WINNIPEG WATERMAIN BACKFILL STUDIES

A Thesis

Presented to

the Faculty of Graduate Studies and Research

University of Manitoba

In Partial Fulfillment

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Master of Science in Civil Engineering

By

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ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Associate Professor A. Baracos for his guidance and criticisms during the investigation and the writing of this thesis.

The author also feels deeply indebted to members of the Division of Building Research, National Research Council, Ottawa, Canada, for the guidance and financial assistance so unselfishly provided; and to the Winnipeg Waterworks Department for their cooperation in providing information and assistance in the field investigations.

ABSTRACT OF THESIS

WINNIPEG WATERMAIN BACKFILL STUDIES

Previous studies have indicated that movements of watermains in the Winnipeg area are of sufficient magnitude to cause flexural failures in corrosion weakened watermains. It was suspected that the type of backfill material, state of density of the backfill, and techniques of backfilling and compacting had an appreciable effect on the resulting movements.

A field investigation was conducted to study backfill material, obtain quantitative densities in backfill and for comparison, in adjacent undisturbed soils; effects of various methods of compaction were also studied. Results indicated that densities produced were highest when the backfill was compacted by mechanical apparatus then decreased as compacted by the hand tamper and water jetting, loosely placed backfill compacted at surface by moving tractor, and by hand tamping, respectively. Trial compaction by the Barco Rammer compactor resulted in densities higher than those produced by any other method of compaction and higher than densities in undisturbed soils.

It was concluded that to backfill and compact in the ideal manner required a very strict moisture content and compaction control, the cost of which would be prohibitive. However, suggestions were made for improvements in the manner

of backfilling and compacting which it is believed would effectively lower the number of flexural breaks in watermains and reduce maintenance costs.

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INTRODUCTION

An earlier investigation conducted jointly by the Division of Building Research, National Research Council, Ottawa, the Department of Civil Engineering, University of Manitoba and the Winnipeg Waterworks Department, in 1955 and 1956 established that vertical ground movements due to soil moisture variations in the Greater Winnipeg area were of sufficient magnitude to cause flexural breaks in corrosion weakened cast iron watermains.[1] It was also suspected that the pipe movements were aggravated by the variation and lack of adequate compaction of the backfill. The decision was therefore made to investigate the effects of past and current watermain backfill and backfilling techniques. As part of this program, an investigation of soil densities in backfill material and in adjacent undisturbed soils was undertaken to determine whether backfill was being placed in a more or less dense condition than the adjacent undisturbed soil.

Two locations were selected. The first location was on Manitoba Avenue where the City of Winnipeg had experimented with various backfill materials using several methods of compaction. However, no evaluation of the densities obtained had been made and it was considered desirable to do so at this time.

In the fall of 1954 a new watermain had been laid along Manitoba Avenue with particular attention given to backfilling over house service pipes. The backfill over the watermain had been loosely placed by a front-end loader tractor. Close inspection of the backfill procedure had been maintained by a senior member of the Winnipeg Waterworks Department. Notes were taken of the type and thickness of each layer of backfill material, type and amount of compactive effort, amount of water jetting if used and length of time required for each backfilling operation. In addition to the compaction the backfill material received in 1954, it had since consolidated.

For comparison purposes it was considered desirable to obtain quantitative density measurements at the second location on Cordova Street where a watermain had been laid in 1951 with backfill being placed loosely by a front-end loader tractor. These two locations offered an opportunity to assess the effective-ness of compaction where different backfilling techniques had been employed.

PRELIMINARY CONSIDERATIONS

Three extremely important reasons necessitate proper backfilling of pipe trenches. They are:[2]

a) to support and protect the pipe

b) to provide a good foundation for any overlying roadways

c) to provide support for adjoining structures

Generally it has been found that backfilling methods to date do not sufficiently satisfy any of the aforementioned reasons. Considering the location of watermains in Winnipeg, only the first two reasons apply in residential districts while all three reasons apply in the downtown commercial area.

The experience by the City of Winnipeg with watermain backfill has shown the following:

1) If the excavated soil is placed as backfill, it eventually subsides and requires continual maintenance for several years. This has been found highly undesirable where the backfill has to support a pavement.

2) Gravel backfill, which has been used extensively for backfilling repaired pipe sections, has the undesirable characteristic of being very permeable. Also, the gravel behaves in a different manner than the adjacent cohesive soil found locally when subjected to moisture variations.

3) Since 1954 the City of Winnipeg has used "unshrinkable" material, which consists of approximately fifty pounds cement to a yard of wetted gravel for backfilling repaired pipe. "Unshrinkable" backfill provides a very dense, cemented condition; however, it has been found difficult to excavate when repairs to the pipe are required and also does not behave as the surrounding soil when subjected to moisture variations.

Observations made by J. J. Hamilton[3] and T. W. Godfrey[4] indicate that flexural failures of watermains are often the result of improper backfilling techniques.

Watermains are laid in trenches excavated by either a trenching machine or a backhoe. Soil excavated by a trenching machine is well mixed and may be considered to have a uniform consistency. When used for backfilling purposes, soils excavated by a trenching machine have been found to compact well with a low percentage of voids. Soil not compacted at time of backfilling has been found to be quite permeable. Subsidence of the backfill occurring over several years will reduce permeability appreciably. However, before appreciable subsidence and when the void ratio of the backfill is large, water can percolate through the backfill to the soils enveloping the pipe. Absorption of moisture by the soil supporting the pipe generally causes the soil to swell, that is, increase in volume. This action may be sufficiently non-uniform along a watermain to result in a flexural break, particularly with corrosion weakened pipe or pipe of small diameter.

Soils excavated by a backhoe present a more severe problem when used for backfilling purposes. Soil excavated by backhoe is usually very lumpy and when used as backfill produces large voids. A breakdown of the soil lumps results in large subsidence of the backfill. Also, water can easily percolate down through the voids. Similarly, as for loosely placed trenching machine excavated backfill, the soil enveloping the watermain absorbs the percolating water, swells, and the resulting movements of the corrosion weakened watermain may be sufficient to result in a flexural failure.

Percolation of surface water through the backfill has been alleviated by the use of "unshrinkable" material; however, as mentioned before, "unshrinkable" backfill also has disadvantages.

Soil moisture determinations made at the University of Manitoba have indicated that desiccation of soils accompanied by shrinkage, at the depth of watermains, can occur. This process would affect the watermain stability by removing support along the pipe and if it is non-uniform, would produce differential movement.

WINNIPEG SOILS

The soils in the Greater Winnipeg area as established by several investigators can be classified as follows:[5]

a) The top surface is a dark grey silty organic clay varying in thickness from several inches up to about two feet.

b) Underlying the organic clay is a tan colored silt, sandy silt or clayey silt varying in thickness up to ten feet. This material generally has two distinct layers distinguished by the presence of soluble salts in the lower layer which have been leached from the overlying material.

c) Below the tan silt is a layer of silty brown plastic clay of glacial lake origin. Its composition consists of horizontal varves of silt and clay. Varves of lighter color are mostly silt and are considered to be sediment occurring during the spring and summer high water or flood periods while the darker clay varves are sediment occurring during fall and winter low water and less movement periods. This stratified clay varies in thickness up to sixteen feet and generally occurs above the seven foot depth. Since watermains are commonly placed at depths greater than seven feet, most watermains are laid in the plastic lacustrine clay.

d) The next stratum is a grey to blue-grey clay commonly referred to as "blue clay". Although it is also susceptible to volume changes, this clay is less plastic than the overlying brown clay and such changes do not generally occur as it is found below the zone of seasonal moisture variation. Deposits of this material up to twenty feet thick are not uncommon.

e) Overlying the material locally known as "hardpan" and underlying the "blue clay" is a stratum of boulder till composed of light grey silt, sand, gravel and boulders of various dimensions. It has sufficient moisture to be dilatant and to have a "putty-like" consistency.

f) The "hardpan" layer has a boulder till composition as above with a high percentage of rock flour and a low moisture content in a dense cemented condition. This stratum may be found at depths from twenty to sixty feet.

g) Below hardpan and occurring at depths below about sixty feet is the Ordovician limestone bedrock.

COMPACTION CHARACTERISTICS

Compaction may be defined as a method of densifying or increasing the density of a soil by the exertion of blows, weight application or vibration, the purpose being to bring the soil particles closer together. The percentage of water in a soil determines the density to which it can be compacted. A specific per cent of water content, called optimum moisture content, will give maximum density to a soil under a particular compactive effort. Optimum moisture content varies for each soil type and decreases with an increase in compactive effort. The relationship between dry density and moisture content can best be illustrated as shown in Figure I.

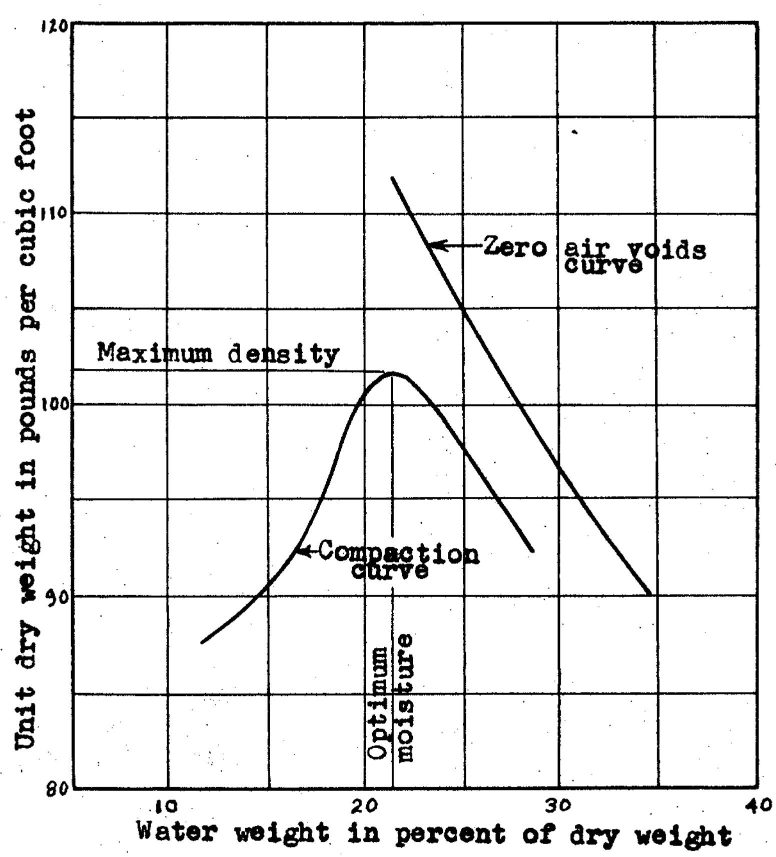


Figure I

The zero air voids density curve in Figure I indicates the relationship of density to moisture content of a soil if the soil contained no air. Some years ago R. R. Proctor developed a laboratory test procedure for determining optimum moisture content. This was later published in 1933. His method was referred to as the standard proctor compaction which was revised to the modified proctor compaction with the advent of heavier construction and and compaction equipment. In field control the required specified density is some per cent of the maximum proctor density. The standard proctor test was performed on soil samples recovered from Manitoba Avenue and Cordova Street because it was felt that the modified proctor density was too high for the type of compaction equipment available.

FIELD INVESTIGATION PROGRAM

The methods used in evaluating backfill and undisturbed soil densities, field and laboratory compaction, have an important bearing on the analysis of the results. For this reason they have been explained in detail under the following headings.

a) EXCAVATION OF TEST PITS

The excavation of all holes for density determination in backfill over watermains and house service pipes was performed by manual labor. Test pits along Manitoba Avenue straddled house service pipes and lay beneath a four inch concrete walk. Excavations were made adjacent to the sidewalk on the pavement side, forming a hole about five feet long, parallel to the sidewalk and two and one-half feet wide. Test pits were usually excavated to a depth of eight feet which was six inches to one foot below the house service pipe. Backfill extended to a depth of seven to seven and one-half feet, therefore, only one density test was taken at the eight foot depth, this being in the undisturbed material.

Test pits along Cordova Street were excavated directly over the pipe with the longer dimension being perpendicular to the direction of the watermain.

b) APPARATUS USED IN DETERMINING SOIL DENSITIES

Undisturbed soil samples had formerly been taken by T. W. Godfrey[6] in two inch diameter shelby tubes for the purpose of determining soil densities. This method was found unsatisfactory as friction between the interior of the tube and the soil sample resulted in compaction of the soil. In the case of the sandy tan silt, as much as two inches compaction per foot long sample was observed. The decision was therefore made to utilize the sand-cone apparatus for measuring soil densities. Later, the rubber balloon, oil weight and bulk sample mercury displacement methods were employed for trial purposes.

c) PROCEDURE IN DETERMINING SOIL DENSITIES

Soil density tests by the sand-cone, rubber balloon and oil weight methods all required the excavation of a small hole, approximately four inches in diameter and four inches deep.

After several trials it was discovered that the same hole could be used for density measurements by all three methods with consistent density values. The sand-cone test was performed first, followed by the rubber balloon method and finally by the oil weight method. It was found that the volume of the hole after the sand-cone and rubber balloon methods were used had not been altered because all the Ottawa sand was removed upon completion of this test and the balloon method did not in any way alter the shape of the hole. Since the oil weight method was used last, it was not essential to recover the oil.

It was found that bulk soil samples could be cut in the cohesive lacustrine clay only. Several bulk samples were cut in two inch cubes, placed in air tight jars and later trimmed to appropriate dimensions for density determinations by displacement in mercury.

d) BACKFILL COMPACTION BY THE BARCO RAMMER

Analysis of the backfill densities along Manitoba Avenue indicated that the various compaction apparatus produced only slightly higher densities than those of undisturbed soils. It was then decided to utilize a compactor which seemed practicable for compacting in narrow trenches, on a trial basis, in one test pit. A Barco Rammer was available and since this had not been used under field control conditions previously, it was therefore employed.

Normally, upon completion of soil density measurements at a particular location the soil was spaded in loosely without any physical compaction. However, upon completion of soil density measurements at the first location on Cordova Street, the Barco Rammer was used. Nine inch layers of soil were spaded in and a single pass made by the Barco Rammer.

DATA

CHARACTERISTICS OF UNDISTURBED SOILS

Except for moisture contents, disturbed and undisturbed soil densities (which have been plotted for every location) a thorough laboratory analysis was not believed necessary at each location investigated.

It was found that the soils at all locations investigated on Manitoba Avenue and Cordova Street were typical of those generally found in the Greater Winnipeg area. A particular location, 266 Manitoba Avenue, was therefore selected for a thorough laboratory analysis of each soil type. The results have been tabulated in Table 1.

TABLE 1 UNDISTURBED SOILS - LABORATORY ANALYSIS

Soil	Depth	Hydrometer Analysis	Liquid Limit	Plasticity Index	Shrinkage Limit	Specific Gravity	Standard Proctor Maximum Dry Density	Standard Proctor Optimum Moisture Content
A	2	sandy silty clay	71.8	44.2	14.69	2.72	89.5	31.2
B	4	clayey sandy silt	23.8	3.5	19.85	2.74	110.5	17.2
C	6	sandy silt	18.0	0.75	19.25	2.73	114	13.0
D	8	sandy silty clay	105.0	70.5	14.70	2.76	81.5	27.5

It was evident from the Atterberg limits that the soils at the four and six foot depths have practically no plasticity and undergo very little shrinkage upon drying, or swelling upon rewetting. However, the brown clay at the eight foot depth is a very plastic material with high possible swelling and shrinkage with moisture changes. This material has a high dry strength, medium susceptibility to frost action and very low permeability in the undisturbed state. Regarding frost heave, data obtained by the Division of Building Research of the National Council showed that frost penetration in backfill or disturbed soil can be one and one-half times that in undisturbed soil.[7] Frost penetration in the Greater Winnipeg area has been found to be about five to six feet in undisturbed soil. Therefore, frost could penetrate to a depth of seven or eight feet in backfill material. A watermain could be subjected to freezing, however, the heat dissipated by the flowing water has been observed to be sufficient to prevent freezing.

CHARACTERISTICS OF BACKFILL

The characteristics of the backfill soils for Manitoba Avenue and Cordova Street have been summarized in Table 2. From visual observation, the backfill at 257 Manitoba Avenue was selected as being typical of backfill soils along Manitoba Avenue. Also, by visual observation the backfill at 480 Cordova Street appeared to be typical of backfill soils along Cordova Street.

TABLE 2 BACKFILL SOILS - LABORATORY ANALYSIS

Location and Depth	Hydrometer Analysis	Liquid Limit	Plasticity Index	Shrinkage Limit	Specific Gravity	Standard Proctor Maximum Dry Density	Standard Proctor Optimum Moisture Content
257 Manitoba Ave. D = 4 ft.	clayey sandy silt	34.5	13.4	24.13	2.77	93.5	23.5
480 Cordova Street D = 4 ft.	clayey sandy silt	25.5	4.4	18.02	2.77	98.0	20.0

The Atterberg limits for backfill at 257 Manitoba Avenue indicate a material of low to medium plasticity. This backfill material also has medium to high dry strength, medium to high susceptibility to frost action, low permeability and medium shrinkage, expansion and elasticity. Similarly, the Atterberg limits for backfill at 480 Cordova Street indicate a material of low plasticity having slight to medium dry strength, medium to very high susceptibility to frost action and slight to medium shrinkage, expansion and elasticity; it is slightly more permeable than the backfill material on Manitoba Avenue.

FIELD INVESTIGATION DATA

Plots of natural moisture contents in undisturbed and backfill soils, densities in undisturbed and backfill soils and soil profiles in undisturbed and backfill soils have been drawn for each location investigated to assist in the analysis of the results of the investigation and to compare the results of different methods of compaction employing various backfill materials.

Further, various combinations of dry density versus moisture content for each type of naturally occurring undisturbed soil, dry density versus moisture content for backfill soils compacted by various methods, depth versus "average" backfill moisture content and depth versus "average" backfill dry density were considered to have significant revelations best illustrated in the form of graphical plots.

Plates 1-17

Natural moisture content and dry density versus depth; undisturbed and backfill soil profiles.

Legend:

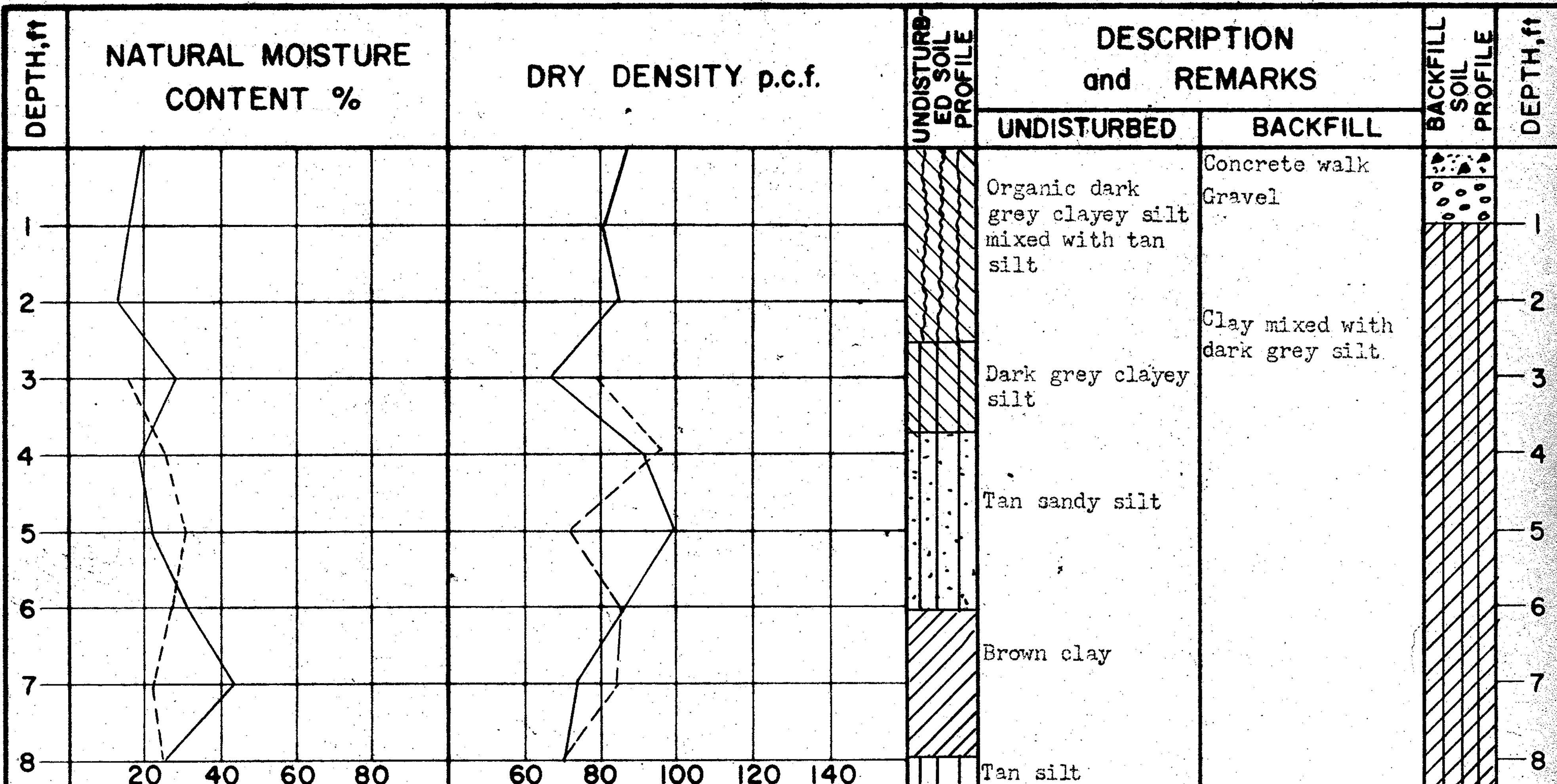
Undisturbed soils moisture content ————

Backfill soils moisture content --------

Undisturbed soils dry density ————

Backfill soils dry density ------------

Barco Rammer backfill compaction —— • ——



LOCATION OF EXCAVATION SW Corner Main Street and Manitoba Avenue
DATE TRENCH BACKFILLED October 20, 1954
DATE OF EXCAVATION August 15, 1958
COMMENTS Clay backfill tamped in one foot layers by Pavement Breaker with 7" diameter head.

DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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WATERMAIN BACKFILL STUDIES

WINNIPEG MANITOBA

Plate 1

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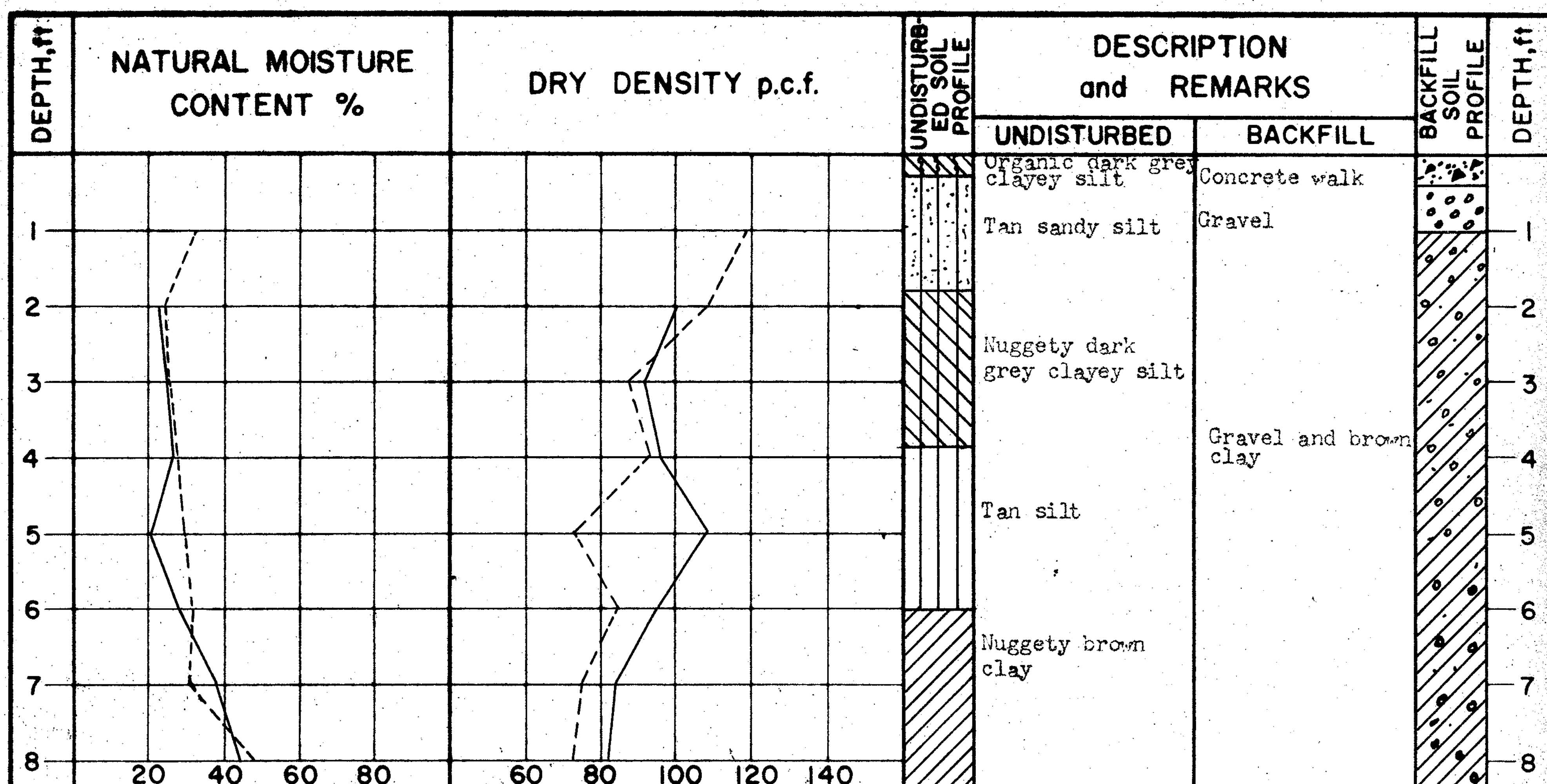

LOCATION OF EXCAVATION: 224 Manitoba Avenue
DATE TRENCH BACKFILLED: October 20, 1954
DATE OF EXCAVATION: July 8, 1958
COMMENTS: Clay backfill tamped with GARDNER DENVER MECHANICAL TAMPER ($5\frac{1}{4}$" diameter head) in one foot layers

DATE PLOTTED: September 1958 PLOTTED BY: J. D. Mishtak

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WATERMAIN BACKFILL STUDIES

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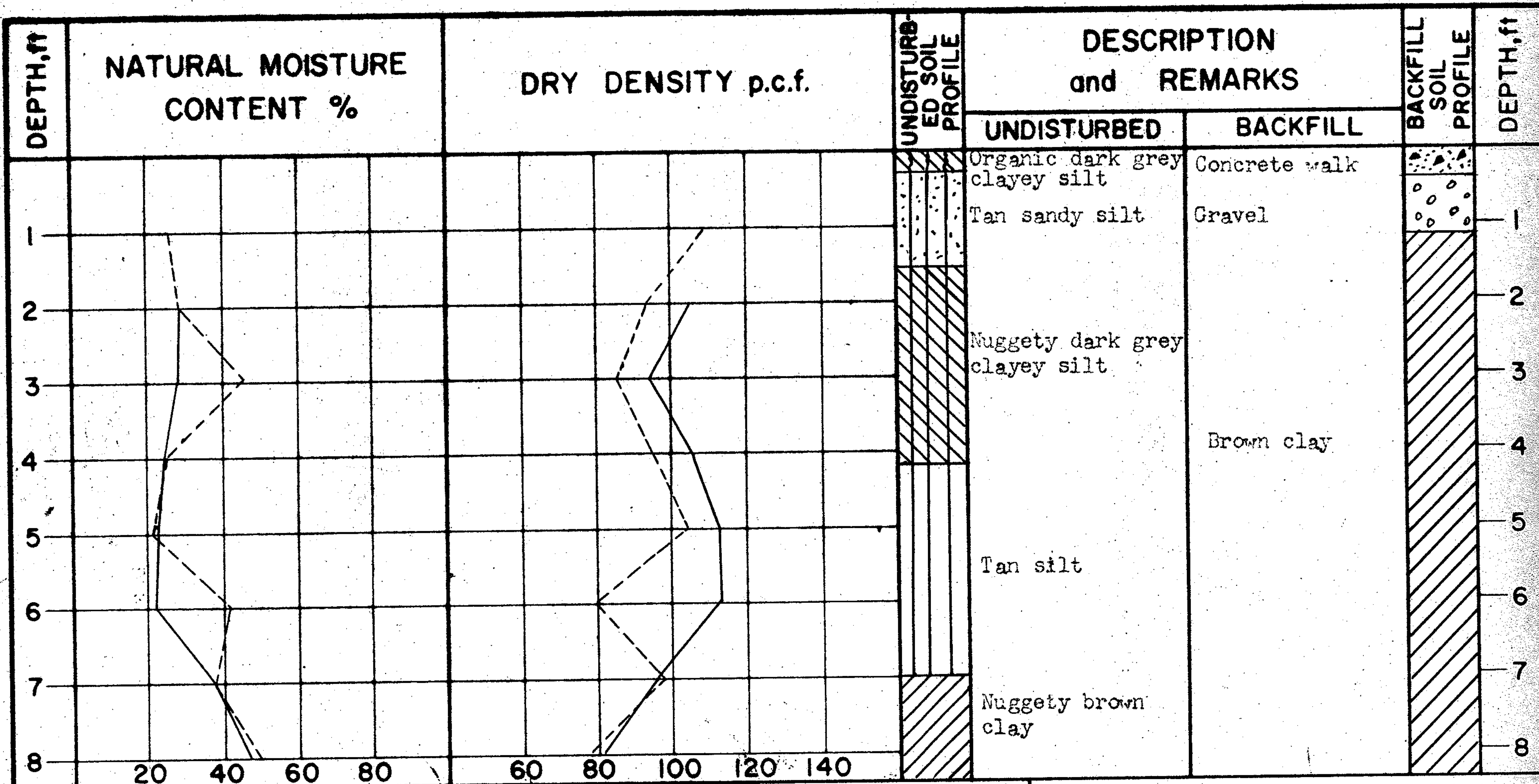
Plate 2



LOCATION OF EXCAVATION: 226 Manitoba Avenue

DATE TRENCH BACKFILLED: October 20, 1954

DATE OF EXCAVATION: July 8, 1958

COMMENTS: Clay backfill tamped with Gardner Denver Mechanical Tamper (5¾" diameter head) in 6" layers, no settlement after water jetting.

DATE PLOTTED: September 1958 PLOTTED BY: J. D. Mishtak

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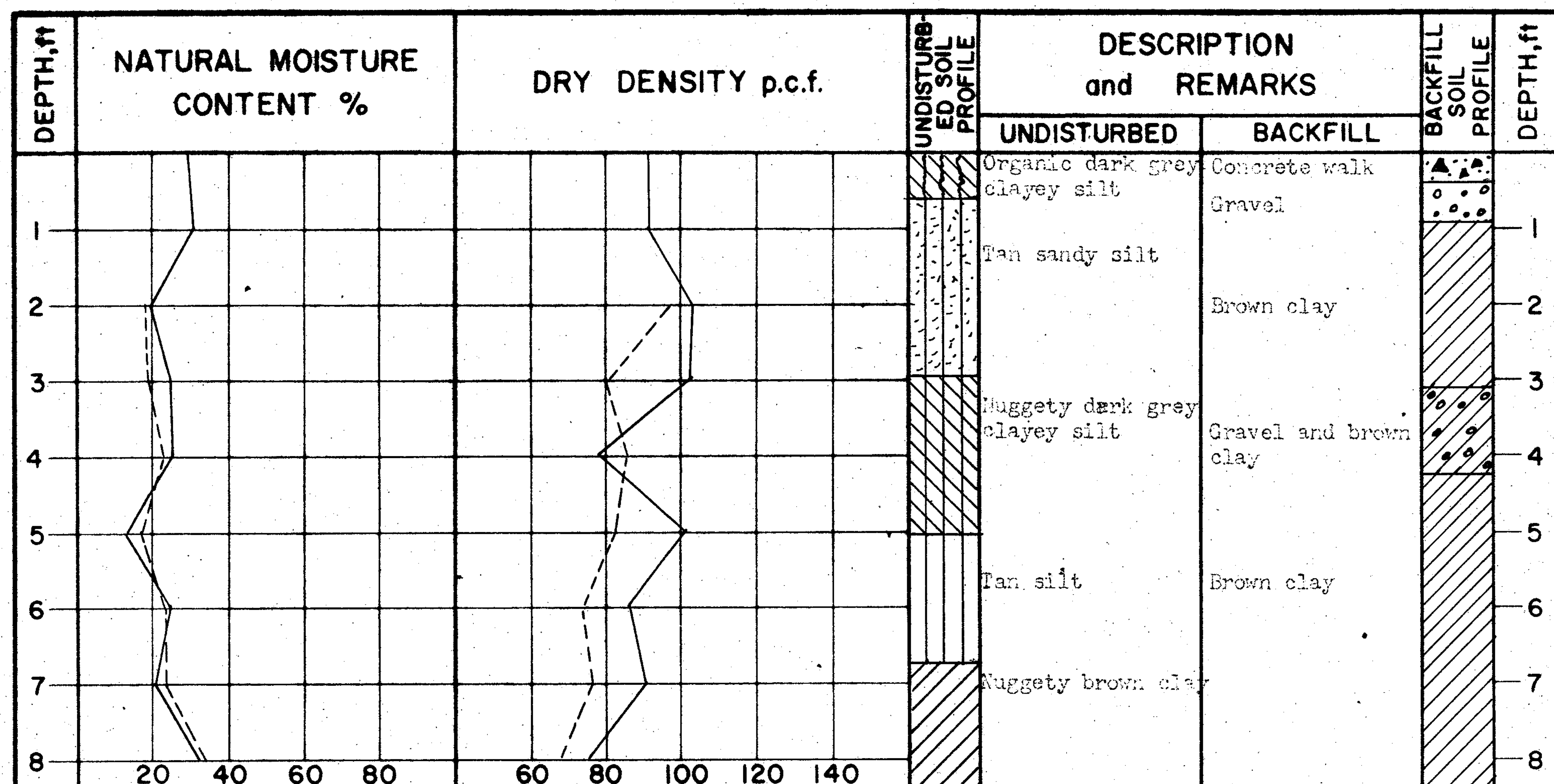
Plate 3



LOCATION OF EXCAVATION 245 Manitoba Avenue

DATE TRENCH BACKFILLED October 20, 1954

DATE OF EXCAVATION July 9, 1958

COMMENTS Clay backfill hand tamped in 7" layers (5½" x 7½" tamper) Water jetted but would not take water.

DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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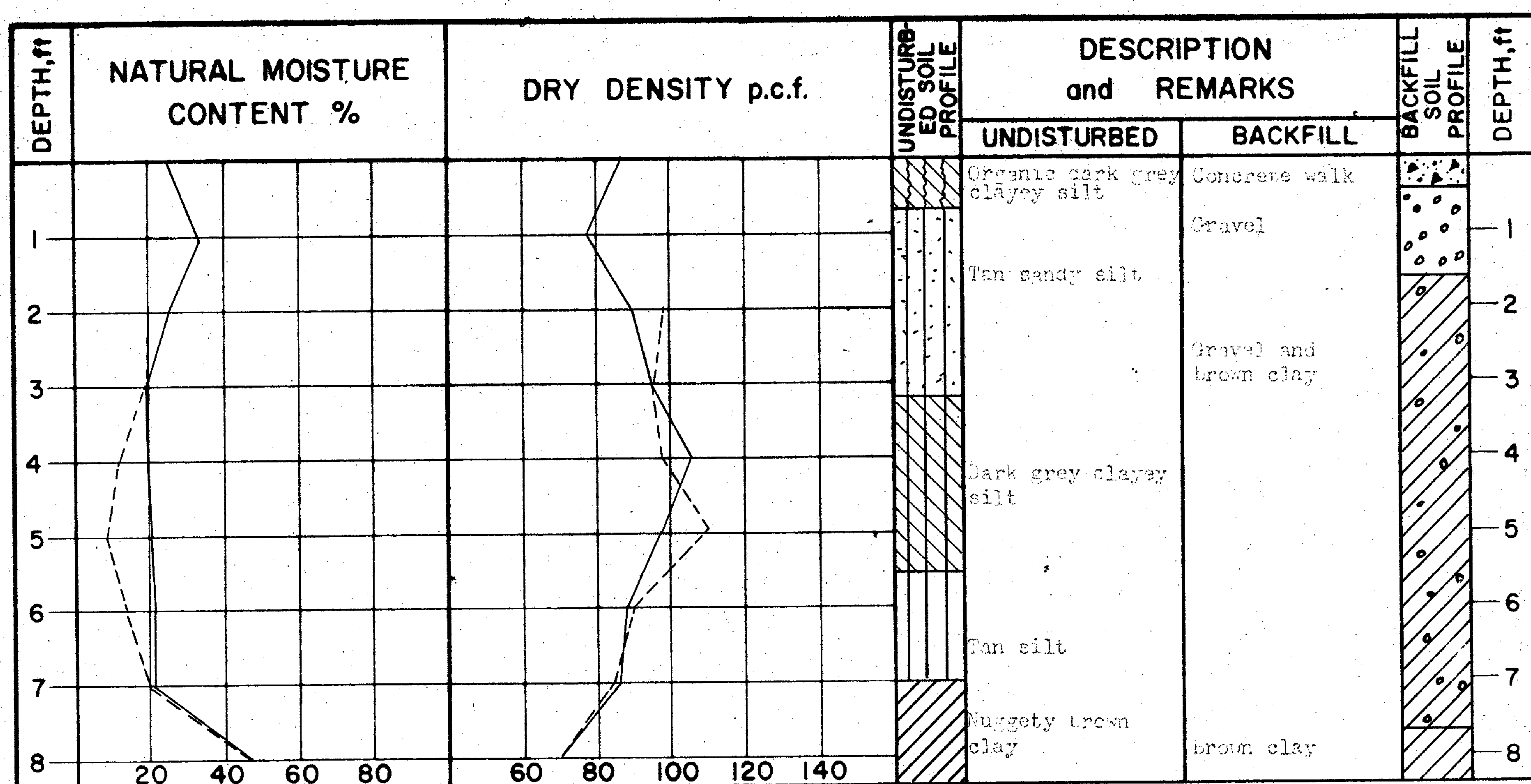
Plate 4



LOCATION OF EXCAVATION 247 Manitoba Avenue
DATE TRENCH BACKFILLED October 21, 1954
DATE OF EXCAVATION July 9, 1958
COMMENTS Clay and gravel backfill hand tamped in 9" layers with Le Roi tamper (5¼" diameter head), water jetted for 6 minutes.

DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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Plate 5

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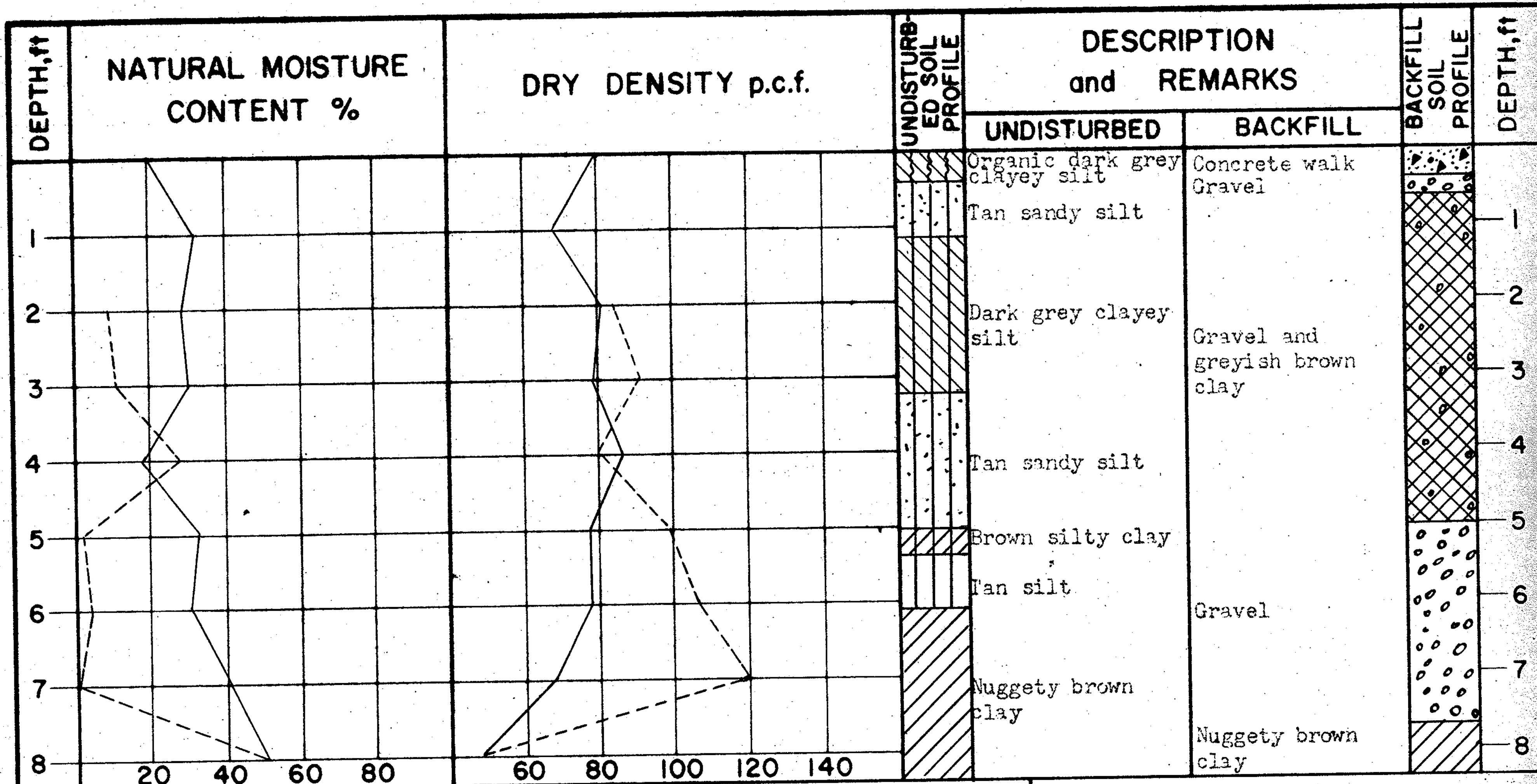

LOCATION OF EXCAVATION 252 Manitoba Avenue
DATE TRENCH BACKFILLED October 21, 1954
DATE OF EXCAVATION August 1, 1958
COMMENTS Clay and gravel backfill compacted in one and one-half foot layers by Le Roi tamper (5½" diameter head)

DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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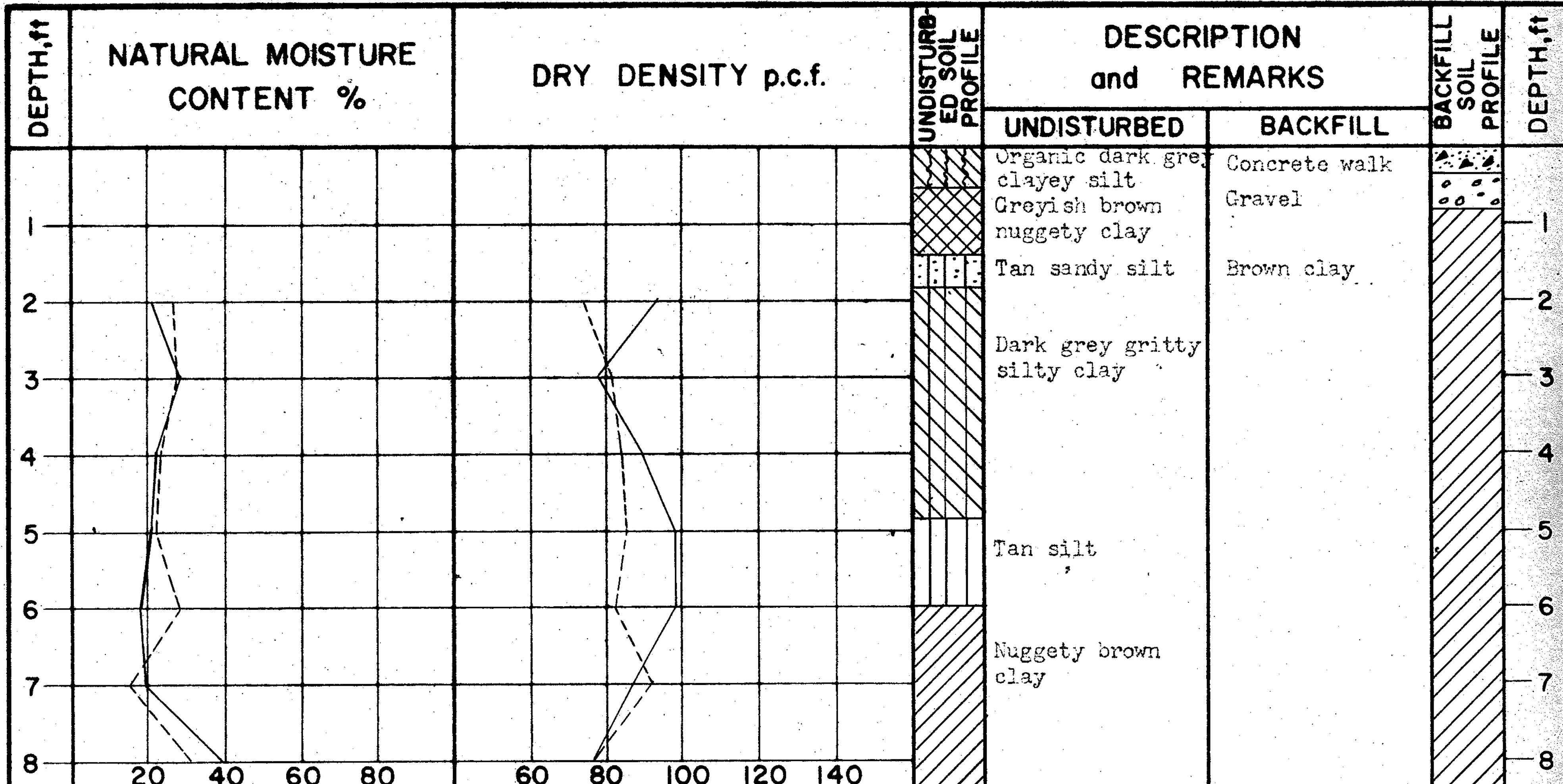
Plate 6



LOCATION OF EXCAVATION 255 Manitoba Avenue

DATE TRENCH BACKFILLED October 19, 1954

DATE OF EXCAVATION July 10, 1958

COMMENTS Clay backfill hand tamped ($5\frac{1}{2}$" x $7\frac{1}{2}$" tamper) in 9" lifts. Water jetted after backfilling resulted in 3" settlement. Top gravel layer tamped with $5\frac{3}{4}$" diameter Gardner Denver Tamper with 3" compaction.

DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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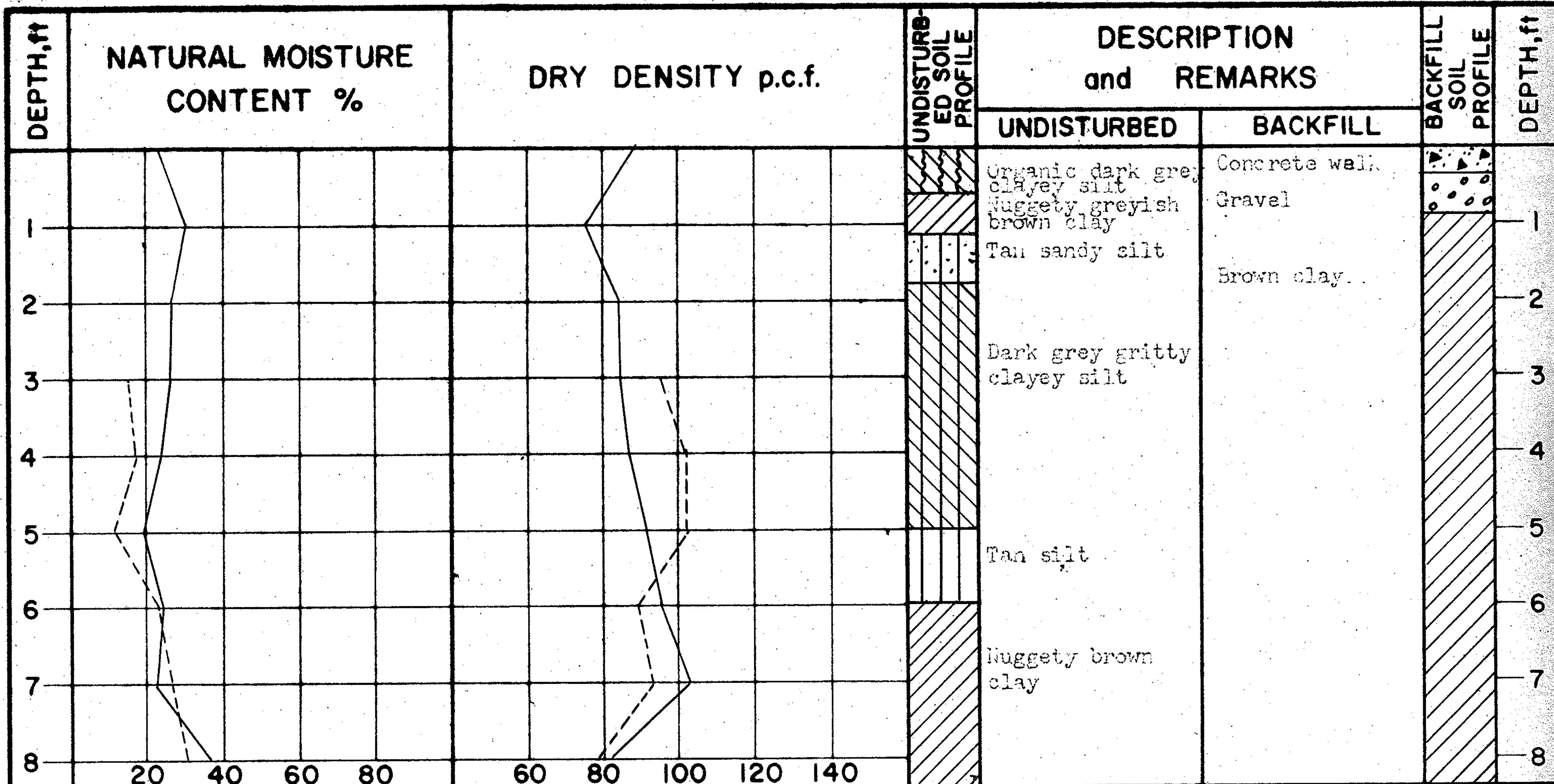
Plate 7



LOCATION OF EXCAVATION 257 Manitoba Avenue

DATE TRENCH BACKFILLED October 19, 1954

DATE OF EXCAVATION July 10, 1953

COMMENTS Clay backfill loosely placed by loader and top hand tamped; Water jetted for 3 minutes

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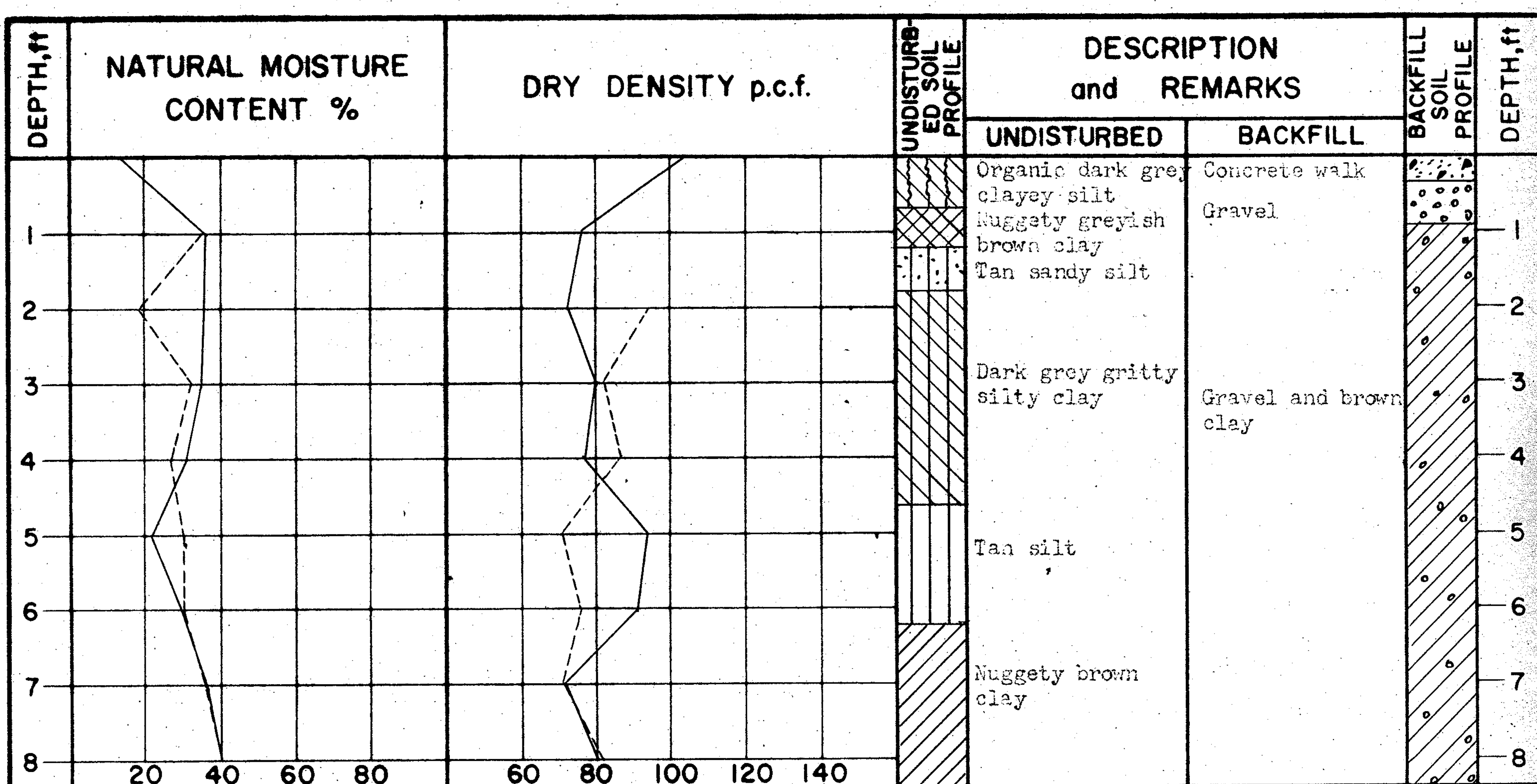
Plate 8



LOCATION OF EXCAVATION	258 Manitoba Avenue
DATE TRENCH BACKFILLED	October 21, 1954
DATE OF EXCAVATION	July 16, 1958
COMMENTS	Gravel and clay backfill loose. Water jetted for 15 minutes. Top gravel layer hand tamped
DATE PLOTTED	September 1958
PLOTTED BY	J. D. Mishtak

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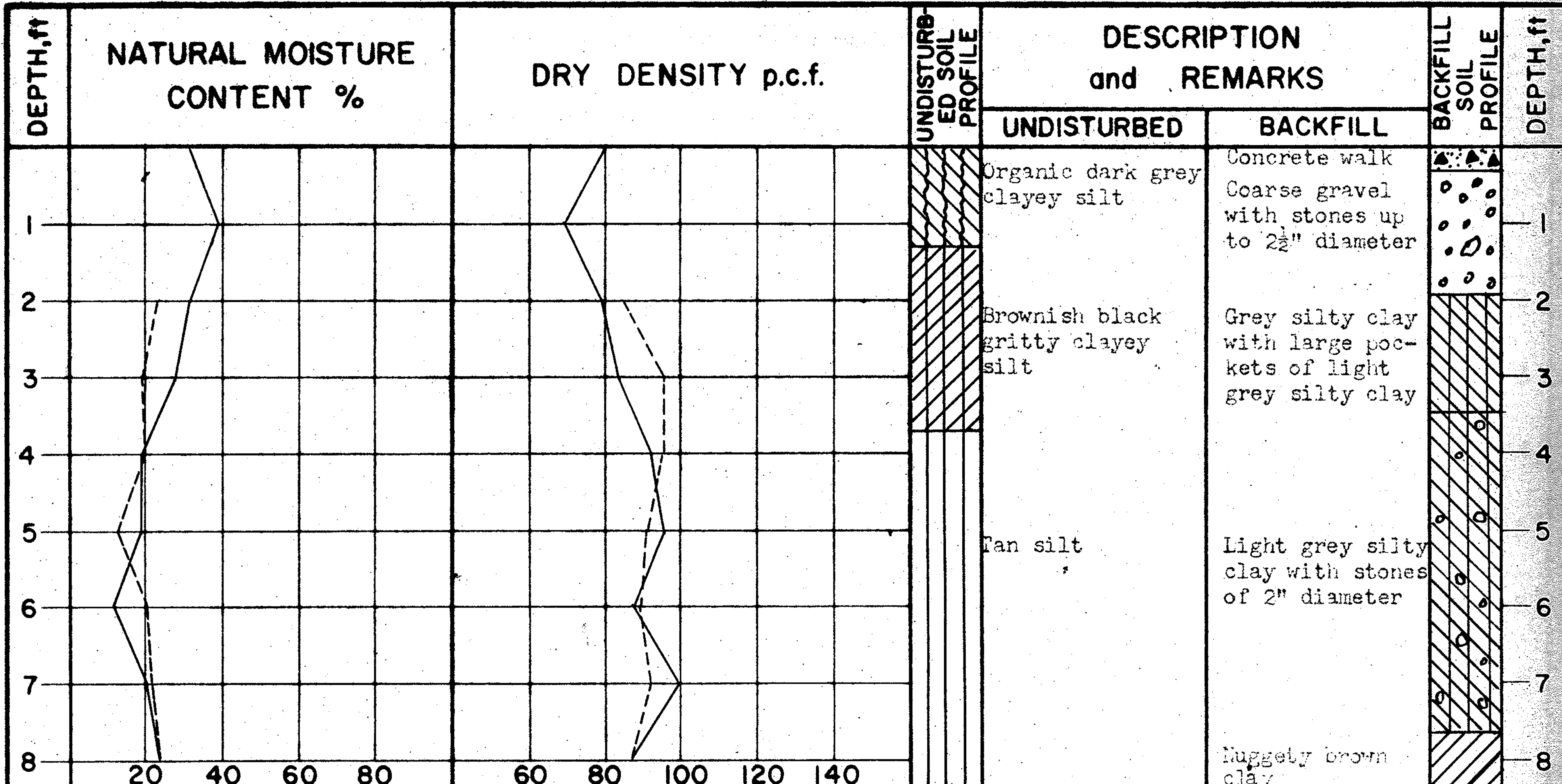
Plate 9



LOCATION OF EXCAVATION: 261 Manitoba Avenue
DATE TRENCH BACKFILLED: October 19, 1954
DATE OF EXCAVATION: July 16, 1953
COMMENTS: Clay and gravel backfill loosely placed by loader. Water jetted 5 minutes. Top gravel layer tamped for 10 minutes with Pavement Breaker (7" diameter head)
DATE PLOTTED: September 1953 PLOTTED BY: J. D. Mishtak

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Plate 10

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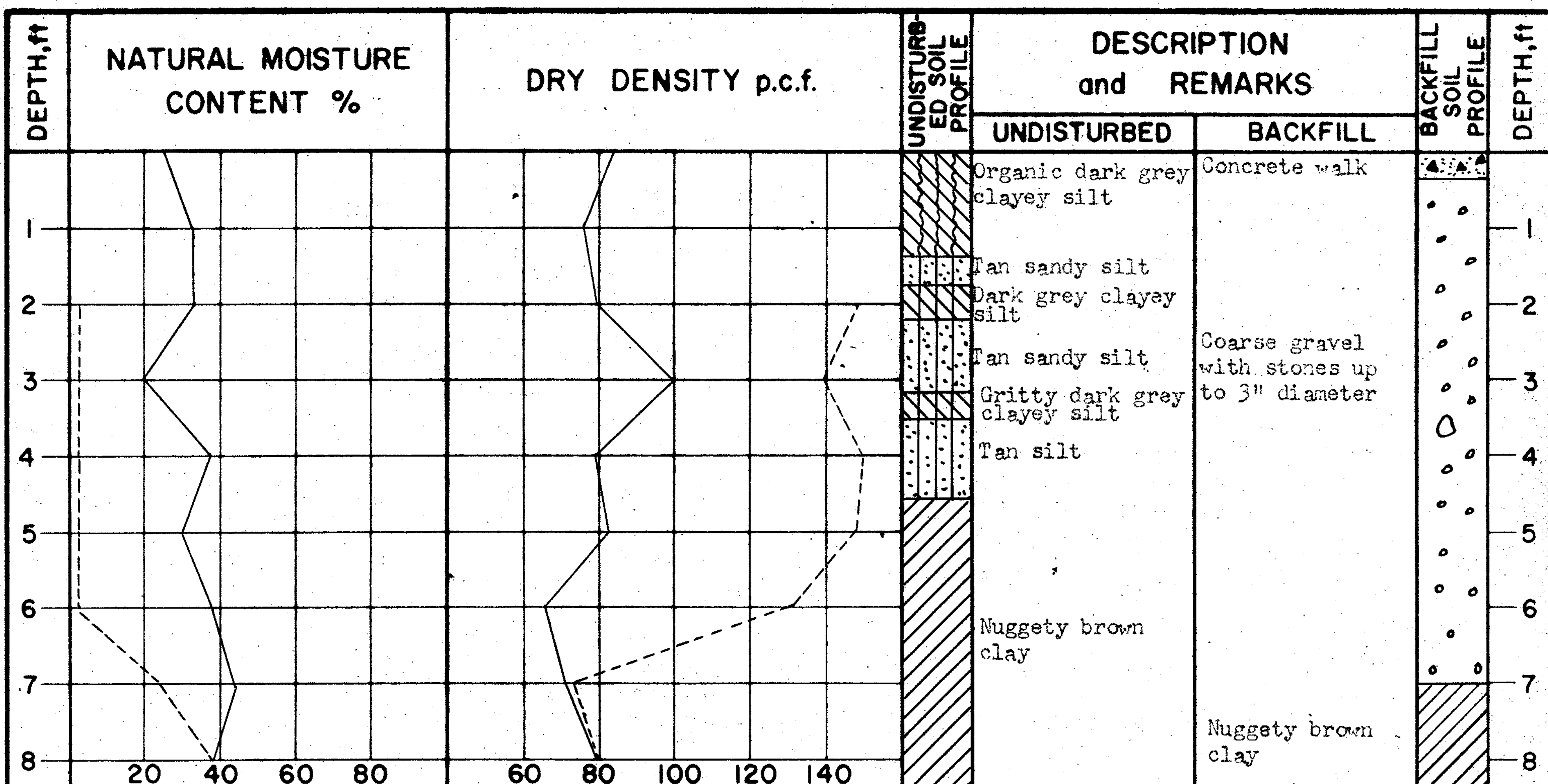

LOCATION OF EXCAVATION 265 Manitoba Avenue

DATE TRENCH BACKFILLED October 19, 1954

DATE OF EXCAVATION July 15, 1958

COMMENTS Backfill composed of 15" clay in bottom of hole and remainder of gravel loosely placed. Water jetted for 12 minutes.

DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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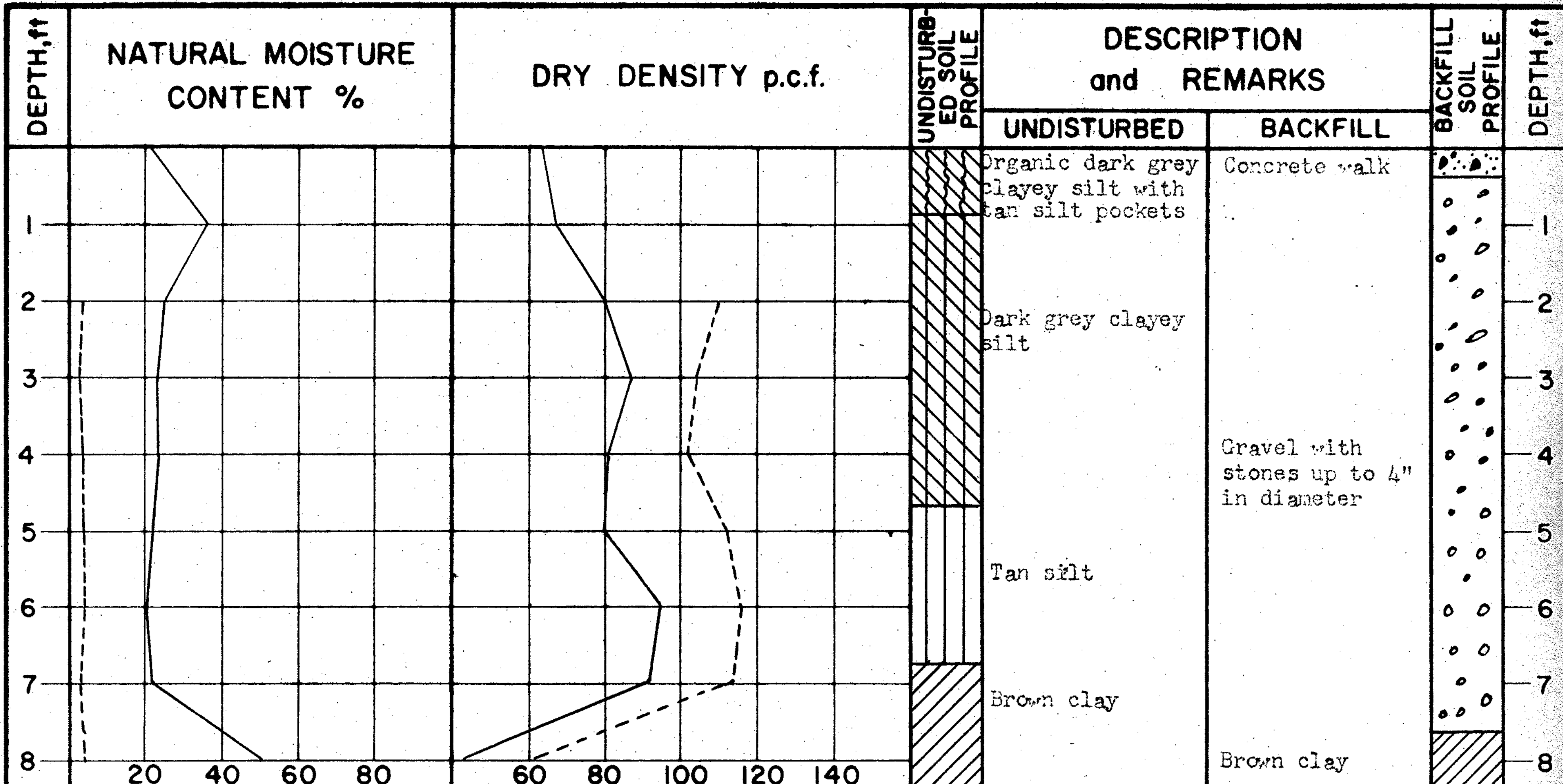
Plate 11



LOCATION OF EXCAVATION 266 Manitoba Avenue

DATE TRENCH BACKFILLED October 21, 1954

DATE OF EXCAVATION August 5, 1958

COMMENTS Gravel backfill, water jetted for eight minutes and hand tamped on surface.

DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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Plate 12

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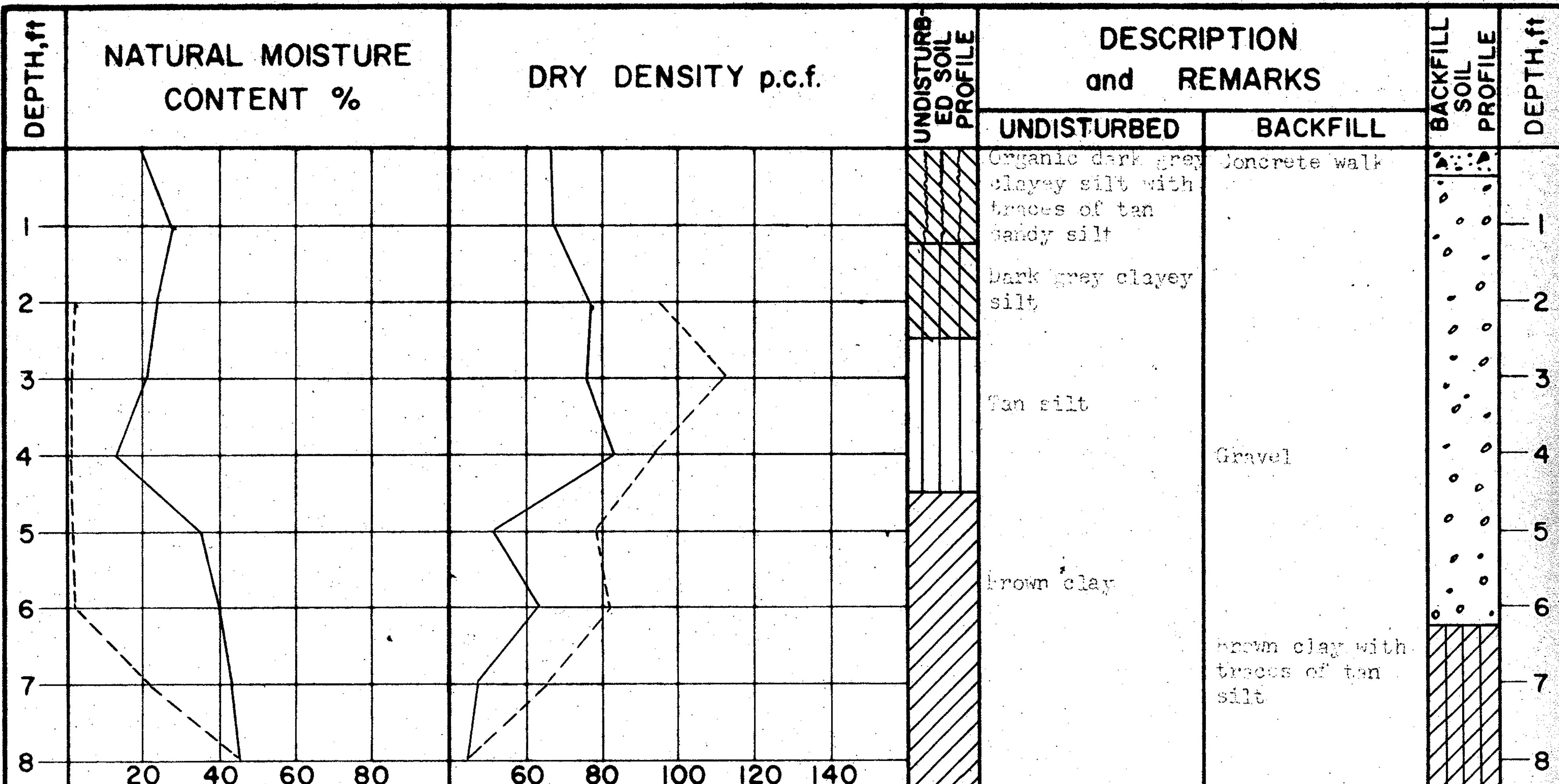

LOCATION OF EXCAVATION 283 Manitoba Avenue
DATE TRENCH BACKFILLED October 19, 1954
DATE OF EXCAVATION August 14, 1953
COMMENTS Backfill composed of gravel to depth of 6'2" followed by clay hand tamped with 5½ x 7½" head. Gravel compacted with Pavement Breaker (7" diameter head).

DATE PLOTTED September 1955 PLOTTED BY J. D. Michtak

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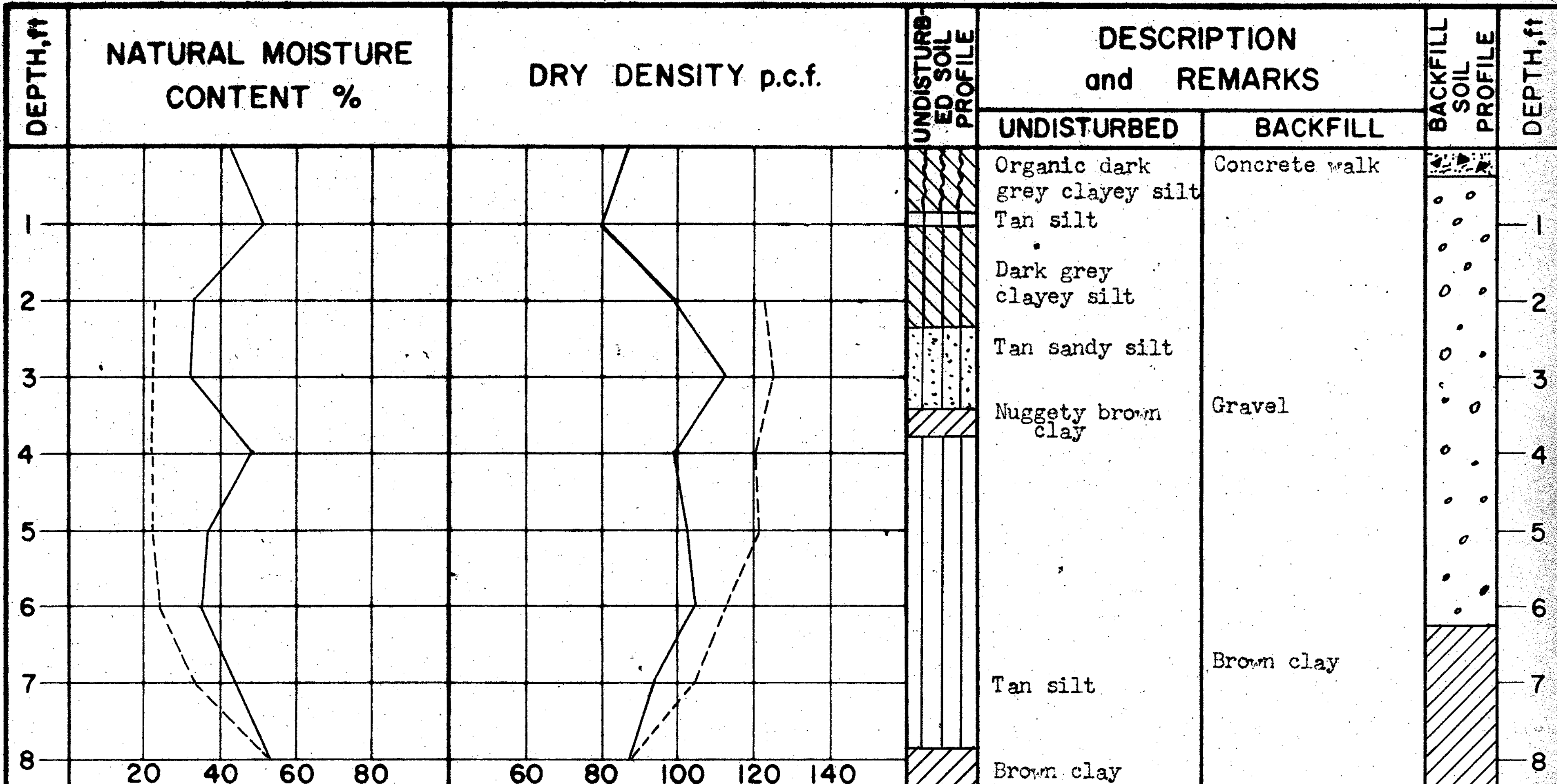
Plate 13



LOCATION OF EXCAVATION 285 Manitoba Avenue

DATE TRENCH BACKFILLED October 19, 1954

DATE OF EXCAVATION August 8, 1958

COMMENTS Backfill composed of gravel to a depth of 6'3" with clay to bottom of pit. Top of clay hand tamped with 6" x 6" tamper. Gravel compacted by Pavement Breaker.

DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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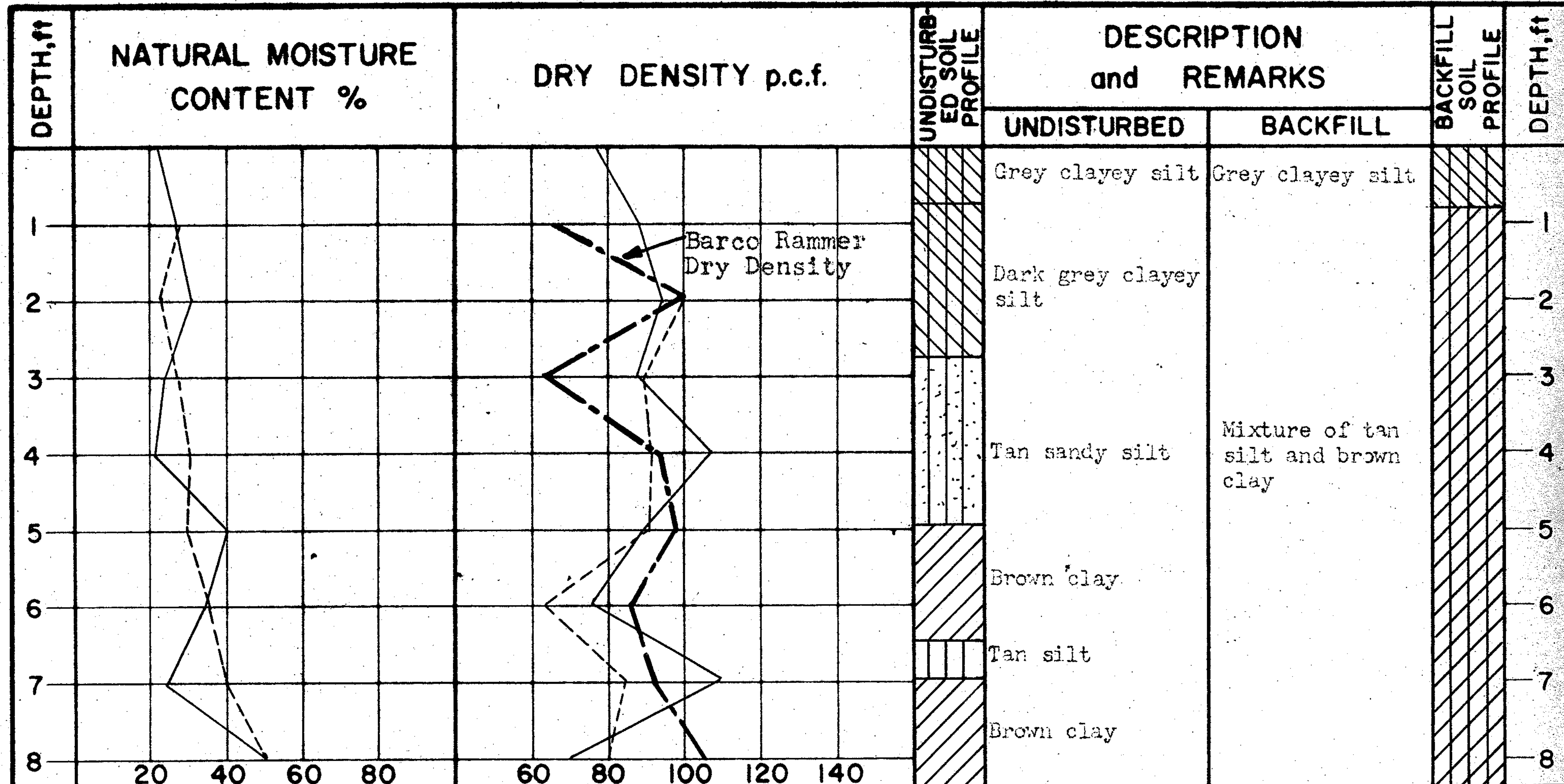
DEPARTMENT OF CIVIL ENGINEER

WATERMAIN BACKFILL STUDIES

WINNIPEG MANITOBA

Plate 14



LOCATION OF EXCAVATION 480 Cordova Street

DATE TRENCH BACKFILLED July 1951

DATE OF EXCAVATION September 9, 1958

COMMENTS Clay and silt backfill (material excavated from trench) not tamped except by equipment driving over backfill after backfilling completed.

DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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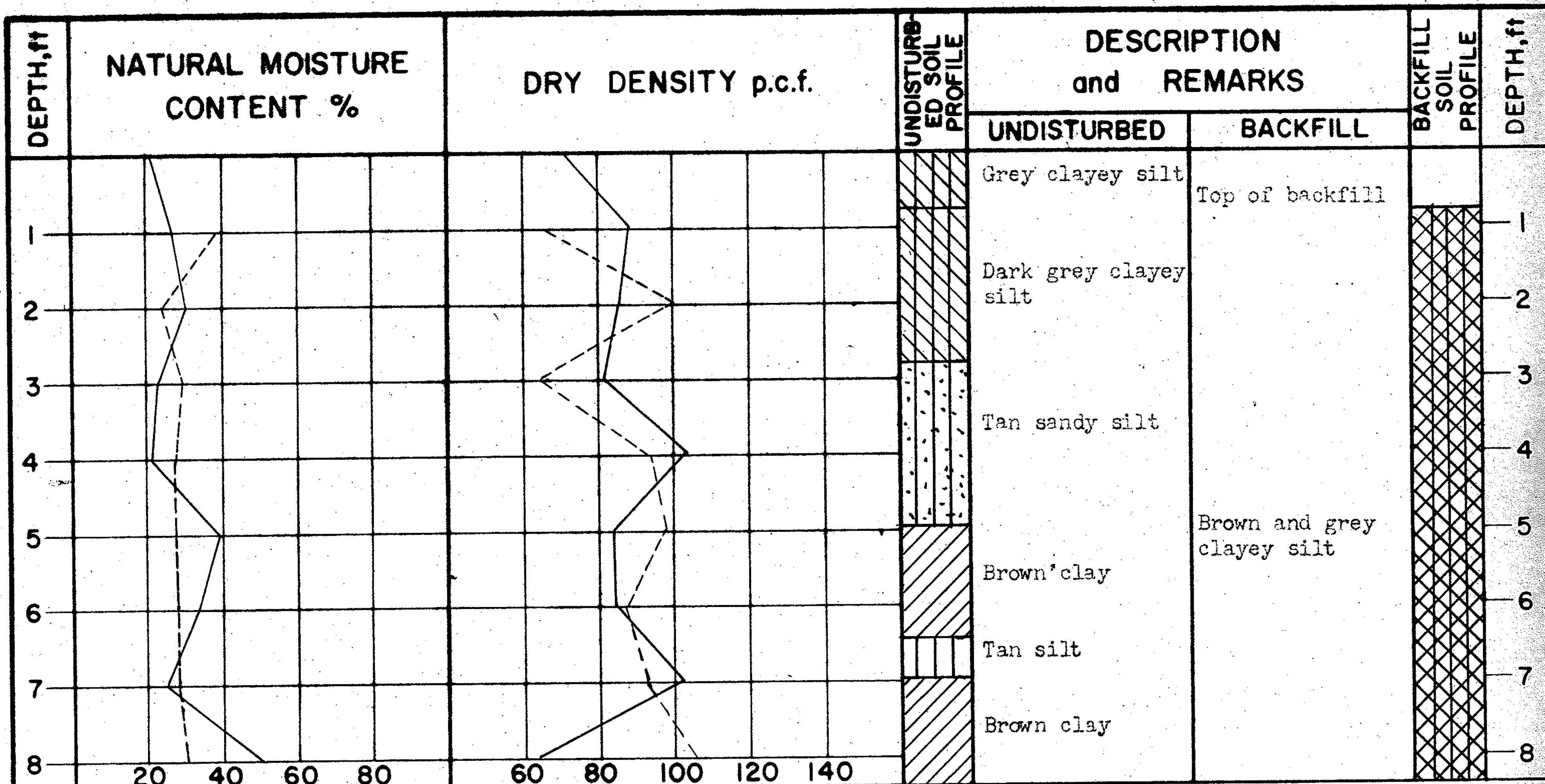
WATERMAIN BACKFILL STUDIES

WINNIPEG MANITOBA

Plate 15

BR 1738



LOCATION OF EXCAVATION 480 Cordova Street

DATE TRENCH BACKFILLED September 10, 1958

DATE OF EXCAVATION September 11, 1958

COMMENTS Clay and silt backfill (material excavated from same location on previous day) tamped in 9" layers by single pass of Barco Rammer.

DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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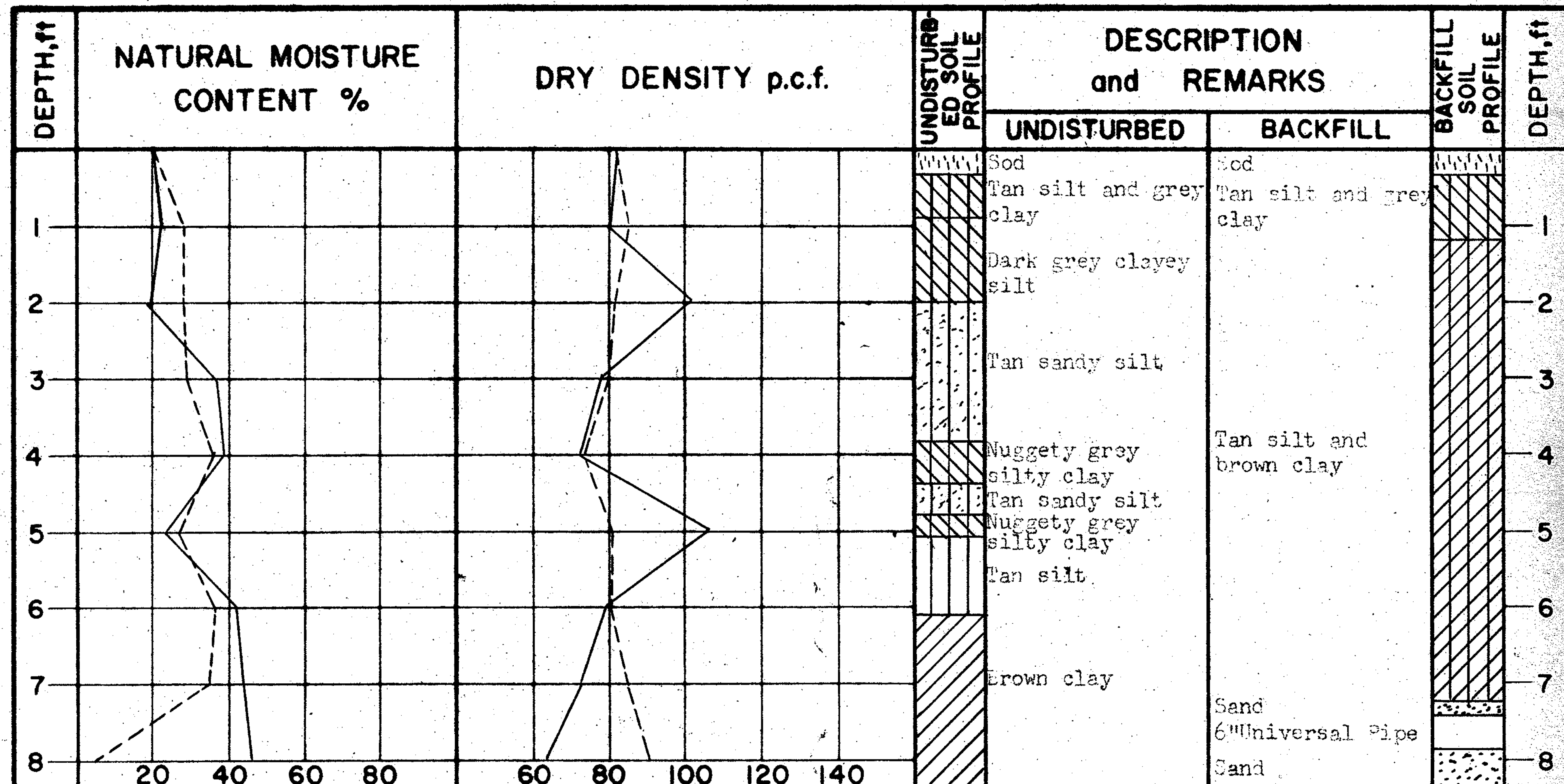
WATERMAIN BACKFILL STUDIES

WINNIPEG MANITOBA

Plate 16



LOCATION OF EXCAVATION 516 Cordova Street
DATE TRENCH BACKFILLED July 1951
DATE OF EXCAVATION September 12, 1958
COMMENTS Clay and silt backfill (material excavated from trench) not tamped except by machines driving over backfill after backfilling completed.
DATE PLOTTED September 1958 PLOTTED BY J. D. Mishtak

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WATERMAIN BACKFILL STUDIES

WINNIPEG MANITOBA

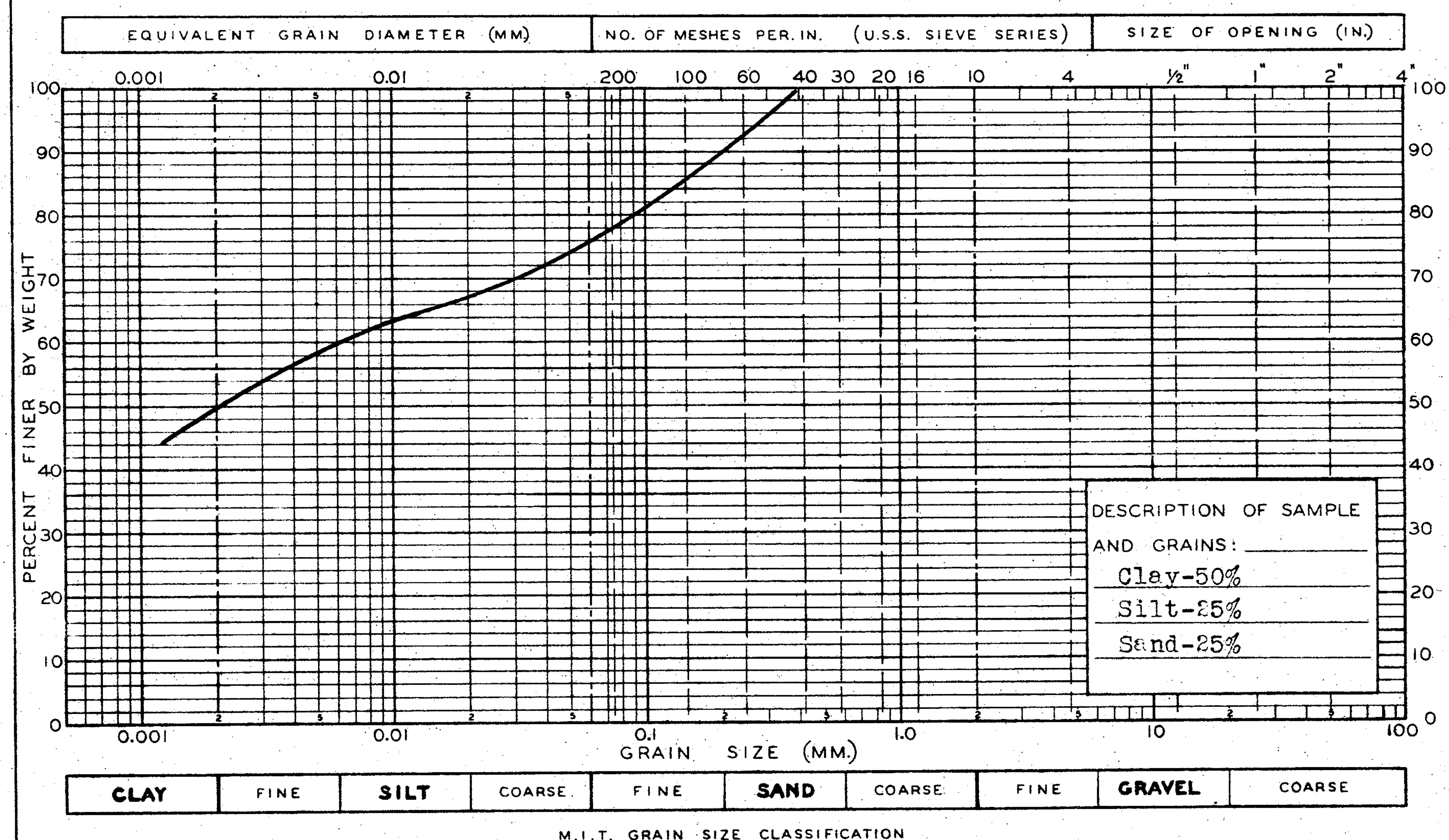
Plate 17

BR 1738

Plates 18-24

Mechanical Analysis Curves

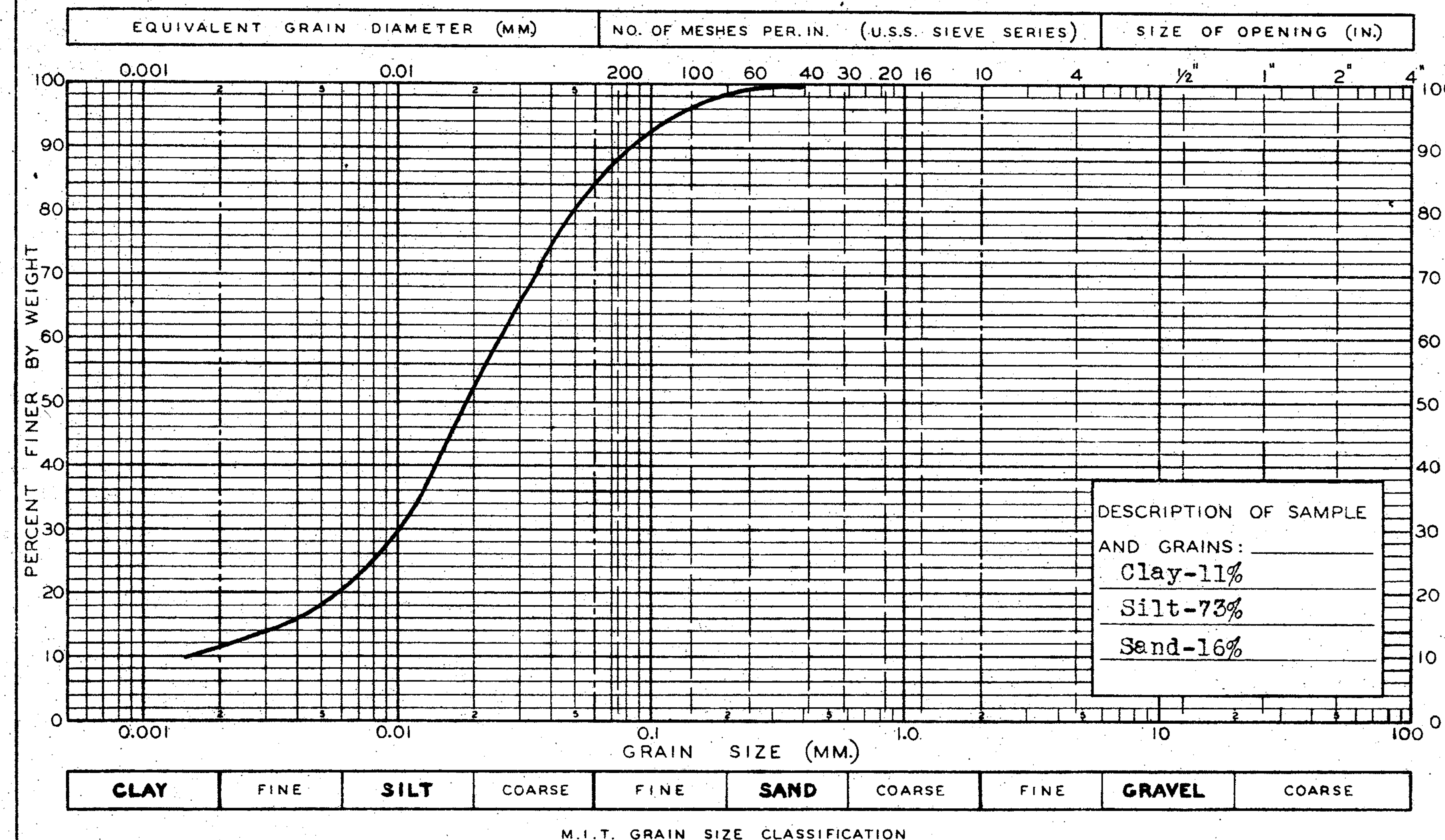
MECHANICAL ANALYSIS OF SOILS



PROJECT: 266 Manitoba Avenue	SAMPLE NO. A, D=2'0"	**SOIL MECHANICS LABORATORY** DEPARTMENT OF CIVIL ENGINEERING UNIVERSITY OF MANITOBA FORT GARRY MANITOBA
PLOTTED: JDM DATE: Nov. 1958	REMARKS: Undisturbed sample	
CHECKED: JDM DATE: Nov. 1958		

Plate 18

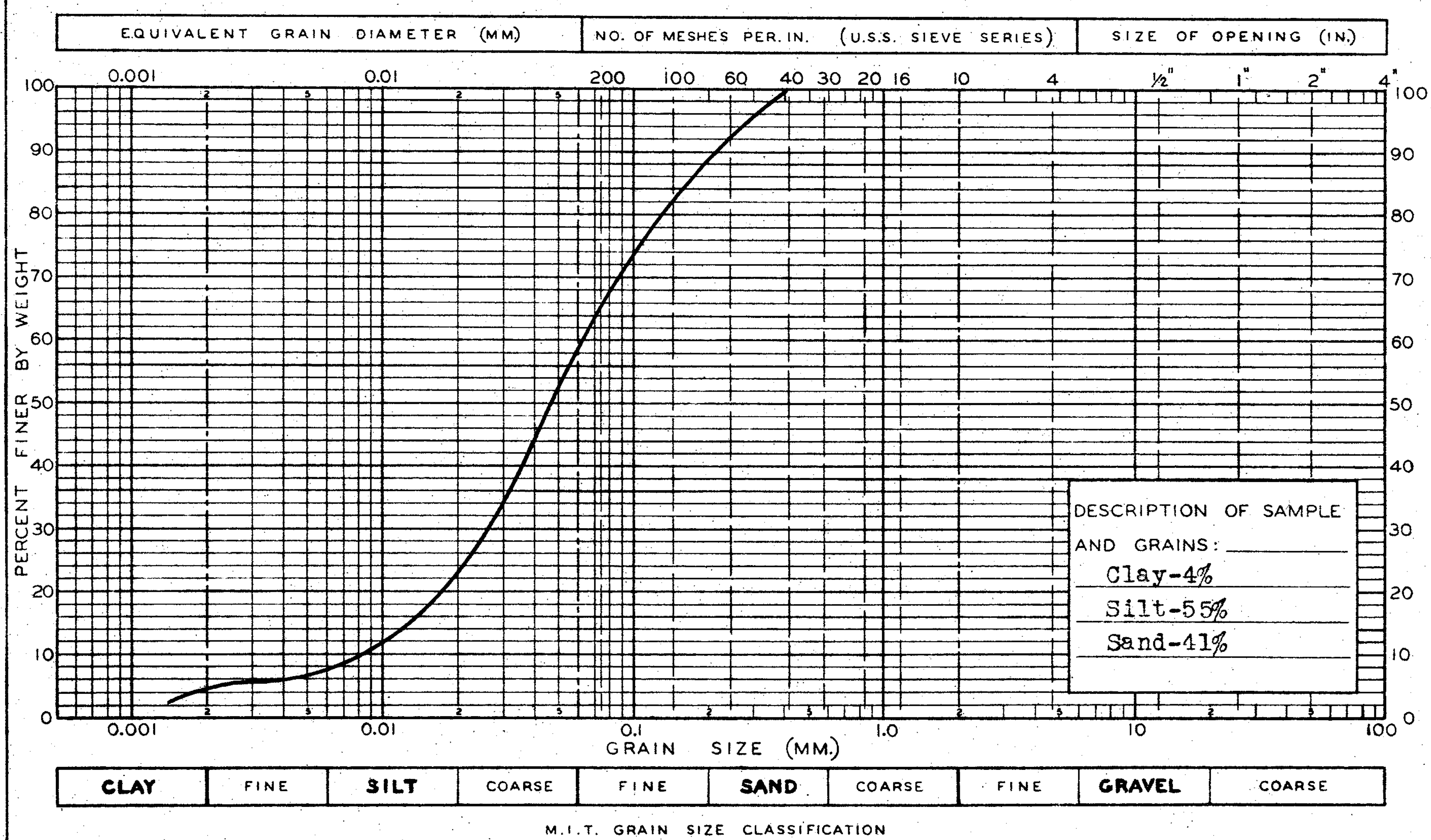
MECHANICAL ANALYSIS OF SOILS



PROJECT: 266 Manitoba Avenue		SAMPLE NO. B, D=4'0"	**SOIL MECHANICS LABORATORY** DEPARTMENT OF CIVIL ENGINEERING UNIVERSITY OF MANITOBA FORT GARRY MANITOBA
PLOTTED: JDM	DATE: Nov. 1958	REMARKS: Undisturbed sample	
CHECKED: JDM	DATE: Nov. 1958		

Plate 19

MECHANICAL ANALYSIS OF SOILS



PROJECT: 266 Manitoba Avenue

SAMPLE NO. C, D=6'0"

PLOTTED: JDM DATE: Nov. 1958

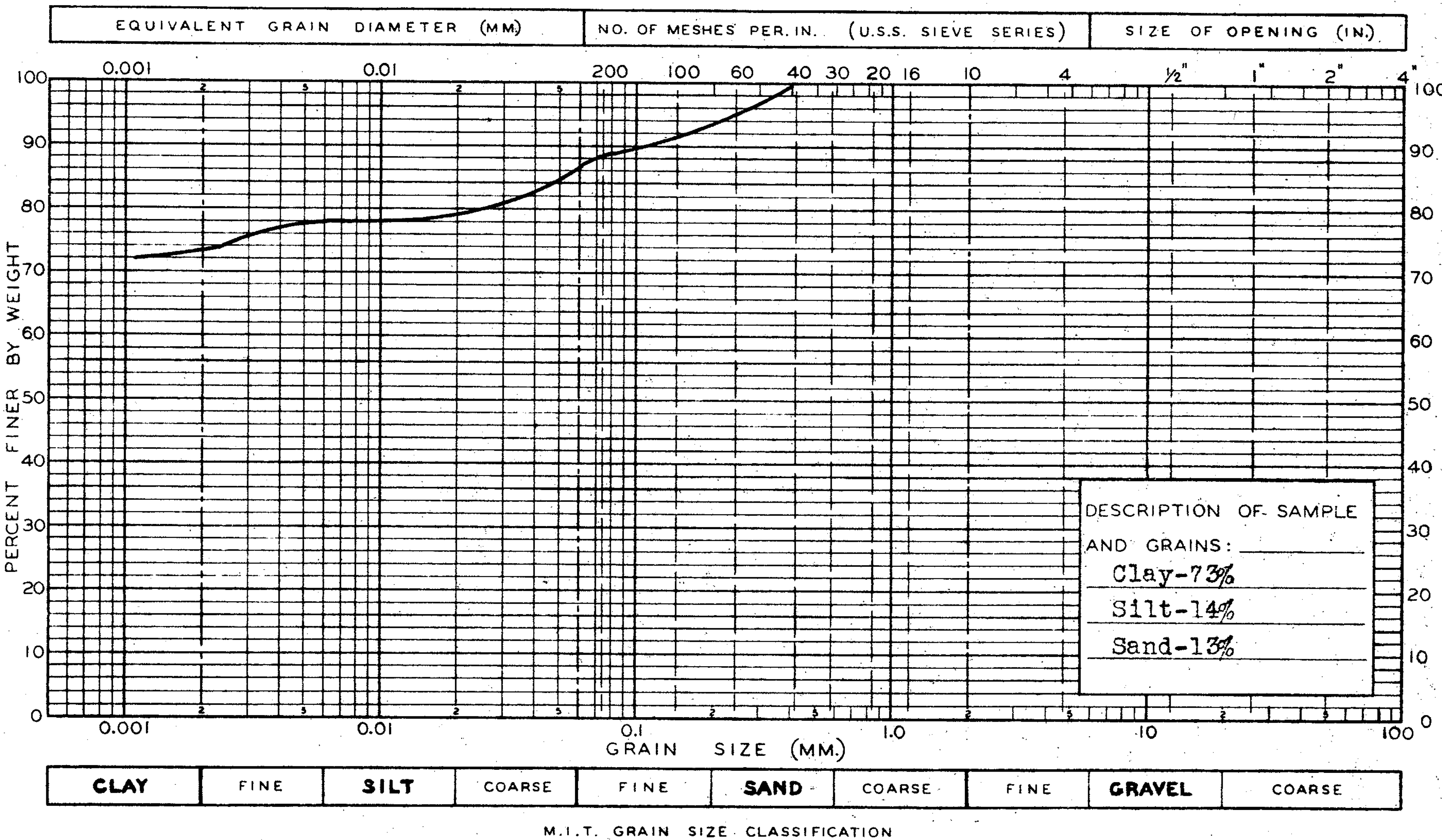
CHECKED: JDM DATE: Nov. 1958

REMARKS: Undisturbed sample

SOIL MECHANICS LABORATORY
DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF MANITOBA
FORT GARRY MANITOBA

Plate 20

MECHANICAL ANALYSIS OF SOILS



PROJECT: 266 Manitoba Avenue

SAMPLE NO. D, D=8'0"

PLOTTED: JDM DATE: Nov. 1958

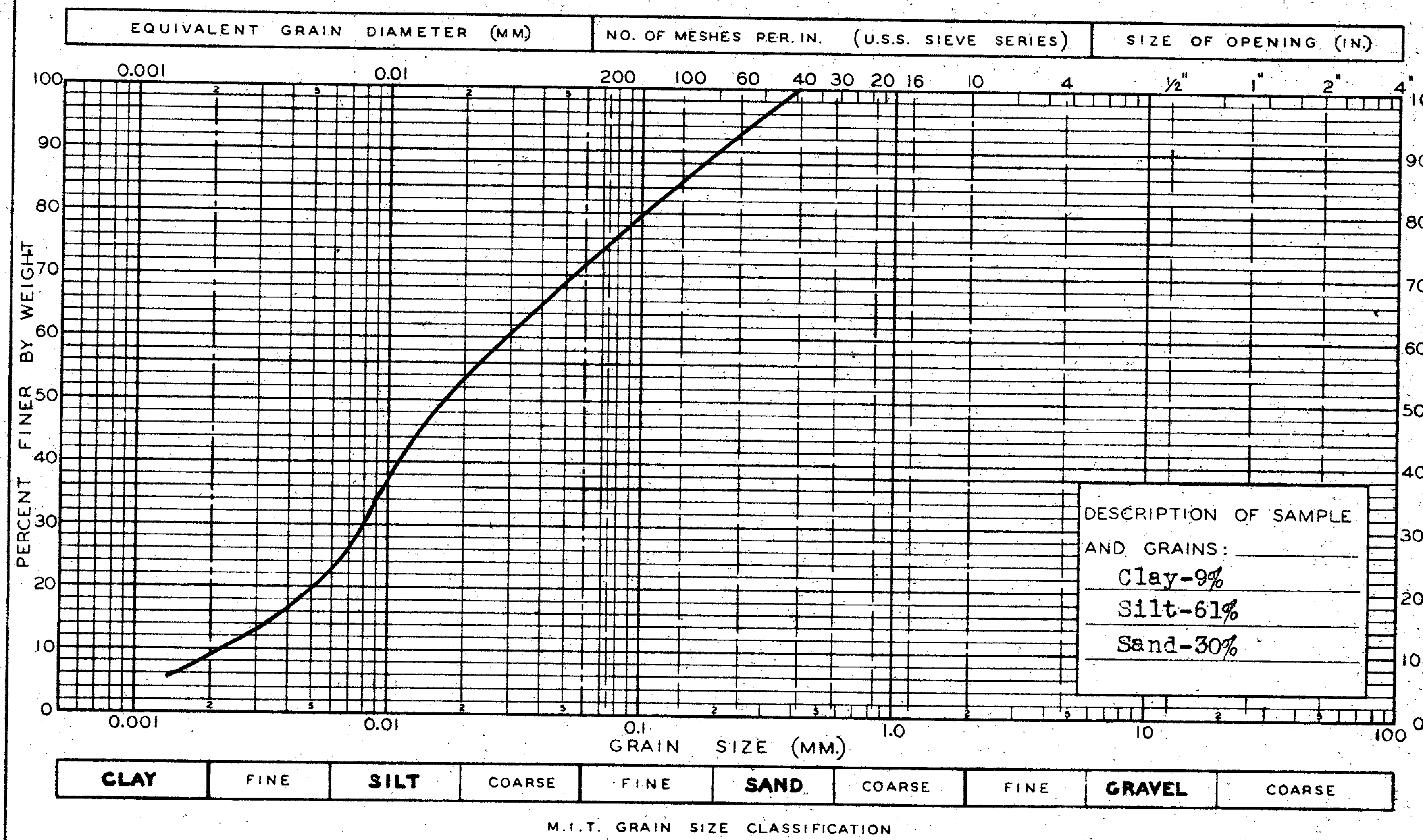
CHECKED: JDM DATE: Nov. 1958

REMARKS: Undisturbed sample

SOIL MECHANICS LABORATORY
DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF MANITOBA
FORT GARRY MANITOBA

Plate 21

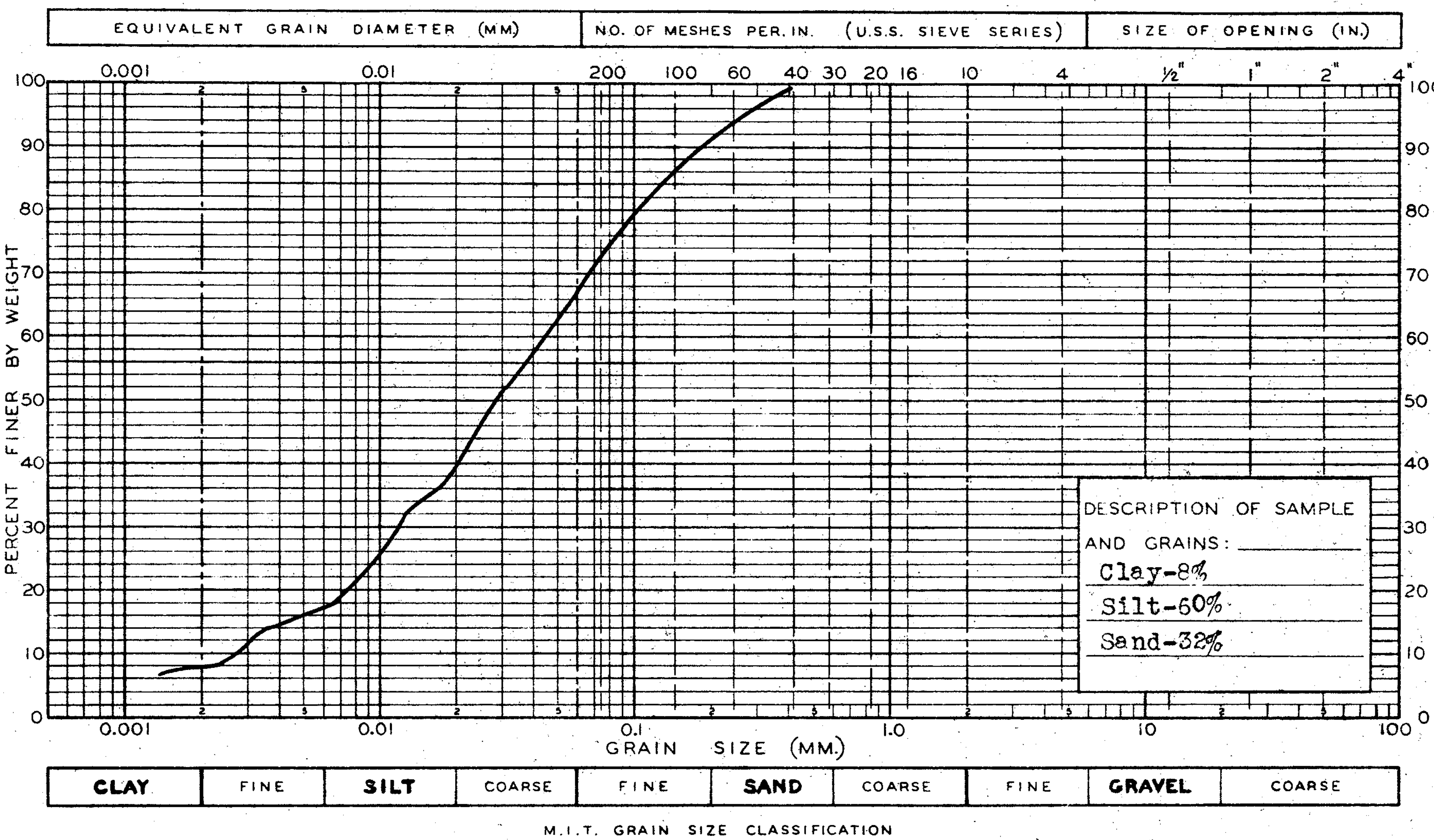
MECHANICAL ANALYSIS OF SOILS



PROJECT: 283 Manitoba Avenue	SAMPLE NO.	**SOIL MECHANICS LABORATORY**
PLOTTED: JDM DATE: Nov. 1958	REMARKS: Backfill soil typical	DEPARTMENT OF CIVIL ENGINEERING, UNIVERSITY OF MANITOBA
CHECKED: JDM DATE: Nov. 1958	for Manitoba Avenue.	FORT GARRY MANITOBA

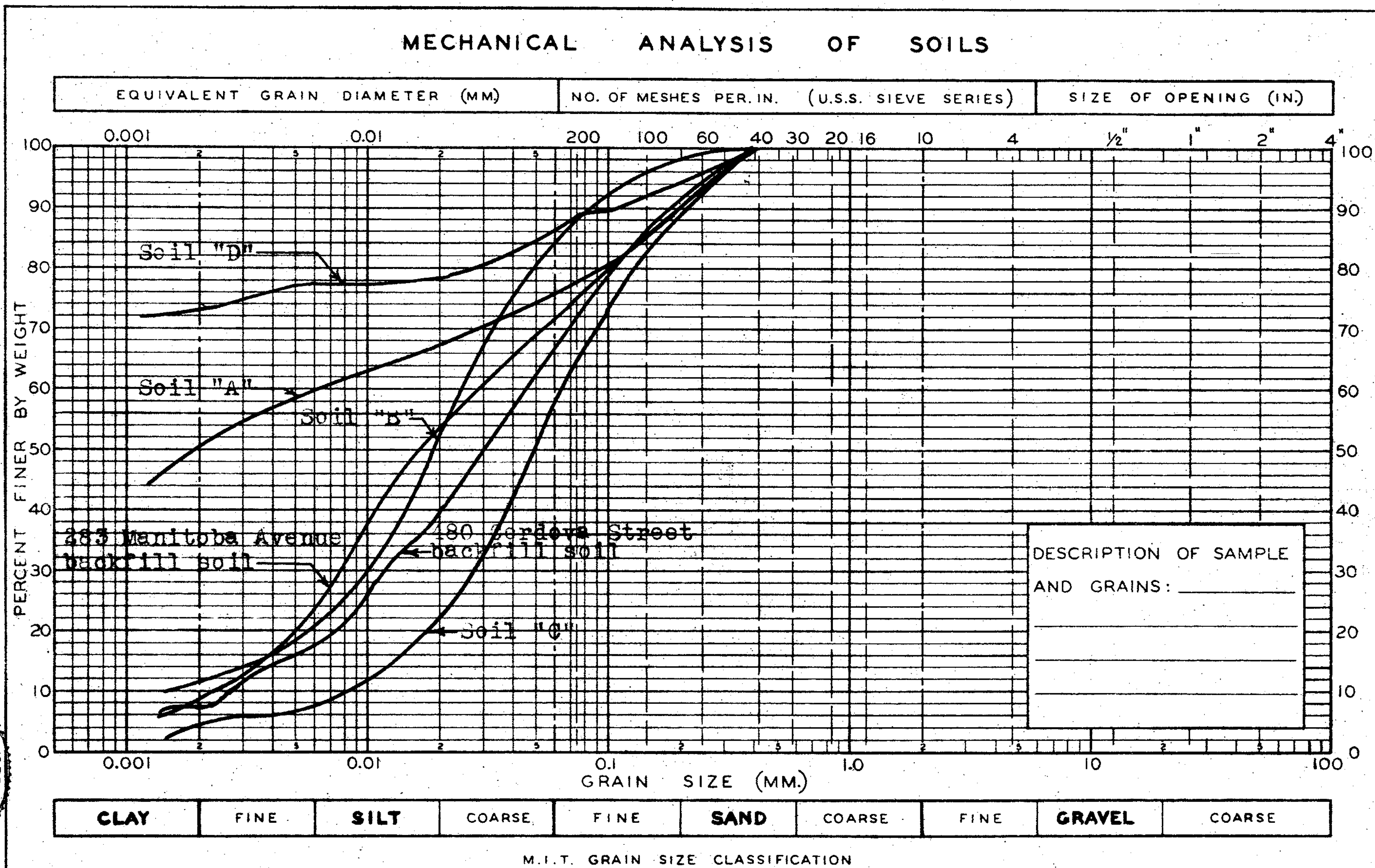
Plate 22

MECHANICAL ANALYSIS OF SOILS



PROJECT: 480 Cordova Street		SAMPLE NO.	**SOIL MECHANICS LABORATORY** DEPARTMENT OF CIVIL ENGINEERING UNIVERSITY OF MANITOBA FORT GARRY MANITOBA
PLOTTED: JDM	DATE: Nov. 1958	REMARKS: Backfill soil typical	
CHECKED: JDM	DATE: Nov. 1958	for Cordova Street.	

Plate 23

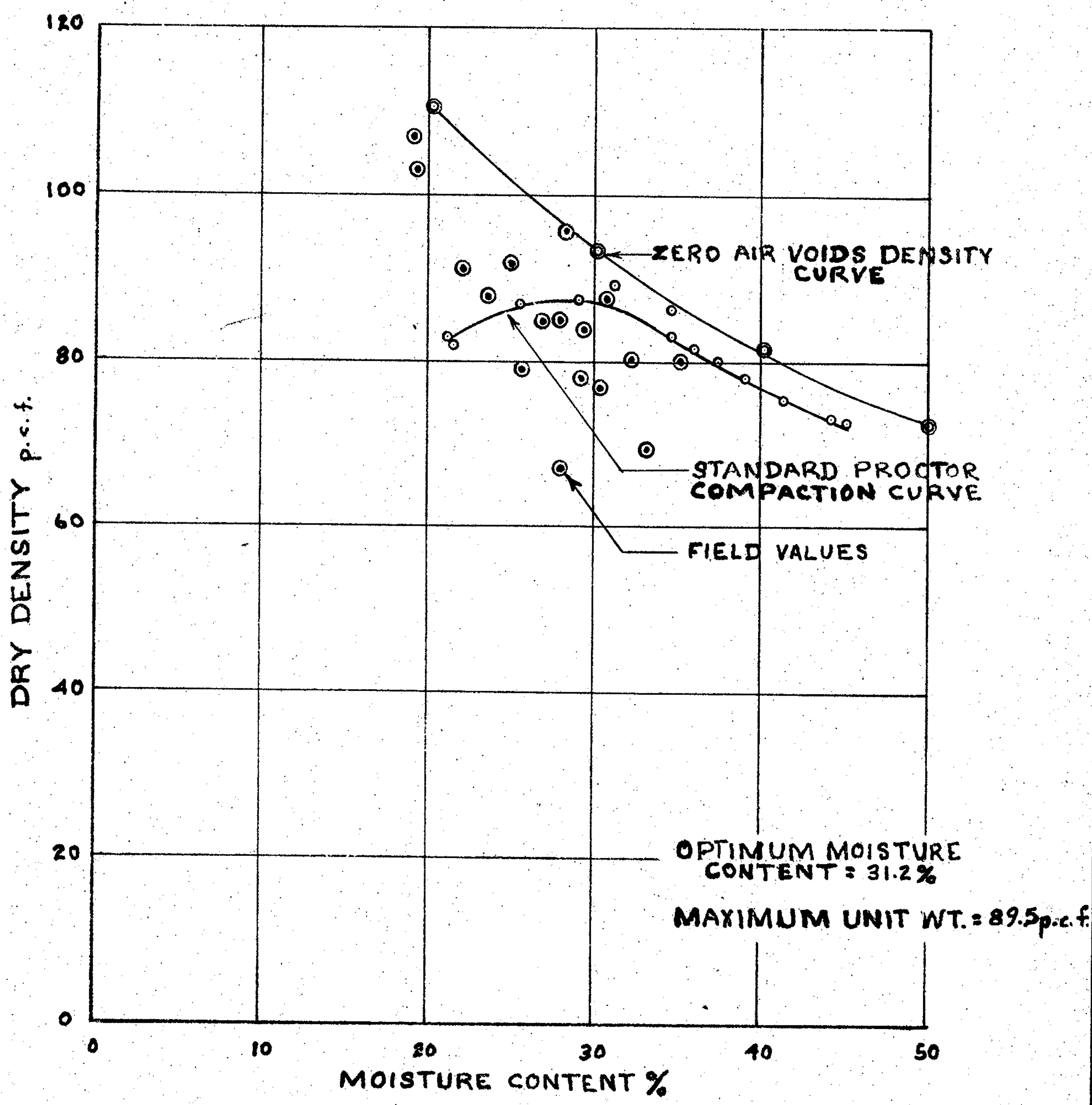


PROJECT: Winnipeg Watermain Backfill Soil	SAMPLE NO.	**SOIL MECHANICS LABORATORY** DEPARTMENT OF CIVIL ENGINEERING UNIVERSITY OF MANITOBA FORT GARRY MANITOBA
PLOTTED: JDM DATE: Nov. 1958	REMARKS: Plots of undisturbed	
CHECKED: JDM DATE: Nov. 1958	and backfill soils	

Plate 24

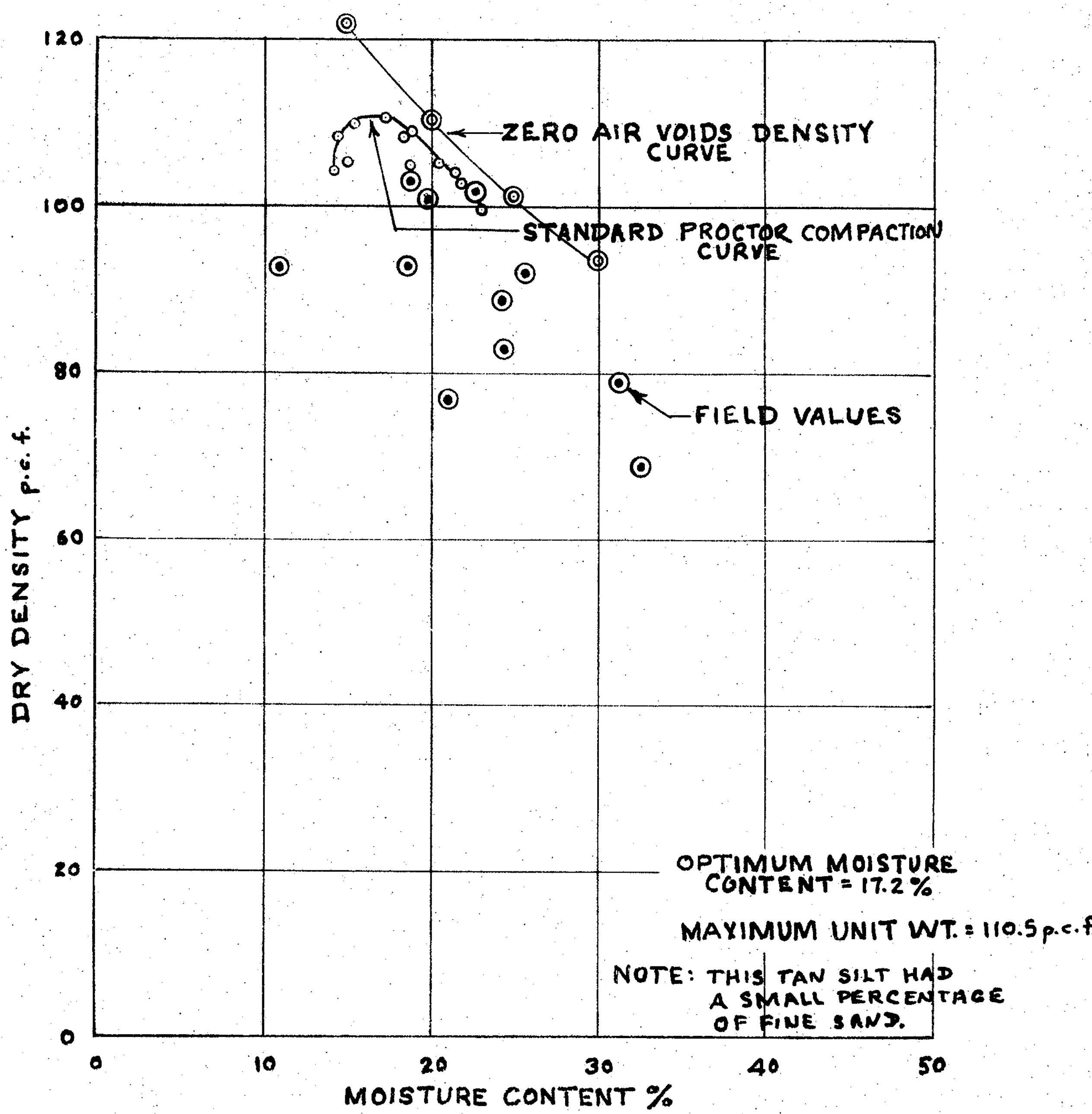
Drawings 1-12

DRY DENSITY vs. MOISTURE CONTENT FOR UNDISTURBED NUGGETY, DARK GREY, SANDY, SILTY CLAY AT DEPTH=2'0" SOIL "A"



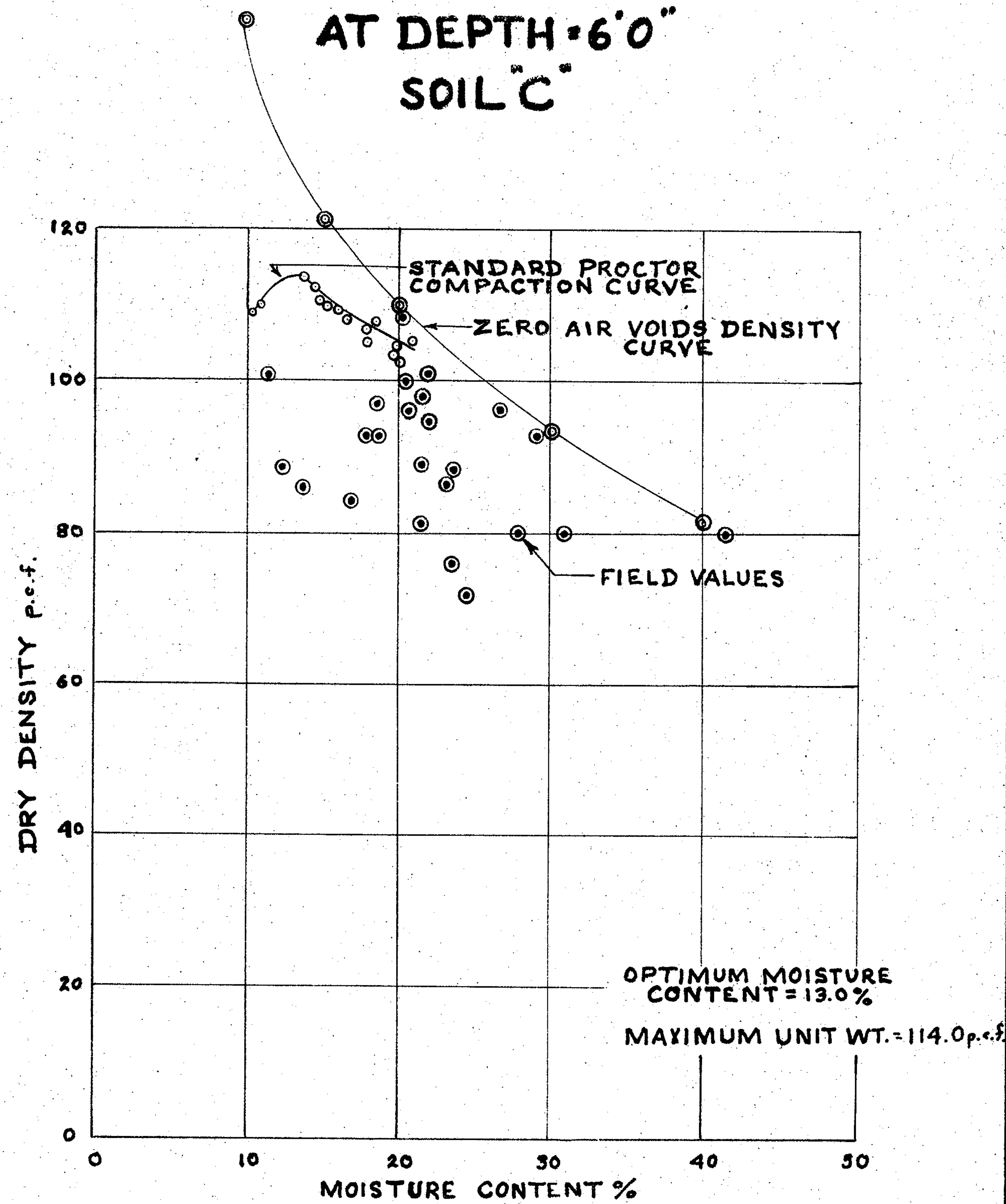
DRAWING 1

DRY DENSITY vs. MOISTURE CONTENT FOR UNDISTURBED TAN SILT AT DEPTH = 4'0" SOIL "B"



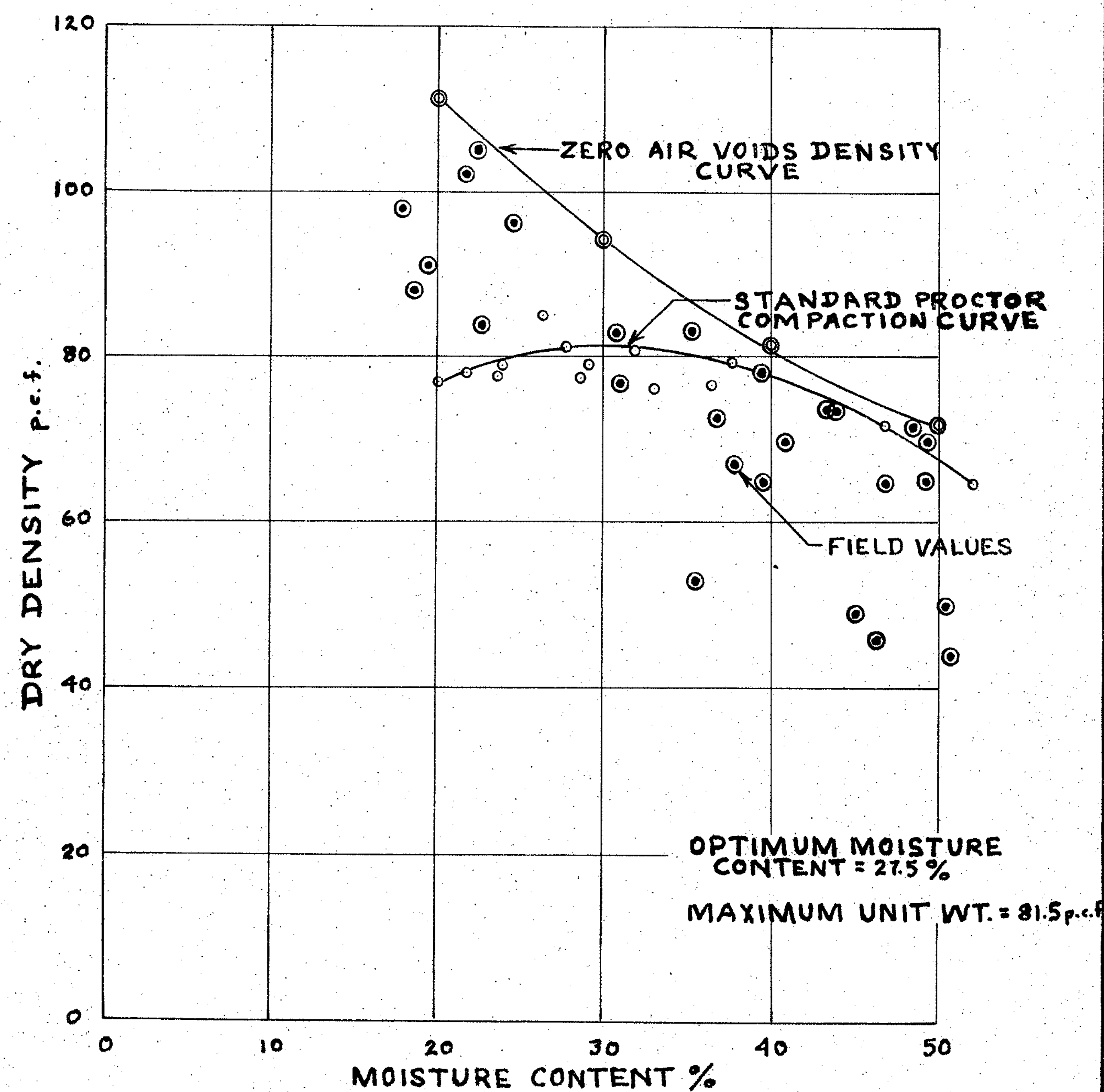
DRAWING 2

DRY DENSITY vs. MOISTURE CONTENT FOR UNDISTURBED TAN SILT AT DEPTH = 6'0" SOIL "C"



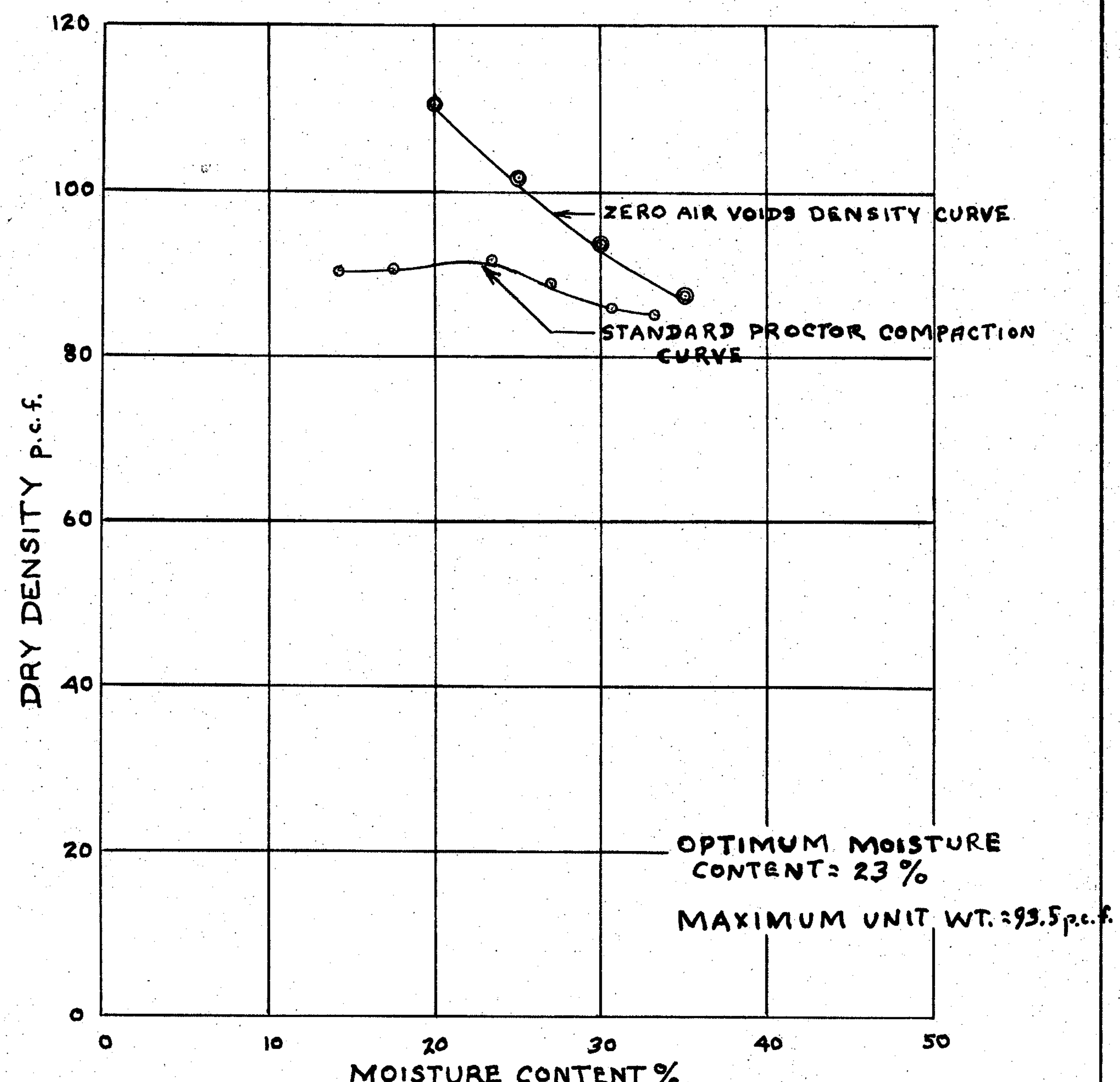
DRAWING 3

DRY DENSITY vs. MOISTURE CONTENT FOR UNDISTURBED NUGGETY, BROWN CLAY AT DEPTH = 8'0" SOIL "D"



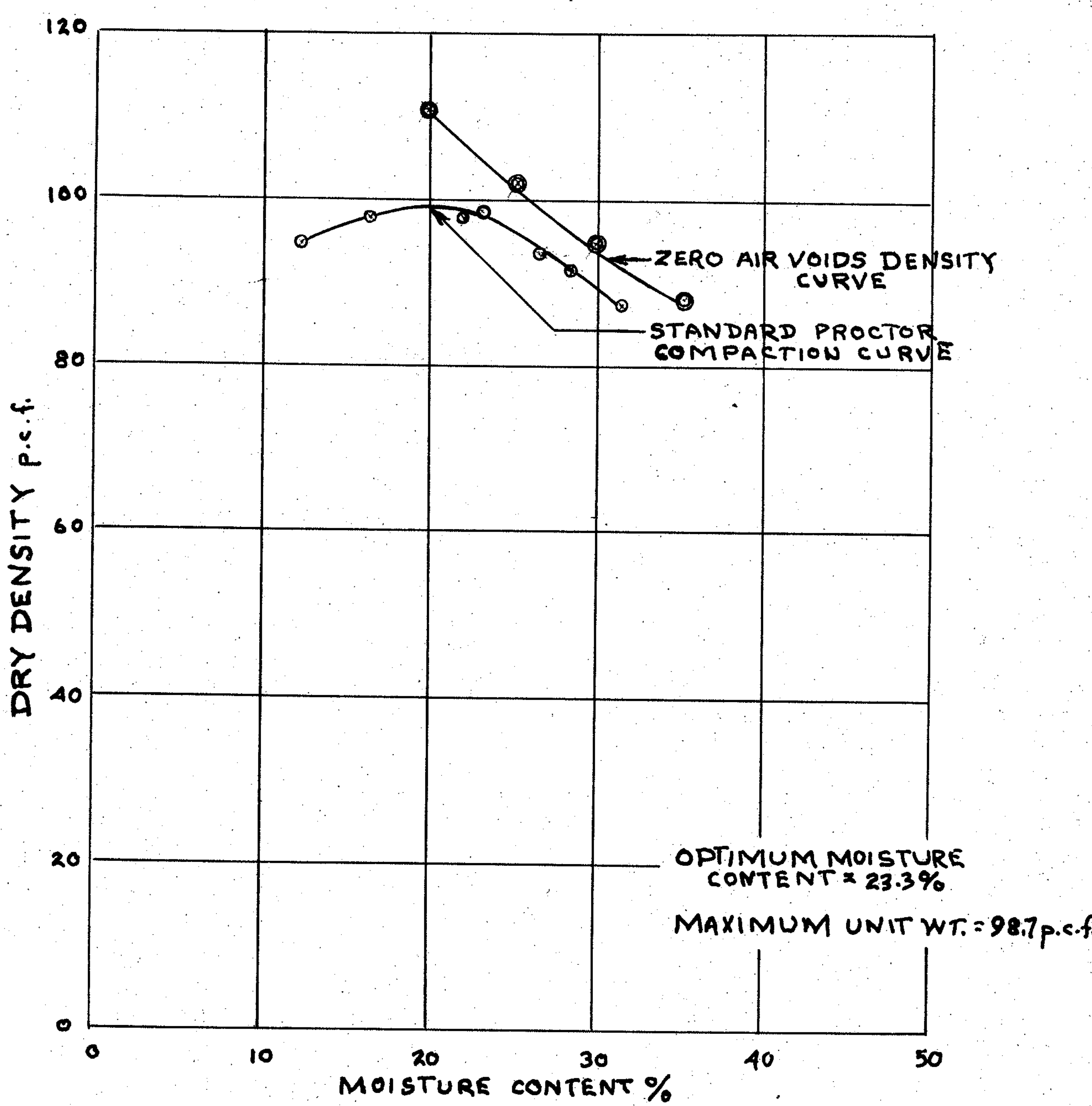
DRAWING 4

DRY DENSITY vs. MOISTURE CONTENT FOR GREY SANDY SILT BACKFILL TYPICAL OF MANITOBA AVENUE



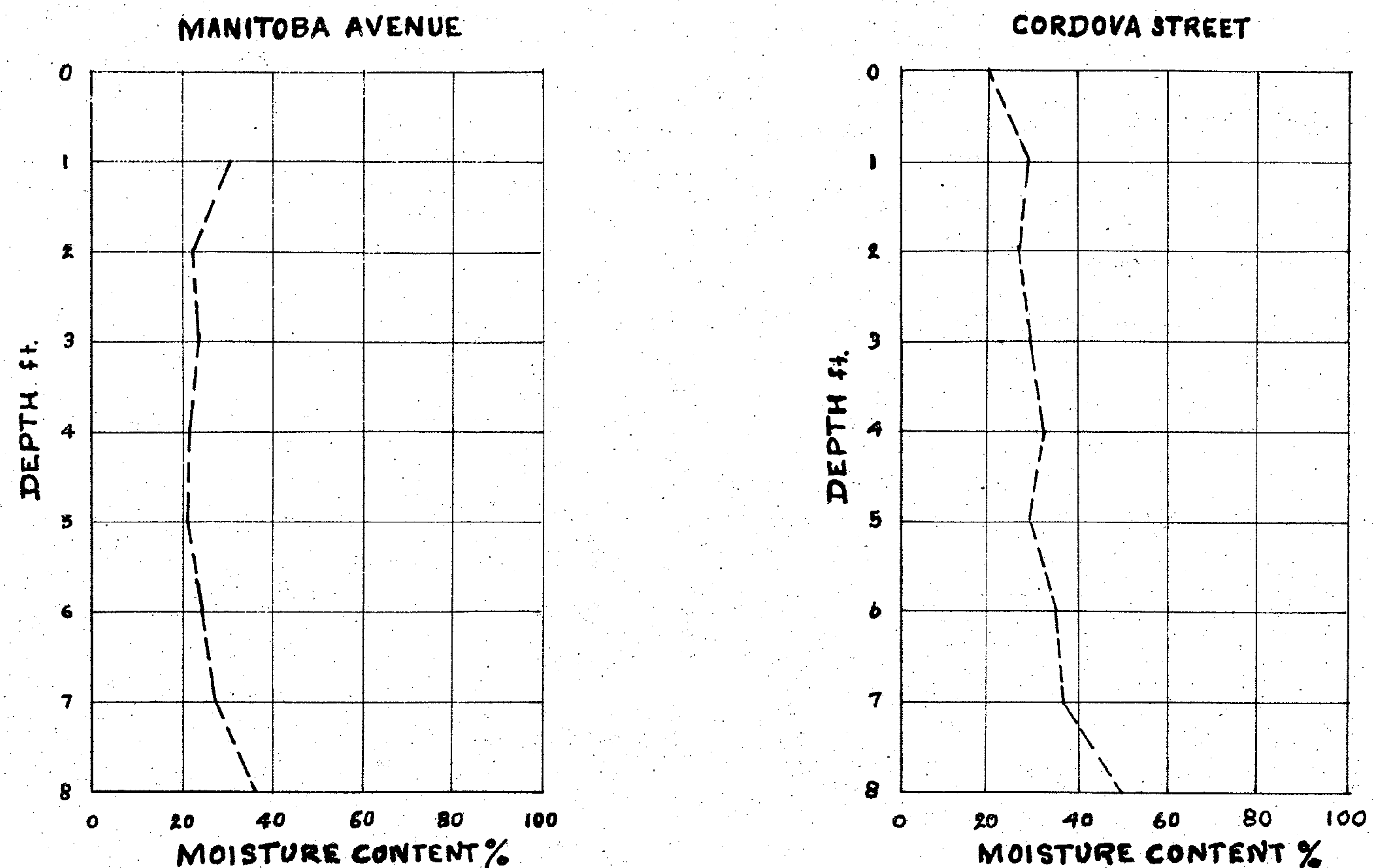
DRAWING 4-1

DRY DENSITY vs. MOISTURE CONTENT FOR GREY SANDY SILT BACKFILL TYPICAL OF CORDOVA STREET



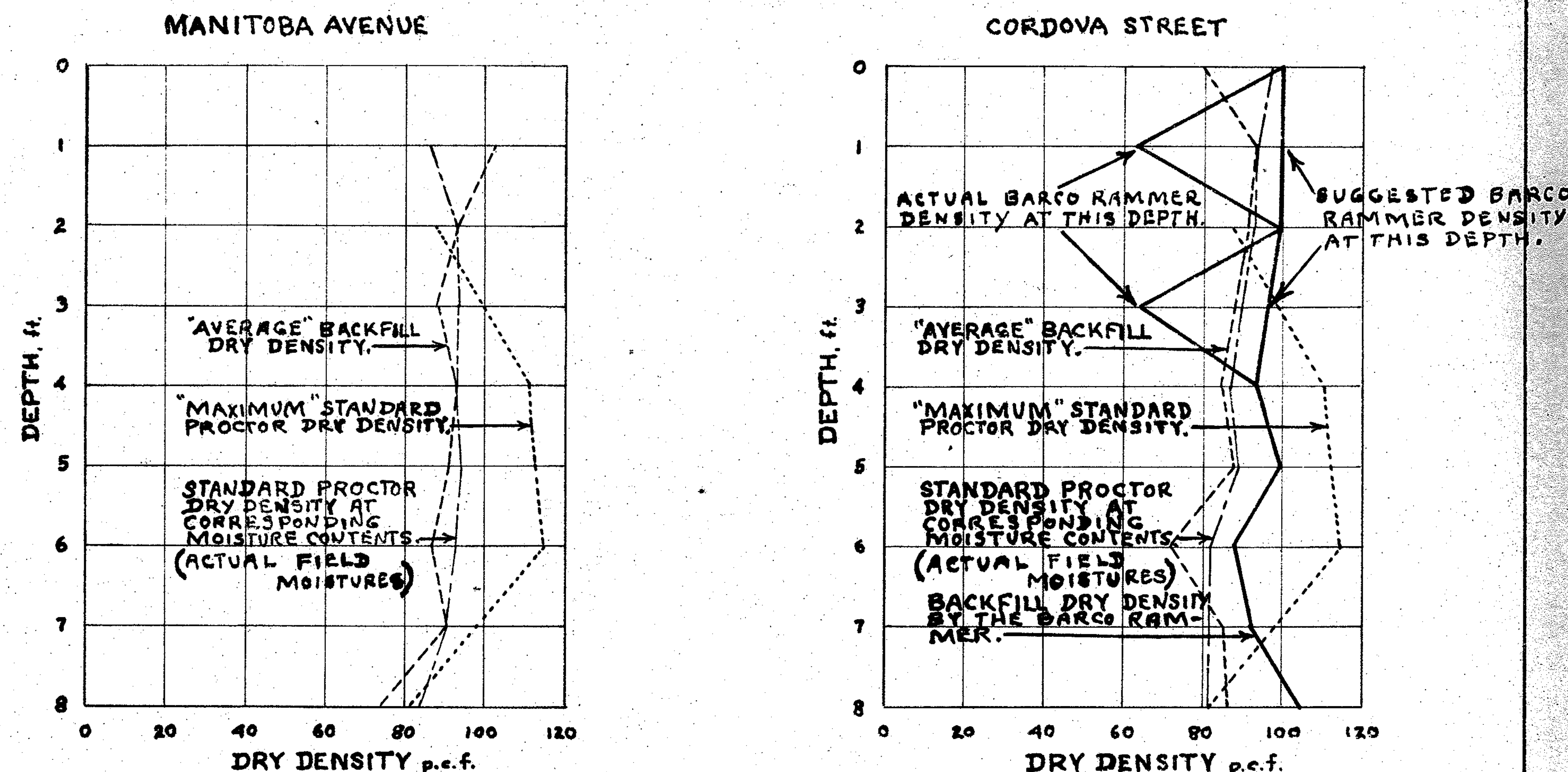
DRAWING 4-2

"AVERAGE" BACKFILL MOISTURE CONTENT PROFILES



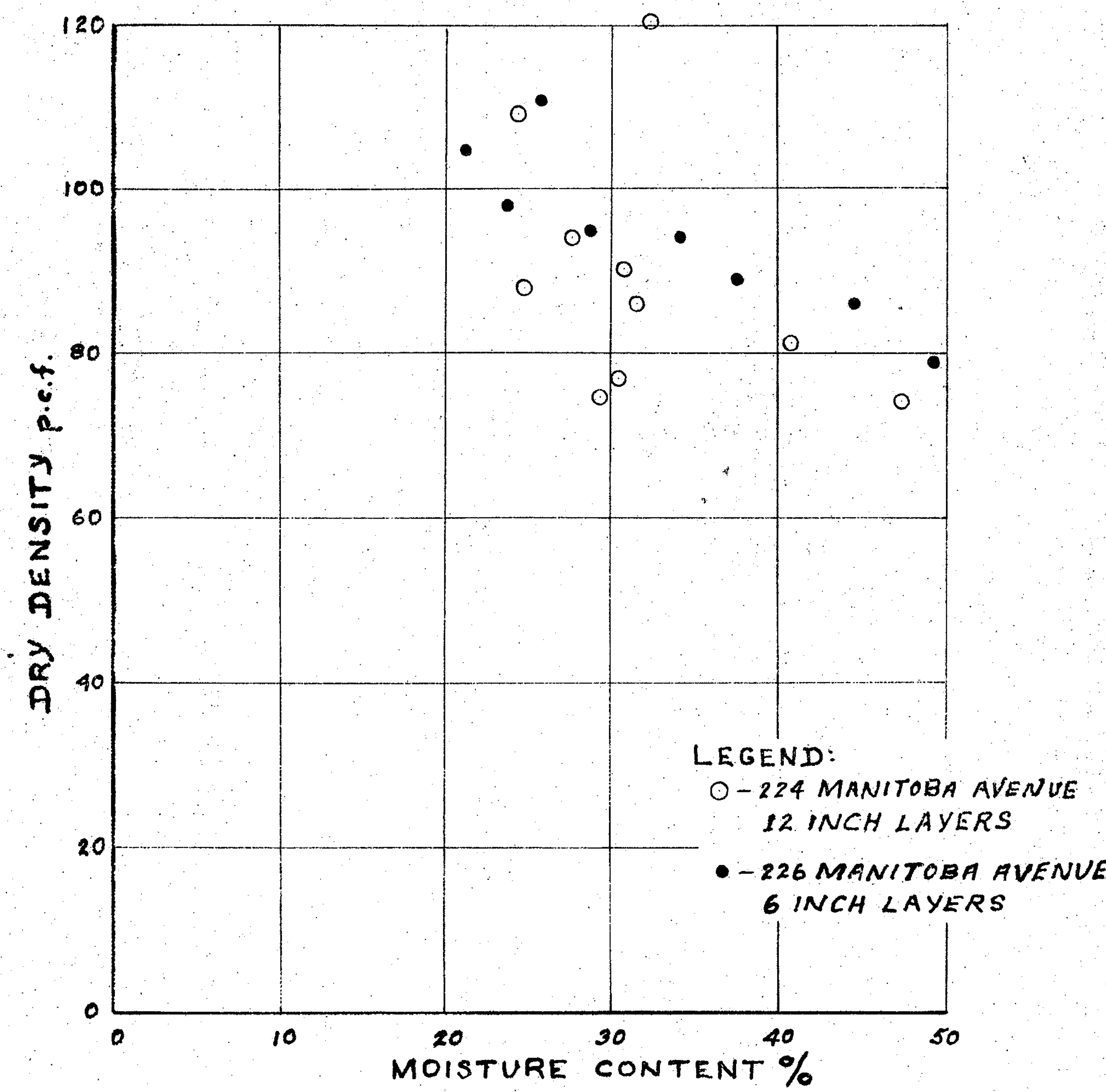
DRAWING 5

"AVERAGE" BACKFILL DRY DENSITY PROFILES



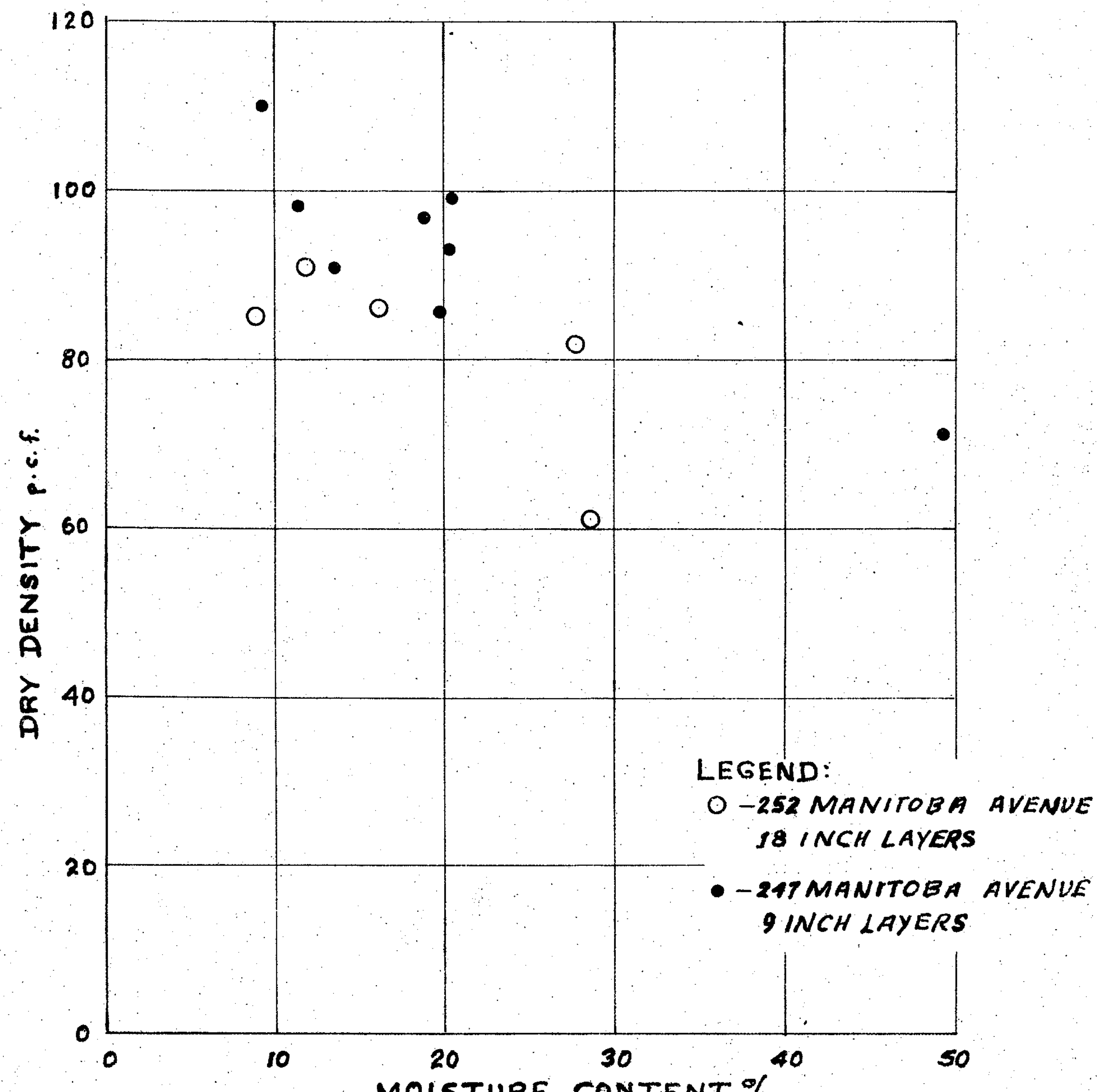
DRAWING 6

DRY DENSITY vs. MOISTURE CONTENT BACKFILL COMPACTED BY THE GARDNER DENVER MECHANICAL TAMPER



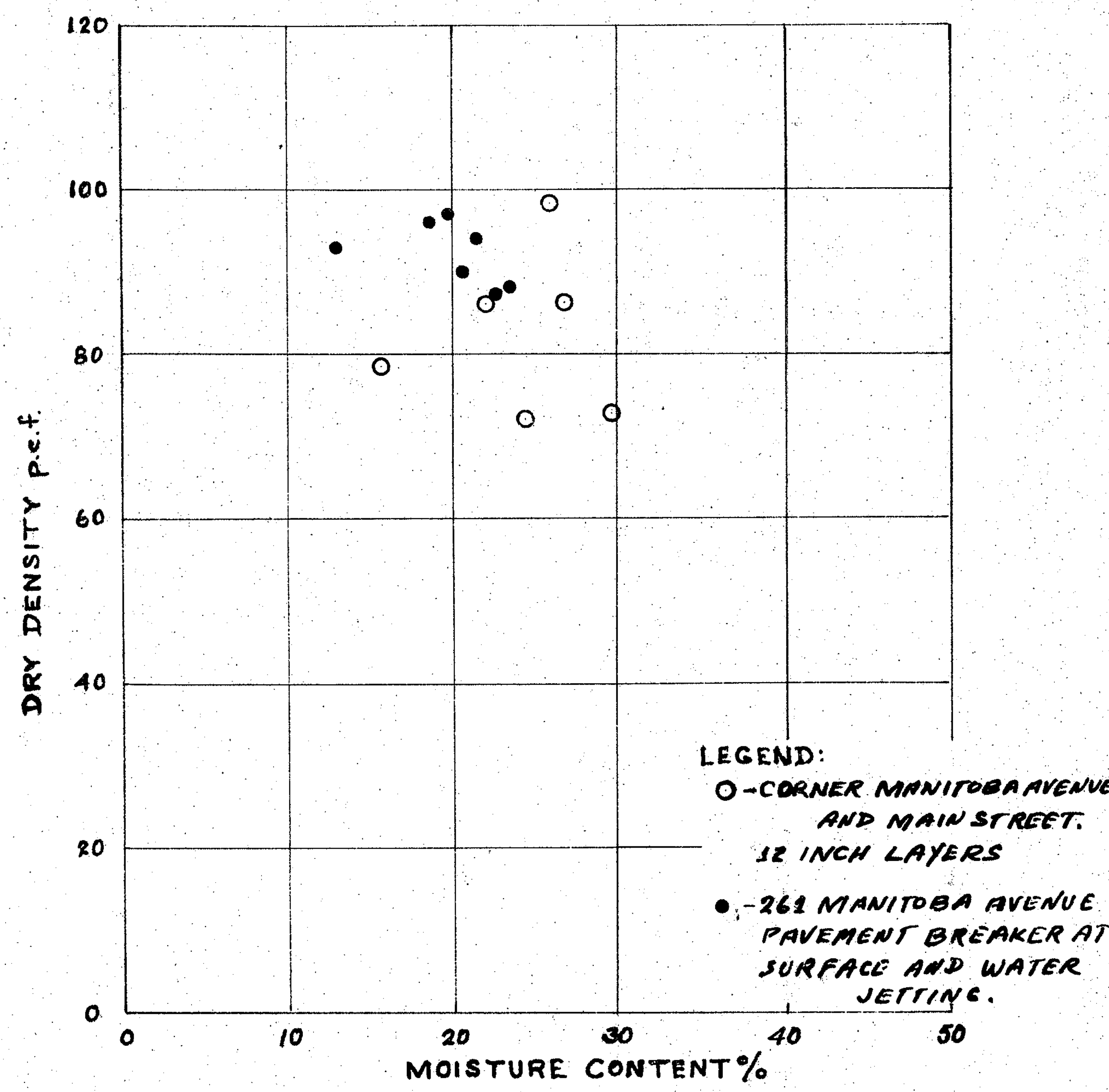
DRAWING 7

DRY DENSITY vs. MOISTURE CONTENT BACKFILL COMPACTED BY THE LE ROI TAMPER



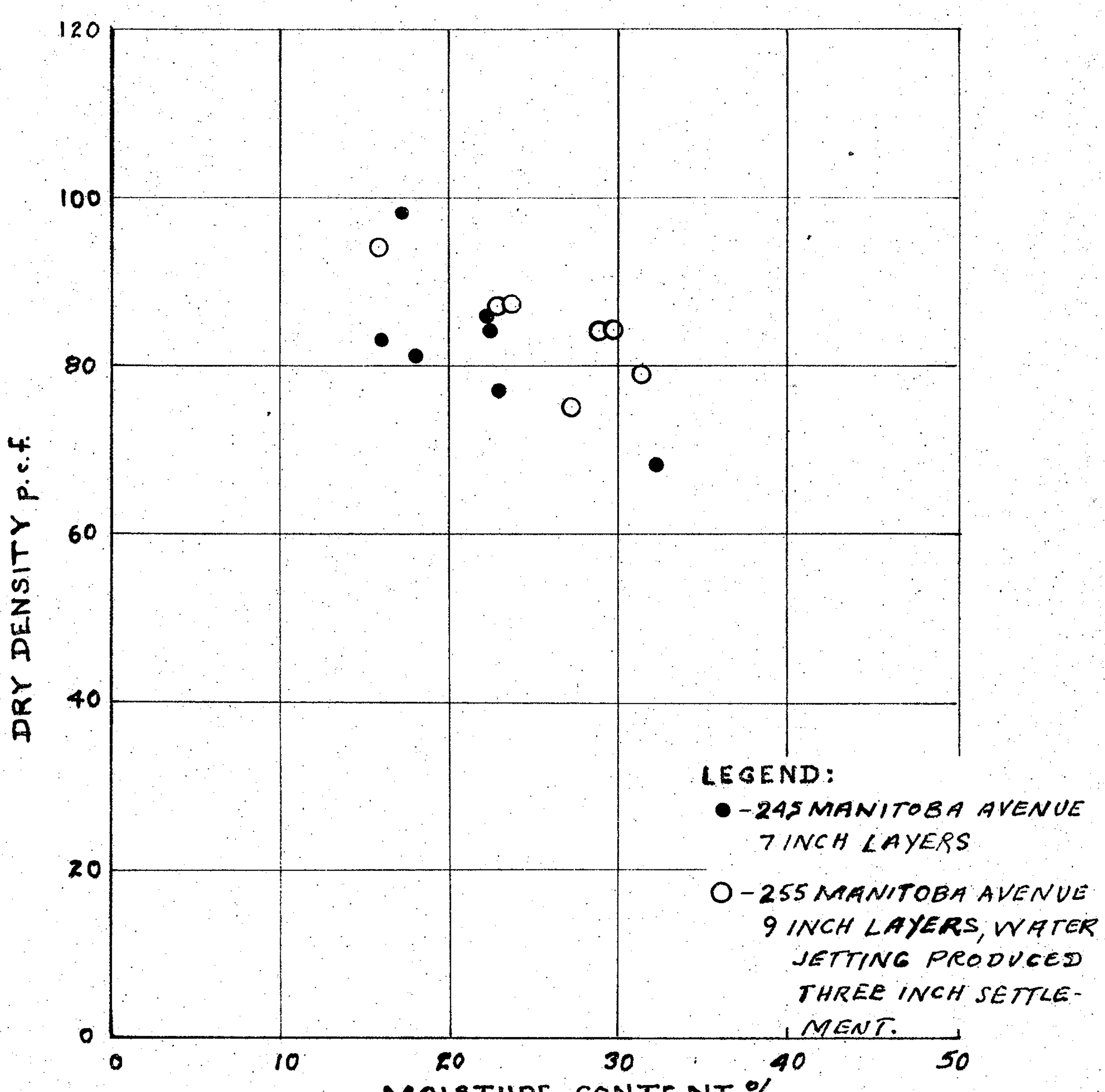
DRAWING 8

DRY DENSITY vs. MOISTURE CONTENT BACKFILL COMPACTED BY THE PAVEMENT BREAKER TAMPER



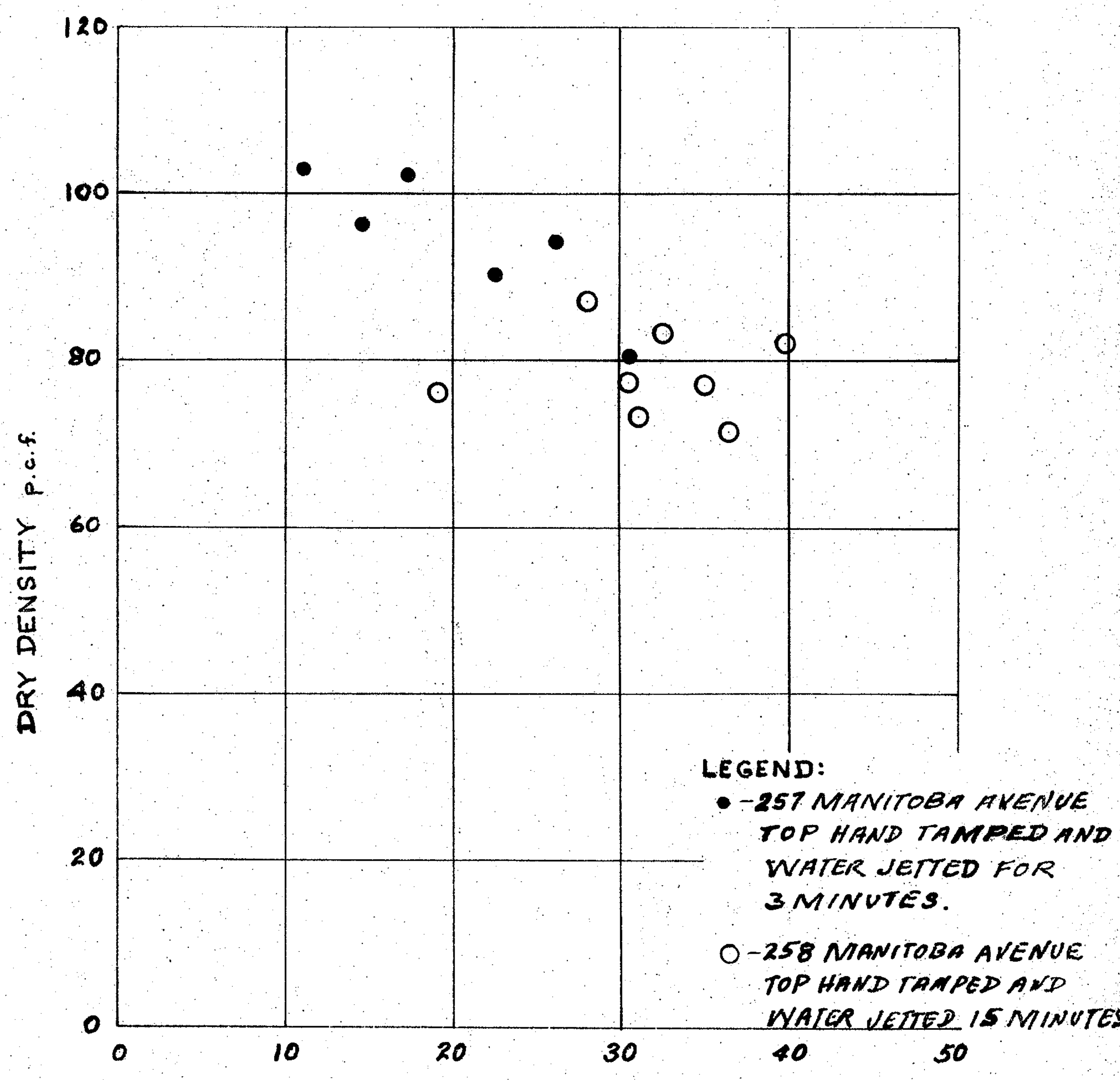
DRAWING 9

DRY DENSITY vs. MOISTURE CONTENT BACKFILL COMPACTED BY THE HAND TAMPER



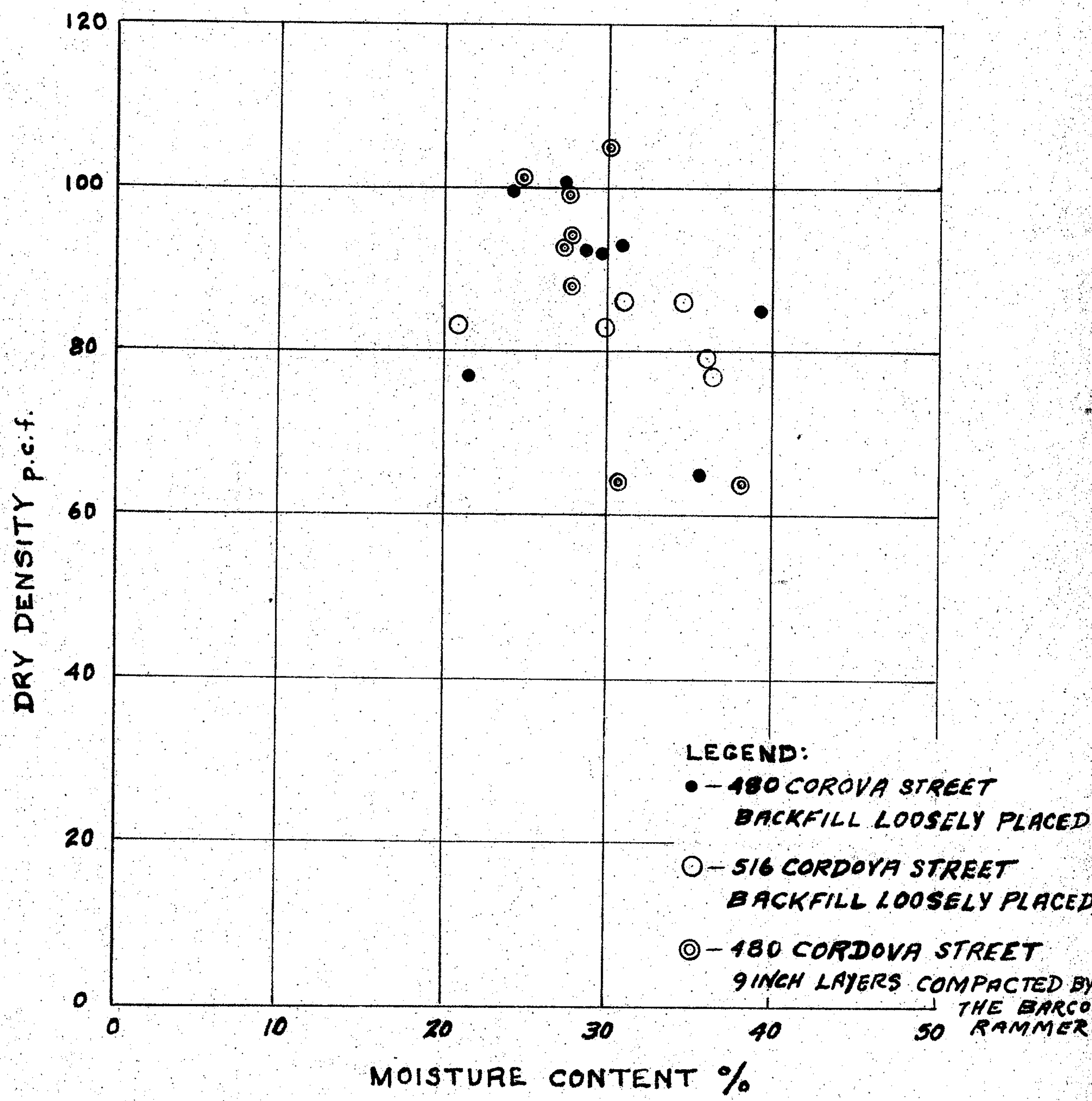
DRAWING 10

DRY DENSITY vs. MOISTURE CONTENT BACKFILL COMPACTED BY HAND TAMPING AND WATER JETTING



DRAWING 11

DRY DENSITY vs. MOISTURE CONTENT BACKFILL LOOSELY PLACED AND BACKFILL COMPACTED BY BARCO RAMMER



DRAWING 12

DISCUSSION

To study significant relationships of soil densities, moisture contents and depth, Drawings 1 to 12 have been prepared. Drawings 1 to 4 contain plots of dry density versus moisture content, standard proctor compaction curves and zero air voids dry density curves for undisturbed soils designated A, B, C and D, corresponding to depths of two, four, six and eight feet respectively. Drawings 4-1 and 4-2 contain plots of dry density versus moisture content and zero air voids dry density curves for backfill soils on Manitoba Avenue and Cordova Street. Drawing 5 consists of plots of "average" backfill moisture content versus depth for Manitoba Avenue and for Cordova Street. Drawing 6 illustrates "average" backfill dry density variation with depth for Manitoba Avenue and Cordova Street. Maximum standard proctor dry density versus depth curves have also been plotted. The Barco Rammer backfill dry density versus depth curve for Cordova Street has been plotted as a comparison with "average" backfill dry densities and maximum proctor densities. In addition, plots of densities obtained by the standard proctor compaction at moisture contents corresponding to "average" backfill moisture contents for the respective depths have been drawn for both Manitoba Avenue and Cordova Street.

Drawings 7 to 12 are plots of dry density versus moisture content as determined during the 1958 investigation for backfill compacted in layers of varying thickness and by several methods as indicated.

The results of the investigation have been discussed under the following headings.

(a) Undisturbed Soil Densities

The dry density versus moisture content plots for the undisturbed soils were found not to follow any pattern. An exception must be made for soil D, for which the plot of densities appeared to parallel the zero air voids dry density curve. No relationship was found between depth and density for any of the soils.

Individual plots of the standard proctor dry density versus moisture content for soils A, B, C, D, indicated the following. For clay type soils, A and D, undisturbed field densities were found to be both higher and lower than standard proctor densities. This indicates that a compactive effort, equivalent to the standard proctor, could produce densities both higher and lower than those in the undisturbed soils. For soils B and C (both silts) the standard proctor densities were found to be generally higher than the undisturbed field densities. Therefore, a compactive effort equivalent to the standard proctor would produce densities higher than existing field densities in the undisturbed silts.

A plot of the zero air voids dry density curve for each of the four soil types showed that some field densities in the undisturbed soils were equivalent to zero air voids dry density. This indicates that because of complete saturation higher densities are not possible without loss of moisture.

(b) "Average" Backfill Dry Density

"Average" backfill dry densities, that is, an average value of all the densities determined at corresponding depths, maximum standard proctor dry densities and standard proctor dry densities corresponding to average moisture contents at the depths shown have been plotted in Drawing 6 for Manitoba Avenue and Cordova Street. For Cordova Street a plot of depth versus backfill dry density produced by the Barco Rammer has also been included.

An analysis of Drawing 6 indicates several significant points as follows:

MANITOBA AVENUE

I) Backfill dry density decreased with depth from the surface to the three foot depth. This indicates that a higher compactive effort had been exerted as the backfilling approached the surface.

2) Maximum standard proctor dry density was found to be greater than backfill dry density at four, six and eight foot depths. On the basis of density along, this is not a fair comparison because natural moisture contents in the backfill were much higher than optimum as indicated by the standard proctor compaction curves. This does, however, show that with proper moisture content control while compacting, densities higher than existing backfill densities are possible.

3) "Average" backfill dry density was found to be slightly less than standard proctor dry density at corresponding moisture contents. The compactive effort applied to the backfill was therefore slightly less than that of the standard proctor assuming existing moisture contents reasonably comparable to those at the time of backfilling.

CORDOVA STREET

I) It was found that backfill dry density increased from the surface to the one foot depth and decreased from the one foot depth to the four foot depth. Since the only compaction applied to this backfill was that of equipment travelling on the surface of the backfilled trench, the densities indicate that this compactive effort had an effect to a depth of four feet in loosely placed backfill. The lower densities above the one foot depth are likely the result of disturbance during subsequent landscaping. Below the four foot depth, erratic variations in density indicate little if any effect from surface compaction.

2) Maximum dry densities by standard proctor compaction were found to be greater than backfill dry densities at the four, six and eight foot depths as was also observed on Manitoba Avenue. This indicates that higher densities in the backfill are possible at optimum

moisture content with a compactive effort equivalent to that of the standard proctor.

3) "Average" backfill dry densities were found to be only slightly less than standard proctor dry densities at corresponding moisture contents. This indicates that the compactive effort applied to the backfill was less than that produced by the standard proctor test. This was evident inspite of any consolidation which would have tended to increase backfill densities.

4) Backfill dry densities by the Barco Rammer were found to be higher than average backfill dry densities and also higher than standard proctor dry densities at corresponding moisture contents. This comparison indicates that a single pass of the Barco Rammer, per nine inch layer of soil, produced densities from ten to eighteen pounds per cubic foot higher than densities in loosely placed backfill receiving only surface compaction from a moving tractor and having consolidated for seven years.

5) At the four and six foot depths the dry densities of the backfill compacted by the Barco Rammer were found to be less than the maximum standard proctor dry densities on the tan silts. This is not a fair comparison as the backfill at these depths consisted of a mixture of clay and silt.

"Average" Backfill Moisture Content

The plot of dry density versus moisture content for Manitoba Avenue indicated a decrease in moisture content between the one to five foot depths followed by a gradual increase to the eight foot depth. The plot for Cordova Street shows a gradual increase in moisture content between the surface and the eight foot depth. This difference can possibly be attributed to more closely spaced and larger trees along Manitoba Avenue as compared to Cordova Street. Past studies have shown that tree growth can remove large amounts of moisture from the soil. It is suspected that moisture removal by trees resulted in the lower moisture contents on Manitoba Avenue. With lower moisture contents nearer to the optimum for compaction, higher backfill densities would result. This leads to the belief that along streets with trees, excavated soils would have moisture contents more nearly at the optimum for maximum density than on streets with negligible tree growth.

COMPACTION EQUIPMENT

The dry densities produced by various methods of compaction have been plotted against moisture contents at the time of investigation, in Drawings 7 to I2 to determine and study any significant relationships. For each method of compaction two plots were made utilizing a different thickness of compacted soil layer to compare densities produced. A direct comparison of resulting densities could not be made because the moisture contents were not equal. A comparison of densities using optimum moisture contents could not be made either because the optimum moisture content listed was that determined for one representative sample and not necessarily the same for all the samples.

In Table 3 the optimum moisture contents are those determined for the backfill soils at 257 Manitoba Avenue and 480 Cordova Street only. A thorough laboratory analysis was not conducted on the backfill material at each location.

Table 3 is a tabulation of summarized compaction data for various types of compaction apparatus.

TABLE 3 COMPACTION DATA

Location	Compaction Apparatus	Thicknesses of* Soil Layer, ins.	Average** Moisture Content	Optimum*** Moisture Content	Average Dry Density p.c.f.
224 Manitoba Ave.	Gardner Denver	12	30.9	23.5	90.4
226 Manitoba Ave.	Gardner Denver	6	34.0	23.5	94.3
252 Manitoba Ave.	Le Roi Tamper	18	16.1	23.5	86.0
247 Manitoba Ave.	Le Roi Tamper	9	20.2	23.5	93.3
261 Manitoba Ave.	Pavement Breaker	Surface Compacted	19.9	23.5	92.1
Manitoba Ave. & Main St.	Pavement Breaker	12	24.0	23.5	82.3
255 Manitoba Ave.	Hand Tamper and Water Jet	9	25.5	23.5	84.3
245 Manitoba Ave.	Hand Tamper	7	21.4	23.5	81.0
257 Manitoba Ave.	Hand Tamper and 3 minutes Water Jet		20.3	23.5	94.2
258 Manitoba Ave.	Hand Tamper and 15 minutes Water Jet		31.4	23.5	78.1
480 Cordova St.	Loosely Placed surface compacted by tractor		31.8	23.3	87.0
516 Cordova St.	Loosely Placed surface compacted by tractor		30.9	23.3	82.5
480 Cordova St.	Barco Rammer	9	29.4	23.3	88.5

* - From City of Winnipeg records.

** - Moisture contents at time of investigation in 1958

*** - From standard Proctor test on representative samples.

A study of the dry density versus moisture content plots (Drawing 7) for the Gardner Denver compactor reveals an erratic scattering of points. It is, however, evident that for the backfill at 226 Manitoba Avenue the optimum moisture content is in the vicinity of 25%. The average density for soil compacted in six inch layers is 94.3 pounds per cubic foot at 34.0% moisture content and 90.4 pounds per cubic foot at 30.9% moisture content when compacted in twelve inch layers.

Similarly, plots of dry density versus moisture content for the Le Roi tamper do not follow any pattern. It may be noted though, that most of the moisture contents are below optimum. The average dry densities are 93.3 pounds per cubic foot at 20.2% moisture content and 86.0 pounds per cubic foot at 16.1% moisture content corresponding to backfill soil layers of 9 and 18 inches, respectively.

The Pavement Breaker produced an average dry density of 92.1 pounds per cubic foot at 19.9% moisture content when tamped at the surface only, as compared to 82.3 pounds per cubic foot at 24.0% moisture content when tamped in twelve inch layers.

A study of the results produced by the hand tamper shows that the average backfill densities are lower than those produced by any other method. The resulting average dry density was found to be higher when hand tamping was combined with some water jetting even though the layers of soil were nine inches thick for the jetted location as compared to seven inch layers for the non-jetted location. Hand tamping in ten inch layers assisted by water jetting for several minutes produced an average dry density equivalent to the density obtained by compacting six inch layers of soil with the Gardner Denver compactor. This, however, can be accounted for by the difference in moisture contents, being 20.3% for the hand tamper (optimum moisture content for 257 Manitoba Avenue was found to be 23.5%) and 34.0% for the Gardner Denver compactor. Further study of the hand tamping results, when assisted by water jetting, indicated a high moisture content corresponding to a long water jetting period. This shows that the moisture added to the backfill by water jetting has been partially retained.

Loosely placed, surface compacted backfill on Cordova Street was found to have an average density less than that produced by hand tamping assisted by water jetting and higher than hand tamping without water jetting. Average densities for the above are 84.8 pounds per cubic foot, 86.2 pounds per cubic foot and 82.7 pounds per cubic foot, respectively. This is not considered to be a fair comparison because an insufficient number of densities are available for Cordova Street which may not be representative of loosely placed, surface compacted backfill.

It is believed that some error exists in the backfill densities produced by the Barco Rammer at 480 Cordova

Street at the one and three foot depths. However, even when using the actual determined densities at these two depths the average backfill density at 88.5 pounds per cubic foot is still higher than that produced by hand tamping, loosely placed (surface compacted) backfill, hand tamping assisted by water jetting, or Pavement Breaker compaction. Omitting the calculated densities at the one and three foot depths would produce an average backfill density higher than that produced by any other means of compaction.

Very significantly, dry densities were generally found to be higher where a thinner layer had been used in compaction. This was indicated even after several years from the time of compaction to the time of investigation. It also indicates that the higher densities so obtained are retained over a considerable length of time.

The ideal condition in backfilling trenches is to use the material that was excavated and to compact it to the same density at the same moisture content as the adjacent undisturbed soils. This would ideally minimize differential movement between the backfill material and the adjacent undisturbed soil. However, since the per cent of moisture content in the soil is a continuous variable with time, to achieve this condition a strict control of the moisture content in the backfill soil would be required during the backfilling procedure. Backfill soil densities would be required in each layer of compacted soil and additional backfill could not be placed until a check indicated whether the layer of backfill soil had been compacted sufficiently. The time required for density and moisture content determinations would make a field control program of this type prohibitive.

Practical solutions are:

1) Backfilling with the excavated soil at its natural moisture content (which is generally higher than optimum) and compacting by mechanical apparatus such as the Barco Rammer, Gardner Denver tamper, Le Roi tamper, or Pavement Breaker tamper. Backfill, prior to compaction should be placed in layers of nine inches or less. Some subsidence and differential movement can be anticipated when backfilling by this method.
2) Backfilling with "unshrinkable" material to within three feet of the ground surface and filling the remainder with excavated soil mechanically compacting nine inch layers of soil or less. This would eliminate the necessity for compaction below the three foot depth (which does not seem to be sufficiently effective) and ease excavation between the surface and the three foot depth when necessary to repair the watermain.

CONCLUSIONS:

An analysis of the results of this investigation suggests several significant conclusions:

I) Plots of dry density versus existing moisture content did not follow any pattern.

2) No relationship was found between depth and dry density in undisturbed soils.

3) The natural densities of the clay soils, A and D, were found to be both higher and lower than the densities produced by standard proctor compaction,

4) The natural densities of the silt soils, B and C, were found generally lower than the densities produced by standard proctor compaction.

5) Some natural densities in the undisturbed soils were equal to the zero air voids density.

6) Some soil moisture along Manitoba Avenue between the one to five foot depth has probably been removed by the roots of trees.

7) Natural soil moisture contents were found to be generally lower than optimum at the two foot depth, higher than optimum at the four and six foot depths and both higher and lower than optimum at the eight foot depths.

8) The density of backfill material was found to generally increase between the three foot depth and the surface.

9) The "average" density of backfill material was found to be slightly less than the density of the same material compacted by the standard proctor compaction at corresponding moisture contents.

10) The Gardner Denver tamper produced highest densities, followed by the Le Roi tamper, Barco Rammer, Pavement Breaker, hand tamper and water jetting, loosely placed backfill compacted at surface by tractor; hand tamping produced the lowest densities.

11) By eliminating the two densities (at the one and three foot depths) which are believed to be in error, the average density produced by the Barco Rammer would be higher than that produced by any other method of compaction investigated. (A single pass was made with the Barco Rammer compacting nine inch layers of backfill)

12) Higher densities were generally obtained when using thinner layers of backfill for compaction.

13) It would appear that backfill soil density can be retained long after compaction.

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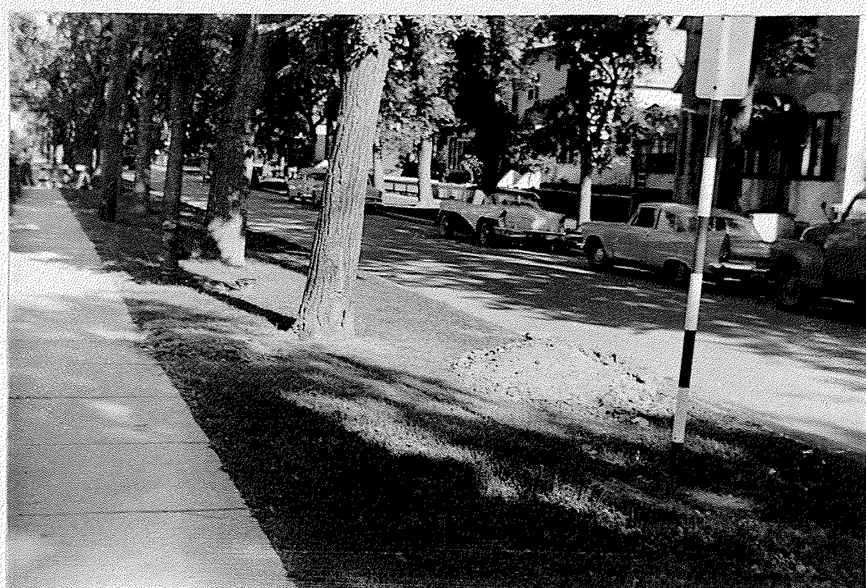
Photograph 1.-Excavated test pit on Manitoba Avenue, note location relative to sidewalk.

Photograph 2.-Manitoba Avenue, showing location of trees relative to sidewalk and street curb.

Photograph 3.-Test pit on Manitoba Avenue in process of excavation showing density determination apparatus, i.e.,sand cone,rubber balloon, and oil weight apparatus.

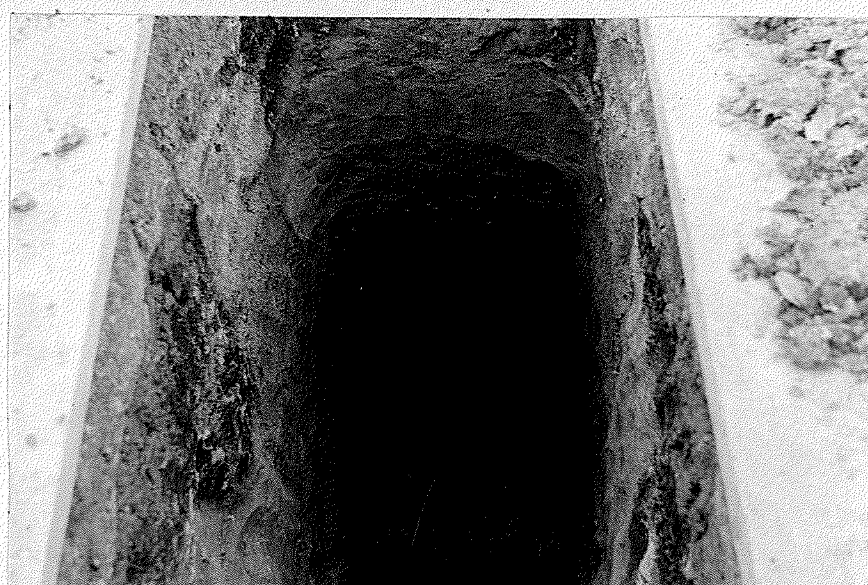
Photograph 4.-Density determination by sand cone apparatus on Manitoba Avenue.

Photograph 5.-Tree root such as encountered along Manitoba Avenue.

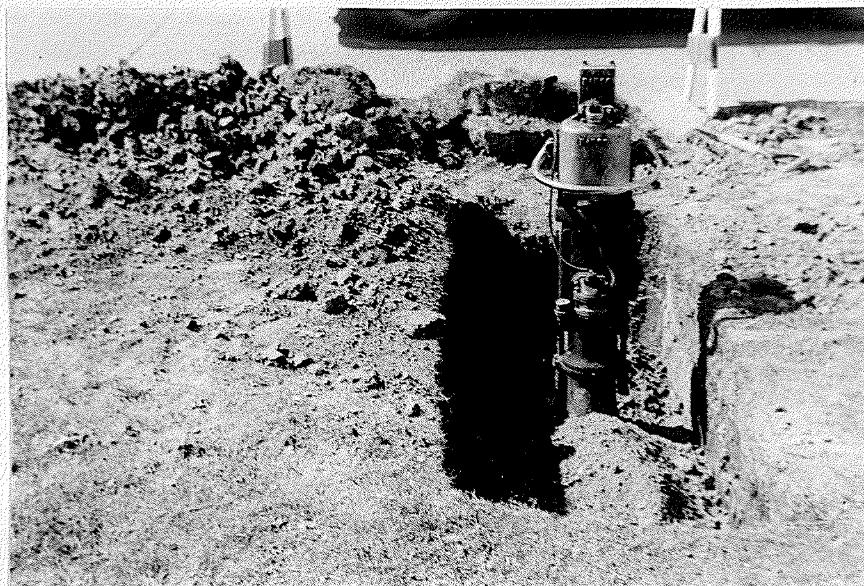


Photograph 6.-Loosely backfilled test pit on Manitoba Avenue, note backfill soil left over.

Photograph 7.-Loosely backfilled test pit on Manitoba Avenue showing result of subsidence.



Photograph 8.-Excavated test pit on Cordova Street.



Photograph 9.-Backfill being compacted by the Barco Rammer.

Photograph 10.-Test pit compacted by the Barco Rammer.

APPENDIX 1

DENSITY MEASUREMENT METHODS

The taking of field density measurements during this investigation by the standard sand cone, rubber balloon, oil weight and mercury displacement methods provided an opportunity for a comparison of the quantitative densities obtained by each method and of the operational advantages and disadvantages.

The standard sand cone was used initially for density measurements. By probable error application it was determined that results obtained by the sand cone were most accurate and therefore were utilized in the investigation analyses. Densities determined by the sand cone were slightly lower than those determined by any other method. Possible minor errors introduced into this method included those of weighing, inconsistency of sand density and an error incurred by improper seating of the base plate. The percentage of error caused by an improper seating of the base plate would vary with the individual, being classified as a "human error". More time was required for a density determination utilizing the sand cone than for any other method, however, it is felt that the accuracy obtained justified the use of such time.

Measurement of soil densities with the rubber balloon apparatus gave the highest densities. It is believed that the accuracy was affected by irregularities in the surface of the hole prepared for density measurement and by any inclination from the vertical of the apparatus. The removal of soil to form a smooth surfaced hole is quite difficult with the result that the rubber balloon cannot fill all the depressions and irregularities. This, it is believed is the factor contributing most to the error involved in density measurement by the rubber balloon method. The rubber balloon does have an advantage in requiring less time for a density measurement than any other method used.

The "oil weight" method gave densities higher than the standard sand cone and lower than the rubber balloon apparatus. Density measurement by the "oil weight" method can be effectively employed only in a soil of low porosity. The accuracy of this method is affected by errors in weighing, inconsistency of oil density, absorption of oil by the soil and difficulty in forming a horizontal surface on the top of the excavated hole. This method was also objectionably messy.

Several undisturbed soil samples were cut from the clays encountered for density determinations by mercury displacement. Small cracks and fissures in the samples, caused by desiccation, made it extremely difficult to make an accurate density determination. If satisfactory soil samples could be obtained the refinements in volume and weight measures possible would make this method the most accurate although it is rather time consuming.

It should be noted that all errors involved in each method of density measurement would vary with the individual and only the average of errors incurred by several investigations would have some significance.

APPENDIX 11

ECONOMICS OF BACKFILL COMPACTION APPARATUS

While backfilling over house service pipes along Manitoba Avenue in 1954, records were kept of all pertinent information including types and thicknesses of layers of backfill material, method, amount and length of time of compaction.

The costs of backfill compaction by various methods were determined using the information available from these City of Winnipeg, Waterworks Department, records for Manitoba Avenue. Unfortunately, the information available was limited and at best the cost determinations are only approximate.

Determinations of compaction costs were made based on the following hourly wage rates (these include overhead costs) which are in effect at time of writing.

Labor - $1.94 Equipment operator - $2.00

Equipment (tractor, compressor, truck) - $1.00

An economic analysis of the several methods of compacting backfill based on a minimum of operational data is presented in Table 4.

TABLE 4 COMPACTION COST SUMMARY

Compaction Equipment	Number of backfill locations studied	Thickness of Soil* layer to be compacted, inches	Cost of compaction per cubic yard of compacted soil
Gardner Denver	2	12	\$4.25
Le Roi Tamper	1	18	\$2.78
Pavement Breaker	2	16	\$3.52
Hand Tamper	8	12	\$2.48
Water Jetting	3	48	\$0.84

* The "thickness of a soil layer to be compacted" for more than one location investigated is the "average" thickness.

The above cost study applies only where the excavated material had been utilized for backfilling. Several of the experimental trenches along Manitoba Avenue were backfilled with gravel and compacted by the Gardner Denver tamper. Backfilling in this manner can be costly after the purchasing and transportation costs have been added to the costs of backfilling and compacting. Two locations, backfilled with gravel and compacted by the Gardner Denver tamper resulted in a backfilling and compacting (in twelve inch layers) cost of \$3.29 per cubic yard of compacted gravel. With gravel priced at \$2.50 per cubic yard, the cost of backfilling with gravel is \$5.79 per cubic yard plus a \$3.00 per hour trucking cost. Considering a minimum trucking time of one hour in Winnipeg, the cost of backfilling with gravel would be $8.79 per cubic yard.

"Unshrinkable" backfill material has also been used quite extensively in Winnipeg. The purchase cost of "unshrinkable" backfill fluctuates with demand, being $6.73 per cubic yard at time of writing. This backfill material requires no compaction and the only other costs are trucking and a small placement cost. "Unshrinkable" backfill in place, costs approximately $8.79 per cubic yard; this is the same as gravel backfill compacted in twelve inch layers.

The cost of compacting backfill by the Gardner Denver tamper, the Le Roi tamper and the Pavement Breaker is approximately $4.25 per cubic yard of material, compacted in twelve inch layers. A cost of compaction comparison with the Barco Rammer was not considered practical because only one location was compacted using the Barco Rammer, for which the rate of compaction was not considered normal. Costs of backfill compaction were available from the Barco Manufacturing Company, however, the extremely low cost and rapid rate of compaction indicated that these cost studies were made with highly skilled and efficient machine operators.

The cost of hand tamping at $2.48 per cubic yard of compacted material is approximately half that of mechanical compaction.

Densifying backfill by water jetting may fluctuate extremely in cost depending on the permeability of the backfill.

A cost of $0.84 per cubic yard of water jetted backfill based on three locations along Manitoba Avenue was approximately twenty per cent of the cost of compacting backfill mechanically.

The data utilized for a cost analysis of backfill compaction and compaction cost determinations is summarized in Table 5.

It should be noted that the various methods of compaction resulted in varying degrees of densification, with the highest densities obtained by mechanical compaction and the lowest densities by the hand tamping and water jetting as indicated earlier.

TABLE 5 COMPACTION COST DATA

House Number Manitoba Avenue	Compacted Soil Layer Thickness Inches	Average Compacted Soil Layer Thickness Inches	Backfilling Hours	Compacting Hours	Water Jetting Hours	Backfilling Cost	Compacting Cost	Water Jetting Cost	Total Cost	Average Cost per Site	Average Cost per Cubic Yard
a) Gardner Denver Tamper on Cohesive Backfill											
224	12	12	1.83	3.67		$5.49	$10.79		$16.28	$17.02	$4.25
226	12		2.00	4.00		6.00	11.76		17.76		
b) Gardner Denver Tamper on Gravel Backfill											
238	12	12	1.50	3.00		4.50	8.82		13.32	13.17	3.29
240	12		1.47	2.93		4.41	8.61		13.02		
c) Le Roi Tamper on Cohesive Backfill											
252	18	18	1.25	2.50		3.75	7.35		11.10		2.78
d) Pavement Breaker on Cohesive Backfill											
Main St.	14	16	1.83	3.67		5.49	10.79		16.28	14.06	3.52
256	18		1.33	2.67		3.99	7.85		11.84		
e) Hand Tamper on Cohesive Soil											
285	12			1.30			2.52		2.52		
283	15			0.87			1.69		1.69		
265	15			3.00			5.82		5.82		
255	12			6.50			12.61		12.61	9.90	2.48
251	12			6.50			12.61		12.61		
247	9			6.00			11.64		11.64		
245	9			7.00			13.58		13.58		
239	9			9.67			18.76		18.76		
f) Water Jetting											
258				1.33	0.25		2.58	0.49	3.07	3.32	0.84
260				1.67	0.25		3.24	0.49	3.73		
266				1.50	0.13		2.91	0.25	3.16		