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# LONG-TERM CHANGES IN THE PROPERTIES OF SOIL LININGS FOR CANAL SEEPAGE CONTROL

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16. ABSTRACT
Field and laboratory test data on typical soils in selected Bureau compacted soil (earth) canal linings show long-term physical changes in the linings. These data are indicative of lining performance. The physical properties (particularly unit weight) of the lining soil that affect permeability and canal seepage were tested at various intervals after lining construction. Unit weight was found to vary significantly from one test site to another from year to year. Although there was a general tendency for unit weight to decrease from the top of the lining to the bottom, in some cases it increased. Based on results of laboratory freezing tests, changes in unit weight for linings in cold climates were largely attributed to frost action. Generally, there appeared to be less (average) change in unit weight in fine-grained soils of low plasticity without gravel than in soils containing a significant gravel fraction. In one heavy clay lining, loss of unit weight was attributed to wetting and expansion of the soil. Based on field tests of permeability and seepage and on observations of seepage adjacent to the canals, it was concluded that the soil changes found did not significantly affect the expected performance of the canals in controlling seepage.

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by

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Geotechnical Branch
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Engineering and Research Center
Denver, Colorado

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# CONTENTS

| | Page |
|---|---|
| Introduction | 1 |
| Conclusions | 1 |
| Soils used for linings | 1 |
| Lining construction | 2 |
| Field test sites | 2 |
| Laboratory tests | 2 |
| Physical properties tests | 2 |
| Freezing tests | 2 |
| Field tests | 5 |
| Unit weight | 5 |
| Permeability and seepage | 8 |
| Discussion | 10 |
| Effects of frost action on compacted soil linings | 10 |
| Heavy clay lining | 22 |
| Low plasticity lining | 22 |
| Miscellaneous influences on soil lining | 23 |
| Recommendations | 23 |
| Applications | 23 |
| Bibliography | 23 |
| Appendix A – Summary of information on test sites | 25 |
| Lateral EL–68, Columbia Basin Project | 27 |
| Potholes East Canal, Columbia Basin Project | 27 |
| West Canal, 4th Section, Columbia Basin Project | 27 |
| Main Canal, Post Falls Unit, Rathdrum Prairie Project | 29 |
| Delta-Mendota Canal, Central Valley Project | 29 |
| Wellton-Mohawk Canal, Gila Project | 33 |
| Southside Canal, Collbran Project | 33 |
| Means and Eden Canals, and Farson Lateral, Eden Project | 33 |
| Hudson Canal, Tucumcari Project | 35 |
| Sunshine Reservoir Supply Canal | 38 |
| Angostura Main Canal, Angostura Unit, PSMRBP | 38 |
| Canal B, Fort Clark Unit, PSMRBP | 40 |
| Helena Valley Canal, Helena Valley Unit | 43 |
| Lateral D, Fort Shaw Division, Sun River Project | 43 |
| Boulder Creek Supply Canal, Colorado-Big Thompson Project | 46 |
| South Platte Supply Canal, Colorado-Big Thompson Project | 48 |
| Cambridge Canal, Frenchman-Cambridge Division, PSMRBP | 48 |
| Culbertson Canal, Frenchman-Cambridge Division, PSMRBP | 50 |
| Franklin Canal, Bostwick Division, PSMRBP | 52 |
| Upper Meeker Canal, Frenchman-Cambridge Division, PSMRBP | 54 |
| Soil reservoir lining on Mt. Elbert Forebay | 54 |
| Appendix B – Soil test data | 61 |

## CONTENTS – Continued

### TABLES


Table — Page

1 Canal lining test sites and freezing indexes ........ 5
2 Data on compacted soil lining test sections ........ 6
3 Permeability and seepage test results on soil lining ........ 18
4 Physical properties of soils from three recompacted canal linings ........ 20
A-1 Unit weights of lining, by location, in Culbertson Canal ........ 54
A-2 Unit weights of lining, by cover, in Culbertson Canal ........ 54
B-1 Field and laboratory soil test data ........ 63


### FIGURES


Figure

1 Location of lining test sites ........ 3
2 Location of unit weight tests in canal lining ........ 8
3 Variations in unit weight of soil in lining on Lateral EL–68 ........ 9
4 Variations in unit weight of soil in lining on Southside Canal ........ 10
5 Variations in unit weight of soil in lining on Helena Valley Canal ........ 11
6 Variations in unit weight of soil in lining on Boulder Creek Supply Canal ........ 12
7 Variations in unit weight of soil in lining on Cambridge Canal ........ 13
8 Variations in unit weight of soil in lining on Culbertson Canal ........ 14
9 Variations in unit weight of soil in lining on Franklin Canal ........ 15
10 Variations in unit weight of soil in lining on Upper Meeker Canal ........ 16
11 Frost penetration and snow depths for the compacted soil lining on the Mt. Elbert Forebay during the winter of 1978-79 with subsequent unit weight (density) test data ........ 17
12 General effects of open- and closed-system freezing on unconfined soil specimens insultated at the sides and frozen uniaxially from the top downward ........ 19
13 Specimens of soil after laboratory freezing tests ........ 19
14 Changes in the unit weight of compacted soil canal linings ........ 20
15 Unit weights and moisture contents of lining soils before and after freezing test ........ 21
16 Average changes in unit weight (in parentheses) and percentages of plus No. 4 fraction (in brackets) for lining soils, plotted on the A-line consistency limit chart ........ 22
A-1 Lateral EL–68 near station 211+00 ........ 27
A-2 Gradation and compaction test results for Lateral EL–68 ........ 28
A-3 Potholes East Canal looking upstream from right bank near station 881+00 ........ 29
A-4 Gradation and compaction test results for Potholes East Canal ........ 30
A-5 Gradation and compaction test results for West Canal ........ 31
A-6 Gradation and compaction test results for Main Canal, Rathdrum Prairie Project ........ 32
A-7 Delta-Mendota Canal at station 5049+50 after 14 years of service ........ 33
A-8 Gradation test results for Delta-Mendota Canal ........ 34
A-9 Southside Canal at station 635+65 ........ 35
A-10 Gradation and compaction test results for Southside Canal ........ 36
A-11 Gradation and compaction test results for Eden Project ........ 37
A-12 Hudson Canal near station 470+00 to station 485+00 ........ 38
A-13 Gradation and compaction test results for Hudson Canal ........ 39
A-14 Gradation test results for Sunshine Reservoir Supply Canal ........ 40
A-15 Gradation and compaction test results for Angostura Main Canal ........ 41
A-16 Gradation and compaction test results for Canal B ........ 42
A-17 Newly-constructed soil lining at station 763+00 in the Helena Valley Canal ........ 43
A-18 Gradation and compaction test results for Helena Valley Canal ........ 44
A-19 Gradation and compaction test results for Lateral D ........ 45
A-20 Boulder Creek Supply Canal at station 246+25 ........ 46
A-21 Gradation and compaction test results for Boulder Creek Supply Canal ........ 47
A-22 Lining test site between stations 1474+98 and 1477+48 on the South Platte Supply Canal after 6 years of canal operation ........ 48

## CONTENTS – Continued


| Figure | | Page |
|---|---|---|
| A-23 | Gradation and compaction test results, South Platte Supply Canal | 49 |
| A-24 | Cambridge Canal at station 1103+00 | 50 |
| A-25 | Gradation and compaction test results for Cambridge Canal | 51 |
| A-26 | Sand-cone unit weight test at station 383+20 on Culbertson Canal | 52 |
| A-27 | Gradation and compaction test results for Culbertson Canal | 53 |
| A-28 | Franklin Canal at station 123+50 | 55 |
| A-29 | Gradation and compaction test results for Franklin Canal | 56 |
| A-30 | Field permeability test in the side slope lining of Upper Meeker Canal at station 723+70 | 57 |
| A-31 | Closeup of shallow-well test in Upper Meeker Canal | 57 |
| A-32 | Gradation and compaction test results, Upper Meeker Canal | 58 |
| A-33 | Range of soil gradations at frost tube locations in Mt. Elbert Forebay reservoir lining | 59 |

## INTRODUCTION

This report presents results of an investigation of typical compacted soil (earth) canal linings constructed since the 1940's on Bureau (Bureau of Reclamation) projects to determine long-term performance with respect to seepage control. Emphasis is primarily on changes in physical properties of typical soil types used in linings that result from climatic influences, canal operation, and maintenance. The main changes determined were in unit weight, which is related to changes in permeability and seepage. Results of a few field permeability and ponding-type seepage tests are included. Some of the data, which have been collected intermittently over the past 25 years, were presented at annual research committee meetings and summarized in memoranda.

Although there is no recent compilation, by 1963 the Bureau had constructed more than 14,000,000 $yd^2$ (11,700,000 $m^2$) of compacted soil linings on more than 600 miles (965 km) of canals and laterals [1][1]. Where suitable soil is readily available near a construction site, compacted soil is usually the least expensive type of permanent lining. Any data on lining performance will be valuable for future canal design and construction.

Possible deterioration from frost action was of particular concern in the lining investigation. Therefore, special attention was directed to linings in relatively cold areas where it was thought that deterioration might occur.

## CONCLUSIONS

The following conclusions are based on limited testing on different types of compacted soil in Bureau canal linings located in widely scattered locations. The tests consisted of field unit weight, field and laboratory permeability, laboratory freezing, and field seepage tests.

- There are significant differences and changes in the unit weight of compacted soil in a canal lining: (1) between relatively close test sites, (2) at one test site over extended time periods, and (3) with depth in the lining. The differences and the changes reported are believed to have been caused mainly by variations in (1) soil properties, (2) climatic influences, (3) canal operation and maintenance, (4) compaction during construction, and (5) different test conditions and procedures used by different technicians performing tests.

- Unit weight tends to decrease more with time toward the top of the lining than toward the bottom. This is caused by the wetting, drying, freezing, thawing, less confinement, and loading of the soil near the top of the lining, and disturbance from canal maintenance.

- For linings of expansive clay, water (moisture) content tends to increase, and unit weight tends to decrease over time.

- Where the water table is not near the canal bottom and the soil lining is subjected to closed-system freezing, the top of the lining may decrease in unit weight, but the unit weight toward the bottom will be more constant or may even increase from frost action. In a few instances, freezing caused a slight increase in the average unit weight of soil in the lining.

- Although open-system freezing from a high water table in a cold climate might be expected to cause deterioration of the lining in a canal not containing water, the extent of such deterioration has yet to be determined.

- Where the ground-water table is higher than the water level in a canal, seepage may cause a decrease in the unit weight of the soil. Under such conditions in a cold climate, frost may further deteriorate the lining. In some cases, seepage into a canal caused linings to slough into the canal.

- Compacted soil linings generally appear to adequately control canal seepage.

## SOILS USED FOR LININGS

Selection of suitable soil and construction of compacted soil linings have been described in Bureau publications [1, 2, 3, 4]. The preferred soils for linings are well-graded gravels or sands with enough clay binder or lean clay to fill voids and provide a material with a low permeability. The presence of gravel and sand particles increases the resistance to surface erosion from water. Silts are sometimes used, but if the silt is cohesionless, erosion protection may be required, particularly on canal curves. Other types of soils, such as heavy clays subject to volume change and silty sands and gravels, have been used to a limited extent with varying degrees of success. According to published guidelines (fig. 108 of [4]), to be sufficiently resistant to erosion from flowing canal water and wave action on canal side slopes, the minimum plasticity index should be 10 or, preferably, 12. To avoid heavy clay, which is often difficult to process for lining and may decrease in unit weight and become unstable because of its expansiveness, the maximum liquid limit recommended in the guidelines is 45. In all cases, the permeability (coefficient of permeability) of soil proposed for lining is determined

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

in the laboratory. A general guide is that the permeability should be below 1 ft/yr ($1 \times 10^{-6}$ cm/s). However, based on soil permeability, seepage through a lining of given dimensions can be calculated (des. E–36(8) of [4]) and the thickness designed to control seepage to the desired degree. The maximum allowable canal seepage for design purposes depends on the economics for a particular canal, but values of 0.1 to 0.2 $ft^3/ft^2/d$ (30 to 60 $L/m^2/d$) have been used for permanent canal linings.

## LINING CONSTRUCTION

Most Bureau compacted soil linings are built up of 6-inch (150-mm) thick compacted soil layers. For the thick lining type, side slopes consist of successive horizontal layers offset to form 2:1 slopes (1½:1 has also be used) that provide a thickness normal to slope of 3.5 feet (1.1 m) for a layer 8 feet (2.4 m) wide. Thicknesses of linings in canal bottoms are varied, but they are commonly about 2 feet (0.6 m).

In 1963, about 13 percent of compacted soil linings were the thin type with the thickness on the bottom and side slopes ranging between 6 and 18 inches (0.15 and 0.46 m) (p. 2 of [1]). In small canals, the thin linings are sometimes constructed by (1) over-excavating the canal, (2) completely filling the excavation with soil lining material, and (3) excavating the filled section to canal prism dimensions, leaving the required amount of compacted material to form the lining. In a few instances, mostly in test reaches, thin linings have been constructed by compacting soil layers parallel to the side slope; however, with conventional equipment, this has been slow, inefficient, and uneconomical.

## FIELD TEST SITES

Twenty-two soil-lined canal reaches were selected for testing. The selections included a range of most soil types used in linings. They were located in widely scattered areas in different climatic conditions of the Western States (fig. 1). Table 1 lists the test canals with their locations by region, project, and state. Table 1 also shows for each test site an approximate mean air-freezing index, which is a measure of the intensity of cold weather. A freezing index is based on the accumulative degree-days during the cold season; each degree-day is the difference between the maximum and minimum daily air temperature and 32 °F (0 °C) (p. 16 of [5]). The freezing indexes in table 1 are taken from a map of the continental United States upon which a distribution of mean air-freezing indexes has been superimposed (fig. 13 of [5]).

Table 2 lists the test sections with stationing, canal characteristics, lining thicknesses, construction specification numbers, and dates of lining construction and field tests.

Where possible, testing was started shortly after lining construction was completed. For a few test sites, only one set of tests was made; these are reported even though it is not possible to determine changes in soil properties.

## LABORATORY TESTS

### Physical Properties Tests

Except for freezing tests, which are described below, *Earth Manual* [4] test procedures were used. Tests were performed by personnel in the Engineering and Research Center and in Bureau field laboratories. Gradation and compaction test results are shown in appendix A, and other test results are listed in appendix B. The canal test sites are arranged in numerical order for the Bureau regions in existence at the time of testing and alphabetically by canal name within regions.

### Freezing Tests

Soil from three canal linings was compacted into cylindrical specimens 3.25 inches (83 mm) in diameter by 9 inches (230 mm) long to unit weights and moisture contents comparable with values in the soil linings. Specimens were set in a cabinet with insulated walls, and dry sand was placed around them. Thermocouples were installed in the specimens at 1-inch (25 mm) depth intervals, and temperatures during freezing were monitored by a voltage bridge system. Changes in specimen heights were monitored by a remote-controlled, mirror-viewing system. The top of the freezing cabinet contained a refrigeration unit that maintained a constant subfreezing temperature in the space above the specimens. As specimens were frozen from the top downward, temperatures in specimens and any frost heave were recorded periodically. To represent closed-system freezing for these tests, no water was supplied at the bottoms of specimens. After a 30-day freezing test period, the specimens were removed and immediately sawed into thirds. Unit weights and moisture contents were determined by tests on the one-third portions of each specimen. More details on the test procedure and a drawing and photographs of the freezing test equipment are given in appendix B of [6].

It should be noted that another type of freezing test, not now recommended, was used for one series of laboratory tests on soil from the Courtland Canal lining [7]. For this type of test, soil specimens compacted in 8-inch (203-mm) standard permeability cylinders (des. E–13 of [4]) were placed in a 10 °F

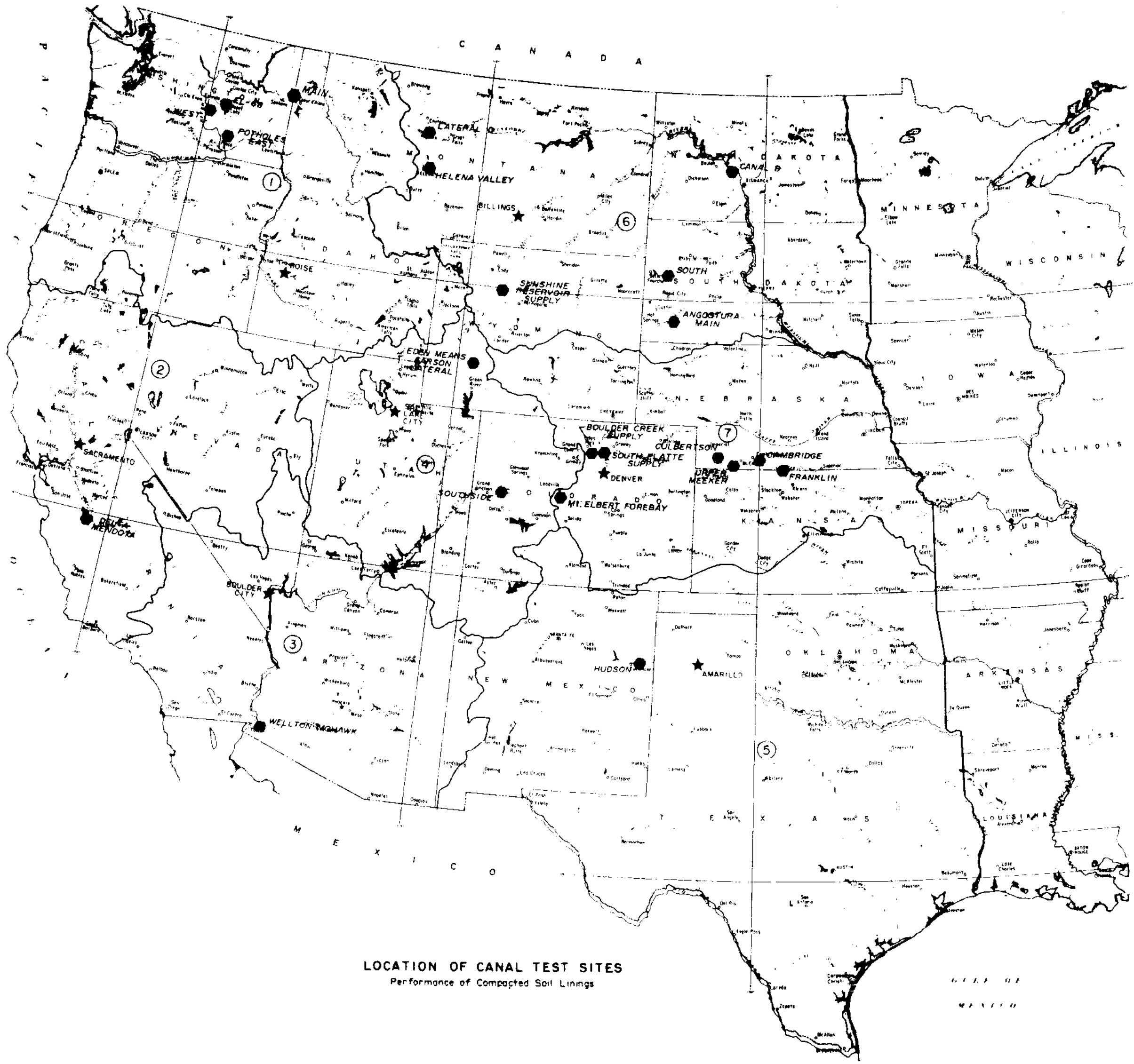


Figure 1. – Location of lining test sites.

Table 1. – Canal lining test sites and freezing indexes.

| Canal | Project | State | Freezing index |
|---|---|---|---|
| | *Pacific Northwest Region* | | |
| Lateral EL–68 | Columbia Basin | Washington | 250 |
| Potholes East | Columbia Basin | Washington | 100 |
| West, 4th Section | Columbia Basin | Washington | 250 |
| Main, Post Falls Unit | Rathdrum Prairie | Washington | 250 |
| | *Mid-Pacific Region* | | |
| Delta-Mendota | Central Valley | California | 0 |
| | *Lower Colorado Region* | | |
| Wellton-Mohawk | Gila | Oregon | 0 |
| | *Upper Colorado Region* | | |
| Southside | Collbran | Colorado | 400 |
| Eden | Eden | Wyoming | 1,100 |
| Farson Lateral | Eden | Wyoming | 1,100 |
| Means | Eden | Wyoming | 1,100 |
| | *Southwest Region* | | |
| Hudson | Tucumcari | New Mexico | 0 |
| | *Upper Missouri Region* | | |
| Sunshine Reservior Supply | Greybull Valley Reservoir | Wyoming | 1,500 |
| Angostura Main | Missouri River Basin | S. Dakota | 950 |
| Lateral B, Fort Clark Unit | Missouri River Basin | N. Dakota | 2,000 |
| Helena Valley | Missouri River Basin | Montana | 1,500 |
| | *Upper Missouri Region* | | |
| Lateral D, Fort Shaw Division | Sun River | Montana | 1,700 |
| | *Lower Missouri Region* | | |
| Boulder Creek Supply | Colorado-Big Thompson | Colorado | 400 |
| South Platte Supply | Colorado-Big Thompson | Colorado | 400 |
| Cambridge | Missouri River Basin | Nebraska | 250 |
| Culbertson | Missouri River Basin | Nebraska | 200 |
| Franklin | Missouri River Basin | Kansas | 250 |
| Upper Meeker | Missouri River Basin | Nebraska | 200 |

(−12 °C) room for 24 hours. The cylinders with soil were then removed from the cold room and allowed to thaw at 74 °F (23 °C) in a 100-percent humidity room for 24 hours. Permeability tests were then performed after different numbers of freezing and thawing cycles. Using this procedure, freezing of the soil progressed through the sides of each specimen as well as through its top and bottom. This caused a decrease in soil unit weight in the sides of the soil specimen relative to that in the center. The decreased soil unit weight near the cylinder wall (sides) tended to allow a higher permeability than in the interior. Therefore, the permeability and unit weight test results reported in [7] tended to be somewhat different from those for tests on specimens with side insulation and frozen uniaxially from the soil surface downward, which is the normal condition for ground freezing.

# FIELD TESTS

## Unit Weight

Unit weight tests were performed by Bureau personnel using the sand cone method (des. E–24 of [4]). Although the same test procedure was used, minor variations ($\pm 2$ lbf/ft$^3$ (0.3kN/m$^3$)) in unit weight of a soil are expected from different technicians and even from the same technician under different soil conditions. A hollow-stem auger sampler was used for unit weight tests in the side slope lining of the water-filled Delta-Mendota Canal (fig. A-7).

Table 2. – Data on compacted soil lining test sections.

| Canal | Stationing, ft | Canal characteristics: Base width, ft (m) | Canal characteristics: Water depth, ft (m) | Canal characteristics: Side slopes | Canal characteristics: Discharge, $ft^3/s$ ($m^3/s$) | Thickness of lining: Sides (hor.), ft (m) | Thickness of lining: Bottom (vert.), ft (m) | Specification | Date of construction | Dates of unit weight tests[1] |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **PN Region** | | | | | |
| Lateral EL–68 | 182+00 to 211+20 | 18 (5.5) | 6.0 (1.83) | 1.75:1 | 4,500 (127.4) | 6 (1.83) | 1.5 (0.46) | 117C-402 | 4/57 | 11/57(p)[1],3/59(p), 3/60(p), 3/77 |
| Potholes East | 881+00 to 1119+75 | 64 to 62 (19.5 to 19.0) | 15.3 (4.66) | 1.5:1 | 3,900 (110.4) | 6 (1.83) | 1.5 (0.46) | DC-3780 DC-4928 | 3/53 3/59 | 3/55, 3/59 |
| West, Section 4 | 2173+00 to 2336+10 | 52 (15.8) | 11.6 (3.54) | 1.5:1 | 2,200 (62.3) | 8 (2.44) | 2 (0.61) | DC-4018 | 3/54 | 3/55, 3/59 |
| Main | 8+86 to 101+32 | 8 to 7 (2.4 to 2.1) | 3.2 to 3.0 (0.98 to 0.91) | 2:1 | 61 to 63 (1.7 to 0.9) | [2]0.5 (0.15) | 0.5 (0.30) | DC-1094 | 4/46 | 5/54, 12/63 |
| | | | | | **MP Region** | | | | | |
| Delta-Mendota | – | 84 to 60 (25.6 to 18.3) | 13.9 (4.24) | 2.5:1 | 3,300 (93.5) | 8 (2.44) | 2 (0.61) | DC-2857 | 1952 | 1951, 3/65, 1/66 |
| | | | | | **LC Region** | | | | | |
| Wellton-Mohawk | 33+00 to 286+50 | 44 (13.4) | 8.8 (2.68) | 2:1 | 1,300 (36.8) | 6 (1.83) | 2 (0.61) | DC-2688 | 2/50 | 6/50, 6/57 |
| | | | | | **UC Region** | | | | | |
| Southside | 632+30 to 635+65 | 14 (4.3) | 4.3 (1.31) | 2:1 | 225 (6.4) | 6 (1.83) | 2 (0.61) | DC-5155 | 11/59 | 11/59, 10/60, 5/62, 10/64 |
| Eden | 681+00 | 14 (4.3) | 4.4 (1.34) | 2:1 | 190 (5.4) | 8 (2.44) | 1.5 (0.46) | DC-4159 | 1955 | 10/60 |
| Farson Lateral | 137+50 | 14 (4.3) | 3.5 (1.07) | 2:1 | 120 (3.4) | 8 (2.44) | 1.5 (0.46) | DC-4807 | 1958 | 10/60 |
| Means | 137+50 | 22 (6.7) | 5.9 (1.80) | 2:1 | 475 (13.5) | 6 (1.83) | 2 (0.61) | DC-3558 | 1952 | 10/60 |
| | | | | | **SW Region** | | | | | |
| Hudson | 79+85 to 823+00 | 16 to 14 (4.9 to 4.3) | 7.0 to 5.6 (2.13 to 1.71) | 1.5:1 | 386 to 260 (10.9 to 7.4) | 8 (2.44) | 1.5 (0.46) | DC-4041 | 2/54 | 12/63 |
| | | | | | **UM Region** | | | | | |
| Sunshine Reservoir Supply | 4+00 to 28+00 | 28 (8.5) | 6 (1.83) | – | 640 (18.2) | 6 (1.83) | 2 (0.61) | – | 1940 | 1952 |
| Angostura Main | 1294+05 to 1335+30 | 7 to 6 (2.1 to 1.8) | 3.4 to 3.0 (1.04 to 0.91) | 1.5:1 | 64 to 50 (1.8 to 1.4) | [2]3 (0.91) | 1 (0.30) | DC-3372 | 7/53 | 11/54, 12/58, 5/59, 3/61 |
| Canal B | 75+50 to 245+05 | 4 to 3 (1.2 to 0.9) | 2.3 to 1.8 (0.70 to 0.55) | 1.5:1 | 25 to 13 (0.7 to 0.4) | [2]1 (0.30) | 2 (0.61) | 600C-80 603C-10(SF) | 8/53 6/57 | 10/57, 5/58 |
| Helena Valley | 740+00 to 1822+30 | 16 to 6 (4.9 to 1.8) | 5.6 to 2.2 (1.71 to 0.67) | 2:1 to 1.5:1 | 350 to 35 (9.9 to 1.0) | 6 (1.83) | 2 (0.61) | DC-4938 | 12/58 | 7/58, 4/59, 3/60(p), 12/62, 11/64, 10/65 |
| Lateral D | 87+00 to 100+00 | 8 (2.4) | 2.5 (0.76) | 3:1, 2:1 (loose cover) | 47 (1.3) | [2]1+ (0.30+) | 1+ (0.30+) | – | 1958 | 4/58, 10/65 |

Table 2. – Data on compacted soil lining test sections. – Continued

| Canal | Stationing, ft | Canal characteristics: Base width, ft (m) | Canal characteristics: Water depth, ft (m) | Canal characteristics: Side slopes | Canal characteristics: Discharge, ft³/s (m³/s) | Thickness of lining: Sides (hor.), ft (m) | Thickness of lining: Bottom (vert.), ft (m) | Specification | Date of construction | Dates of unit weight tests[1] |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **LM Region** | | | | | |
| Boulder Creek Supply | 57+30 to 246+65 | 12 (3.7) | 4.6 (1.40) | 1.5:1 | 200 (5.7) | 5.4 (1.65) | 2 (0.61) | DC-3953 | 8/54 | 11/54, 3/55, 11/55, 11/57, 4/61, 4/65 |
| South Platte Supply | 1474+93 to 1477+63 | 12 (3.7) | 3.4 (1.40) | 2:1 | 125 (3.5) | [2]1.5 (0.46) | 1.5 (0.46) | DC-4505 | 5/56 | 11/56(p), 11/57(p), 11/59(p), 11/62(p) |
| Cambridge | 1103+25 to 1115+60 | 12 (3.9) | 3.9 (1.19) | 1.5:1 | 175 (5.0) | 6 (1.83) | 0 | DC-3554 | 4/53 | 3/55, 3/57, 4/58, 4/60, 4/62 |
| Culbertson | 36+38 to 368+25 | 20 (6.1) | 6.2 (1.89) | 2:1 | 400 (11.3) | 8 (2.44) | 2 | DC-5089 | 1959 | 5/60(p), 10/60, 4/62 3/63(p), 10/81 |
| Franklin | 72+50 to 602+80 | 14 (4.3) | 4.8 (1.46) | 1.5:1 | 230 (6.5) | [2]3.3 to 1.5 (1.01 to 0.46) | 1.5 | DC-4289 | 5/55 | 5/55, 6/56, 5/57, 11/58(p) |
| Upper Meeker | 392+00 to 738+63 | 16 (4.9) | 5.2 (1.58) | 1.5:1 | 250 (7.1) | 6 (1.83) | 2 | DC-4695 | 12/57 | 9/57(p), 4/58, 10/58(p), 4/60(p), 4/62(p) |

[1]The symbol (p) indicates that field permeability tests were conducted.
[2]Thickness normal to lining surface.

Three typical canal sections in each test reach were selected for investigation. If there appeared to be differences in conditions along the canal, one section each was selected in the best, poorest, and average condition. For thick-compacted linings, five unit weight tests were performed in each of the three canal sections at locations shown on figure 2, for a total of 15 tests each year tests were performed. In most cases, a survey was made from known construction elevations in the vicinity of test reaches so original surface elevations and depths in the lining could be determined. Where a survey was not made, the location of the top of the compacted lining had to be judged by excavation to firm soil. Where the original canal prism had been disturbed by water erosion or by canal maintenance equipment, the original location of the lining was indefinite. Therefore, a few of the unit weight test results were probably in uncompacted soil, which would account for some of the low test values, particularly those near the top and bottom of the linings. Sites for unit weight tests were selected short distances upstream or downstream from prior sites. Except for Delta-Mendota and Wellton-Mohawk canals, which are operated all year, the canals tested were dewatered, and field tests were performed between irrigation seasons. In Delta-Mendota and Wellton-Mohawk canals, the tests were performed in the lining of the side slopes above water level. At a few of the other sites, tests were not performed in the canal bottom because of shallow standing water that had not drained away at the time of testing.

Appendix B lists average unit weight test values for the total material and the minus No. 4 (4.75 mm) soil fraction obtained at each test site for each year of test. Because there is considerable variation in individual test results, averages are necessary to show the general trends of changes. From field and laboratory results, percentages of the maximum laboratory unit weight are listed for each year of testing. The differences in these percentages show the degree of change in unit weight from one year to another. Tables in appendix B show the number of tests made, the percentage of plus No. 4 soil fraction, moisture content, laboratory compaction data, liquid and plastic limits, soil classification, and test site location.

Figures 3 through 10 are plots of unit weights obtained at different depths in side slope and bottom linings for selected canals where numerous tests were performed. Each plotted point is the average value at approximately the same depth for all results for a particular test year. A scale is given for the percentage of laboratory maximum unit weight. Figure 11 shows the results of unit weight tests made in the 5-foot (1.5-m) thick lining of Mt. Elbert Forebay after frost had penetrated completely through the lining during the winter of 1978-79. There is no prior record of unit weights in the forebay lining, other than from construction control, where the specified minimum degree of compaction was 98 percent of laboratory maximum unit weight.

**Permeability and Seepage**

Most of the field permeability tests in the soil lining (table 3) were performed using the shallow well method (des. E–36 of [4]), but a few in the thick side slope lining were performed by the well-permeameter method (des. E–19 of [4]). Results from these tests cannot be considered as true coefficients of permeability (they are probably somewhat higher) because the tests were not run long enough in the low permeability soils to fully develop a saturated flow

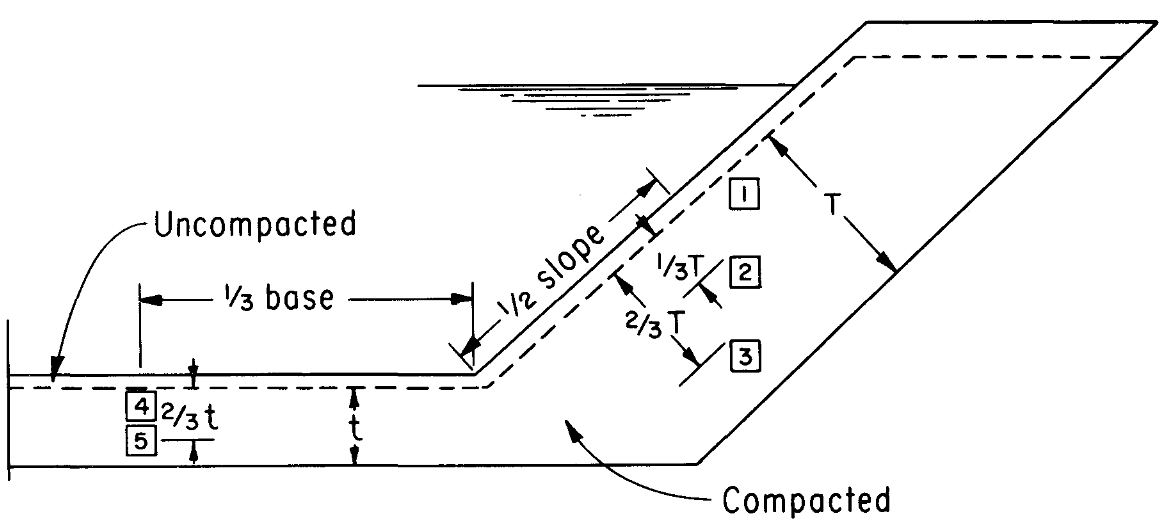


Figure 2. – Location of unit weight tests in canal lining. Note: Figures in squares are test numbers.

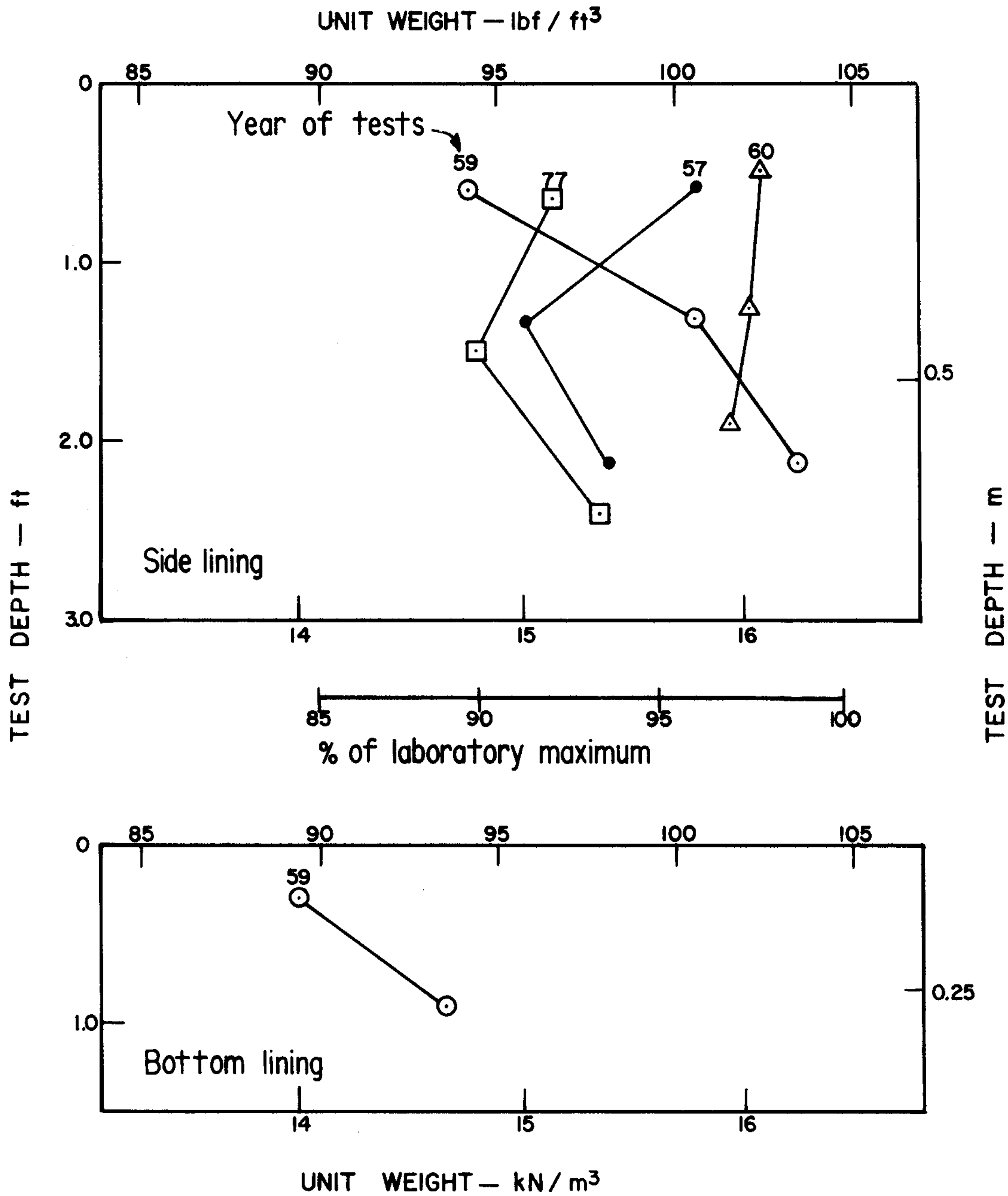


Figure 3. – Variations in unit weight of soil in lining on Lateral EL–68.

envelope that is assumed in the theoretical development of the equations for the tests. To develop saturated envelops would require weeks or months, therefore, a 5-day test period was generally established as a practical limit. However, since the same sizes of wells and depths of water were maintained for successive years of test, the tests results are index values denoting changes in permeability. A few of the permeability test values on table 3 are, as noted, from laboratory permeability tests on recompacted lining soils.

Ponding-type seepage tests were performed in reaches isolated by constructing earth dikes or by sealing existing canal structures. An isolated reach was filled with water by pumping or by canal water flow. The drop in water level in the pond was measured during recorded time intervals. With the cross action of the canal and the volume of water loss from the drop in water level known, the seepage rate could be calculated in terms of cubic feet per square foot per day (liters per square meter per day). For very low seepage rates, the evaporation rate was included

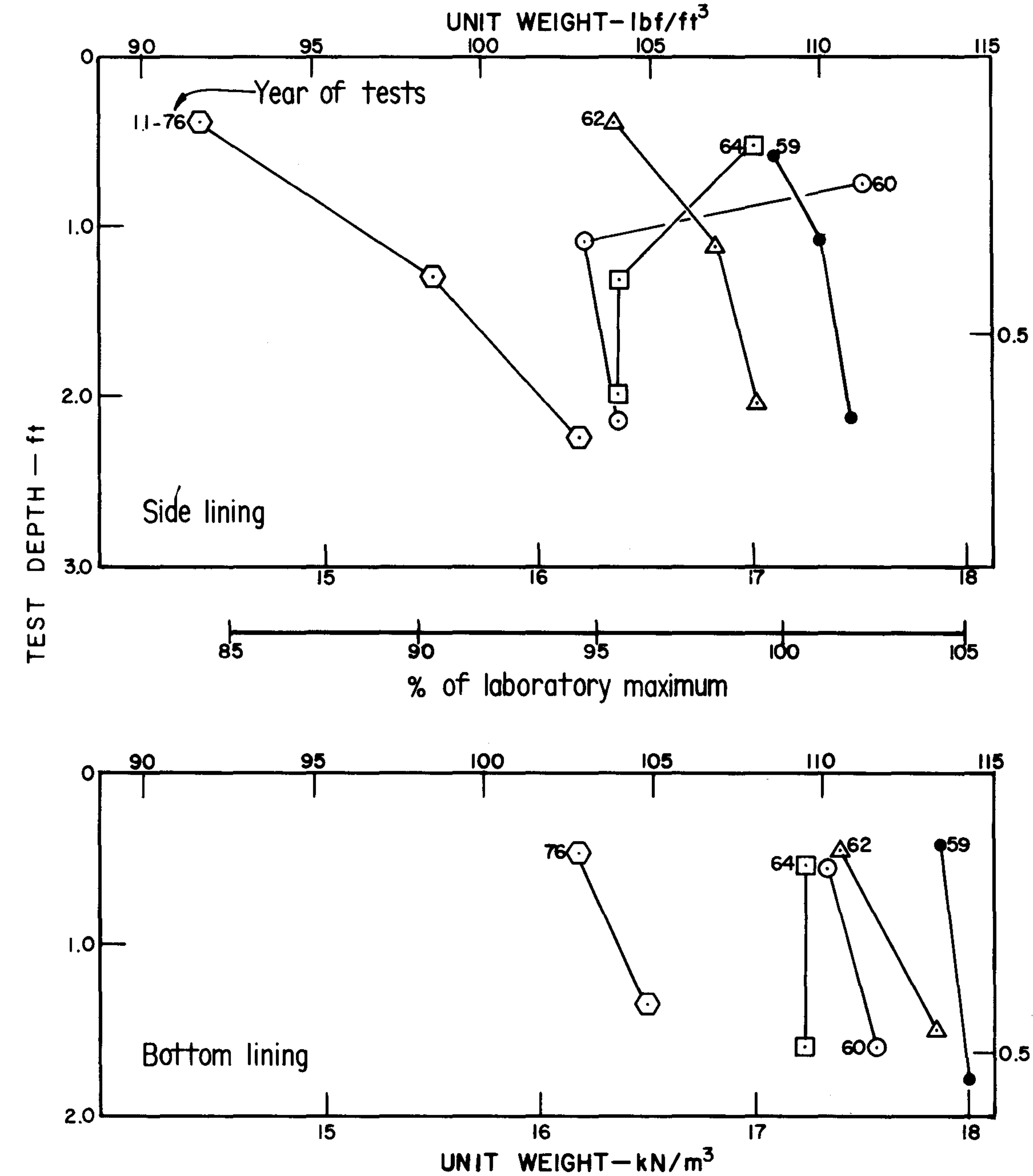


Figure 4. – Variations in unit weight of soil in lining on Southside Canal.

in the calculations. Reference [8] describes the complete procedure for performing ponding-type seepage tests.

## DISCUSSION

### Effects of Frost Action on Compacted Soil Linings

The effects of frost action on soils are well known from the results of many investigators, particularly the Corps of Engineers Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire. The Bureau has published information on the effects of frost action on earth dams, canal linings, and structure foundations with suggested methods of control to reduce damage [5,6]. The following paragraphs briefly cover aspects of frost action that can affect the performance of compacted soil linings.

Frost action in soils is generally classified as closed– or open-system freezing. Closed-system freezing is

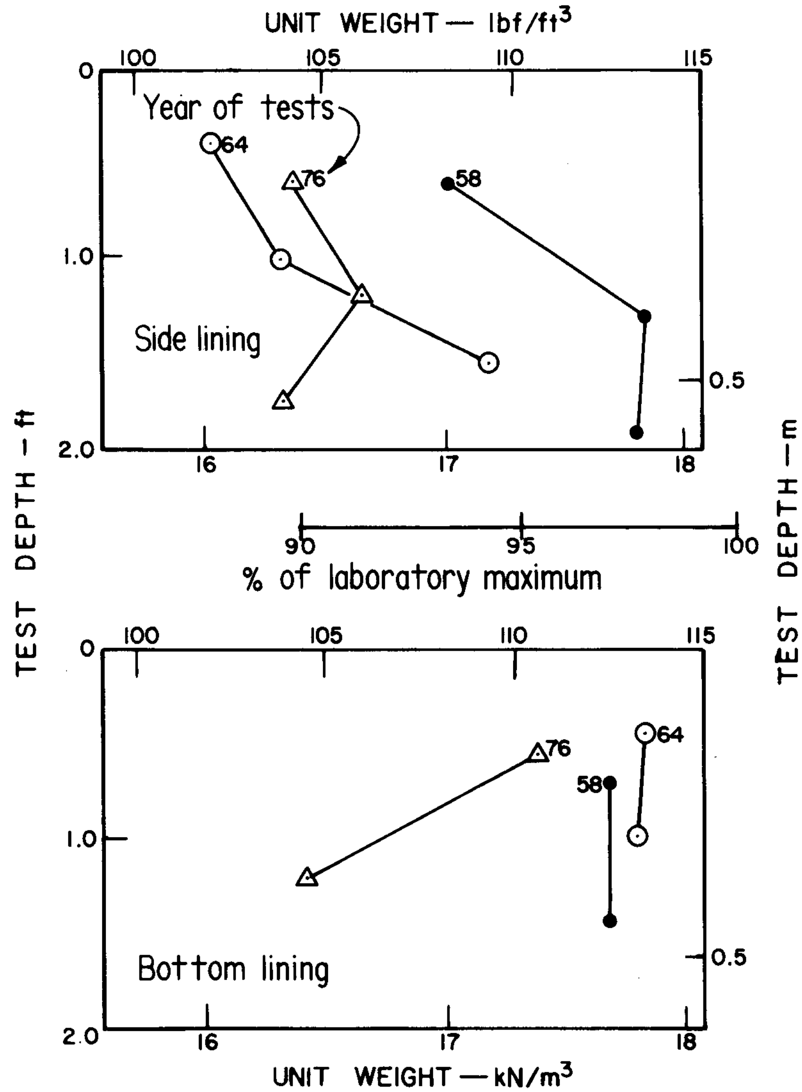


Figure 5. – Variations in unit weight of soil in lining on Helena Valley Canal.

the condition in which no water is available during the freezing process other than that originally in the voids of the soil at and near the zone of freezing. Open-system freezing is the 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.

Effects of open- and closed-system freezing on soil specimens have been demonstrated in laboratory freezing tests and are illustrated on figure 12. Open-system freezing in soil results in the formation of ice lenses above the freezing level, and in frost heave. In closed-system freezing there is a redistribution of moisture and unit weight with an increase in moisture and a decrease in unit weight towards the top of a soil specimen frozen from the top downward and a corresponding decrease in moisture with capillary (suction) forces that resist a decrease in unit weight toward the bottom of the specimen. Figure 13 shows laboratory specimens of lean clay (plasticity index = 12) that have been subjected to open- and closed-system freezing.

A soil lining in a cold climate on a canal that is dewatered after the irrigation season would be subjected to closed-system freezing if the water drains from the canal and the depth from the bottom of the lining to ground-water table is greater than the height of capillary rise. Height of capillary rise depends on soil type, gradation, and unit weight, but, for practical purposes, is usually about 5 to 10 feet (1.5 to 3 m) [5]. If the water table is above the height of capillary rise, water can be supplied to the lining to cause open-system freezing.

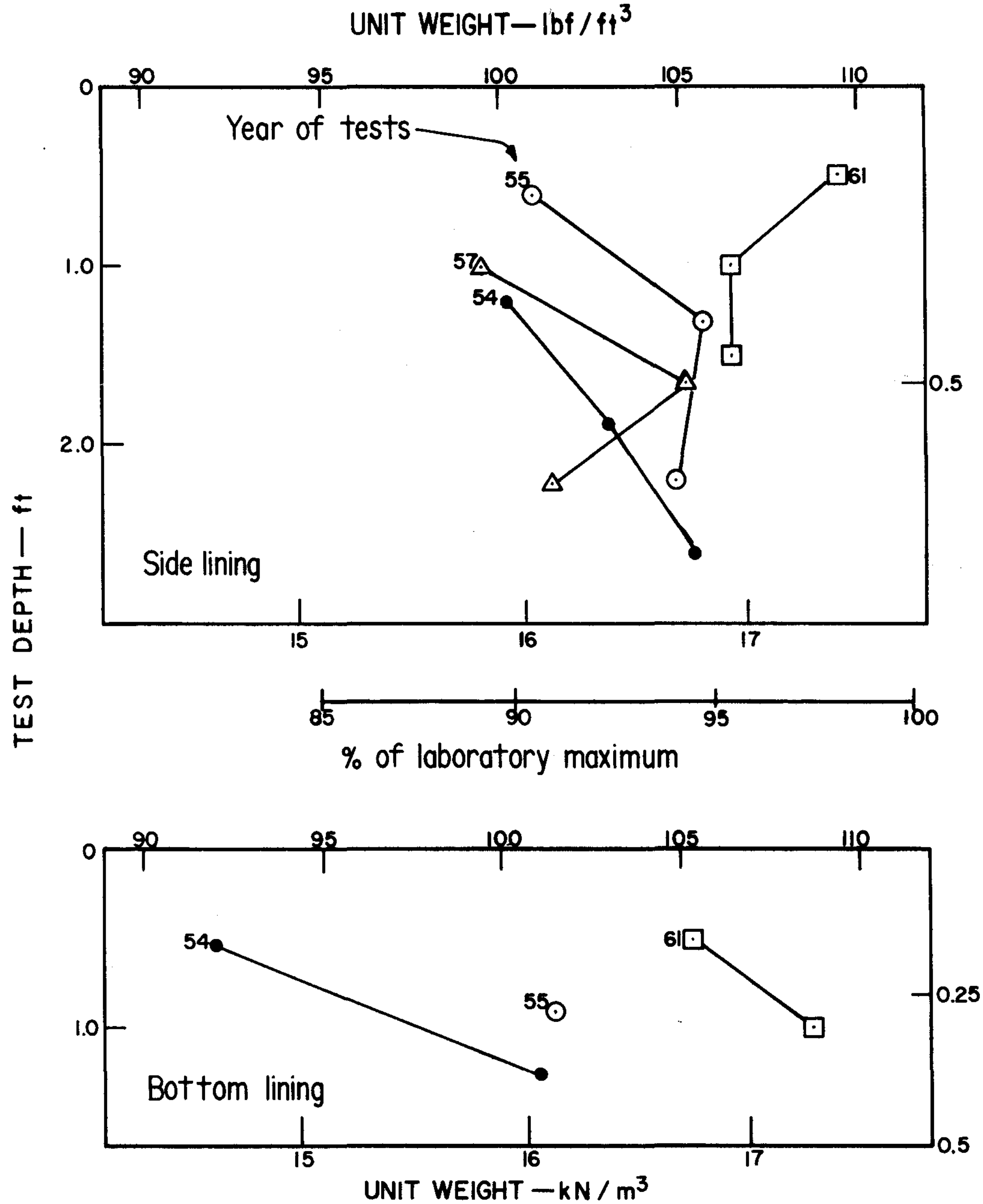


Figure 6. – Variations in unit weight of soil in lining on Boulder Creek Supply Canal.

In the 1950's, when many compacted soil linings were being constructed, there was particular concern about possible deterioration of the linings from frost action. Unit weight tests were showing considerable variation in results from one year to another; some unit weights decreased, some remained about the same, and a few even increased slightly. Figure 14 shows small yearly increases in average unit weights for tests on South Platte Supply and Upper Meeker canals.

The greatest decrease in unit weight was in several loessial soil linings in the Kansas-Nebraska area; therefore, attention was focused on linings, including Franklin Canal, in that area and a report on the linings was compiled [7]. In 1958, two ponding tests were made to determine seepage rates on Franklin Canal (table 3). The seepage rates for both ponds were less than 0.1 $ft^3/ft^2/d$ (30 $L/m^2/d$), which is generally considered an acceptable limit for canal linings.

During the investigation of loessial-type soil linings, unit weight test results showed that, in general, the greatest decrease was near the top of the lining and the least change near the bottom. At that time this

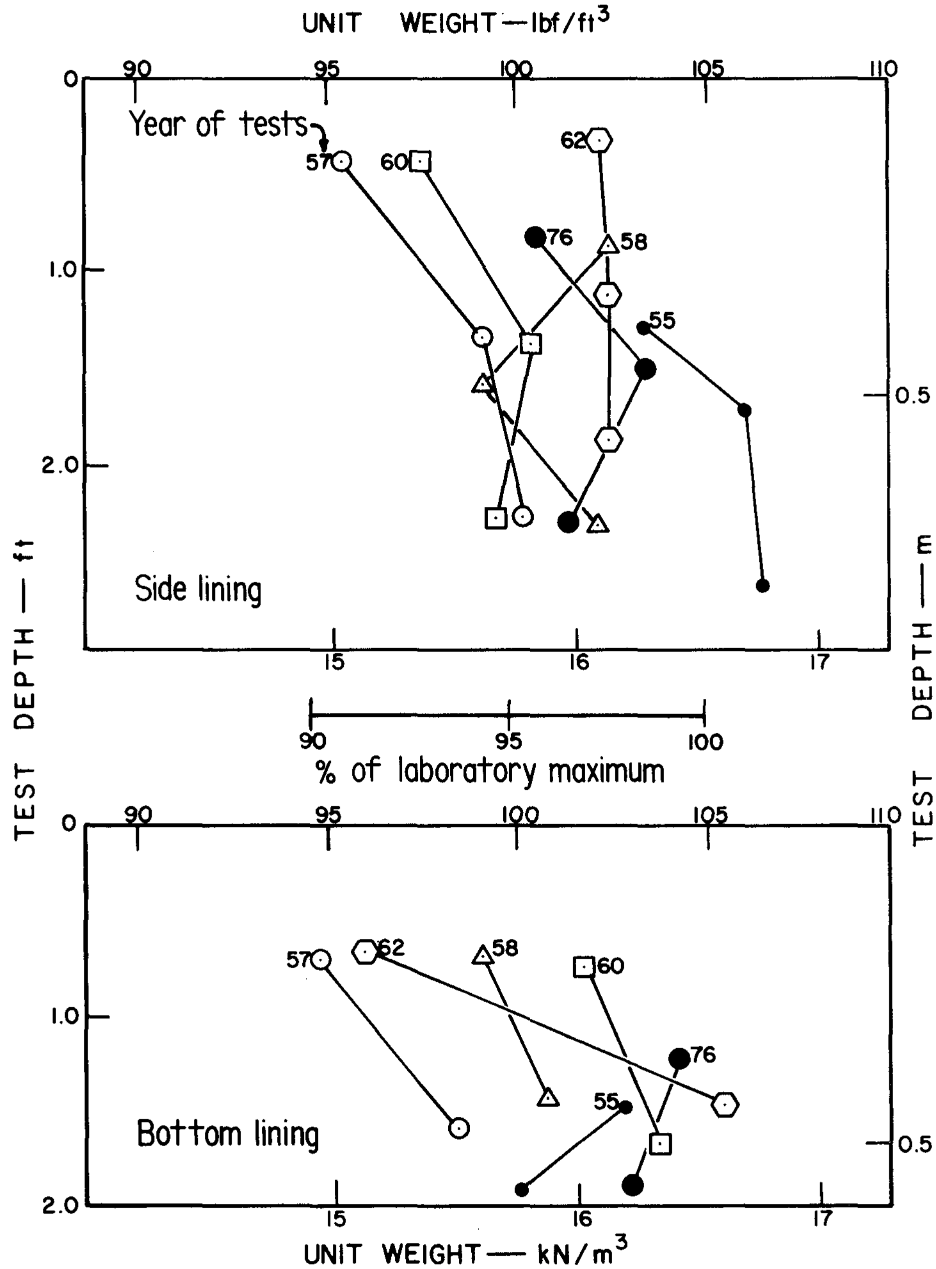


Figure 7. – Variations in unit weight of soil in lining on Cambridge Canal.

variation was attributed to differences in depth of the mass of soil overlying the test elevation.

As part of the lining investigation, laboratory permeability tests were performed on soil from one canal lining after cycles of freezing and thawing. Because the freezing procedure is not now recommended, as explained previously under "Freezing Tests," the test results are not included in this report.

In the 1960's, laboratory closed-system freezing tests by the approved freezing cabinet method were performed on recompacted lining soil. Properties of three such soils are shown in table 4.

After freezing, the frozen specimens were cut into thirds and the unit weight and water content of each one-third portion determined. Figure 15 illustrates initial unit weights and moisture contents before freezing and final values after freezing. These test results show a significant redistribution of unit weights and moisture contents caused by freezing. Unit weights and moisture contents in the middle one-third of the specimens were not changed much by freezing, but the decrease in unit weight and increase in moisture content in the top one-third and the small converse changes in the bottom one-third are significant. A redistribution of unit weight is evident in many of the

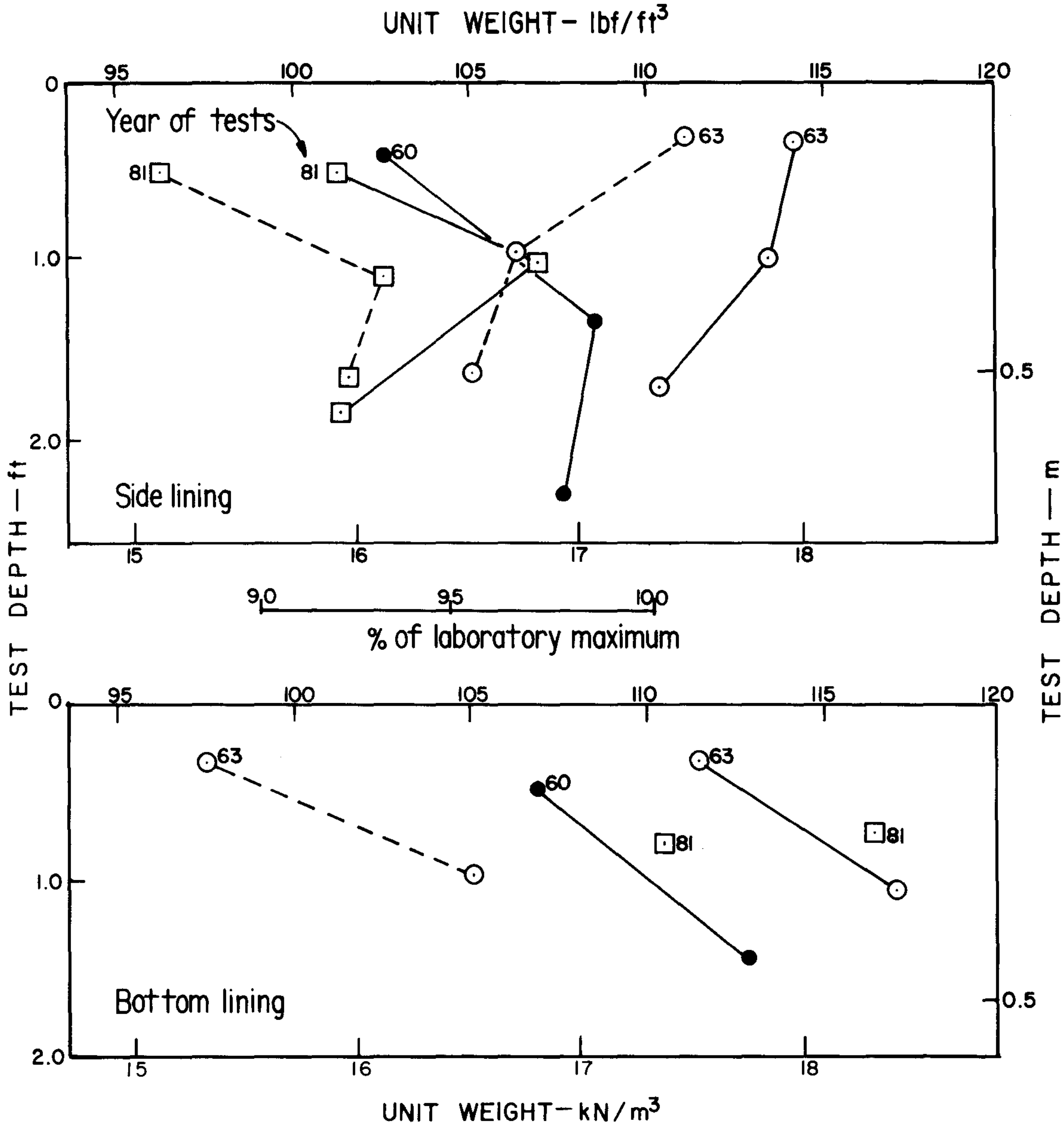


Figure 8. – Variations in unit weight of soil in lining on Culbertson Canal. Notes: 1) Solid lines connect averge values of tests near stations 44+50 and 75+15, 2) Dashed lines connect average values of tests near stations 177+00 and 178+00, and 3) Test depths for 1981 were estimated; no survey was made.

compacted soil linings (figs. 3 through 11), with a significant decrease in unit weight toward the top of the lining. Although maintenance of compacted unit weight at more constant levels toward the bottom of the lining may be partly due to the confinement from the mass of overlying soil, capillary forces during freezing would tend to compact the soil and maintain unit weight. Although a decrease in moisture content with depth caused by frost is evident from some of the field tests, it is not evident in others. Soil moisture near the lining surface would be influenced by climatic conditions, particularly precipitation and drying.

For soil linings in cold climates in areas of high ground water, open-system freezing in the linings cah occur. The degree to which frost affects the properties of the lining and causes deterioration depends primarily on (1) the moisture content of soil and the availability of additional water; (2) the type of soil and its susceptibility to frost action; (3) the climatic conditions, including the time period and rate of freezing in the soil as influenced by air temperatures, length of exposure to sun or shade, and insulation by snow cover; and (4) the confining effect of an overlying soil mass. Ice lenses, oriented predominantly perpendicular to the freezing front, would be expected to form

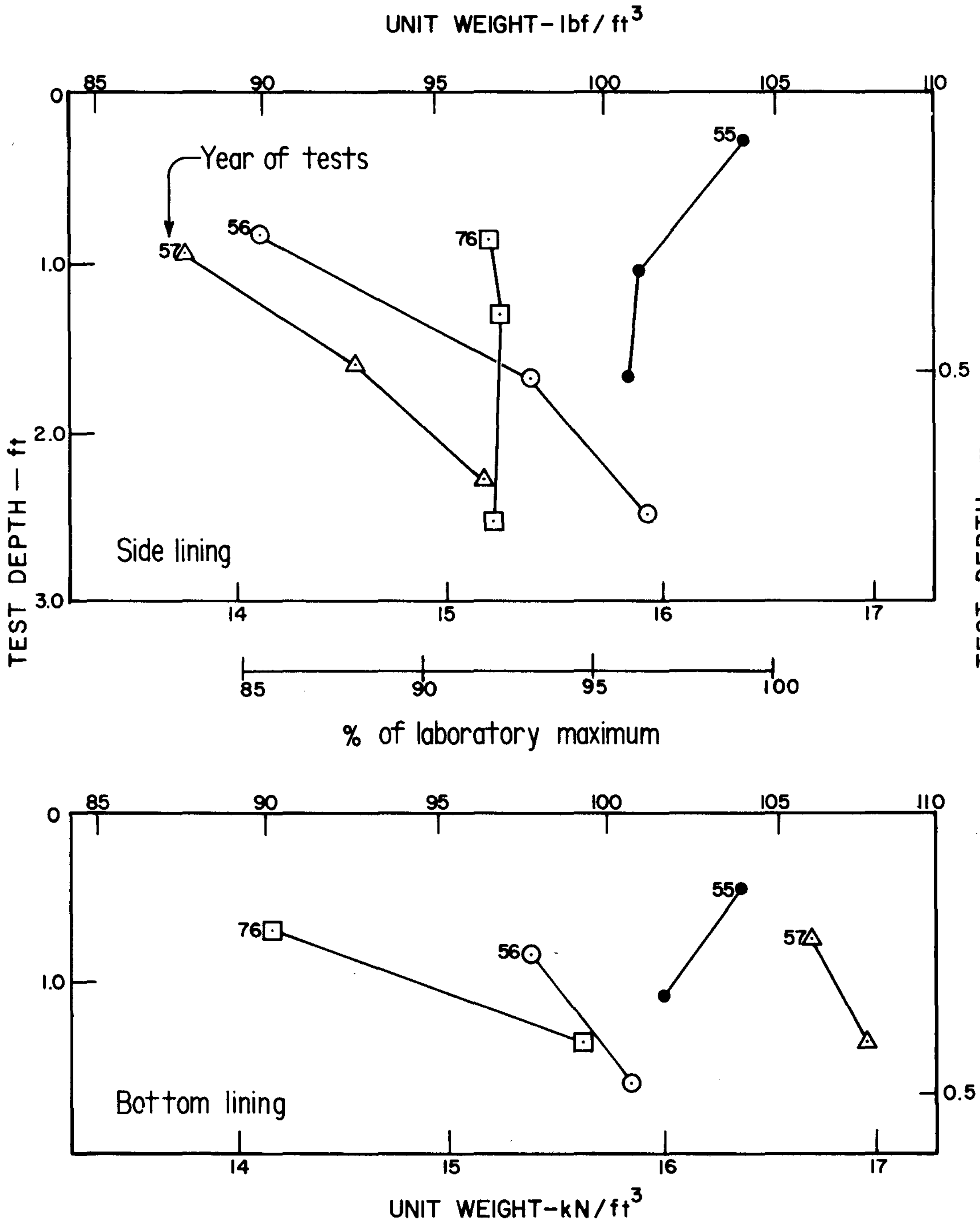


Figure 9. – Variations in unit weight of soil in lining on Franklin Canal.

in the lining and cause frost heaving. During freezing, there is normally some consolidation of soil between ice lenses caused by capillary forces. The condition of the lining and its resistance to seepage after the ice melted and the soil settled would be important to know. Damage to the lining that tends to increase seepage could be expected, but the extent of such damage has not yet been determined in any lining. Research has been proposed to investigate existing soil linings where open-system freezing is known to have occurred. Changes in physical properties of the linings would be determined and seepage evaluated by ponding and field permeability tests in the lining.

There were instances where the water table, after the canal was dewatered, were higher than the canal bottom and water seeped into the canal. Such "reverse" canal seepage, particularly when accompanied by freezing, caused a decrease in soil unit weight that was evident from digging into the lining

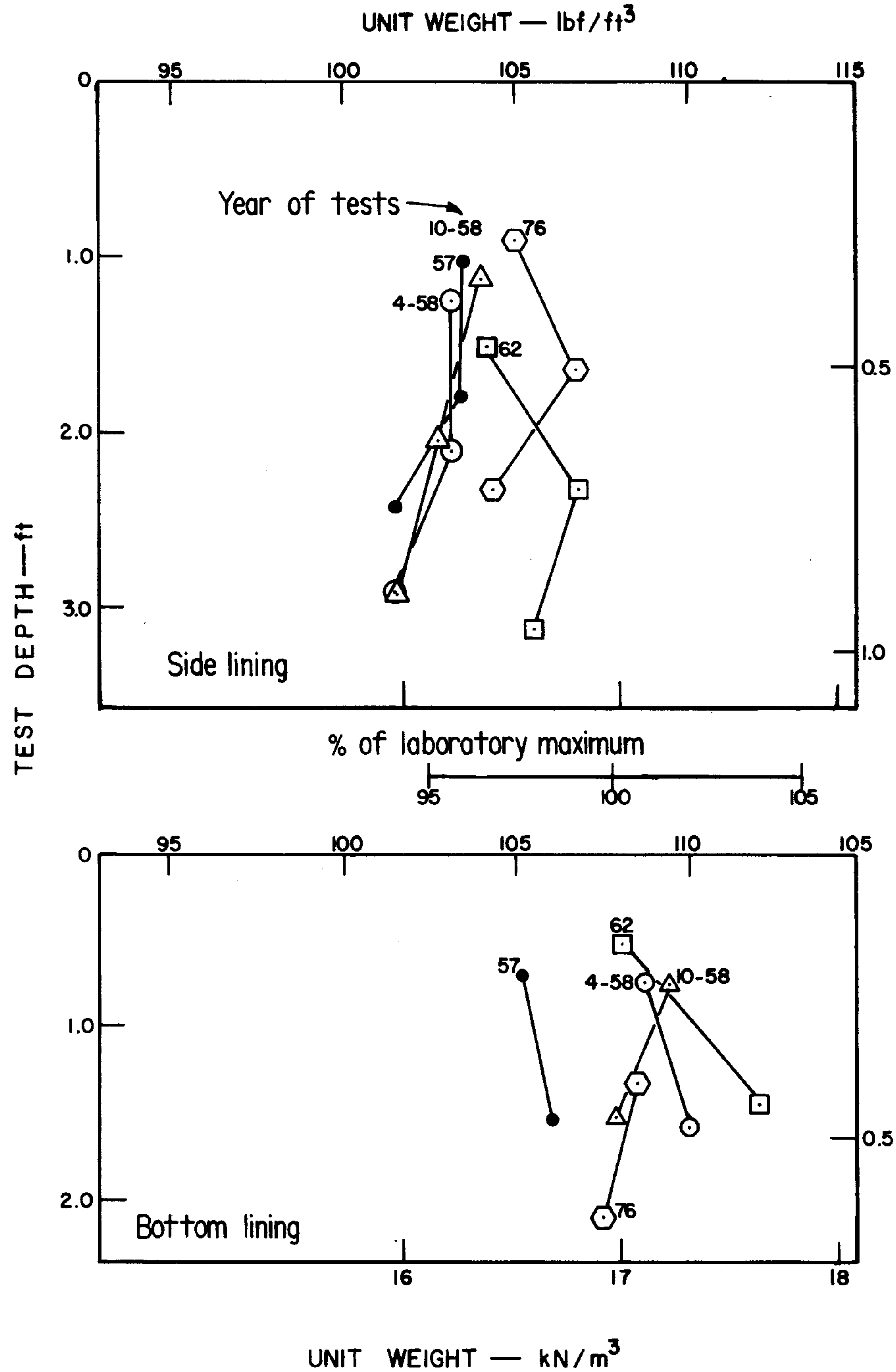


Figure 10. – Variations in unit weight of soil in lining on Upper Meeker Canal.

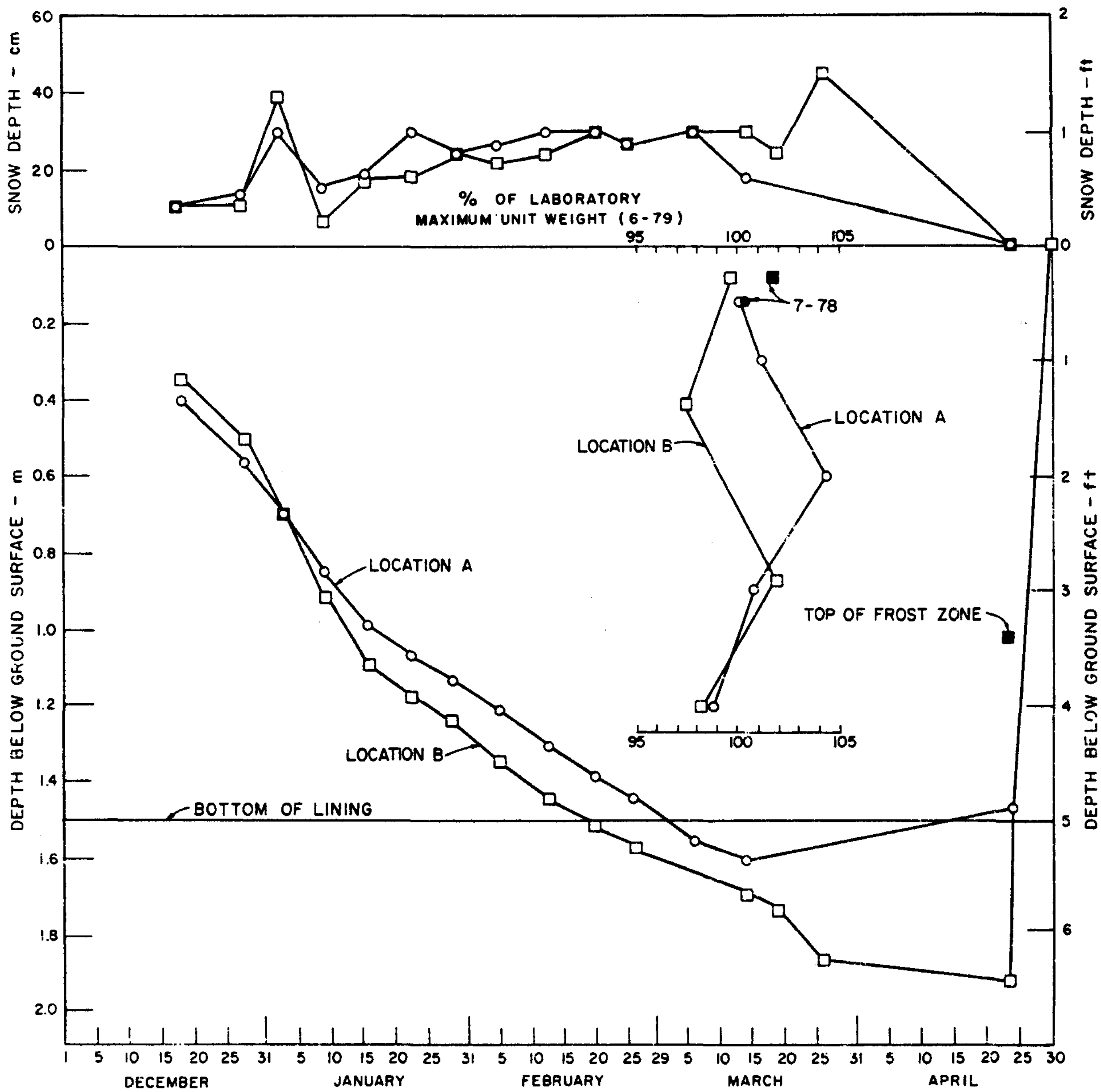


Figure 11. – Frost penetration and snow depths for the compacted soil lining on the Mt. Elbert Forebay during the winter of 1978-79, with subsequent unit weight (density) test data. From figure 7 of [6].

or from unit weight tests. In one such case, an 8-inch (200-mm) thick soil lining in a canal bottom was in a "quick" condition, causing a person stepping on the lining to sink in about 4 inches (100 mm). In some instances, seepage pressures from a high water table behind the lining caused soil lining to slough into the canal.

Typical soils that have medium to high susceptibility to frost action and ice lens formation with resulting frost heave are silt, lean clay, silty or clayey sand or gravel, and combinations of these soil types [6]. For clayey soils, the degree to which frost action affects soil properties varies inversely with the amount of clay and its activity, as indicated by consistency values. When the permeability of such soils is low, ice lens formation is limited by a relatively low flow of water during the freezing period.

Figure 16 shows possible relationships between changes in unit weight and (1) consistency values (liquid limit and plasticity index), and (2) the percentage of gravel in the soil. It is significant that for the lining soils on Lateral EL–68, Culbertson, South Platte Supply, and Upper Meeker canals, which are mostly silts and lean clays with plasticity indexes of 7 or less, the average unit weights remained about the same or increased slightly during the test years.

Table 3. – Permeability and seepage test results on soil lining.

| Canal | Date of test | Permeability, [1]ft/yr | Seepage rate ft³/ft²/d | Seepage rate L/m²/d |
|---|---|---|---|---|
| | *PN Region* | | | |
| Lateral EL–68 | November 1957 | 42 | – | – |
| | March 1959 | 34 | – | – |
| | March 1960 | 31 | – | – |
| Main | [2]May 1954 | 0.09 | – | – |
| | | 5.0 | – | – |
| | | 8.0 | – | – |
| | *SW Region* | | | |
| Hudson | 1963 | [3]0.03 | – | – |
| | *UM Region* | | | |
| Angostura Main | [4]October 1964 | 78 | 0.24 | 73 |
| Canal B | August 1962 | – | .6 | 183 |
| Helena Valley (station 1173+97 to 1213+38) | October 1959 | – | [5].08 | 24 |
| | May 1960 | 149 | – | – |
| Helena Valley | October 1961 | – | .34 | 104 |
| (station 1132+12 to 1172+37) | 1962 | – | .21 | 64 |
| (station 1814+13 to 1823+33) | 1962 | – | .23 | 70 |
| (station 1471+63 to 1503+83) | October 1964 | – | .23 | 70 |
| Helena Valley Unit (Lateral 14.8) | 1966 | – | 0.40 | 122 |
| Helena Valley Unit (Lateral 26.2) | 1966 | – | .22 | 67 |
| Lateral D | October 1966 | – | .09 | 27 |
| | *LM Region* | | | |
| South Platte Supply | November 1956 | 11 | – | – |
| | November 1957 | 29 | – | – |
| | November 1959 | 11 | – | – |
| | November 1962 | 1.9 | – | – |
| Culbertson | May 1960 | 82 | – | – |
| | March 1963 | 87 | – | – |
| Franklin | May 1955 | [3]6.8 | – | – |
| | November 1958 | 56 | – | – |
| Franklin (station 116+00 to 130+00) | 1958 | – | [6].03 | 9 |
| Franklin (station 548+00 to 562+00) | 1958 | – | .09 | 27 |
| Upper Meeker | September 1957 | 26 | – | – |
| | October 1958 | 8.7 | – | – |
| | April 1960 | 58 | – | – |
| | April 1962 | 111 | – | – |

[1] 1 ft/yr = $\pm 10^{-6}$cm/s. When multiplied by $10^{-6}$, the values of permeability in the table in ft/yr are approximately the same as values in centimeters per second.
[2] Laboratory tests on soil compacted to 95, 90, and 85 percent of the maximum laboratory unit weight, respectively.
[3] Laboraborty tests on soil compacted to field unit weight.
[4] Laboratory tests on soil placed at 90 percent of the maximum laboratory unit weight.
[5] About half of the 0.08 ft³/ft²/d measured was estimated to be from evaporation.
[6] Lining 18 inches (0.46 m) thick placed on 3:1 side slopes.

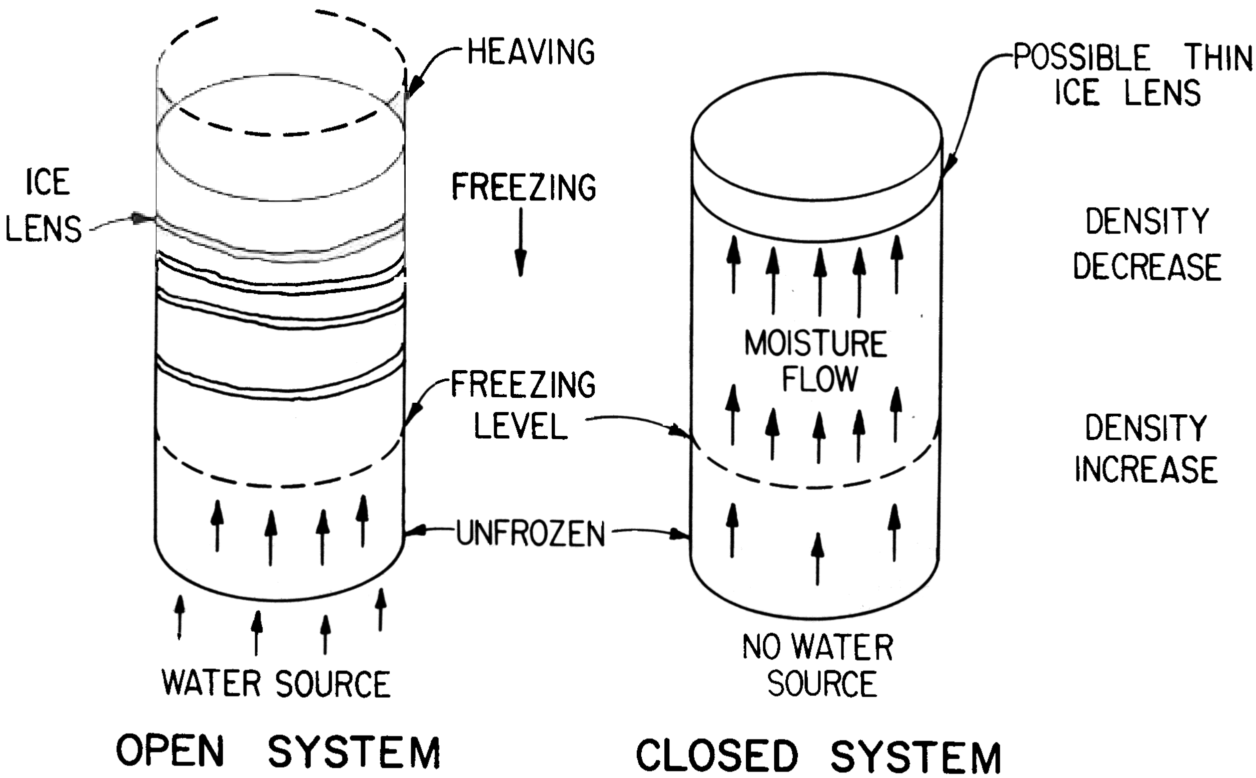


Figure 12. – General effects of open- and closed-system freezing on unconfined soil specimens insulated at the sides and frozen uniaxially from the top downward.

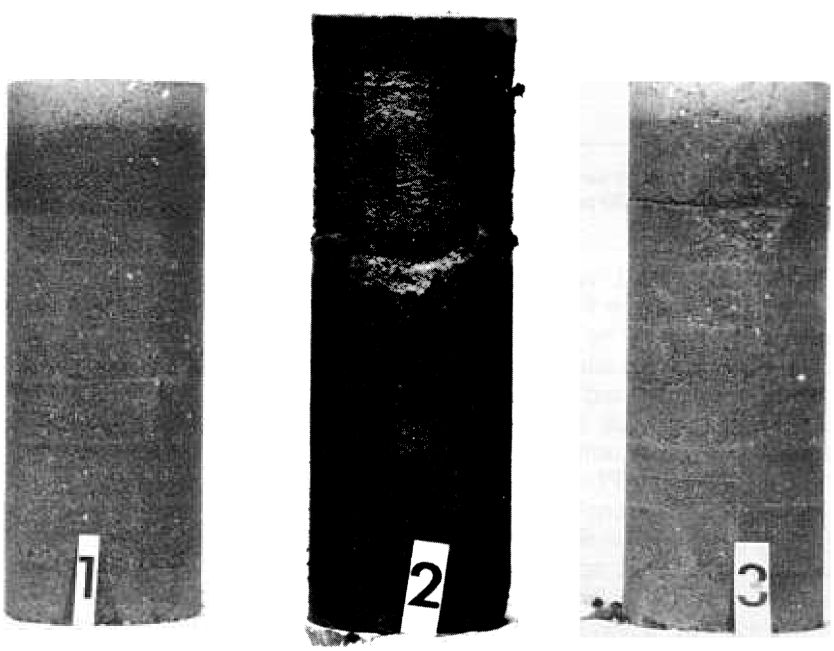


Figure 13. – Specimens of soil after laboratory freezing tests. Sepcimen 2 was the only one frozen by the open-system with water available at the specimen bottom. Note the thin ice lens in specimen 3, which was subjected to closed-system freezing. E–1887–4.

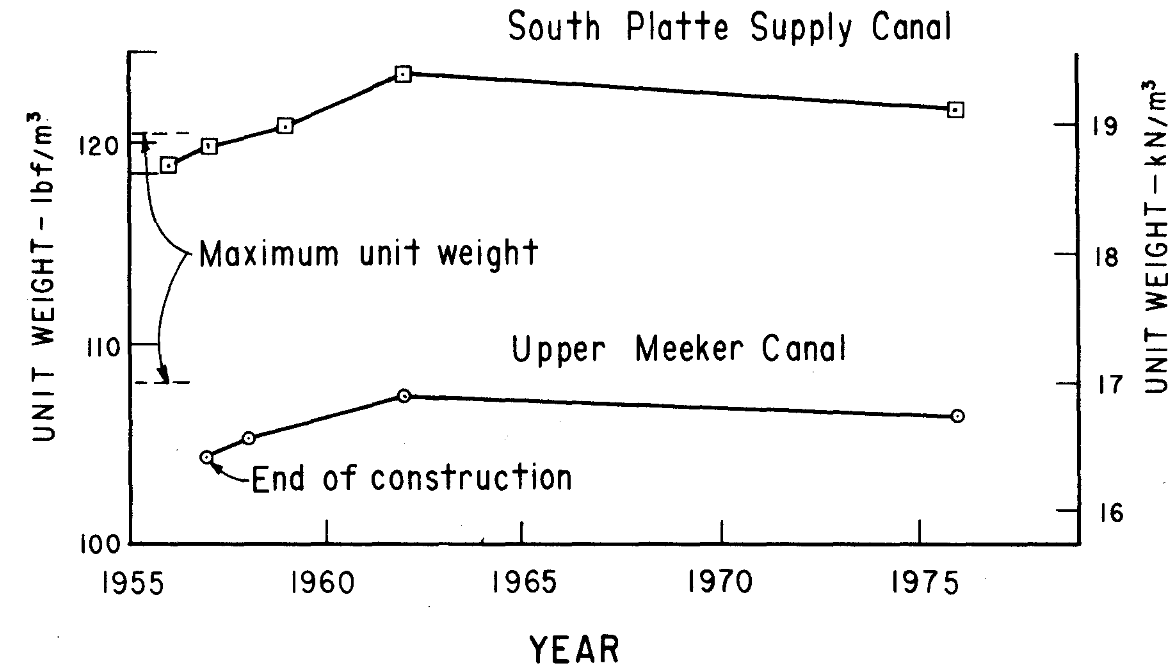


Figure 14. – Changes in the unit weight of compacted soil canal linings.

Table 4. – Physical properties of soils from three recompacted canal linings.

| | Upper Meeker | South Platte Supply | Hudson |
|---|---|---|---|
| Classification | ML | SM | CL |
| Specific gravity | 2.64 | 2.69 | 2.69 |
| Liquid limit | 25 | 23 | 24 |
| Plasticity index | 1 | 10 | 13 |
| Max. lab. unit wt., lbf/ft³ (kN/m³) | [1]108.1 (17.0) | [2]120.7 (19.0) | [2]121.0 (19.0) |
| Optimum moisture (%) | 16.0 | 11.3 | 11.8 |

[1]Unit weight of specimens for freezing was 94 percent of the laboratory maximum
[2]Unit weight of specimens for freezing was 100 percent of the laboratory maximum

The unit weights on Angostura Canal, which had a lean or silty clay lining with an average PI (plasticity index) of 19, also increase slightly. The soil of the Mt. Elbert Forebay lining, which was a silty to clayey gravel with an average PI of 10, still had a high unit weight after having been frozen to full lining depth and thawed. Other lean clays from Southside (PI = 16), Cambridge (PI = 19), and Franklin (PI = 14) canals showed decreases in unit weight. From these data and the laboratory freezing test data on South Platte Supply and Upper Meeker canals, it appears that frost action in soils of medium to high frost susceptibility may sometimes, but not always, assist in maintaining compacted unit weight in the soil.

A phenomenon that may occur, particularly in sandy or gravelly soils subjected to repeated freezing and thawing, is particle migration, or "sorting." Laboratory studies [9, 10] have demonstrated that sorting does occur, and mounds or "islands" of fine soil surrounded by coarser particles have been observed in arctic regions. There are different theories on the mechanism causing such particle movement. In addition, the upward movement of large rock fragments toward the ground surface as a result of frost action is well known.

The effects of particle movement caused by frost action on the unit weight and permeability of a compacted soil lining have not been investigated. In some instances thin striations of slightly coarser soil in an unfrozen compacted soil lining of low plasticity silt were noted and were attributed to possible sorting from previous frost action. It was noted that of the linings in this investigation, those with the most plus No. 4 material (fig. 16) (West Canal with an average

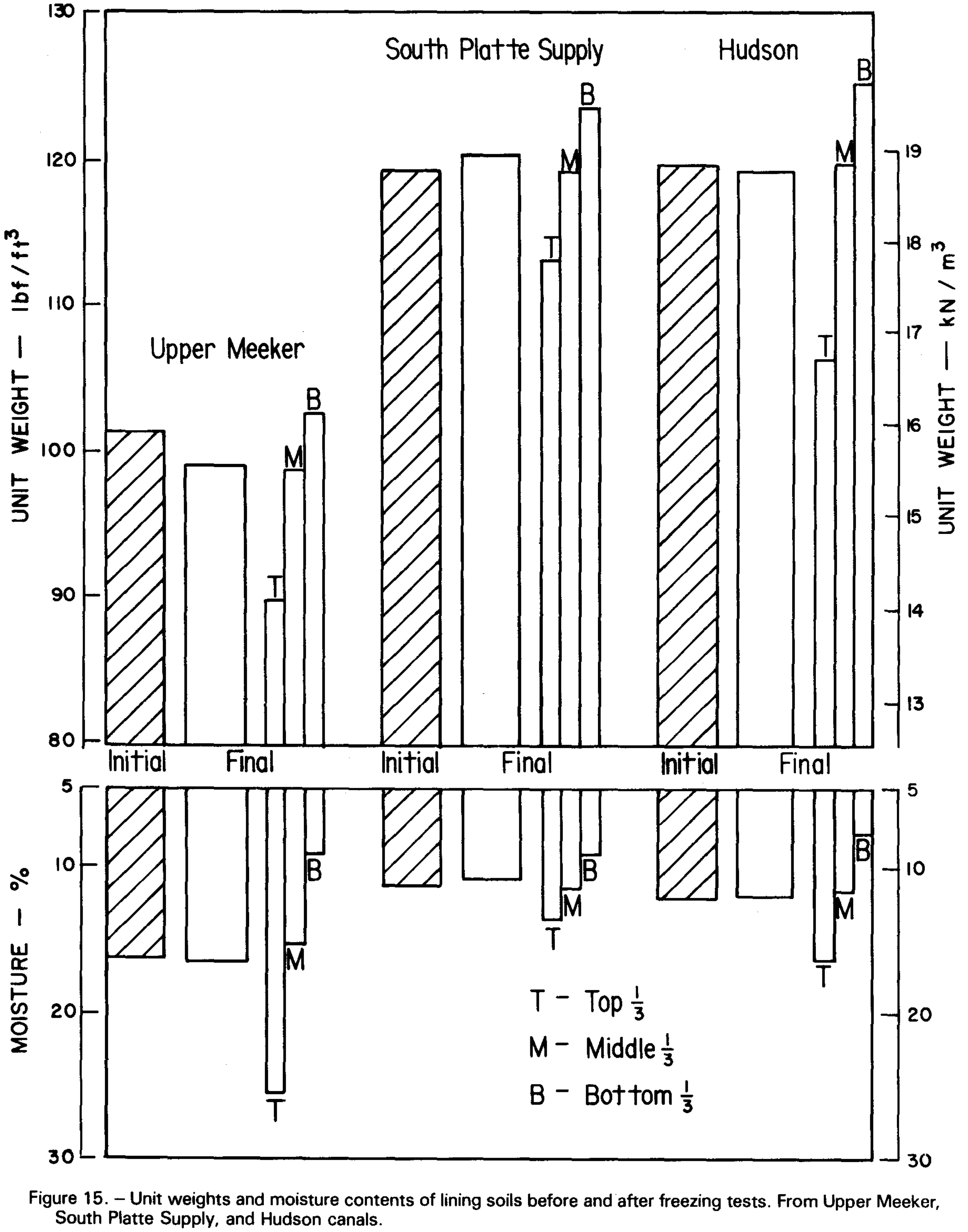


Figure 15. – Unit weights and moisture contents of lining soils before and after freezing tests. From Upper Meeker, South Platte Supply, and Hudson canals.

of 35 percent and Helena Valley Canal with 24 percent) showed some of the largest decreases in percent of laboratory maximum unit weight. It is possible that a repeated, slight movement of particles from freezing could cause a decrease in unit weight of soil over a period of time. The soil in the Mt. Elbert Forebay lining, despite having up to 27 percent gravel, maintained a high unit weight; however, unit weight was determined after only one season of freezing after the lining was proof-rolled (app. A).

The effect on permeability and canal seepage depends on the rearrangement of particles to form a soil structure that provides easier or more difficult

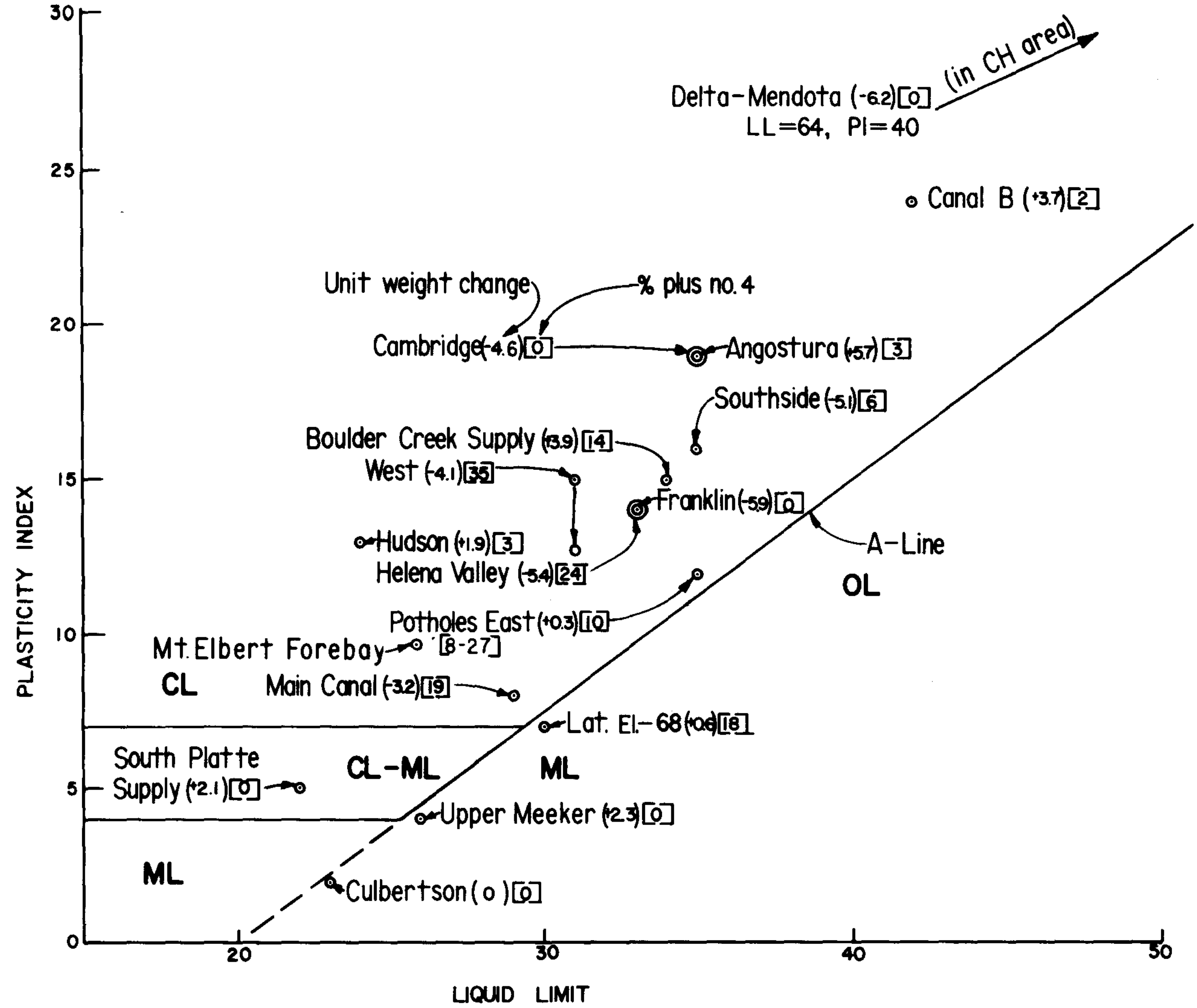


Figure 16. – Average changes in unit weight (in parentheses) and percentages of plus No. 4 fraction (in brackets) for lining soils, plotted on the A-line consistency limit chart.

passages for water flow. The lamination effects of sorting generally extend perpendicular to the freezing front, which are also perpendicular to the direction of water flow through the lining.

### Heavy Clay Lining

Soil lining on the Delta-Mendota Canal consists of an expansive clay with a liquid limit of 64 and a plasticity index of 40 (fig. 16). A maximum liquid limit of 45 is normally recommended for linings (p. 263 of [4]) to ensure that the soil is not difficult to process and remains stable upon saturation. The average moisture content of the Delta-Mendota soil lining was 30 percent during the 1966 unit weight tests compared with the optimum moisture content of 23.7 percent during the lining construction. This is an example of a heavy clay lining that is relatively stable on 2½:1 side slopes despite a high liquid limit and plasticity index.

### Low Plasticity Lining

According to present Bureau guidelines (p. 263 of [4]), a soil for compacted linings should have a minimum plasticity of 10 or, preferably, 12 for sufficient cohesion to resist erosion from flowing canal water and from water-wave action. There is a current research program to determine performance with respect to erosion for Bureau canal linings having a plasticity index less than 10. Examination of a few of the low plasticity linings to date shows that at least some on straight reaches are performing satisfactorily with respect to erosion; however, some of the linings on curves have required gravel protection. The present guidelines should be retained until the erosion investigation is completed.

### Miscellaneous Influences on Soil Lining

In certain areas other factors, some minor, can affect seepage through compacted soil linings:

1. Chemicals in canal water may, over a long time, cause undetermined changes. For example, soil containing bentonite that comes into contact with water containing calcium can result in a base exchange reaction, which tends to increase soil permeability and seepage. Conversely, water high in sodium ions will cause clay to disperse and reduce permeability.

2. The viscosity of water varies with temperature; this will affect the rate of water flow through soils.

3. Because many canals are not fenced, cattle that drink canal water from puddles in the canal or that cross a wet canal bottom can disturb the soil lining near the surface and develop paths in side slopes.

4. Sediment accumulated in a canal must be removed. Unfortunately, because of carelessness or because it is sometimes difficult to distinguish between the bottom of the sediment and the top of the lining, the top part of the lining may be removed, decreasing the effective lining thickness.

## RECOMMENDATIONS

Future research on compacted soil linings should be directed toward:

1. Field and laboratory freezing tests on compacted soil linings containing a relatively large proportion of gravel. Additional unit weight tests could be made on Helena Valley and West canals to determine whether there has been a further decrease in unit weight. The movement of separation of larger particles from the finer soil matrix could be detected if samples are taken from the lining while frozen and examined in the laboratory while still frozen and after thawing. Laboratory freezing tests could also be made on specimens of compacted soil lining with attention directed toward possible changes in the arrangement of the various soil particle sizes and toward the effects of such changes on unit weight and permeability.

2. Laboratory water erosion tests on compacted soil after having been frozen to determine changes in resistance to surface erosion. This could be done with flowing water in a test flume or in an apparatus for generating waves.

3. Field and laboratory investigations on soil lining, such as the lining on McClusky Canal, Garrison Diversion Unit, and Pick-Sloan Missouri Basin Program that have been subjected to open-system freezing caused by a high ground-water condition.

4. Developing a simple method that allows canal maintenance personnel to determine the location of the compacted soil lining surface to avoid excessive excavation of the lining.

## APPLICATIONS

The research programs that collected data on compacted soil linings provided an opportunity to monitor the performance of the soil in the linings over much of the life of the linings. The information collected will be useful in forming decisions during the design and construction of compacted soil linings where soils and field conditions are similar to those investigated.

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No. 331, *Soil Behavior Associated with Freezing,* pp. 46-66, Highway Research Board, NAS–NRC, Washington, D.C., 1962.

[11] "Completion report — Earth Lining — Cambridge Canal, Station 1102+00 to Station 1117+00," Frenchman-Cambridge Division, Nebraska, Missouri River Basin Project, 1954.

[12] Merriman, John, *Soil Tests with Nuclear Density-Moisture Equipment,* Bureau of Reclamation Report No. REC–ERC–73–21, Washington, D.C., 1973.

# APPENDIX A

# SUMMARY OF INFORMATION ON TEST SITES

This appendix presents a summary of pertinent information and comments on most of the compacted soil linings tested. Plots of gradation and compaction tests and some photographs are also included. Lists of laboratory and field test data are given in appendix table B-1. The canal stationing in appendices A and B are in feet.

### Lateral EL-68, Columbia Basin Project

The soil lining constructed on Lateral EL–68 (figs. A-1 and A-2) in 1957, was a borderline clayey-silt with a plasticity index of 7 and 14 to 25 percent gravel. It was protected against erosion by a 6-inch (150-mm) thick gravel beach belt extending down the slopes from the elevation 1 foot (300 mm) above the normal water surface to the elevation at two-thirds the normal water depth.

Based on average values of unit weight (table B-1) during the tests, there was less than 1 percent average change in soil unit weight from construction in 1957, to the last tests in 1977. Field permeability tests performed in 1957, 1959, and 1960 (table 3) indicated a slight decrease in permeability.

The unit weight in the side slope lining remained between 90 and 100 percent of the laboratory maximum (fig. 3). The only tests in the canal bottom were performed in 1959; the unit weight was 85 to 90 percent of the laboratory maximum. During the other tests, water remained in the canal bottom. It is possible that freezing of saturated soil in the bottom lining may account for the unit weight being lower than that for the lining in the side slopes.

In fall 1984, the EL–68 lining was reported[1] to be performing well. There had been no seepage problems, and no significant maintenance had been required.

### Potholes East Canal, Columbia Basin Project

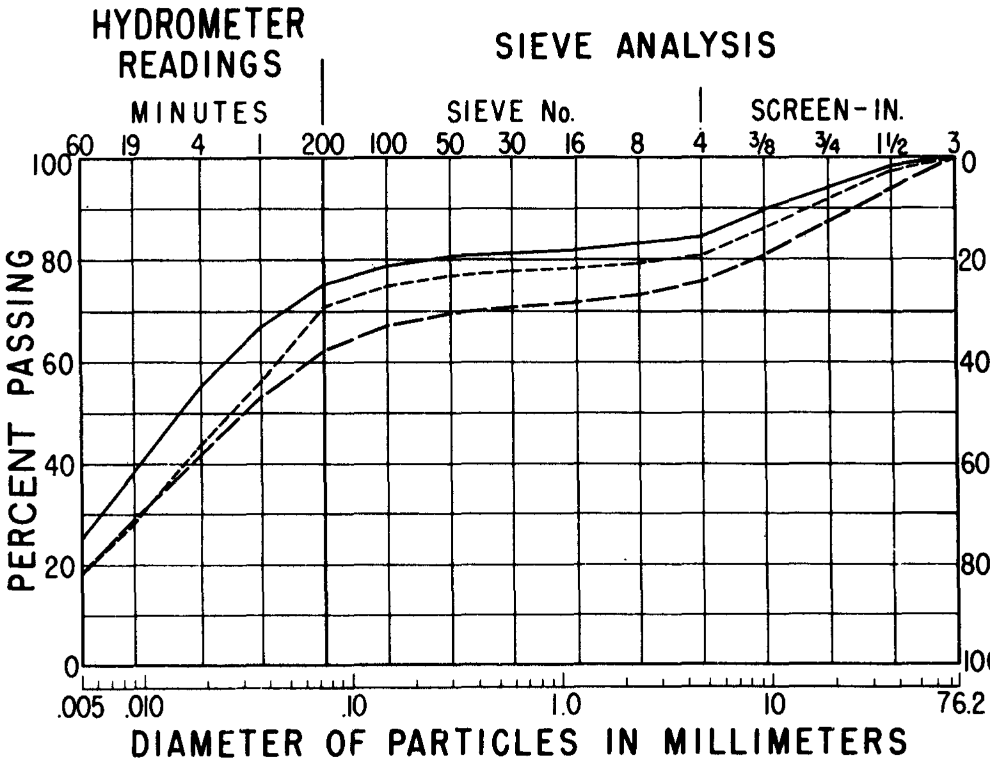
The selected soil linings on Potholes East Canal (figs. A-3 and A-4), constructed in 1953, were generally clayey sands, lean clay, and borderline lean clay-silts with a plasticity index of 12 (excluding one sample of fat clay having a plasticity index of 40) and 3 to 20 percent gravel. Unit weight tests were performed in the sides and bottom lining in 1955, but only in the sides in 1959. A comparison of tests in the side lining at those dates shows no significant change in unit weight; the percentage of maximum laboratory unit weight remained at about 89 percent for both test years. This canal is operated year-round with the water level about 6 inches (0.15 m) below design depth. There has been no cleaning or maintenance, since at least 1969. There is no problem of lining erosion or of seepage opposite the lined reach.[2]

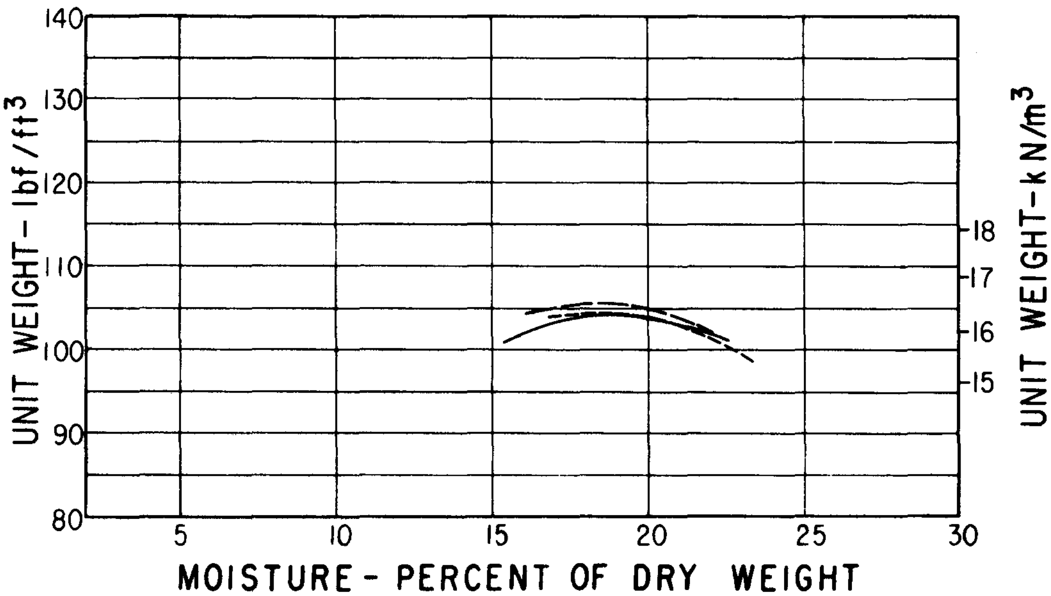
### West Canal, 4th Section, Columbia Basin Project

The soil lining constructed in 1954, on West Canal consisted of silty gravel, clayey, gravel, silty sand, borderline silty gravel-clayey gravel, and borderline

[1] Telephone call of November 5, 1984, from C. W. Jones to Richard Erickson, Secretary-Manager, East Columbia Basin Irrigation District, Othello, Washington.
[2] Telephone call of October 12, 1984, from C. W. Jones to Shannon McDaniel, Assistant Manager, South Columbia Basin Irrigation District.

Figure A-1. – Lateral EL–68 near station 211+00. General view of soil lining showing trench excavated to conduct unit weight tests. A permeability test is in progress on the canal slope under a tarpaulin to protect against freezing. November 1957. P–222–116–39930.




**EXPLANATION**

Sta. 182 + 00 ----- Sta. 200 + 00 — — —

Sta. 211 + 00 ———

Figure A-2. – Gradation and compaction test results for Lateral EL–68.

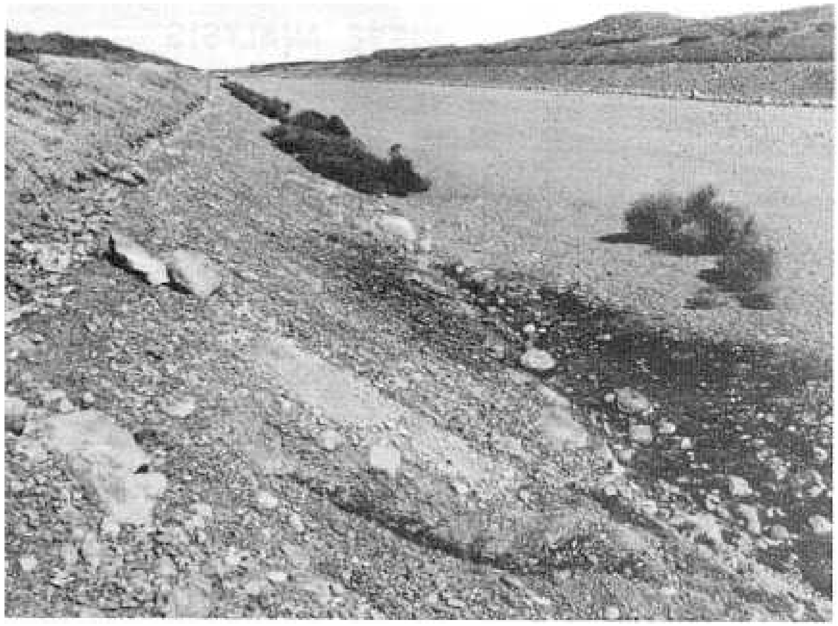


Figure A-3. – Potholes East Canal looking upstream from right bank near station 881+00. Gravel cover varies in thickness from 6 to 15 inches. Lining has experienced two operating seasons. Excavation in low center is for unit weight tests. March 1955. P–222–117–36308.

silty sand-clayey sand with 15 to 60 percent gravel (fig. A-5) The plasticity ranged from nonplastic to a plasticity index of 15. Unit weight tests results obtained in 1955 to 1959, showed a decrease in the percentage of the maximum unit weight from 90 to about 86 percent of laboratory maximum unit weight. The effect of frost action on the soil with a significant amount of gravel in the lining may have caused a decrease in unit weight (see discussion of frost action in the text of this report).

### Main Canal, Post Falls Unit, Rathdrum Prairie Project

This canal (fig. A-6), which was constructed in 1946, has a 6-inch (15-cm) thick clayey-sand lining with a plasticity index of 8. Compaction was accomplished with a track-type tractor. The lining was covered with 6 inches (150 mm) of gravel for protection against erosion.

Between 1954 and 1963, the average soil unit weight decreased 3.2 percent. Some of the lining samples received in 1963, contained much higher percentages of plus No. 4 material than the samples received from the same locations in 1954. It is believed that this high increase was caused by the inadvertent mixing of some of the cover material with the thin layer of clay lining; the original lining material was basically a clayey sand.

Laboratory permeability tests conducted in 1954 (table 3), on soils from the lining at unit weights of 95, 90, and 85 percent of the maximum unit weight showed rates of 0.9, 5, and 8 ft/yr ($8.7 \times 10^{-7}$, $4.8 \times 10^{-6}$, and $7.7 \times 10^{-6}$ cm/s), respectively.

### Delta-Mendota Canal, Central Valley Project

The large Delta-Mendota Canal (figs. A-7, A-8) has a thick compacted soil lining. It was constructed in 1951-52 of highly expansive, Porterville clay. The lining has an average liquid limit of 64, plasticity index of 40, and shrinkage limit of 13.

Unit weight tests were obtained in the top portion of the side slope lining when the water level was lowered for canal repairs in 1965 and 1966. In the reach between miles 107.8 and 115.9, a comparison was made between the unit weight and moisture conditions during construction and in 1965, 13 years after construction. During the intervening years, the soil moisture content increased about 8 percent and the soil unit weight decreased about 6 percent. These changes are attributed to the expansiveness of the soil. In 1966, unit weight tests were made near the top of the lining between mile 98.7 and mile 102.7. For this reach, the average unit weight was about 93 percent of the laboratory maximum unit weight. Observations along this reach of the canal during the field tests found no noticeable seepage adjacent to the canal, and the lining was considered to be performing in an excellent manner. This canal

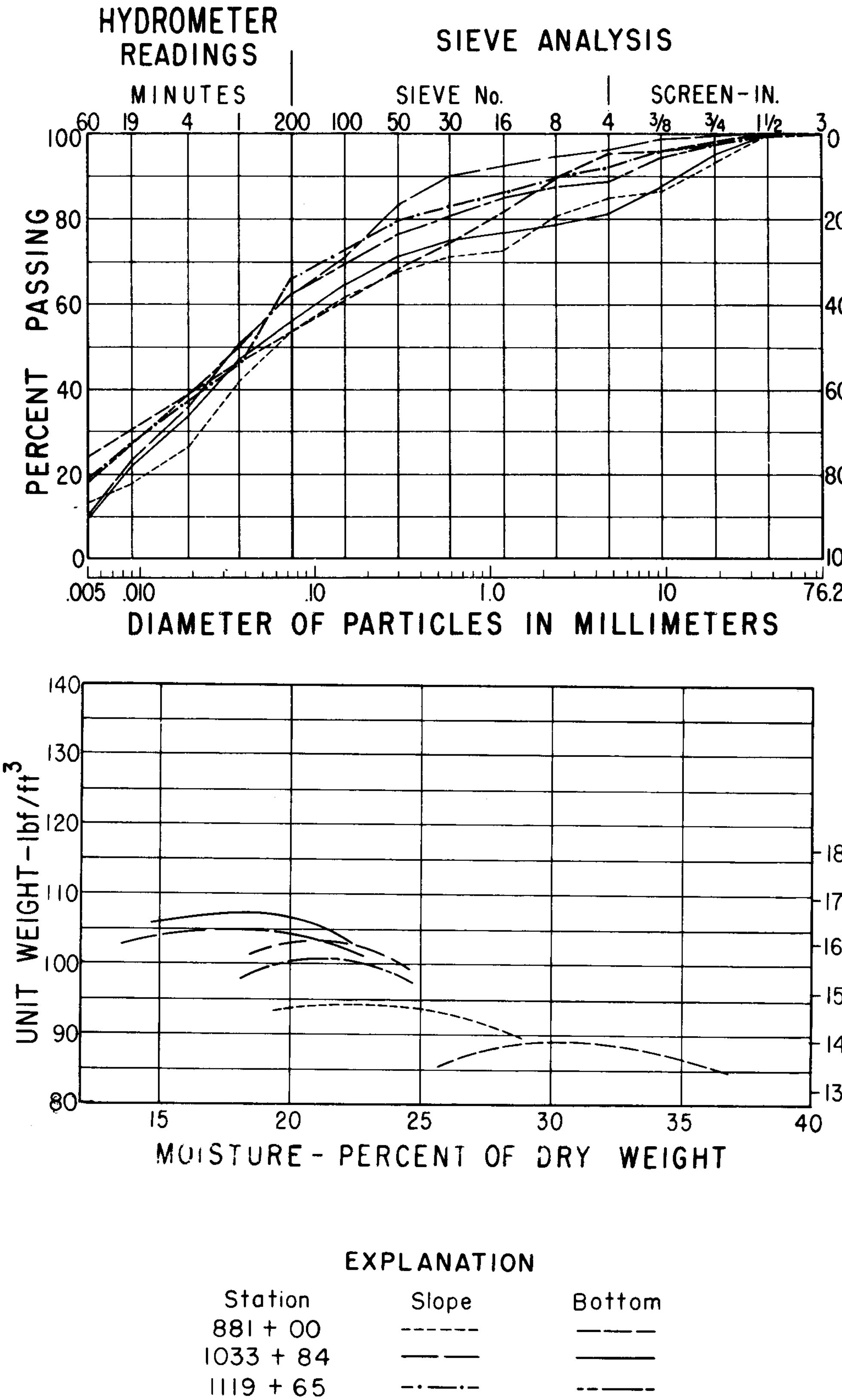



Figure A-4. – Gradation and compaction test results for Potholes East Canal.

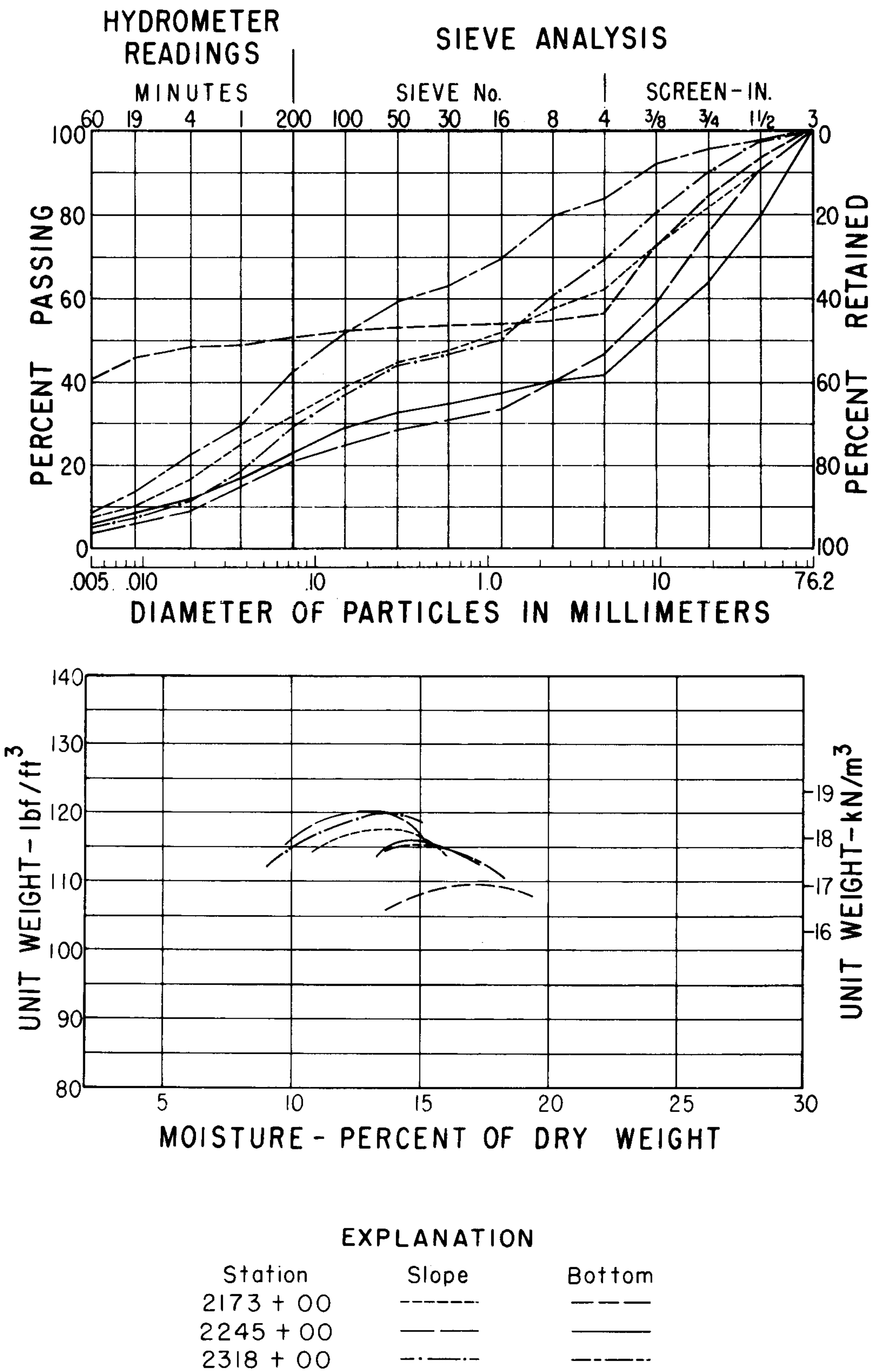
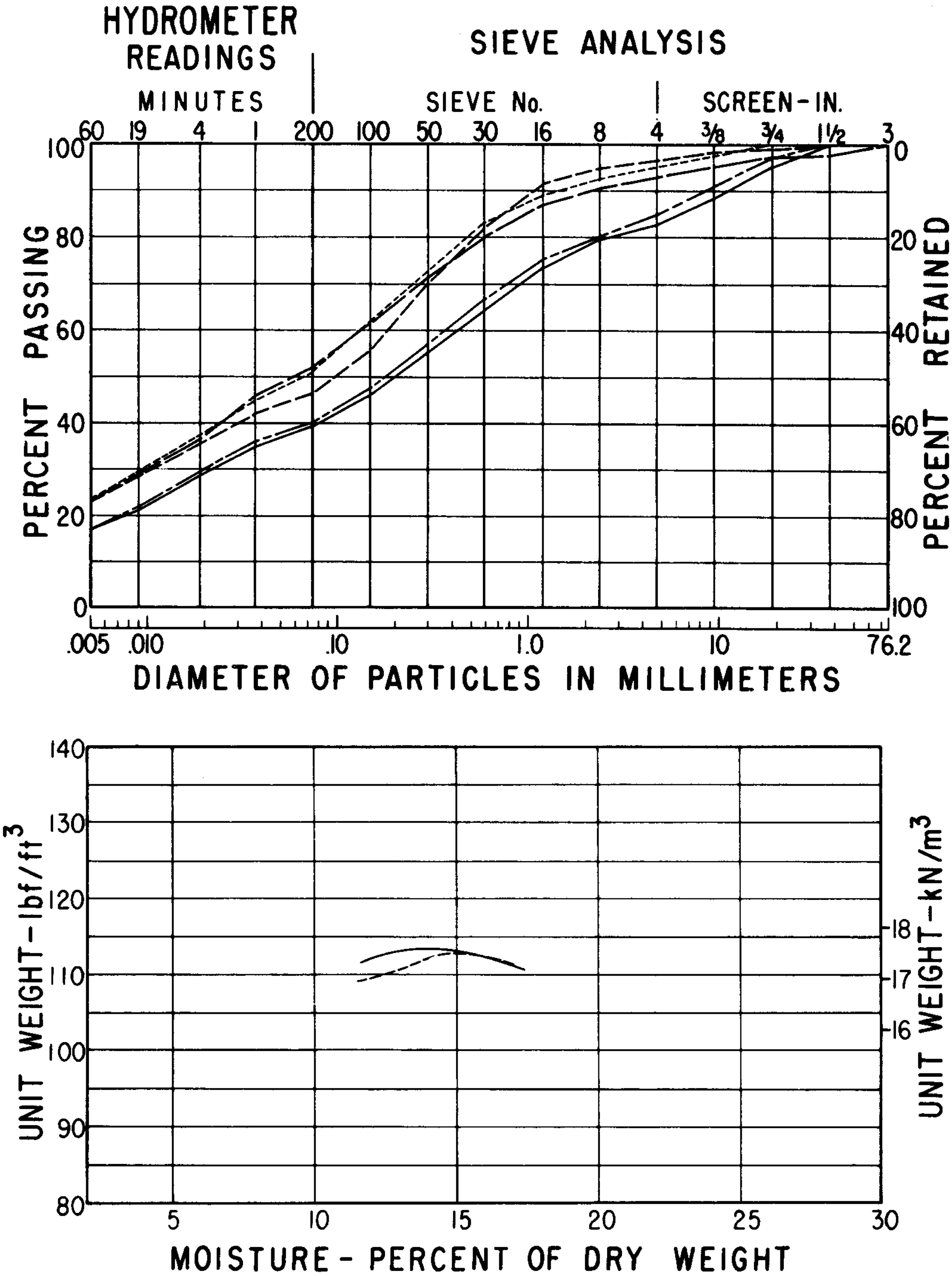



Figure A-5. – Gradation and compaction test results for West Canal.




EXPLANATION

Sta. 8 + 86, Bottom-------
Sta. 73 + 92, Slope—·—
Sta. 40 + 74, Slope— — —
Sta. 101 + 32, Slope———
Sta. 114 + 66, Slope—— ——

Figure A-6. – Gradation and compaction test results for Main Canal, Rathdrum Prairie Project.

Figure A-7. – Delta-Mendota Canal at station 5049+50 after 14 years of service. Drillers are obtaining undisturbed, hollow-stem auger samples from the top of the lining for unit weight measurements. March 1965. P214-D-63660.

had been in operation continuously since construction except for occasional partial dewatering for repair. In 1984, no seepage was evident opposite soil-lined reaches on the Delta-Mendota Canal.[3]

### Wellton-Mohawk Canal, Gila Project

A reach of Wellton-Mohawk Canal, was constructed in 1950, with a thick compacted lining of well-graded clayey gravel with 51 to 61 percent gravel. It has been in continuous operation since construction, except for short periods of canal repair. Unit weight tests were obtained above the canal water operating level near the top of the side slope lining in 1957, from test holes somewhat smaller than recommended for canal lining work. At that time, the average dry unit weight of the minus No. 4 fraction of the soil was 101.7 $lbf/ft^3$ (16.0 $kN/m^3$) compared with 107.2 $lbf/ft^3$ (16.8 $kN/m^3$) obtained from construction records. No laboratory tests data, other than that from compaction tests, is available from lining samples. However, clays in the general canal area are known to be expansive, which could account for the decrease in soil unit weight during the 6 years following construction. A well-graded gravel with sufficient clay binder to fill voids, similar to the soil used on this canal, is considered an ideal soil for compacted soil linings. Such a soil has low permeability, and the gravel provides resistance to erosion from canal water.

### Southside Canal, Collbran Project

The soil-lined reaches of Southside Canal (figs. A-9 and A-10) were constructed in 1959. The soil is a sandy lean clay with a plasticity index of about 16. Unit weight tests were conducted in the lining after construction in November 1959, October 1960, May 1962, October 1964, and November 1976. The unit weight test data (table B-1) show that after construction in 1959, the average percent of maximum laboratory unit weight was 102.2, and by 1976, it had decreased about 10 percent to 91.8 percent. A plot of soil unit weights with depth of lining (fig. 4) showed that the unit weights stayed generally above 95 percent of the laboratory maximum unit weight, except for the 1976 tests in the top and middle of the side slope lining.

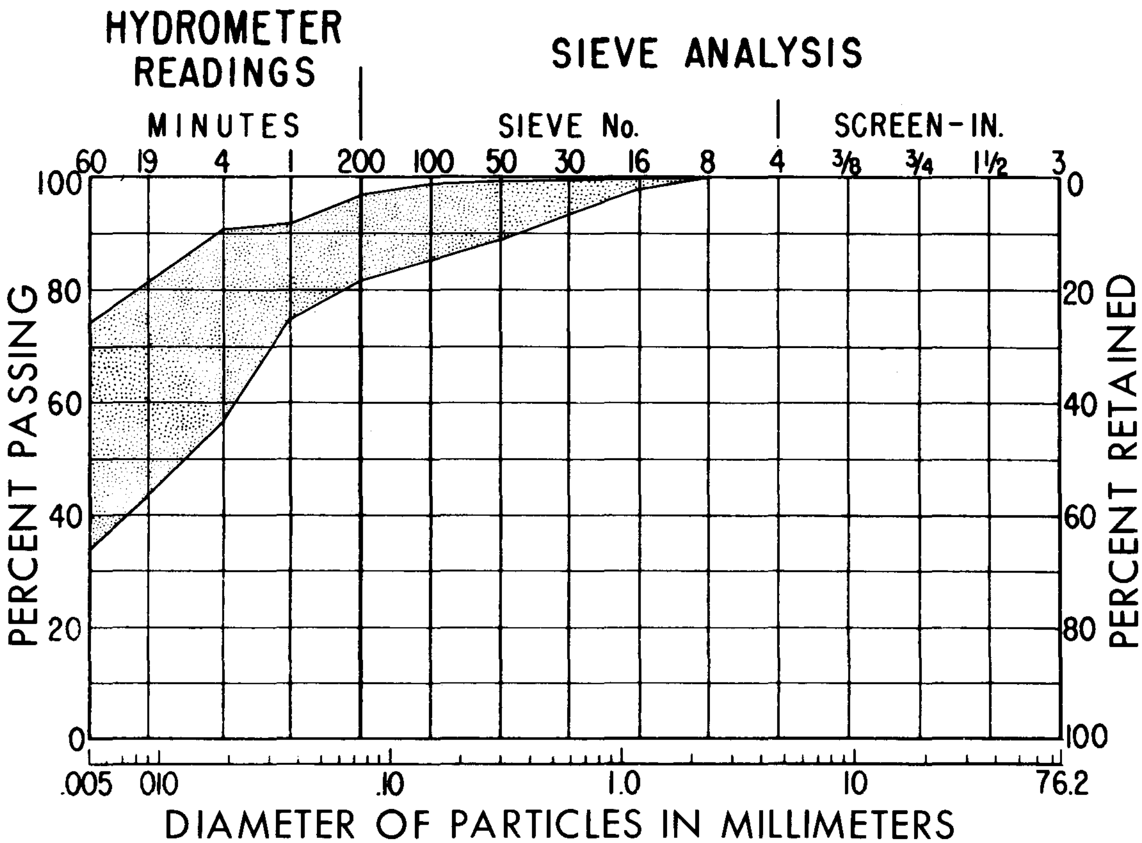
On September 20, 1984, it was reported[4] that the compacted soil lining on the Collbran Project was performing well. There was no evidence of seepage from soil-lined reaches. There has been no significant erosion of the lining and not much cleaning has been required. The preceding 2 years had been unusually wet, and there had been some movement of the soil on hillsides and sliding of outer canal banks.

### Means and Eden Canals and Farson Lateral, Eden Project

Compacted soil linings on Means Canal, Eden Canal, and Farson Lateral (fig. A-11) were constructed in the 1950's. The soil in the Means Canal lining is a lean clay with a plasticity index of 22, and the soils in the Farson Lateral and Eden Canal are clayey sands with average plasticity indexes of 9 and 14, respectively. Unit weight tests made in 1960, showed the percent of laboratory maximum unit weight ranged

[3] Telephone call of October 2, 1984, from C. W. Jones to W. E. Kron, Project Construction Engineer, Fresno, California.

[4] Telephone call of September 20, 1984, from C. W. Jones to Bob Byers, Manager, Collbran Conservancy District.




NOTE: The average maximum unit weight and optimum moisture for samples from these stations were 97.3 lbf/ft$^3$, and 23.8%, respectively.

**EXPLANATION**

**Stations 5002+14, 5049+50, 5091+00, 5110+00, 5144+29, 5194+78, 5241+16 and 5450+00.**

Figure A-8. – Gradation test results for Delta-Mendota Canal.

Figure A-9. – Southside Canal at station 635+65. Unit weight test being performed in canal bottom. Note the numerous cattle tracks.

from 93.4 for the test site on the Farson Lateral to 100.7 for Means Canal and 106.1 for Eden Canal. No unit weight tests were performed in other years to show any changes.

At the time of the 1960 unit weight tests, erosion of soil linings near the waterline, particularly on the Means Canal, was reported. Since that time, much of the soil-lined and unlined portions of the canals and laterals on this project have been covered with a shale material conveniently available on the project. This has been added partly to protect against soil erosion at the waterline and partly to reduce weed growth and to inhibit formation of silt berms above the waterline.

Soil linings on the Eden Project were selected in a canal lining erosion study started in 1984, and selected linings were inspected in the spring of that year and in the fall of 1985. The shale used for protection against erosion has proved an excellent material for that purpose, and the shale-covered soil linings on the canal are in very good condition.

Erosion of the soil linings was determined by trenching through the cover material on the side slopes. In August 1986, the canal lining erosion study was still in progress. Laboratory tests have shown that the soil in the Eden Canal lining is dispersive, which could account for the erosion. Erosion of linings on Means Canal and Farson Lateral have not yet been accounted for. However, on the particular reach of Means Canal being studied, water stands in the canal bottom during winter. This could cause freezing and thawing on the side slopes, resulting in progressive loosening of the soil lining near the surface and increasing the susceptibility of the soil to erosion from wind-wave action. The Eden Project area is subject to unusually high winds that can cause severe wave action on canal side slopes.

No seepage opposite soil-lined reaches on the Eden Project has been reported. However, in several places the lining has sloughed into the canal or lateral as a result of back pressure behind the lining. In one location the lining was still in place, but seepage into the canal was causing a loose and "quick" condition in the canal bottom.

**Hudson Canal, Tucumcari Project**

Hudson Canal (figs. A-12 and A-13) was constructed in 1954. In four reaches it has a thick compacted lining of lean clay to sandy lean clay covered with 12 inches (305 mm) of gravel blanket on the side slopes to prevent erosion. Opposite two of these lined reaches, seepage occurred on adjacent farmland. Therefore, in 1963, unit weight tests were conducted in the lining opposite seepage areas, and the results were compared with unit weight test results obtained during construction. The unit weight values in 1963 were slightly higher (1.9%) than at the time of construction in 1954. Laboratory permeability tests of soil compacted to the 1963 average field unit weights resulted in an average permeability rate of 0.03 ft/yr ($3 \times 10^{-8}$ cm/s) (table 3).

Laboratory freezing tests (fig. 15) were conducted on soil from this lining to determine changes in unit

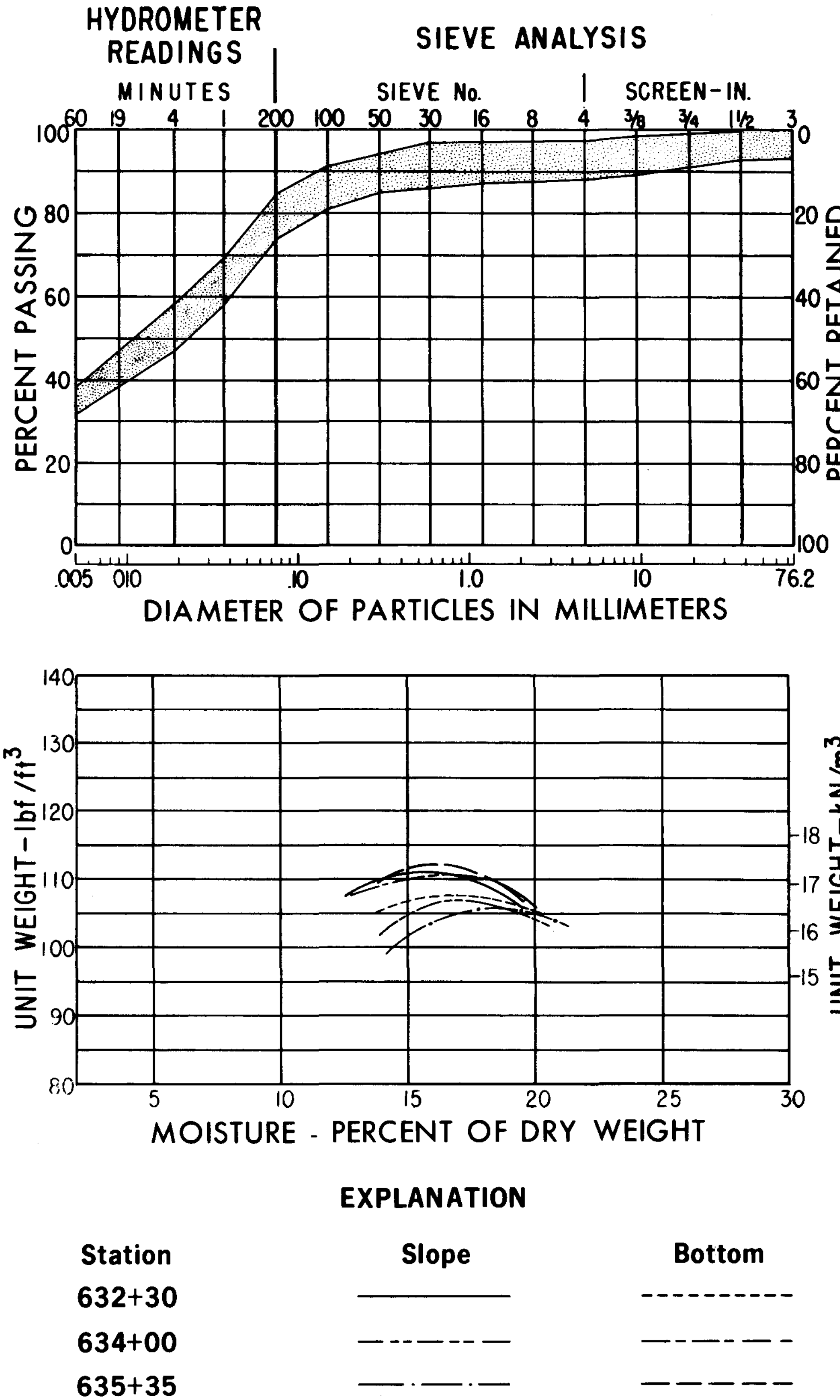
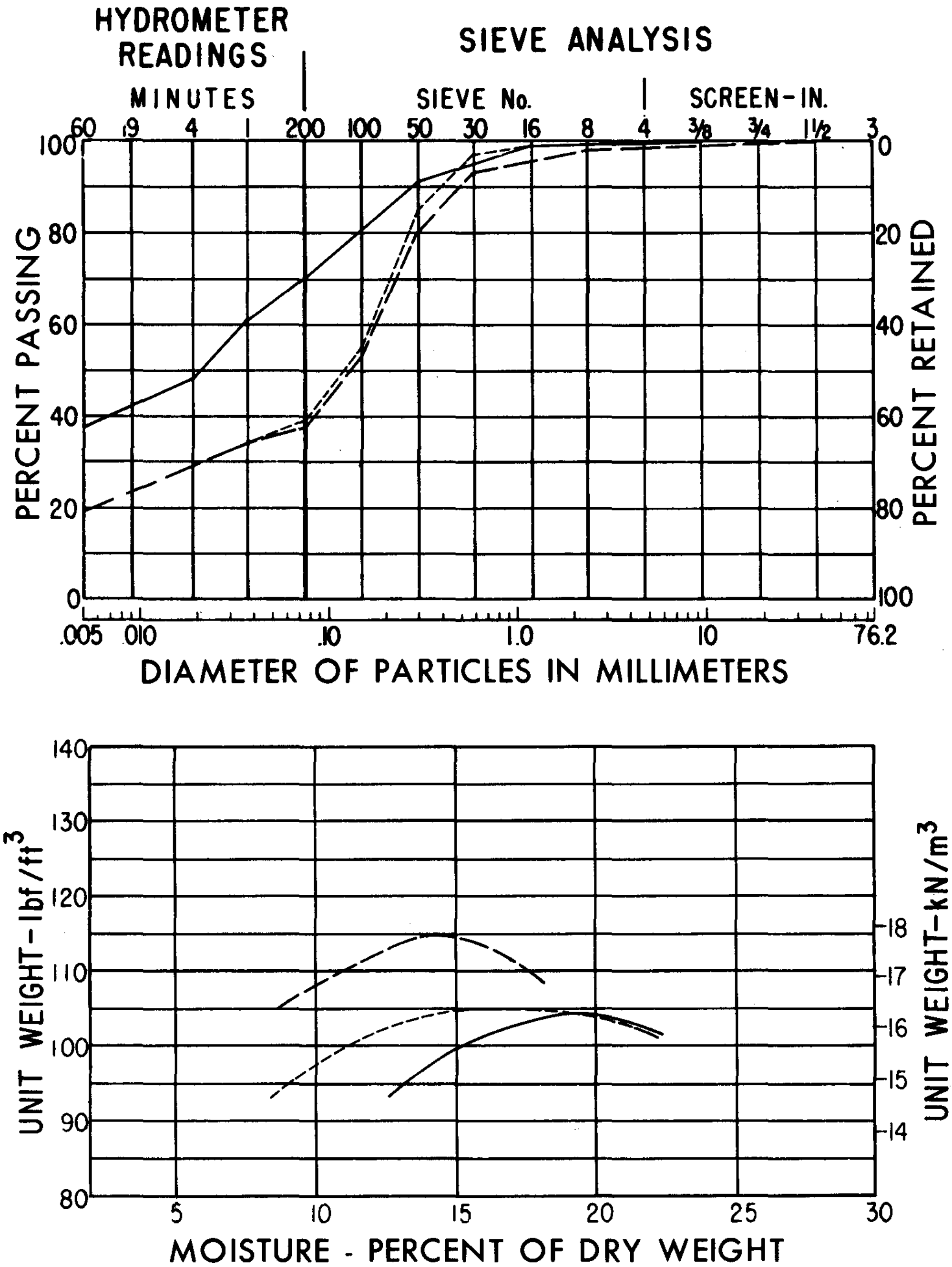



Figure A-10. – Gradation and compaction test results for Southside Canal.




**EXPLANATION**

| | STATION | |
|---|---|---|
| MEANS CANAL | 137+50 | ———————— |
| FARSON LATERAL | 137+50 | — — — — — |
| EDEN CANAL | 681+00 | - - - - - - - - |

Figure A-11. – Gradation and compaction test results for Eden Project.


Figure A-12. – Hudson Canal near stations 470+00 to 485+00. Seepage through the lining has damaged adjacent farmland. March 1963. CTP 257–D–37824.

weight caused by freezing action. Unit weight tests on soil cylinders before and after freezing showed a decrease in unit weight toward the top of specimens and an increase toward the bottom. The unit weight of the total specimen was not changed significantly by freezing. From tests and observations, it appeared that in 1963, the earth lining was in excellent condition and should have been performing satisfactorily. During the excavation for unit weight tests in the lining, some grass and weed roots were observed extending horizontally out of the lining. Construction inspectors recalled that the canal bank had been used for haul roads at various stages during lining construction, and some weeds grew along the roadway. Therefore, it is possible that there were highly compacted horizontal planes in the lining at roadway elevations where the layers were not completely bonded when additional lining was placed. In addition, an impervious soil layer existed 1 to 5 feet (0.3 to 1.5 m) below the canal bottom, making seepage from the canal likely to flow horizontally to adjacent farmland. This would aggravate any slight seepage condition.

A partially successful attempt to alleviate the seepage conditions was made by constructing interceptor ditches parallel to the outside canal bank near the toe of the slope. Later, a vertical cutoff wall of plastic film was also constructed in a trench along the toe of the canal bank.

### Sunshine Reservoir Supply Canal

Although the lining on this canal (fig. A-14) was not on a Bureau project, it was included as a lining test site because it was a very early example of a compacted soil lining in a cold climate. The lining was considered successful when unit weight tests were conducted in fall 1952, approximately 12 years after it was constructed. The canal was built by WPA labor for the Greybull Valley Irrigation District. It carries water from the Upper Sunshine Reservoir Dam on the Greybull River, 17 miles above the town of Meeteetse, Wyoming, to the Greybull River Valley in Park and Bighorn counties.

After construction of the unlined canal, it was noted that where the canal was not in compacted embankment, seepage was occurring. Therefore, the shale foundation material was moistened, pulverized, and used as a canal lining for a 4,000-foot (1220-m) reach. The resulting soil was a lean to sandy clay with a plasticity index of 14 and from 1 to about 20 percent gravel. Compaction was by 16 trips of a sheepsfoot roller of unknown mass on 6-inch (15-cm) thick compacted layers. Unit weights averaged 94.4 percent of maximum laboratory unit weight (table B-1).

### Angostura Main Canal, Angostura Unit, PSMRBP[5]

The Angostura Main Canal (fig. A-15) was constructed in 1953. Three sections of the canal were lined with thick compacted soil lining, and one test site was established in each section. Tests were performed in the lining in 1954, 1958, 1959, 1961, and 1964. The soils near stations 1294+05 and 1318+88 were clayey sands with an average plasticity index of 16, and those near station 1334+91 were a sandy clay with a plasticity index of 26. In table B-1, the unit weights of all three test sites were first averaged for each year of tests; then, because the properties of the soil near station 1334+91 were somewhat different from those at the other two

[5]Pick-Sloan Missouri River Basin Project.

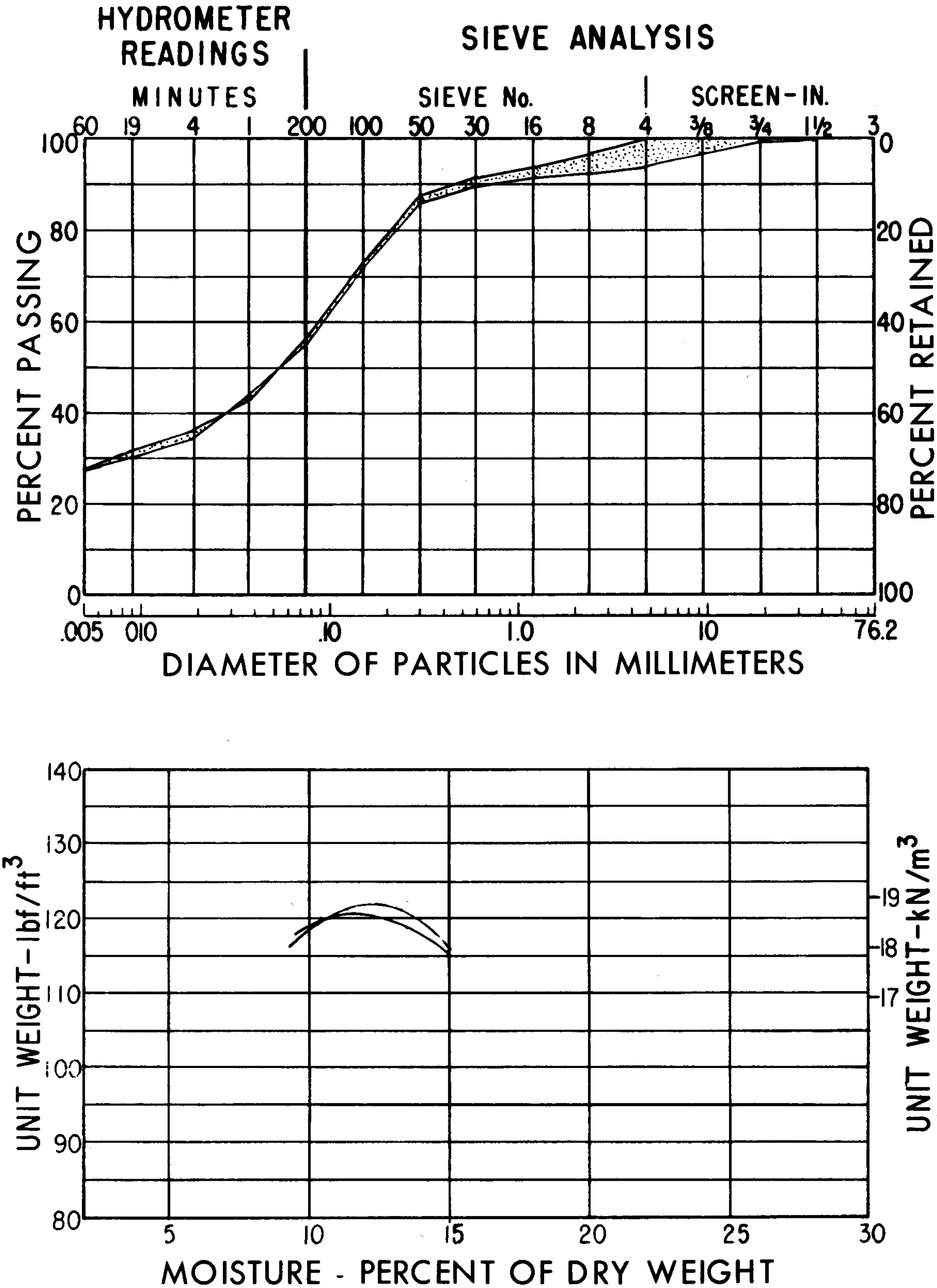



Figure A-13. – Gradation and compaction test results for Hudson Canal.

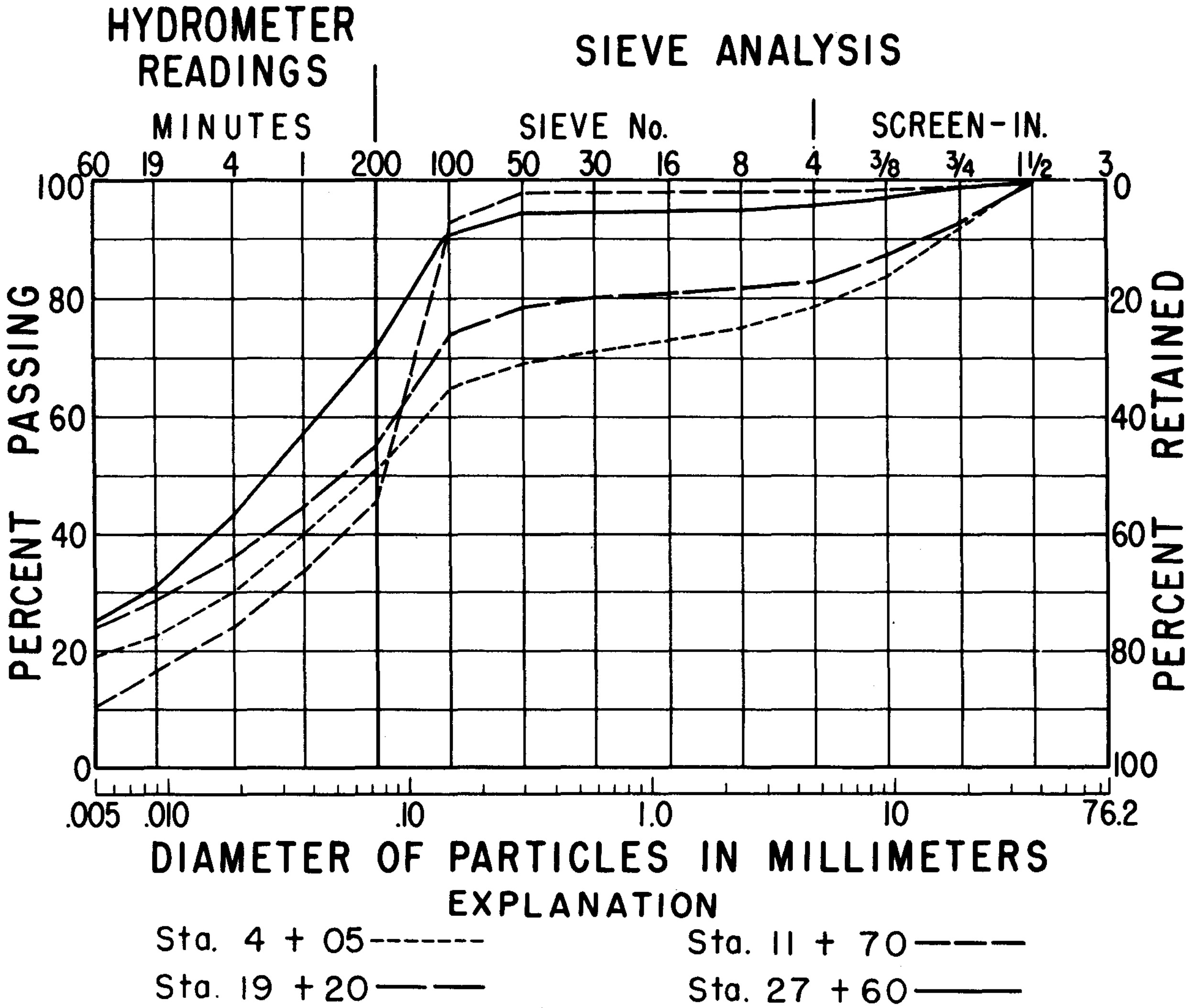



Figure A-14. – Gradation test results for Sunshine Reservoir Supply Canal.

sites, it was averaged separately. This provided a better comparison of changes for the two different soils. For the clayey sand, after showing increases in 1958, 1959, and 1961, the unit weight had decreased from 97.4 percent of maximum laboratory unit weight the year after construction to 94.0 percent in 1964, 10 years after construction. The unit weight for the sandy clay had increased from 93.6 percent to 103.5 percent during this time. As shown on figure 16, the overall average change for all three test sections was an increase of 5.7 percent.

Apparently because of seepage through the lining near the outlet of the Cheyenne River siphon, a high ground-water condition developed that threatened the safety of the outlet. In 1964, a ponding seepage test was conducted on the soil-lined test reach near the siphon, and the resulting seepage rate was 0.24 $ft^3/ft^2/d$ (73 $L/m^2/d$). Although the results of the tests do not indicate failure of the lining, it was nevertheless considered advisable to reduce seepage to the smallest amount practical because of the rather critical location adjacent to the siphon and because downstream irrigable lands adjacent to the canal were receiving too much seepage. Therefore, the compacted soil-lined reaches were relined with asphalt-membrane lining.

**Canal B, Fort Clark Unit, PSMRBP**

In 1955-56, after several years of operation, seepage appeared opposite unlined Canal B (fig. A-16) in two areas after construction of Garrison Dam caused removal of silt from the canal water. In May and June 1957, three reaches of the canal totaling 3,900 feet (1.2 km) were soil-lined.

About 2 feet (0.6 m) of wind-deposited sand was excavated from the bottom of the canal. The lining material was a lean clay (glacial till) with a plasticity index of 24. Soil was placed in the bottom part of the canal section and compacted in 4- to 6-inch (100-

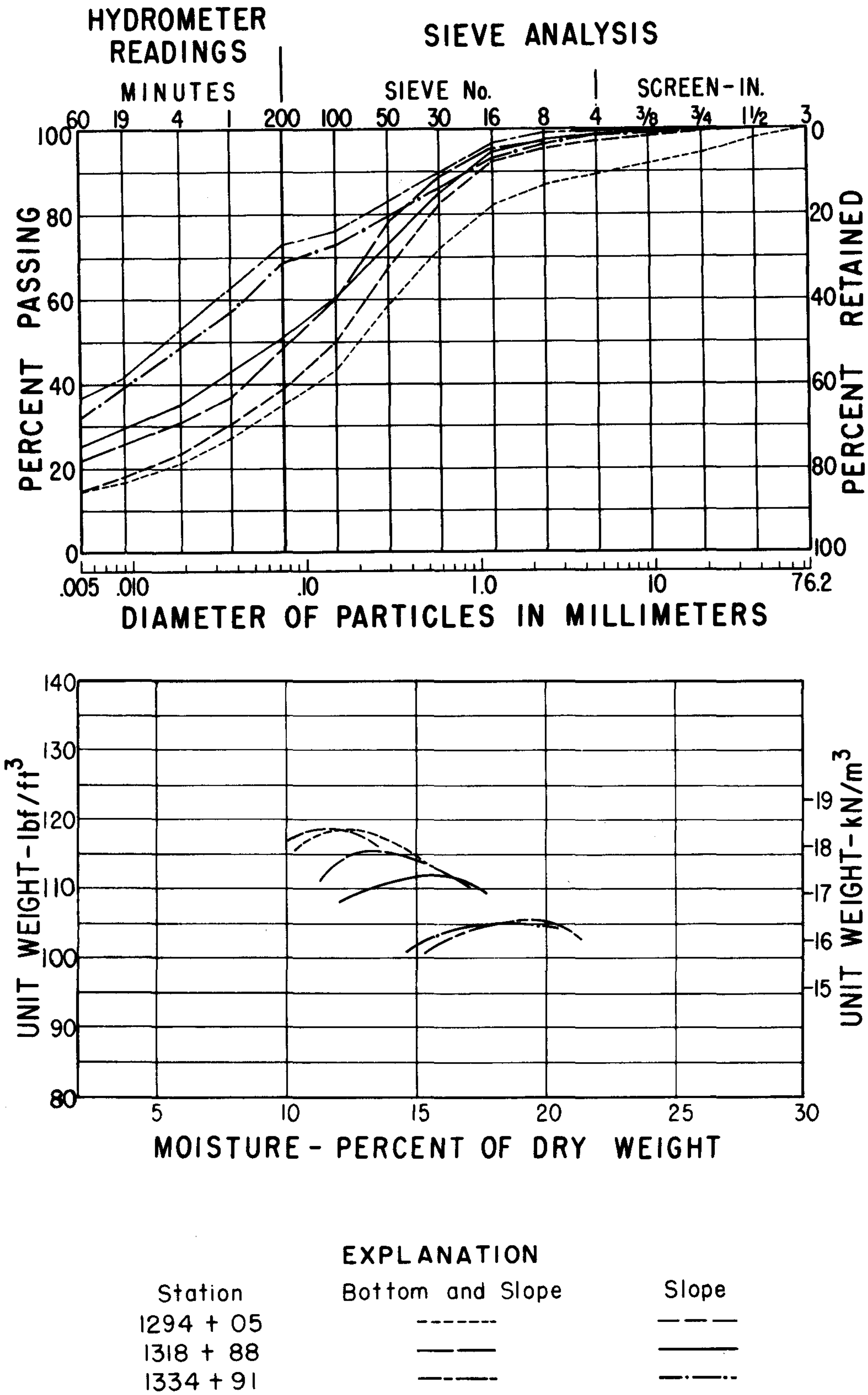
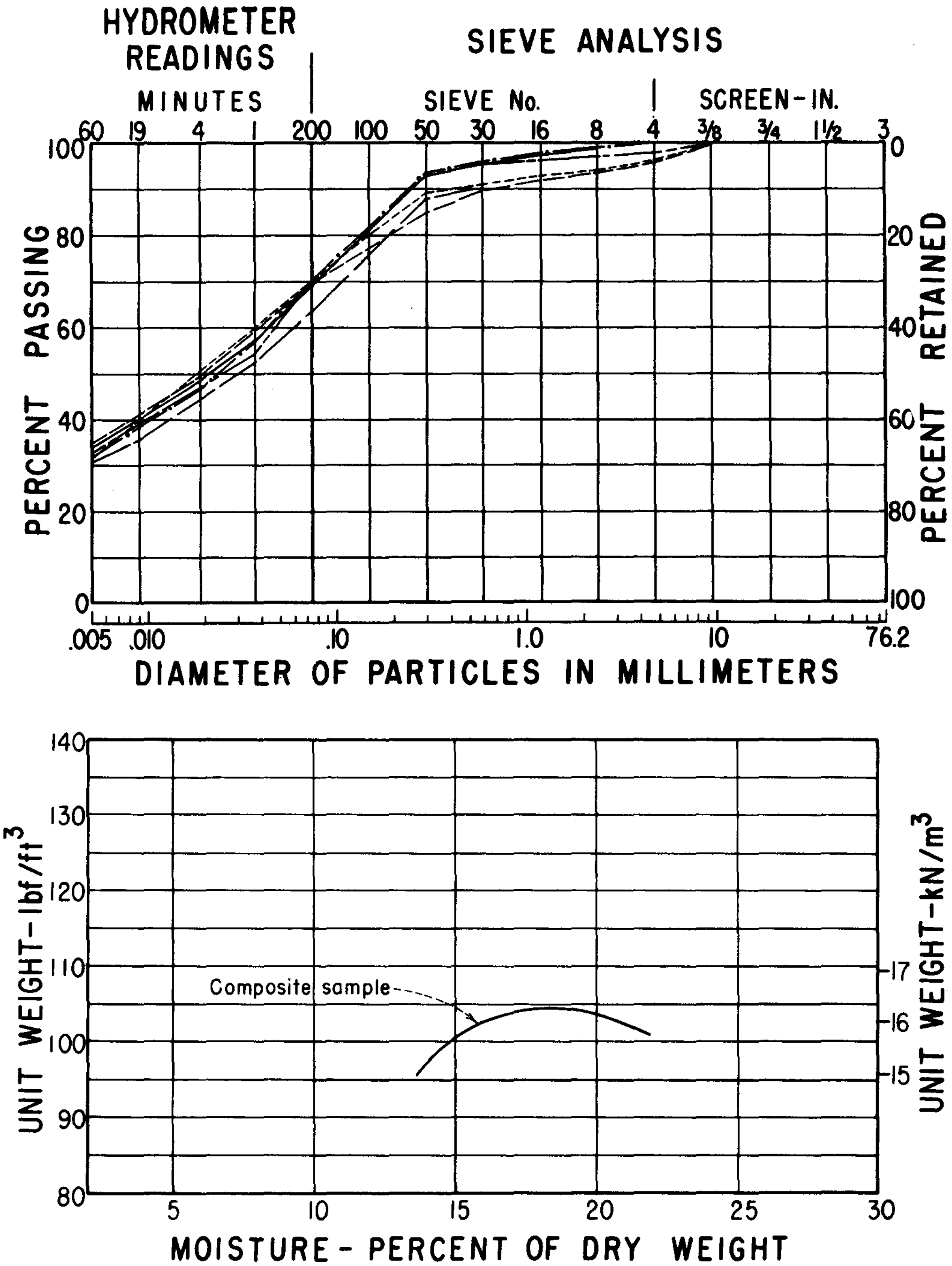



Figure A-15. – Gradation and compaction test results for Angostura Main Canal.




### EXPLANATION

| Station | Center line | 5 Ft. Left |
|---|---|---|
| 75 + 50 | ------- | — — — |
| 236 + 00 | —— —— | ———— |
| 245 + 00 | —·——·· | --——- |

Figure A-16. – Gradation and compaction test results for Canal B.

to 150-mm) lifts by tractor and scraper transporting the soil. The soil between the equipment wheel tracks was compacted by a small rubber-tire tractor. After placement of soil in the bottom of the canal, the canal prism was excavated by a ditcher. Canal shoulders were built up by soil excavated by the ditcher and compacted by treads of a crawler-type tractor and the ditcher wheels. The lining had a minimum thickness of 2 feet (0.6 m) on the canal bottom and 1 foot (0.3 m) on side slopes at water surface.

Subsequent settlement of the upper part of the lining indicated that equipment travel was not entirely successful in obtaining the required degree of compaction. As shown in table B-1, the unit weight was very low; it averaged 79 percent of maximum laboratory unit weight in 1957, and 82.7 percent in 1958.

In August 1962, a ponding seepage test was conducted on Canal B. At the design water depth of 1.9 feet (0.6 m) at the test site, the seepage rate was about 2.0 $ft^3/ft^2/d$ (610 $L/m^2/d$), but at water depth of 1.3 feet (0.4 m) the rate leveled off at 0.6 $ft^3/ft^2/d$ (183 $L/m^2/d$). Project personnel reported that the sides of the lining had settled to approximately normal water surface elevation. Project personnel also reported that excessive weed growth could have caused reduced unit weights.

This is an example of a lining rather crudely constructed when compared with usual Bureau standards. In addition, the height of the lining provided little, if any, freeboard. Conclusions from this test were that effective soil linings should be well designed and sufficient compactive effort should be provided during construction to provide adequate unit weight for the required low permeability.

### Helena Valley Canal, Helena Valley Unit

Helena Valley Canal (figs. A-17 and A-18) was constructed in 1958. The soil in the thick, compacted soil lining is predominantly a sandy clay with about 24 percent gravel and an average plasticity of 14.

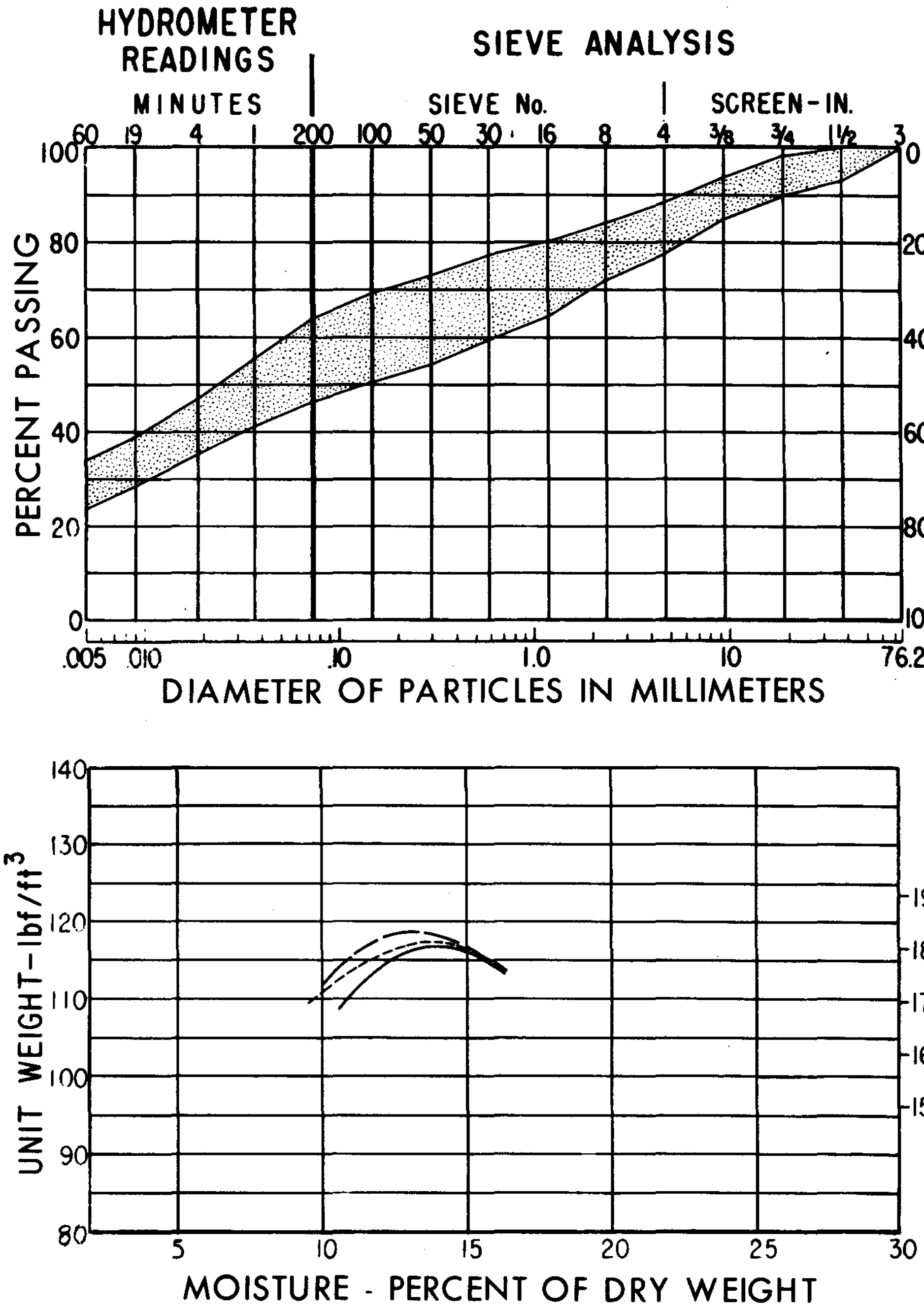
Unit weight tests obtained near stations 740+00, 923+00, and 1507+00 in 1958, 1964, and 1976, showed a decrease of 12.7 percent during the 18 years after construction. Tests made near station 1195+00 in 1958, 1960, 1962, and 1964, showed a decrease of 5.6 percent. Results of ponding tests (table 3), although successive tests were not performed at identical locations, indicated that seepage was very low when the lining was first constructed, but that seepage may have increased significantly with time. In [6]1983, there had been no seepage observed opposite soil-lined reaches on the Helena Valley Canal, but some seepage in one of the soil-lined laterals in high ground-water areas had occurred.

### Lateral D, Fort Shaw Division, Sun River Project

In fall 1957 and spring 1958, Lateral D (fig. A-19) on the Fort Shaw Irrigation District, Sun River Project,

[6]Telephone call of December 12, 1983, from C. W. Jones to Ron Schofield, Manager, Helena Valley Irrigation District, and to Bert Madsen, Irrigation Manager.

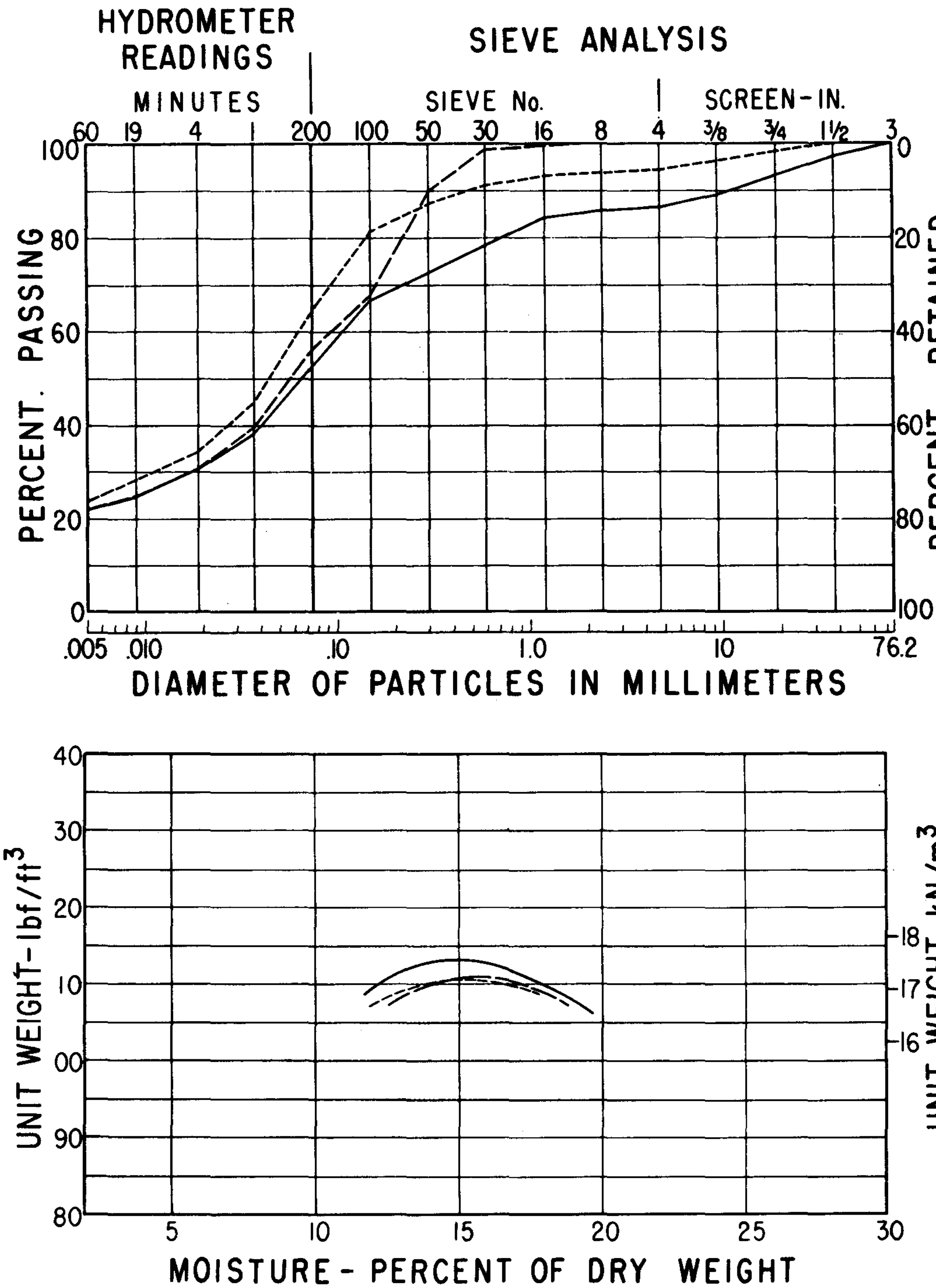
Figure A-17. – Newly-constructed soil lining at station 763+00 in the Helena Valley Canal. August 1958. P596–600–810.




**EXPLANATION**

| | Station | |
|---|---|---|
| — — — — — | **1463+00** | **BOTTOM** |
| ----------- | **1463+00** | **RIGHT SLOPE** |
| ———— | **1412+00** | **RIGHT SLOPE & BOTTOM** |

Figure A-18. – Gradation and compaction test results for Helena Valley Canal.




**EXPLANATION**

| Station | Slope | Bottom |
| --- | --- | --- |
| 1 + 90 | – – – | - - - - - - |
| 9 + 00 | | ——— |

Figure A-19. – Gradation and compaction test results for Lateral D.

was lined with a thin soil layer from station 87+00 to station 102+00. This was an old lateral where seepage on adjacent land had become a problem.

The soil for the lining was excavated from the bottom and sides of the lateral. It was a sandy lean clay with 0 to 33 percent gravel. The average liquid limit was 29 and the plastic limit was 11.

The lining was placed by project forces. The lateral was excavated 1 foot (0.3 m) below grade, and the side slopes reduced from 2:1 to 3:1. The soil was compacted in lifts up to 1-foot (0.3-m) deep by a sheepsfoot roller. Uncompacted soil was placed on the lining to form 2:1 side slopes. All compaction was accomplished by equipment moving parallel to the canal centerline. Cost of the lining was reported to be $0.42/yd^2$ ($0.50/m^2$). After the lining operation, seepage conditions adjacent to the canal improved markedly. Results of unit weight tests after construction in 1958 and in 1965 are shown in table B-1. The unit weight tests performed in 1965 were not near the 1958 test sites, and test results cannot be directly compared.

**Boulder Creek Supply Canal, Colorado-Big Thompson Project**

Soil-lined reaches on this canal (figs. A-20 and A-21) were constructed in 1954. The lining was a sandy lean clay with about 8 to 20 percent gravel. Average unit weights for test years (table B-1) show a small increase from the time of construction until the last tests in 1961. Some of the lowest unit weight values were obtained after construction in 1954, and the highest values were measured in 1961, the last year tests were performed. Unit weights averaged from nearly 90 percent to over 100 percent (fig. 6) of laboratory maximum, with the exception of 1954 tests in the bottom lining at 0.5-foot (0.15-m) depth, which averaged less than 85 percent. In 1961, the average unit weight was above 95 percent. At approximately station 163+00 on the right side of the canal, the lining sloughed for a short distance. This was caused by high ground-water seepage entering the canal through the lining when there was no water in the canal.

In 1957, an inspection was made on this canal to determine the extent of erosion that had been noted previously. In places, up to about one-half of the 3-foot (0.9-m) normal thickness of the lining had eroded; the erosion was more pronounced on curves. However, the inspection report at that time did not mention any seepage opposite the lining. Maintenance forces had placed a considerable amount of a coarse granular soil in some areas to prevent further erosion. The experience with this lining emphasizes the importance of a thick compacted lining to provide extra protection against erosion.

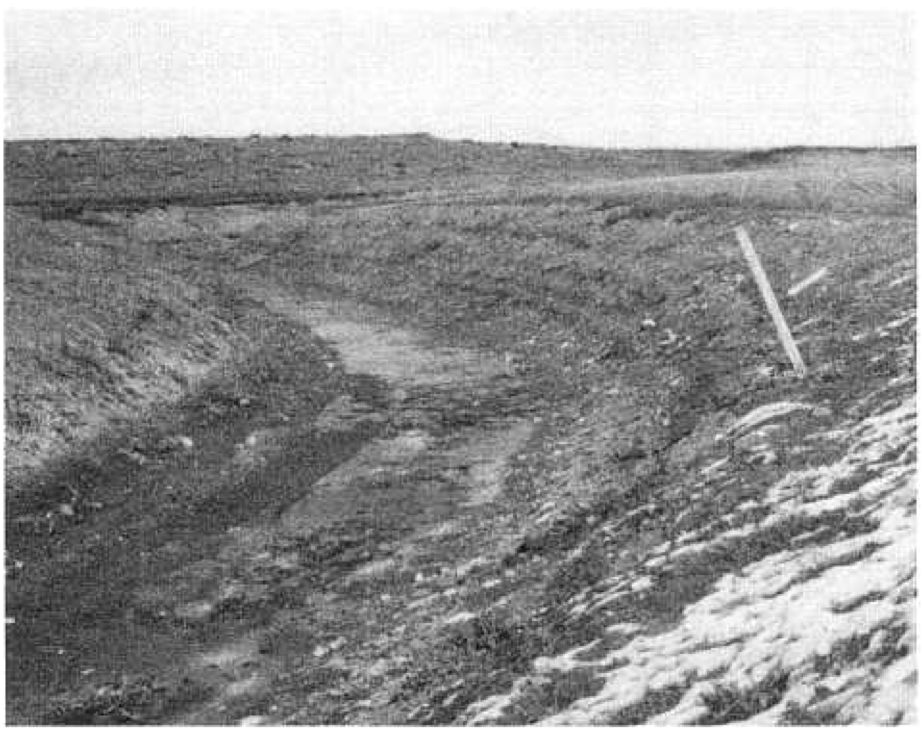
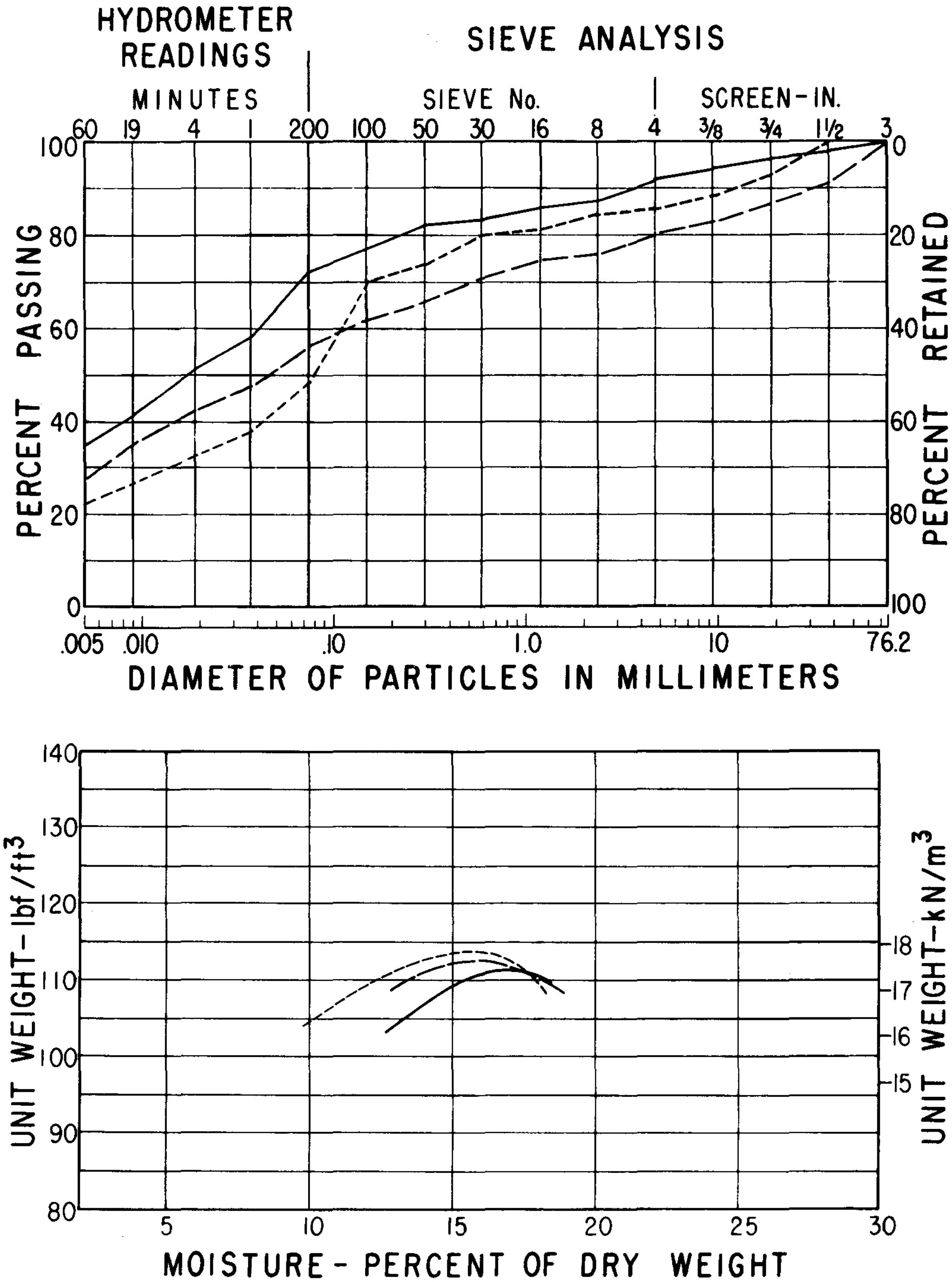


Figure A-20. – Boulder Creek Supply Canal at station 246+25. November 1957. E–1856–11.




EXPLANATION

Sta. 57 + 30 ------ Sta. 164 + 00 — — —

Sta. 246 + 25 ———

Figure A-21. – Gradation and compaction test results for Boulder Creek Supply Canal.

## South Platte Supply Canal, Colorado-Big Thompson Project

South Platte Supply Canal (figs. A-22 and A-23), constructed in 1956, had a compacted soil lining 1.5 feet (460 mm) thick for both canal bottom and slopes. The lining material consisted of lean clay blended with fine sand, which resulted in a borderline silt-lean clay with a plasticity index of 5. Six test locations were selected between stations 1474+98 and 1477+48. Unit weight and field permeability tests were conducted in the lining in 1956, 1957, 1959, and 1962. The average unit weight increased to a maximum in 1962, then dropped to 2.2 percent above maximum laboratory unit weight in 1976. At that time, most of the lining in the canal sides was gone, and the unit weight tests were performed in the bottom lining. During the 1976 tests, seepage on land opposite the lined test area was reported. Since the side lining was intact the first 6 years after construction, it is believed that lining material had been excavated during canal cleaning. This shows the need for refinement in canal cleaning methods, particularly if thick compacted linings are not used.

Laboratory freezing tests (fig. 15) were conducted on soil from this lining to determine changes in unit weight caused by freezing. Unit weight tests on soil cylinders before and after freezing showed a characteristic decrease in unit weight toward the top of specimens, and a slight increase toward the bottom.

Shallow-well field permeability tests (pp. 747-754 of [4]) were performed in the canal lining in 1956, 1957, 1959, and 1962 (table 3). The permeability test values indicated that a low rate of seepage was maintained for the first 6 years after construction. This is an example of a thin compacted soil lining giving excellent performance as long as it remained intact.

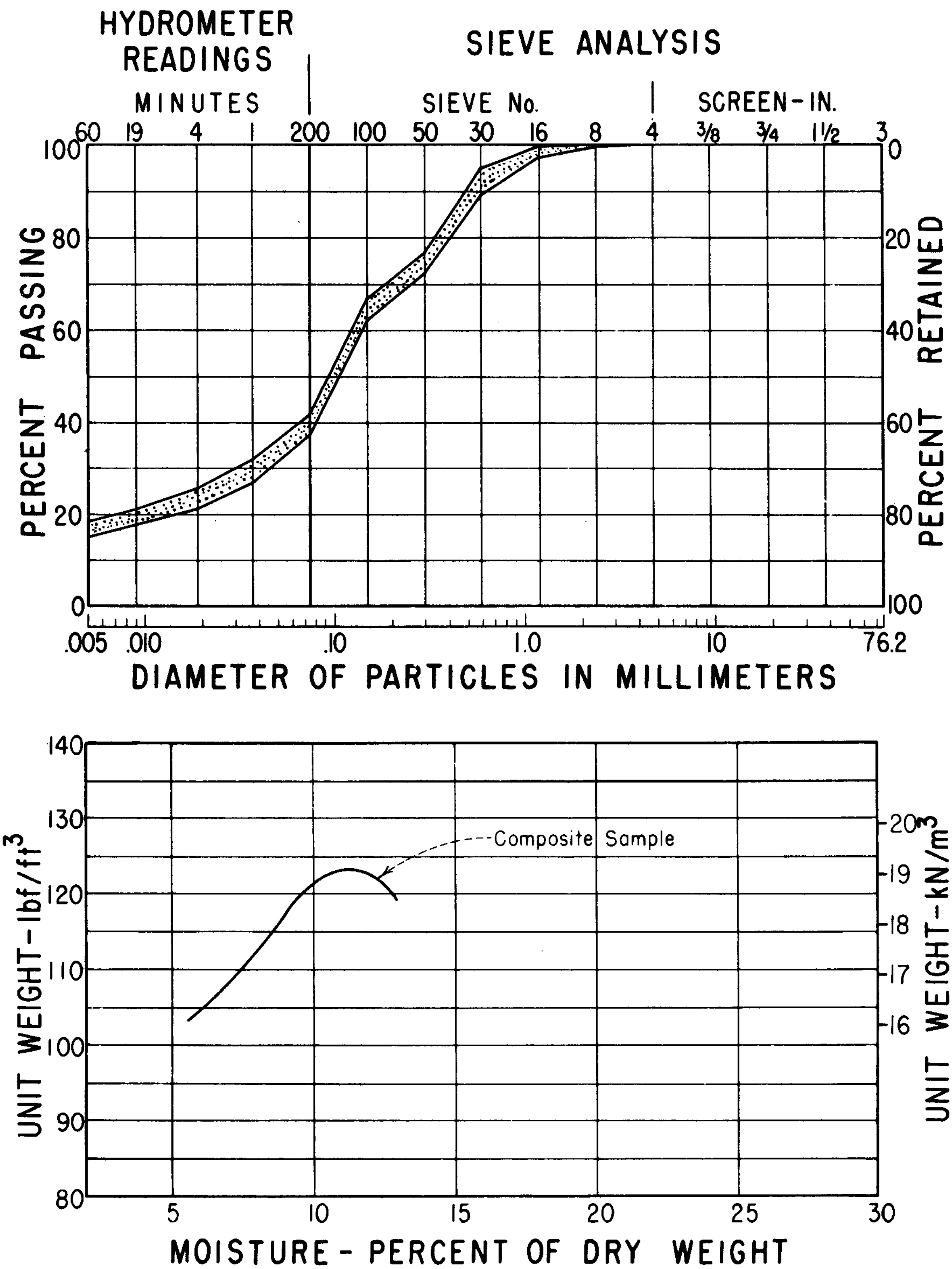
During the 1962 series of unit weight tests on the South Platte Supply Canal lining, nuclear moisture and nuclear unit weight meters were used for a comparison of their results with those obtained by the standard sand cone method. The average unit weights obtained by the sand cone and by the nuclear meter were 123.6 and 120.9 lbf/ft$^3$ (19.4 and 19.0 kN/m$^3$), respectively; the corresponding average moisture contents by the oven-dry method and by the nuclear moisture meter were 12.8 and 11.1, respectively. The difference in test results by these two methods are typical of results found on other Bureau projects [12].

## Cambridge Canal, Frenchman-Cambridge Division, PSMRBP

After the first season of operation of the third section of Cambridge Canal (figs. A-24 and A-25), it was considered necessary to line the canal to reduce seepage between stations 1102+00 and 1117+00. The compacted soil lining was constructed in 1954 by Government forces [11]. The lining consisted of lean clay with a plasticity index of 18. The average unit weight of the lining from control tests made during lining construction was 105.8 lb/ft$^3$ (16.6 kN/m$^3$), which was 101.6 percent of laboratory maximum unit weight.

The plot of average unit weight with depth in the lining (fig. 7) shows a significant decrease in unit weight between 1955 and 1957; the decrease amounted to 10 percent (table B-1) in maximum unit

Figure A-22. – Lining test site between stations 1474+98 and 1477+48 on the South Platte Supply Canal after 6 years of canal operation. November 1962. CTX–D–36555.




Stations 1474 + 98.3, 1475 + 48.3, 1475 + 98.3
1476 + 48.3, 1476 + 98.3 and 1477 + 48.3

Figure A-23. – Gradation and compaction test results, South Platte Supply Canal.

Figure A-24. – Cambridge Canal at station 1103+00. March 1957. P–328–701–6730.

weight from the time of construction. However, in 1976, the percentage decrease was only 3.0 percent from time of construction.

## Culbertson Canal, Frenchman-Cambridge Division, PSMRBP

The compacted soil lining constructed in Culbertson Canal (figs. A-26 and A-27) in 1959, consisted of silt to about station 1014+00 and lean clay at test sites beyond that point. Unit weight tests were performed at various places in the lining in 1960, 1963, and 1981.

For unit weight tests in both side and bottom linings near stations 44+38 and 75+15 (PI<1), the average percentage of the laboratory maximum (table B-1) increased 5.2 percent between 1960 and 1963, to values above 100 percent. In 1981, the percentage had dropped to slightly below (−0.6 percent) the 1960 level.

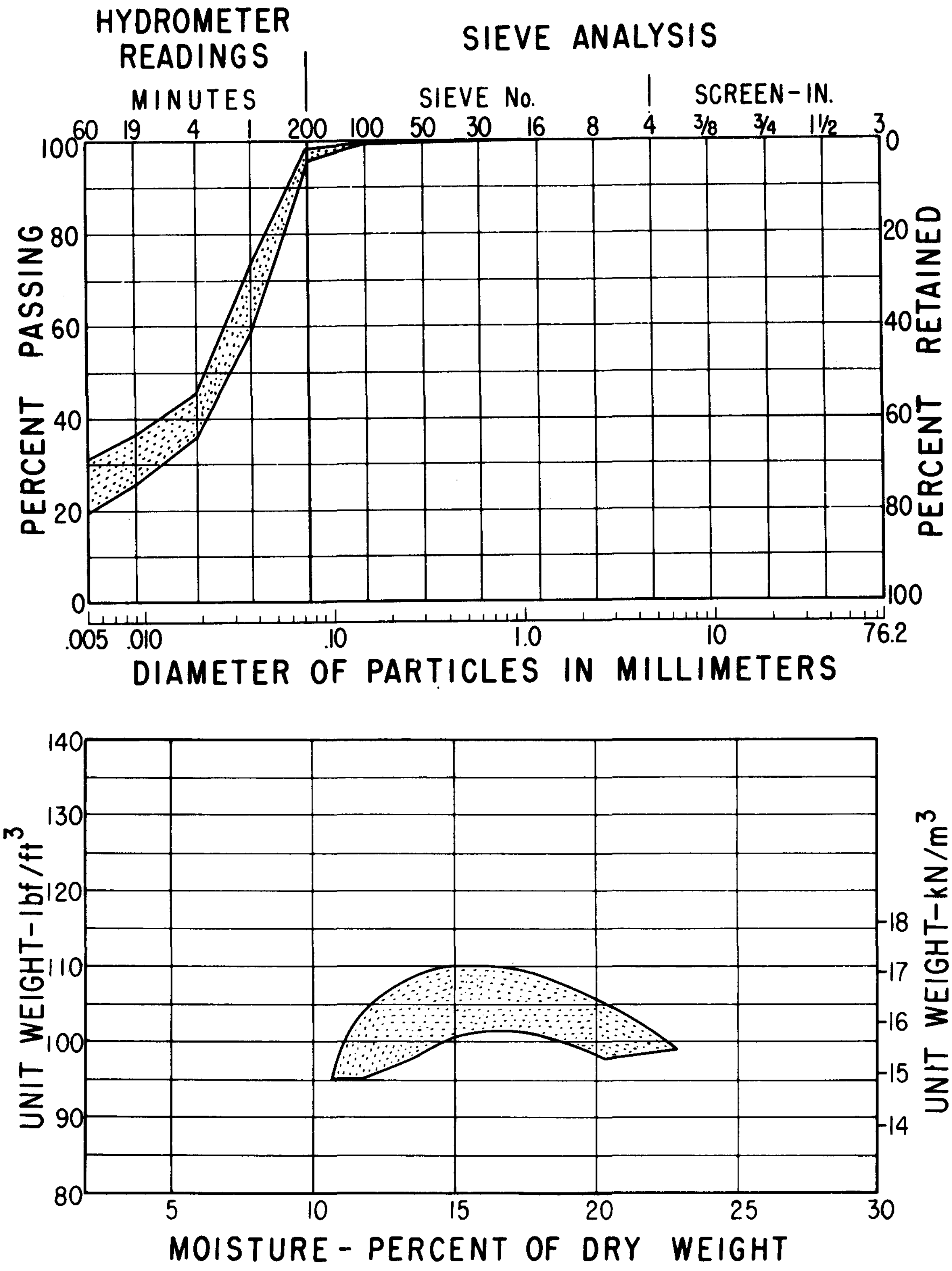
For the unit weight tests near stations 177+00 and 178+00 performed in 1963 and 1981, the percent of maximum laboratory unit weight decreased 4.6 percent.

Table A-1 shows average unit weights for test years on all of the test sites on Culbertson Canal and the percentages of the 1981 maximum unit weights.

For selected soil-lined reaches between stations 41+00 and 386+00 on Culbertson Canal, the lining on the bottom was covered with 1 foot (0.3 m) of uncompacted soil lining material as a protective measure to reduce possible detrimental effects from frost. In 1960, 1962, 1963, and 1981, unit weight tests were performed at about midlevels in the bottom lining that was covered by uncompacted soil and in bottom lining on uncovered reaches between stations 177+68 and 1024+35. Table A-2 shows the average unit weights of the soil lining for test years and percentages of the 1981 maximum laboratory unit weights.

Soil lining tested where there was uncompacted cover was predominantly silt with plasticity indexes ranging from nonplastic to 6, whereas that tested where there was no cover was mostly lean clay with plasticity indexes ranging from 3 to 17 (average 12). The lower unit weight for the clay lining can be at least partially explained by the fact that lean clay normally has a lower maximum unit weight than silt. As shown in table A-2, the percentage of the 1981 maximum laboratory unit weight was about the same for both covered and uncovered lining.

Before enlargement of the desilting basin below the headworks of Culbertson Canal in mid-1960, much canal cleaning was required to remove silt. After the basin was enlarged, less canal cleaning was required. However, there has been some reshaping of the canal section by maintenance personnel, who have redistributed soil eroding from the outside of curves and collecting as sediment on the insides of downstream curves. During 1981 unit weight testing, no survey was made to find elevations of the original lining surface, and it was difficult in some places to determine




Stations 1103 + 30, 1109 + 55 and 1115 + 45

Figure A-25. – Gradation and compaction test results for Cambridge Canal.

Figure A-26. – Sand cone unit weight test at station 383+20 on Culbertson Canal. The cracks in the soil surface are in sediment. October 1981.

whether the unit weight tests were in soil originally compacted or in soil that had been disturbed during canal maintenance. This may have accounted for some of the low values of unit weight—the unit weight test locations were probably not in original compacted lining. However, the test results do show that much of the soil lining remains at a relatively high unit weight.

During the 1981 field tests, the irrigation manager reported that there was no evidence of seepage on land opposite soil-lined reaches on the Culbertson Canal.

**Franklin Canal, Bostwick Division, PSMRBP**

The lining soil on Franklin Canal (figs. A-28 and A-29) is a lean clay with an average plasticity index of 14. Unit weight tests were performed near stations 72+50, 118+00, and 602+80 where the lining, constructed in 1955, was built up to a 1.5-foot (0.5-m) thickness in layers parallel to a 3:1 side slope by equipment moving on the slope longitudinally with the canal. The lining was covered with uncompacted soil from canal excavation to form 1½:1 side slopes. Average results of unit weight tests performed in the lining in 1956, 1957, and 1976, showed decreases in unit weight values of 4.6, 7.1, and 6.1 percent, respectively, based on 1955 tests performed soon after construction. Except for tests in the top half of the bottom lining, the 1976 percentages of maximum laboratory unit weight ranged from 90 to 95 percent (fig. 9).

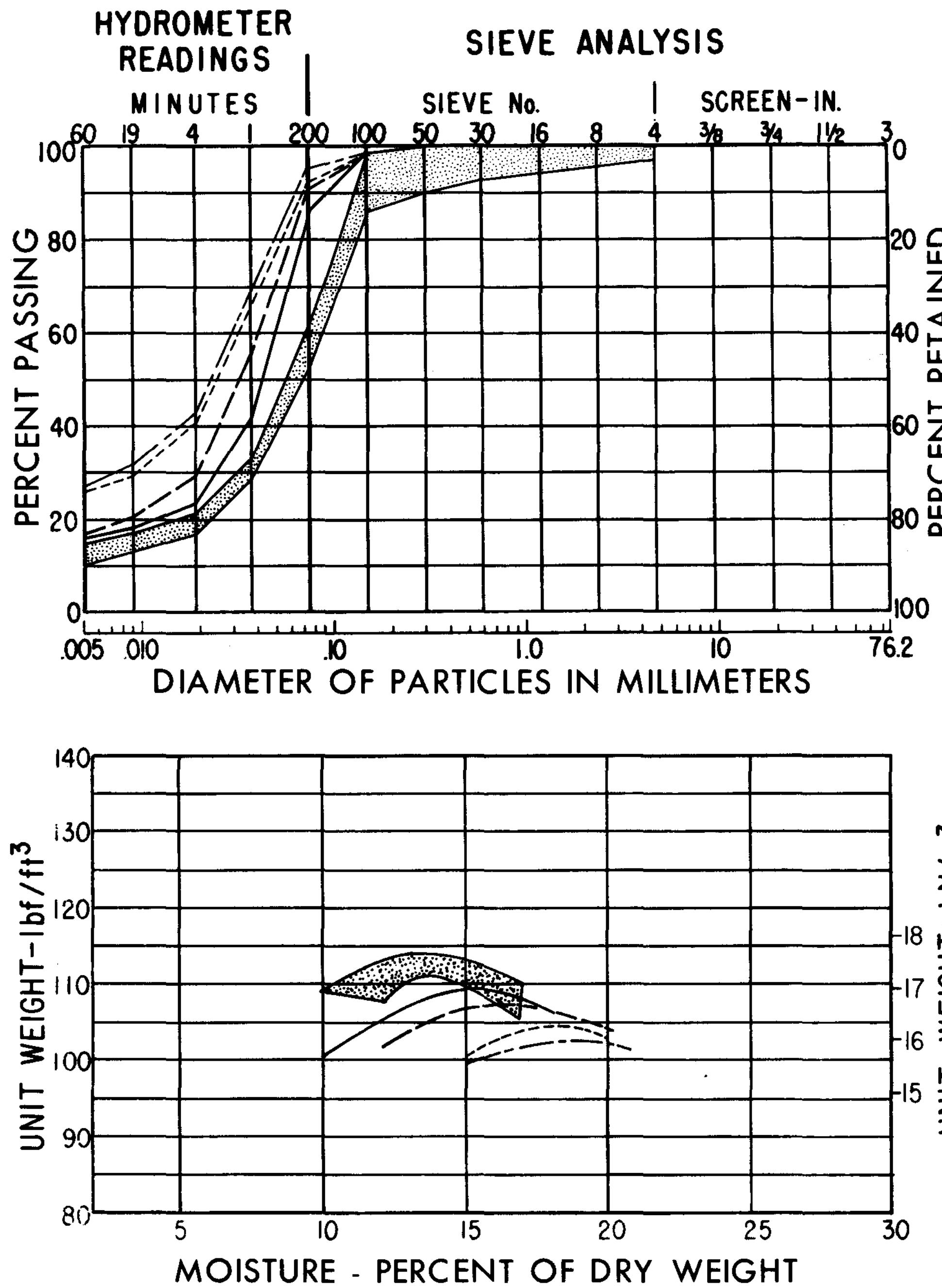
In the late 1950's there was concern about possible deterioration of compacted soil linings, particularly of loessial soils in cold climates, and test data on Franklin and other canals in the Kansas-Nebraska area were published [7]. Up to that time, the soil linings on Franklin Canal had suffered the greatest loss in unit weight, and in the fall of 1958, two ponding tests were performed to determine canal seepage.

Seepage pond 1, which extended from station 116+00 to 130+00 in the 3:1 soil-lined reach, had a seepage rate of 0.03 $ft^3/ft^2/d$ (9 $L/m^2/d$). Using specified canal lining dimensions and the depth of water during the ponding test, the calculated coefficient of permeability was 4 ft/yr ($3.9 \times 10^{-6}$ cm/s).

Seepage pond 2 extended from station 548+00 to 562+00. This was in a thick compacted soil-lined reach with side slope lining placed in horizontal layers by the conventional lining method. The seepage rate for pond 2 was 0.09 $ft^3/ft^2/d$ (27 $L/m^2/d$), and the corresponding coefficient of permeability calculated from the seepage rate was 13 ft/yr ($1.3 \times 10^{-5}$ cm/s).

The average unit weight of nine tests performed in the lining of the pond 1 reach after the seepage test was 98.3 $lbf/ft^3$ (15.4 $kN/m^3$), which was 93.4 percent of maximum laboratory unit weight. The average unit weight of 12 tests performed in the lining of pond 2 after the seepage test was 88.9 percent of maximum laboratory unit weight.

Although there was a high loss of unit weight for some of the tests in the top of the lining, there was less variation toward the bottom, and the lining was




**EXPLANATION**

| Stations | | Stations | |
|---|---|---|---|
| 41+00 to 75+20 | (stippled band) | 1014+15 to 1015+15 | ‑‑‑‑ — ‑ |
| 177+68 to 178+68 | ———— | 1022+85 to 1024+35 | - - - - - - - - - |
| 380+00 to 386+00 | — — — — — | | |

Figure A-27. – Gradation and compaction test results for Culbertson Canal.

Table A-1. – Unit weights of lining, by location, in Culbertson Canal.

| Locations | Unit weight, lbf/ft³ (kN/m³) 1960 | 1963 | 1981 | Percent of max. lab. unit wt. in 1981 |
|---|---|---|---|---|
| Bottom | 110 (17.3) | 109 (17.1) | 109 (17.1) | 99 |
| Sides | 106 (16.7) | 110 (17.3) | 99 (15.6) | 89 |
| Bottom and sides | 108 (17.0) | 109 (17.1) | 103 (16.2) | 93 |

Table A-2. – Unit weights of lining, by cover, in Culbertson Canal.

| Cover | Unit weight, lbf/ft³ (kN/m³) 1960 | 1962 | 1963 | 1981 | Percent of max. lab. unit wt in 1981 |
|---|---|---|---|---|---|
| Loose soil cover | 108 (17.0) | 112 (17.6) | 113 (17.8) | 109 (17.1) | 98 |
| No cover | 99 (15.6) | 99 (15.6) | 99 (15.6) | 101 (15.9) | 97 |

considered to be reducing seepage to an acceptable level. As previously mentioned, for design purposes 0.1 ft³/ft²/d (30 L/m²/d) is often used as an allowable upper limit for seepage through different types of canal lining.

## Upper Meeker Canal, Frenchman-Cambridge Division, PSMRBP

At selected unit weight test locations on the Upper Meeker Canal (figs. A-30, A-31, and A-32), which was constructed in 1957, the soil in the lining was silt to lean clay, with a plasticity index of 4.

A comparison of average unit weights for 5 years of tests (fig. 14 and table B-1) shows that unit weight increased to a maximum of 3.6 percent in 1962. Unit weights in the lining in 1976 averaged higher than 95 percent of maximum laboratory unit weight (fig. 10). In addition, the unit weight of the soil in the top half of the lining did not decrease as much as for some of the other linings, and unit weights remained relatively constant with depth.

Shallow-well permeameter tests, (figs. A-31 and table 3) conducted in the lining showed an increase in permeability, particularly between 1958 and 1962. Observations during the 1962 tests showed that at one test site the soil at a depth of about 9 inches (0.2 m) from the lining surface had a laminated appearance, which was attributed to frost during preceding winters.

Sections of Upper Meeker Canal were selected for an investigation of erosion resistance of low plasticity soil linings. During a visit to the canal in 1984, the canal section in straight reaches was relatively stable, and a gravel blanket had been placed on curves to prevent erosion. At that time, the irrigation manager reported that no evidence of seepage adjacent to compacted soil linings had been noticed.

## Soil Reservoir Lining on Mt. Elbert Forebay

Unit weight test data were obtained from the 5-foot (1.5-m) thick compacted soil of Mt. Elbert Forebay (fig. A-33) after frost had penetrated completely through the lining (p. 15 of [6]). The forebay is located near Twin Lakes Dam on the Frying Pan-Arkansas Project in Colorado (freezing index ±2000). The lining, which was a silty to clayey gravel with about 8 to 27 percent gravel and an average plasticity index of 10, was constructed in 1976-77, and "proof-rolled" in 1977-78, with a sheepsfoot roller followed by a 75-ton pneumatic-tire roller. During the winter of 1978-79, periodic measurements of frost penetration in the lining and of snow depths were made at two locations in the lined area. Figure 11 shows the results of these measurements and the results of unit weight tests performed at various depths in the lining. The average value of the unit weight tests was about 100 percent of maximum laboratory unit weight, which is above the 98 percent minimum specified for the lining.

Figure A-28. – Franklin Canal at station 123+50. May 1957. P271–701–3224.

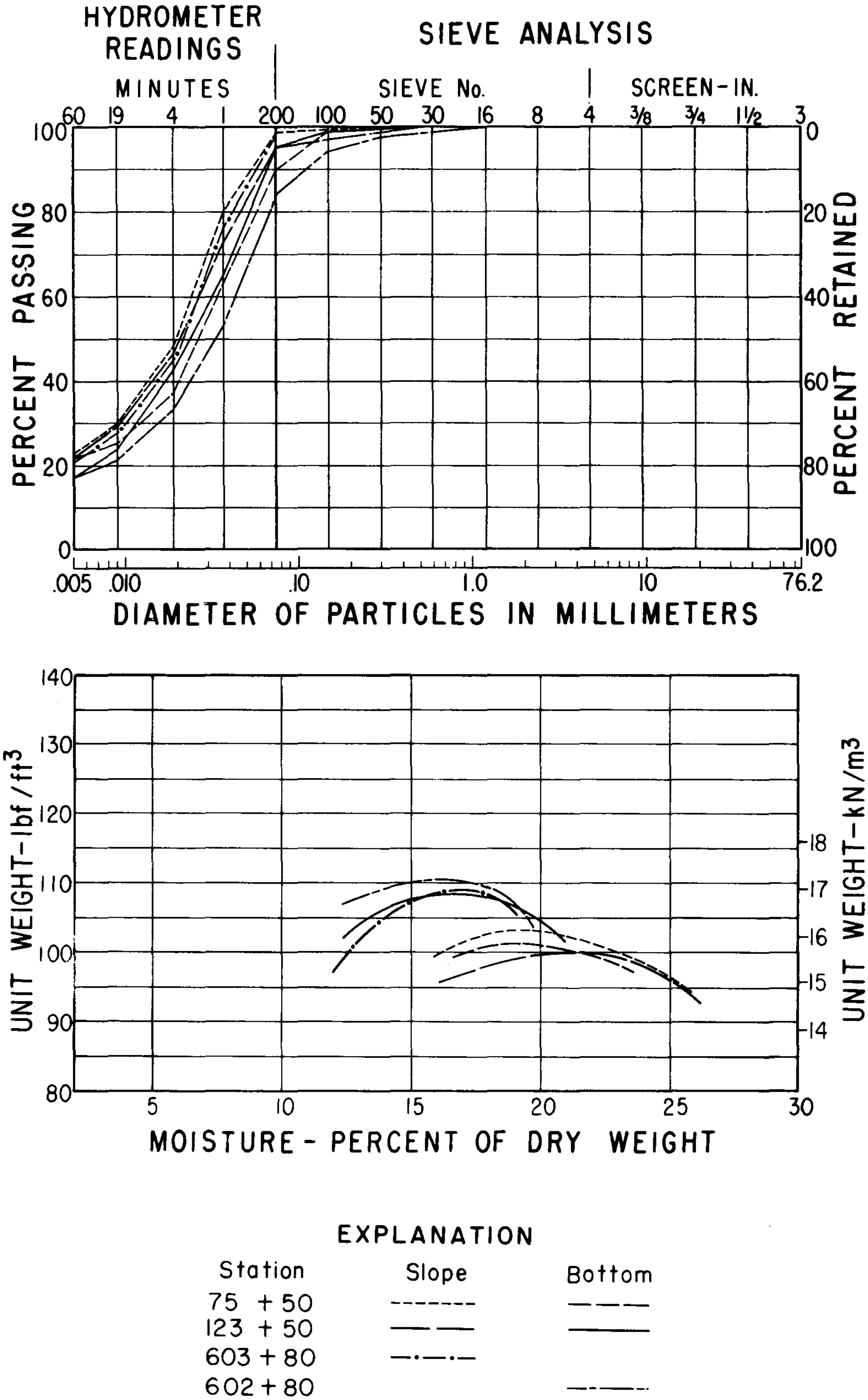
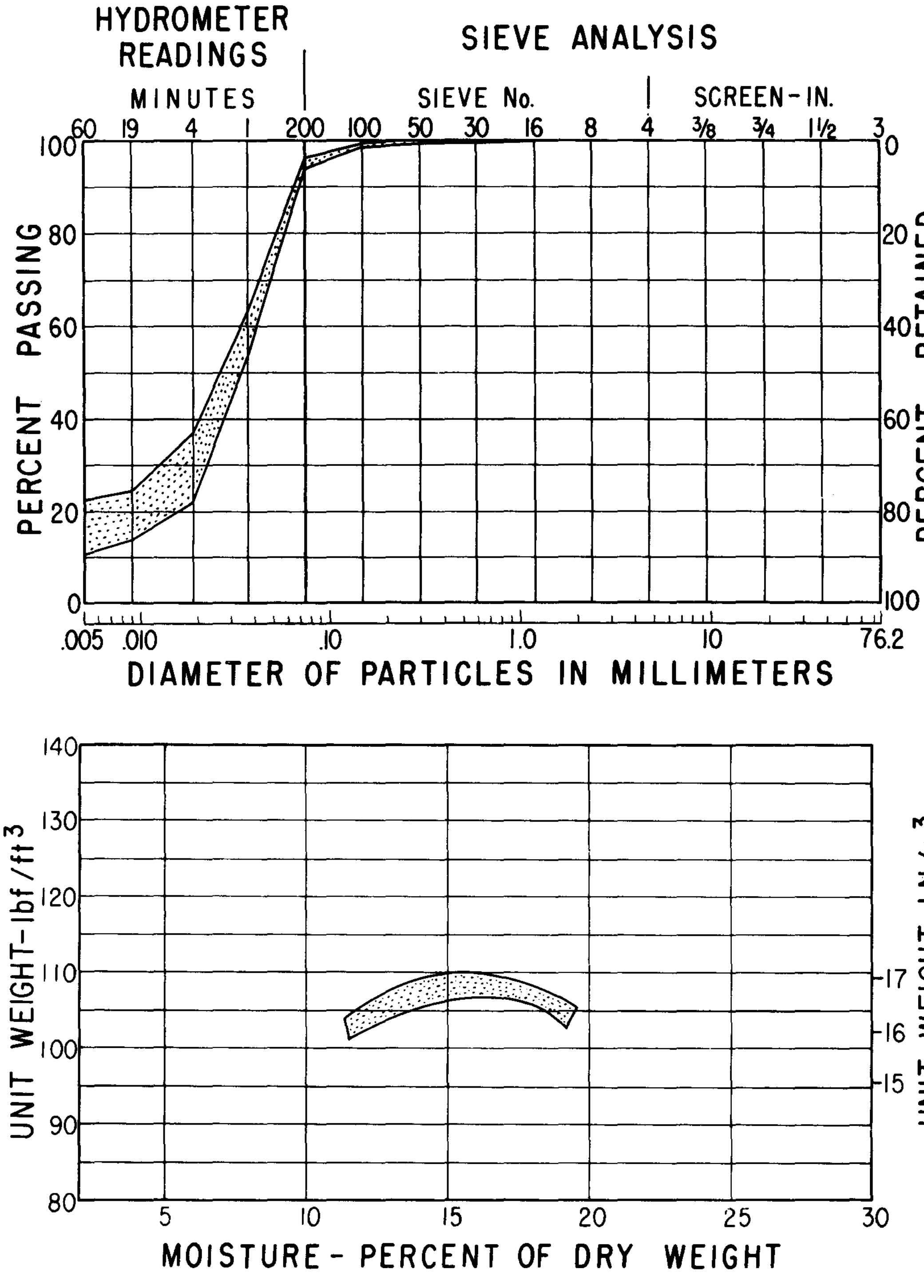



Figure A-29. – Gradation and compaction test results for Franklin Canal.

Figure A-30. – Field permeability test in side slope lining of Upper Meeker Canal at station 723+70. November 1958. P328–701–7491.

Figure A-31. – Closeup of shallow-well test in Upper Meeker Canal. See Figure A-30. November 1958. Technician is measuring water temperature in the well. The barbed wire fence is to prevent possible disturbance of the equipment by cattle. P328–701–7492.




Stations 723 + 65, 727 + 30 and 737 + 80

Figure A-32. – Gradation and compaction test results, Upper Meeker Canal.

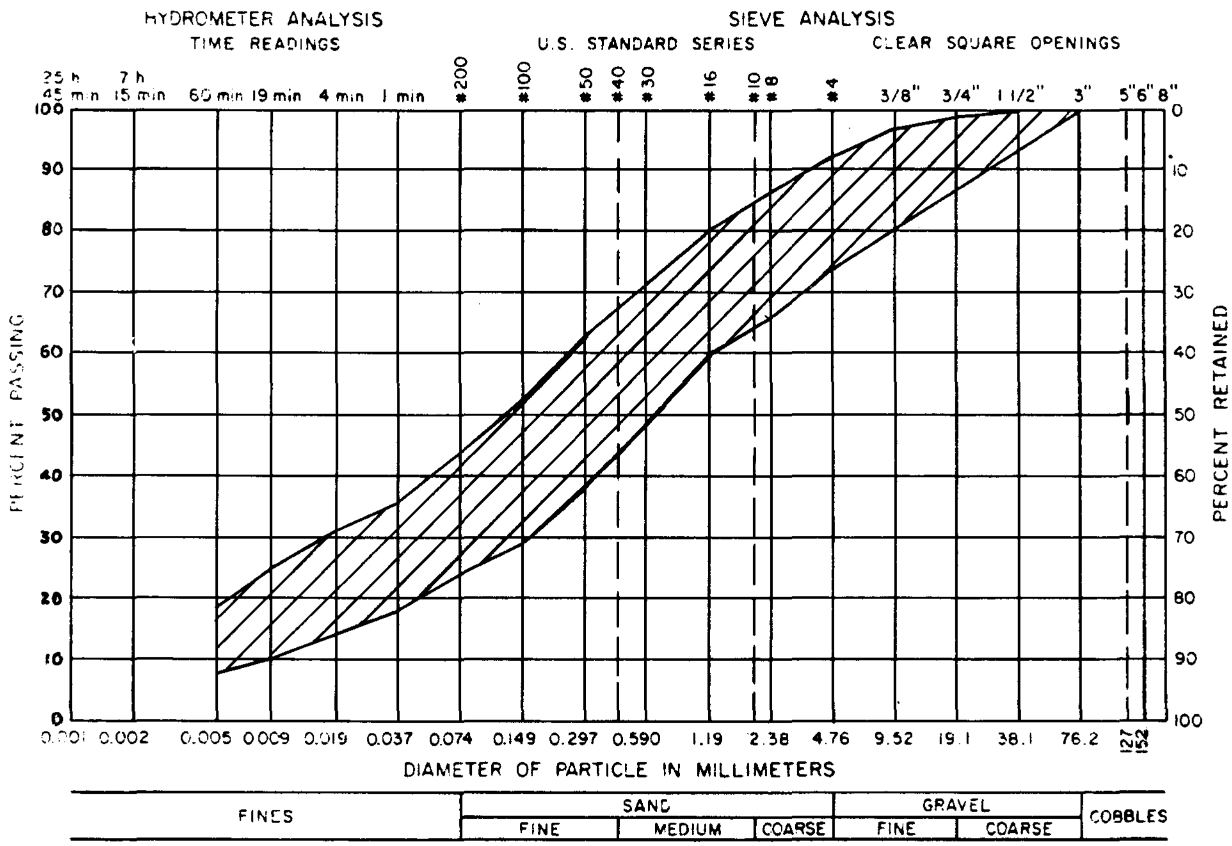



Figure A-33. – Range of soil gradations at frost tube locations in Mt. Elbert Forebay reservoir lining. Figure 16 in [6].

# APPENDIX B
# SOIL TEST DATA

Table B-1. – Field and laboratory soil test data.

| | | | | Field tests | | | | | | Laboratory tests | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Unit weight | | | | | | Compaction | | | | | | |
| | | | | Total material | | Minus No. 4 | | | | Max. unit wt | | | | | | |
| Date of test | No. of tests | % plus No. 4 | $W_c$ | lbf/ft³ | (kN/m³) | lbf/ft³ | (kN/m³) | % of lab. max. | Change, % | lbf/ft³ | (kN/m³) | Opt. $W_c$ | LL | PI | Predominant classification | Stationing at test sites, ft |
| **Lateral EL–68 (1957)[1]** | | | | | | | | | | | | | | | | |
| 11-57 | 9 | 20 | 25.3 | 102.3 | (16.1) | 98.2 | (15.4) | 93.6 | – | 104.9 | (16.5) | 18.6 | 30 | 7 | ML-CL | 182+00, 200+00, 211+00 |
| 3-59 | 15 | – | 23.5 | 101.9 | (16.0) | 94.8 | (15.0) | 90.4 | −3.2 | [2]104.9 | (16.5) | – | – | – | – | 182+05, 200+05, 211+05 |
| 3-60 | 9 | 14 | 25.3 | 104.6 | (16.4) | 102.0 | (16.0) | 97.2 | +3.6 | [2]104.9 | (16.5) | – | – | – | – | 182+15, 200+15, 211+15 |
| 3-77 | 9 | 19 | 25.0 | 103.1 | (16.2) | 98.0 | (15.4) | 95.1 | +1.5 | 103.0 | (16.2) | 20.5 | – | – | – | 182+00, 200+00, 211+00 |
| Average | 11 | 18 | 24.8 | 103.0 | (16.2) | 98.3 | (15.5) | 94.1 | +0.6 | 104.0 | (16.4) | 19.6 | – | – | | |
| **Potholes East Canal (1953)** | | | | | | | | | | | | | | | | |
| 3-55 | 15 | 10 | 29.9 | 95.5 | (15.0) | 91.1 | (14.3) | 90.6 | – | 100.6 | (15.8) | 21.9 | 33 | 10 | CL-ML | 881+00, 1033+84, 1119+65 |
| 3-55 | 5 | 9 | 29.4 | 92.6 | (14.5) | 90.6 | (14.2) | 88.3 | – | 102.6 | (16.1) | 21.1 | 37 | 13 | CL-ML | 1119+65 |
| 3-59 | 3 | 10 | 30.6 | 94.8 | (14.9) | 90.9 | (14.3) | 88.6 | +0.3 | [2]102.6 | (16.1) | – | – | – | – | 1119+75 |
| Average | 8 | 10 | 30.0 | 94.3 | (14.8) | 91.0 | (14.3) | 89.2 | +0.3 | 101.6 | (16.0) | 21.5 | 35 | 12 | | |
| **West Canal (1954)** | | | | | | | | | | | | | | | | |
| 3-55 | 18 | 35 | 15.5 | 119.7 | (18.8) | 104.3 | (16.4) | 90.0 | – | 115.9 | (18.2) | 14.5 | 31 | NP-15 | SM-GM | 2173+00, 2245+00, 2318+00, 2336+00 |
| 3-59 | 9 | – | 17.9 | 119.8 | (18.8) | 99.6 | (15.6) | 85.9 | −4.1 | [2]115.9 | (18.2) | – | – | – | – | 2173+10, 2245+10, 2318+10, 2336+10 |
| Average | 14 | – | 16.7 | 119.8 | (18.8) | 102.0 | (16.0) | 88.0 | – | – | – | – | – | – | | |
| **Main Canal (1946)** | | | | | | | | | | | | | | | | |
| 5-54 | 15 | 9 | 17.9 | 106.8 | (16.8) | – | – | – | – | 112.7 | (17.7) | 14.7 | 29 | 8 | SC | – |
| 12-63 | 11 | 29 | 17.4 | 103.4 | (16.2) | – | – | – | −3.2 | 115.0 | (18.1) | 13.8 | – | – | | – |
| Average | 13 | 19 | 17.7 | 105.1 | (16.5) | – | – | – | – | 114.0 | (17.9) | 14.3 | – | – | | |
| **Delta Mendota Canal (1952)** | | | | | | | | | | | | | | | | |
| 1952 | 12 | – | 24.7 | – | – | 93.9 | (14.8) | 96.7 | – | 97.1 | (15.3) | 23.9 | – | – | – | Construction control tests, Miles 107.8 to 115.9 |
| 1965 | 12 | – | 32.4 | – | – | 87.9 | (13.8) | 90.5 | −6.2 | [2]97.1 | (15.3) | – | 64 | 40 | CH | Miles 107.8 to 115.9 |
| 1-66 | 15 | – | 32.2 | – | – | 92.2 | (14.5) | 93.1 | – | 99.0 | (15.6) | 23.5 | – | – | – | Miles 98.7 to 102.7 |
| Average | 13 | – | 30.0 | – | – | 91.3 | (14.4) | 93.4 | −6.2 | 98.1 | (15.5) | 23.7 | – | – | | |
| **Wellton-Mohawk Canal (1950)** | | | | | | | | | | | | | | | | |
| 6-50 | 4 | 55 | 11.5 | – | – | 107.2 | (16.8) | 88.3 | – | 121.4 | (19.1) | 11.9 | – | – | GC | Construction control tests, |
| 6-57 | 9 | 59 | [3]7.1 | 127.1 | (20.0) | 101.7 | (16.0) | 83.8 | −4.5 | [2]121.4 | (19.1) | – | – | – | GC | Average of 1957 tests |
| 6-50 | 1 | 58 | 9.1 | – | – | 103.0 | (16.2) | 85.5 | – | 120.5 | (18.9) | 12.0 | – | – | – | 33+00 |
| 6-57 | 3 | 61 | 6.5 | 129.0 | (20.3) | 101.5 | (15.9) | 84.2 | −1.3 | [2]120.5 | (18.9) | – | – | – | – | 33+00 |
| 6-50 | 2 | 54 | 12.0 | – | – | 103.4 | (16.2) | 85.2 | – | [2]121.4 | (19.1) | 11.8 | – | – | – | 182+00 |
| 6-57 | 3 | 59 | 8.0 | 125.8 | (19.8) | 99.4 | (15.6) | 81.9 | −3.3 | [2]121.4 | (19.1) | – | – | – | – | 180+00 |
| 6-50 | 1 | 51 | 13.0 | – | – | 119.0 | (18.7) | 97.2 | – | 122.4 | (19.2) | 12.1 | – | – | – | 286+50 |
| 6-57 | 3 | 59 | 6.8 | 126.4 | (19.9) | 104.2 | (16.4) | 85.1 | −12.1 | [2]122.4 | (19.2) | – | – | – | – | 286+50 |
| Average | 3.3 | 58 | 9.3 | 127.1 | (20.0) | 104.9 | (16.5) | 86.4 | −5.3 | 121.4 | (19.1) | 12.0 | – | – | | |

Table B-1. – Field and laboratory soil test data. – Continued

| Date of test | No. of tests | % plus No. 4 | $W_c$ | Field tests: Unit weight: Total material lbf/ft³ | Total material (kN/m³) | Minus No. 4 lbf/ft³ | Minus No. 4 (kN/m³) | % of lab. max. | Change, % | Laboratory tests: Compaction: Max. unit wt. lbf/ft³ | Max. unit wt. (kN/m³) | Opt. $W_c$ | LL | PI | Predominant classification | Stationing at test sites, ft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Southside Canal (1959) | | | | | | | | |
| 11-59 | 15 | 6 | 16.9 | – | – | 111.5 | (17.5) | 102.2 | – | 109.1 | (17.1) | 16.6 | 34 | 17 | CL | 632+30, 634+00, 635+35 |
| 10-60 | 15 | 6 | 18.0 | – | – | 108.0 | (17.0) | 99.0 | –3.2 | [2]109.1 | (17.1) | – | 36 | 16 | – | 632+40, 634+10, 635+45 |
| 5-62 | 15 | – | 18.8 | – | – | 108.6 | (17.1) | 99.5 | –2.7 | [2]109.1 | (17.1) | – | 36 | 16 | – | 632+50, 634+20, 635+55 |
| 10-64 | 15 | – | 20.3 | – | – | 107.0 | (16.8) | 98.1 | –4.1 | [2]109.1 | (17.1) | – | – | – | – | 632+60, 634+30, 635+65 |
| 11-76 | 15 | – | 17.9 | – | – | 100.2 | (15.7) | 91.8 | –10.4 | [2]109.1 | (17.1) | – | – | – | – | 635+75, 634+40, 632+70 |
| Average | 15 | 6 | 18.4 | – | – | 107.1 | (16.8) | 98.1 | –5.1 | 109.1 | (17.1) | – | 35 | 16 | – | |
| | | | | | | | | Eden Canal (1955) | | | | | | | | |
| 10-60 | 4 | 0 | 13.0 | – | – | 111.4 | (17.5) | 106.1 | – | 105.0 | (16.5) | 17.5 | 34 | 14 | SC | 681+00 |
| | | | | | | | | Farson Lateral (1958) | | | | | | | | |
| 10-60 | 4 | 2 | 8.8 | – | – | 107.2 | (16.4) | 93.4 | – | 114.8 | (18.0) | 14.0 | 30 | 9 | SC | 137+50 |
| | | | | | | | | Means Canal (1952) | | | | | | | | |
| 10-60 | 5 | 0.2 | 16.8 | – | – | 105.0 | (16.5) | 100.7 | – | 104.3 | (16.4) | 18.7 | 42 | 22 | CL | 137+50 |
| | | | | | | | | Hudson Canal (1954) | | | | | | | | |
| 2-54 | 6 | – | 11.9 | – | – | 117.2 | (18.4) | 98.2 | – | 119.4 | (18.8) | 12.6 | – | – | CL-SC | Construction control tests |
| 12-63 | 9 | – | 11.8 | – | – | 120.1 | (18.9) | 100.1 | +1.9 | 119.5 | (18.8) | 12.4 | 24 | 13 | – | 472+92, 476+02, 483+00 476+00 |
| | | | | | | | | Sunshine Reservoir Supply Canal (1940) | | | | | | | | |
| 1952 | 8 | 12 | 17.9 | – | – | 103.2 | (16.2) | 94.4 | – | 109.3 | (17.2) | 17.3 | 31 | 14 | CL | – |
| | | | | | | | | Angostura Canal (1953) | | | | | | | | |
| 11-54 | 12 | 3 | 10.4 | 104.7 | (16.4) | 103.8 | (16.3) | [4]92.9 | – | 112.7 | (17.7) | 15.3 | 33 | 18 | SC-CL | 1294+05, 1318+88, 1334+91 |
| 12-58 | 12 | 3 | 16.2 | 114.7 | (18.0) | – | – | 101.8 | +8.9 | [2]112.7 | (17.7) | – | – | – | – | 1294+15, 1318+98, 1335+01 |
| 5-59 | 12 | 3 | 15.7 | 112.8 | (17.7) | – | – | 100.1 | +7.2 | [2]112.7 | (17.7) | – | – | – | – | 1294+25, 1319+08, 1335+11 |
| 3-61 | 12 | – | 14.1 | 114.2 | (17.9) | – | – | 101.3 | +8.4 | [2]112.7 | (17.7) | – | – | – | – | 1294+35, 1319+18, 1335+30 |
| 10-64 | 19 | – | – | 107.8 | (16.9) | – | – | 99.4 | +6.5 | 108.4 | (17.0) | – | – | – | – | 1292+84 to 1335+40 |
| 11-54 | 7 | 4 | 7.9 | 113.3 | (17.8) | 110.0 | (17.3) | 97.4 | – | 116.3 | (18.3) | 13.4 | 28 | 14 | SC–CL | 1294+05, 1318+88 |
| 12-58 | 8 | 4 | 14.3 | 119.3 | (18.7) | – | – | 102.6 | +5.2 | [2]116.3 | (18.3) | – | – | – | – | 1294+15, 1318+98 |
| 5-59 | 8 | 4 | 13.3 | 118.0 | (18.5) | – | – | 101.5 | +4.1 | [2]116.3 | (18.3) | – | – | – | – | 1294+25, 1319+08 |
| 3-61 | 8 | – | 13.5 | 117.9 | (18.5) | – | – | 101.3 | +3.9 | [2]116.3 | (18.3) | – | – | – | – | 1294+35, 1319+18 |
| 10-64 | 8 | – | – | 109.3 | (17.2) | – | – | 94.0 | –3.4 | [2]116.3 | (18.3) | – | – | – | – | 1294+45, 1319+28 |
| 11-54 | 4 | 1 | 14.8 | 98.8 | (15.5) | 98.5 | (15.5) | 93.6 | – | 105.5 | (16.6) | 19.0 | 43 | 26 | CL | 1334+91 |
| 12-58 | 4 | 2 | 20.0 | 105.5 | (16.6) | – | – | 100.0 | +6.4 | [2]105.5 | (16.6) | – | – | – | – | 1335+01 |
| 5-59 | 4 | 1 | 20.5 | 102.4 | (16.1) | – | – | 97.1 | +3.5 | [2]105.5 | (16.6) | – | – | – | – | 1335+11 |
| 3-61 | 4 | – | 15.3 | 106.8 | (16.8) | – | – | 101.2 | +7.6 | [2]105.5 | (16.6) | – | – | – | – | 1335+30 |
| 10-64 | 6 | – | – | 109.2 | (17.2) | – | – | 103.5 | +9.9 | [2]105.5 | (16.6) | – | – | – | – | 1335+40 |
| Average | 8 | 3 | 14.7 | 110.3 | (17.3) | 104.1 | (16.4) | 99.2 | +5.7 | 110.7 | (17.4) | 15.9 | 35 | 19 | | |

Table B-1. – Field and laboratory soil test data. – Continued

| Date of test | No. of tests | % plus No. 4 | $W_c$ | Field tests: Unit weight: Total material lbf/ft³ | Total material (kN/m³) | Minus No. 4 lbf/ft³ | Minus No. 4 (kN/m³) | % of lab. max. | Change, % | Laboratory tests: Compaction: Max. unit wt. lbf/ft³ | Max. unit wt. (kN/m³) | Opt. $W_c$ | LL | PI | Predominant classification | Stationing at test sites, ft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Canal B (1957) | | | | | | | | |
| 10-57 | 5 | 2 | 25.8 | – | – | 82.5 | (13.0) | 79.0 | – | 104.4 | (16.4) | 18.4 | 42 | 24 | CL | 75+50, 236+00, 245+00 |
| 5-58 | 5 | – | 23.4 | – | – | 86.3 | (13.6) | 82.7 | +3.7 | [2]104.4 | (16.4) | – | – | – | – | 75+55, 236+05, 245+05 |
| Average | 5 | – | 24.6 | – | – | 84.4 | (13.3) | 80.9 | – | – | – | – | – | – | | |
| | | | | | | | | Helena Valley Canal (1958) | | | | | | | | |
| 10-58 | 15 | 26 | 12.6 | – | – | 112.0 | (17.6) | 100.0 | – | 111.6 | (17.5) | 14.5 | 38 | 17 | SC | 740+00, 923+00, 1507+00 |
| 11-64 | 14 | 25 | 16.1 | 118.1 | (18.6) | 108.3 | (17.0) | 91.9 | –8.1 | 117.9 | (18.5) | 13.8 | – | – | – | 740+15, 923+10, 1507+00 |
| 11-76 | 15 | 25 | 16.3 | 113.6 | (17.8) | 103.8 | (16.3) | 87.3 | –12.7 | 118.9 | (18.7) | 13.0 | 28 | 10 | – | 740+20, 923+20, 1507+10 |
| 10-58 | 5 | 23 | 13.5 | – | – | 109.1 | (17.1) | 95.5 | – | [2]114.2 | (17.9) | – | – | – | – | 1195+00 |
| 4-60 | 5 | 25 | 18.2 | – | – | 109.5 | (12.2) | 95.9 | +0.4 | [2]114.2 | (17.9) | – | – | – | – | 1195+20 |
| 12-62 | 5 | – | – | – | – | 107.9 | (17.0) | 94.5 | –1.0 | [2]114.2 | (17.9) | – | – | – | – | 1195+00 |
| 11-64 | 5 | 22 | 20.4 | 112.0 | (17.6) | 102.7 | (16.1) | 89.9 | –5.6 | 114.2 | (17.9) | 15.4 | – | – | – | 1195+10 |
| Average | 9 | 24 | 16.2 | 114.6 | (18.0) | 107.6 | (16.2) | 93.6 | –5.4 | 115.7 | (18.2) | 14.2 | 33 | 14 | | |
| | | | | | | | | Lateral D (1958) | | | | | | | | |
| 4-58 | 3 | 7 | 15.4 | 110.8 | (17.4) | 104.4 | (16.4) | 94.6 | – | 110.4 | (17.3) | 16.3 | 29 | 11 | – | 1+90, 9+00 |
| 10-65 | 2 | 0 | 26.2 | – | – | 94.7 | (14.9) | 88.7 | – | 106.8 | (16.8) | 17.8 | – | – | – | 88+90 |
| 10-65 | 2 | 33 | 12.2 | 126.6 | (19.9) | 117.8 | (18.5) | 91.6 | – | 128.6 | (20.2) | 11.0 | – | – | – | 96+25 |
| 10-65 | 2 | 6 | 14.9 | 108.3 | (17.0) | 106.3 | (16.7) | 89.5 | – | 118.8 | (18.7) | 14.3 | – | – | – | 102+00 |
| Average | 2 | 15 | 17.2 | 115.2 | (18.1) | 105.8 | (16.6) | 91.1 | – | 116.2 | (18.3) | 14.9 | – | – | | |
| | | | | | | | | Boulder Creek Supply Canal (1954) | | | | | | | | |
| 11-54 | 12 | – | 15.1 | 105.4 | (16.6) | 101.0 | (15.9) | 89.7 | – | 112.6 | (17.7) | 16.4 | 36 | 21 | CL | 57+30, 164+00, 246+25 |
| 3-55 | 10 | 11 | 15.9 | 107.6 | (16.9) | 103.8 | (16.3) | 93.5 | +3.8 | 111.0 | (17.4) | 18.0 | 33 | 13 | CL,SC | 57+75, 164+21, 246+08 |
| 11-55 | 8 | – | 16.1 | 105.7 | (16.6) | 102.0 | (16.0) | 91.9 | +2.2 | [2]111.0 | (17.4) | – | – | – | – | 57+34, 164+04, 246+29 |
| 11-57 | 7 | 16 | 17.1 | 108.0 | (17.0) | 102.5 | (16.1) | 92.3 | +2.6 | [2]111.0 | (17.4) | – | – | – | – | 58+00, 163+99, 246+35 |
| 1961 | 12 | – | 18.6 | – | – | 107.3 | (16.9) | 96.6 | +6.9 | 111.1 | – | 16.2 | 33 | 12 | CL | 57+70, 59+80, 164+30, 246+45 |
| Average | 10 | 14 | 16.6 | 106.7 | (16.8) | 103.3 | (16.2) | 92.8 | +3.9 | 111.6 | (17.6) | 16.9 | 34 | 15 | | |
| | | | | | | | | Cambridge Canal (1954) | | | | | | | | |
| 4-54 | 13 | – | 17.2 | – | – | 105.8 | (16.6) | 101.6 | – | 104.1 | – | 18.4 | – | – | – | Construction control tests, |
| 3-55 | 15 | – | 20.1 | – | – | 103.9 | (16.3) | 100.5 | –1.1 | 103.4 | – | 19.1 | 35 | 18 | CL | 1103+25, 1109+50, 1115+40 |
| 3-57 | 15 | – | 21.7 | – | – | 97.6 | (15.3) | 91.6 | –10.0 | 106.6 | – | 17.4 | 35 | 19 | CL | 1103+30, 1109+55, 1115+45 |
| 4-58 | 15 | – | 22.0 | – | – | 100.8 | (15.8) | 96.8 | –4.8 | [2]104.1 | – | – | – | – | – | 1103+35, 1109+60, 1115+50 |
| 4-60 | 15 | – | 21.7 | – | – | 100.7 | (15.8) | 96.7 | –4.9 | [2]104.1 | – | – | – | – | – | 1103+43, 1109+78, 1115+55 |
| 4-62 | 15 | – | 21.0 | – | – | 101.8 | (16.0) | 97.8 | –3.8 | [2]104.1 | – | – | – | – | – | 1103+48, 1109+70, 1115+60 |
| 3-76 | 15 | – | 17.7 | – | – | 102.6 | (16.1) | 98.6 | –3.0 | [2]104.1 | – | – | – | – | – | 1103+50, 1109+50, 1115+35 |
| Average | 15 | 0 | 20.7 | – | – | 101.2 | (15.9) | 96.5 | –4.6 | 104.7 | – | 18.3 | 35 | 19 | | |

Table B-1. – Field and laboratory soil test data. – Continued

| Date of test | No. of tests | % plus No. 4 | $W_c$ | Field tests – Unit weight – Total material lbf/ft³ | Total material (kN/m³) | Minus No. 4 lbf/ft³ | Minus No. 4 (kN/m³) | % of lab. max. | Change, % | Laboratory tests – Compaction – Max. unit wt. lbf/ft³ | Max. unit wt. (kN/m³) | Opt. $W_c$ | LL | PI | Predominant classification | Stationing at test sites, ft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Culbertson Canal (1959) | | | | | | | |
| 5-60 | 10 | – | 15.7 | – | – | 107.8 | (16.9) | 96.4 | – | 111.8 | (17.6) | 13.5 | 22 | 0.3 | ML | 44+48, 75+20 |
| 3-63 | 10 | – | 14.7 | – | – | 113.4 | (17.8) | 101.6 | +5.2 | 111.6 | (17.5) | – | – | – | – | 44+38, 75+15 |
| 10-81 | 8 | – | 14.8 | – | – | 107.0 | (16.8) | 95.8 | –0.6 | [2]111.7 | (17.5) | – | – | – | – | 44+58, 75+05 |
| 3-63 | 10 | – | 18.5 | – | – | 104.8 | (16.5) | 96.3 | – | 108.8 | (17.1) | – | 25 | 3 | ML | 176+95, 177+85 |
| 10-81 | 8 | – | 17.4 | – | – | 99.8 | (15.7) | 91.7 | –4.6 | [2]108.8 | (17.1) | – | – | – | – | 177+05, 177+95 |
| Average | 9.2 | – | 16.2 | – | – | 106.6 | (16.7) | 96.4 | – | 110.7 | (17.4) | – | 23 | 2 | | |
| | | | | | | | | | Franklin Canal (1955) | | | | | | | |
| 5-55 | 15 | – | 18.4 | – | – | 102.4 | (16.1) | 97.4 | – | 105.1 | (16.5) | – | – | – | CL | 72+50, 122+00, 603+89 |
| 6-56 | 15 | – | 21.4 | – | – | 97.5 | (15.3) | 92.8 | –4.6 | [2]105.1 | (16.5) | – | – | – | – | 72+50, 122+00, 603+89 |
| 5-57 | 15 | – | 22.7 | – | – | 94.9 | (14.9) | 90.3 | –7.1 | 105.1 | (16.5) | 18.6 | 33 | 14 | – | 72+60, 123+50, 602+80, 603+80 |
| 10-76 | 15 | – | 21.7 | – | – | 96.0 | (15.1) | 91.3 | –6.1 | [2]105.1 | (16.5) | – | – | – | – | 72+60, 121+90, 603+99 |
| Average | 15 | 0 | 21.1 | – | – | 97.7 | (15.4) | 93.0 | –5.9 | – | – | – | – | – | | |
| | | | | | | | | | South Platte Supply Canal (1956) | | | | | | | |
| 11-56 | 6 | – | 13.8 | – | – | 118.8 | (18.7) | 96.3 | – | 123.4 | (19.4) | 11.2 | 22 | 5 | SC-SM | 1474+93.3 to 1477+63 |
| 11-57 | 6 | – | 12.8 | – | – | 119.8 | (18.8) | 97.1 | +0.8 | [2]123.4 | (19.4) | – | – | – | – | 1474+93.3 to 1477+63 |
| 11-59 | 6 | – | 12.7 | – | – | 120.7 | (19.0) | 97.8 | +1.5 | [2]123.4 | (19.4) | – | – | – | – | 1474+93.3 to 1477+63 |
| 11-62 | 5 | – | 12.3 | – | – | 123.6 | (19.4) | 100.2 | +3.9 | [2]123.4 | (19.4) | – | – | – | – | 1474+93.3 to 1477+63 |
| 11-76 | 6 | – | 12.5 | – | – | 121.5 | (19.1) | 98.5 | +2.2 | [2]123.4 | (19.4) | – | – | – | – | 1474+93.3 to 1477+63 |
| Average | 6 | – | 12.8 | – | – | 120.9 | (19.0) | 98.0 | +2.1 | – | – | – | – | – | | |
| | | | | | | | | | Upper Meeker Canal (1957) | | | | | | | |
| 9-57 | 15 | – | 15.5 | – | – | 104.0 | (16.3) | 95.9 | – | 108.5 | (17.0) | 16.5 | 25 | 3 | ML | 723+65, 727+30, 737+80 |
| 4-58 | 15 | – | 18.2 | – | – | 105.4 | (16.6) | 98.3 | +2.4 | 107.2 | (16.8) | 15.2 | – | – | – | 723+70, 727+35, 737+85 |
| 10-58 | 15 | – | 18.8 | – | – | 103.8 | (16.3) | 96.2 | +0.3 | [2]107.9 | (17.0) | – | 26 | 4 | ML | 723+75, 727+40, 737+90 |
| 4-62 | 15 | – | 17.1 | – | – | 107.4 | (16.9) | 99.5 | +3.6 | [2]107.9 | (17.0) | – | – | – | – | 723+85, 727+50, 738+00 |
| 3-76 | 15 | – | 16.6 | – | – | 106.5 | (16.7) | 98.7 | +2.8 | [2]107.9 | (17.0) | – | – | – | – | 723+55, 727+20, 738+60 |
| Average | – | – | 17.2 | – | – | 105.2 | (16.6) | 97.2 | +2.3 | 107.9 | (16.9) | 15.9 | 26 | 4 | | |

[1] Year of construction.
[2] Values used for calculating the percentage of the minus No. 4 unit weight for the particular year of calculation in the absence of compaction data for that year.
[3] The moisutre content for the 6-57 tests on Wellton-Mohawk was based on the minus 3-inch soil fraction.
[4] Percentage based on the unit weight of total material and the laboratory maximum on the minus No. 4 fraction, applies to all of Angostura unit weight tests.



GPO 853-862

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