezing (no source of water except that in voids) of compacted soils performed by other investigators, and the laboratory and field data collected from Water and Power Resources Service experiences are presented. For compacted soil canal linings, laboratory and field test results show that under certain soil and temperature conditions, freezing decreases soil density near the surface, but increases density at depth. In two linings, the average density increased slightly during a 20-year period. Frost penetration measurements made during the 1978-79 winter on a 1.5-m-thick reservoir lining, on three earth dams under construction, and on the Teton Dam remnant are shown along with associated soil conditions, air freezing indexes, and insulating effects of snow and, for one dam, a loose soil cover. There is a discussion of (1) frost penetration in different types of soil with and without gravel particles, (2) the effect of freezing on soil near the surface of partially completed earth dams during winter shutdown periods, (3) the need for investigating frost conditions in preparation for resumption of embankment placement in the spring, (4) a suggestion of possible detrimental freezing action at the interface between a rock abutment and an earth embankment, and (5) the possibility of crack formation caused by soil shrinkage during freezing action.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS — / frost action/ frozen soils/ soil density/ soil moisture content/ earth lining/ earth dams / frost protection/

b. IDENTIFIERS — / closed-system freezing/ freezing indexes/ frost penetration/

c. *COSATI Field/Group* 08M   *COWRR:* 0813

18. DISTRIBUTION STATEMENT

Available from the National Technical Information Service, Operations Division, Springfield, Virginia 22161.

(Microfiche and/or hard copy available from NTIS)

19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
UNCLASSIFIED	52
20. SECURITY CLASS (THIS PAGE)	**22. PRICE**
UNCLASSIFIED	

REC-ERC-81-1

CLOSED-SYSTEM FREEZING OF SOILS IN LININGS AND EARTH EMBANKMENT DAMS

by

C. W. Jones

March 1981

Geotechnical Branch
Division of Research
Engineering and Research Center
Denver, Colorado

SI METRIC

UNITED STATES DEPARTMENT OF THE INTERIOR ★ WATER AND POWER RESOURCES SERVICE

CONTENTS

FIGURES

CONTENTS — Continued

CONTENTS — Continued

APPENDIXES TABLES AND FIGURES

INTRODUCTION

Closed-system freezing in a soil is a condition in which no source of water is available during the freezing process beyond that originally in the voids of the soil at and near the zone of freezing, while open-system freezing is a condition in which pore water, in excess of that originally contained in the voids of the soil, is available to be moved to the surface of freezing to form segregated ice in frost susceptible soil. There is much less available information on closed-system freezing than for open-system freezing, particularly with regard to field applications. Closed-system freezing has been considered relatively less important because it does not usually result in damaging frost heave. However, closed-system freezing does have important effects on some soil structures, particularly in irrigation works on compacted soil (earth) linings for canals and reservoirs and on earth embankment dams.

Some compacted soil linings have been constructed in cold areas subject to freezing and thawing action and there is concern about the performance of the lining. On incompleted earth embankment dams, freezing occurs near the surface during the winter period when construction is halted. Here, attention must be given to any decrease in soil density caused by freezing which will require soil removal, conditioning, and recompaction as necessary before additional embankment is placed.

After a brief review of work by other investigators of closed-system freezing, this report will cover information on the effects of closed-system freezing on soil density and moisture as found from field and laboratory investigations by the Water and Power Resources Service.

CONCLUSIONS

- In compacted fine-grained soil susceptible to frost action, closed-system freezing progresses inward from the soil surface at a slow to moderate rate; either in a laboratory test specimen or in a field structure, the following takes place: (1) moisture in the soil voids migrates toward the cold surface, (2) soil density near the surface decreases, (3) density in a zone at some depth in the soil increases, (4) thin ice lenses may or may not form, and (5) under certain soil and freezing conditions, overall shrinkage of the soil may occur.

- For some compacted soils in canal linings, an increase in density at depth, as well as a decrease near the surface of the lining, can be attributed to closed-system freezing.

- It is possible for closed-system freezing to cause the formation of ice on the underside of a plastic membrane lining on a slope which could result in a plane of slippage as the ice melts.

- The closed-system type of freezing that occurs below the surface of an earth embankment when construction is halted by cold weather may significantly affect soil moisture and density. This will require the removal and/or recompaction of the upper zone of soil which has a density below the specification limits.

- The depth to which frost penetrates in soil with resulting frost action is determined mainly by cumulative, below-freezing temperatures, degree of shading, snow or other surface cover, and the thermal properties of the soil. Frost penetrates deeper in soil with significant amounts of gravel because the thermal conductivity of gravel is higher than that of finer soil.

- Because of the higher thermal conductivity of solid bedrock compared to soil, it is possible that closed-system freezing could occur in compacted embankment soil in contact with a bedrock abutment at depths below those in the embankment and to some distance from the abutment. This could cause a zone of soil with higher moisture content and lower density near the abutment contact which, if not corrected, might produce a condition conducive to piping of the soil.

- During the unusually cold winter of 1978-79, frost penetrations to a maximum depth of 2.1 m (7 ft) were measured by frost tubes in Water and Power Resources Service dams under construction.

- A loose soil cover is effective in reducing frost action in a compacted embankment.

- In certain soil and climatic conditions, closed-system freezing can cause soil shrinkage and the formation of cracks which might be detrimental to soil barriers for retaining water.

APPLICATION

Although the effects on soil from closed-system freezing have been demonstrated in laboratory tests by other investigators, examples of field applications on earth irrigation structures have apparently not been published. At this stage in our knowledge of the subject, design and construction engineers of earth structures should be aware of and make allowances for the freezing action. After more information is obtained on the subject, it may be possible to monitor the freezing process on field structures, and within the variations of climate, use the process to improve soil properties in specific applications. Also, there would be a considerable economic advantage in cold climates if, for example, it should be determined that a contractor could reduce the amount of excavation of soil required after the freezing period or could proceed with embankment construction without waiting for frozen soil in the embankment to thaw.

OTHER INVESTIGATIONS OF CLOSED-SYSTEM FREEZING

When air temperatures fall below freezing and frost penetrates below the ground surface, there is migration of moisture in the soil upward to the frostline where ice may form. There are various theories that explain this by means of capillary flow, suction force, thermodynamics, or vapor transfer. [1, 2].[1] The resulting effects on the soil depend mainly upon the chemical and physical properties of soil, rate of freezing, and soil moisture conditions. For the open-system freezing condition where a subsurface source of free water (e.g., a water table) is available, ice lenses are formed in certain types of soils and heaving of the ground surface occurs. For a closed-system freezing condition, the only water available at or near the frostline is in the soil voids; in this case, ice lenses are usually thin or nonexistent. As the moisture redistribution occurs, there is also a change in soil density, with the portion near the ground surface tending to decrease in density and tending to increase at some depth below the surface. The frozen top surface may heave a relatively small amount, or in some cases of laboratory specimens, the specimen height has been observed to remain the same or to decrease slightly, denoting shrinkage.

Other investigators have performed research with regard to closed-system freezing. Dirksen and Miller [3] conducted closed-system freezing tests on unsaturated laboratory test specimens to study the movement of water to ice lens growth. They found that during initial stages of freezing, the movement within the frozen zone of water in the liquid form exceeds, by several orders of magnitude, that which could be accounted for as vapor movement through the unfilled pore space. Later, as the rate of ice accumulation diminishes, the hydraulic gradient is dissipated and the thermal water transport becomes relatively more important, but by this time, heaving has nearly ceased.

Quinn, et al. of the U.S. Army Corps of Engineers, conducted laboratory closed-system freezing and thawing tests on three different types of soils to determine their stability if used in MESL (membrane encapsulated soil layers) for road construction in cold regions [4]. Ellsworth clay had a maximum laboratory density of 1700 kg/m^3 (106.1 lb/ft^3), optimum moisture content of 18 percent using a compactive effort of 1.24 MPa (26 000 ft·lb/ft^3) by method CE-26, liquid limit of 49, and a plasticity index of 25. When 150-mm (6-in) long specimens of the soil were frozen from the top downward at a rate of 13 mm/d (0.5 in/d), there was very little overall moisture redistribution. Instead of heaving, these specimens shrank slightly (maximum of 1.6 percent) and the amount of shrinkage increased as the placement moisture content of different specimens increased toward the optimum moisture. The clay was expansive and the shrinkage was attributed to small amounts of water being withdrawn and redistributed in localized areas due to freezing of the soil water; where water was withdrawn, shrinkage would occur.

Elmendorf clay had a maximum density of 1840 kg/m^3 (114.9 lb/ft^3), an optimum moisture of 15.3 percent, a liquid limit of 40, and a plasticity index of 18. Specimens were molded at 62 to 97 percent saturation and during the freezing tests on this soil, the moisture content in the top 13 mm (0.5 in) of the specimens increased an average of 20 percent. For molded specimens up to 1 to 2

---

[1] Numbers in brackets refer to entries in the Bibliography.

percent below the optimum moisture content, no heaving developed; for specimens above this level, there was heaving to a maximum of 6 percent.

Hanover sandy silt had a maximum density of 1730 kg/m^3 (108.0 lb/ft^3), optimum moisture of 15 percent, a liquid limit of 27, and was nonplastic. For this soil, there was considerable movement of water toward the tops of specimens (maximum of 12.4 percent in the top 25 mm (1 in)) and the increase in water depended upon the molded density and moisture content. The greater increases in moisture content developed only in specimens with higher molding moisture contents and the molded density was not a significant influence on moisture changes. The total heave of specimens depended strongly on molding moisture content and degree of saturation, and the heave was much greater for molding moisture contents above 12 percent. The maximum heave was about 3.6 percent.

The Corps of Engineers' closed-system laboratory freezing tests on soils for MESL's have been followed by field test sections from which soil properties changes and traffic data have been gathered. One test was near Fairbanks in central Alaska where a lean clay with a liquid limit of 40 and plasticity index of 18 was used in a MESL [5]. The density of the soil at the top of the MESL fill was about 1410 kg/m^3 (88 lb/ft^3) which was 85 percent of the laboratory compaction values for the CE-12 compactive effort (0.57 MPa (12 000 ft·lb/ft^3)) at 13.2 percent moisture content; this was about 3 percent below the optimum moisture content of 16.4 percent. During the winter freezing season, the freezing rate was approximately 38 mm/d (1.5 in/d); this relatively high freezing rate was attributed to the low moisture content and density of the soil. Soil moisture tests after the soil had frozen showed a uniform moisture distribution in the 0.9-m (3-ft) depth of the MESL indicating no significant moisture migration toward the top or freeze-front during freezing.

Previous laboratory freezing tests on an undisturbed soil sample from the same Fairbanks source had been performed. The tests were on 100-percent saturated specimens at a freezing rate of 6 mm/d (0.25 in/d). The moisture redistribution in the sample after freezing ranged from 6.8 percent in the bottom unfrozen zone to 45 percent in the top 25 mm (1 in) as compared with a uniformly distributed 26.8 percent before freezing. Total heave of the 150-mm (6-in) high specimen was 15.1 percent and it occurred in about 12 days. The dry density of the sample was 1554 kg/m^3 (97 lb/ft^3). These tests show that differences in soil properties can occur in similar soil due to differing moisture, density, and freezing rate.

The Corps of Engineers [6] has conducted laboratory closed-system freezing tests along with open-system tests for improvement of highway and airfield pavements. Specimens which were about 150 mm (6 in) long and approximately the same diameter were frozen from the top downward at a rate of about 6 mm/d (0.25 in/d) with the bottoms maintained at temperatures between 1 to 3 °C (35 to 38 °F). Investigators found that for the closed-system tests the water contents at the bottom of specimens decreased to values which were relatively insensitive to the initial degree of saturation. On undisturbed and remolded lean clay specimens, the water content redistribution in highly plastic clay was extremely localized. The greatest change in moisture distribution was in silt. In one example of a New Hampshire silt with an original uniform moisture content of 23 percent, the moisture content at the end of the freezing test was 38 percent at the top and about 2 percent at the bottom; this specimen heaved about 7.8 percent. Evidence to date indicates that reduction of initial saturation to about 70 percent does not eliminate ice segregation and heave but does reduce it substantially as well as reducing moisture gain in the top 25 mm (1 in) of the specimen. For four different clays subjected to closed-system freezing, comparisons were made between the heaving of specimens of undisturbed soil with those of soil remolded to about the same dry density and degree of saturation. The heave percentage of the undisturbed specimens ranged from 2 percent for Fargo clay to 10.7 percent for Boston Blue clay. In three of the four clays, the percentage heave ranged from about 3 to 330 percent more for the remolded than for the undisturbed specimens. For the fourth stratified clay, the percentage heave for the undisturbed specimens was 6.8 percent, and 5.0 percent for the remolded specimens. For the open-system tests, the reverse was generally true in that frost heave in most cases was significantly reduced when the soil was remolded. This was explained by the reduction of permeability due to remolding which limited moisture transport from the free water source.

The Corps of Engineers has conducted laboratory tests on four fine-grained soils with plasticity indexes ranging from 0 to 20 to determine changes in soil structure and permeability during open-system freezing [7]. Each soil was prepared in the form of a slurry and degassed under vacuum. The samples were placed in a special consolidometer where they were consolidated to three different applied-effective-stress levels. Each sample was frozen in the consolidometer from the bottom upward while the top had access to water. Vertical permeability tests were performed on the sample in the consolidometer before and after cycles of freezing and thawing. In all cases, freezing and thawing caused a reduction in void ratio and an increase in permeability and these changes were greatest in the soils with the highest plasticity. Thin sections of the soil samples where clay was predominant showed the formation of vertical shrinkage cracks with a polygonal pattern and the increased permeability was attributed to these cracks. For the coarser-grained soils of low plasticity, cracks did not form and the increased permeability was attributed to a closer packing of fine soil particles between the coarser silt and sand particles which probably had grain to grain contact.

Wang and Roderick [8] studied the frost behavior of laboratory specimens of compacted, fine-grained soils during open- and closed-system freezing tests.

The 150-mm (6-in) high specimens were subjected to a constant temperature of −4 °C (25 °F) at the top and 7 °C (45 °F) at the bottom in a cold chest for 5 days. Temperatures at different depths in the specimens were monitored by thermocouples and specimen length changes by dial gages. An X-ray machine was used to detect ice lenses. Three test soils were used: Providence silt, and two mixtures of Providence silt with different amounts of commercial Ca-montmorillonite plus sand-sized particles. One mixture had 21 percent Ca-montmorillonite plus 4 percent sand by mass, and the other had 57 percent Ca-montmorillonite plus 10 percent sand. The plasticity indexes ranged from 4 for the silt alone to 21 for the mixture with the highest clay content. In addition to the different soil textures, the test variables were dry density and degree of saturation.

For a 60-percent saturation, the effect of dry density on the depth of freezing temperature penetration was insignificant for the closed system; whereas, in the open system, the freezing temperature penetration increased significantly with an increase in density. The rate of freezing in the closed system was faster than for the open system because of the additional latent heat of fusion to be removed for the open system. For the particular test conditions, the rate of frost penetration increased above a depth of 57 mm (2.25 in) but below this depth, the rate tended to decrease as the content of fines smaller than 0.002 mm increased. Water content determinations at the end of the freezing test showed the typical moisture migration toward the tops of specimens. Frost heave for the closed-system specimens was much less than for the open-system specimens, and in some cases, shrinkage occurred. Also, ice lenses (as measured by X-ray) in the closed-system specimens were much thinner than for the open-system specimens. Penetration of the ice front approached a maximum sooner in the closed system than in the open system.

One cause of differential volume change in clayey highway subgrades causing cracking of asphaltic pavements has been attributed to shrinkage of the clay due to freezing action. This can occur without significant moisture migration, particularly if the freezing is rapid. Hamilton [9] explored this phenomenon in the laboratory by closed-system freezing of compacted clay specimens. The soils were lean to heavy clays with plasticity indexes from 17 to 59, and from 23 to 75 percent finer than 0.002 mm. Maximum shrinkage occurred at degrees of saturation between 60 to 70 percent with 86 to 90 percent saturation being required for no volume change. Increasing the compactive effort caused a reduction in the maximum measured shrinkage in a highly plastic, lacustrine clay. Hamilton explains the soil volume changes as follows; this is based on a theory by Power and Helmuth [10] on volume changes in cement pastes on freezing. "Upon freezing to a given temperature, two opposing forces develop tending to cause volume change in the soil mass. An expansionary tendency is created by the volume increase which results when soil water freezes. Shrinkage forces also are present as freezing of the soil water reduces the thickness of adsorbed water films around individual soil particles and packets of soil particles, and increases soil suction in a manner similar to drying. In general, the tendency to expansion will predominate in soils at high degrees of saturation, while overall shrinkage occurs at lower degrees of saturation. At very low degrees of saturation, shrinkage is limited by the very large attractive forces exerted by the clay particles on the adsorbed water, which prevents freezing except at very low temperatures."

Hamilton found that the total vertical shrinkage to a depth of 1070 mm (42 in) in the clay subgrade of a highway was 15 mm (0.60 in), or 1.4 percent.

Investigators in the Soviet Union have studied "frost-cleft cracking" of soils in earth dams up to 15 m (49 ft) in height [11]. They were concerned about dam failures due to water flowing through transverse cracks in the dam body and through gaps formed during winter between the abutment and the embankment. They derived formulas for calculating the amount of shrinkage and conducted tests on an existing dam in Central Yakutia on the Suola River. The program consisted of determining (1) temperature stresses and strains in the dam body, (2) soil temperatures in the dam, (3) deformation between the dam body and abutment, and (4) moisture changes in the dam. A special dial gage extensometer was made to measure horizontal and vertical strains; these were installed in the dam body and between the embankment and abutment. The average minimum air temperature was −43 °C (−45 °F) and the average minimum temperature in one of the bore holes −23 °C (−9 °F). The results of the tests compared reasonably well with a method of calculation they developed. They established that temperature stresses in a dam built of sandy loam can be appreciable and found that a 4- to 5-mm gap formed between the embankment and abutment which could cause dam failure during the spring runoff season. It was concluded that in planning a dam in a cold area, a verification of frost-cleft cracking was a mandatory step.

The Soviets also devised laboratory tests for determining the short- and long-term compressive and tensile strength characteristics of frozen sandy loam soils in the range of −1 to −6 °C [12]. From the tests, the temperature stresses could be estimated and the formation of frost-cleft cracks in the body of a dam predicted.

LOCATION OF SOIL FROST TEST SITES AND FREEZING INDEX VALUES

The locations of canal, reservoir, and earth embankment sites where field tests are mentioned in this report are shown in figure 1. These locations are superimposed on a map of the continental United States having isolines of design freezing index which was developed for pavements. An annual freezing index for a particular geographical area is found by averaging daily maximum and minimum air temperatures during the cold season, plotting a cumulative curve of differences between these temperatures and freezing and determining the difference between maximum and minimum points on the curve. The freezing duration is the number of days elapsed between the maximum and minimum points on the curve. The freezing index is expressed in terms of degree-days. The design freezing index values on the map are cumulative degree-days for the coldest year in a 10-year cycle or the average of the three coldest years in a 30-year cycle. The values on the map should be used as a general guide only, because the freezing index can vary widely within short distances, particularly where ground elevations change rapidly as in or near mountainous areas. Where possible, the actual freezing index should be obtained from temperatures obtained at the structure location.

CANAL LININGS

Canal soil linings are built up of relatively impervious soils placed in 150-mm (6-in) thick horizontal layers compacted to a minimum of 95 percent of the maximum Proctor density and near optimum moisture content [14, 15]. For the thick type of lining usually recommended, the total thickness is about 0.6 m (2 ft) on the canal bottom, and about 1.1-m (3.5-ft) thick normal to a 2:1 side slope. During the winter nonirrigation season, when the canal is not in operation, the only water in the canal is from ground water, precipitation, and snow melt. Except in certain areas where the ground water level may remain near the lining, the water drains away from underneath the lining and any freezing action in the lining takes place in essentially a closed system.

About 25 years ago, the Water and Power Resources Service began an investigation of selected soil canal linings to measure soil moisture and density at time intervals beginning with the time of lining construction. Any significant changes in seepage through the lining would be reflected by changes in soil density. Of particular concern were silty soils in cold climates where frost action would occur; a report [16] on several linings was published. From data gathered during

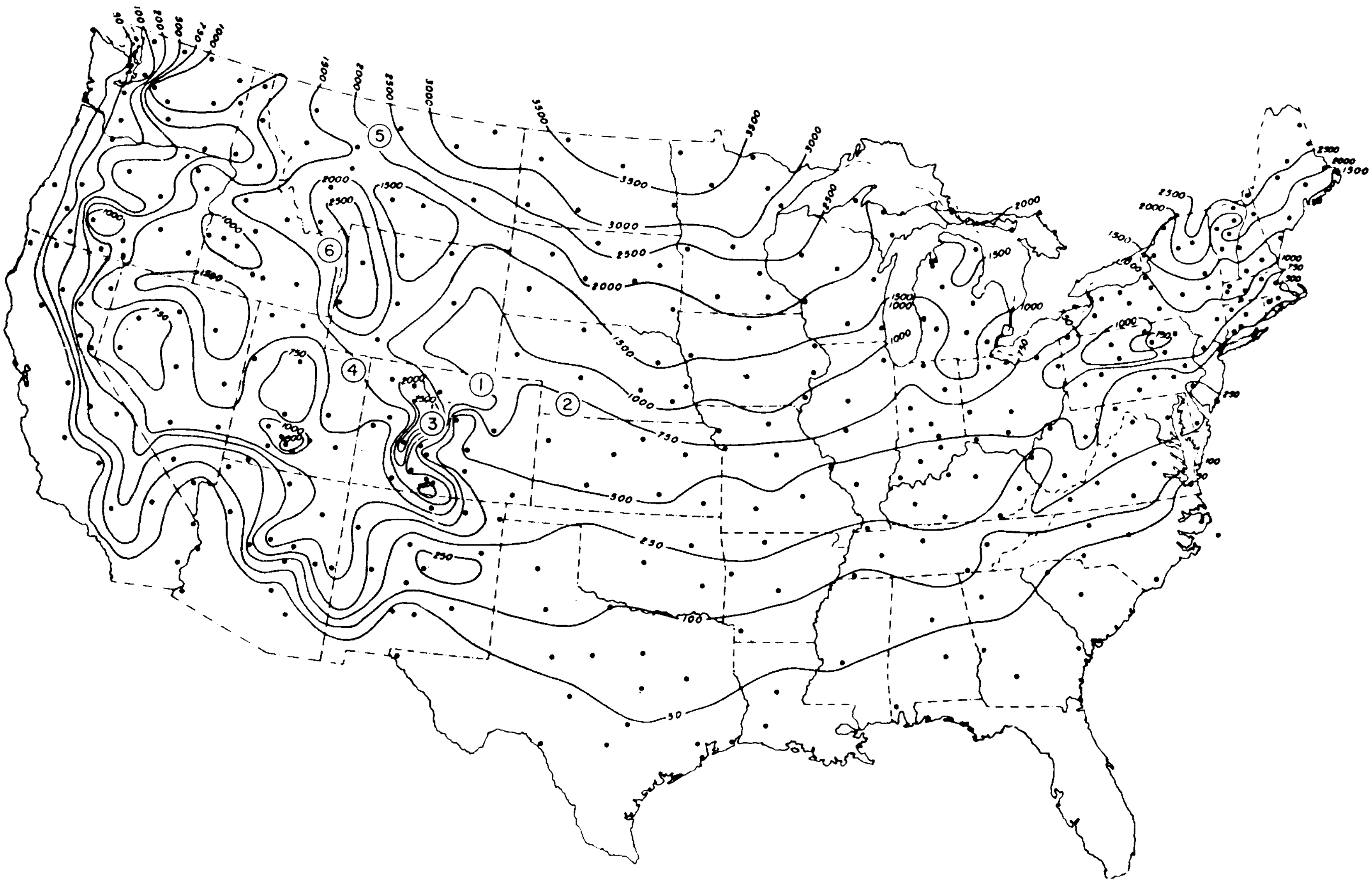

Figure 1.—Location of soil frost tests superimposed on distribution of design freezing index values (°F·d) in continental United States (adapted from reference [13]).

(1) South Platte Supply Canal,
(2) Upper Meeker Canal,
(3) Mt. Elbert forebay and Twin Lakes Dam,
(4) Red Fleet Dam,
(5) Tiber Dam, and
(6) the Teton Dam remnant.

this investigation, it was found that the density, particularly in the top half of the lining, changed from year to year, sometimes increasing, sometimes decreasing. Although most of the linings show some degree of density decrease with time, in several cases the average density for the full lining thickness has increased and remained higher than that at the time of construction. Such was the case with lining of the South Platte Supply Canal located near Denver, Colo., and Upper Meeker Canal near McCook, Nebr. According to figure 1, the design freezing index for the South Platte Supply Canal is about 550 °C·d (1000 °F·d) and that for Upper Meeker Canal is about 415 °C·d (750 °F·d). This apparent anomaly in density change led to a laboratory freezing investigation for a possible explanation. The procedure for the laboratory freezing tests is given in appendix B.

Soil Lining on South Platte Supply and Upper Meeker Canals

Field density tests.—The South Platte Supply Canal lining, completed in 1956, consisted of a clayey sand made by mixing two soils. It was only 0.46 m (1.5 ft) thick, which is thinner than normally recommended for soil linings. The canal had a bottom width of 3.7 m (12 ft), a water depth of 1.04 m (3.4 ft), and 2:1 side slopes. The test reach was 82-m (270-ft) long and five field density tests were obtained in the sides and bottom each year it was tested. Figure 2 shows the averages of five sets of tests obtained from the end of construction to 1976; the maximum density increase was 77 kg/m^3 (4.8 lb/ft^3) and the final increase of 43 kg/m^3 (2.7 lb/ft^3). The field density increased to be greater than the maximum Proctor density. Although the lining was intact in 1962, by 1976, most of the side lining was gone and the result shown for that year is from tests on compacted soil remaining in the canal bottom. The side lining had either eroded from water action, or, as is more likely, had been scoured out during canal cleaning; this is one of the reasons for usually requiring a thicker lining.

The Upper Meeker canal lining, constructed in 1957, consisted of silt. It had a thickness of 0.6 m (2 ft) on the canal bottom and 1.0 m (3.3 ft) on the sides which had a slope of 1.5:1. The canal bottom width was 4.9 m (16 ft) and the water depth 1.58 m (5.2 ft). Three different sections of the canal were selected for density tests within a 10 570-m (34 663-ft) reach. At each section, three tests in the side lining (one at each of the quarter points in the depth of the lining normal to the slope) and two tests in the bottom lining (one at each of the third points in the lining depth) were obtained for a total of 15 tests each

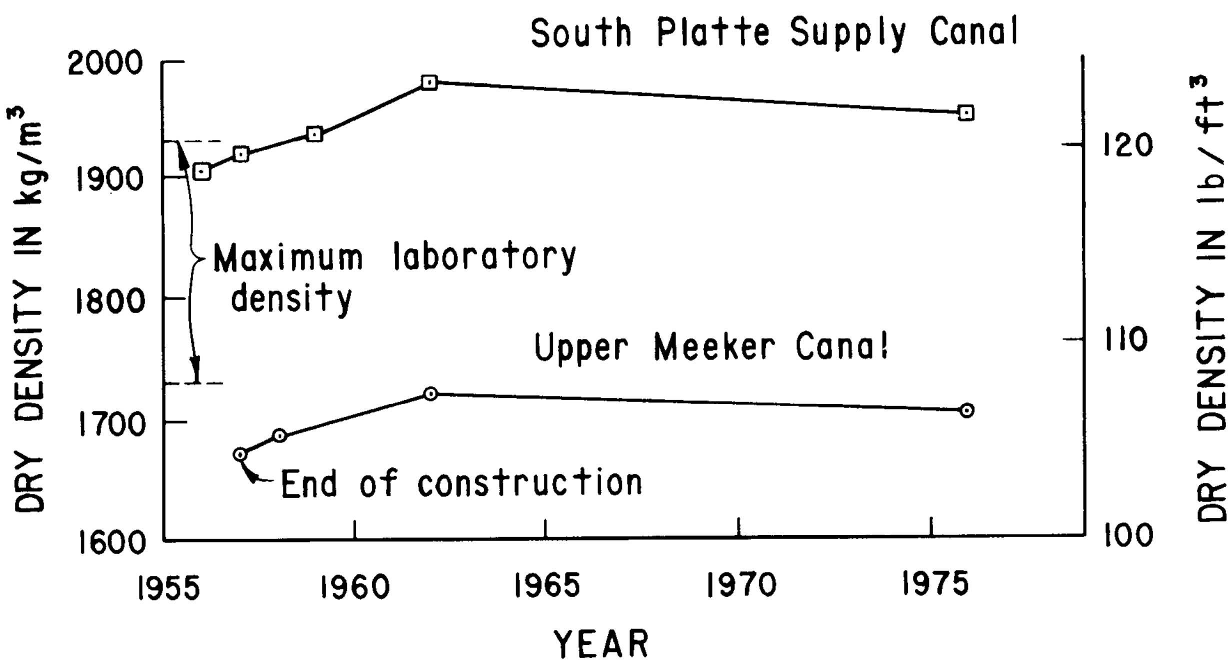

Figure 2.—Changes in the density of compacted soil canal linings.

year tests were conducted. Figure 2 shows the averages of four sets of tests conducted from the end of construction to 1976.

Frost penetration measurements.—In March 1960, frost penetration depths and observations of snow and ice were made on Upper Meeker Canal (table A-1) and the maximum penetration was 0.76 m (2.5 ft). Measurements made during the winter of 1961-62 in this lining showed that the maximum frost penetration was about 0.55 m (1.8 ft). Once, when holes were being augered in this lining, fine, horizontal striations about 0.1 to 0.2 m (0.3 to 0.7 ft) from the top of hole were noticed. These were attributed to have resulted from frost action during some previous winter.

Soil properties.—In addition to the soil from the South Platte Supply and Upper Meeker Canals, an additional soil from Hudson Canal located near Tucumcari, N. Mex., was used in the laboratory freezing investigation. This provided a source of lean clay soil for comparison of results with the other two canal soils. Because only one set of density test in this lining was obtained, no field density changes were determined.

The gradation test analyses of the soils used in the freezing tests are shown in figure 3 and the laboratory compaction curves in figure 4. All laboratory tests reported herein were conducted in accordance with procedures in the Earth Manual [18], unless otherwise noted. Other physical properties of the soils used in the laboratory freezing tests are as follows:

	Upper Meeker	South Platte Supply	Hudson
Classification	ML	SC	CL
Relative mass density (specific gravity)	2.64	2.69	2.69
Liquid limit	25	23	24
Plasticity index	1	10	13
Max. lab. density, kg/m³ (lb/ft³)	1730 (108.1)	1935 (120.7)	1940 (121.0)
Optimum moisture (%)	16.0	11.3	11.8

The results of petrographic and chemical analyses on these soils are summarized in appendix C.

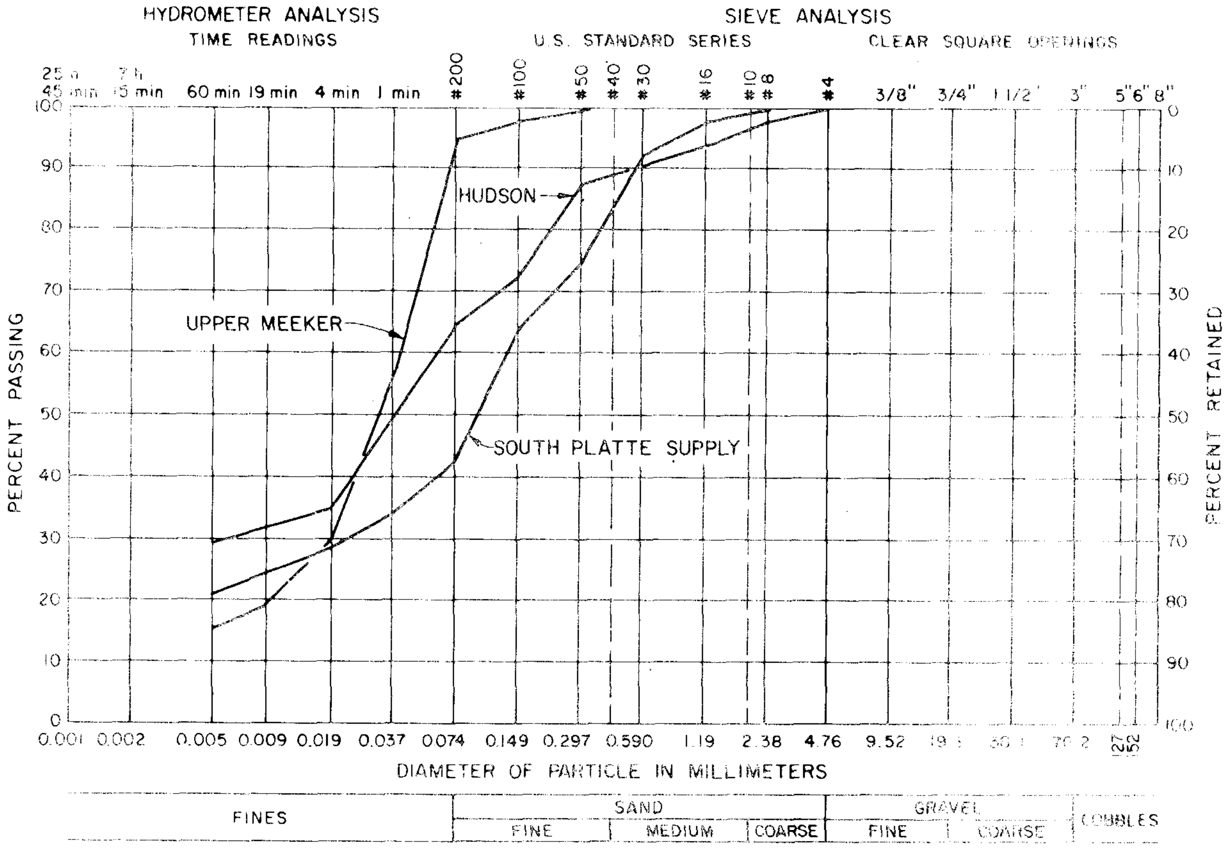

Figure 3. – Gradation analyses of canal lining soils.

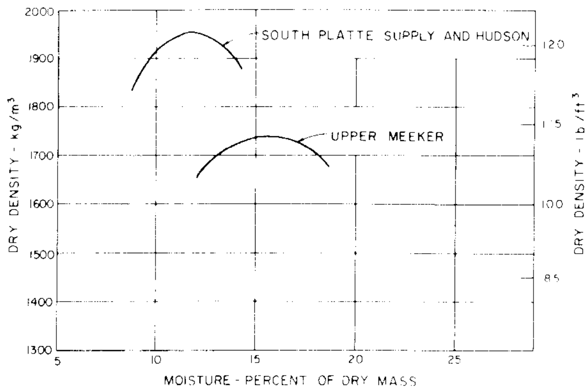

Figure 4.—Proctor compaction curves for canal soils.

Laboratory freezing tests.—There were two series of laboratory closed-system freezing tests conducted on duplicate soil specimens 83 mm (3.25 in) in diameter by 230 mm (9 in) long; series A consisted of three tests on the Upper Meeker soil placed at 94 percent of the maximum Proctor density and with (a) optimum moisture content, (b) 2 percent above optimum, and (c) 4 percent above optimum. Test series B was on specimens of Upper Meeker soil placed at 94 percent of the maximum laboratory density, and South Platte Supply and Hudson soils placed at 100 percent of the maximum laboratory density. The moisture contents for this series were at optimum. In both test series the specimens were frozen from the top downward. Test series A was conducted over a 30-day period and series B over a 90-day period. Plots of temperatures and specimen length changes for test series A and B are shown in figures 5 and 6, respectively. The frozen specimens were cut into thirds and moisture content determinations were made on each third. In addition, for test series B, density tests were made on each third. The results of tests in series A and B are shown in figures 7 and 8, respectively.

For test series A, the specimens of Upper Meeker soil at optimum moisture decreased a maximum of 0.8 percent in length. Those at 2 percent above optimum increased a maximum of 0.5 percent, while those at 4 percent above optimum increased a maximum of 2.3 percent in length. Most of the length changes occurred during the first 5 to 10 days of freezing, and thereafter, for the specimens placed above optimum moisture, the specimen lengths decreased about 0.3 percent. The soil density (fig. 7) increased slightly for the specimens at optimum, remained about the same for those at 2 percent above, and decreased slightly for those at 4 percent above. Moisture content determinations on the top, middle, and bottom thirds of specimens clearly showed a redistribution of moisture from the bottoms toward the tops, particularly for specimens originally with moisture contents at 2 and 4 percent above optimum where the final top moisture was about 11 percent higher than the bottom.

For test series B, the lengths of specimens of the South Platte Supply and Hudson soils increased a maximum of about 1 percent during freezing, while those from Upper Meeker increased about 2.5 percent (fig. 6). In comparing the length and density changes of the Upper Meeker soil, note that at the slower freezing rate (test series B), the specimens expanded, whereas at the higher rate, they shrank slightly (test series A). The Upper Meeker soil in test series B with the slower freezing rate showed a greater redistribution of moisture toward the top than in test series A; the differences between the top and bottom were 18 and 7 percent, respectively. At the higher freezing rate, there was apparently insufficient time for the maximum amount of moisture redistribution to take place.

For the freezing tests on the South Platte soil (test series B), it is interesting to note that both the specimen length and the density increased. This would indicate that a lateral shrinkage of the specimen occurred.

Laboratory Tests on Whitestone Flats and Oakes Section Soils

In 1974, an investigation was made into concrete lining failures on the Whitestone Flats Canal on the Chief Joseph Dam Project in north-central Washington. One possible cause was frost action in the soil subgrade causing heaving and cracking of the concrete lining. Therefore, open- and closed-system laboratory freeze tests were conducted on samples of the subgrade.

In 1958, laboratory open- and closed-system freezing tests were conducted on soil from the Oakes Section, Garrison Diversion Unit, of the Pick-Sloan Missouri Basin Program, in northern South Dakota [17]. The soil was representative of borrow areas proposed for compacted soil lining. The proposed construction was in areas of high ground water and the average freezing index was about 1100 °C·d (2000 °F·d).

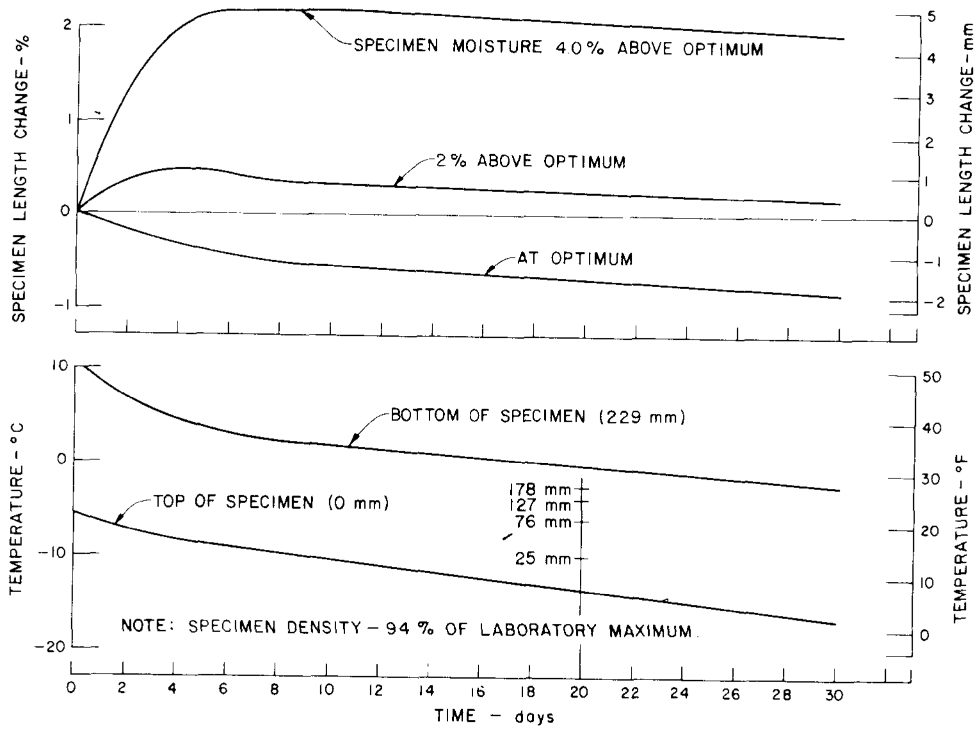

Figure 5.—Temperature and specimen length changes during laboratory freezing tests on soil from Upper Meeker Canal lining, test series A.

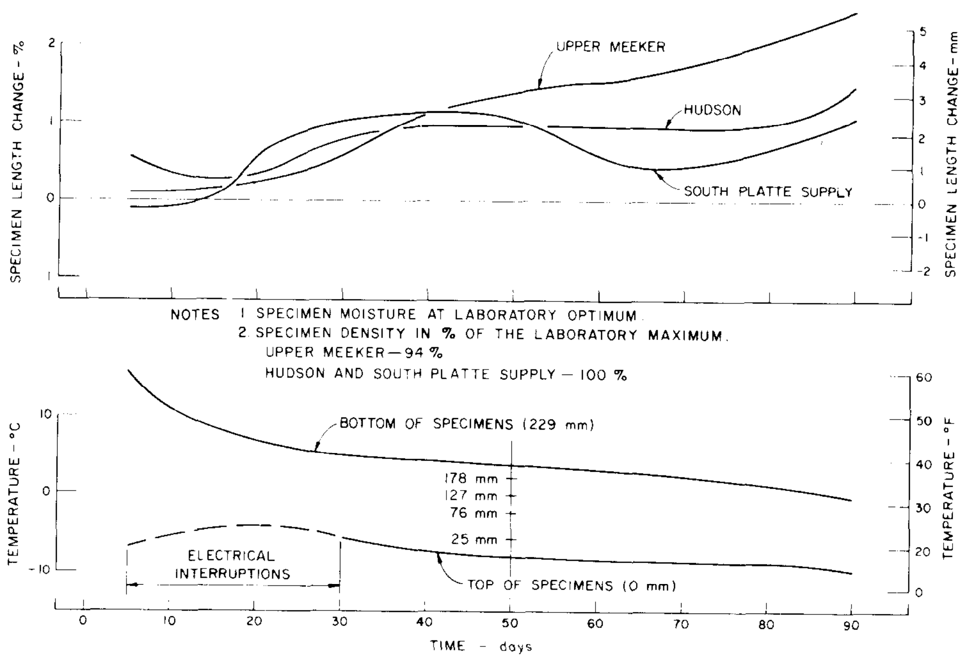

Figure 6.—Temperature and specimen length changes during laboratory freezing tests on soil from Upper Meeker, South Platte, and Hudson Canal linings, test series B.

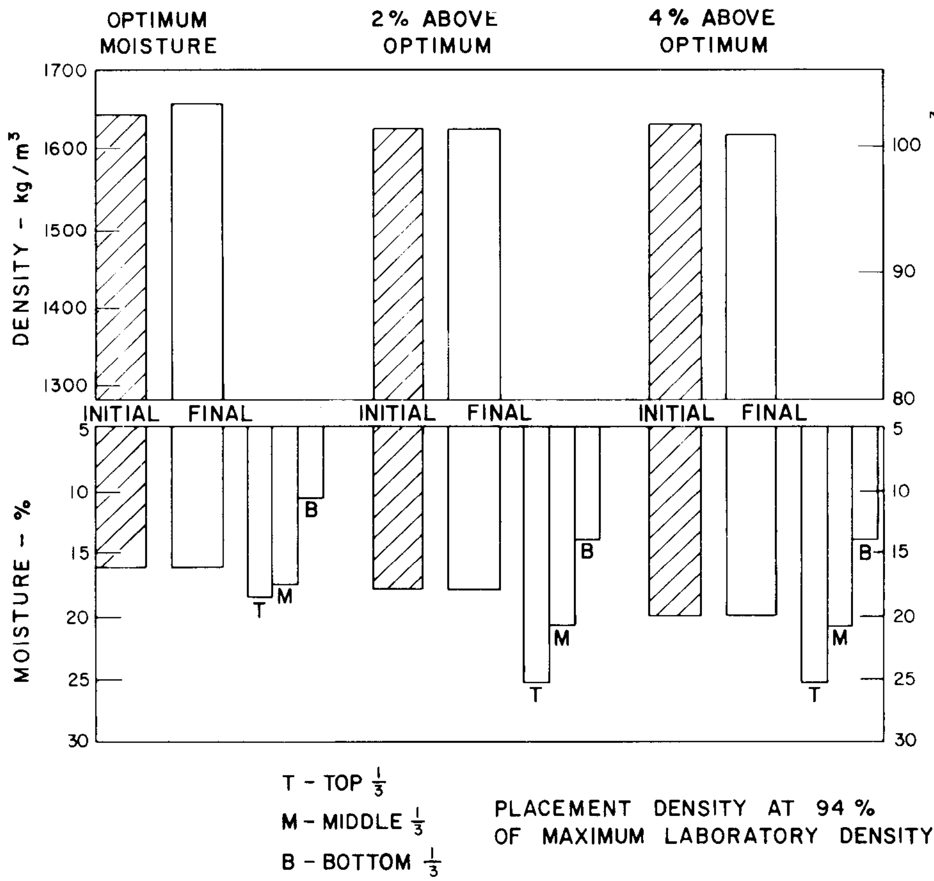

Figure 7.—Density and moisture contents of Upper Meeker Canal lining soil before and after freezing test, test series A.

The laboratory gradation and moisture-density curves for the soils from the Whitestone Flats Canal and the Oakes Section are shown in figures 9 and 10, respectively. A summary of the physical properties follows:

Soil	Classification	Max. lab density, kg/m³ (lb/ft³)	Optimum moisture (percent)	LL	PI
Whitestone Flats	CL-ML	1799 (112.3)	14.0	23	5
Oakes Section Glacial till	CL	1794 (112.0)	15.4	28	12

The freezing test procedure on these soils was similar to that described for the canal lining soils except the specimens were only partially frozen and they were provided with plastic top plates. They were compacted under nearly optimum laboratory moisture conditions, with the density of the Whitestone Flats soil being near the maximum Proctor density and that for the Oakes Section soil at 95 percent of the maximum. Both open- and closed-system tests were conducted on each soil. Because the main purpose of these tests was to assess frost heave potential, no moisture or density tests were conducted on the specimens after freezing.

The freezing test for the Whitestone Flats Canal soil (fig. 11) was conducted over a 30-day period. For the first 13 days of the test, the temperature of the specimen tops was above freezing and there were negligible specimen length changes; the open-system specimens absorbed less than 100 mL of water. After the 20th day of the test, absorbed water rose rapidly (to 280 mL) and the length increased a maximum of 40 mm (1.6 in), or

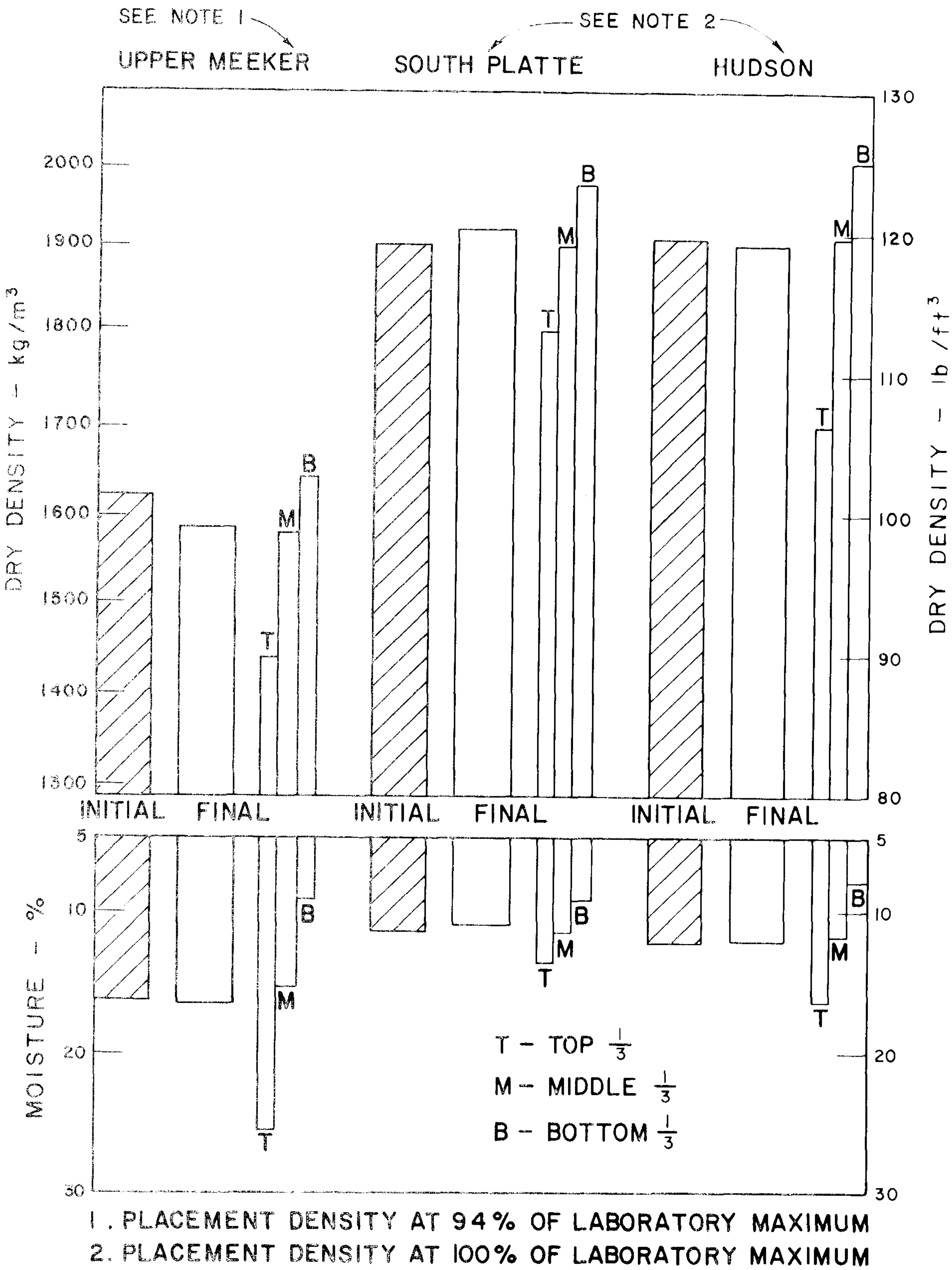

Figure 8.--Density and moisture contents of canal lining soils before and after freezing tests, test series B.

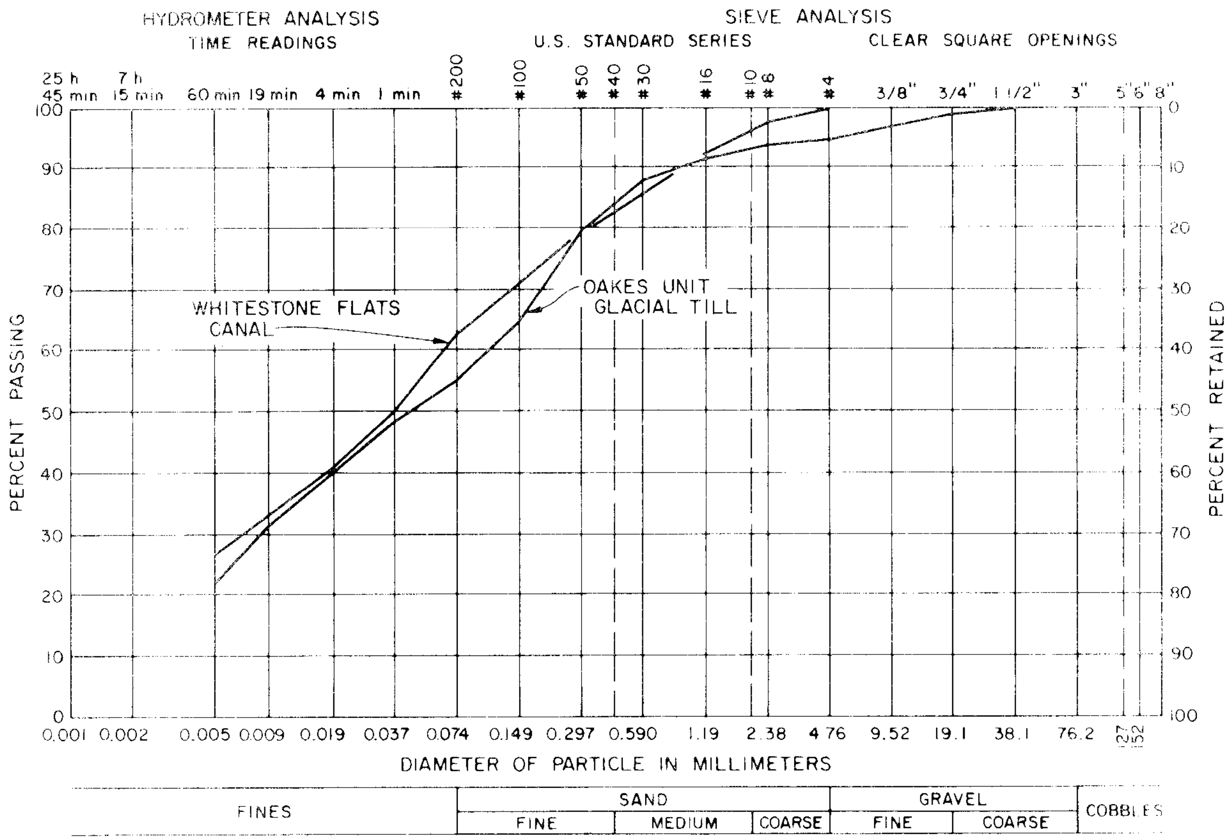

Figure 9.– Gradation analyses of Whitestone Flats Canal and Oakes Section glacial till soils.

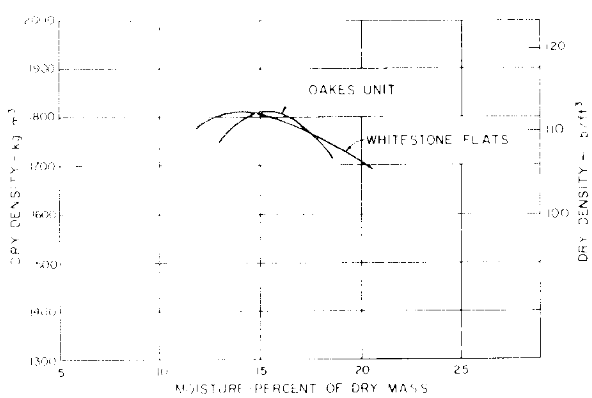

Figure 10.– Proctor compaction curves of soils from Whitestone Flats Canal and Oakes Section.

nearly 2 percent. The closed-system specimen only increased about 3 mm (0.1 in) in length. The maximum depth of freezing for these specimens was about 75 mm (3 in), one-third of the specimen length. A photograph (fig. 12) taken immediately after the specimens were removed from the freezing test container, dramatically shows the difference in effects of the open- and closed-system freezing on this soil. No ice lenses were observed in the closed-system specimen; however, the top portion of the open-system specimen was filled with thin, disconnected ice lenses.

The freezing test for the Oakes Section glacial till was over a 21-day period (fig. 13). The temperature of the tops of the specimens was lowered to freezing in about 3 days and the maximum depth of frost during the test was about 75 mm (3 in). The length change of the open-system specimens increased sharply after the initial 3-day period and reached 2.8 percent at the end of a 21-day freezing period. The water absorption of the open-system specimens rose sharply at the beginning of the test; after about 8 days, it rose more gradually until it reached about 200 mL. A photograph (fig. 14) taken immediately after the freezing test shows the difference between the open- and the closed-system tests. One of the closed-system specimens showed no evidence of ice, while in the second closed-system specimen,

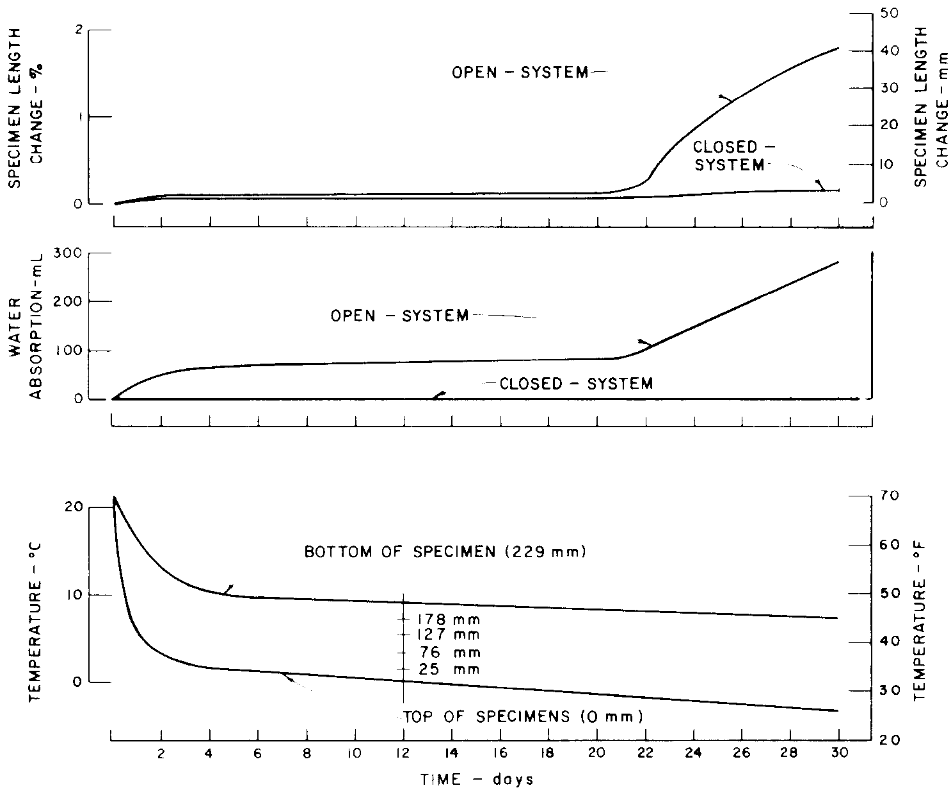

Figure 11.—Temperatures, water absorption, and length changes of specimens of Whitestone Flats Canal soil during freezing tests.

a thin ice lens had formed about a quarter of the way down from the top. For the open-system specimen, two bands of freezing in the top one-third of the specimen were evident.

Failure of Buried Plastic Membrane Lining

The following is believed to be an example of closed-system freezing causing the failure of a short section of buried plastic membrane canal lining. Fortunately, this type of failure is an isolated instance, but it resulted in corrective measures to prevent future recurrence in new construction.

On February 15, 1977, a slide occurred on the PVC (polyvinyl chloride) lined right bank of Pilot Canal of the Riverton Project, Wyoming, between stations 185+93 and 186+54 m (610+00 and 612+00 ft) (fig. 15). The 10-mil-thick lining was placed in November 1976 and no water had been placed in the canal before the slide occurred. The cover over the membrane consisted of 0.23 m (9 in) of soil from canal excavation superimposed by 0.23 m of pit-run gravel. This section of canal has a water depth of 3 m (10 ft), bottom width of 9.15 m (30 ft), and 2:1 side slopes.

For a major portion of the slide, slippage occurred between the membrane and the soil underneath. Observations of an adjacent section of lining revealed a thin layer of ice directly underneath the lining. Also, for about a 50-mm (2-in) depth beneath the lining, there was a series of ice lenses about 1 to 2 mm (1/16 to 1/8 in) thick, alternating with layers of soil, which is typical of frost action. The soil beneath the membrane was a sandy clay with a liquid limit of 37 and a plasticity index of 19. Ninety-six percent of the soil particles passed the No. 4 sieve, 90 percent passed the No. 40, 60 percent passed No. 200, and 25 percent were finer than 0.005 mm.

There was no water table under the lining sufficiently near the canal surface to have caused open-system freezing. Apparently, as frost penetrated into the subgrade, moisture migrated upward and froze at and in thin lenses immediately below the plastic lining barrier. The record of

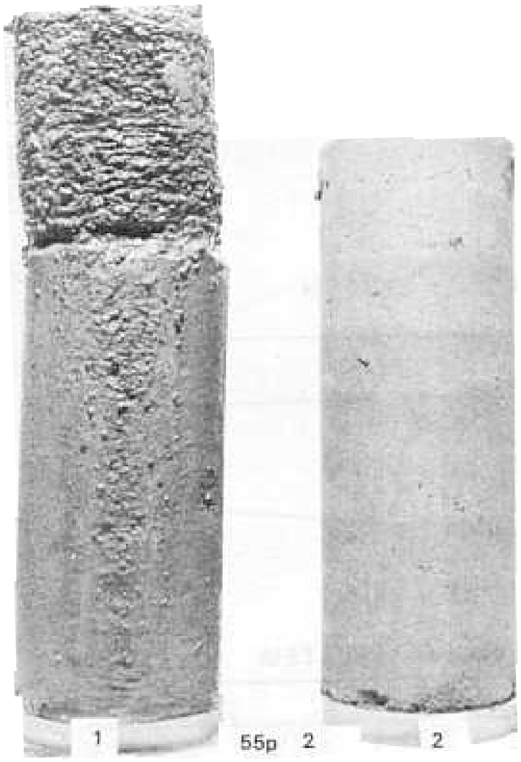

Figure 12.—Results of laboratory open-system (left) and closed-system (right) freezing tests on duplicate specimens of silty, lean clay from Whitestone Flats Canal. Photo E-2343-6

daily temperatures in the general area showed an unseasonable warming trend for a few days prior to the slide, with the maximum temperatures up to 13 °C (55 °F). This probably caused thawing to depths immediately below the plastic membrane. Melting water would be trapped between the plastic membrane and frozen material below and lubrication under the lining seems to be a plausible explanation for the cause of the slide.

Previous to the time of the slide, the subgrade for PVC lining was lightly compacted by rolling to form a smooth surface to avoid puncturing the plastic by rock particles. For new construction since the slide, the uncompacted subgrade surface is dragged to remove projecting particles likely to cause puncturing. Also, a 50-mm (2-in) layer of sand of unspecified grading may be applied at the option of the contracting officer. These measures are intended to provide more frictional resistance to sliding and drainage below the membrane.

SOIL RESERVOIR LINING ON MT. ELBERT FOREBAY

Mt. Elbert Forebay (elevation about 2925 m (9600 ft)) is part of the Mt. Elbert Pumped-Storage Project at Twin Lakes Dam in Colorado. The reservoir was lined with 1.5 m (5 ft) of compacted soil during construction of the dam and forebay in 1976-77. Subsequent to the lining placement there has been concern about potential sliding of slopes in the penstock area between the forebay and the pumping plant. The ground-water level has been monitored by piezometers and an attempt was made to determine whether seepage through the lining could affect the slope stability. The soil in the forebay lining is a silty to clayey sand with about 8 to 27 percent gravel (fig. 16). The liquid limit of samples taken from two locations where frost penetration was measured averaged 26 and the plasticity index 10.

In the fall of 1977, field permeability tests were conducted in the lining. Twenty well-permeameter tests [18] were conducted and the rates ranged from 0.2 to 33 $\times$ 10^{-8} m/s (1×10^{-8} m/s is approximately the same as 1 ft/yr) with an average of 8.5×10^{-8} m/s. Simultaneously, four ring-permeameter tests [19] were conducted and the results of these tests were 0.22, 1.3, 3.3, and 5.4×10^{-8} m/s, which average 2.5×10^{-8} m/s.

Neither of these tests is ideal for determining the permeability of a 1.5-m (5-ft) layer of soil. The well for the well-permeameter test, because of the required ratio of depth to diameter, penetrates too deeply into the layer which would tend to cause the rates to be high. On the other hand, the ring-permeameter test which was made near the lining surface, has the limitation that the soil immediately below the test zone must have equal or greater permeability than that of the test zone. Experience with soil linings on canals generally has been that soil permeability decreases with depth in the lining. In 1977-78, the surface of the soil lining was "proof rolled" to decrease permeability by increasing the density. After scarification and the addition of moisture, a sheepsfoot roller followed by a 75-ton pneumatic-tired roller was used.

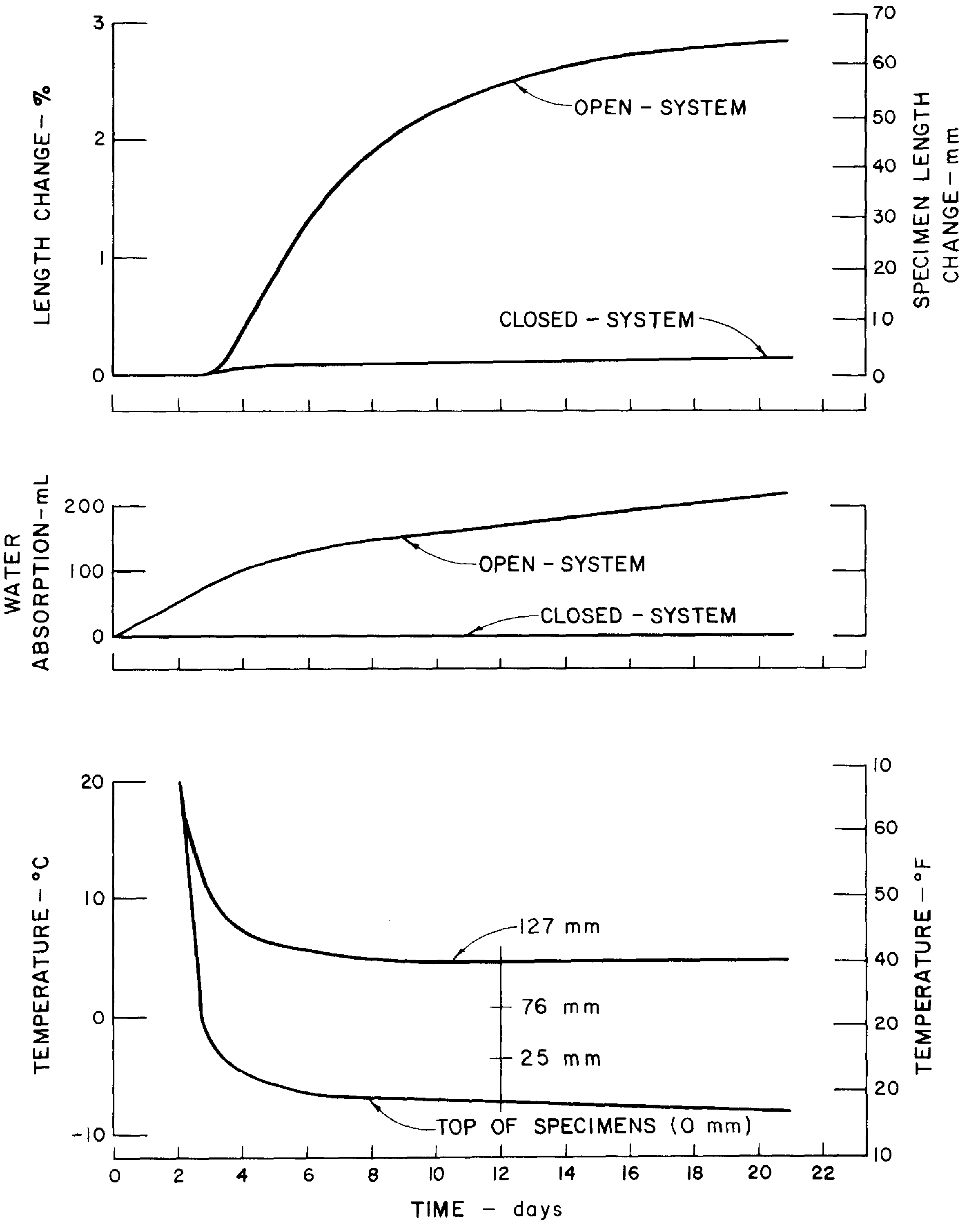

Figure 13.—Temperatures, water absorption, and length changes of Oakes Section glacial till during laboratory freezing tests.

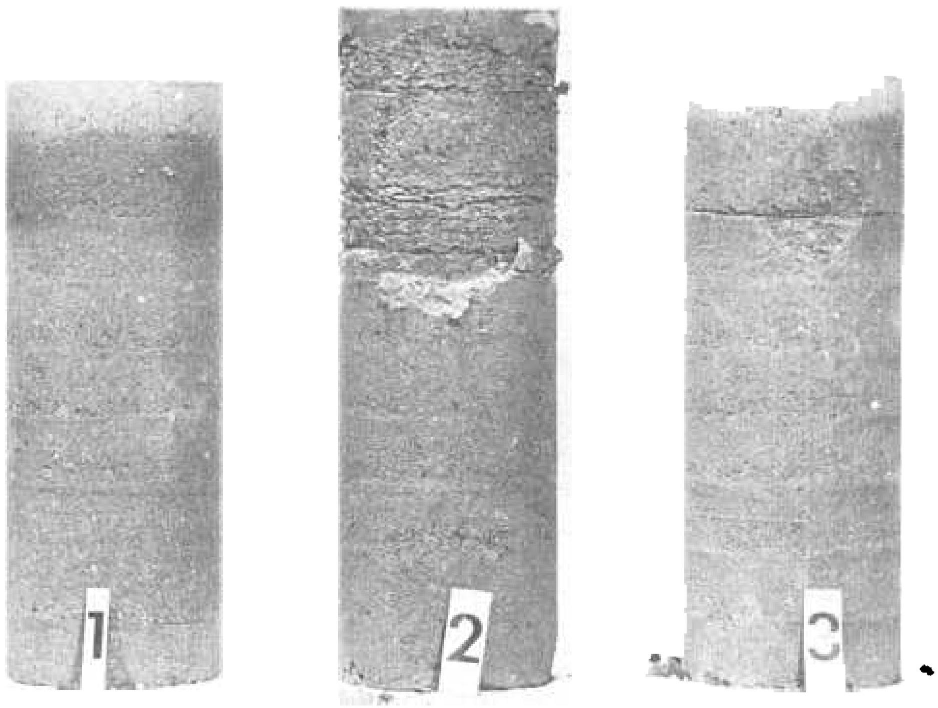

Figure 14.—Specimens of Oakes Section soil after laboratory freezing tests. Specimen 2 was the only one with the open system. Note the thin ice lense in specimen 3 which was subjected to closed-system freezing. Photo E-1887-4.

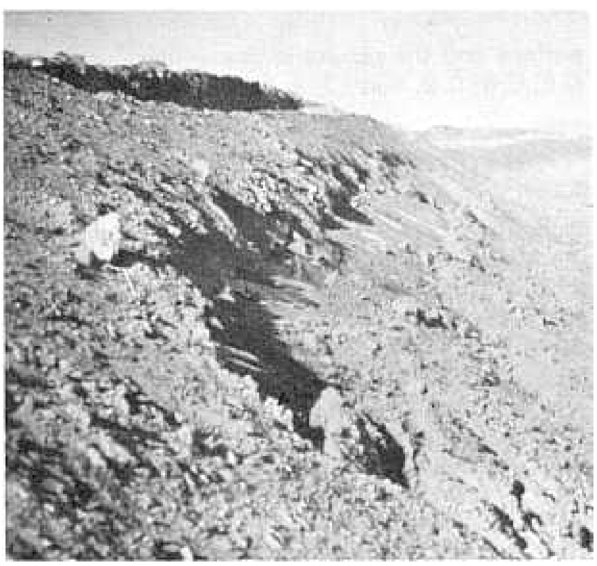

Figure 15.—Slippage of polyvinyl chloride membrane lining due to closed-system freezing. Photo P801-D-79452

During the winter of 1978-79, two frost tubes were installed in the lining to determine frost penetration (fig. 17). The tubes were installed about the middle of December 1978 when there was about 0.4 m (1.3 ft) of frost in the ground. By March, the frost had completely penetrated the lining, and it was about the first of May before all frost was out. Snow depths ranged up to 45 cm (1.5 ft).

In June 1979, two test pits were excavated in the forebay lining adjacent to the frost tube locations and field density tests conducted. The results of these tests are plotted on figure 17 and are also shown in table A-2 with relative mass density, liquid limit, and plasticity index test results. The density tests averaged about 100 percent of the maximum Proctor density, with the lowest value being 97.4 percent. In one test pit, the density of the compacted soil immediately below the grade level was 99.7 percent of the maximum Proctor density compared to 101.7 percent in July 1978 after the proof-rolling. In the sides of the test pit

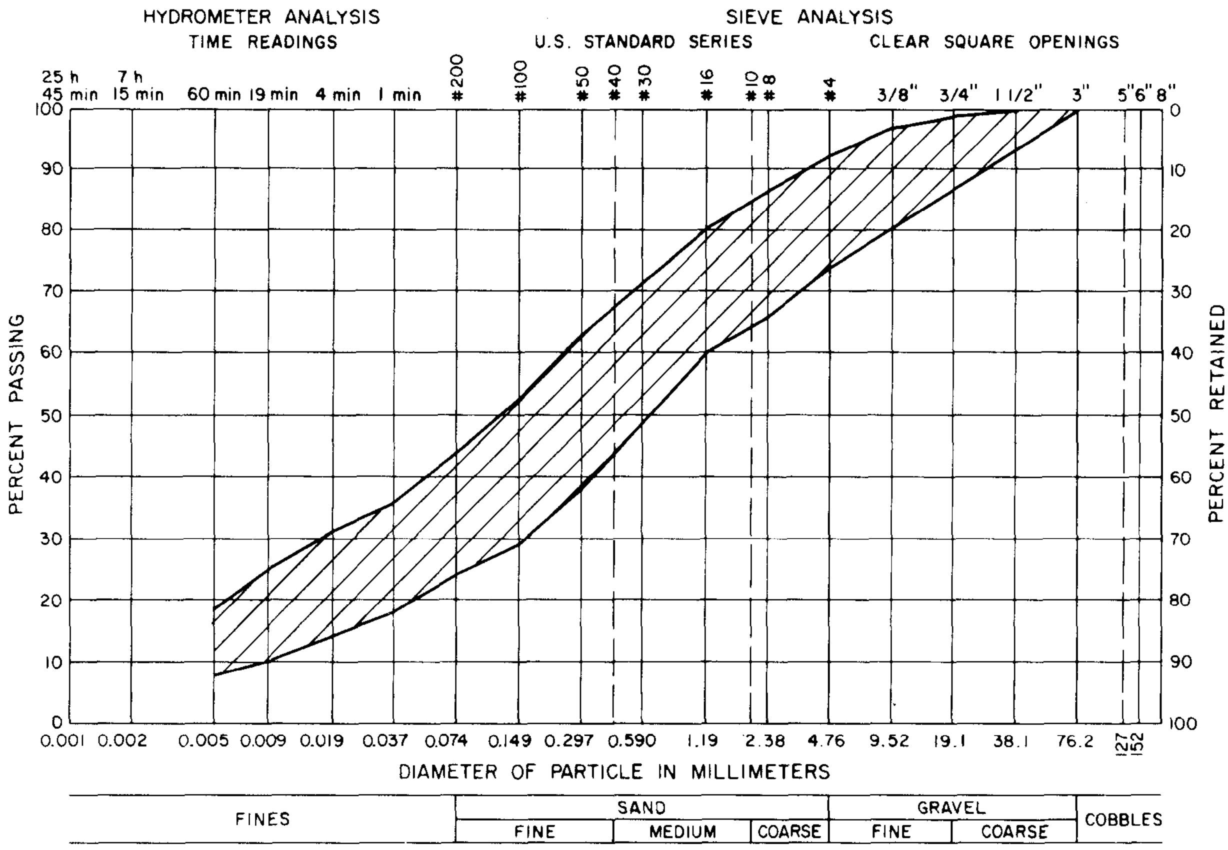

Figure 16.—Range of soil gradations at frost tube locations in Mt. Elbert forebay reservoir lining.

where the density tests were taken, cracks averaging about 0.5 mm (1/32 in) but ranging up to 1 mm (1/16 in) in width were found in a zone from the lining surface to a depth of about 0.4 m (15 in). These cracks were generally in a horizontal direction and were thought by the observer to have been caused by frost action; this may have been an example of shrinkage caused by freezing. In the other test pit, the density of the compacted soil immediately below the grade level was 100.2 percent of the laboratory maximum compared to 100.4 percent in July 1978 after the proofrolling. The density test pit in this area filled with rainwater before an examination for cracks or other effects of frost action could be made.

During the summer and early fall of 1979, five ring-permeameter tests were conducted in the lining after removal of any loose material on the surface and the results of these tests were 1.1, 0.8, 0.6, 0.9, and 11×10^{-8} m/s.

EARTH EMBANKMENT DAMS

During the cessation of compacted embankment placement due to cold winter weather, closed-system freezing occurs near the embankment surface. Soil with a density decrease below the minimum specification limit needs to be recompacted prior to the addition of new soil. During the unusually cold winter of 1978-79, frost penetration measurements were made on the following dams where, with the exception of Teton, construction activities were halted: (1) Red Fleet (Tyzack), Central Utah Project (2) Twin Lakes, Fryingpan-Arkansas Project, Colorado; (3) Tiber (rehabilitation), Lower Marias Unit, Montana; and

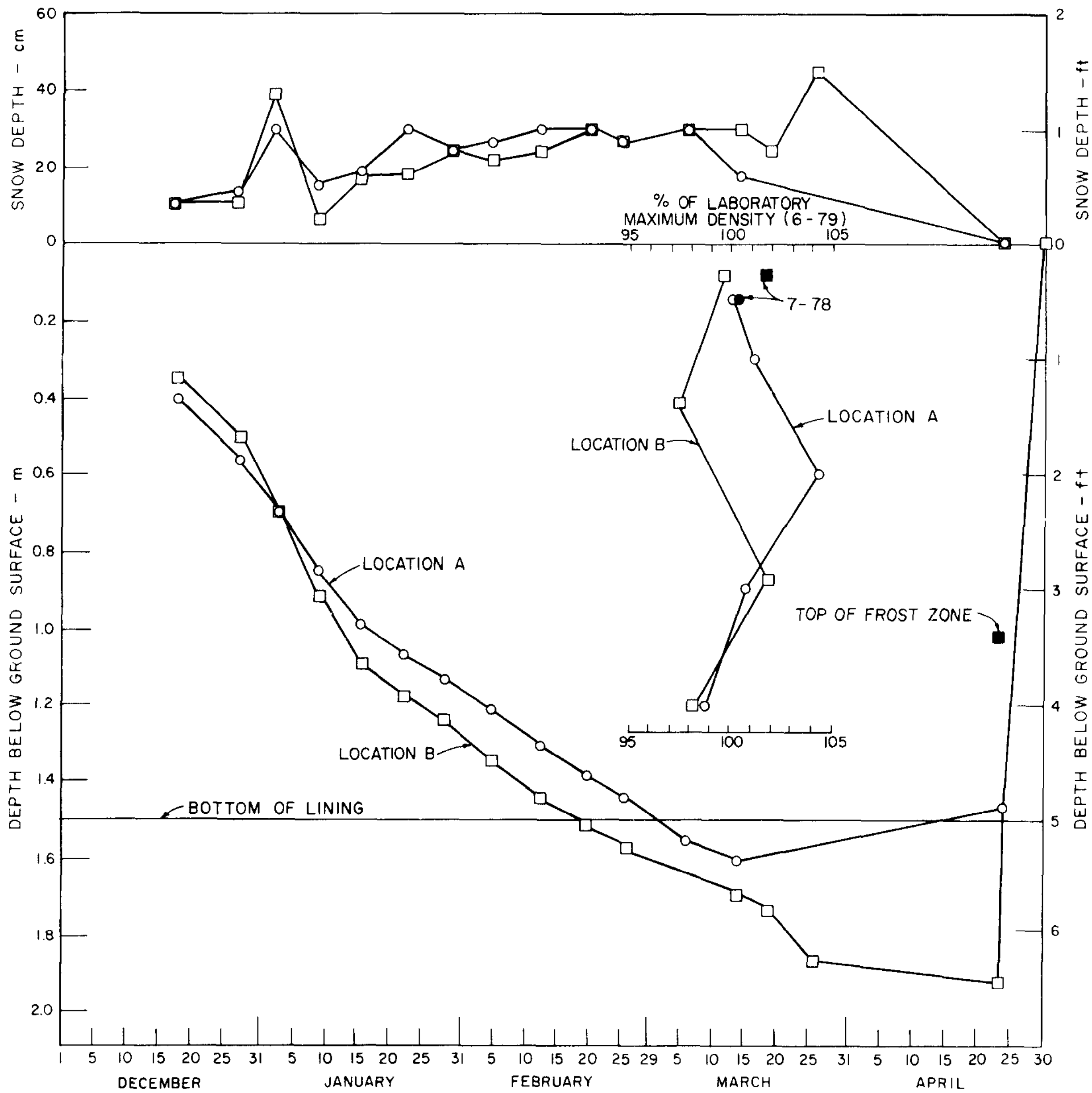

Figure 17.—Frost penetration and snow depths on the compacted soil lining on the Mt. Elbert forebay during the winter of 1978-79 with subsequent soil density test data.

(4) the Teton Dam remnant, Teton Basin Project, Idaho. In connection with the frost measurements, air temperatures and snow depths were recorded, and, in some cases, soil moisture, density, and other physical properties tests were conducted. The purpose of these tests was to determine changes in soil density and moisture during the winter freezing period.

About once a week during the winter, frost penetration was measured by frost tubes (FT) which consisted of a plastic tube filled with a water solution of methylene blue dye (fig. 18). The tube was installed in a hole excavated in the soil where frost was to be measured. As the ground froze from the surface downward, the freezing line in the tube corresponded to that in the soil and the frozen liquid became clear ice in contrast to the unfrozen blue liquid below. The tube was removed from the casing and the frost depth measured.

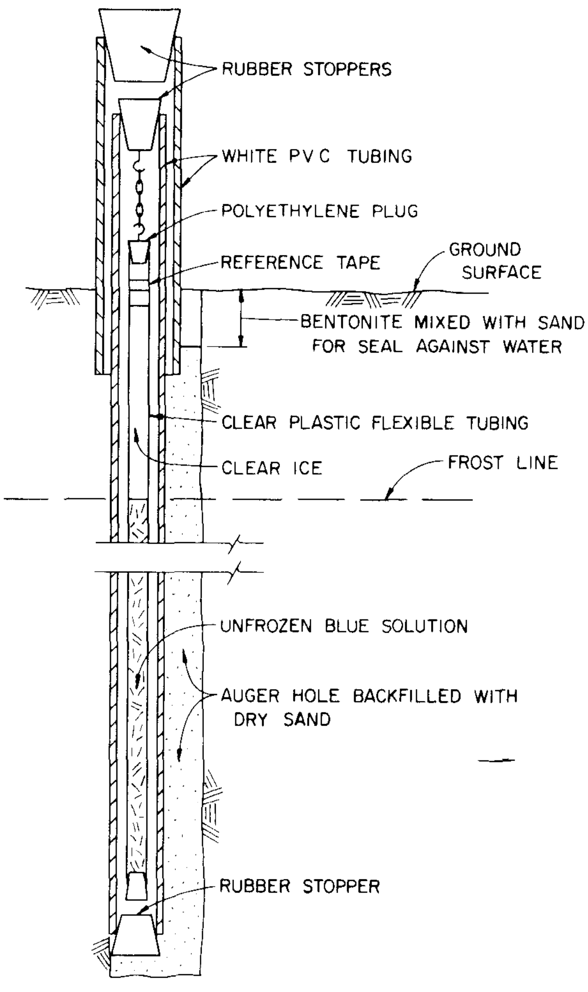

Figure 18.—Assembly for measurement of frost penetration in soil.

At the same time the frost penetration measurement was made, the average snow depth in the vicinity of each frost tube was also measured. Because snow has insulating properties, it significantly affects frost penetration and thawing of the soil.

The following data lists the freezing indexes in Celsius degree-days for Red Fleet, Twin Lakes, and Tiber Dams as calculated from maximum and minimum daily temperatures obtained at or near the damsites. For Teton Dam, the freezing index is from temperatures taken at the U.S. Weather Bureau station at Ashton, Idaho; a previous investigation during the winter of 1974-75 showed that the temperatures at Ashton followed reasonably well those obtained at Teton Dam. Based on freezing indexes during the 31 years of temperature records at Ashton, the winter of 1978-79 was the third coldest, and that for the winter of 1974-75 the sixth coldest. The tabulation also shows the freezing duration which is the number of days between the maximum positive and the maximum negative accumulative values of degree-days.

Dam	Freezing index °C·d (°F·d)	Freezing duration, days
Red Fleet	469 (844)	122
Twin Lakes	654 (1178)	154
Tiber	1371 (2467)	115
Teton (Ashton)	924 (1664)	126

Red Fleet Dam

Red Fleet Dam is located on Big Brush Creek approximately 10 miles northeast of Vernal, Utah, and is a feature of the Central Utah Project. The locations of the frost tubes installed in December 1978 are listed in table A-3. A double-tube auger with a 125-mm (5-in) diameter thin-wall tube was used to excavate the holes for the tubes.

At the time of frost tube installation, the ground was snow-covered to depths of 30 to 75 cm (1 to 2.5 ft) and the ground surface at FT-2 through FT-7 was unfrozen. At FT-8, which was located in zone 1A in the vicinity of the right abutment midway between the cutoff trench and the intake structure for the river outlet works, the surface of the fill was frozen. This apparently resulted from removal of snow by the contractor.

Soils and rock.—The following project test data were reported during July through October 1978 on 14 samples of zone 1 soil and on 8 samples of zone 1A:

	Percent passing				
Zone	0.005 mm	No. 200	No. 4	LL	PI
1	26-63	49-95	100	28-53	11-37
1A	25-32	40-67	95-100	23-35	6-25

From September 26 to October 16, 1978, of 20 field density tests obtained in zone 1 which contained no plus No. 4 material, the average fill dry density was 1836 kg/m^3 (114.6 lb/ft^3) which was 103.8 percent of the Proctor maximum density. The average fill moisture content was 16.3 percent which was a +0.5-percent variation (dry) from the optimum moisture. For seven tests in the zone 1A soil, there was no plus No. 4 soil and the average fill density was 1788 kg/m^3 (111.6 lb/ft^3) which was 102.7 percent of the Proctor maximum density. The average fill moisture content was 16.9 percent which was a +0.3-percent (dry) variation from the optimum moisture.

Frost tubes were placed in the rock abutments to determine the depth of penetration relative to that in the embankment. From the closest exploratory drill hole in the left abutment, the material is described geologically as "SHALE, dark gray to black, some very silty layers, massive, some air-slaking on exposure, parts on beddings, some light gray sandstone inclusions, core weak with little to moderate cementing, a few open joints." In the area of FT-10 in the right abutment, the material is described as "SANDSTONE, medium-grained, friable, close-spaced bedding joints, water-stained, locally sucrosic, dark gray to light gray."

Snow depth and frost penetration.—For zone 1 (fig. 19), the snow depths at frost tube locations were 30 cm (1 ft) or less except for one measurement of 67 cm (2.2 ft) on March 6 for FT-2. This tube was located near the left abutment in a partially shaded area, but with the snow being somewhat deeper than for the other locations the frost depth was only moderate (1 m (3.3 ft)). The greatest frost penetration was at FT-7 where it reached 1.3 m (4.3 ft) during the first part of March. The least frost penetration was at FT-5 which was on a 4:1 southward facing slope; the maximum depth of penetration at this location was about 0.75 m (2.5 ft) during January and February. All snow was gone at the zone 1 frost tube locations by the middle of March and the frost was out of the ground by the end of the month.

In zone 1A (fig. 20), the snow depths at the frost tube locations ranged between 0 and 30 cm (1 ft) with that at FT-8 being generally less than the others. The frost depth at FT-8 measured on December 26 was 0.9 m (3 ft) and this increased to a maximum of 1.6 m (5.4 ft) during the first week in March. The depth of the thawed zone increased from 0.3 m (1 ft) on March 20 to 0.85 m (2.8 ft) on April 10. Meanwhile, the bottom of the frozen zone for FT-8 remained below 1.5 m (5 ft) until April 11 when frost rapidly left the ground and was completely gone on April 17. The removal of the snow with its attendant loss of insulation no doubt accounts for the deeper penetration at this location. The least frost penetration was at FT-6 which was located on a southward-facing 4:1 slope where less frost penetration might be expected.

Figure 21 shows the frost penetration in the rock abutments. The maximum depth of freezing was 0.67 m (2.2 ft) in the shale (FT-1) and 0.43 m (1.4 ft) in the sandsone (FT-2). These depths are less than those measured in the embankment. However, the snow depths for the frost tube locations in rock averaged about 95 cm (3.2 ft) for February and the maximum depths (with one exception) for the embankment were about 30 cm (1 ft). The insulating effect of the snow undoubtedly reduced frost penetration in the abutments, which prevented a valid comparison of frost penetration in rock and soils, under similar cover conditions. Also, the rock was not sufficiently solid to achieve maximum penetration.

Field density tests.—The results of field density tests conducted during the period October 1978 through April 1979 in zones 1 and 1A are shown in tables A-4 and A-5, respectively. When the tests in zone 1 were made in January in connection with the frost tube investigation, some of the soil was frozen. The April tests were conducted immediately prior to resumption of embankment placement. All of the tests reported were above the minimum specification limit with only 2 of 26 tests being below 100 percent of the maximum laboratory density. The April 1979 construction

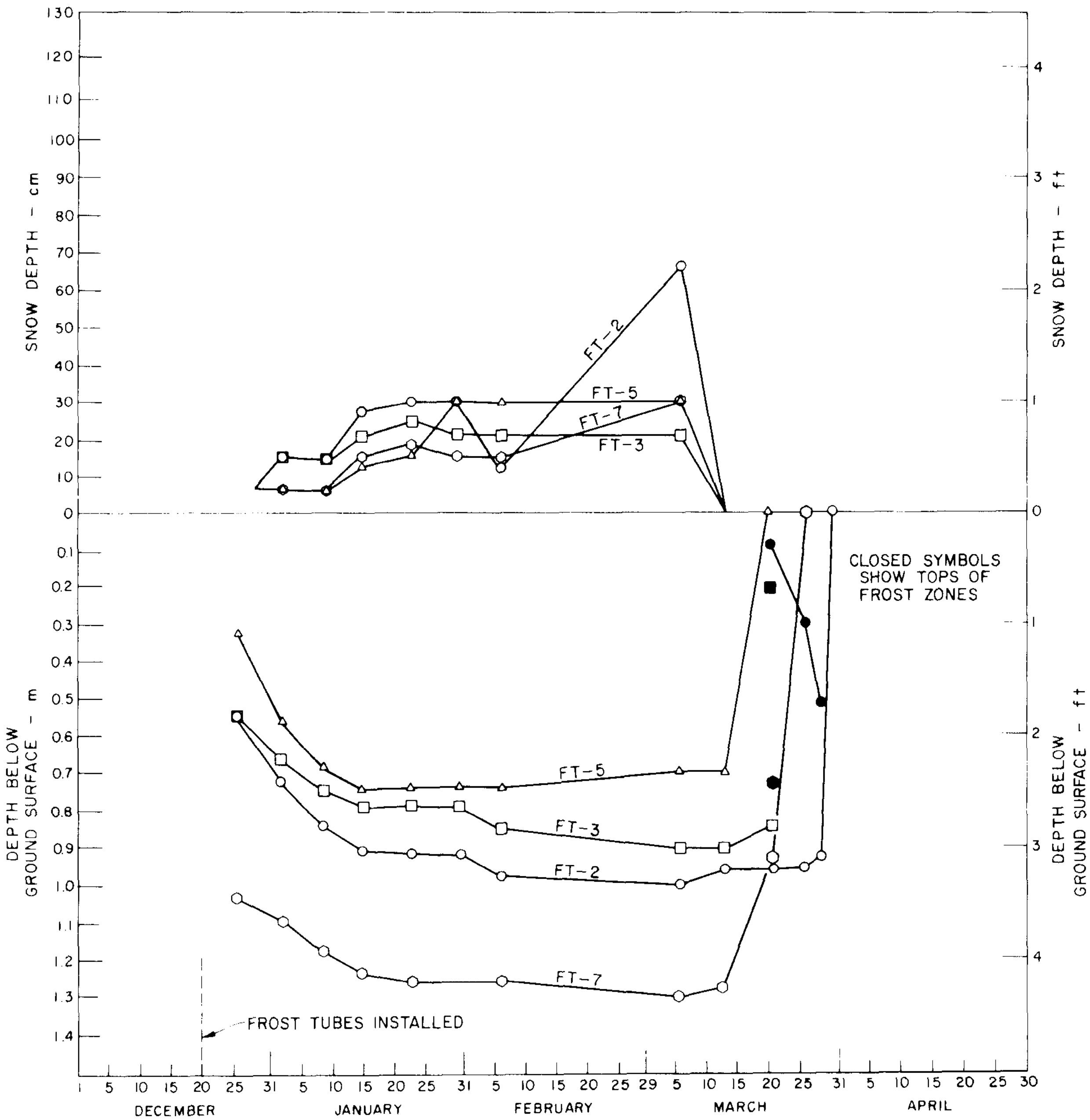

Figure 19.—Snow depths and frost penetration in zone 1 of Red Fleet Dam.

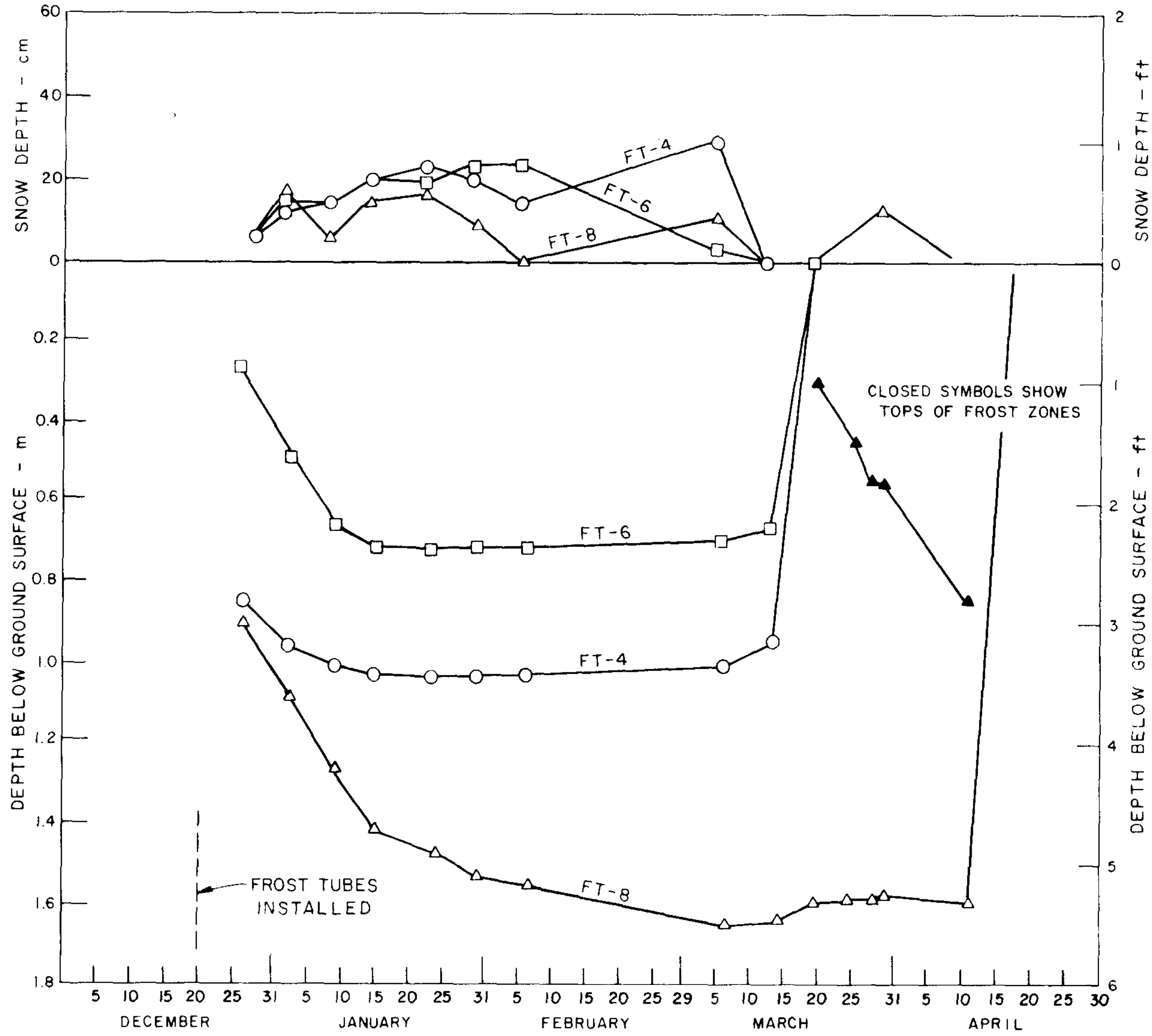

Figure 20.—Snow depths and frost penetration in zone 1A of Red Fleet Dam.

control report states that the "contractor removed zone 1 embankment material that had been frost damaged and any loose dry material on the embankment."

Twin Lakes Dam

Twin Lakes Dam (Specifications No. DC-7300) at an elevation of about 2805 m (9200 ft) is located approximately 19 km (12 mi) south of Leadville, Colo., in Lake County. The dam is part of the Fryingpan-Arkansas Project.

When construction of the dam was halted in the fall of 1978 due to cold weather, the contractor was directed to place a loose layer of soil on the surface of the completed zone 1 and 1A embankment to provide cold weather protection. The specified depth was 0.6 m (2 ft), but in places, the blanket was up to 0.9 m (3 ft) thick. The blanket was a nonplastic silty sand with a range of grading shown in figures 22 and 23. The moisture content of the soil blanket, when placed, was estimated at 4 percent.

The soil characteristics presented in this report are from tests on samples taken near the frost tube locations. The zone 1 soil was clayey sand with a liquid limit of about 30 and a plasticity index of 11 (see gradation in fig. 22). The zone 1A soil is a silty sand which ranged from nonplastic to a liquid limit of 17 and a plasticity index of 3.

In December 1978, six frost tubes, each about 1.8 m (6 ft) long, were placed in the zones 1 and 1A embankment. These frost tubes were located as shown in table A-6.

Plots of frost penetration and snow depths at frost tube locations in zones 1 and 1A soil are shown in figures 24 and 25, respectively. For the zone 1 soil, the frost penetrated 0.40 to 0.55 m (1.4 to 1.8 ft) below the 0.6-m (2-ft) frost blanket with the maximum depth occurring about the middle of February. Snow cover (0 to 12 cm) was too thin to provide much insulation to reduce frost penetration.

At FT-3 in zone 1A, the frost blanket depth was 0.6 m (2 ft) thick and snow cover was lacking except for some in December and for a period from the second week in January to the middle of February when the maximum depth was 12 cm (0.4 ft). At this location, frost penetrated 0.58 m (1.9 ft) below the blanket. At FT-4, the frost blanket was about 0.9 m (3 ft) thick and there was snow cover all winter with a maximum depth of 75 cm (2.5 ft) at the end of January. At this location, the frost zone extended a maximum of 0.75 m (2.5 ft) into the frost blanket; the insulating effect of the snow is clearly shown. Also, the insulating effect of the snow during the spring thawing period should be noted. With the lack of snow at FT-3, the cold air temperatures prevented rapid thawing and the frost depth was about

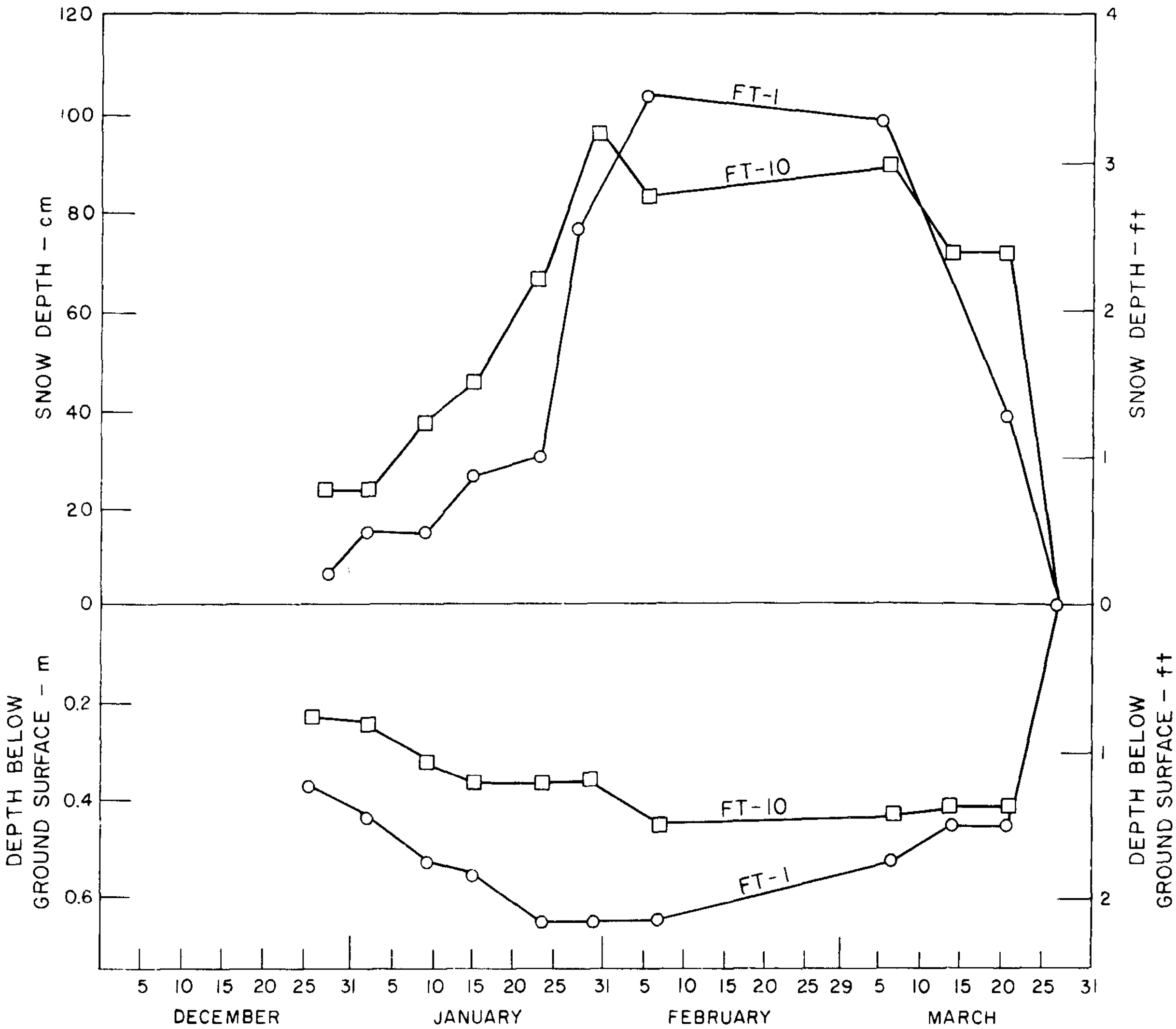

Figure 21.—Snow depths and frost penetration in bedrock abutments of Red Fleet Dam.

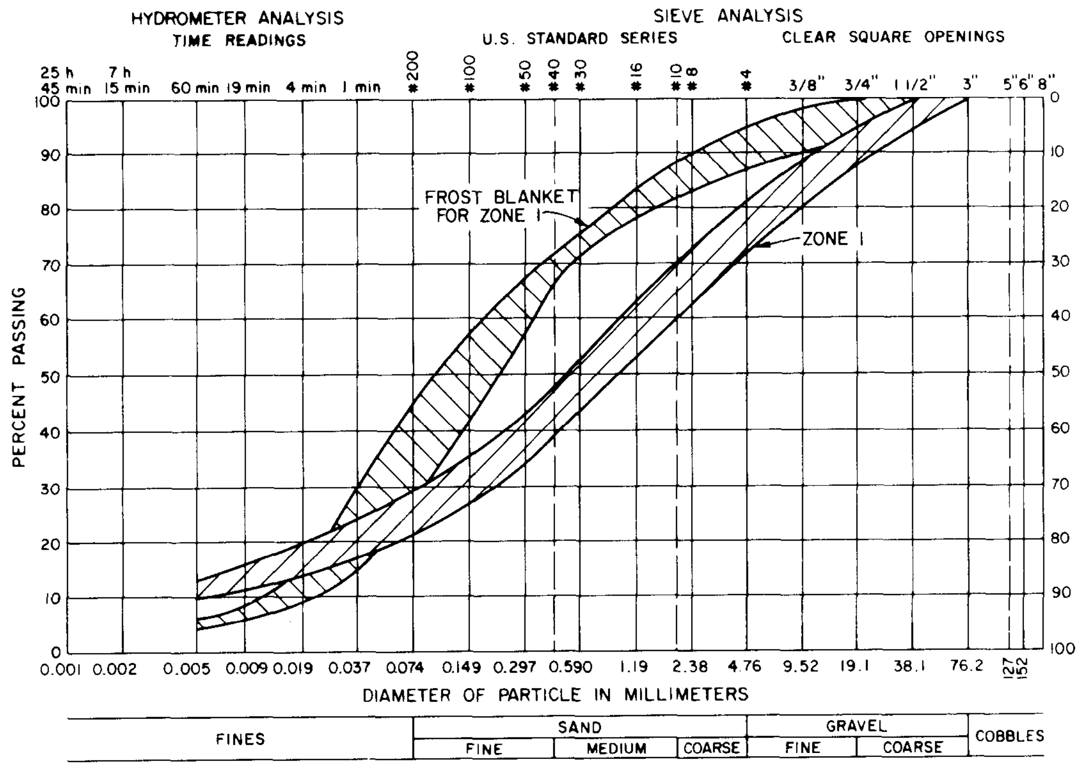

Figure 22.—Range of gradations for zone 1 soil and frost blanket at Twin Lakes Dam.

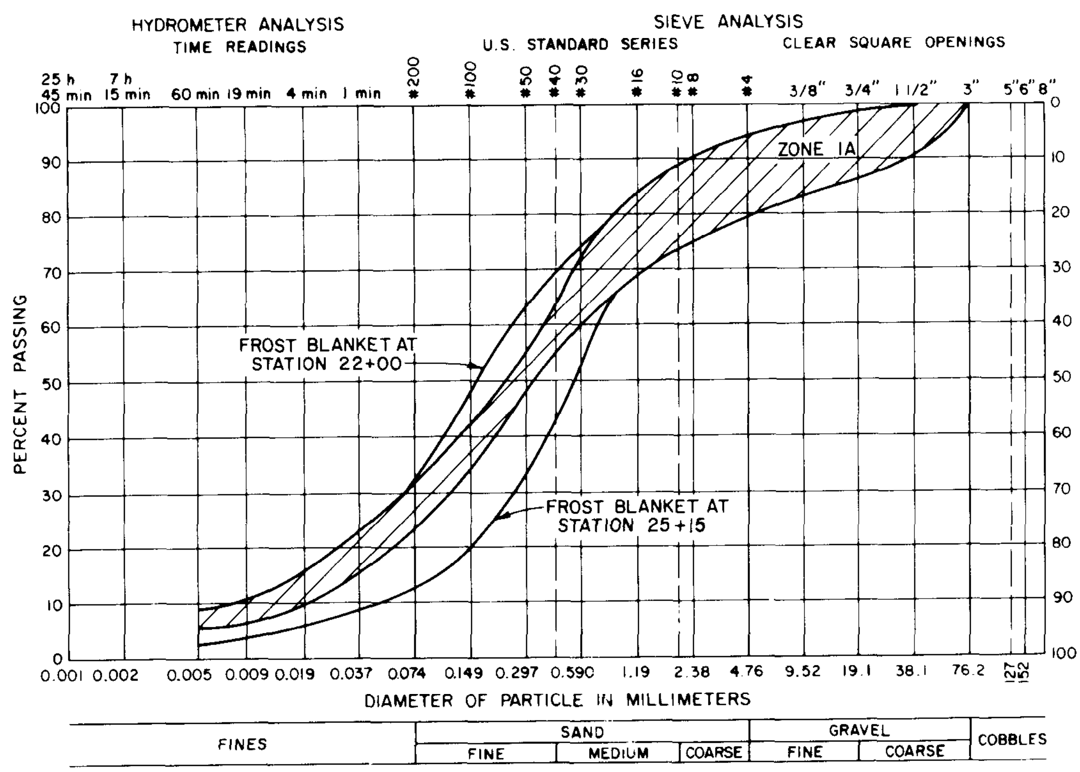

Figure 23.—Range of gradations for zone 1A soil and frost blanket for zone 1A at Twin Lakes Dam.

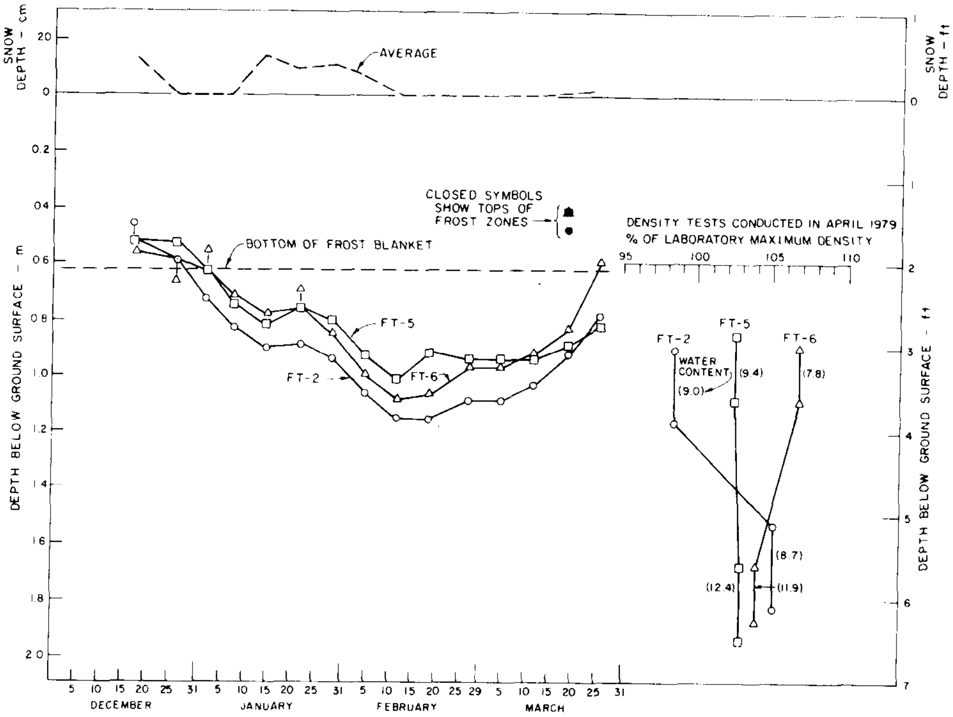

Figure 24.—Snow depths and frost penetration zone 1 soil at Twin Lakes Dam with density test data.

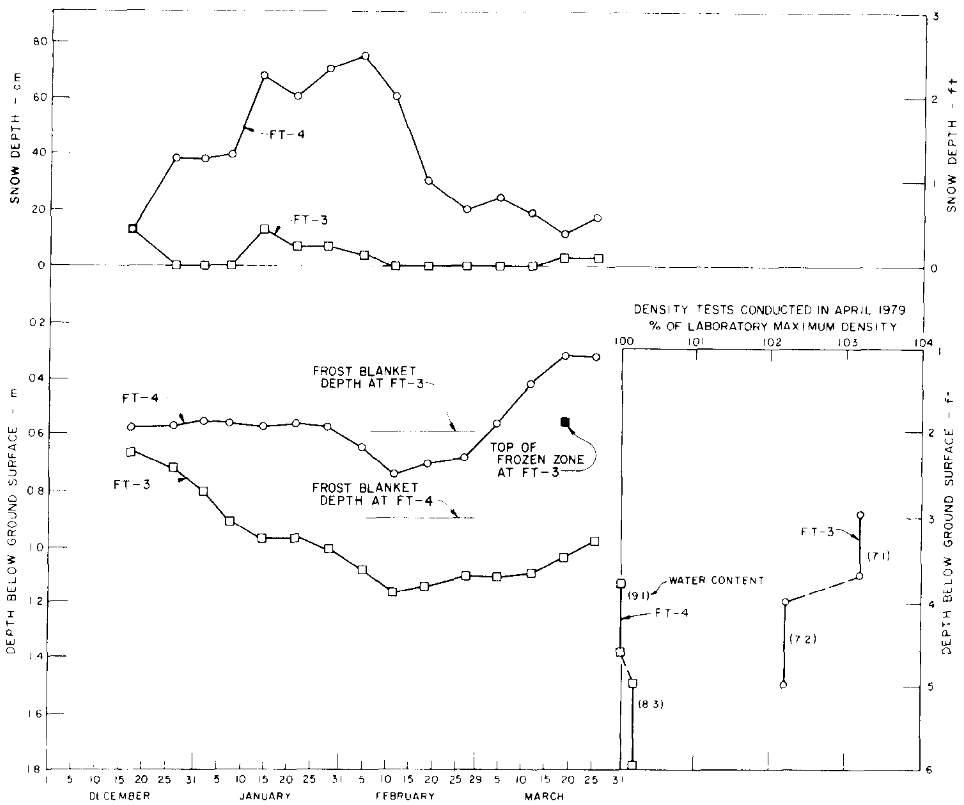

Figure 25.—Snow depths and frost penetration in zone 1A soil at Twin Lakes Dam with density test data.

0.9 m (3 ft) from the top of the frost blanket during the last week in March. The snow cover at FT-4 insulated the ground surface and allowed thawing to proceed from the bottom of the frozen zone.

During April 14-17, 1979, density tests (table A-7) were conducted in zones 1 and 1A soils below the frost blanket to determine any effects of freezing during the winter so any soil with densities below the specification limit could be removed prior to placement of new fill. All results of density tests were above the specified minimum density. For zone 1, the average dry density from six tests was 2052 kg/m^3 (128.1 lb/ft^3) which was 103.2 percent of the laboratory maximum (fig. 24). The average moisture content was 9.9 percent which was 1 percent dry of optimum. For zone 1A, the average dry density of four tests was 2056 kg/m^3 (128.3 lb/ft^3) which was 101.7 percent of the maximum dry density (fig. 25). The average moisture content was 7.9 percent which was 1.5 percent dry of the optimum moisture. Note that although the soil densities before freezing are not known for the location (FT-3) where frost penetration was below the protective soil blanket, the soil density was higher than for the location (FT-4) where frost did not penetrate the blanket. There was no definite trend of density or moisture changes with depth in the soil for either zone 1 or 1A.

Tiber Dam

Tiber Dam, located in north-central Montana along the Marias River on the Pick-Sloan Missouri Basin Program, is an earthfill structure constructed during 1952-56. The frost investigation was made during rehabilitation of the spillway and associated reconstruction; frost tubes were installed in the existing dam and embankment, in the cutoff trench, and in the counterfort area for the crest structure (table A-8).

Soils.—The soil in the existing zone 1 embankment was a lean clay with 2 to 5 percent gravel and 73 percent passing the No. 200 sieve (fig. 26). It had liquid limits of 34 to 37 and plasticity indexes of 20 to 25. The soil in the cutoff trench and in the counterfort area for the crest structure was a clayey gravel with 30 to 50 percent gravel and 25 to 45 percent passing the No. 200 sieve. It had a liquid limit of 32 and a plasticity index of 18.

Snow depth and frost penetration (fig. 27).—The FT-1 in the existing dam embankment was on a level bench about 8 feet wide on a general 4:1 slope facing southwest. The maximum snow depth was about 24 cm (0.8 ft) and this occurred during the last half of January. The maximum frost penetration was about 0.9 m (3 ft) and this occurred during the last half of February and the first week in March.

FT-2 in the cutoff trench was in a level, sun-exposed area. It had a maximum snow depth of about 18 cm (0.6 ft), which was less than the other frost tube locations. The maximum frost penetration was 2.1 m (7 ft).

FT-3 and FT-4 in the counterfort area were shaded which would tend to cause deeper frost penetration than in sun-exposed areas if other conditions were the same; FT-3 was completely shaded and FT-4 was exposed to the sun for about an hour each day. These areas had a maximum snow depth of about 28 cm (0.9 ft). In this soil, the frost penetrated between 1.9 and 2.1 m (6 and 7 ft). Because the frost depths at these locations (also at FT-2) were greater than the 1.5-m (5-ft) length tubes, in February they were removed and replaced with tubes 3 m (10 ft) long. FT-3 and FT-4 were removed before frost was out of the ground because the backfill had been found to be unsuitable and the contractor started excavating it in March.

Table A-9 shows the results of field density tests conducted in March and April 1979 after frost was out of the ground; results of tests at stations 2 + 96.0 and 3 + 37.4 m (9 + 71 and 11 + 07 ft) in the embankment were included although no frost tubes were located there. The results of density and moisture tests at the frost tube locations are shown in figure 27.

For both the embankment and cutoff trench, the density of the top 0.3 m (1 ft) of soil was significantly lower than the soil below it with all less than the specified 95 percent of the maximum laboratory density; the percentage of the maximum laboratory density ranged from 82.1 to 94.1. With one exception, there was a consistent decrease in moisture with depth which amounted to about 3.5 percent for depths of soil tested. The exception was at station 3 + 37.4 m (11 + 07 ft); here, the moisture increased about 2 percent.

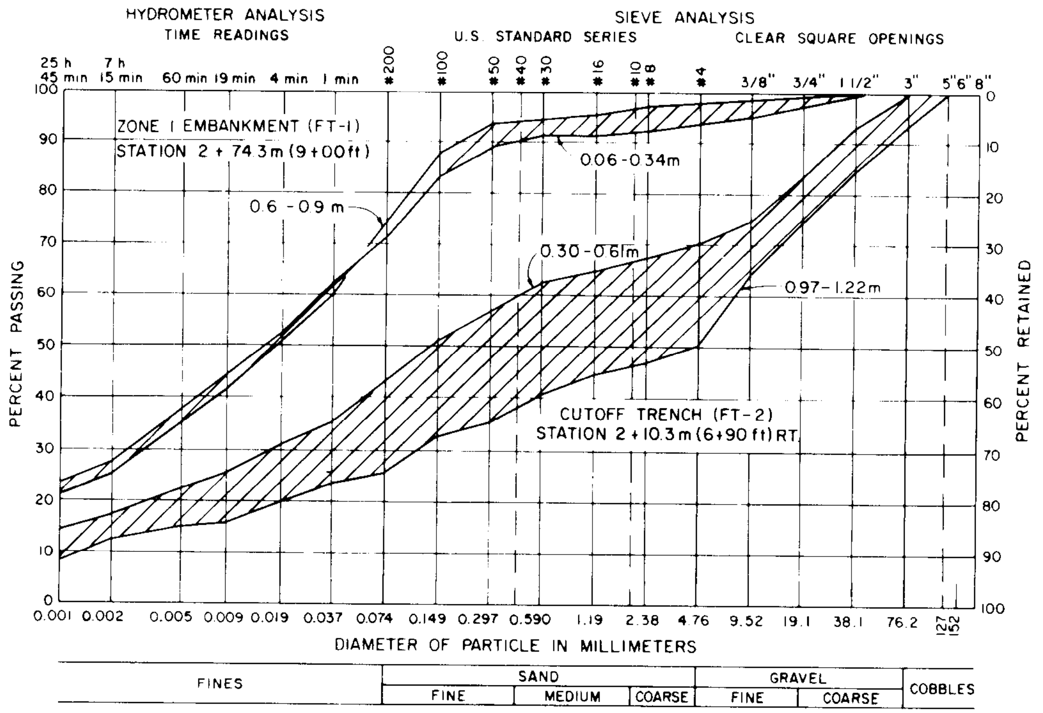

Figure 26.—Gradation analyses of soils at frost tube location on Tiber Dam.

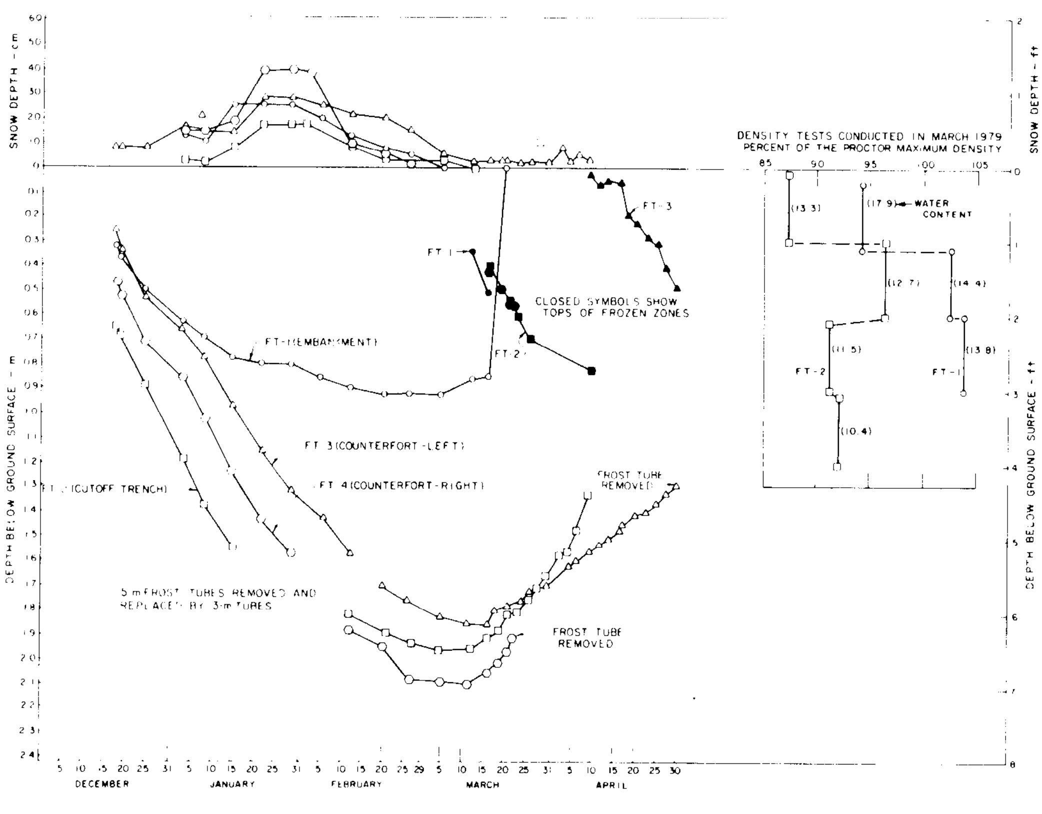

Figure 27.—Snow depths and frost penetration in soil at Tiber Dam with density test data.

Teton Dam Remnant

Teton Dam which failed in June 1976 was part of the Teton Basin Project located on the Teton River, about 3 miles northeast of Newdale, Idaho.

Near the end of February 1978, five frost tubes were installed at convenient access points in the remnant of zone 1 embankment which was composed of silt, and frost penetration was monitored for about 1 month until the frost left. During this period, the deepest frost penetration was at FT-1 where it reached 0.24 m (0.85 ft). (FT-1 is located 30 m (100 ft) upstream of centerline at station 6+35.5 m (20+85 ft) at elevation 1607 m (5723 ft).) This location was shaded for about half the daylight hours during February and March and winds kept the snow from accumulating. At the frost tube locations, soil samples to depths of 1.0 to 1.8 m (3.3 to 6.0 ft) were obtained. Moisture content (fig. 28) decreased from the ground surface down to about 1 m (3.3 ft) with a slight tendency to increase below this depth. The higher moisture content toward the ground surface was likely due to frost action although it is possible that precipitation could have contributed. Ground surface elevation

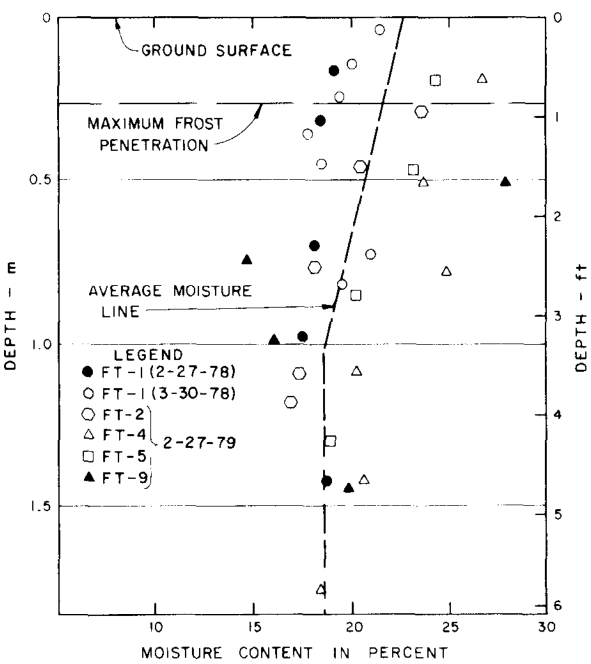

Figure 28.—Moisture contents of zone 1 soil in the Teton Dam remnant, winter of 1978.

measurements at the frost tube locations showed no significant change due to frost action in the soil.

The frost tubes were replaced at the same locations during the winter of 1978-79, when the freezing index was 924 °C·d (1664 °F·d) compared with 806 °C·d (1451 °F·d) for the preceding winter. Again, there was no snow recorded at FT-1 but deep snow and vandalism at other locations limited frost penetration measurements to only two locations besides FT-1. Figure 29 shows the record of frost penetration and snow depths. The deepest frost penetration was at FT-1 with a maximum penetration of 1 m (3.2 ft). Frost penetration depths for a bare-ground condition as calculated by the Modified Berggren equation [20] have been plotted on figure 29; this resulted in a maximum depth of 1.2 m (3.9 ft). For comparison, the frost record for FT-1 in 1978 has been added to figure 29. For the other two frost tube locations where the maximum snow depth was about 30 cm (1 ft), the frost penetration ranged from 0.37 to 0.52 m (1.2 to 1.7 ft).

In July 1979, undisturbed samples taken with a 125-mm (5-in) diameter Denison sampler were obtained adjacent to the FT-1 location, and in October 1979, laboratory density and moisture content tests were performed on the samples. The results of the density tests on the Denison samples and other density tests on samples obtained in February and March 1978, are shown in figure 30; the 1978 tests were on samples obtained by driving a 48-mm (1-7/8-in) split tube sampler, which would not provide test results as reliable as for those on Denison samples. The density results were erratic but if three of the extreme densities are disregarded, there appears to be a tendency for an increase in density to a depth between 0.3 and 0.6 m (1 and 2 ft) and a decrease below that depth.

Figure 31 shows a plot of the 1979 moisture test results along with the results of tests made in February and March 1979 at the FT-1 location. These tests show trends of decreasing moisture content from the ground surface to levels below the maximum frost penetration depths and a slight tendency for the moisture to increase for some distance below those depths.

The Denison soil samples from the hole at FT-1 were composited for gradation analysis (fig. 32) and Proctor compaction (fig. 33) tests. The soil

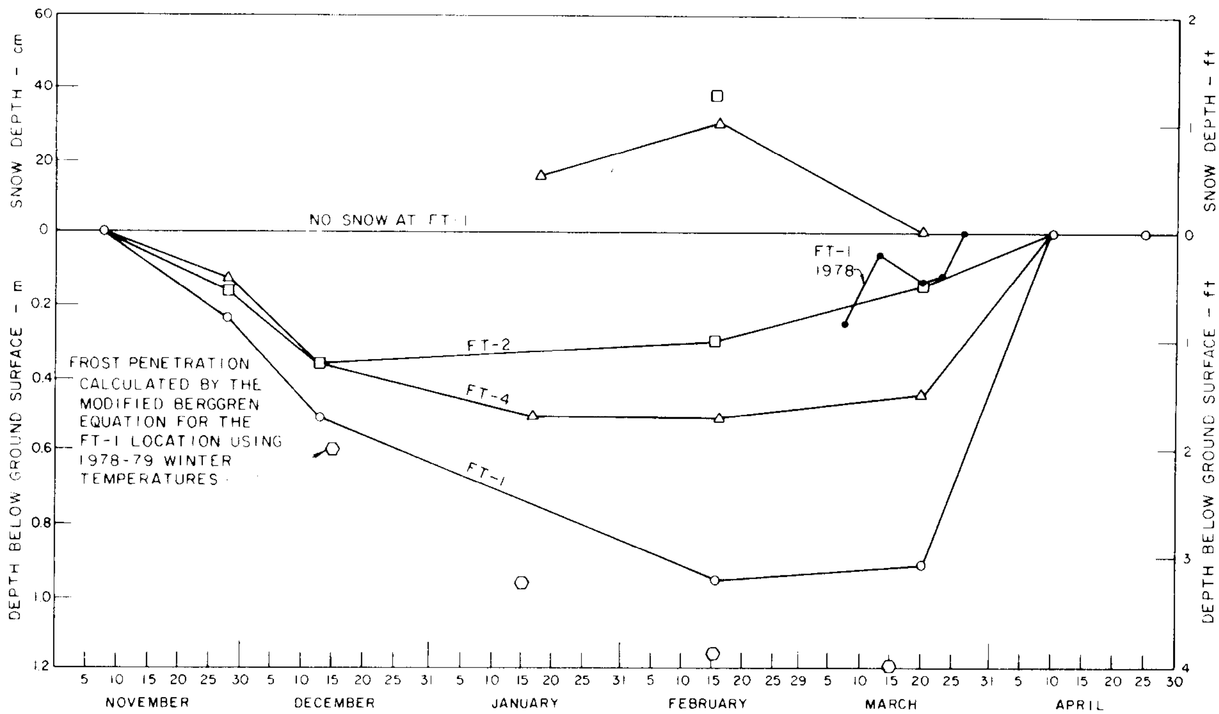

Figure 29.—Snow depths and frost penetration in the zone 1 embankment of the Teton Dam remnant during the winter of 1978-79.

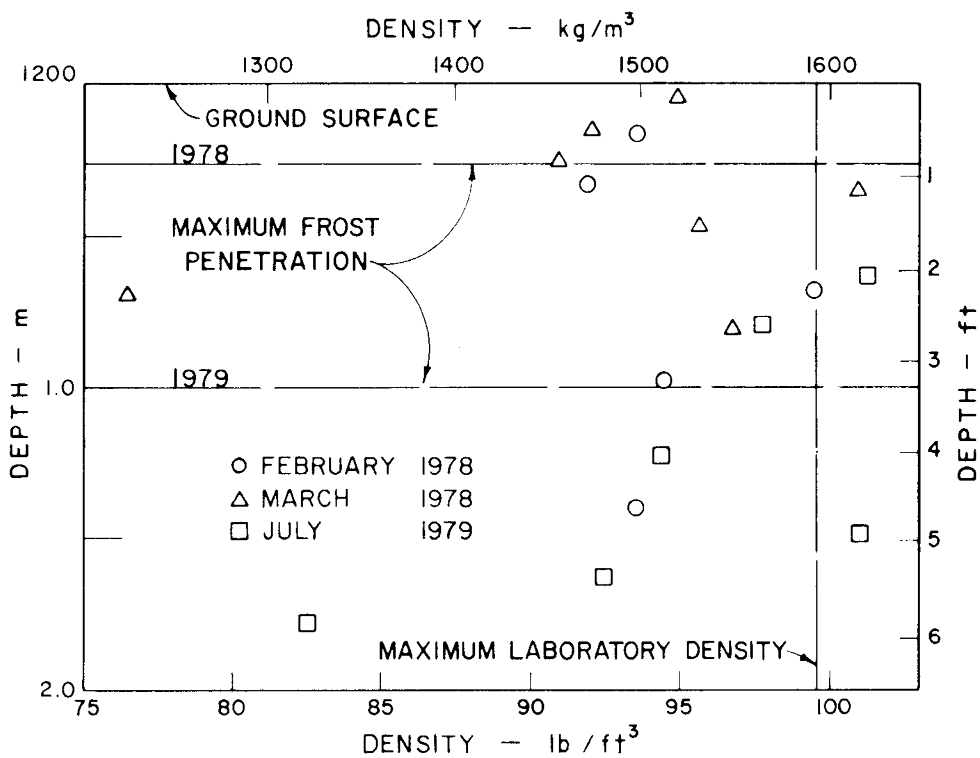

Figure 30.—Density of soil at frost tube 1 in the zone 1 embankment of the Teton Dam remnant.

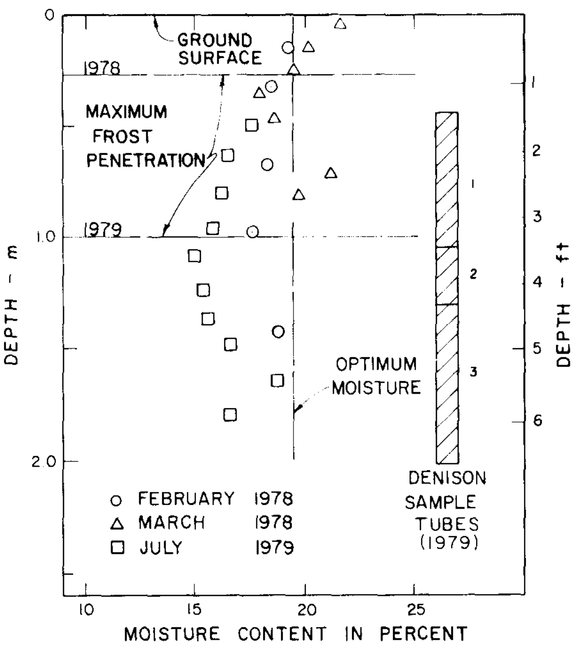

Figure 31.—Moisture content of soil at frost tube 1 in the zone 1 embankment of the Teton Dam remnant.

was a nonplastic silt with a relative mass density (specific gravity) of 2.69.

DISCUSSION

The density and moisture content of compacted soil as placed in canal linings and embankments are generally quite variable. For soils with no available water source except for moisture in the voids, measurable changes in these properties occur near ground surfaces due to freezing. Large numbers of tests would be required as a background for a complete understanding and possible prediction of changes taking place in soils of different types under the variability of field conditions. There are several uncertainties involved in trying to predict effects of frost action. However, from the limited number of laboratory and field tests made on compacted soils, certain trends in moisture and density changes are apparent.

Compacted Soil Linings

For compacted soil linings, the effects of freezing action on the soil can be quite variable within short distances. This is due to differences in the soil properties, orientation of the canal, and climatic influences. A section of canal lying in an east-west direction will have the north side slope exposed more or less directly to the sun's rays whereas the other slope will be shaded or partially shaded in winter. Due to drifting, snow cover will vary from one side to the other and the depth and duration of snow cover changes with time. Where the soil is exposed, the radiation, absorptive, and reflective properties vary with the surface characteristics and the angle of the sun's rays relative to the soil surface. These differences tend to balance or amplify one another in their effects on frost penetration in soil.

Ice Formation Under Membrane Linings

The failure of the buried plastic membrane lining on the Riverton Project canal due to slippage on a melting ice layer is the only such instance that has been noted. Such slippage on a canal is likely to occur only during the spring thawing period and then only under certain soil and temperature conditions. Thus, it may not be economical to require special provisions such as a sand layer for long stretches of canal to control slippage when the risk of failure is low and repair could be made without great expense. However, for other membrane-lined structures, such as the pumped-storage forebay reservoir where failure would be more critical, special provisions to prevent sliding should be considered. For the forebay in a cold climate, the water level would be fluctuating continually and there would be more opportunity than in a canal for the required temperature conditions to occur to melt an ice layer under the membrane and cause slippage. In such cases, a sand layer of sufficient thickness and gradation to prevent capillary water from reaching the underside of the membrane and forming an ice layer could be provided. In addition, the subgrade surface beneath the sand should be made uneven to prevent a plane of ice being formed between the subgrade and sand layer. This could be done by serrations or indentations, as from a sheepsfoot roller, on the subgrade surface.

Frost Penetration Depth

The depth of frost penetration and the number of freeze-thaw cycles in soil have important bearing on resulting soil property changes. Other climatic influences being equal, the depth of frost penetration in soil is governed by the type of soil, its degree of compactness, and its moisture content. Figure 34 shows differences for various soil types with the depths of frost penetration plotted for increasing air-freezing indexes and a bare ground condition. From this, it is seen that penetration in

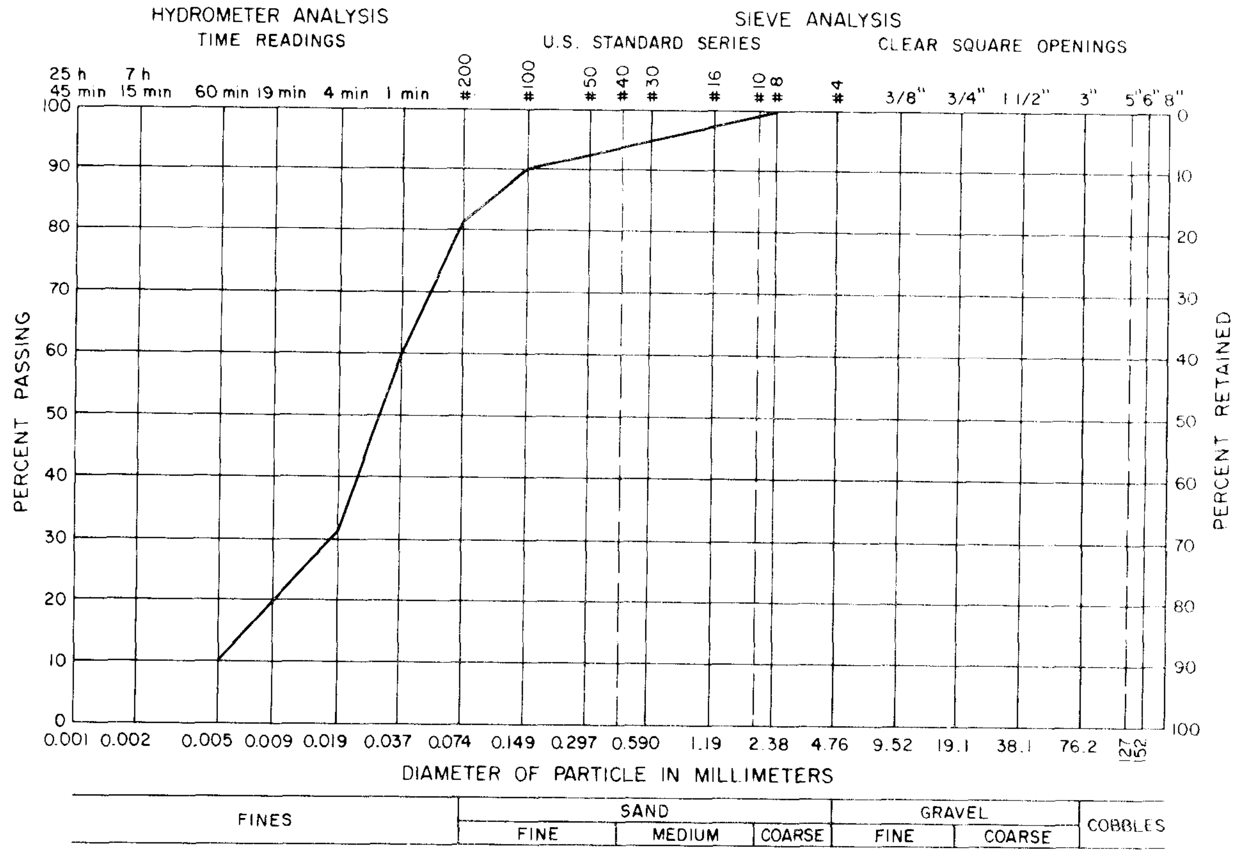

Figure 32.—Gradation analysis of soil at frost tube 1 in the zone 1 embankment of the Teton Dam remnant.

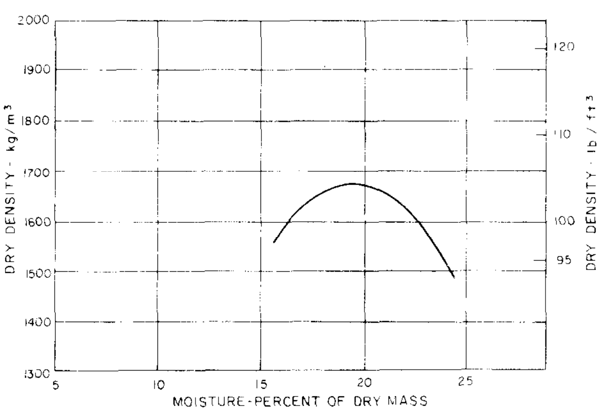

Figure 33.—Proctor compaction curve for soil at frost tube 1 in zone 1 embankment of the Teton Dam remnant.

the finer grained soils is less than for those with coarser grains, particularly for soils with gravel particles. Well-drained, sandy gravel shows the deepest penetration, which would make it a poor insulator, compared to finer soils. No doubt one reason for the deeper penetration in soils with gravels is the higher thermal conductivity of rock particles compared to finer soil. The bottom curve shows that frost would penetrate deeper in concrete than soil; this would also be generally true for solid rock. On the James Bay Project in Canada, it was reported [21] that frost penetrated 7.9 m (26 ft) in bedrock and 2.4 to 3 m (8 to 10 ft) in soil.

For the soils and climatic conditions mentioned in this report, the shallowest frost penetration of 1 m (3.3 ft) for bare ground and part-time shaded conditions, with the relatively high freezing index of 924 °C·d (1664 °F·d) was in the silt of the Teton Dam remnant. The deepest penetration (2.1 m, (7 ft)) was recorded on Tiber Dam where the soil contained 30 to 50 percent gravel, and the freezing index was 1371 °C·d (2467 °F·d). The surface had a light snow cover (maximum of 28 cm (0.9 ft) and the particular area was completely shaded. For these reasons, no direct comparison of frost penetration between the types of soils at these two dams can be made.

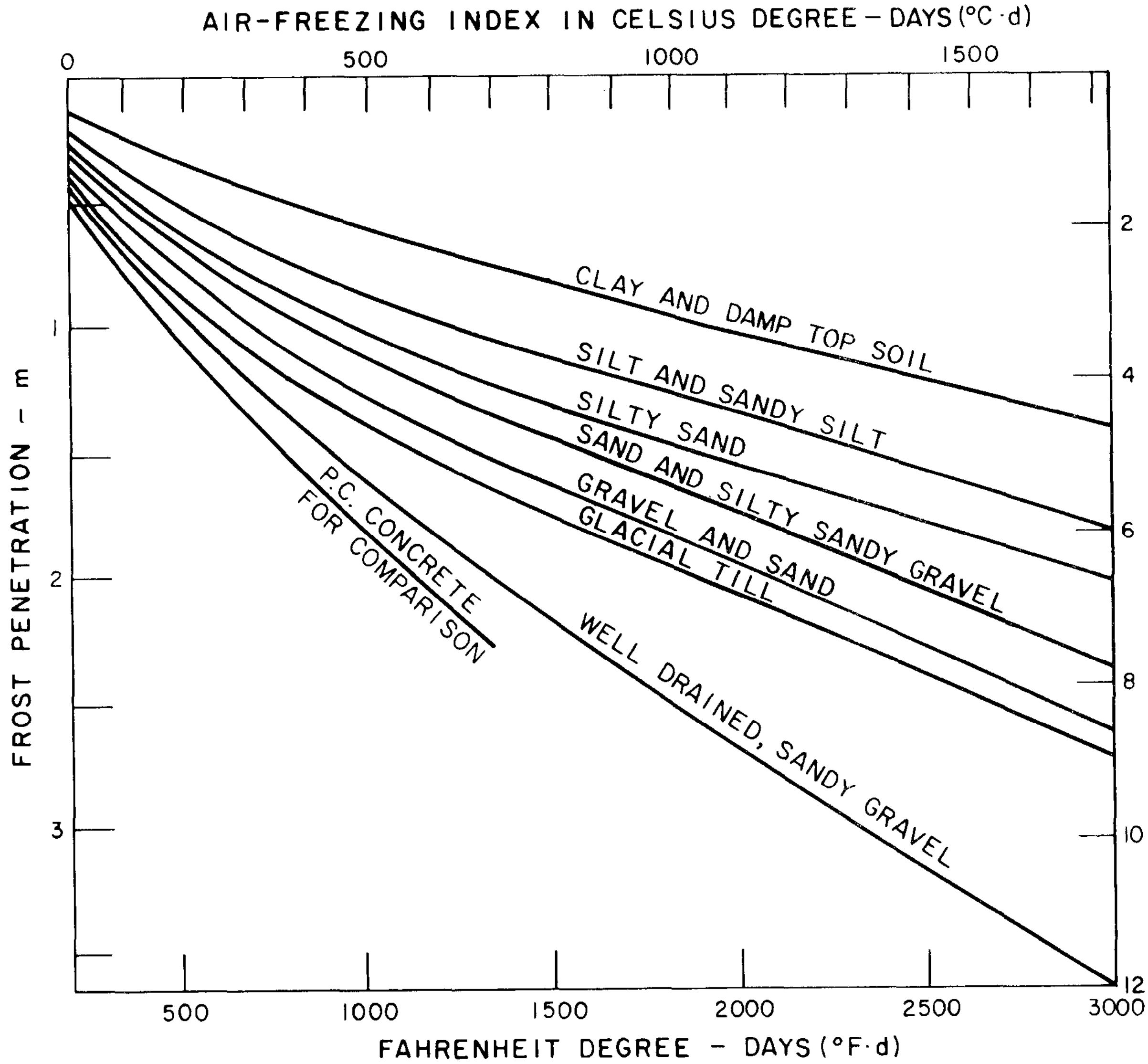

Figure 34.—Relationship between freezing index and frost penetration into homogeneous soils for bare ground conditions (modified from reference 20).

Construction Control Considerations

In the construction of an earth embankment dam in a cold climate where it is necessary to cease embankment placement because of frozen soil, the main questions regarding frozen embankment are: (1) when should embankment placement be stopped? (2) what provisions, if any, are there to limit frost penetration in the dam? and (3) under what conditions can embankment placement be resumed?

Water and Power Resources Service specifications state that "no embankment material shall be placed in the embankment when either the material or the foundation or embankment on which it would be placed is frozen." It might be of interest to mention that some fine-grained soils compacted at temperatures slightly above freezing result in densities slightly lower than when compacted at significantly higher temperatures with the same compactive effort [22]. This is probably a minor consideration and could be compensated for by increased compaction effort, if desired. Also, when soil is near freezing, it may be necessary to keep close track of soil temperatures not only as the soil is compacted but some time after it has been placed. In one undocumented instance, soil backfill at a structure was thought to be placed at temperatures slightly above freezing;

however, when it became necessary in the spring to excavate a trench in the backfill, it was found to have been frozen to a 5.8-m (19-ft) depth.

Frost Blankets

Frost penetration in the compacted soil can be lessened by the addition of a soil blanket before the onset of freezing weather, as was done with the 0.6- to 0.9-m (2- to 3-ft) thickness added on Twin Lakes Dam. For the most effectiveness in reducing frost penetration, the blanket should be fine-grained, loosely placed soil. The soil moisture content for optimum frost protection would depend on heat flow under transient conditions of freezing, density, and moisture for a given soil and blanket thickness. Thus, the most effective moisture content would be difficult to estimate.

On Canadian embankment construction when nature did not provide sufficient snow for insulation, artificial snow was added [21].

Exploration for Frost

To fulfill the specification requirements it would be necessary before resuming embankment placement in the spring, to thoroughly explore for frozen soil. In the Teton Dam remnant, it was not possible by conventional mechanical sampling equipment to determine frost depth in the compacted silt nor to tell by observation or scratching the side of the hole with a special tool. Possibly a seismic or electrical resisitivity method would be practicable as a rapid method to determine subsurface frozen layers; this is an area for investigation. If frost penetration is monitored by frost tubes installed in strategic areas, these will show when frost is out of the ground. Any areas where snow cover was deficient during the winter due to wind action or contractor operations should receive special attention. Density tests in the embankment should be conducted to sufficient depth to determine soil to be removed and/or recompacted to specification limits before any new soil is added.

Shrinkage Cracks in Soil from Freezing

Freezing can cause shrinkage cracks in compacted soil through a wide range of soil plasticity. However, cracks may be very narrow and not noticed unless revealed by careful investigation. The cracks in the top 0.4 m (1.25 ft) of the Mt. Elbert forebay lining were noticed in a test pit for density testing when looking for effects of freezing on the soil. Normally, the person performing a density test near the ground surface would not be likely to notice fine cracks because of soil disturbance during the surface leveling and hole excavation for the test. If cracks are present, the results of a density test may be higher than the average embankment density, depending on the location of the density test hole relative to the crack pattern. The density test values in the forebay lining remained near 100 percent of the Proctor maximum in spite of the cracks.

Cracks near the compacted soil surface could result from shrinkage during drying of soil in a zone where freezing has caused a decrease in density and an increase in moisture. Cracks could form in a lower zone in the embankment where freezing action has removed water and increased density.

If cracks form, there is a question of whether they would close from later redistribution of moisture or from the placement of overlying embankment. This would depend somewhat upon the plasticity and other properties of the soil and the loading of overlying embankment placed; horizontal cracks would close more readily than vertical ones. According to Soviet investigators, shrinkage of soil in an earth dam forming transverse cracks and gaps between abutment and embankment is of much concern in considering dam safety and must be accounted for in the design. However, the Soviet dams investigated were in very cold areas and details on soil properties and construction are lacking. It is not apparent how important these effects may be in our more temperate climate, but they should be considered for dams in northern sections of the United States or high elevations.

In addition to conducting density tests in the embankment prior to resumption of embankment placement after winter shutdown, it would be well to look for cracks and consider removing a cracked zone in spite of density test values above minimum specification limits. This would avoid possible high seepage through a cracked zone.

Freezing at a Soil-Rock Abutment Interface

There is one aspect of closed-system freezing in an incompleted earth embankment dam that could possibly be a cause for failure of the dam, but which seems to not have been published. This has to do with frost action in embankment material in contact with a solid bedrock abutment. The thermal conductivity of rock can be an order of magnitude greater than that of soil [23].

Therefore, it seems logical that under certain conditions, frost could penetrate much deeper at the soil-rock interface than it would in the embankment at some distance from the interface (fig. 35). This difference could be accentuated by (1) snow cover on the embankment reducing frost penetration, (2) little snow cover on the rock abutment, and (3) shading of the abutment. Freezing of the soil at the contact area would tend to draw moisture from the embankment toward the rock with a simultaneous decrease in density near the interface (fig. 36) and with the possible development of thin ice lenses. At some distance from the interface, the capillarity action with decreased moisture content would consolidate the soil.

Therefore, a thin zone of low-density, highly permeable soil near the interface could be formed that would be critical for piping of soil susceptible to such action. Judging from results of tests on some laboratory specimens which shrank slightly during closed-system freezing, and on the type of soil with its degree of saturation, there could even be a small crack at the soil-rock interface formed by the soil pulling away from the rock. Also, it is possible that shrinkage cracks could develop in the consolidated soil zone some distance from the interface. The critical zone could be very thin (a matter of a few millimeters) for piping to start and continue as the reservoir was filled, provided the soil particles at the end of the "pipe" could pass into some open space, such as a crack in the abutment, and were not restrained, as by a filter. The formation of a critical piping zone at the interface could be accentuated by any water from snowmelt, precipitation, or contractor operations, flowing down the abutment and freezing in the embankment. The possibility of dam failure is predicated upon the assumption that construction personnel were not aware of the deep freezing and possible effects and did not excavate the soil deep enough and recompact it to specification limits. The low density of a very thin zone at the interface could not be detected by the usual soil density test methods. However, the moisture content of the soil very close to the rock could be obtained to show moisture resulting from freezing action and external sources such as snow melt.

It would be possible to insulate the soil-rock interface by mounding loose soil against the abutment. This would also help absorb minor quantities of water running down the abutment before it drained into the embankment.

Recommended Precautions for Construction Control of Earth Embankment Dams

The following are measures that can be taken to avoid possible unfavorable effects of freezing action on embankment soil during cessation of construction in winter:

1. Record daily maximum and minimum air temperatures and precipitation at or near the embankment.

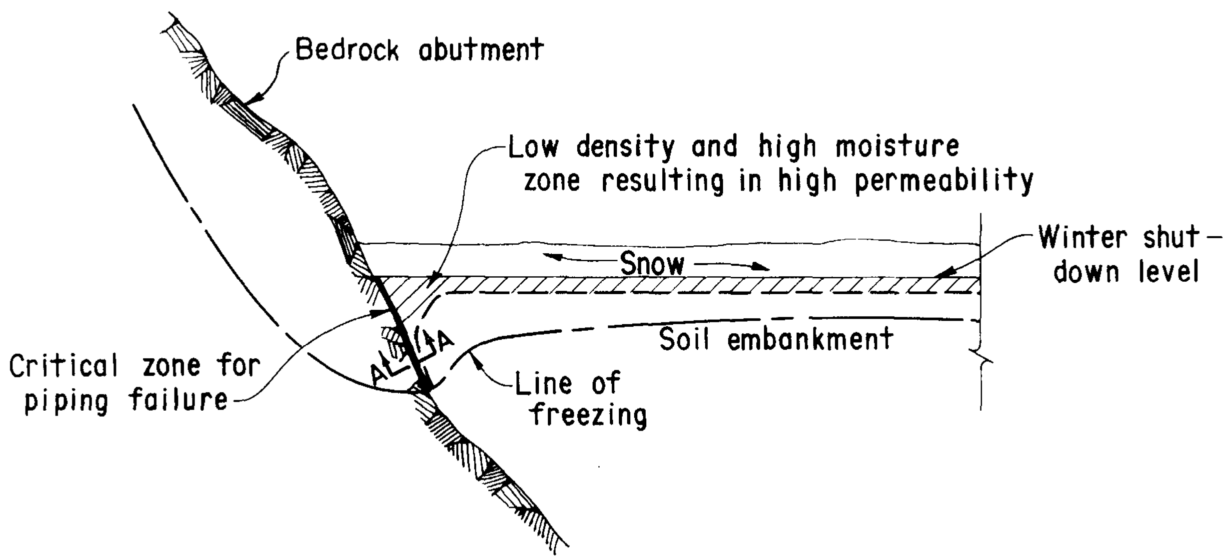

Figure 35.—Frost action on embankment soil in contact with bedrock abutment.

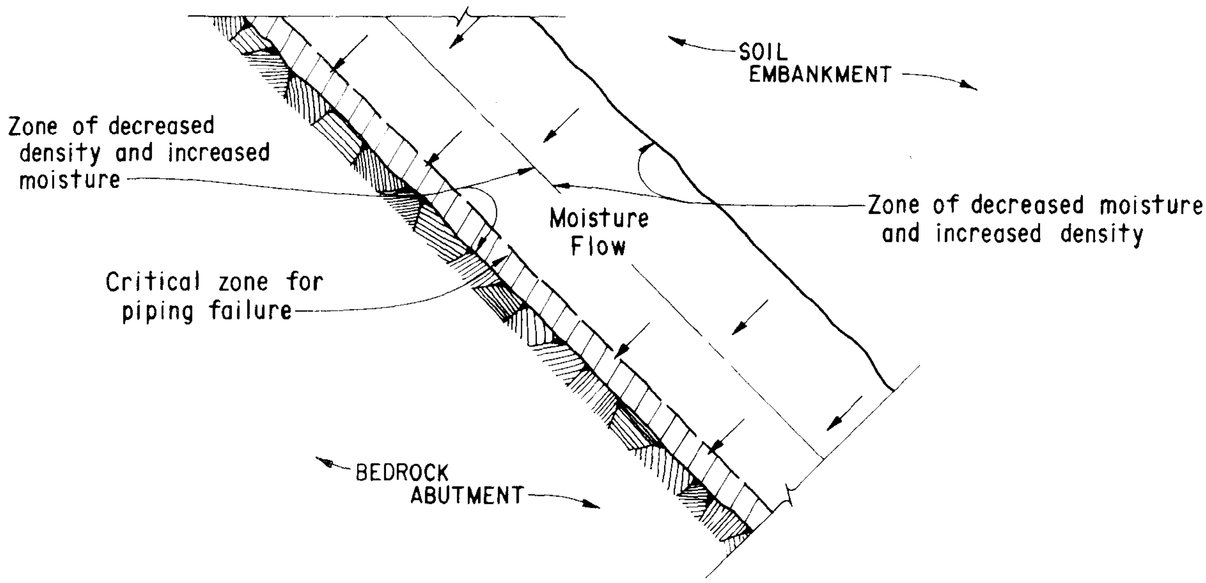

Figure 36.—Moisture and density changes during freezing at contact between soil embankment and bedrock abutment (section AA of fig. 35).

2. During the final days before embankment placement is stopped by cold weather and for a few days in the spring after placement is resumed, record the soil temperatures when field density tests are conducted.

3. To minimize possible detrimental effects of freezing on compacted embankments, place insulation such as loose soil or artificial snow, over the surface of the embankment with the greatest depth at embankment-rock abutment contacts. The cost of placement and removal of the insulation should be compared against the cost of removal of compacted embankment not meeting specification requirements. Other treatments such as the use of salt or other additives could be considered.

4. Before the onset of freezing weather, install frost tubes in areas where the deepest frost penetration would be expected and monitor frost penetration until it is out in the spring.

5. During the winter, periodically record measurements of snow depth at various locations on the embankment, taking note particularly where contractor operations or the wind reduces snow depth.

6. Before resuming embankment placement, systematically explore the embankment for remaining frost and for any visible effects such as cracks, which have been caused by freezing. Particularly explore at intervals along the embankment where it contacts a bedrock abutment. Carefully dig the soil away from the rock and look for high moisture content or cracks where the soil might have shrunk away from the rock or cracks some distance away from the interface where the soil might have consolidated.

7. Conduct density tests in the soil to establish that it meets density and moisture requirements. Locate some of the density tests as close as possible to bedrock abutments. Also, determine the moisture content of the soil in contact with the rock.

8. In addition to removal and replacement of soil not meeting specification limits for density and moisture, consider removing any soil where effects of freezing, such as cracks, are visible regardless of the density test values.

RECOMMENDATIONS FOR RESEARCH

As mentioned previously in this report, actual field data on the effects of closed-system freezing on soil performance are quite limited. Only a few field applications have been made since Beskow, an early investigator of frost action in soils in the 1930's, stated that this type of freezing was "of some theoretical interest." The collection of data in the Water and Power Resources Service during the winter of 1978-79 showed that worthwhile information could be obtained during construction. Where opportunities arise, this should be continued by personnel trained to conduct frost investigations.

Specific areas of research involving the effects of closed-system freezing on soils were inferred from questions raised in the discussion and are summarized below:

1. The investigation of possible soils, rock, and climatic conditions under which deep freezing might occur in an earth embankment dam in contact with a bedrock abutment causing changes in the soil properties detrimental to the performance of the dam.

2. The investigation of soil shrinkage in earth embankment dams located in northern United States causing cracking with a possible threat to the safety of the dam.

3. The application of an existing method or development of a new method if necessary to rapidly detect the presence and extent of subsurface frozen soil over a wide area in a compacted embankment.

BIBLIOGRAPHY

[1] Young, R. N., and B. P. Warkentin, *Introduction to Soil Behavior,* Macmillan, New York, 1966.

[2] Jumikis, A.R., *Soil Mechanics,* Von Nostrand, Princeton, New Jersey, 1962.

[3] Dirksen, C., and R.D. Miller, "Closed-System Freezing of Unsaturated Soil", *Proceedings, Soil Science Society of America,* Vol. 30, 1966.

[4] Quinn, William F., David Carbee, and Thaddeus C. Johnson, "Membrane Encapsulated Soil Layers (MESL) for Road Construction in Cold Regions", Roads Research, Symposium on "Frost Action in Roads", Paris, 1973.

[5] Smith, North, "Construction and Performance of Membrane Encapsulated Soil Layers in Alaska",U.S. Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory, Report 79-16, June 1979.

[6] "Frost Investigations, Cold Room Studies, Third Interim Report of Investigations", Technical Report No. 43, Arctic Construction and Frost Effects Laboratory, Corps of Engineers, U.S. Army, October, 1958.

[7] Chamberlain, Edwin J., and Anthony J. Gow, "Effect of Freezing and Thawing on the Permeability and Structure of Soils", International Symposium on Ground Freezing, Bochum-Germany, March 1978.

[8] Wang, Mian-Chang and Gilbert L. Roderick, "Frost Behavior of Compacted Soils", Highway Research Record No. 360 Frost Action and Drainage, 1971.

[9] Hamilton, A.B., "Freezing Shrinkage in Compacted Clays", *Canadian Geotechnical Journal,* Volume III, Number 1, February 1966.

[10] Powers, T.C., and R.A. Helmuth, "Theory of Volume Changes in Hardened Portland-Cement Paste During Freezing", Proceedings, Highway Research Board 32:285-97, 1953.

[11] Grechischev, S.Ve., and Yu. B. Sheshin (VSEGINGEO), "Theoretical and Experimental Studies of Temperature Stresses and Strains in Earth Dams During Winter", (USSR Ministry of Geology). All-Union Scientific Research Institute of Hydrogeology and Engineering Geology. Unpublished MS, Trudy (Transactions), No. 55, Moscow, 1973, pp 77-94. TL 449, CRREL Draft Translation 449, November 1974.

[12] Sheshin, Yu. B. (VSEGINGEO) "Results Obtained from Investigating the Mechanical Properties and Temperature Expansion of Frozen Ground in Connection with Construction of Earth Dams in Central Yakutia", (USSR Ministry of Geology). All-Union Scientific Research Institute of Hydrogeology and Engineering Geology, Unpublished MS, Trudy (Transactions), No. 55, Moscow, 1973, pp 95-101, CRREL Draft Translation 449, November 1974.

[13] "Pavement Design for Frost Conditions", TM5-818-2, Department of the Army Technical Manual, July 1965.

[14] Holtz, W.G., "Construction of Compacted Soil Linings for Canals", Bureau of Reclamation, Report No. EM-383, October 1954.

[15] Holtz, W.G., "Thick Compacted Earth Linings for Canals", Bureau of Reclamation, Report No. EM-462, August 1956.

[16] Jones, Chester W., and Clemith A. Lowitz, "Performance of Compacted Loessial-Soil Canal Linings," Bureau of Reclamation, Report No. EM-575, July 1960.

[17] Lowitz, Clemith A., "Frost Action Tests on Proposed Embankment and Lining Materials — Oakes Section — Garrison Diversion Unit — Missouri River Basin Project, North Dakota", Bureau of Reclamation, Report No. EM-544, December 1958.

[18] *Earth Manual*, U.S. Department of the Interior, Bureau of Reclamation, 2nd Edition, 1974.

[19] *Drainage Manual,* U.S. Department of the Interior, Bureau of Reclamation, 1st Edition, 1978.

[20] "Calculation Methods for Determination of Depths of Freeze and Thaw in Soils", TM 5-852-6, Department of the Army Technical Manual, January 1966.

[21] "James Bay Hydro Blooms in Remote Barren Wilds", *Engineering News-Record,* August 3, 1978.

[22] Highter, W.H., A.G. Altschaeffl, and C.W. Lovell, Jr., "Low Temperature Effects on the Compaction and Strength of a Sandy Clay", *Highway Research Record No. 304,* NAS-NAE, 1970.

[23] *Handbook of Physical Constants,* The Geological Society of America, Inc., Memoir 97, Sidney P. Clark, Jr., Editor, 1966.

APPENDIX A — Tables

Table A-1.—*Frost and snow depth measurements on Upper Meeker Canal for March 1960*

Station, meters (ft)	Location	Frost depth, meters (feet)	Comments
220+37	Canal bottom	0.06 (0.2)	10 cm of snow on 7.5 cm of ice
(723+00)	Left slope	0.21 (0.7)	10 cm of snow
	Right slope	0.64 (2.1)	10 cm of snow
221+59	Canal bottom	0	12 cm of ice
(727+00)	Left slope	0.15 (0.5)	20 cm of snow
	Right slope	0.76 (2.5)	15 cm of snow
224+64	Canal bottom	0	15 cm of snow, 8 cm of ice
(737+00)	Left slope	0.15 (0.5)	
	Right slope	0.09 (0.3)	15 cm of snow

Table A-2.—*Record of field and laboratory test data on Mt. Elbert forebay lining, June 1979*

Depth, meters	Percent, +No. 4	Density of fill, kg/m^3	Percent of the laboratory maximum density	Water content (%)	Optimum minus fill water content (%)	Relative mass density (Sp.Gr.) −No. 4	Liquid limit	Plasticity index	Class.
			"A" X = 78 212 m, Y = 263 542 m (local grid)						
0.09	14	1852	[1]100.2	15.5	−0.9	2.66	27	7	SC-SM
0.30	11	1972	101.2	11.5	0.4	2.68	26	8	SC
0.61	7	2137	104.4	7.9	1.9	2.60	22	6	SC-SM
0.91	6	2071	100.8	7.9	1.7	2.66	20	5	SC-SM
1.22	8	1978	98.8	9.8	1.1	2.67	30	13	SC
Average:	9	2002	101.0	10.5	0.8	2.65	25	8	
			"B" X = 78 212 m, Y = 263 957 m						
Grade	19	2054	[2]99.7	10.1	−0.4	2.67	16	2	SM
0.43	15	1911	97.4	13.2	−1.4	2.68	26	8	SC
0.88	9	1876	102.0	15.9	0.5	2.69	41	24	SC
1.22	8	1807	98.3	15.5	−0.5	2.71	31	13	SC
Average:	13	1912	99.4	13.7	−0.4	2.69	29	12	

[1] The result of a test taken at an adjacent location on July 23, 1978, was 100.4 percent.
[2] The result of a test taken at an adjacent location on July 25, 1978, was 101.7 percent.

Table A-3.—*Location of frost tubes in Red Fleet Dam during 1978-79 winter*

Frost Tube No.	Station, meters (ft)	Offset,[1] meters	Elevation, meters	Zone
1	5+07.5 (16+65)	0.31	1683.7	In left abutment (shale)
2	5+06.3 (16+61)	3.05	1693.2	1
3	4+90.1 (16+08)	14.0	1692.8	1
4	4+91.0 (16+11)	34.1	1692.2	1
5	4+19.4 (13+76)	8.53	1680.1	1
6	4+25.8 (13+97)	43.28	1681.6	1
7	3+80.1 (12+47)	26.52	1673.7	1
8	2+21.9 (7+28)	57.30	1683.2	1
10	2+12.8 (6+98)	50.90	1683.7	In right abutment (sandstone)

[1] All offsets are upstream (left).

Table A-4.—*Record of field density tests on Red Fleet Dam, zone 1*

Date	Station, meters (ft)	Offset (m)	Elevation (m)	Density of fill (kg/m³)	Percent of the lab. max. density	Fill moisture (%)	Optimum minus fill water content (%)	Borrow area
10-30-78	3+10.9 (10+20)	48.8 left	1670.6	1762	102.8	18.2	+0.2	M
10-31-78	3+50.5 (11+50)	21.3 left	1671.5	1773	103.5	18.5	−0.1	M
11-06-78	3+53.6 (11+60)	15.2 left	1672.4	1780	104.2	17.3	−0.2	M
11-08-78	3+59.7 (11+80)	40.2 left	1672.1	1724	102.7	18.7	+0.5	M
11-09-78	3+59.7 (11+80)	38.1 left	1673.0	1761	102.8	18.7	0.0	M
	3+81.0 (12+50)	13.4 right	1672.7	1938	105.1	13.2	+1.1	M
1-11-79	5+05.0 (16+57)	5.8 left	[1]1693.1	1873	101.5	14.6	+0.2	B
		5.8 left	1692.8	1833	99.3	13.2	+0.9	R
1-12-79	5+05.0 (16+57)	5.8 left	[2]1692.5	1916	106.4	14.6	+0.3	B
		5.8 left	1692.2	1954	106.0	13.8	+0.2	B
4-23-79	3+10.6 (10+19)	17.4 left	1671.4	1777	103.6	19.2	−0.2	M
		17.4 left	1670.8	1841	107.0	17.7	+0.6	B
	3+11.5 (10+22)	32.9 right	1672.0	1929	102.5	14.9	+0.3	B
		32.9 right	1671.4	1863	101.0	15.0	−0.2	B
	3+83.4 (12+58)	21.0 left	1672.6	1866	108.8	16.1	+2.6	M
		21.0 left	1672.0	1796	105.7	18.8	−0.5	M

[1] Soil frozen.
[2] Frost lenses in top of hole.

Table A-5.—*Record of field density tests on Red Fleet Dam, zone 1A*

Date	Station, meters (ft)	Offset[1] (m)	Elevation (m)	Density of[2] fill (kg/m³)	Percent of the lab. max. density	Fill moisture (%)	Optimum minus fill water (%)
4-21-79	1+84.4 (6+05)	57.9	1682.2	1809	96.5	7.7	+2.5
4-20-79	1+84.4 (6+05)	57.9	1682.8	1929	100.8	10.8	+1.7
4-20-79	2+24.0 (7+35)	61.0	1682.8	1994	103.4	11.5	−0.1
4-21-79	2+24.0 (7+35)	61.0	1682.2	1966	101.6	10.4	+1.5
4-20-79	2+51.5 (8+25)	45.7	1677.3	1993	104.4	11.9	+1.3
4-20-79	2+51.5 (8+25)	45.7	1677.9	1972	103.1	11.5	+1.4
4-21-79	2+83.5 (9+30)	61.3	1672.7	2003	105.8	13.0	−0.2
4-21-79	3+48.1 (11+42)	73.2	1672.4	1946	105.2	14.1	−0.3
4-20-79	3+51.7 (11+54)	51.8	1672.4	1943	103.4	13.6	−0.7
4-20-79	3+74.9 (12+30)	43.9	1672.7	1977	102.8	11.4	+1.2

[1] All offsets were to the left (upstream).
[2] All soil passed the No. 4 sieve.

Table A-6.—*Locations of frost tubes in Twin Lakes Dam*

Date Tube Installed	Frost Tube No.	Station, meters (ft)	Offset, meters	Elevation, meters	Zone
12-13-78	1	4+57.2 (15+00)	℄	2788.9	Natural ground
12-12-78	2	6+70.4 (21+99.60)	℄	2791.8	1
12-13-78	3	6+70.7 (22+00.59)	12.1 left	2792.1	1A
12-12-78	4	6+66.6 (25+15.12)	13.6 left	2794.8	1A
12-5-78	5	9+14.4 (30+00)	0.5 right	2802.4	1
12-5-78	6	11+12.6 (36+50)	0.3 right	2804.5	1

Table A-7.—*Field density tests in Twin Lakes Dam - April 14-17, 1979*

Station, meters (ft)	Offset (m)	Depth[1] (m)	+No. 4 (%)	Dry density of −No. 4 (kg/m^3)	Percent of maximum density	Water content of −No. 4 (%)	Optimum minus fill water content (%)
			Zone 1-*Green Hill Borrow*				
6+70.5	1.8 left	0.28-0.53	23	1972	98.2	9.0	+1.7
(22+00)	1.8 left	0.91-1.22	22	2111	105.1	8.7	+1.4
9+14.4	1.8 right	0.23-0.46	19	2023	102.5	9.4	+0.8
(30+00)	1.8 right	1.07-1.37	9	2014	102.9	12.4	+0.1
11+12.5	1.5 right	0.25-0.46	26	2156	106.8	7.8	+1.6
(36+50)	1.5 right	1.07-1.28	10	2035	103.8	11.9	+0.2
		Average:	18	2052	103.2	9.9	+1.0
			Zone 1A-*Reservoir Borrow*				
6+70.5	12.2 left	0.30-0.51	5	2044	103.2	7.1	+2.2
(22+00)	12.2 left	0.61-0.91	7	2073	102.2	7.2	+1.9
7+66.6	14.0 left	0.25-0.49	13	2027	100.0	9.1	+0.8
(25+15)	14.0 left	0.61-0.91	19	2081	101.5	8.3	+1.1
		Average:	11	2056	101.7	7.9	+1.5

[1] Depths are below the surface of compacted embankment at end of 1978 embankment placement season.

Table A-8.—*Location of frost tubes in Tiber Dam during the winter of 1978-79*

Frost tube No.	Station, meters (ft)	Offset, meters (ft)	Structure areas
1	2+74.3 (9+00)	-	Existing dam embankment
2	2+10.3 (6+90)	-	Cutoff trench
3	2+99.6 (9+83)	76.8 left (252)	Counterfort area for crest structure
4	2+99.6 (9+83)	16.8 right (55)	Counterfort area for crest structure

Table A-9.—*Field density tests performed in March and April 1979 after frost was out of the ground - Tiber Dam*

Date	Station, meters (ft)	Offset[1] (m)	Elevation (m)	Depth (m)	+No. 4 (%)	Fill density of −No.4 (kg/m³)	Percent of lab. maximum density	−No. 4 Water content (%)	Optimum minus fill water content (%)
				Embankment					
3-22-79	[2]2+74.3 (9+00)	-	[3]913.79	0.06-0.34	5	1668	94.1	17.9	−0.3
				0.34-0.61	5	1855	102.3	14.4	0.6
				0.61-0.91	3	1865	103.4	13.8	1.7
3-19-79	2+96.0 (9+71)	21.3	896.1		8	1503	82.1	14.7	0.9
		21.3	895.2		17	1870	97.5	11.7	0.5
			894.7		21	1914	99.8	11.3	0.4
4-18-79	3+37.4 (11+07)	15.2	893.37		32	1839	91.8	9.1	0.2
			892.76		20	1943	98.3	10.1	0.0
			892.15		42	1956	97.7	11.3	0.2
				Cutoff trench					
	[4]2+10.3 (6+90)	1.8 rt	[3]900.80	0.03-0.30	28	1680	87.4	13.3	−2.5
				0.30-0.61	29	1886	96.3	12.7	−2.0
				0.64-0.91	25	1801	91.2	11.5	−0.3
				0.97-1.22	49	1841	92.1	10.4	−0.9
				Counterfort backfill					
3-23-79	2+99.6 (9+83)	17.1	896.4		34	-	-	11.4	-
			895.5		37	1741	91.6	11.8	−1.9
			894.9		11	1813	100.8	15.8	−0.5

[1] All offsets were to the right (downstream).
[2] Tests adjacent to location of frost tube 1.
[3] Surface elevation.
[4] Tests adjacent to location of frost tube 2.

APPENDIX B

Laboratory Freezing Test for Soil

The laboratory freezing test used by the Water and Power Resources Service consists essentially of freezing cylindrical soil specimens from the top downward in an insulated cabinet (fig. B-1). For the tests described in the body of this report, the cabinet floor was wood without insulation and no attempt was made to regulate the temperature at the bottoms of specimens which would be near room temperature.

Up to six specimens were simultaneously placed in the cabinet for freezing tests (fig. B-2). For the tests reported herein, dry sand (about No. 30 size) was placed in the space around the specimens (fig. B-3). The use of sand was probably adopted from procedures of early investigators of laboratory frost tests. However, sand is less desirable for this purpose than insulation such as sawdust or vermiculite because the thermal conductivity of the sand would undoubtedly be higher than that of the soil and some lateral freezing of the specimens would occur whereas only vertical freezing was intended. Also, an array of piezometers, each spaced 25 mm apart, level with the specimens and surrounded with the sand in the center of the cabinet would not exactly reflect the temperatures at corresponding levels in the specimens.

The temperatures were recorded by a direct reading bridge or a digital thermometer. After the refrigeration unit was installed on top of the cabinet, the air circulated by a fan over the tops of the specimens was temperature controlled.

The tops of the specimens could be viewed for specimen height measurement by a mirror-viewing system. The height measurements were made by a dial indicator with a long vertical stem joined to a horizontal arm that was moved from one specimen top to another. The free end of the arm which rested on the specimen top had an electrical contact point on a spring so when it was

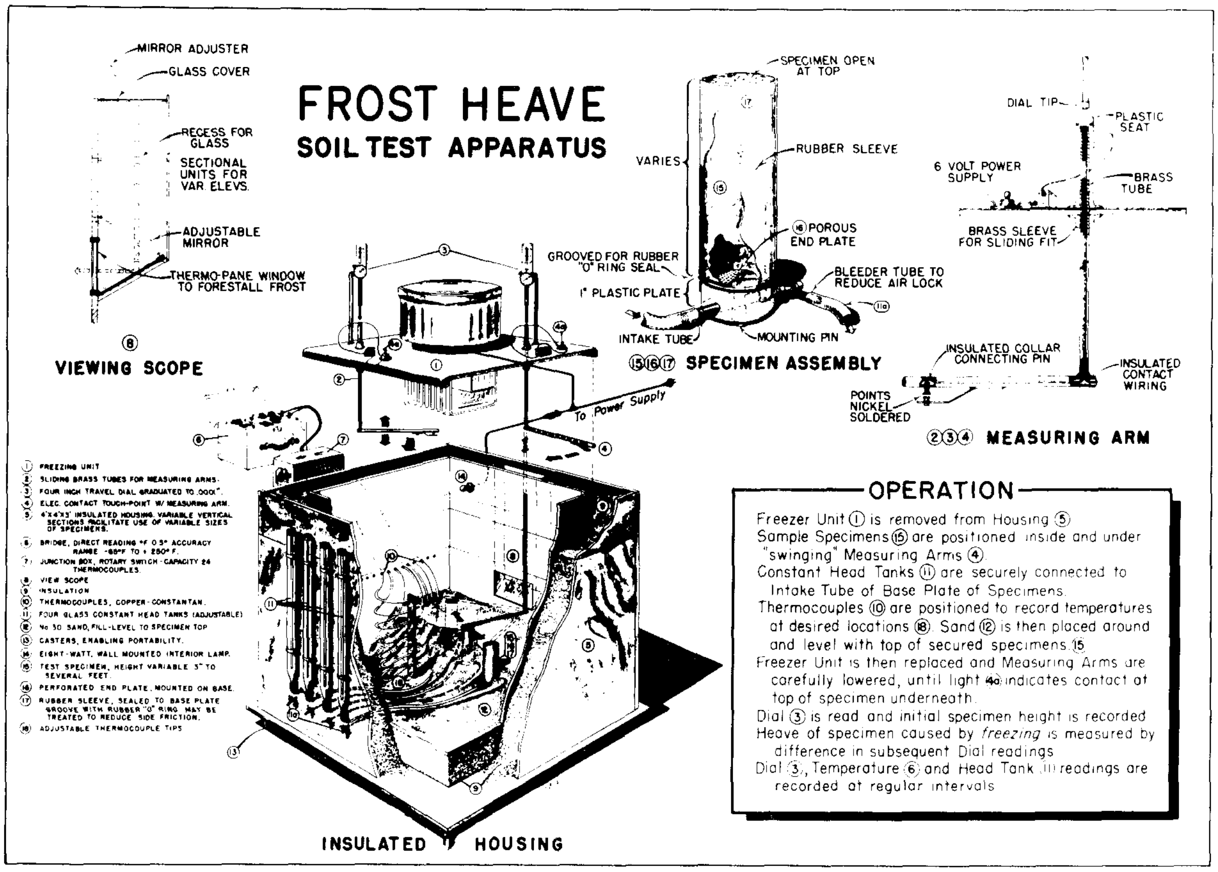

Figure B-1.—Frost heave soil test apparatus.

Figure B-2.—Soil specimens in insulated housing being prepared for freezing test. The center bank of thermocouples on the wooden post can be seen. Photo E-2343-2

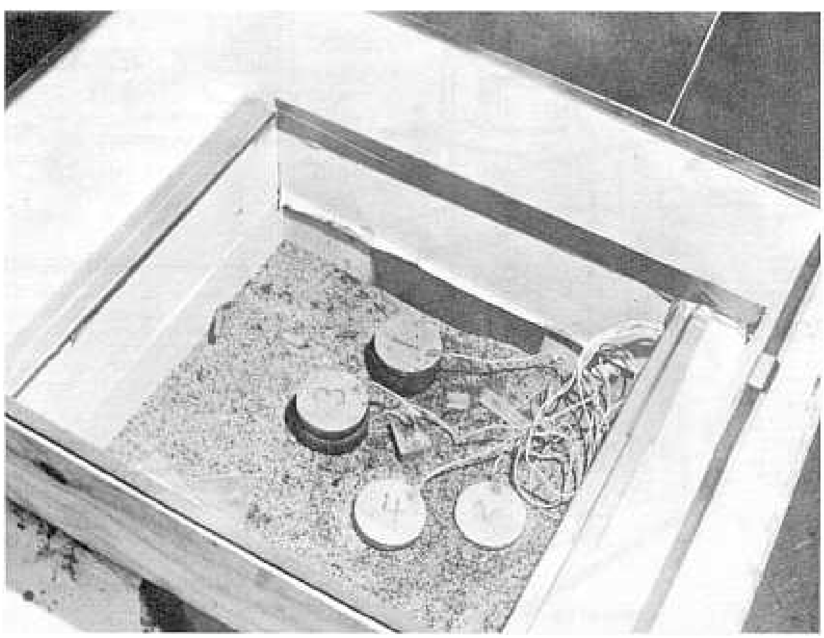

Figure B-3.—Sand has been added around the specimens. Photo E-2343-1 set on a specimen, an electrical circuit was closed, a light in the top of the housing came on, and a dial indicator reading results. Subsequent readings were compared with the initial reading, showing any changes in specimen height.

For an open-system test, a calibrated head tank with water at room temperature, attached to the exterior of the housing, had tubing leading to a perforated bottom plate attached at the specimen bottom. The water level in the head tank was maintained about 25 mm (1 inch) above the specimen bottom throughout the freezing test. For the closed-system tests, each specimen was provided with a solid plastic base plate and no water from an outside source was supplied.

APPENDIX C

Results of Petrographic and Chemical Analyses on Canal Lining Soils Used in Laboratory Freezing Tests

The soil tested from Upper Meeker Canal was obtained from the right canal slope at station 220+56 m (723+65 ft). It was mostly angular to rounded quartz and feldspar grains with a little mica and other miscellaneous minerals. There was a small amount of calcite as shell fragments and possibly some caliche. The clay minerals are bidellite and illite in about equal amounts with a minor amount of kaolinite.

The soil from the South Platte Canal was obtained from the left slope between stations 449+63 and 449+92 m (1475+18 and 1476+13 ft). It consisted of igneous rock fragments, quartz, and feldspar grains, a few limestone particles, ferruginous concretions, mica flakes, and a wide variety of miscellaneous detrital minerals in small amounts. The primary clay mineral present was bidellite, with some illite, and a very minor amount of kaolinite.

The soil used from the Hudson Canal was obtained from the right slope at station 145+08 m (476+00 ft). This soil was reddish in color and had a few rock fragments of limestone, ferruginous concretions, and chert particles up to No. 8 size. There were rounded quartz grains and some feldspar present. The clay was predominantly illitic with some bidellite and minor amounts of kaolinite.

Chemical analyses of the soils used in the laboratory freeze test were made and the results are:

	Upper Meeker	South Platte Supply	Hudson
Acidity of saturated paste (pH)	7.8	8.1	8.1
*Exchange capacity	15.8	10.2	9.69
*Total sodium	0.70	0.55	0.35
*Soluble sodium	0.21	0.14	0.13
*Exchangeable sodium	0.49	0.41	0.22
*Total potassium	1.15	0.40	0.30
*Soluble potassium	0.06	0.01	0.01
*Exchangeable potassium	1.09	0.39	0.29

*Milliequivalents per 100 grams of soil