UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

LABORATORY TESTS TO REFINE THE MAXIMUM DENSITY PROCEDURE FOR COHESIONLESS SOILS USING A VIBRATORY TABLE

Report No. EM-697

Soils Engineering Branch
DIVISION OF RESEARCH

OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

March 25, 1965

CONTENTS

	Page
Abstract	v
Introduction	1
Equipment	2
Soils	3
Test Procedure	3
Minimum Density	3
Maximum Density	4
Variations in Test Procedure for Tests on Soil No. 24N-339	5
Tests on a Sieve Shaker	6
Discussion of Test Results	6
Tests on a Natural Dune Sand	7
Tests on Two Artificially Prepared Soils	8
Conclusions and Recommendations	10
Bibliography	10
Acknowledgments	11

	Table
Results of Tests on a Natural Dune Sand	1
Results of Tests on a Natural Dune Sand	2
Results of Tests on a Poorly Graded Sand and Gravel	3
Results of Tests on a Poorly Graded Sand and Gravel	4
Results of Tests on a Poorly Graded Sand and Gravel	5
Results of Tests on a Poorly Graded Fine Sand	6
Results of Tests on a Poorly Graded Fine Sand	7
Results of Tests on a Poorly Graded Fine Sand	8

	Figure
Grain Size Distribution--Soil No. 24N-339	1
Grain Size Distribution--Soil No. 7	2
Grain Size Distribution--Soil No. 10	3
Pouring Minimum Density in 0.1-cu-ft Measure	4
Large Electromagnetic Table-type Vibrator (No. 9) with 0.1-cu-ft Measure, Guide Sleeve and 2-psi Surcharge	5
Small Electromagnetic Table-type Vibrator (No. 10) with 0.1-cu-ft Measure, Guide Sleeve and 2-psi Surcharge	6
Eccentric-weight Table-type Vibrator (No. 11). Dismounted to Show Vibrator Attached to Shop-made Table	7

CONTENTS--Continued

	Figure
Placing Surcharge Baseplate on Soil Specimen. Note Solid 2-psi Surcharge Weight on Vibratory Table.	8
Making Final Dial Reading on 0.1-cu-ft Measure	9
Amplitude vs Load on Vibrator at Maximum Rheostat Setting. .	10
Amplitude of Vibration vs Rheostat Setting	11
Frequency vs Rheostat Setting for Vibrator No. 11.	12
Dry Density vs Time of Vibration and Rheostat Setting--Soil No. 24N-339	13
Dry Density vs Time of Vibration--Soils No. 7 and 10	14
Dry Density vs Density Before Vibration--Soils No. 7 and 10	15
Dry Density vs Rheostat Setting--Soils No. 7 and 10.	16

APPENDIX A

Retesting of Soils to Compare Results Obtained With New Test Procedure and Equipment With Previous Results.

	Page
Purpose.	37
Test Procedure	37
Test Results	37
Discussion of Test Results	37
Conclusion	37

	Table
Average Densities Obtained During Relative Density Research.	A-1

	Figure
Grain Size Distribution--Soil No. 1.	A-1
Grain Size Distribution--Soil No. 2.	A-2
Grain Size Distribution--Soil No. 3.	A-3
Grain Size Distribution--Soil No. 4.	A-4
Grain Size Distribution--Soil No. 6.	A-5
Grain Size Distribution--Soil No. 7.	A-6
Grain Size Distribution--Soil No. 9.	A-7

APPENDIX B

Tests Using a Sieve Shaker to Obtain the Maximum Density of Cohesionless Soils.

Page

Purpose. 48
Test Procedure 48
Test Results 48
Discussion and Conclusion. 48

Table

Comparison of Densities Obtained by Sieve Shaker with Densities obtained by Vibrator No. 9 on a Poorly Graded Sand and Gravel (Soil No. 7) Ovendry. B-1
Comparison of Densities Obtained by Sieve Shaker with Densities obtained by Vibrator No. 9 on a Poorly Graded Fine Sand (Soil No. 10) Ovendry B-2

Figure

Sieve Shaker for Determining the Gradation of Coarse Grained Soils. B-1
Steel Plate Adapter for Sieve Shaker B-2
Sieve Shaker as used to Determine the Maximum Density of Cohesionless Soils B-3

APPENDIX C

Characteristics of Vibrators Used to Obtain the Maximum Density of Cohesionless Soils.

Page

Introduction 55
Power Supply 55
Load-Amplitude Relationship. 55

Table

Variation of Amplitude with Rheostat Setting and Load--Large Electromagnetic Vibrator No. 9. Amplitudes Measured on the Handles of the 0.5 Cubic-Foot Measure. C-1

Variation of Amplitude with Rheostat Setting and Load--Large Electromagnetic Vibrator No. 9. Amplitude Measured on the Vibrator Table C-2

CONTENTS--Continued

Table

Variation of Amplitude with Rheostat Setting and Load--Small Electromagnetic Vibrator No. 10. Amplitudes Measured on the Handles of the 0.5 Cubic-Foot Measure C-3
Variation of Amplitude with Rheostat Setting and Load--Eccentric Weight Motor Vibrator No. 11. Amplitudes Measured on the Handles of the 0.5 Cubic-Foot Measure. C-4

Figure

Photograph of Recording-Type Vibrometer Used to Measure Amplitudes of Vibration C-1
Photograph of Weights Used to Determine the Effect of Load on the Amplitude of Vibration C-2

ABSTRACT

To improve the test procedure for determining the maximum laboratory dry density of cohesionless soils, time of vibration, initial dry density, amplitude and frequency of vibration, and the moisture condition of the material were investigated. Changes in the gradation during vibration increased both the minimum and maximum dry densities of a weakly-cemented dune sand. The increase in density was insignificant for times of vibration greater than 6 minutes except for the weakly-cemented material. The initial density of the soil prior to vibration did not have a significant effect on the final density. No conclusions could be drawn as to the effect of the amplitude and frequency of vibration on the dry density from the results using two electromagnetic vibrators and one eccentric weight vibrator. The difference between the densities obtained using ovendried soil and initially saturated soil was not significant for the two soils tested: a poorly graded sand and gravel, 3-inch maximum-size, and a poorly graded fine sand. The results did not suggest any revisions which would improve the Bureau's current method for determining the maximum laboratory density of cohesionless soils.

DESCRIPTORS-- *vibrators/ electrical/ vibrations/ *relative density/ *soil compaction/ *noncohesive soils/ dry density/ test procedures/ sands/ time/ dry condition/ gravel/ soil moisture/soil investigations/ soil mechanics/ soil tests/ *laboratory equipment/ research and development/ graphical analysis/ dune sand/ saturation
IDENTIFIERS-- amplitudes/ surcharge/ frequency/ electromagnetic vibrators/ eccentric weight vibrators

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Office of Chief Engineer
Division of Research
Soils Engineering Branch
Denver, Colorado
March 25, 1965

Laboratory Report No. EM 697
Author J. Hardin
Checked by: F. B. Larcom
Reviewed by: H. C. Pettibone
C. W. Jones
Submitted by: H. J. Gibbs

Subject: Laboratory tests to refine the maximum density procedure for cohesionless soils using a vibratory table

INTRODUCTION

The Bureau of Reclamation has used the relative density of cohesionless soils to control compaction since about 1950. The relative density method of control specifies the required field density as a percentage of the range between the minimum and maximum density of the soil as determined in the laboratory.1/* Therefore, it is desirable to have a standard procedure for obtaining the maximum and minimum densities. Experience has shown that a reasonable amount of care in the laboratory will insure determination of a suitable value for the minimum density.2/ However, the maximum density of cohesionless soil appears to be extremely sensitive to the details of the test procedures.2,3/

Based on the results of previous investigations, the Bureau of Reclamation has established an alternate procedure for determining the maximum density of cohesionless soil. This procedure utilizes a vibratory table and has been adopted for Bureau-wide use.1/ The alternate procedure appears to give satisfactory maximum densities for most of the soils encountered in Bureau projects, but occasionally some projects have reported relative densities greater than 100 percent when the maximum density was obtained by the vibratory table method.

Since by definition the maximum density used in the relative density method of control should exceed the density which can be obtained by the field equipment, it was felt that additional research was needed to improve the laboratory procedure. Previous investigations3,4/ by the Bureau and a cooperative investigation2/ sponsored by ASTM have indicated that table-type vibrators most often give the maximum densities for cohesionless soils. However, the mechanisms which affect the densification of soils subject to vibrations are poorly understood. In

*Refer to references at end of report.

this investigation an attempt has been made to isolate and determine the direction and magnitude of some of the factors believed to affect the maximum density obtained by a vibratory table. Variables considered in this investigation were: (1) time of vibration, (2) density before vibration, (3) amplitude and frequency of vibration, and (4) moisture condition of material (ovendried or initially saturated).

EQUIPMENT

The following major items of equipment were used in this research:

a. Cylindrical unit weight measures of the capacity and dimensions given in the tabulation below:

Volume		Inside				Thickness				Material
		Diameter		Height		Wall		Bottom		
Cu ft	Cu m	In.	Cm	In.	Cm	In.	Cm	In.	Cm	
0.1	.0028	6	15.2	6	15.2	5/16	.79	5/16	.79	Cast silicon aluminum ASTM-SG-704
0.5	.0142	11	27.9	9	22.9	5/16	.79	5/16	.79	

b. Vibrator No. 9--Electromagnetic table-type vibrator, frequency 3,600 cpm, net weight 116 pounds (52.6 kg), 230-v power supply. The amplitude can be varied by a rheostat graduated from 0 to 100. The graduations on the rheostat are not directly correlated with the power supplied to the vibrator.

c. Vibrator No. 10.--Electromagnetic table-type vibrator, frequency 3,600 cpm, net weight 45 pounds (20.4 kg), 230-v power supply. The amplitude can be varied by a rheostat graduated from 0 to 100. The graduations on the rheostat are not directly correlated with the power supplied to the vibrator.

d. Vibrator No. 11.--Eccentric weight-type vibrator attached to a shop-made table. The amplitude and frequency could be varied by a rheostat graduated from 0 to 120 volts, but vibration was not detectable for a setting less than 40 volts. The amplitude and frequency could not be varied independently.

e. Single-piece guided deadweight surcharge equal to 2 psi (.14 kg/cm^2) for the two measure sizes.

f. A specially mounted dial gage for determining the volume of the specimen after vibration.

SOILS

The following three soils were used in this investigation:

Soil No.	Description	Source
24N-339	Poorly graded fine sand 10 percent fines (dune sand)	Norton, Kansas
7	Poorly graded sand and gravel, 3-inch (7.6-cm) maximum-size, no fines	South Platte River, Denver, Colorado (artificial gradation)
10	Poorly graded fine sand 10 percent fines	Cherry Creek, Denver, Colorado (artificial gradation)

The Soils No. 7 and 10 correspond to numbers used to designate these soils in previous investigations of relative density.3,4/ The gradations of the three soils are shown in Figures 1, 2, and 3. A limited number of tests were run on Soils No. 1, 2, 3, 4, 6, 7, and 9. These tests are discussed in Appendix A.

TEST PROCEDURE

Minimum Density

Ovendried material was placed as loosely as possible in a measure as shown in Figure 4 and the excess carefully struck off. The pouring device and measure were selected according to the maximum size soil particles as given in the following tabulation:

Maximum size soil particle In.	cm	Pouring device used for minimum density tests	Unit weight measure Cu ft	Cu m
3	7.6	Shovel or large scoop	0.5	.0142
1-1/2	3.8	Scoop	0.1	.0028
3/8	1.0	1-inch (2.5-cm) spout	0.1	.0028
No. 4	0.5	1/2-inch (1.3-cm) spout	0.1	.0028

The minimum density procedure was not investigated in this research, but was used to control the initial placement condition for most of the maximum density tests.

Maximum Density

Two sizes of electromagnetic vibrators attached to commercially supplied tables, Vibrators No. 9 and 10, shown in Figures 5 and 6, respectively, were used for this series of tests on a poorly graded sand and gravel with 3-inch (7.6-cm) maximum-size (Soil No. 7), a natural dune sand (Soil No. 24N-339), and a poorly graded fine sand (Soil No. 10). An eccentric weight electric motor attached to a shop-made table, Vibrator No. 11 shown in Figure 7, was used for additional tests on Soils No. 7 and 10.

A limited number of tests were run using a sieve shaker as a vibrator. The results of these tests are discussed and compared with densities obtained with other vibrators in Appendix B.

Before actual testing of soil specimens, some preliminary tests were run to determine the frequency and amplitude characteristics of the vibrators under various loads in the range commonly used in vibrating the soil specimens. The details of these tests are presented in Appendix C.

The rheostat settings were varied from 30 to 100 on the electromagnetic vibrators to study the effect of the amplitude of vibration on the soil density obtained. The rheostat settings were varied from 70 to 120 on the eccentric weight electric motor vibrator to study the effect of the frequency of vibration on the soil density.

A 2-psi (.14 kg/cm^2) deadweight surcharge was used as shown in Figure 8 for all tests. The 0.1-cubic-foot measure was used for all tests on Soils No. 24N-339 and 10, and the 0.5-cubic-foot measure was used for all tests on Soil No. 7.

The average height of the soil was obtained by dial gage readings on opposite sides of the surcharge baseplate as shown in Figure 9. Using this information and the cross-sectional area of the measure, the volume of the specimen after vibration was computed.

Most of the tests were run on ovendried soil, but a few were run with initially saturated soil using the rheostat setting which produced the highest density on the dried soil. The tests on the initially saturated specimens were run for a total of 20 minutes with density determinations every 4 minutes.

A total time of vibration of 16 minutes, with density determinations made every 4 minutes, was used for the tests to study the effect of amplitude, frequency, and time of vibration on the soil density.

The effect of placing the soil at various densities before the start of vibration was investigated by placing the specimens at minimum density, minimum plus 5 pcf (.08 gm/cc) and minimum plus 10 pcf (.16 gm/cc). These specimens were vibrated a total of 12 minutes; densities were determined at 1, 3, 5, 7, 9, and 12 minutes after the test began. All tests on Soils No. 7 and 10 were run in duplicate, but only single tests were run on Soil No. 24N-339.

A quantity of soil equal to about twice the amount required for a single test was prepared for Soils No. 7 and 10. After each test the entire quantity of soil was mixed and then the amount required for the following test was taken from the sample. For Soil No. 24N-339 a quantity slightly greater than that required to fill the 0.1-cubic-foot measure was taken from a sack sample. This quantity was then used for all tests, except that it was once necessary to add more material to the original quantity to fill the 0.1-cubic-foot measure. The maximum density may be significantly affected by repeated vibration of a sample of material.

A grain-size analysis was performed for each of the three soils before and after the testing program to determine the effect of vibration on the grain-size distribution.

<u>Variations in Test Procedure for Tests on Soil No. 24N-339</u>

The rheostat settings and times of vibration described above were not used for tests on Soil No. 24N-339. In these tests a sample was vibrated according to the following tabulation without being removed from the table.

Rheostat setting	Increment of time	Cumulative time
100	8	8
100	4	12
90	8	20
80	8	28
80	4	32
70	8	40
60	8	48
60	4	52
50	8	60
40	8	68
40	4	72

Density determinations were made after each entry in the above table. Vibrators No. 9 and 10 were used.

Tests were run at rheostat settings varied from 50 to 90 in increments of 10 for a total of 12 minutes at each setting with density determination after 8 and 12 minutes. The soil was removed from the measure and mixed with the original sample after the run at each rheostat setting. These tests were performed on Vibrator No. 9 only.

A test was run at a rheostat setting of 80 for 36 minutes and at a rheostat setting of 60 for 60 minutes with density determinations every 4 minutes on Vibrator No. 9. Similar tests were run at rheostat settings of 100 and 80 on Vibrator No. 10.

Tests on a Sieve Shaker

A few tests were run to investigate the feasibility of a sieve shaker as a vibrator for obtaining the maximum density of cohesionless soils. These data are presented in Appendix B.

DISCUSSION OF TEST RESULTS

The load-amplitude relationship for each of the three vibrators using the maximum rheostat setting is shown in Figure 10. For the electromagnetic vibrators (Nos. 9 and 10) the amplitude generally decreased as the load on the vibrating table was increased. The amplitude of the eccentric weight vibrator was independent of the load.

The amplitude-rheostat setting relationship of each of the three vibrators for loads of 100 and 250 lbs (consisting of loose steelplates on the vibrating table) is shown in Figure 11. The loads of 100 and 250 lbs (45.4 and 90.7 kg) are approximately equal to the loads on the vibrating table during actual testing of the soil samples. The amplitude generally increased with increasing rheostat settings for the electromagnetic vibrators, but was constant for the eccentric weight vibrator. The amplitude-rheostat settings relationship is shown in Figure 11B for the single-piece 2-psi surcharge weight (264 lbs) and the 0.5-cubic-foot measure. The amplitude of vibration for the 250-lb load and the 264-lb load was significantly different due to the use of a loose plate load or a single piece load.

The frequency (constant 3,600 cpm) of the electromagnetic vibrators was independent of the rheostat settings and of loads in the range from 0 to 300 pounds (0 to 136.1 kg). The frequency of the eccentric weight vibrator varied with the rheostat setting as shown in Figure 12, but the frequency was independent of the load. A more complete discussion of the characteristics of the vibrators is given in Appendix C.

<u>Tests on a Natural Dune Sand</u>

The intended purpose of this group of tests was to investigate the effect of the amplitude on the maximum density obtained and to compare two sizes of electromagnetic table-type vibrators (Vibrators No. 9 and 10) for efficiency in obtaining the maximum density of this soil.

As shown in the following discussion, the gradation of Soil No. 24N-339 was probably changing continuously with time of vibration; therefore, no attempt is made to evaluate the effect of the amplitude of vibration on the maximum density nor to compare the two vibrators for efficiency. However, the data from these tests do serve to illustrate the effect of changes in gradation (for one soil) on the minimum and maximum density. Further investigation is needed to determine the relationship between soil gradation and the minimum and maximum density.

The results of tests on Soil No. 24N-339, using Vibrators No. 9 and 10, are presented in Tables 1 and 2 respectively. The significant feature of these tests is the change in minimum density with time of vibration as shown in Figure 13 where the maximum and minimum densities of this soil are plotted as a function of the total time of vibration and the rheostat setting. The soil was removed and mixed with the original sample at each point on the minimum density curve in Figure 13. A visual inspection of a sample of Soil No. 24N-339, which had not been vibrated, revealed a presence of numerous agglomerations which could be reduced to individual grains by slight pressure between the fingers. The increase in the minimum density with vibration is attributed to the breakdown of a weak cement present in the material.

The breakdown of Soil No. 24N-339 due to vibration is illustrated in Figure 1. In Figure 1, Curve A represents the gradation of Soil No. 24N-339 obtained by shaking 10 minutes on the sieve shaker before vibration in the maximum density test; Curve B represents the gradation obtained by this same method after the sample had been vibrated for about 300 minutes in the maximum density test; and Curve C represents the gradation obtained by the standard procedure using a mechanical disperser. The actual gradation when the first minimum density was poured was probably coarser than represented by Curve A of Figure 1 because many of the agglomerates were broken down during the shaking for 10 minutes with the sieve shaker.

Tests on Two Artificially Prepared Soils

To avoid the problem of changing soil gradation during vibration, two cohesionless soils were prepared to represent a wide range in gradation. Soil No. 7 was prepared by mixing selected sizes from sand and gravel obtained from the South Platte River near Denver, Colorado. Soil No. 10 was prepared to have a gradation similar to Soil No. 24N-339 by mixing selected sizes from Cherry Creek sand. The gradations of Soils No. 7 and 10 in Figures 2 and 3, respectively, are designated "before" and "after" to indicate the change in gradation during the testing program. It is obvious from Figures 2 and 3 that the gradation of the artificially prepared soils changed somewhat during testing.

The results of maximum density tests on a poorly graded sand and gravel (Soil No. 7) using Vibrators No. 9, 10, and 11 are presented in Tables 3, 4, and 5, respectively, and the results for a poorly graded fine sand (Soil No. 10) are presented in Tables 6, 7, and 8.

The results of a group of tests to determine the required time of vibration are presented in Figures 14A and B. The data indicate that the increase in density after about 6 minutes is negligible. These tests were also used to observe the reproducibility of the results and to check the possibility of binding of the surcharge baseplate against the sides of the measure. The two tests represented by closed circles in Figure 14A, were run by the same operator on the same date, and the two tests represented by closed squares were run by different operators and at times near the beginning and the end of the investigation. These limited data indicate a reproducibility of approximately 1 pcf (.016 gm/cc). For the data presented in Figure 14B, the surcharge baseplate was removed and reseated at each point represented by the open symbols, but was not disturbed in the tests represented by the solid symbols. The data seem to eliminate the possibility of binding of the surcharge baseplate as a factor influencing the maximum density.

The effect of the initial density (density before vibration) on the maximum density of Soils No. 7 and 10 (obtained by a vibration time of

12 minutes on Vibrators No. 9, 10, and 11) is shown in Figures 15A and B. Tests were performed at initial densities equal to the minimum, minimum plus 5 pcf (.08 gm/cc), and minimum plus 10 pcf (.16 gm/cc). The densities equal to minimum plus 5 pcf and to the minimum plus 10 pcf were obtained by tapping the side of the measure until the desired amount of soil could be added. The soil and measure were then placed on the vibrating table and vibrated a total of 12 minutes. The effect of the initial density on the maximum density does not appear to be significant for either Soil No. 7 or 10.

The results of a group of tests to investigate the effect of amplitude and frequency on the maximum density are presented in Figures 16A and B where the dry density obtained by vibrating for 16 minutes is shown as a function of the rheostat setting. The rheostat setting was varied from 30 to 100 in increments of 10 for the electromagnetic vibrators (Vibrators No. 9 and 10). In this range of rheostat settings, the frequency was constant at 3,600 cpm and the amplitude varied as shown in Figures 11A and B. The rheostat setting was varied from 70 to 120 on the eccentric weight vibrator (Vibrator No. 11). In this range of rheostat settings the amplitude of vibration was constant as shown in Figures 11A and B, and the frequency varied as shown in Figure 12. For Soil No. 7, the three vibrators gave similar maximum densities with erratic variation within a range of approximately 4 pcf. For Soil No. 10 the three vibrators gave nearly identical maximum densities at rheostat settings greater than 60 for Vibrators No. 9 and 10 and settings greater than 80 for Vibrator No. 11. At rheostat settings less than 60, the density for Soil No. 10, obtained using Vibrator No. 9 increased slightly but the density obtained using Vibrator No. 10 decreased rapidly. The density obtained for Soil No. 10, using Vibrator No. 11, decreased rapidly for rheostat setting less than 80.

The limited data presented in Figures 11, 12, and 16 indicate:

(1) The density obtained by vibration is independent of the frequency in the range 3,600 cpm to 8,400 cpm at an amplitude of approximately .005 inch (.013 cm), but drops rapidly for frequencies immediately below 3,600 cpm.

(2) The density obtained by vibration is independent of the amplitude in the range from .010 to .020 inch (.025 to .051 cm) at a frequency of 3,600 cpm, but drops rapidly for amplitudes less than .010 inch (.025 cm) or is very erratic at amplitudes in the range .005 to .010 inch (.013 to .025 cm).

It should be emphasized that (1) and (2) are not based on sufficient data to qualify as conclusions, but are listed here only as possible aids in future research to determine the effect of amplitude and frequency on the soil density.

Tests using initially saturated material were performed for all combinations of Soils No. 9 and 10 and Vibrators No. 9, 10, and 11. The differences in the densities obtained using ovendried and initially saturated material were not considered significant for the conditions tested.

CONCLUSIONS AND RECOMMENDATIONS

The increase in density was insignificant for times of vibration greater than about 6 minutes for the soils and equipment used in this investigation. The vibration time of 8 minutes required by the current Bureau of Reclamation procedure* is a reasonable and sufficient time when equipment similar to Vibrators No. 9 and 10 are used.

The initial density (before vibration) did not have a significant effect on the final density obtained by a vibration time of 12 minutes. The minimum density procedure should be used to fill the measure for maximum density tests because this procedure helps provide a representative sample in the measure and minimizes segregation before the start of vibration.

There was evidence that the amplitude and frequency of the vibrating instrument affected the results indicating that certain limiting ranges for operation are recommended. For the equipment and soil used in this research, the maximum density was nearly independent of frequence in the range 3,600 to 8,400 cpm at an amplitude of .005 inch (.013 cm) and is nearly independent of amplitude in the range .010 to .020 inch (.025 to .051 cm) at a frequency of 3,600 cpm. Further research in which the frequency or amplitude is held constant while the other is varied over a wide range is needed to clarify the effect of these variables on the soil density obtained by vibration.

The difference between the densities obtained using ovendried soil and initially saturated soil was not significant for the two soils tested. The data available at this time do not allow a reliable correlation between soil gradation and the appropriate moisture condition; therefore the maximum density of an unfamiliar soil should be determined using both ovendried and initially saturated material.

Changes in the gradation of a weakly cemented dune sand during vibration were found to increase both the minimum and maximum densities obtained for this material.

The current method for determining the maximum density of cohesionless soils was developed during the preliminary phases of this study and as a result of previous progress reports. The research of this study gives greater confidence in the procedure and provides information for several questions of possible variables that affect the results. Although the general procedure appears satisfactory, certain limiting ranges of operation for the vibrators were indicated. The possibility of inaccuracies in the volume determination of the density test hole in the field is suggested as a contributing cause for reported field densities of more than 100 percent relative density, and special care should be given to this problem in control testing.

---

*Designation E-12B 1/

BIBLIOGRAPHY

1. U.S. Bureau of Reclamation, Earth Manual, First Edition, Revised 1963, p 474 through 474j

2. Felt, Earl J., "Laboratory Method of Compacting Granular Material," American Society for Testing and Materials, Special Technical Publication No. 239, 1958, p 89

3. U.S. Bureau of Reclamation, "Development of a Maximum Density Test for Cohesionless Soil by a Vibratory Method," Earth Laboratory Report No. EM-557, Denver, Colorado, May 8, 1961

4. Pettibone, H. C., and J. Hardin, "Research on Vibratory Maximum Density Test for Cohesionless Soils," presented at the Symposium on "Compaction of Soils," 67th Annual Meeting of the American Society for Testing and Materials, June 21-26, 1964

ACKNOWLEDGMENTS

The tests on Soil No. 24N-339 were performed by C. T. Coffey and R. L. Gilbert. The tests on Soils No. 7 and 10 were performed by J. Hardin, J. L. Lawrence, C. C. Miller, and C. T. Coffey. The testing program was carried out under the direction of H. C. Pettibone with the approval of C. W. Jones.

Table 1

RESULTS OF TESTS ON A NATURAL DUNE SAND--24N-339--AUGUST 1963
Electromagnetic Vibrator No. 9, 0.1-cu-ft Measure
2-psi Single-piece Surcharge, Frequency = 3,600 cpm

Time of vibration, min: Increase	Time of vibration, min: Total	Rheostat setting, percent	Amplitude of vibration, inch	Initial density, pcf	Final density, pcf
8	8	100	.011	88.4	112.82
4	12	100	.011		115.36
8	20	90	.011		115.97
8	28	80	.010		117.51
4	32	80	.010		118.45
8	40	70	.008		118.45
8	48	60	.006		118.77
4	52	60	.006		118.77
8	60	50	.006		118.61
8	68	40	-		118.92
4	72	40	-		118.77
8	8	90		93.94	114.82
4	12	90			115.38
8	8	80		95.23	116.26
4	12	80			116.40
8	8	70		96.02	116.10
4	12	70			116.67
8	8	60		96.92	116.77
4	12	60			117.61
8	8	50		96.42	112.79
4	12	50			113.58
8	8	80		95.83	116.85
4	12	80			117.70
4	16	80			117.50
4	20	80			117.93
4	24	80			118.37
4	28	80			118.66
4	32	80			118.81
4	36	80			118.96
8	8	60	.006	96.48	115.20
4	12	60			115.89
4	16	60			116.45
4	20	60			116.59
4	24	60			116.87
4	28	60			117.15
4	32	60			117.43
4	36	60			117.72
4	40	60			118.00
4	44	60			118.29
4	48	60			118.44
4	52	60			118.73
4	56	60			118.58
4	60	60			119.02

Table 2

RESULTS OF TESTS ON A NATURAL DUNE SAND--No. 24N-339--AUGUST 1963
Electromagnetic Vibrator No. 10, 0.1-cu-ft Measure
2-psi Single-piece Surcharge, Frequency = 3,600 cpm

Time of vibration, min		Rheostat setting, percent	Amplitude of vibration, inch	Initial density, pcf	Final density, pcf
Increase	Total				
8	8	100	.027	96.42	119.04
4	12	100			119.18
8	20	90	.027		119.36
8	28	80	.021		119.95
4	32	80			119.95
8	40	70	.021		120.40
8	48	60	.006		121.61
4	52	60			121.76
8	60	50	.006		122.07
8	68	40	.004		121.76
4	72	40			121.91
8	8	100		97.12	120.05
4	12	100			120.34
4	16	100			120.64
4	20	100			120.79
4	24	100			120.94
4	28	100			121.09
4	32	100			120.94
4	36	100			121.09
8	8	80		97.71	119.90
4	12	80			120.05
4	16	80			120.20
4	20	80			120.20
4	24	80			120.34
4	28	80			120.34
20	20	80	Initially saturated; final moisture = 11.23%		116.89

Table 3

RESULTS OF TESTS ON A POORLY GRADED SAND AND GRAVEL--NO. 7--JANUARY 1964
Electromagnetic Vibrator No. 9, 0.5-cu-ft Measure
2-psi Single-piece Surcharge, Frequency = 3,600 cpm

Time of vibration, min	Rheostat setting, percent	Initial density, pcf	Moisture, final percent	Dry density, pcf	Av dry density, pcf
1/ (1) 1	100	118.0	Ovendry	135.7	135.4
3	100			136.4	136.1
5	100			136.5	136.1
7	100			136.8	136.6
9	100			136.9	136.7
12	100			137.3	137.0
1/ (2) 1	100	117.8	Ovendry	135.0	
3	100			135.8	
5	100			135.7	
7	100			136.3	
9	100			136.5	
12	100			136.7	
(1) 12	100	123.0 min+5	Ovendry	137.2	136.6
(2) 12	100	123.0 min+5	Ovendry	136.1	
(1) 12	100	128.0 min+10	Ovendry	135.3	135.8
(2) 12	100	128.0 min+10	Ovendry	136.3	
(1) 16	100	117.7	Ovendry	136.2	136.2
(2) 16	100	117.9	Ovendry	136.2	
(1) 16	90	114.1	Ovendry	133.4	133.2
(2) 16	90	116.9	Ovendry	133.1	
(1) 16	80	117.3	Ovendry	134.2	133.8
(2) 16	80	116.1	Ovendry	133.1	
(1) 16	70	117.3	Ovendry	135.7	135.6
(2) 16	70	120.1	Ovendry	135.5	
(1) 16	60	117.3	Ovendry	128.0	134.0
(2) 16	60	116.3		135.5	
(1) 16	50	116.1	Ovendry	132.2	134.1
(2) 16	50	117.5		136.0	
(1) 16	40	116.5	Ovendry	133.0	133.8
(2) 16	40	112.1		133.1	
(1) 16	30	116.9	Ovendry	131.6	132.3
(2) 16	30	119.7		133.0	
(1) 20	100	-	6.9	135.7	-
(1) 20	70	-	7.6	132.5	133.6
(2) 20	70	-	7.3	134.7	

1/Nos. (1) and (2) indicate duplicate samples.

Table 4

RESULTS OF TESTS ON A POORLY GRADED SAND AND GRAVEL--NO. 7--JANUARY 1964
Electromagnetic Vibrator No. 10, 0.5-cu-ft Measure
2-psi Single-piece Surcharge, Frequency = 3,600 cpm

Time of vibration, min	Rheostat setting, percent	Initial density, pcf	Moisture, final percent	Dry density, pcf	Av dry density, pcf
1/ (1) 1	100	114.1	Ovendry	131.7	131.8
2	100			133.0	132.8
4	100			133.0	133.0
6	100			133.0	133.1
8	100			132.3	132.7
10	100			132.7	133.0
12	100			132.7	133.0
1/ (2) 1	100	118.1	Ovendry	131.9	
3	100			132.5	
5	100			133.0	
7	100			133.1	
9	100			133.2	
12	100			133.3	
(1) 12	100	123.0 min+5	Ovendry	132.2	133.2
(2) 12	100	123.0 min+5	Ovendry	134.2	
(1) 12	100	128.0 min+10	Ovendry	132.5	132.8
(2) 12	100	128.0 min+10	Ovendry	133.0	
(1) 16	100	117.3	Ovendry	134.4	134.0
(2) 16	100	117.3		133.7	
(1) 16	90	116.1	Ovendry	132.8	133.4
(2) 16	90	117.3		133.9	
(1) 16	80	118.1	Ovendry	134.5	133.6
(2) 16	80	119.3		132.8	
(1) 16	70	118.5	Ovendry	133.4	133.6
(2) 16	70	118.5		133.7	
(1) 16	60	117.9	Ovendry	131.9	131.4
(2) 16	60	118.1		130.9	
(1) 16	50	118.5	Ovendry	133.1	132.6
(2) 16	50	118.5		132.2	
(1) 20	100	-	6.9	134.9	134.2
(2) 20	100	-	7.6	133.6	

1/Nos. (1) and (2) indicate duplicate samples.

Table 5

RESULTS OF TESTS ON A POORLY GRADED SAND AND GRAVEL--NO. 7--JANUARY 1964
Eccentric-weight-type Vibrator No. 11, 0.5-cu-ft Measure
2-psi Single-piece Surcharge--Variable Frequency

Time of vibration, min	Rheostat setting, volts	Initial density, pcf	Moisture, final percent	Dry density, pcf	Av dry density, pcf
1/ (1) 1	120	117.4	Ovendry	133.3	133.3
3	120			133.8	134.0
5	120			134.1	134.3
7	120			134.2	134.4
9	120			134.5	134.7
12	120			134.5	134.8
1/ (2) 1	120	117.6	Ovendry	133.3	
3	120			134.2	
5	120			134.5	
7	120			134.7	
9	120			134.9	
12	120			135.0	
(1) 12	120	123.0 min+5	Ovendry	135.1	135.2
(2) 12	120	123.0 min+5	Ovendry	135.3	
(1) 12	120	128.0 min+10	Ovendry	136.3	136.4
(2) 12	120	128.0 min+10	Ovendry	136.5	
(1) 16	120	118.9	Ovendry	136.3	136.0
(2) 16	120	118.9	Ovendry	135.7	
(1) 16	110	117.7	Ovendry	135.0	135.4
(2) 16	110	118.5	Ovendry	135.9	
(1) 16	100	117.1	Ovendry	133.1	134.2
(2) 16	100	117.4	Ovendry	135.4	
(1) 16	90	117.9	Ovendry	131.9	132.3
(2) 16	90	117.9	Ovendry	132.7	
(1) 16	80	118.3	Ovendry	134.7	135.0
(2) 16	80	118.3	Ovendry	135.3	
(1) 16	70	119.5	Ovendry	133.4	132.6
(2) 16	70	119.5	Ovendry	131.9	
20	120	-	7.4	133.5	-

1/Nos. (1) and (2) indicate duplicate samples.

Table 6

RESULTS OF TESTS ON POORLY GRADED FINE SAND--NO. 10--JANUARY 1964
Electromagnetic Vibrator No. 9, 0.1-cu-ft Measure
2-psi Single-piece Surcharge, Frequency = 3,600 cpm

Time of vibration, min	Rheostat setting, percent	Initial density, pcf	Moisture, final percent	Dry density, pcf	Av dry density (1) & (2) pcf
1/ (1) 1	100	90.9	Ovendry	111.2	111.2
3				112.6	112.8
5				112.1	112.6
7				112.4	112.7
9				112.4	112.7
12				113.0	113.0
1/ (2) 1	100	89.8	Ovendry	111.2	
3				112.9	
5				113.0	
7				113.0	
9				113.0	
12				113.0	
(1) 12	100	95.1 min+5	Ovendry	113.9	113.4
(2) 12	100	94.7 min+5	Ovendry	113.0	
(1) 12	100	100.0 min+10	Ovendry	113.4	113.3
(2) 12	100	100.0 min+10	Ovendry	113.2	
(1) 16	100	89.7	Ovendry	112.4	112.9
(2) 16	100	89.7	Ovendry	113.4	
(1) 16	90	89.5	Ovendry	113.3	113.3
(2) 16	90	89.9	Ovendry	113.3	
16	80	91.1	Ovendry	113.0	113.4
16	80	90.1	Ovendry	113.7	
16	70	89.5	Ovendry	113.6	113.9
16	70	90.2	Ovendry	114.2	
16	60	91.5	Ovendry	113.2	113.6
16	60	90.0	Ovendry	114.0	
16	50	91.5	Ovendry	114.0	114.2
16	50	89.8	Ovendry	114.3	
16	40	89.6	Ovendry	116.7	116.2
16	40	89.9	Ovendry	115.7	
16	30	91.6	Ovendry	115.0	115.7
16	30	89.8	Ovendry	116.4	
16	20	90.5	Ovendry	115.0	115.4
16	20	90.1	Ovendry	115.7	
20	100	-	15.0	114.2	114.4
20	100		14.4	114.5	
20	30	-	16.2	113.3	113.5
20	30		15.4	113.7	

1/Nos. (1) and (2) indicate duplicate samples.

Table 7

RESULTS OF TESTS ON POORLY GRADED FINE SAND--NO. 10--JANUARY 1964
Electromagnetic Vibrator No. 10, 0.1-cu-ft Measure
2-psi Single-piece Surcharge, Frequency = 3,600 cpm

Time of vibration, min	Rheostat setting, percent	Initial density, pcf	Moisture final percent	Dry density, pcf	Av dry density, pcf
1/ (1) 1	100	90.8	Ovendry	111.9	112.0
3	100			112.7	113.2
5	100			113.0	113.6
7	100			113.4	113.8
9	100			113.8	114.1
12	100			113.1	113.8
1/ (2) 1	100	90.3	Ovendry	112.1	
3	100			113.8	
5	100			114.1	
7	100			114.2	
9	100			114.4	
12	100			114.5	
(1) 12	100	95.1 min+5	Ovendry	113.2	113.2
(2) 12	100	95.1 min+5	Ovendry	113.1	
(1) 12	100	98.9 min+10	Ovendry	113.7	113.6
(2) 12	100	98.9 min+10	Ovendry	113.6	
(1) 16	100	91.1	Ovendry	114.0	113.8
(2) 16	100	90.5	Ovendry	113.6	
(1) 16	90	90.8	Ovendry	112.9	113.1
(2) 16	90	90.6	Ovendry	113.3	
(1) 16	80	90.7	Ovendry	114.0	113.6
(2) 16	80	91.0	Ovendry	113.1	
(1) 16	70	91.7	Ovendry	113.7	113.6
(2) 16	70	90.4	Ovendry	113.5	
(1) 16	60	91.3	Ovendry	114.2	113.8
(2) 16	60	90.7	Ovendry	113.4	
(1) 16	50	91.5	Ovendry	112.9	113.0
(2) 16	50	91.2	Ovendry	113.1	
(1) 16	40	91.5	Ovendry	111.4	111.1
(2) 16	40	90.9	Ovendry	110.8	
(1) 16	30	91.5	Ovendry	102.7	106.4
(2) 16	30	90.9	Ovendry	110.0	
(1) 20	100		15.6	113.7	112.1
(2) 20	100		14.9	110.5	
(1) 20	90		15.3	113.2	
(1) 20	80		16.2	112.7	
(1) 20	70		16.2	111.5	

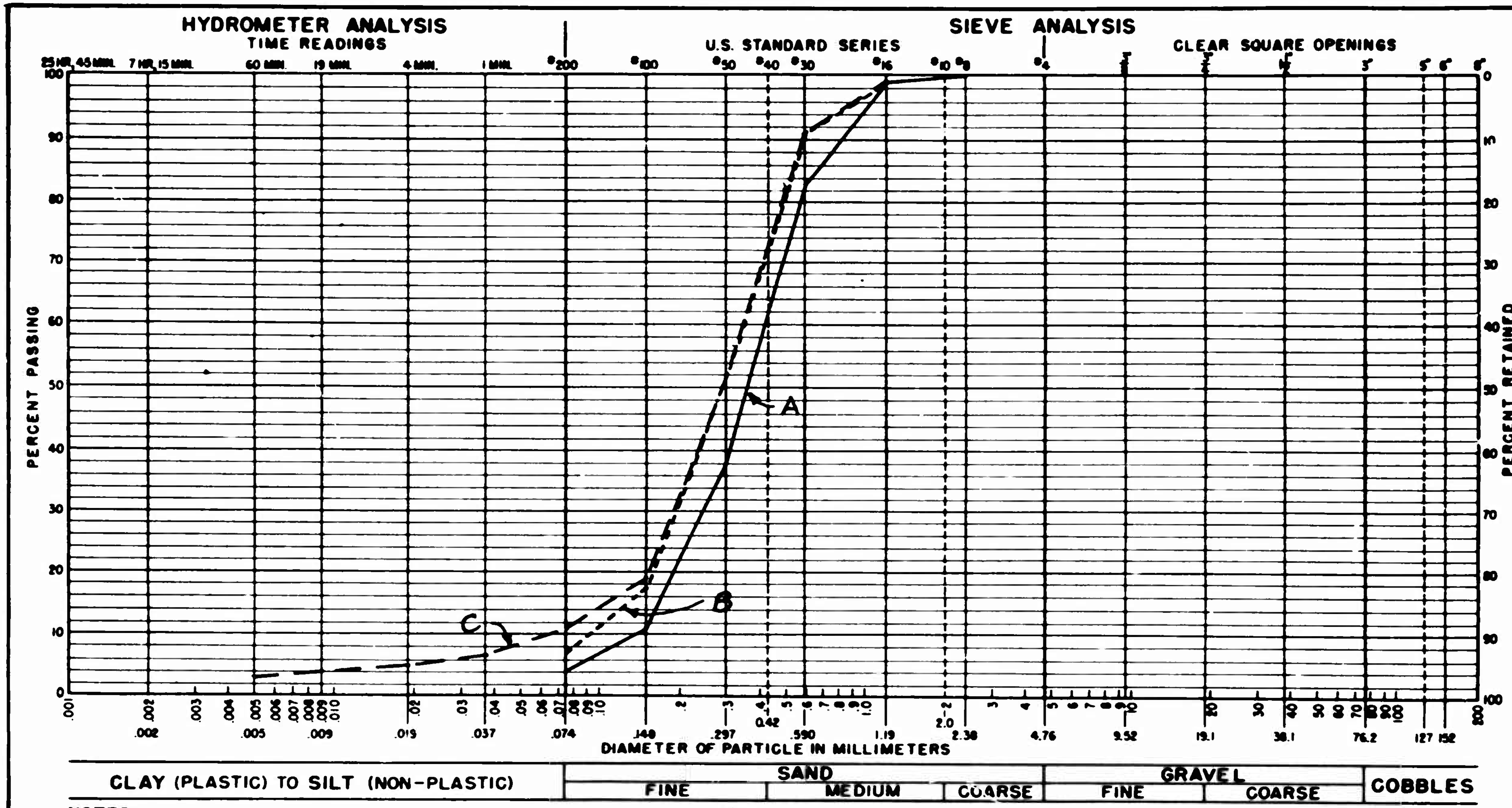
1/Nos. (1) and (2) indicate duplicate samples.

Table 8

RESULTS OF TESTS ON POORLY GRADED FINE SAND--NO. 10--JANUARY 1964
Eccentric-weight-type Vibrator No. 11, 0.1-cu-ft Measure
2-psi Single-piece Surcharge, Variable Frequency

Time of vibration, min	Rheostat setting, volts	Initial density, pcf	Moisture, final percent	Dry density, pcf	Av dry density, pcf (1) & (2)
1/ (1) 0.5	120	89.7	Ovendry	106.6	
1				109.7	
3				110.5	
5				111.5	
7				112.0	
9				112.8	
12				112.6	112.2
1/ (2) 2	120	89.3	Ovendry	109.2	
4				110.2	
6				110.9	
8				111.0	
10				111.4	
12				111.8	
(1) 12	120	95.1 min+5	Ovendry	114.0	114.2
(2) 12	120	95.1 min+5	Ovendry	114.4	
(1) 12	120	100.1 min+10	Ovendry	113.7	113.4
(2) 12	120	100.1 min+10	Ovendry	113.0	
(1) 16	120	89.9	Ovendry	112.6	113.4
(2) 16	120	91.0	Ovendry	114.1	
(1) 16	110	90.9	Ovendry	113.8	113.2
(2) 16	110	90.6	Ovendry	112.5	
(1) 16	100	91.5	Ovendry	112.9	113.2
(2) 16	100	90.9	Ovendry	113.6	
(1) 16	90	90.5	Ovendry	113.3	113.6
(2) 16	90	91.0	Ovendry	113.9	
(1) 16	80	90.7	Ovendry	113.3	113.3
(2) 16	80	90.6	Ovendry	113.3	
(1) 16	70	90.9	Ovendry	109.6	110.1
(2) 16	70	90.5	Ovendry	110.6	
(1) 20	120	-	16.3	111.2	108.2
(2) 20	120	-	14.7	105.3	

1/Nos. (1) and (2) indicate duplicate samples.



NOTES:

Soil No. 24N339
Poorly graded fine sand, 10 percent fines
(dune sand)

Key:

GRADATION TEST

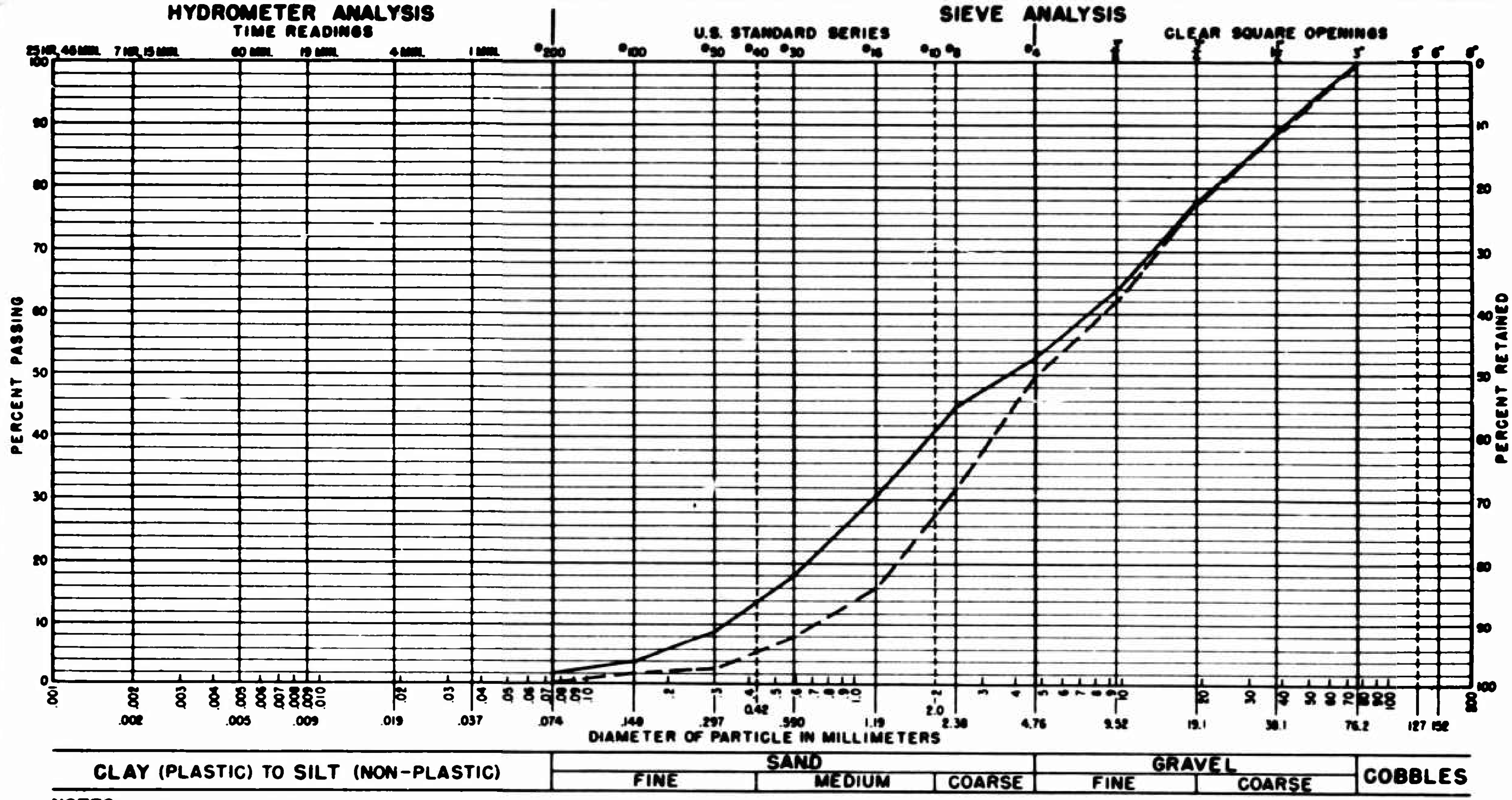
———— Before vibration--10 minutes on sieve shaker

- - - - - After vibration--10 minutes on sieve shaker

— — — — Before vibration--by standard procedure using a mechanical disperser

LABORATORY SAMPLE No. 24N339 FIELD DESIGNATION ______ EXCAVATION No. ______ DEPTH ______ FT.

FIGURE NO. 1



NOTES: Soil No. 7

Poorly graded sand and gravel--3-inch maximum size, no fines (artificial gradation), South Platte River, Denver, Colorado

Key:

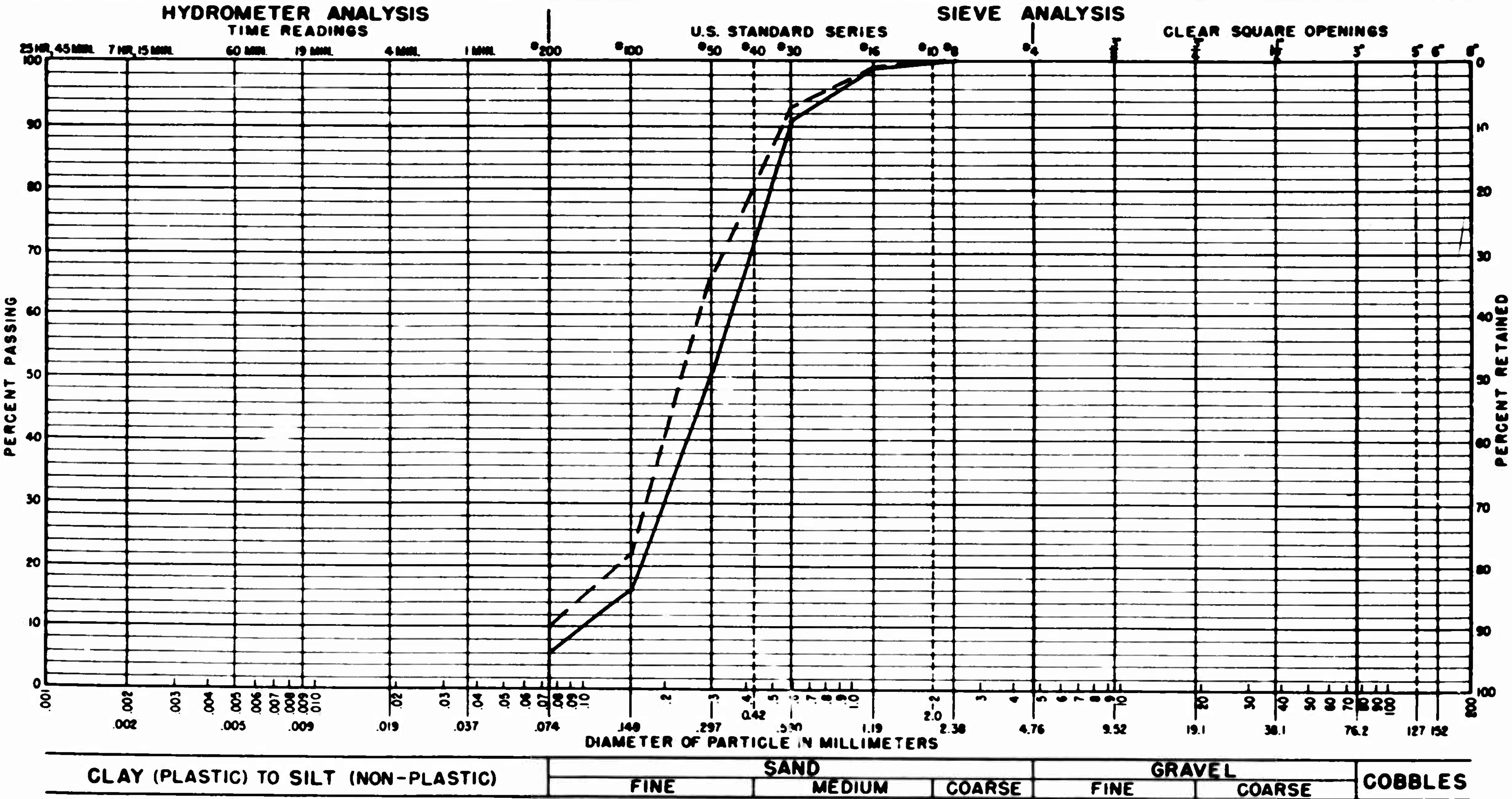
———— Before vibration

– – – – After vibration

GRADATION TEST

LABORATORY SAMPLE No. 24E-7 FIELD DESIGNATION ________ EXCAVATION No. ________ DEPTH ________ FT.

FIGURE NO. 2



NOTES: Soil No. 10
Poorly graded fine sand--10 percent fines (artificial gradation)--Cherry Creek, Denver, Colorado

Key:
———— Before vibration
– – – – After vibration

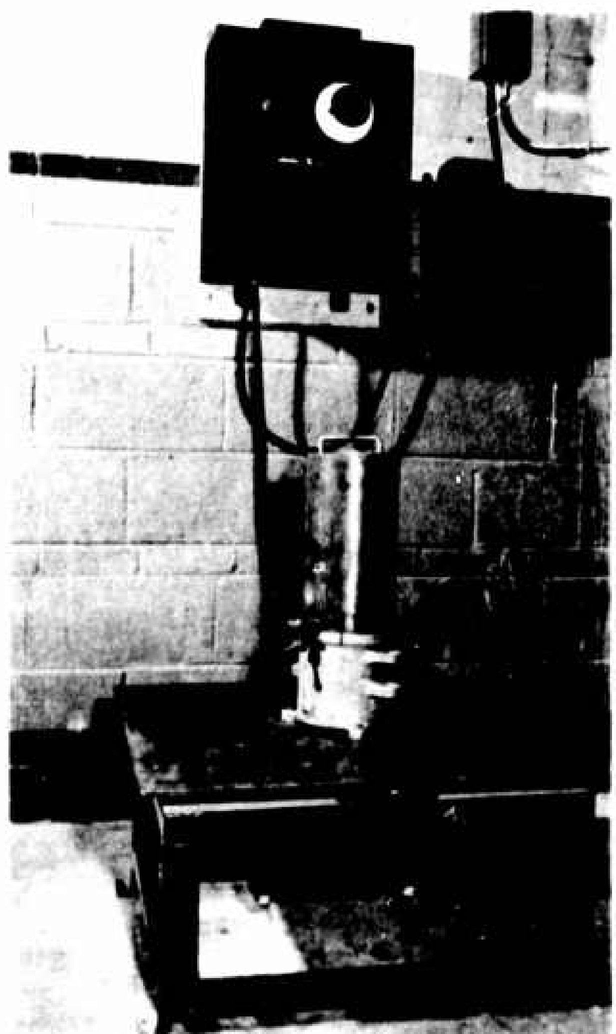
GRADATION TEST

LABORATORY SAMPLE No. 24E-10 FIELD DESIGNATION ______ EXCAVATION No. ______ DEPTH ______ FT.

FIGURE NO. 3

Pouring minimum density in 0.1-cu-ft measure.

Figu



PX-D-27356 A

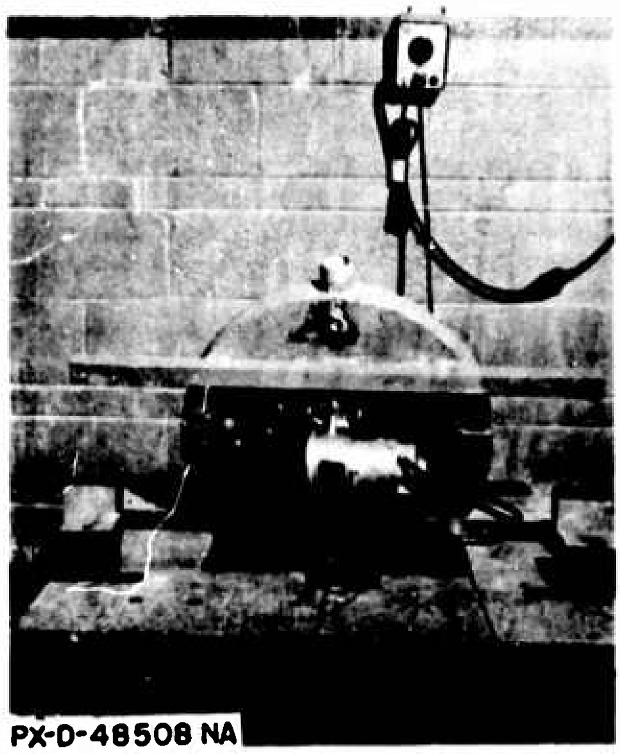
Large electromagnetic table-type vibrator (No. 9) with 0.1-cu-ft measure, guide sleeve and 2-psi surcharge.

Figure 5

PX-D-43294 NA

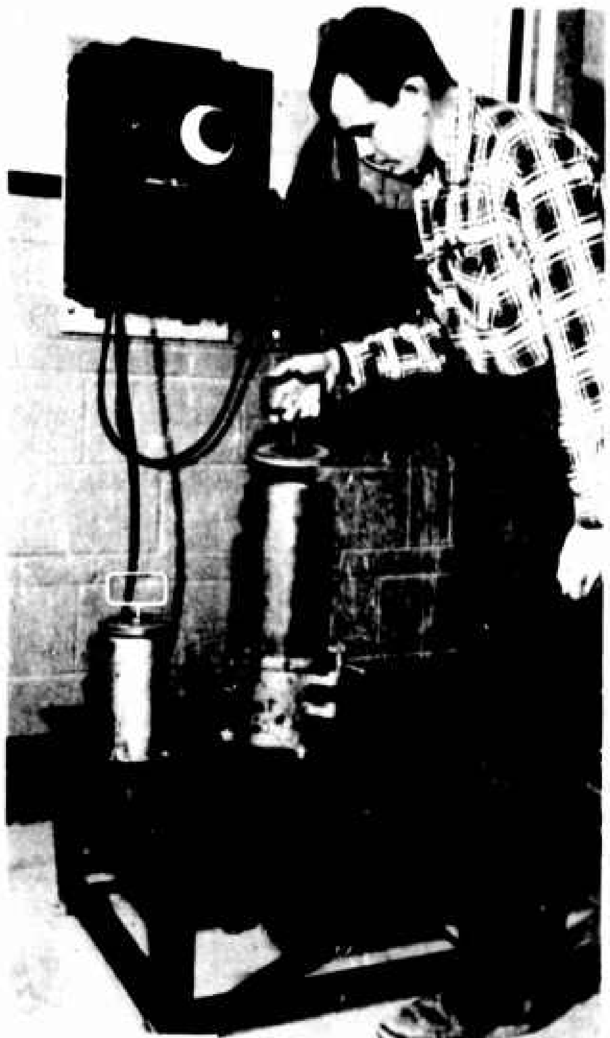
Small electromagnetic table-type vibrator (No. 10) with 0.1-cu-ft measure, guide sleeve and 2-psi surcharge.

Fig



PX-D-48508 NA

Eccentric-weight table-type vibrator (No. 11). Dismounted to show vibrator attached to shop-made table.


PX-D-31799 A

Placing surcharge baseplate on soil specimen. Note solid 2-psi surcharge weight on vibratory table.

Figure 8

Making final dial reading on 0.1-cu-ft measure.

Figure 9

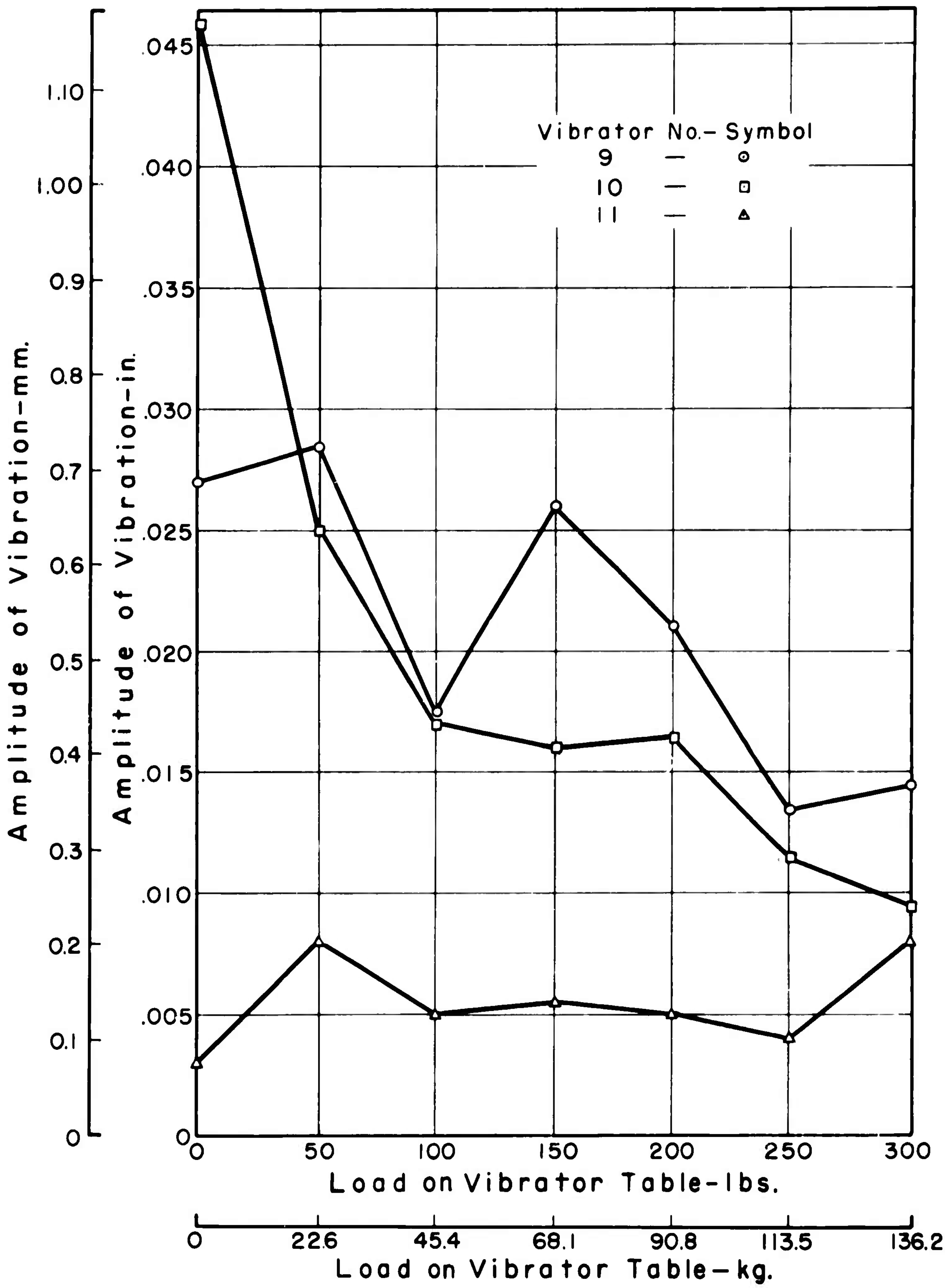


Fig.10 Amplitude vs. Load on Vibrator at Maximum Rheostat Setting

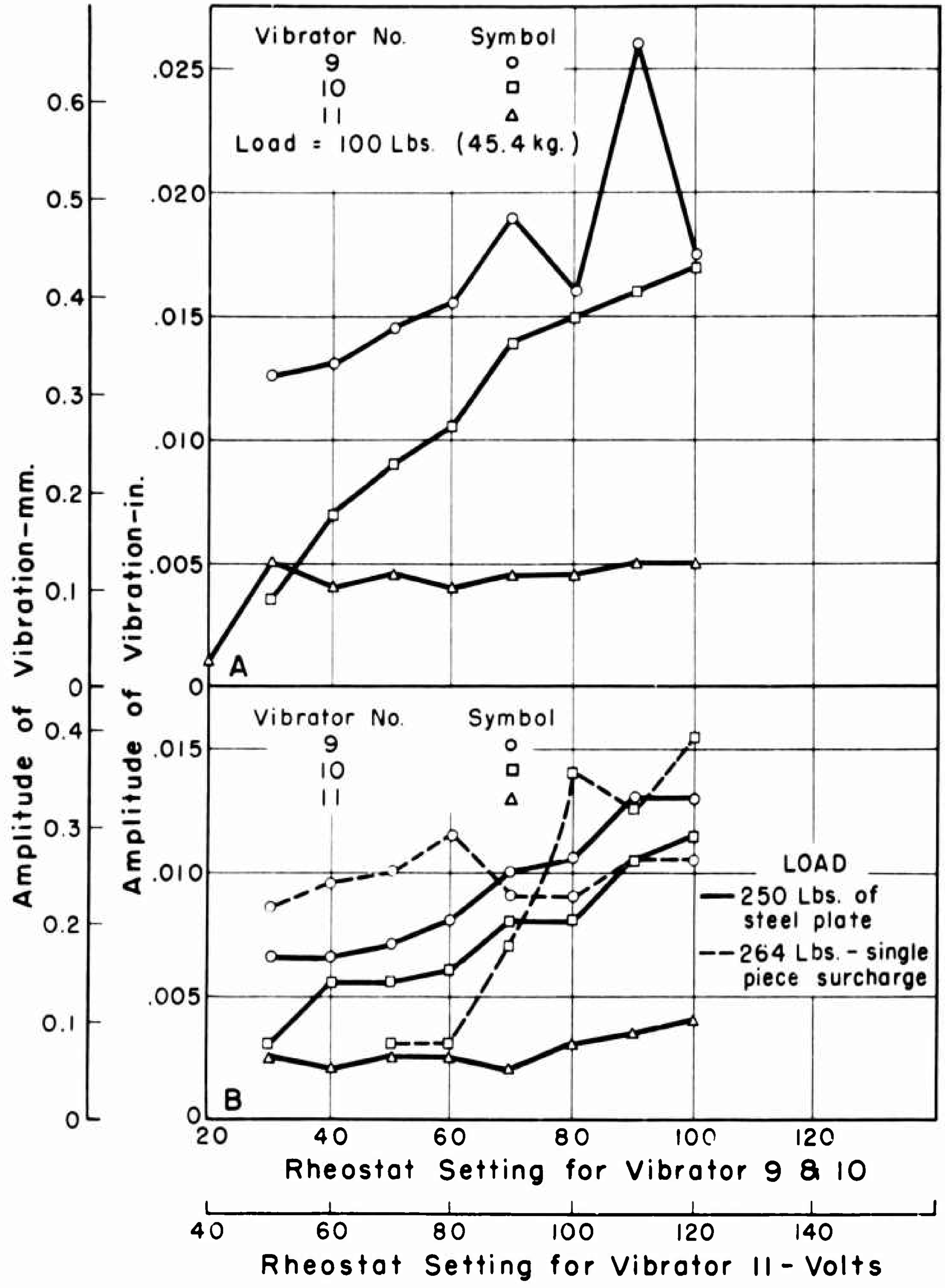


Fig. 11 Amplitude of Vibration vs. Rheostat Setting

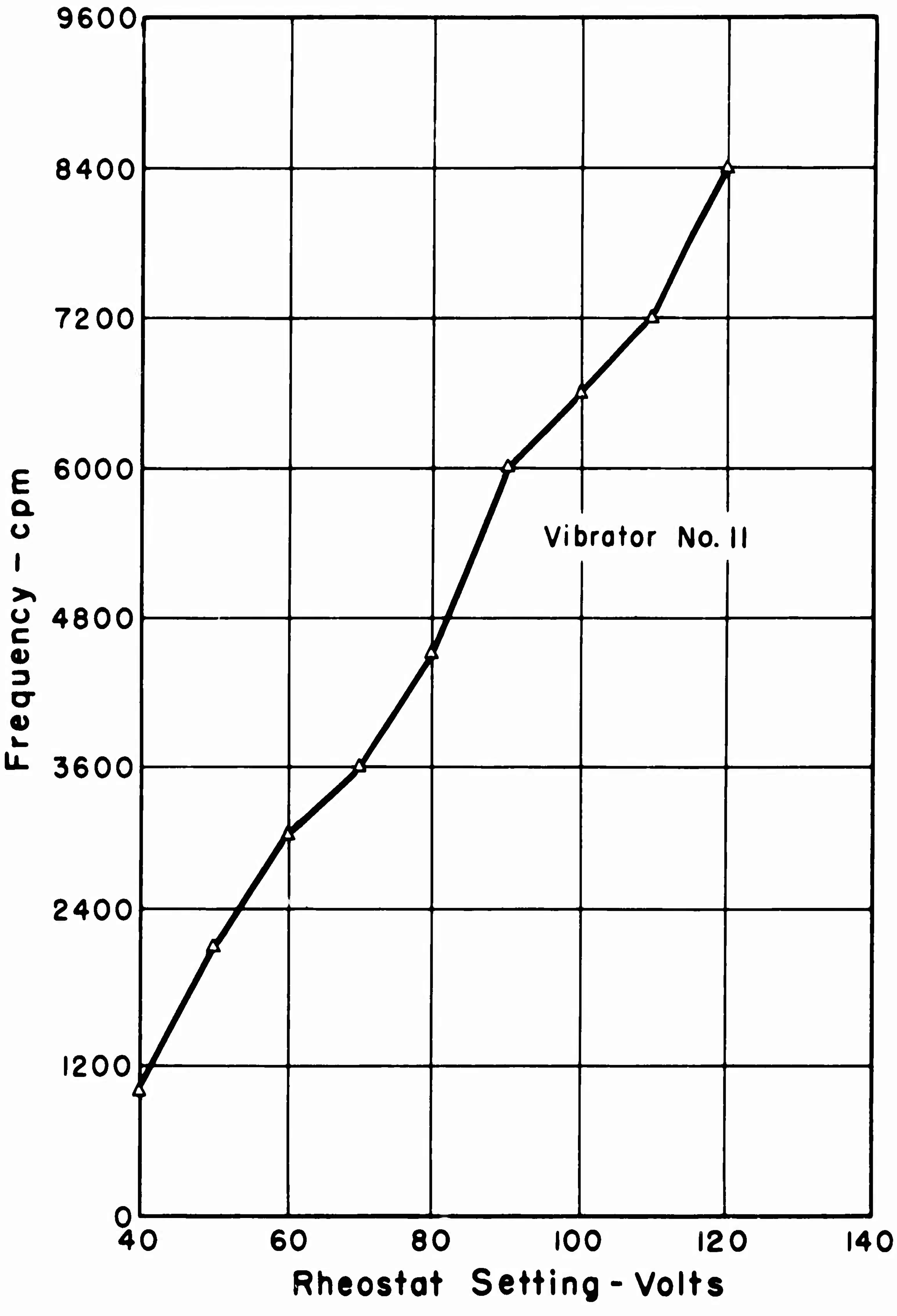


Fig. 12 Frequency vs. Rheostat Setting for Vibrator No. 11

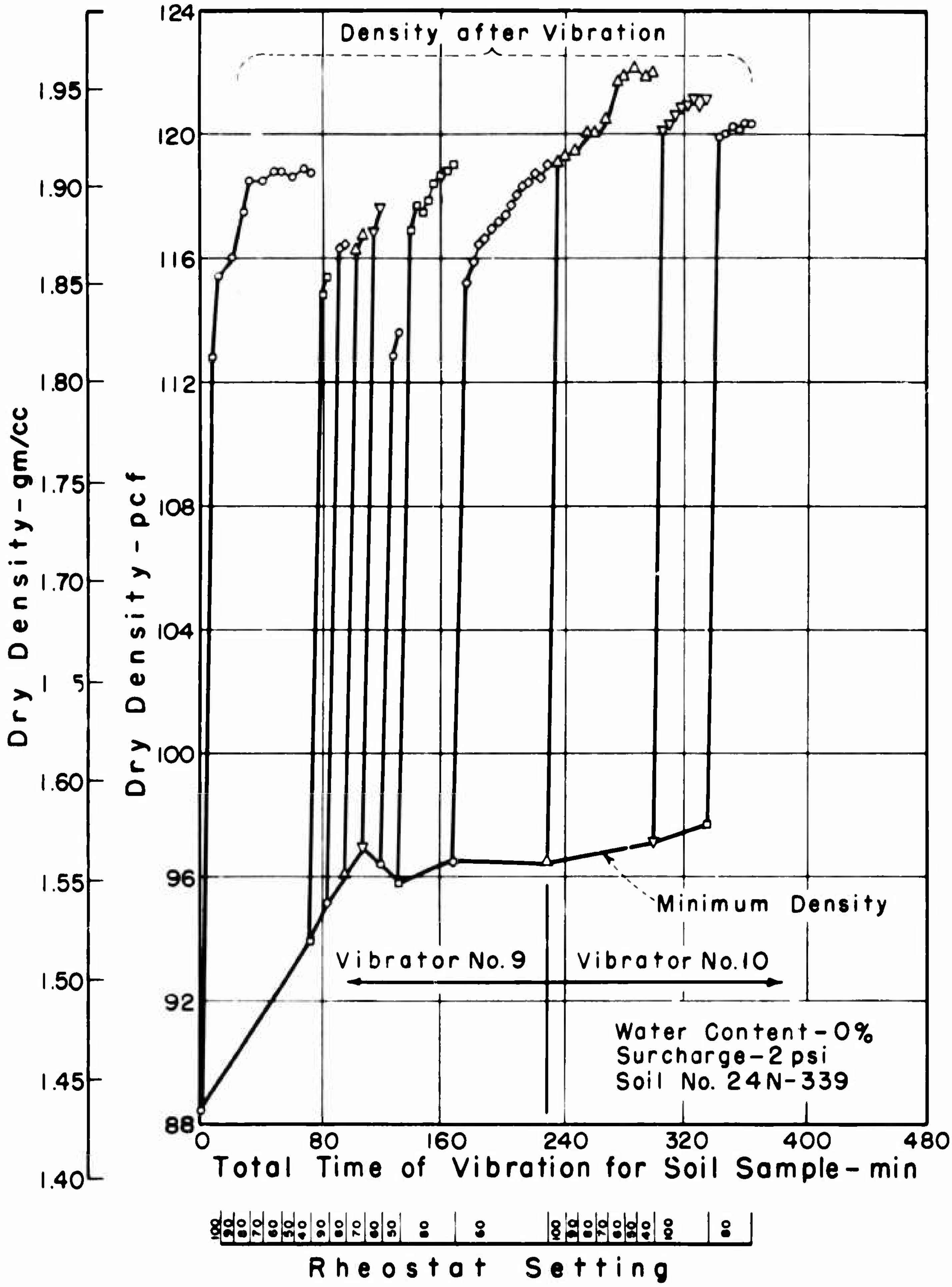


Fig. 13 Dry Density vs. Time of Vibration and Rheostat Setting

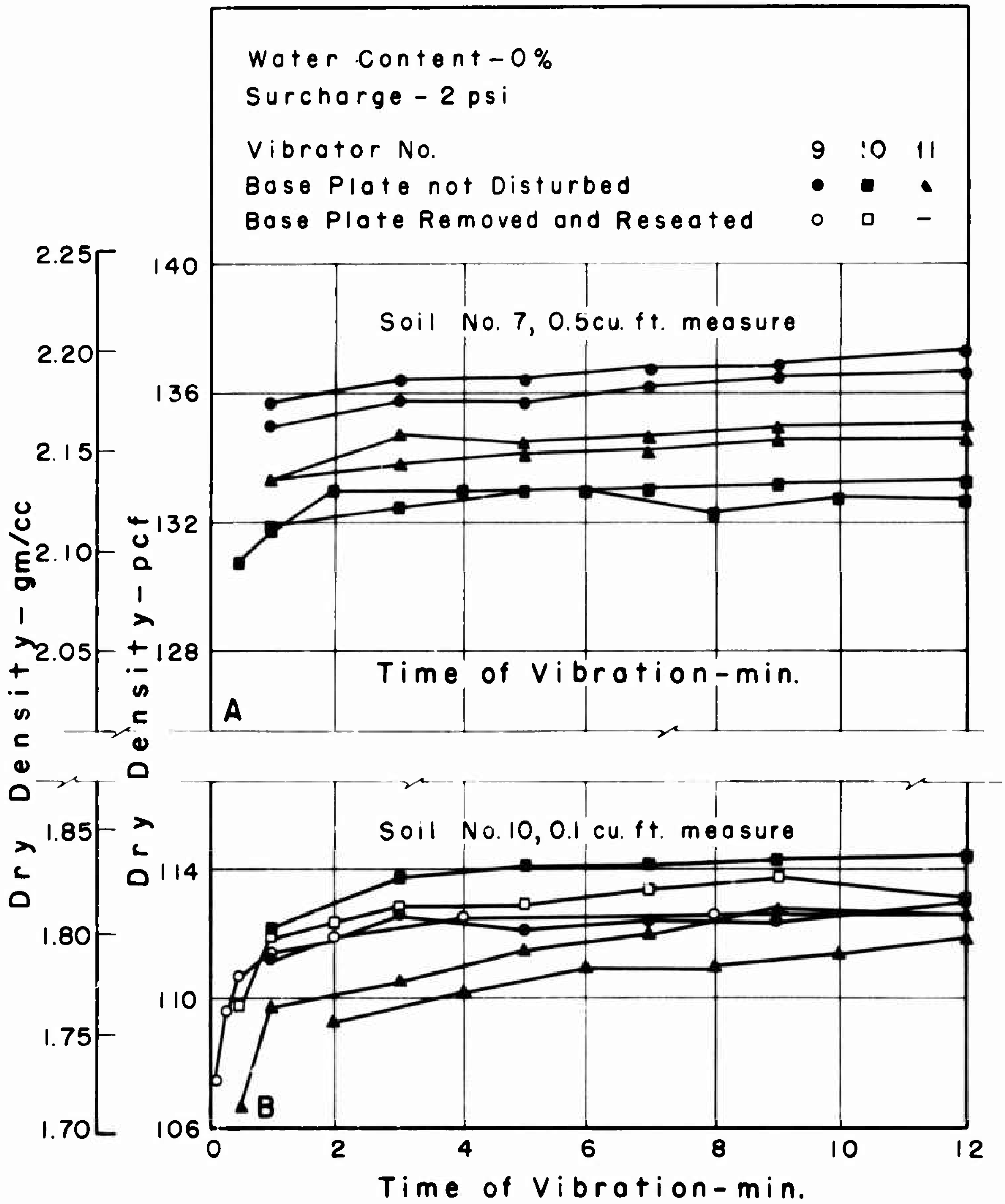


Fig. 14 Dry Density vs Time of Vibration

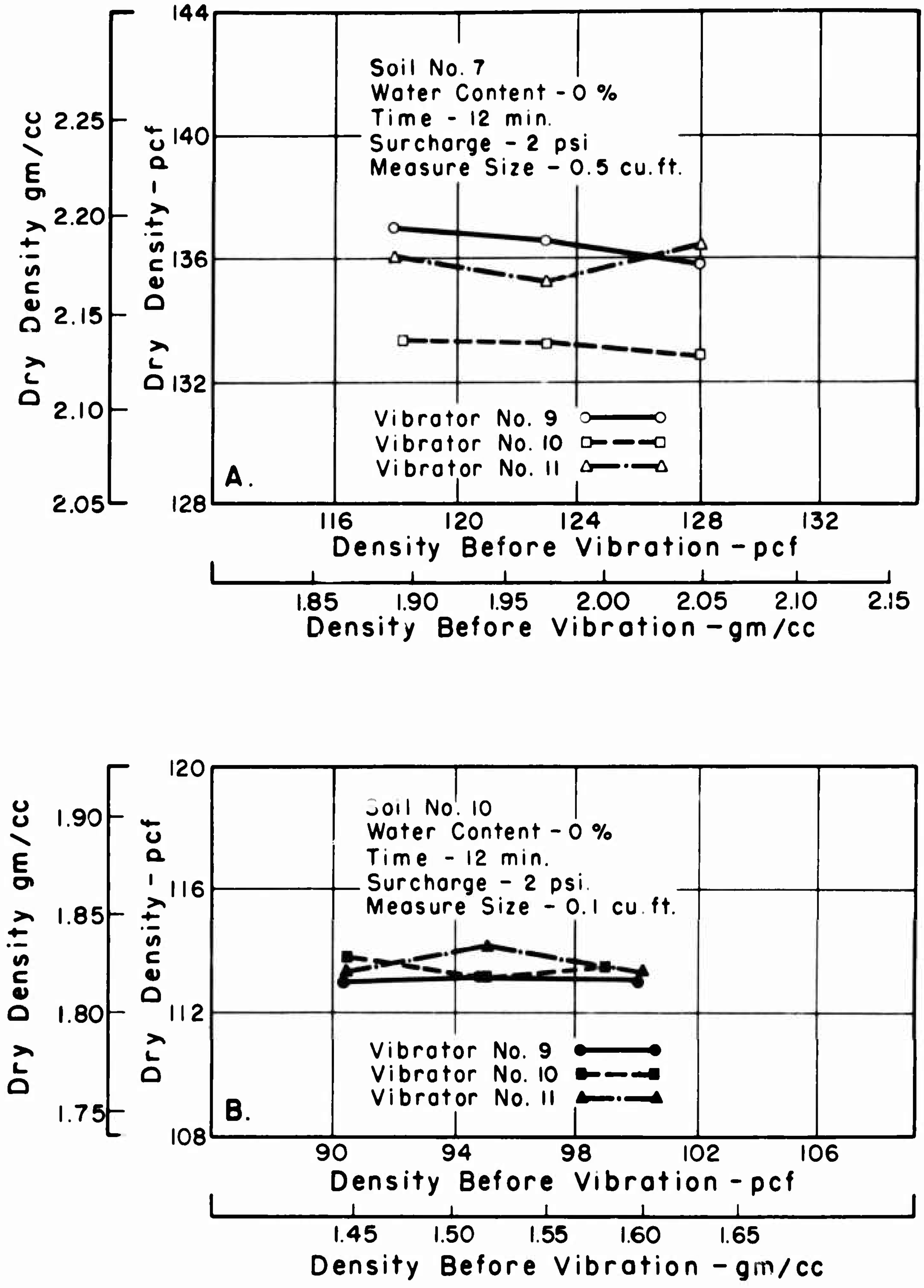


Fig. 15 Dry Density Vs. Density Before Vibration

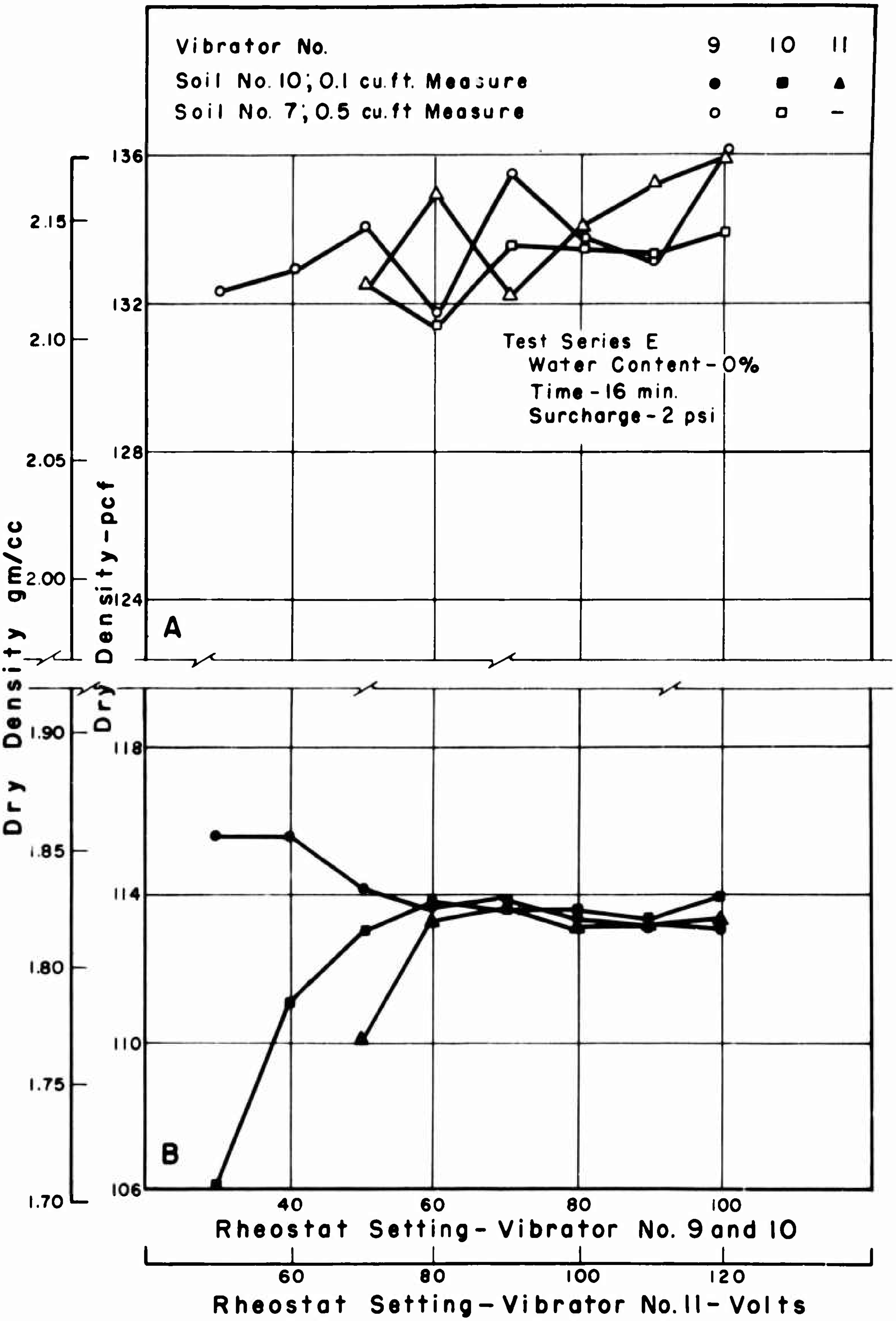


Fig. 16 Dry Density vs Rheostat Setting

APPENDIX A

Retesting of Soils to Compare Results Obtained with New Test Procedure and Equipment with Previous Results

PURPOSE

Investigations of methods to determine the maximum density of cohesionless soils have been carried on in the Soils Engineering Branch since about 1954. A number of different types of vibrators and a wide variety of soils have been tested. The tests reported in this appendix were run to compare present methods with some of the methods used in the past.

TEST PROCEDURE

A number of tests were run according to the test procedure prescribed in Designation E-12B1/ using Vibrators No. 9, 10, and 11 on Soils No. 1, 2, 3, 4, 6, 7, and 9 which had been used in previous investigations.2,3,4/ Standard gradation tests (Designation E-6)1/ were run on each soil and compared with the results of standard gradation tests which were run on the soils before they were vibrated the first time.

TEST RESULTS

The maximum densities obtained during this retesting of Soils No. 1, 2, 3, 4, 6, 7, and 9 are compared with the maximum densities obtained in previous tests in Table A-1. The results of gradation tests on these soils before and after vibration are presented in Figures A-1 through A-7. The gradation before vibration was determined when the material was first received in the laboratory in the year 1957 while the gradation after vibration was determined in 1964. Between the before and after gradations the soils had been subject to various types of vibration for a total of about 6 hours.

DISCUSSION OF TEST RESULTS

Major changes in gradation occurred in Soils No. 1, 2, 3, and 4 between the time the material was received and tests in 1964. Soils No. 1, 2, and 4 became coarser while Soil No. 3 became finer. Two mechanisms work to change soil gradation: (1) a breakdown of particles by mechanical action, and (2) a loss of the finer material during storage and handling and by migration of fines from the top of the measure during vibration testing. Minor changes in gradation were also observed for Soils No. 6 and 7, but no appreciable change was noted in the gradation of Soil No. 9.

Since the effect of gradation changes on the soil density obtained in a vibration test is unknown, no conclusions can be drawn as to the efficiency of the present procedure compared to the procedures used in earlier investigations.

CONCLUSION

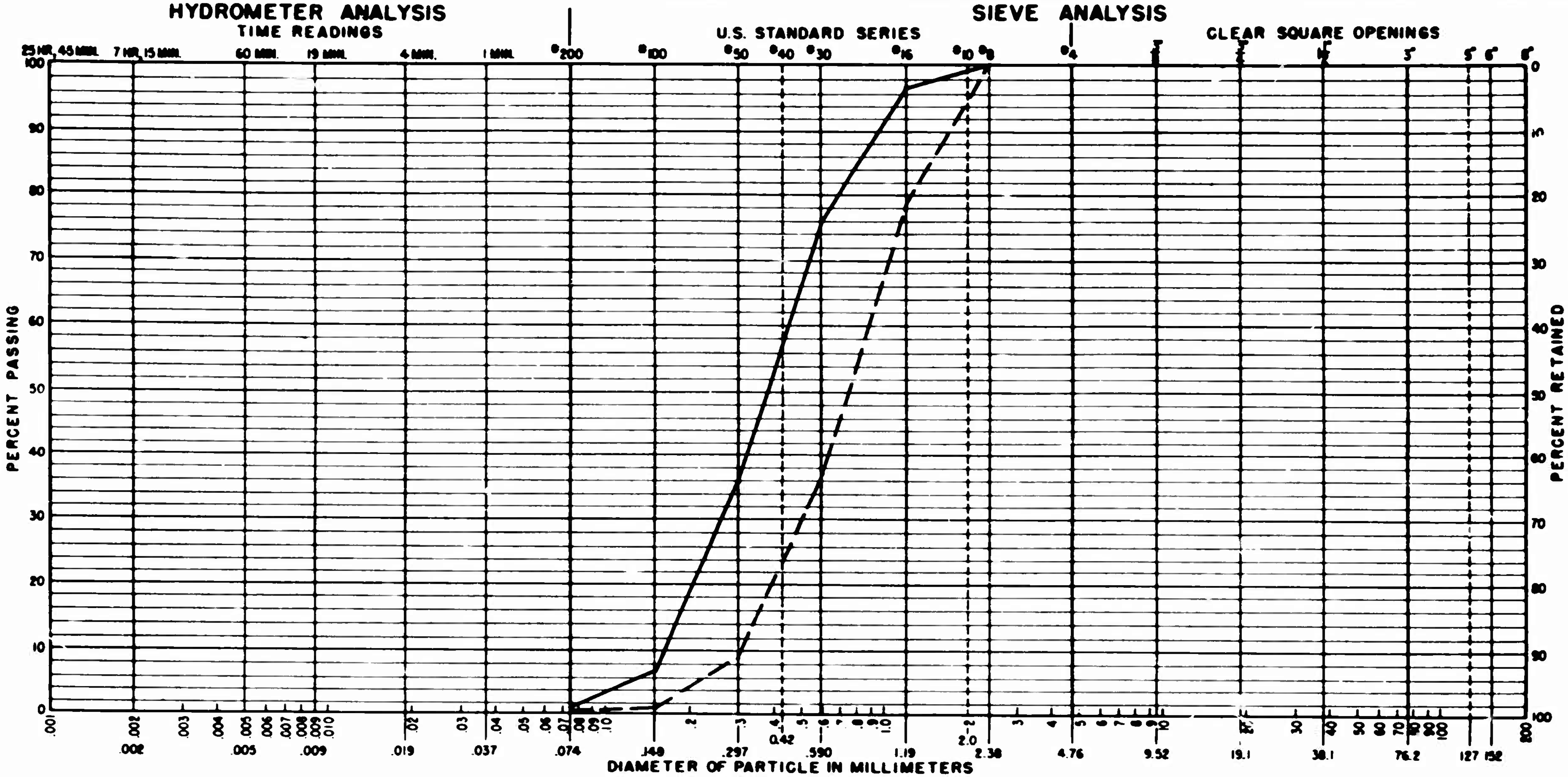
The meaning of the results presented in this Appendix is not clear from the available data, but are presented here for possible use in future investigations.

Table A-I

AVERAGE DENSITIES OBTAINED DURING RELATIVE DENSITY RESEARCH

Soil type	Av of 3 tests Av max density, pcf	Av of 3 tests Av min density, pcf	Vibrator No.	Mold size, cu ft	Av of 3 tests moisture percent	Surcharge	
						Amount PSI	G = Guided H = Hand held
1	111.6	91.5	1	0.1	0	0.53	H
1	110.5	1/ 93.4	9	0.1	0	2.0	G
1	109.8	1/ 93.4	10	0.1	0	2.0	G
2	123.5	102.6	1	0.1	0	1.14	H
2	119.2	1/ 101.4	9	0.1	0	2.0	G
2	120.1	1/ 101.4	10	0.1	0	2.0	G
2	121.5	1/ 101.4	11	0.1	0	2.0	G
3	121.6	98.4	1	0.1	0	1.14	H
3	116.1	1/ 101.1	9	0.1	0	2.0	G
3	120.1	1/ 101.1	10	0.1	0	2.0	G
4	140.8	121.6	1	0.5	0	0.17	H
4	1/ 144.8		7	0.5	1/ 4.5	2.0	G
4	147.3	1/ 119.3	9	0.1	4.2	2.0	G
4	146.5	1/ 119.3	10	0.1	4.4	2.0	G
6	132.4	101.3	1	0.1	0	1.15	H
6	1/ 144.0		7	0.1	6.0	2.0	G
6	141.7	1/ 109.3	9	0.1	6.8	2.0	G
6	135.2	1/ 109.3	10	0.1	8.7	2.0	G
7	1/ 147.5		7	0.5	7.5	2.0	G
7	136.8	120.1	9	0.5	6.7	2.0	G
7	133.6	118.9	10	0.5	7.3	2.0	G
9	1/ 141.5		7	0.5	4.9	3.0	G
9	139.4	118.7	9	0.5	5.7	2.0	G
9	133.8	1/ 120.0	10	0.5	6.5	2.0	G

1/Only one test.



CLAY (PLASTIC) TO SILT (NON-PLASTIC)	SAND			GRAVEL		COBBLES
	FINE	MEDIUM	COARSE	FINE	COARSE	

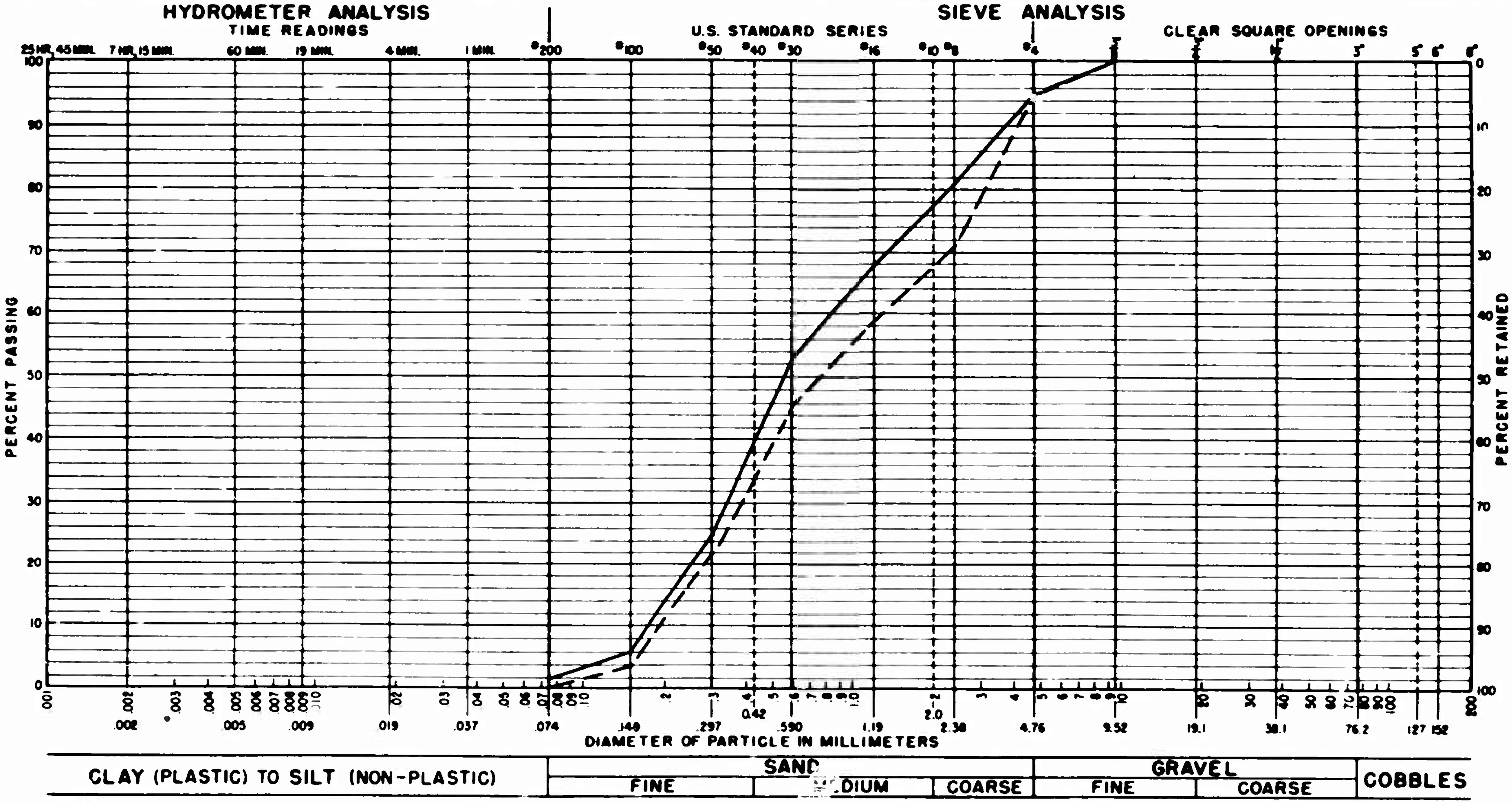
NOTES:
Soil No. 1
Natural fine sand

Key:
——— Before vibration
– – – – After vibration

GRADATION TEST

LABORATORY SAMPLE No. 24E-1 FIELD DESIGNATION ______ EXCAVATION No. ______ DEPTH ______ FT.

FIGURE NO. A-1



NOTES: Soil No. 2
Natural medium sand

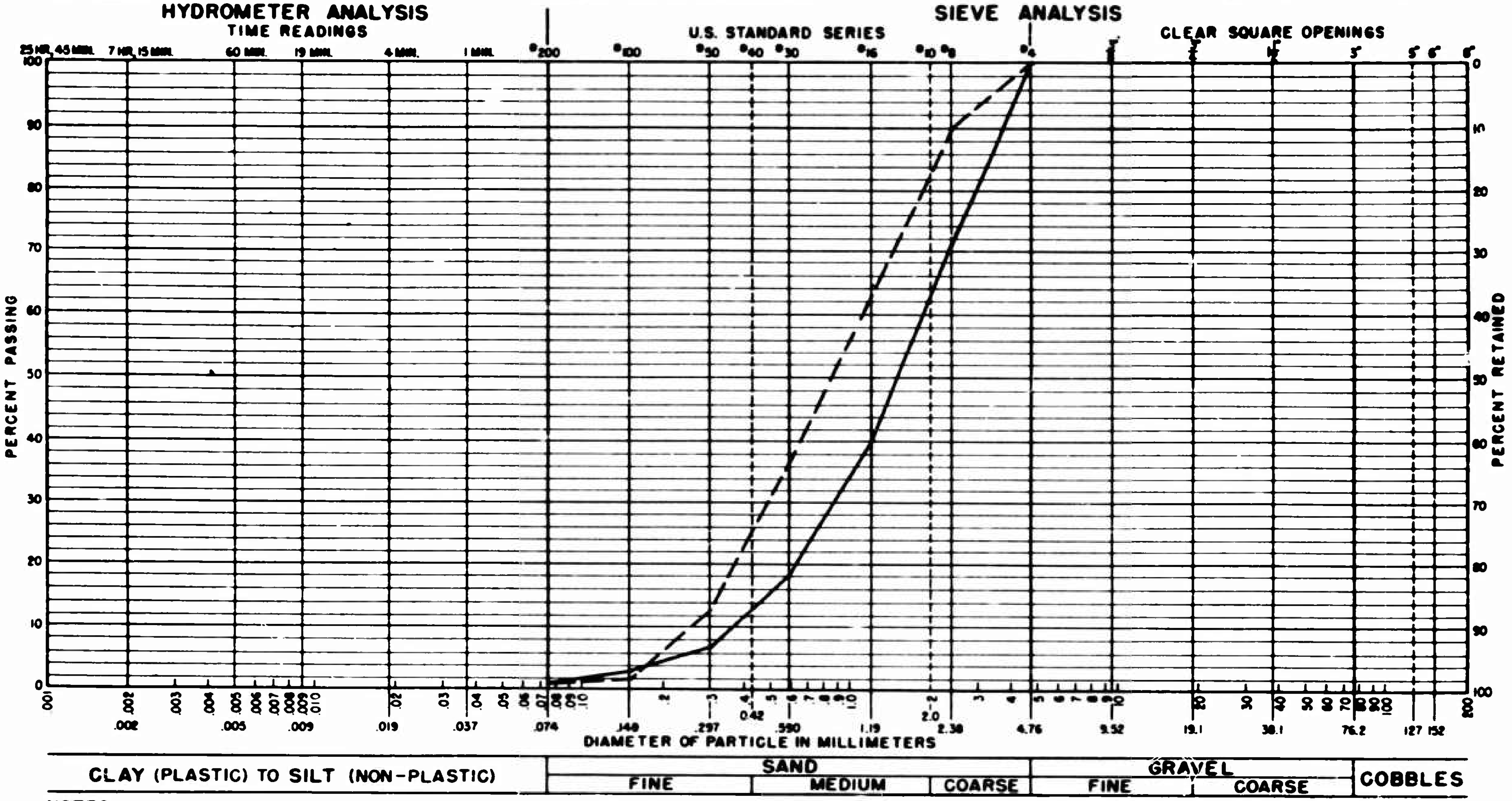
Key:

——— Before vibration
– – – – After vibration

GRADATION TEST

LABORATORY SAMPLE No. 24E-2 FIELD DESIGNATION ____ EXCAVATION No. ____ DEPTH ____ FT.

FIGURE NO. A-2



GRADATION TEST

NOTES:

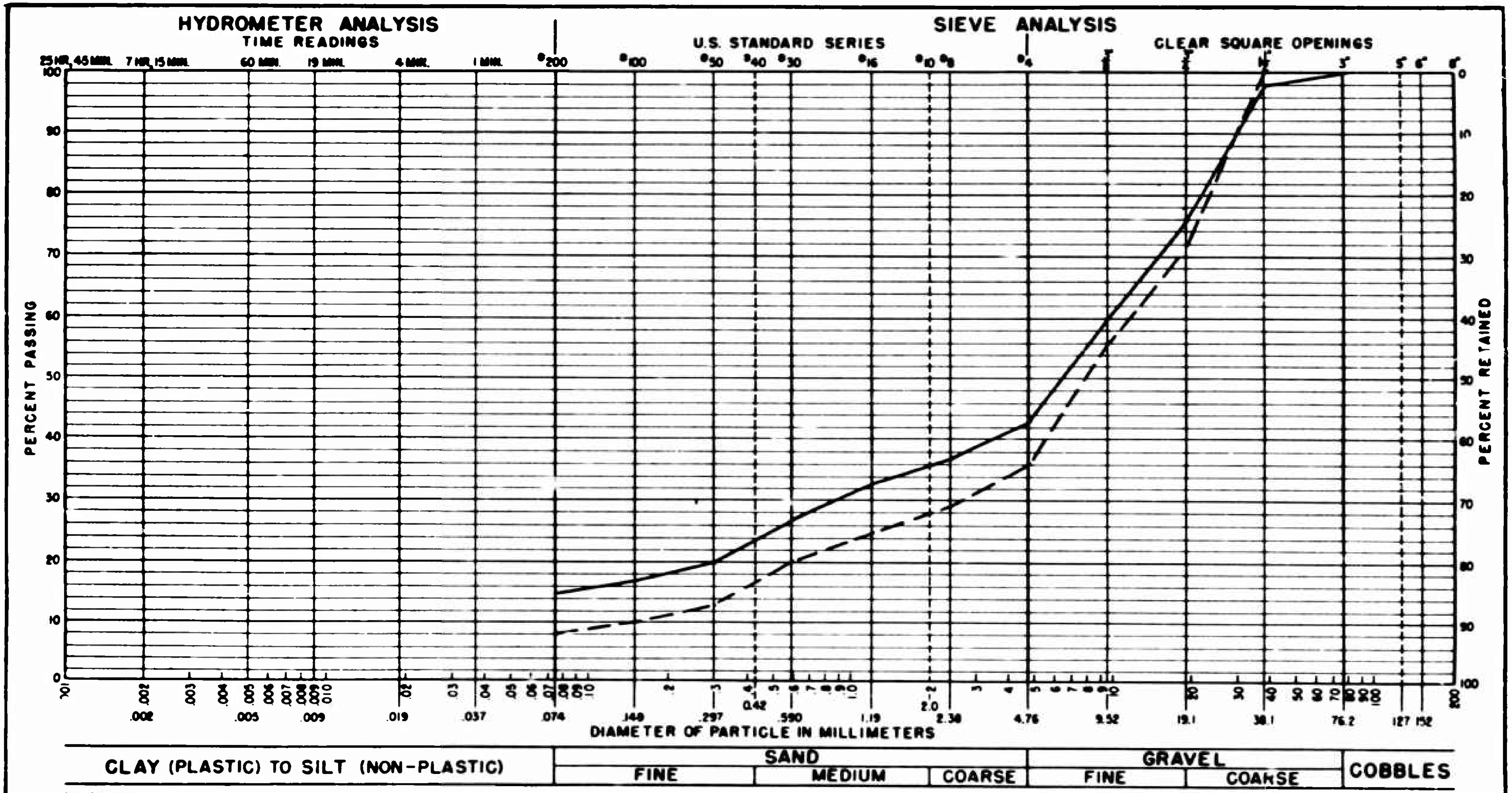
Soil No. 3
Natural coarse sand

Key:

——— Before vibration
– – – – – After vibration

LABORATORY SAMPLE No. 24E-3 FIELD DESIGNATION ______ EXCAVATION No. ______ DEPTH ______ FT.

FIGURE NO. A-3



NOTES:

Soil No. 4
Natural sand and gravel with binder

Key:

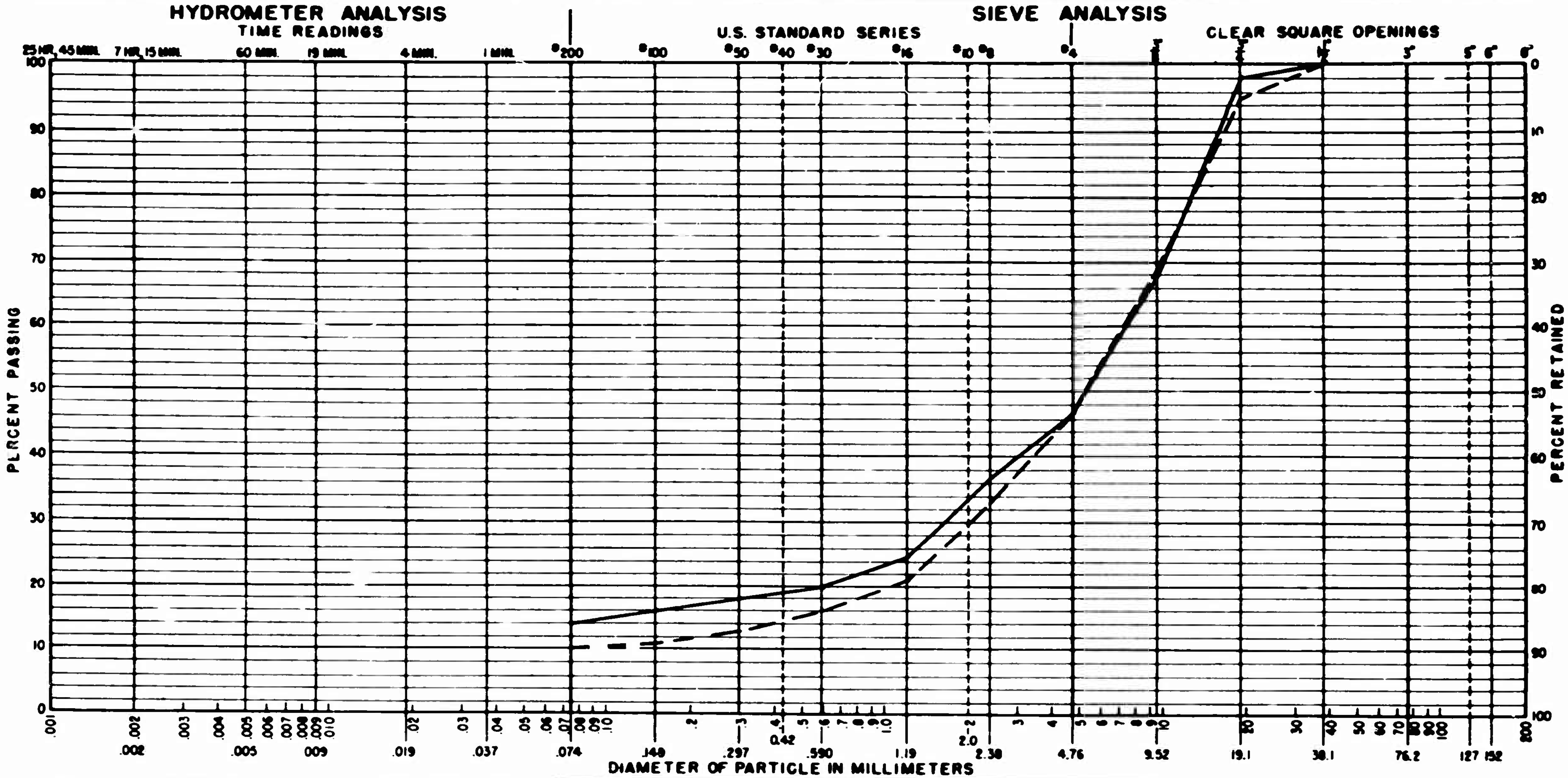
——— Before vibration

– – – – After vibration

GRADATION TEST

LABORATORY SAMPLE No. 24E-4 FIELD DESIGNATION ______ EXCAVATION No. ______ DEPTH ______ FT.

FIGURE NO. A-4



CLAY (PLASTIC) TO SILT (NON-PLASTIC)	SAND			GRAVEL		COBBLES
	FINE	MEDIUM	COARSE	FINE	COARSE	

NOTES: Soil No. 6
Coarse-graded crushed limestone

Key:

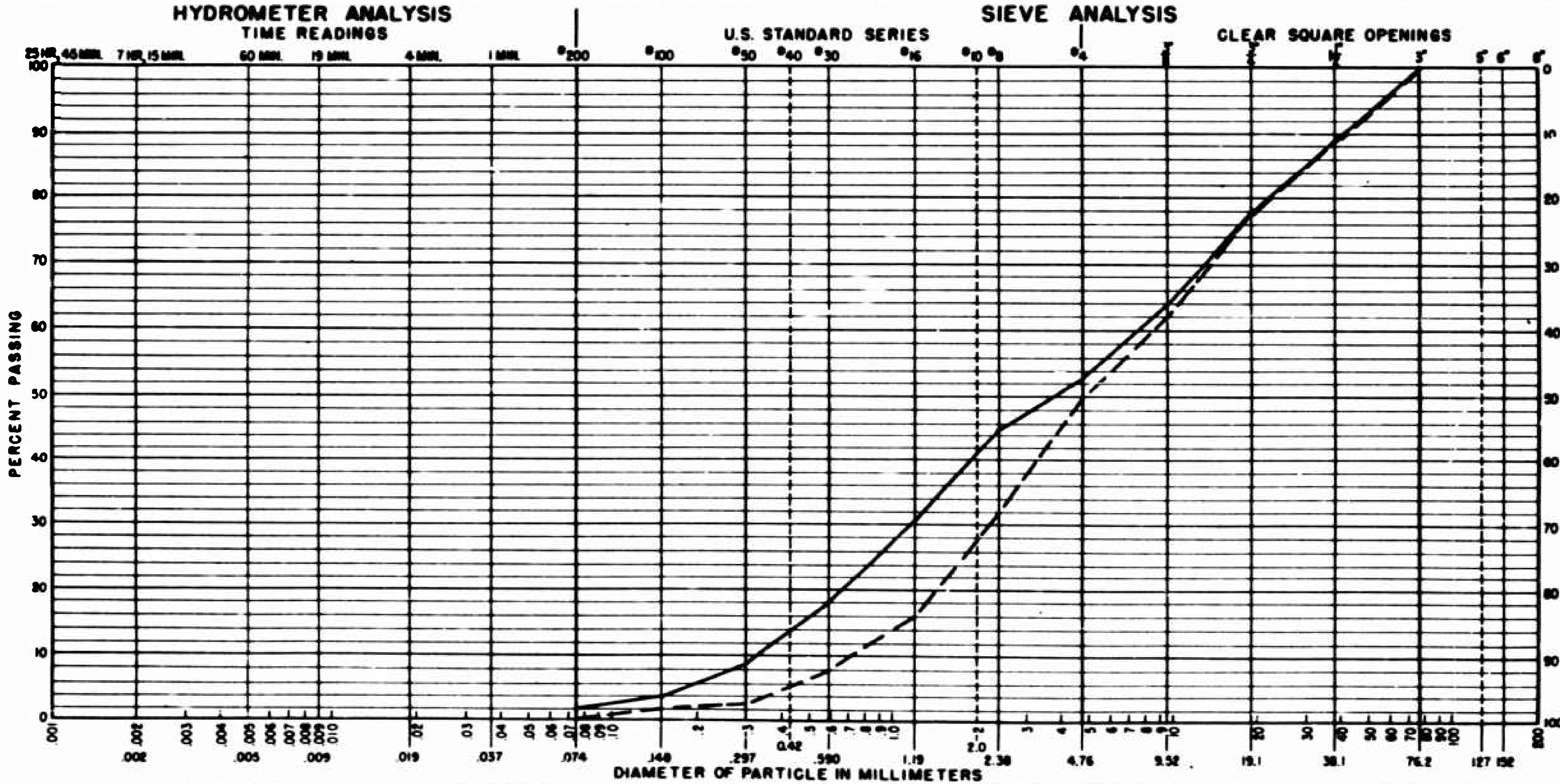
——— Before vibration

– – – – After vibration

GRADATION TEST

LABORATORY SAMPLE No. 24E-6 FIELD DESIGNATION ______ EXCAVATION No. ______ DEPTH ______ FT.

FIGURE NO. A-5



CLAY (PLASTIC) TO SILT (NON-PLASTIC)	SAND			GRAVEL		COBBLES
	FINE	MEDIUM	COARSE	FINE	COARSE	

NOTES: Soil No. 7

Poorly graded sand and gravel--3-inch maximum size, no fines (artificial gradation), South Platte River, Denver, Colorado

Key:

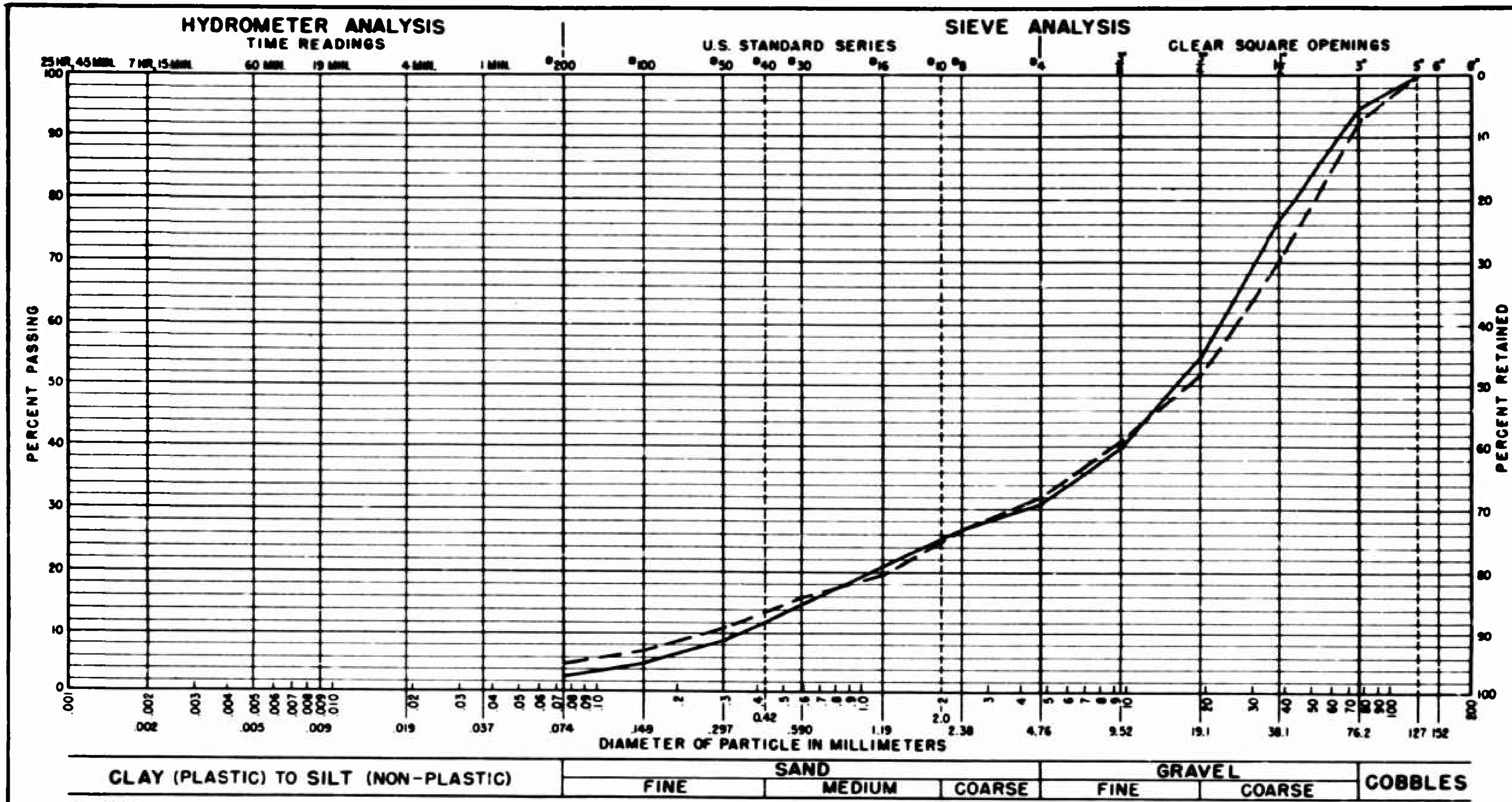
——— Before vibration

– – – – – After vibration

GRADATION TEST

LABORATORY SAMPLE No. 24E-7 FIELD DESIGNATION ______ EXCAVATION No. ______ DEPTH ______ FT.

FIGURE NO. A-6



NOTES: Soil No. 9

Poorly graded sand and gravel, 5-inch maximum size, 3 percent fines--Little Wood River Project, Idaho

Key:

——— Before vibration

- - - - - After vibration

GRADATION TEST

LABORATORY SAMPLE No. 24E-66 FIELD DESIGNATION____ EXCAVATION No.____ DEPTH____ FT.

FIGURE NO. A-7

APPENDIX B

Tests Using a Sieve Shaker to Obtain the Maximum Density of Cohesionless Soils

PURPOSE

The sieve shaker shown in Figure B-1 is used in many laboratories to determine the gradation of coarse-grained soils. The frequency of "shaking" is about 600 cpm and the amplitude is approximately 0.5 inches. These values of amplitude and frequency differ greatly from those of the vibrators used in investigations of the maximum density of cohesionless soils. A limited number of tests were run to compare the efficiency of the sieve shaker with vibrators previously used.

TEST PROCEDURE

A steelplate was fabricated to fit one of the sieve slots. The measure was attached to the steelplate as shown in Figure B-2. The measure was filled with soil and the steelplate and measure were tightened in the shaker as shown in Figure B-3. Other aspects of the test procedure were the same as described in the body of this report.

TEST RESULTS

Duplicate tests were run on two soils: a poorly graded sand and gravel (Soil No. 7) and a poorly graded fine sand (Soil No. 10). The densities obtained using the sieve shaker are compared with the densities obtained with the large electromagnetic vibrator (No. 9) in Tables B-1 and B-2. The shaker performed well under the load of approximately 100 pounds required for tests on Soil No. 10; but under the load of approximately 250 pounds required for tests on Soil No. 7 the motor overheated and stopped after running about 10 minutes.

DISCUSSION AND CONCLUSION

From the comparison in Table B-1, it is obvious that the sieve shaker cannot be used to obtain the maximum density of Soil No. 7, since the density obtained by the shaker is approximately 10 pounds less than the density obtained by Vibrator No. 9. Also, the motor overheated under the load required for the 0.5-cubic-foot measure.

The sieve shaker appears to give higher maximum densities for Soil No. 10 than were obtained by other vibrators, and the sieve shaker appears to operate very well under the load required for the 0.1-cubic-foot measure.

From the limited number of tests available, it appears that the sieve shaker gives slightly higher maximum densities for some soils, but much lower maximum densities for other soils.

Table B-1

COMPARISON OF DENSITIES OBTAINED BY SIEVE SHAKER WITH DENSITIES OBTAINED BY VIBRATOR NO. 9 ON A POORLY GRADED GRAVEL (SOIL NO. 7)

Ovendry

Sieve shaker		Vibrator No. 9	
Density, pcf	Time of vibration, min	Density, pcf	Time of vibration, min
115.7	0 (minimum)	118.0	0 (minimum)
123.9	2	135.7	1
124.5	4	136.4	3
125.8	8	136.5	5
125.8	12	136.8	7
		136.9	9
		137.3	12
116.8	0 (minimum)	117.8	0 (minimum)
126.7	4	135.0	1
123.3	8	135.8	3
123.4	12	135.7	5
124.0	16	136.3	7
			9
			12

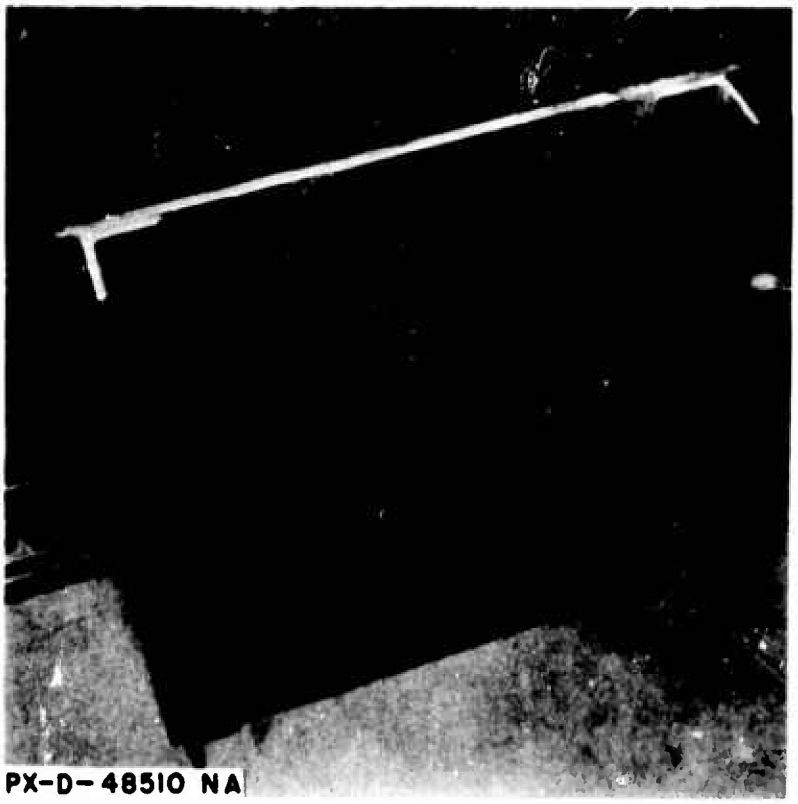
Table B-2

COMPARISON OF DENSITIES OBTAINED BY SIEVE SHAKER WITH DENSITIES OBTAINED BY VIBRATOR NO. 9 ON A POORLY GRADED GRAVEL (SOIL NO. 10)

Sieve shaker		Vibrator No. 9	
Density, pcf	Time of vibration, min	Density, pcf	Time of vibration, min
Ovendry			
88.4	0 (minimum)	90.9	0 (minimum)
108.2	2	111.2	1
109.2	4	112.6	3
113.1	8	112.1	5
116.1	16	112.4	7
		112.4	9
		113.0	12
110.7	4	89.8	0 (minimum)
111.9	8	111.2	1
114.6	12	112.9	3
115.1	16	113.0	5
		113.0	7
		113.0	9
		113.0	12
Initially saturated			
107.5	4	114.2	4
109.5	8	114.0	8
111.6	12	114.1	12
113.7	16	114.1	16
		114.2	20
111.7	4	114.6	4
113.1	8	114.5	8
114.2	12	114.7	12
115.2	16	114.7	16
116.0	20	114.5	20

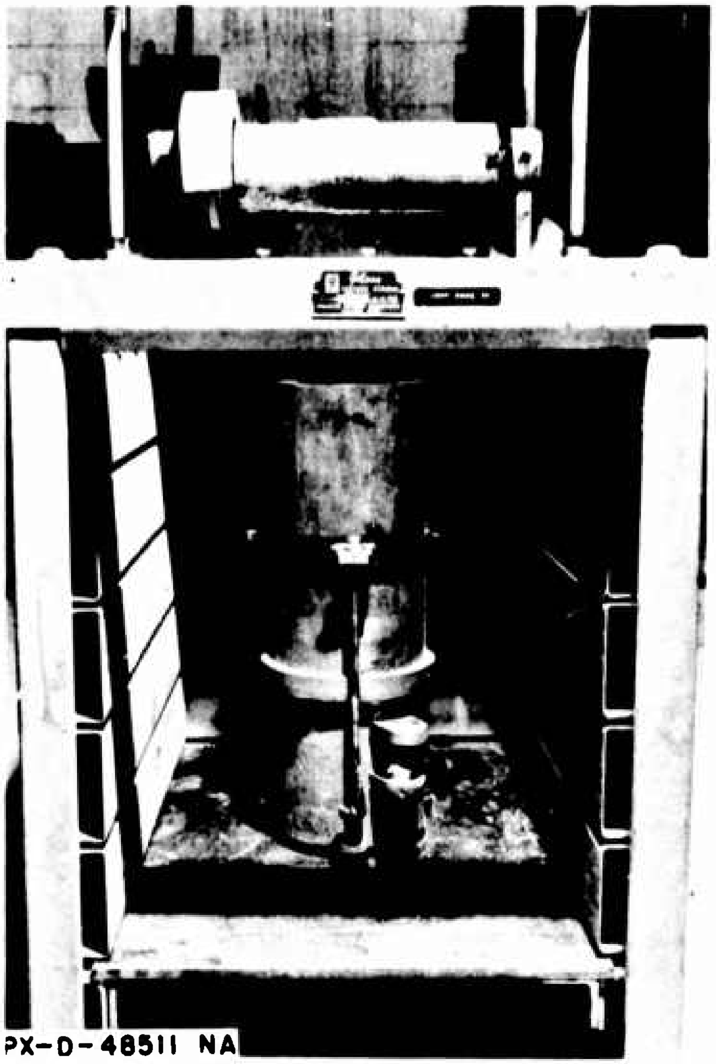
PX-D-48509 NA

Sieve shaker for determining the gradation of coarse-grained soils.



Steelplate adapter for sieve shaker.

Figure B-2



Sieve shaker as used to determine the maximum density of cohesionless soils.

Figure B-3

APPENDIX C

Characteristics of Vibrators Used to Obtain the Maximum Density of Cohesionless Soils

INTRODUCTION

The maximum density obtained by vibration of a cohesionless soil is believed to depend on the amplitude and frequency of vibration. The purpose of this appendix is to discuss in more detail the characteristics of the vibrators used in this study.

POWER SUPPLY

A 230-volt source was used for the two electromagnetic vibrators. Although these vibrators may be purchased for use with a 115-volt source, the data presented here are probably applicable only when a 230-volt source is used. A 115-volt source was used for the eccentric weight vibrator. Each of the vibrators is equipped with a rheostat by which the power can be varied from 0 to 100 percent.

LOAD-AMPLITUDE RELATIONSHIP

Since the load on the vibrator depends on the maximum grain size of the material being tested, the amplitude was determined for loads between 0 and 300 pounds at various rheostat settings.

The load was applied in increments of 50 pounds by varying the amount of sand in a 0.5-cubic-foot measure and combinations of 20- and 35-pound steelplates. The amplitude was measured at various loads and rheostat settings by a recording-type vibrometer on opposite sides of the measure as shown in Figure C-1. The arrangement of plates and measure for the 250-pound load is shown in Figure C-2. The amplitudes were also measured when the solid 2-psi surcharge weights were used as in an actual test.

The results of amplitude measurements are presented in Tables C-1 and C-2 for Vibrator No. 9, in Table C-3 for Vibrator No. 10, and in Table C-4 for Vibrator No. 11. Selected portions of these data are presented graphically in Figures 10, 11, and 12 in the body of this report. It is evident from these data that the amplitude varies at different points on the measure and on the vibrating table. The reason for these variations is not apparent. Observations during vibration tests indicate that particles tend to migrate from points of high amplitude to points of low amplitude; therefore the variation in amplitude may have a significant effect on the soil density obtained. Further investigation is required to determine the magnitude of this effect.

Table C-1

VARIATION OF AMPLITUDE WITH RHEOSTAT SETTING AND LOAD - LARGE ELECTROMAGNETIC VIBRATOR NO. 9. AMPLITUDES MEASURED ON THE HANDLES OF THE 0.5 CUBIC FOOT MEASURE

Rheostat Setting	Load = 0 lbs Amplitude, in. 1/	Load = 50 lbs Amplitude, in. 2/		Load = 100 lbs Amplitude, in. 2/		Load = 150 lbs Amplitude, in. 2/	
		1	2	1	2	1	2
30	.013	.011	.019	.010	.015	.008	.010
40	.014	.019	.014	.011	.015	.010	.013
50	.018	.016	.025	.013	.016	.013	.015
60	.023	.019	.025	.011	.020	.013	.017
70	.023	.022	.027	.017	.021	.014	.021
80	.022	.022	.030	.011	.021	.011	.023
90	.027	.023	.032	.029	.023	.019	.023
100	.027	.024	.033	.017	.018	.019	.033

Rheostat Setting	Load = 200 lbs Amplitude, in. 2/		Load = 250 lbs Amplitude, in. 2/		Load = 263 lbs Amplitude, in. 3/		Load = 300 lbs Amplitude, in. 3/	
	1	2	1	2	1	2	1	2
30	.005	.010	.005	.008	.004	.012	.005	.004
40	.006	.012	.006	.007	.006	.013	.006	.008
50	.008	.015	.004	.010	.007	.013	.008	.010
60	.010	.017	.006	.010	.008	.015	.013	.015
70	.013	.017	.010	.010	.005	.013	.014	.016
80	.015	.019	.010	.011	.005	.013	.013	.015
90	.015	.023	.011	.015	.006	.015	.011	.015
100	.017	.025	.011	.015	.006	.015	.012	.017

1/Measured in center of table.
2/The amplitudes were measured on opposite sides of the measure at points designated 1 and 2. A combination of loose steel plates, the 0.5 cubic foot measure, and soil were used for this load.
3/A solid 2 piece surcharge weight and the 0.5 cubic foot measure filled with soil were used for this load.

Table C-2

VARIATION OF AMPLITUDE WITH RHEOSTAT SETTING AND LOAD - LARGE ELECTROMAGNETIC VIBRATOR NO. 9. AMPLITUDES MEASURED ON THE VIBRATOR TABLE

Rheostat Setting	Load = 0 lbs Amplitude, in. 1/	Load = 50 lbs Amplitude, in. 2/		Load = 100 lbs Amplitude, in. 2/		Load = 150 lbs Amplitude, in. 2/	
		1	2	1	2	1	2
30	.013	.015	.019	.011	.017	.011	.010
40	.017	.014	.021	.015	.016	.015	.015
50	.018	.021	.021	.017	.019	.013	.019
60	.019	.021	.025	.015	.016	.013	.017
70	.021	.025	.026	.022	.022	.013	.019
80	.023	.026	.029	.024	.015	.015	.023
90	.025	.027	.029	.027	.018	.017	.023
100	.029	.030	.033	.017	.025	.023	.033

Rheostat Setting	Load = 200 lbs Amplitude, in. 2/		Load = 250 lbs Amplitude, in. 2/		Load = 263 lbs Amplitude, in. 3/		Load = 300 lbs Amplitude, in. 3/	
	1	2	1	2	1	2	1	2
30	.008	.009	.006	.006	.006	.003	.006	.008
40	.006	.012	.005	.009	.008	.010	.006	.017
50	.008	.013	.004	.010	.006	.010	.008	.017
60	.010	.011	.008	.009	.009	.015	.008	.021
70	.013	.015	.007	.010	.013	.016	.005	.011
80	.013	.019	.010	.015	.011	.013	.007	.014
90	.014	.021	.010	.015	.012	.017	.005	.015
100	.015	.025	.010	.015	.011	.019	.006	.018

1/Measured in center of table.
2/The amplitudes were measured on opposite sides of the table at points designated 1 and 2 located beneath the handles of the 0.5 cubic foot measure. A combination of loose steel plates, the 0.5 cubic foot measure, and soil were used for this load.
3/A solid 2 piece surcharge weight and the 0.5 cubic foot measure filled with soil were used for this load.

Table C-3

VARIATION OF AMPLITUDE WITH RHEOSTAT SETTING AND LOAD - SMALL ELECTROMAGNETIC VIBRATOR No. 10
AMPLITUDES WERE MEASURED ON THE HANDLES OF THE 0.5 CUBIC FOOT MEASURE

Rheostat Setting	Load = 0 lbs Amplitude, in. 1/	Load = 50 lbs Amplitude, in. 2/		Load = 90.5 lbs Amplitude, in. 3/		Load = 100 lbs Amplitude, in. 2/		Load = 150 lbs Amplitude, in. 2/	
		1	2	1	2	1	2	1	2
0	.004	.002	.003			.002	.002	.001	.001
10	.010	.004	.004			.002	.002	.002	.003
20	.013	.005	.005			.003	.003	.003	.004
30	.018	.006	.006			.004	.003	.003	.005
40	.021	.010	.010			.008	.006	.004	.007
50	.028	.013	.010			.010	.008	.005	.006
60	.033	.017	.013	.006	.006	.011	.010	.006	.006
70	.038	.021	.017	.019	.005	.015	.013	.010	.010
80	.043	.029	.023	.015	.015	.015	.015	.011	.012
90	.044	.029	.027	.015	.015	.017	.015	.018	.015
100	.046	.029	.021	.019	.023	.017	.017	.017	.015

Rheostat Setting	Load = 200 lbs Amplitude, in. 2/		Load = 250 lbs Amplitude, in. 2/		Load = 264 lbs Amplitude, in. 3/		Load = 300 lbs Amplitude, in. 3/	
	1	2	1	2	1	2	1	2
0	.001	.002	.002	.001			.001	.001
10	.002	.004	.002	.003			.001	.002
20	.002	.006	.002	.004			.001	.003
30	.003	.007	.002	.004			.002	.003
40	.002	.009	.003	.008			.002	.003
50	.003	.010	.003	.008	.002	.004	.003	.006
60	.003	.011	.004	.008	.002	.004	.004	.007
70	.008	.019	.003	.013	.003	.011	.005	.009
80	.009	.019	.003	.013	.005	.023	.006	.016
90	.011	.019	.003	.018	.004	.021	.008	.019
100	.010	.023	.008	.015	.003	.028	.004	.015

1/Measured in center of table.
2/The amplitudes were measured on opposite sides of the measure at points designated 1 and 2. A combination of loose steel plates, the 0.5 cubic foot measure, and soil were used for this load.
3/A solid 2 psi surcharge weight and the 0.1 cubic foot measure filled with soil were used for this load. Amplitudes were measured on opposite side of the 0.1 cubic foot measure.
4/A solid 2 piece surcharge weight and the 0.5 cubic foot measure filled with soil were used for this load.

Table C-4

VARIATION OF AMPLITUDE WITH RHEOSTAT SETTING AND LOAD - ECCENTRIC WEIGHT MOTOR VIBRATOR NO. 11. AMPLITUDES WERE MEASURED ON THE HANDLES OF THE 0.5 CUBIC FOOT MEASURE

Rheostat Setting volts	Load = 0 lbs Amplitude, in. 1/	Load = 50 lbs Amplitude, in. 2/		Load = 90.4 lbs Amplitude, in. 3/		Load = 100 lbs Amplitude, in. 2/		Load = 150 lbs Amplitude, in. 2/	
		1	2	1	2	1	2	1	2
40	.011	.004	.008			.001	.001		
50	.011	.007	.015			.005	.005	.004	.005
60	.017	.008	.007			.004	.004	.004	.004
70	.019	.008	.008			.005	.004	.004	.004
80	.011	.008	.006	.003	.002	.004	.004	.005	.003
90	.010	.007	.005	.006	.003	.005	.004	.005	.003
100	.009	.008	.006	.006	.004	.005	.004	.004	.004
110	.008	.008	.008	.005	.005	.005	.005	.005	.004
120	.007	.008	.008	.004	.005	.005	.005	.006	.005

Rheostat Setting volts	Load = 200 lbs Amplitude, in. 2/		Load = 250 lbs Amplitude, in. 2/		Load = 264 lbs Amplitude, in. 4/		Load = 300 lbs Amplitude, in. 2/	
	1	2	1	2	1	2	1	2
40	.003	.004	.003	.002			.002	.002
50	.003	.004	.003	.002			.002	.002
60	.003	.003	.002	.002			.002	.001
70	.002	.002	.003	.002			.002	.001
80	.003	.002	.003	.002	.002	.002	.002	.001
90	.003	.002	.002	.002	.004	.001	.003	.001
100	.004	.002	.004	.002	.005	.003	.006	.001
110	.006	.003	.005	.002	.006	.004	.006	.002
120	.006	.004	.006	.002	.006	.005	.006	.008

1/Measured in center of table

2/The amplitudes were measured on opposite sides of the measure at points designated 1 and 2. A combination of loose steel plates, the 0.5 cubic foot measure, and soil were used for this load.

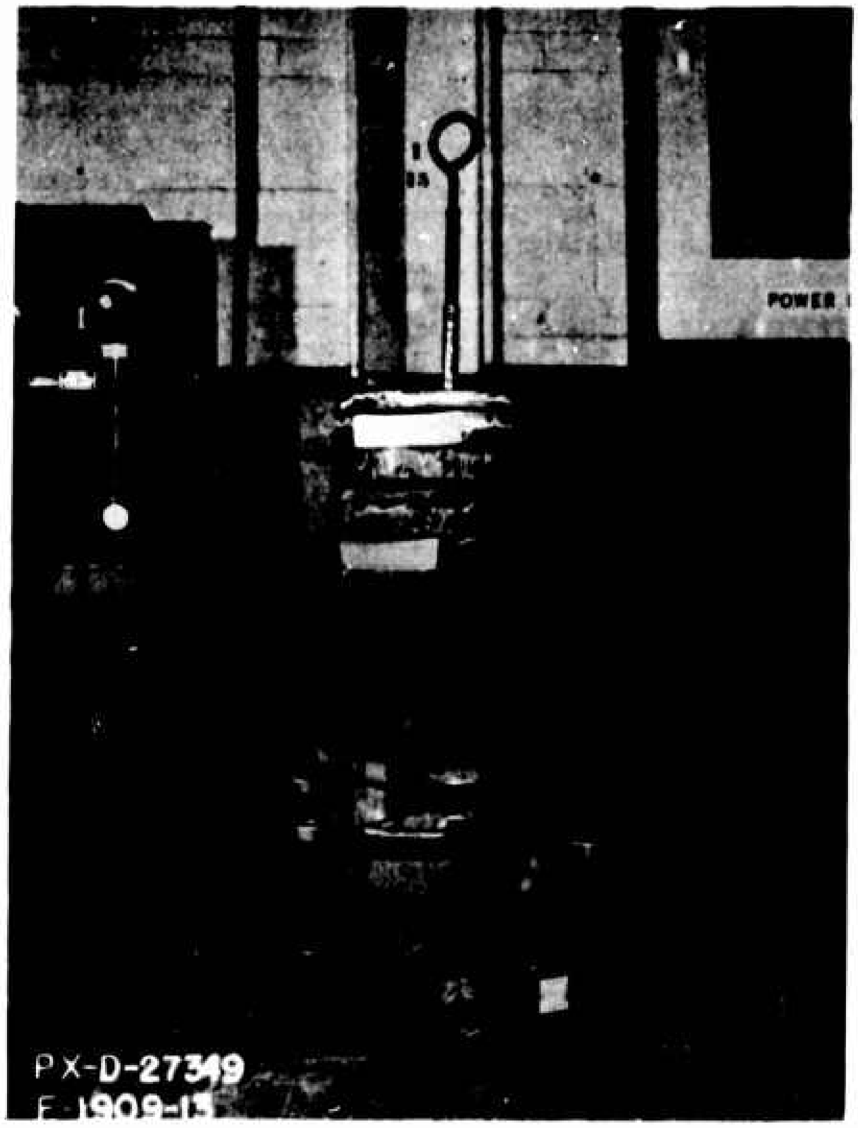
3/A solid 2 psi surcharge weight and the 0.1 cubic foot measure filled with soil were used for this load. Amplitudes were measured on opposite sides of the 0.1 cubic foot measure.

4/A solid 2 piece surcharge weight and the 0.5 cubic foot measure filled with soil were used for this load.

GPO 850-605

Recording-type vibrometer used to measure amplitude of vibration

Figure C-1



Photograph of weights used to determine the effect
of load on the amplitude of vibration

Figure C-2

7-1750
(10-64)

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Table 1

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03 (exactly)*	Square centimeters
	0.092903 (exactly)	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	9,463.58	Cubic centimeters
	0.946358	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873×10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	0.3048*	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5}*	Dynes
WORK AND ENERGY*		
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.02903* (exactly)	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

GPO 835.237