1964

Soil Particle Size by Time-weight Accumulation of Sedimentation

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SOIL PARTICLE SIZE BY TIME-WEIGHT ACCUMULATION OF SEDIMENTATION

BY

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A thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science, Major in
Civil Engineering, South Dakota
State University

1964

SOIL PARTICLE SIZE BY TIME-WEIGHT

ACCUMULATION OF SEDIMENTATION

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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Thesis Adviser Date

Head, Civil Engineering Department Date

ACKNOWLEDGMENTS

Extreme gratitude is given to Associate Professor Emil R. Hargett for his technical assistance, suggestions, and encouragement throughout the course of the work reported here and the preparation of this thesis.

Acknowledgment is also extended to Professor Junis Storry for his assistance with the I.B.M. program, to Mrs. Joseph Paulson for her assistance with diction and grammar, and to Mrs. Deanna Bullis for the typing.

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INTRODUCTION

Significance of Soil Particle Size Distribution

The principal reason for measuring particle size distribution is for the utilization of the relationships that exist between particle size and soil performance characteristics. For example the nonerodible velocity of water in an open channel is related directly to the size of the soil particles of which the channel is composed.[1] Perhaps the most interesting property of finely divided substances is the tremendous surface-to-weight ratio which they possess. The surface-to-weight ratio varies inversely with the square of the particle diameter.[2] Thus properties of particles which depend upon the amount of exposed surface are generally influenced by the size of the particles.

The behavior of cohesionless soils can often be related to the size of the particles. For example, the permeability of a cohesionless soil is approximately proportional to the square of the diameter.[3] Also, the rise of water in a capillary opening is proportional to the reciprocal of the diameter of the opening.[4] The design of earth dams,

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[1] Ven Te Chow, Open-Channel Hydraulics, (New York: McGraw Hill Book Company, Inc., 1959), p. 166.

[2] R. D. Cadle, Particle Size Determination, (New York: Interscience Publishers, Inc., 1955), p. 2.

[3] T. W. Lambe, Soil Testing For Engineers, (New York: John Wiley & Sons, Inc., 1958), p. 30.

[4] Ibid.

levees, inverted filters, and many other engineering structures require a study of particle size distribution. Also, the present criterion for establishing susceptibility of soils to frost damage is based in part on grain size of the soil. Grain size curves have been widely used in the identification and classification of soils. For example, grain size distribution curves are used to determine classification and type of clay minerals. From the preceding discussion, it is clear that grain size distribution is very useful in the field of soils engineering.

Methods of Particle Size Determination

Particle size may be measured by any one of several methods. However, these methods are not suitable for all purposes. For example, sieves are used as a satisfactory means of obtaining particle size distribution as long as the material is relatively coarse, but when 70 to 95 per cent of the sample passes the 200-mesh screen, some other analysis is recommended. The microscopic method is time consuming and employs the use of a very small sample. The elutriation method appears unsuitable due to its doubtful accuracy and the length of time required to separate the sample into a large number of fractions. Methods involving light-scattering seem to show promise for the determination of the total surface, but these are not reliable for particle size distributions.[1]

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[1] Knapp, Robert, Ind. and Chem. Eng., Vol. 6, June 15, 1934, p. 66.

Probably the most promising and the most widely used methods for determining particle size distributions in the subsieve range are based on sedimentation.[1] Most of these methods are simple to perform, give accurate results, and require inexpensive equipment. Many of these methods can be applied to materials which are dispersed in water for the test and are not recovered from the water at the completion of the test.

The sedimentation methods are of two types. The first and the most popular type is known as the incremental method. Pipette, hydrometer, and photoextinction are examples of this method. For this method measurements are made to determine changes in the concentration in a settling suspension. The American Society for Testing and Materials has a standard test procedure for the determination of soil particle size (ASTM: D 422-54T). This test procedure employs the use of the hydrometer for particle size determination in the subsieve range. The second type, called cumulative, involves the measurement of the overall accumulation of the settled suspension, usually by a balance introduced into the sedimentation.

Scope of Study

An apparatus for measuring sedimentation rates and soil particle size distribution indirectly was devised under the supervision of Emil R. Hargett, Associate Professor of Civil Engineering. A

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[1] Ibid.

chainomatic balance was selected to find the accurate weights of particles which are introduced at the top of a column of clear water and are deposited on a pan placed at the bottom of the cylinder.

In the conventional sedimentation devices, the measuring gear causes inhomogenity and gravitational instability which tend to destroy the accuracy of the particle size distribution curve. The significant points of the test procedure described in this thesis are the nature of the chainomatic balance, and the minimum interference by the measuring operation with the natural sedimentation.

In all conventional sedimentation methods which employ a uniform suspension, it is necessary to differentiate the sedimentation curve in order to evaluate the size distribution. The method described in this thesis has an advantage over the others because it does not necessitate such differentiation, which is very tedious and time consuming. A further advantage is that it is unnecessary to make an accurate determination of the initial weight. Particle size distribution curves for three different samples were plotted from weight accumulation test data as well as hydrometer test data. Comparative tests with the hydrometer analysis confirm the reliability of this testing procedure.

SIGNIFICANT STUDIES RELATING TO SOIL PARTICLE SIZE DETERMINATION

Every year a greater need for an accurate test method for the determination of the particle size distribution of subsieve soils is being felt by the engineer, because of the relationship of particle size to other properties of the soil mass. The majority of the investigations which have been made were based on the change in the concentration at a given level, such as pipette, hydrometer, photo-extinction, and different manometer methods. On the other hand, there has not been much research work dealing with the other kind of sedimentation, which is based on the change in the overall concentration. Extensive studies have been hampered by difficulties encountered in measuring the rate of sedimentation accurately.

As early as 1916, Oden[1] had been credited with the development of the first balance for measuring the amount of material which settled from a suspension during various time intervals. The pan of the balance was hung in the suspension and the weights of the material which settle on the pan were determined directly. Later, this development was considered inaccurate because of the movements of the pan which disturbed the settlement of the particles in the suspension.

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[1] Oden, S., Proc. Roy. Soc., Edinburgh, 36, p. 219 (1916).

Jacobson and Sullivan[1] discovered that when a relatively flat balance pan is used, a fairly large fraction of the particles settle around and beneath the pan instead of on it. This difficulty was overcome by replacing the pan with a cylindrical cup. The top of the cup was extended so that it would be within a short distance of the surface of the suspension. This method was never popular because of the inaccurate results obtained.

In 1952 Rim[2] used an apparatus where only external measurements of bouyancy were taken on a column of settling particles. In his apparatus two liquids of different densities were employed to maintain gravitational stability. The more dilute solution serves as the dispersing medium for the material. The sample was mixed uniformly with a dispersing medium in a small cylinder. This small cylinder was then placed mouth down in a large cylinder containing a solution with a larger specific gravity than the dispersed medium. The small cylinder was constructed with a weighted bottom and a sealed air compartment at the top so that it would float in a vertical position. This small cylinder will tend to rise as the particles settle out. The additional weights necessary to reestablish equilibrium must equal

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[1]Jacobson, A. E., and Sullivan, W. F., Ind. Eng. Chem. Anal. Ed., p. 855 (1947).

[2]Rim, M., "A Rigorous, Simple Method for Measuring and Recording Particle Size Distribution in Dispersed Material," American Geographical Union, 33, June, 1952, pp. 423-426.

the apparent weight of the particles which had meanwhile settled out of the tube. The disadvantage of this method is that the set-up of the apparatus is rather difficult. By the time the apparatus is stable, a large portion of the coarse particles have been settled down, and the most interesting and important features of the particle size distribution curve are lost.

THEORETICAL BACKGROUND

When a small spherical body is allowed to fall freely in a viscous liquid, it soon reaches a velocity where the downward acceleration is balanced by the friction between the body and the liquid. Therefore, the velocity ceases to increase. This velocity is expressed by the equation known as Stokes' Law:[1]

$$V = \frac{2g(\rho - \rho')\, r^2}{9\eta} \qquad \ldots\ldots\ldots\ldots (1)$$

or

$$V = \frac{g(\rho - \rho')\, d^2}{18\eta} \qquad \ldots\ldots\ldots\ldots (2)$$

where V = velocity of fall

g = acceleration of gravity

ρ = density of falling substance

ρ' = density of fluid medium

η = viscosity of fluid medium

r = radius of the particle

d = diameter of the particle

For the present purpose, the diameter of the falling particle is more interesting than the velocity. Therefore the equation

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[1] R. D. Cadle, Particle Size Determination, (New York: Interscience Publishers, Inc., 1955, pp. 192-193.

becomes

$$d = \sqrt{\frac{18\eta V}{(\rho - \rho')g}}$$

or

$$d = \sqrt{\frac{18\eta}{(\rho - \rho')g}} \sqrt{\frac{H}{T}}$$

where T = time of fall

H = height of fall

If the height (41.90 cm. in the apparatus described previously), viscosity, and densities are held constant, this equation becomes

$$d_{mm} = \frac{K}{\sqrt{T_{min}}}$$

where K is a constant

$$K = \sqrt{\frac{41.90 \times 18\eta}{(\rho - \rho')g}} = \sqrt{\frac{0.773\eta}{\rho - \rho'}}$$

This equation may then be used to convert the results of sedimentation tests to the particle size distributions.

The maximum particle size which could be obtained by solving the above equation is related to Reynolds number. The Reynolds number is a dimensionless quantity which, for spherical particles falling

through a fluid, is defined as Vd/ν . V is the velocity of the particle falling through the fluid, d is the diameter of the particle, and ν is the Kinematic viscosity of the fluid. The Kinematic viscosity is the viscosity divided by the density. From equation (2) and the definition of Reynolds number the following equation can be obtained, by relating the maximum particle size, d , which could be used, to the maximum Reynolds number, Re:

$$d^3 = \frac{18 Re \eta^2}{\rho'(\rho - \rho')g}$$

If particles of soils having a specific gravity of 2 are measured while they are settling in the water, the particle diameter corresponding to a Reynolds number of 0.82 is about 120 microns. Much larger particles may be tested by applying Stokes' law and using liquids whose viscosity is considerably greater than that of water. Stokes' law is valid only when the resistance to the motion of the falling particle is entirely due to the viscosity of the medium fluid. Also the particles must be spherical and rigid if they are to obey Stokes' law. It is obvious that soil particles almost fulfill this requirement, but there are some exceptions. For example clay which has a flaky shape and swells when suspended in water is one of these exceptions. Particle concentration also affects the results

if Stokes' law is applied. The maximum volume concentration which can be used without appreciably affecting the results is about 2%.[1]

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[1]Davidson, D. T. and Associates, Methods for Testing Engineering Soils, Iowa State University, 1960.

EQUIPMENT AND MATERIALS

The principal items of testing equipment are as follows: a precise speedigram balance, receiving pan and linkage, dispersion machine, sedimentation cylinders, deflocculating agent, and soil samples.

Voland Speedigram Balance -- This balance consists of two units:

1 -- Speedigram Unit (weight-placing mechanism) with stainless steel and aluminum weights. These weights, which cover a range from 0.0 to 99.0 grams, are controlled by the three direct dials located in the front of the cabinet (see Figure 7). The positions of these dials determine the selection of weights which are deposited only upon release of the beam, thereby protecting sensitive knife edges. A safety interlock prevents accidental addition or removal of weights while the beam is released. An extra 100 gram weight, which can be placed on the right pan when needed, is furnished in a special compartment in the cabinet, making possible the utilization of the entire capacity of the balance without extra weights.

2 -- Visigram Unit -- Weights from 0.0000 to 0.1000 gm., are obtained by rotating the visigram wheel located at the right side of the cabinet. The weight corresponding to the amount of chain deposited on the beam is read directly on the counter.

The balance has the following specifications: capacity - 200 grams; sensitivity - 0.05 mg., at full load; sensitivity reciprocal -

0.4 mg., per division maximum, (0.4 mg. maximum at full load, shifts rest point one division); beam arm accuracy - within ten parts per million; accuracy and precision - within 0.2 mg.

Two Cylinders: one is 5 5/8" inside diameter and 18" in height; the other is 3.5" inside diameter and 17" in height. The smaller cylinder is open from both ends, and around one end a metal clamp with three arms projected outside is fastened (see Figure 6 and Figure 7).

Two Sieves: No. 10 Sieve is 3" in diameter and 1.25" in height; No. 20 Sieve is 3 1/8" in diameter and 0.5" in height (see Figure 5).

Receiving Pan is 5" in diameter and 1.5" in height (see Figure 6 and Figure 7).

PREPARATION OF TEST SPECIMEN

Representative samples of soil passing the No. 140 sieve and weighing between 50-100 grams were used for the tests. All soil lumps were broken in a mortar with a rubber covered pestle. Each specimen was mixed with water until it formed a smooth thin paste. A deflocculation agent (sodium silicate) was added to the paste, and the mixture was washed into the cup of the dispersion machine. The paste was mixed in the machine until the soil was broken down into its individual particles (about 10 minutes). While the soil and water were being mixed, the smaller cylinder was placed inside the larger one, and they were filled with water. The two sieves (No. 20 sieve was placed to cover the bottom of No. 10 sieve as shown in Figure 5) were placed on the surface of the water and settled down to the bottom of the cylinders. The suspension was left to settle for a few hours (the time required for the particles to settle down to the sieves depends upon the soil classification; for example, sandy soils do not take as long as clay soils). After most of the particles had settled down on the sieves, the inside cylinder was removed and the sieves were pulled out very slowly. The sieves containing the specimen were placed in an evaporating dish, and the excess water on the top of the specimen was left to drain out. The No. 20 sieve was removed, and the particles around the sieve containing the specimen were wiped out. Then the specimen was ready for testing. In case of very fine clay sample, it was found that it is necessary to use filter cloth under the sieves so that the soil grains would not be washed out.

TEST PROCEDURE

The receiving pan was placed at the bottom of the large cylinder, and the smaller cylinder was arranged inside the larger one. The nylon strings, to which the receiving pan is suspended, were connected to the balance beam through the metal linkage (as shown in Figure 6 and Figure 7). The triangular support was placed on the top of the smaller cylinder. Water was poured into the cylinders until the level of the water submerged the triangular support. Sufficient weights were placed on the right pan, and the balance was brought to equilibrium. The third knob and the visigram were used for small weights to bring the balance to equilibrium. The apparatus was left for a few minutes until the water temperature reached the room temperature. The balance was adjusted again to bring the indicator to the zero mark. A thermometer was inserted in the water, and the temperature was recorded. The beam of the balance was arrested by turning the arrest knob clockwise, and weights were added by using one or more of the three weight control knobs (the amount of the added weights were varied according to the classification of the soil samples). The beam was released, and the prepared sample was placed on the triangular support. As soon as the particles started falling down from the sieve, the timer was started. As soon as the indicator needle deflected to the right and reached the zero mark, the time was recorded. Then, the beam was arrested and more weights were added. The beam was released and the deflection of the indicator was observed. Again as soon as the

indicator shifted to the right and reached the zero mark, the total elapsed time was recorded for the weight shifted. The same procedures of adding weights, releasing the beam, observing the indicator, and recording the total elapsed time for every weight increment were repeated. For every sample a curve of particle size distribution was plotted and checked by the hydrometer and sieve analysis in accordance with procedures outlined in Soil Testing by T. W. Lambe.

TEST RESULTS

(a) Time-Weight accumulation test

For every weight increment selected, the total elapsed time was recorded. For every weight fraction deposited, the particle size was found by solving Stokes' law, and the percentages by weight finer than any given size were found and the results were tabulated as shown below (see Table I-a, I-b, and I-c).

Wt. Increments in gm.	Total Wt. in gm.	Time Min.	Time Sec.	Temperature in C°	Diameter in mm.	Percent Finer
10.0	10.0	-	21	28	0.100	62.1
3.8	13.8	-	34		0.086	49.3
3.0	16.8	-	41		0.078	38.0

(b) Hydrometer Test

The total elapsed time was recorded for every hydrometer reading, and the distances from the suspension surface to the center of the hydrometer bulb were found from a calibration chart. Again by applying Stokes' law, the diameters of the particles were found. The percentages finer, N, were calculated from the equation:

$$N = \frac{G}{G-1} \frac{V}{W_s} \gamma (r - r_w)\ 100\ \%$$

in which G = specific gravity of soils,

V = volume of suspension,

W_s = weight of dry soil,

γ = unit weight of water,

r = hydrometer reading in suspension,

r_w = hydrometer reading in water.

The results were tabulated in Tables II-a, II-b, and II-c, as shown below.

Elapsed Time in min.	R = 1000 (r-1)	R_w = 1000 (r_w-1)	Temperature in C°	R-R_w	N in %	Zr in cm.	D in mm.
0.25	17.5	- 1.0	24	18.5	49	10.2	0.0819
0.50	15.0			16.0	41	10.3	0.0576
1.0	12.0			13.0	34	10.6	0.0410

(c) Sieve Test

A nest of sieves was employed for the coarse portion of every sample. The retained weight on every sieve was found and the percentages by weight finer than any given size were calculated using the following steps:

a-Cumulative percentage retained on any sieve = sum of percentages retained on all coarser sieves.

b-Percentage finer than any sieve size = 100% minus cumulative percentage retained.

The data were tabulated in Tables III-a, III-b, and III-c as shown below:

Sieve No.	Sieve Opening in mm.	Wt. Sieve in gm.	Wt. Sieve Soil in gm.	Wt. Soil Retained in gm.	% Retained	Cumulative % Retained	% Finer
20	0.840	491.7	491.7	0	0	0	100.0
40	0.420	528.4	542.2	13.8	8.1	0	100.0

DISCUSSION OF RESULTS

The test data obtained were plotted on semi-log paper with the weight percent finer versus the logarithm of the particle size as shown in Figures 1, 2, and 3. The results were compared with those of the hydrometer analysis. It has been observed that the agreement is good over most of the size range and the slight discrepancy has been detected. As a further check, and to demonstrate the adaptability of the method, sieve analyses were carried out on the coarser part of the samples. It has been again observed that the agreement is remarkably good as the figures show a smooth transition between the sieve results and those of the time-weight accumulation.

The shapes of the size distribution curves for the three samples are very typical ones. For sample No. 1 and sample No. 2 (see Figure 1 and Figure 2), the shape of each of the curves is said to be a composite;[1] it means that they are composed of two types of soils. The coarser half of the first type is relatively uniform, whereas the size of the grains in the finer half varies over a wide range as shown in the figures. Conversely, the distribution of the second type corresponds to a sample in which the coarser grains are of widely different sizes and the finer ones are more uniform.

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[1]Terzaghi, Karl, and Peck, Ralph, Soil Mechanics in Engineering Practice, (New York: John Wiley & Sons, Inc., 1960), p. 19.

Figure 3 shows that the coarser half of sample No. 3 is uniform, whereas the grain sizes in the finer half vary over a wide range.

Figure 1, 2, and 3, show that particle size determination in the clay range finer than 0.001 mm. has been neglected because of the long time necessary for settling; also because gravity settling of a soil is not practical for particle size determination below 0.001 mm. because of the effect of Brownian movement and convection currents arising from slight changes in temperature.

The discrepancy between the hydrometer results and the results of the proposed method was due to some minor factors. These factors include the assumption of spherical particle shape in the application of Stokes' law, (see theoretical background) and the uncertain effective specific gravity of the clay particles which may vary with the amount of adsorbed water and kind of clay minerals.[1] Also Stokes' law is concerned only with terminal velocity. The velocity obtained for every reading was not terminal velocity, because a certain time must elapse after a particle starts to settle before the terminal velocity is reached. Fortunately, this time is negligible compared with the settling times involved in particle size determinations for particles in the subsieve range.

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[1]Davidson, D. T. and Associates, Methods for Testing Engineering Soils, Ames, Iowa, Iowa State University, 1960.

Another minor factor is that the layer of sample is considerably more dense than the underlying liquid. The condition was slightly unstable and the sample tended to go as masses to the bottom, forming some eddy currents on the way.

The movements of the pan during the arresting and releasing of the beam could have been responsible for some of the discrepancy. These movements were very slight and may be overcome in part by an additional arresting mechanism.

Normally, particle sizes of a soil sample settling through a liquid medium are found by applying Stokes' law. The conventional solution of Stokes' law is a lengthy one because it involves five variables

$$d = \sqrt{\frac{18 \eta H}{(\rho - \rho') g T}}$$

When the solution is repeated for a large number of time intervals, it becomes time consuming.

By using the I.B.M. machine much time is saved; therefore an I.B.M. program was prepared. Particle sizes were solved for time intervals from 15 seconds to 500 minutes. The values obtained were plotted on a semi-log paper with the time intervals versus the logarithm of the particle size as shown in Figures 4a, 4b, and 4c. Particle size may then be obtained graphically if the specific gravity of the soil ranges from 2.4 to 2.8 and the temperature ranges from

$20^{o}C$ to $28^{o}C$. The majority of soils will fall within this range in specific gravity, and range in temperature is considered normal room temperature variation. Figure 4a gives the particle sizes for any time interval range from 15 seconds to 6 minutes. Figure 4b gives the particle sizes for any time interval range from 6 minutes to 40 minutes. Figure 4c gives the particle sizes for any time interval range from 40 minutes to 500 minutes.

CONCLUSIONS

It was concluded from the study that the weight accumulation method presents the soils engineers with a simple and accurate method for particle size determination in the subsieve range.

Sedimentation curves plotted from a sufficient number of time-weight accumulations may be used for a graphical determination of particle size.

This test method may be used satisfactorily on soils that have a large percentage of the same size, or on soils that have a wide variation in particle size.

Because this method employs Stokes' Law for the particle size distribution, it is adaptable to any soil having a grain size equal to or smaller than 0.12 mm.

For coarser soil, a supplementary method, such as sieve analysis, should be used.

It is not practical to determine particle size distribution for particles having size below 0.001 mm.

Corresponding values taken from the time-weight accumulation test and the hydrometer test differed by an average value of 2.75 percent. In all the three samples, the hydrometer test values tend to be slightly lower.

Since the time necessary for fine particles to settle down is long, the time of the arresting and releasing of the beam is also long; this means the interference of the settlement is eliminated and the determination of fine particles is very accurate.

For soils with a large portion of the particles ranging in size from 0.10 to 0.01 mm., it is better for accurate work that values of weight fraction deposited should be determined at time intervals, increased by a factor of not more than the square root of two.

Since η , the viscosity of water, varies with temperature, adequate temperature control of the sedimentation cylinders is necessary. A room with slight temperature variation is adequate as temperature control.

LITERATURE CITED

1. Cadle, R. D., Particle Size Determination, (New York: Interscience Publishers, Inc., 1955), pp. 2; 197-200.

2. Chow, Ven Te, Open-Channel Hydraulics, (New York: McGraw Hill Book Company, Inc., 1959), p. 166.

3. Davidson, D. T. and Associates, Methods for Testing Engineering Soils, Ames, Iowa, Iowa State University, 1960.

4. Jacobson, A. E., and Sullivan, W. F., Ind. Eng. Chem. Anal. Ed., p. 855, 1947.

5. Knapp, Robert, "New Apparatus for Determination of Size Distribution of Particles in Fine Powder," Industrial and Engineering Chemistry, 6, January 15, 1934, p. 66.

6. Lambe, T. W., Soil Testing for Engineers, (New York: John Wiley & Sons, Inc., 1958), pp. 29-36.

7. Oden, S., Proc. Roy. Soc., Edinburgh, 36, p. 219 (1916).

8. Rim, M., "A Rigorous, Simple Method of Measuring and Recording Particle-Size Distribution in Dispersed Material," American Geographical Union, 33, June, 1952, pp. 423-426.

9. Terzaghi, Karl, and Peck, Ralph, Soil Mechanics in Engineering Practice, (New York: John Wiley & Sons, Inc., 1960), p. 19.

APPENDIX A

TABULAR DATA

Table Ia. Time-Weight Accumulation
(Sample No. 1)

Increment Weight in gm.	Total Weight in gm.	Time		Temp. in C°	Diameter in mm.	Percent Finer
		Min.	Sec.			
10.0	10.0	--	22	28	0.110	71.1
10.5	20.5	1	02		0.071	40.7
0.7	21.2	3	28		0.035	38.6
1.4	22.6	4	19		0.030	34.7
0.9	23.5	8	07		0.022	32.0
1.3	24.8	17	13		0.015	28.1
1.4	26.2	20	04		0.014	24.2
0.4	26.8	40	22		0.010	22.4
3.0	29.8	48	16		0.0090	14.1
0.6	30.4	70	37		0.0074	12.3
2.2	32.6	80	49		0.0070	6.0
1.4	34.0	109	--		0.0061	1.8

Table Ib. Time-Weight Accumulation
(Sample No. 2)

Increment Weight in gm.	Total Weight in gm.	Time		Temp. in C°	Diameter in mm.	Percent Finer
		Min.	Sec.			
10.0	10.0	--	21	28	0.100	62.1
3.8	13.8	--	34		0.086	49.3
3.0	16.8	--	41		0.078	38.0
1.9	18.7	--	52		0.070	29.3
0.6	19.3	1	01		0.066	26.9
1.7	21.0	2	13		0.400	20.7
0.8	21.8	8	47		0.021	17.8
0.2	22.0	30	16		0.011	16.6
0.2	22.2	120	--		0.0058	15.8
0.3	22.5	310	--		0.0035	14.9
1.1	23.6	375	--		0.0033	10.9
1.3	24.9	525	--	28	0.0028	5.8

Table Ic. Time-Weight Accumulation
(Sample No. 3)

Increment Weight in gm.	Total Weight in gm.	Time		Temp. in C°	Diameter in mm.	Percent Finer
		Min.	Sec.			
15.0	15.0	--	26	27	0.094	70.5
18.8	33.8	--	43		0.076	33.4
3.2	37.0	--	57		0.069	27.2
4.0	41.0	1	29		0.054	19.5
2.7	43.7	1	48		0.040	14.0
0.9	44.6	4	02		0.032	12.1
0.2	44.8	7	49		0.024	11.9
0.4	45.2	14	53		0.017	11.2
1.5	46.7	45	23		0.0094	8.1
1.6	48.3	95	37		0.0066	5.0
0.2	48.5	300	--	27	0.0038	4.5

Table IIa. Hydrometer Analysis
(Sample No. 1)

Elapsed Time in min.	R = 1000 (r-1)	R_w = 1000 (r_w-1)	Temperature in C°	R-R_w	N in %	Zr in cm.	D in mm.
0.25	17.5	- 1.0	24	18.5	49	10.2	0.0819
0.50	15.0			16.0	41	10.3	0.0576
1.0	12.0			13.0	34	10.6	0.0410
2	12.0			13.0	33	11.1	0.0302
5	11.0	- 0.5	25	11.5	30	10.3	0.0181
10	9.5			10.0	26	10.8	0.0131
15	8.0			8.5	21	12.0	0.0113
20	7.5			8.0	19	13.5	0.0107
25	7.0	- 1.0	26	8.0	11	14.2	0.0093
30	4.5			5.5	8	14.6	0.0087
35	3.0			4.0	6	15.0	0.0081
40	2.0			3.0	4	15.7	0.0077
50	1.5	- 0.5		2.0	3	15.8	0.0069
70	0.5	- 0.5	27	1.0	1	16.8	0.0059

Specific Gravity	2.695
Wt. Container in gm.	360.9
Wt. Container + Dry Soil in gm.	408.2
Wt. Dry Soil in gm.	47.3
Meniscus Correction	0.5

Table IIb. Hydrometer Analysis
(Sample No. 2)

Elapsed Time in min.	R = 1000 (r-1)	R_w = 1000 (r_w-1)	Temperature in C°	R-R_w	N in %	Zr in cm.	D in mm.
0.25	26.0	1.0	27	27.0	31.4	10.6	0.0800
0.50	24.5			25.5	29.6	11.0	0.0580
1.0	23.0			24.0	27.9	11.4	0.0420
2.0	21.0			22.0	25.6	11.9	0.0300
5	19.5			20.5	23.8	11.0	0.0180
10	17.0			18.0	20.9	11.7	0.0130
20	15.0			16.0	18.6	12.2	0.0096
40	13.5			14.5	16.8	12.8	0.0069
105	11.5			12.5	14.5	13.2	0.0043
240	10.5	0	25	10.5	12.2	13.4	0.0029
14 hr.	8.0	0	25	8.0	9.3	14.1	0.0016
40 hr.	7.0	0	25	7.0	8.1	14.4	0.0010

Specific Gravity	2.638
Wt. Container in gm.	577.8
Wt. Container + Dry Soil in gm.	627.0
Wt. Dry Soil in gm.	49.2
Meniscus Correction	0.5

Table IIc. Hydrometer Analysis
(Sample No. 3)

Elapsed Time in min.	R = 1000 (r-1)	R_w = 1000 (r_w-1)	Temperature in C°	R-R_w	N in %	Zr in cm.	D in mm.
0.25	24.0	- 0.5	25	24.5	24.9	11.1	0.0840
0.50	21.0			21.5	21.8	11.9	0.0614
1.0	17.5			18.0	18.3	12.8	0.0447
2.0	14.0			14.5	14.7	13.8	0.0356
5	10.0			10.5	10.7	13.6	0.0208
10	8.0			8.5	8.7	14.1	0.0150
20	7.0			7.5	7.6	14.4	0.0107
40	5.5	0	26	5.5	5.6	18.8	0.0075
80	4.5	0		4.5	4.6	15.0	0.0055
135	4.0	0		4.0	4.1	15.2	0.0045
275	3.0	0	25	3.0	3.1	15.4	0.0030
15 hr.	2.0	0	25	2.0	2.0	15.7	0.0016
42 hr.	1.0	0	25	1.0	1.0	16.0	0.0010

Specific Gravity	2.585
Wt. Container in gm.	367.1
Wt. Container + Dry Soil in gm.	424.1
Wt. Dry Soil in gm.	57.0
Meniscus Correction	0.5

Table IIIa. Sieve Analysis
(Sample No. 1)

Sieve No.	Sieve Opening in mm.	Wt. Sieve in gm.	Wt. Sieve + Soil in gm.	Wt. Soil Retained in gm.	% Retained	Cumulative % Retained	% Finer
20	0.840	491.7	491.7	0	0	0	100.0
40	0.420	528.4	542.2	13.8	8.1	0	100.0
60	0.250	433.8	486.8	53.0	31.2	8.1	91.9
140	0.105	416.1	454.9	38.8	22.8	39.3	60.7
Pan	---	493.9	558.3	64.4	37.9	100.0	---

Specific Gravity	2.695
Wt. Container in gm.	361.1
Wt. Container + Dry Soil in gm.	531.1
Wt. Dry Soil in gm.	170.0

Table IIIb. Sieve Analysis
(Sample No. 2)

Sieve No.	Sieve Opening in mm.	Wt. Sieve in gm.	Wt. Sieve + Soil in gm.	Wt. Soil Retained in gm.	% Retained	Cumulative % Retained	% Finer
20	0.840	491.8	496.2	4.4	2.0	0	100.0
40	0.420	528.1	541.3	13.2	6.0	2.0	98.0
60	0.250	433.8	517.3	83.5	37.9	8.0	92.0
140	0.105	416.1	456.6	40.5	18.4	45.9	54.1
Pan	---	494.0	572.5	78.5	35.6	100.0	---

Specific Gravity	2.638
Wt. Container in gm.	361.2
Wt. Container + Dry Soil in gm.	581.3
Wt. Dry Soil in gm.	220.1

Table IIIc. Sieve Analysis
(Sample No. 3)

Sieve No.	Sieve Opening in mm.	Wt. Sieve in gm.	Wt. Sieve + Soil in gm.	Wt. Soil Retained in gm.	% Retained	Cumulative % Retained	% Finer
20	0.840	491.8	491.8	0	40.32	0	100.00
40	0.420	528.2	640.0	111.8	26.61	0	100.00
60	0.250	433.8	507.6	73.8	21.93	40.32	59.68
140	0.105	416.0	477.6	60.8	21.93	66.93	33.07
Pan	---	494.1	525.0	30.9	11.14	100.00	---

Specific Gravity	2.585
Wt. Container in gm.	361.2
Wt. Container + Dry Soil in gm.	638.5
Wt. Dry Soil in gm.	277.3

APPENDIX B

GRAPHS, I.B.M. PROGRAM, SKETCHES, PHOTOGRAPHS

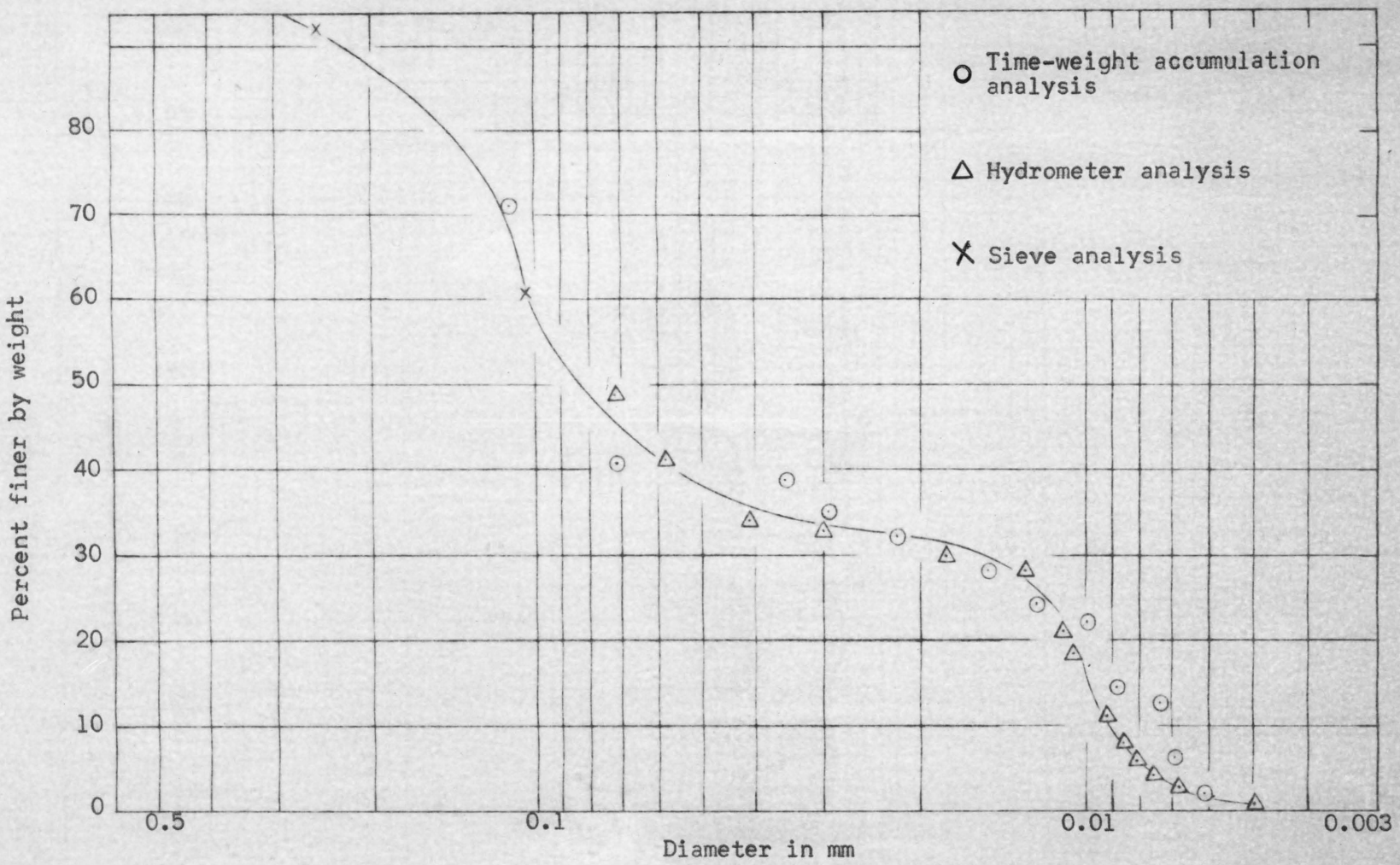

Figure 1. Grain-Size Distribution (sample No. 1)

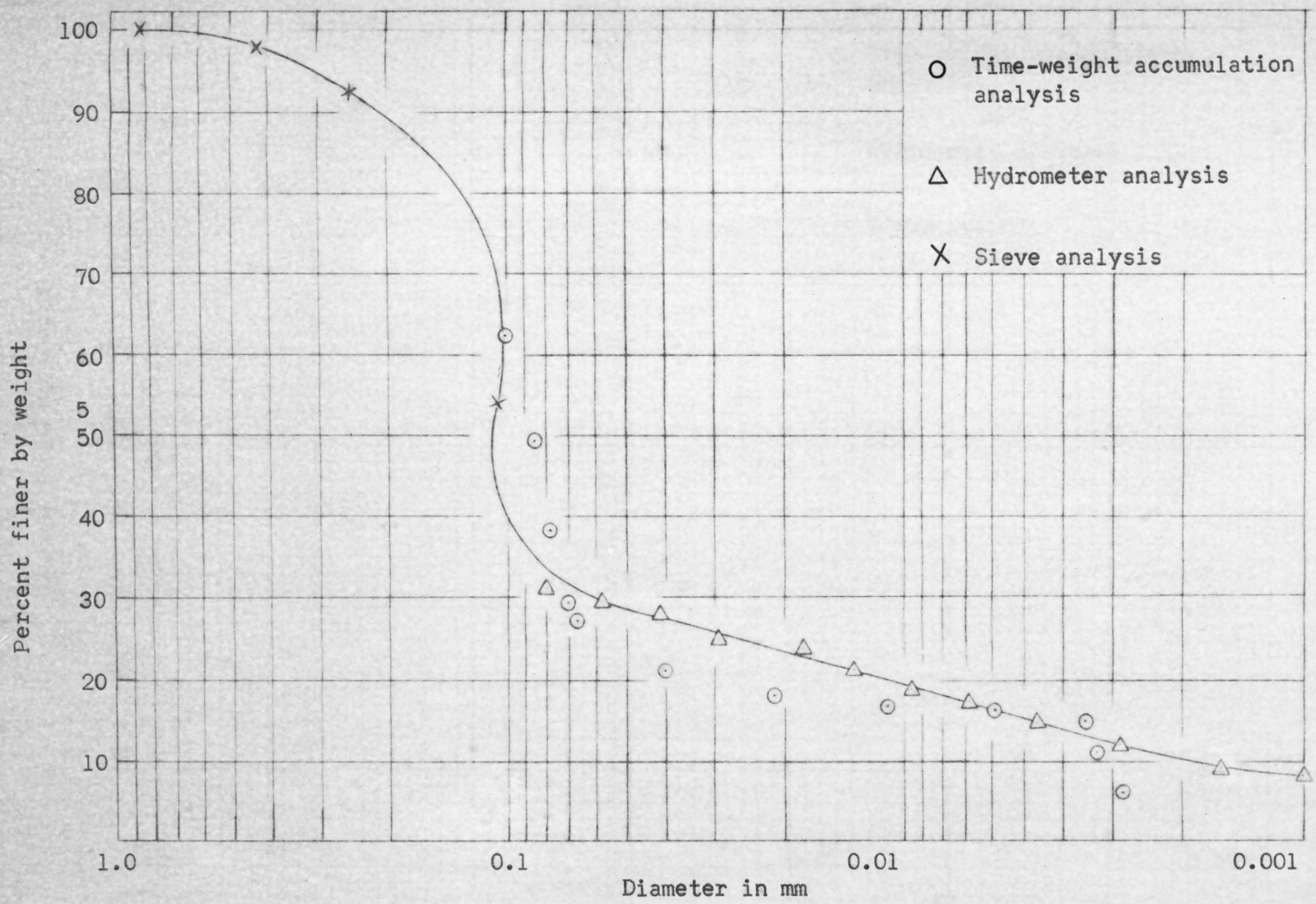

Figure 2. Grain-Size Distribution (sample No. 2)

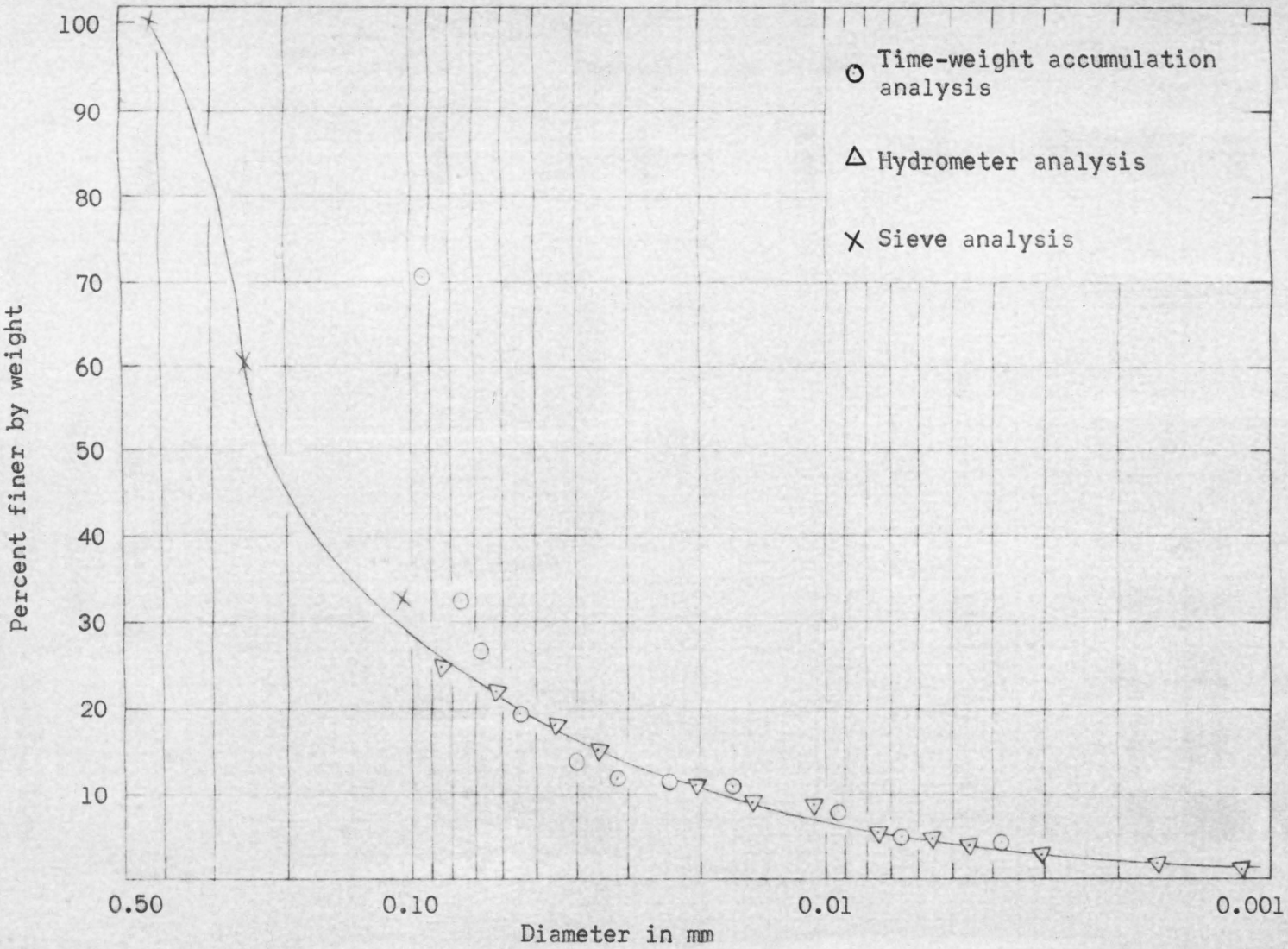

Figure 3. Grain-Size Distribution (sample No. 3)

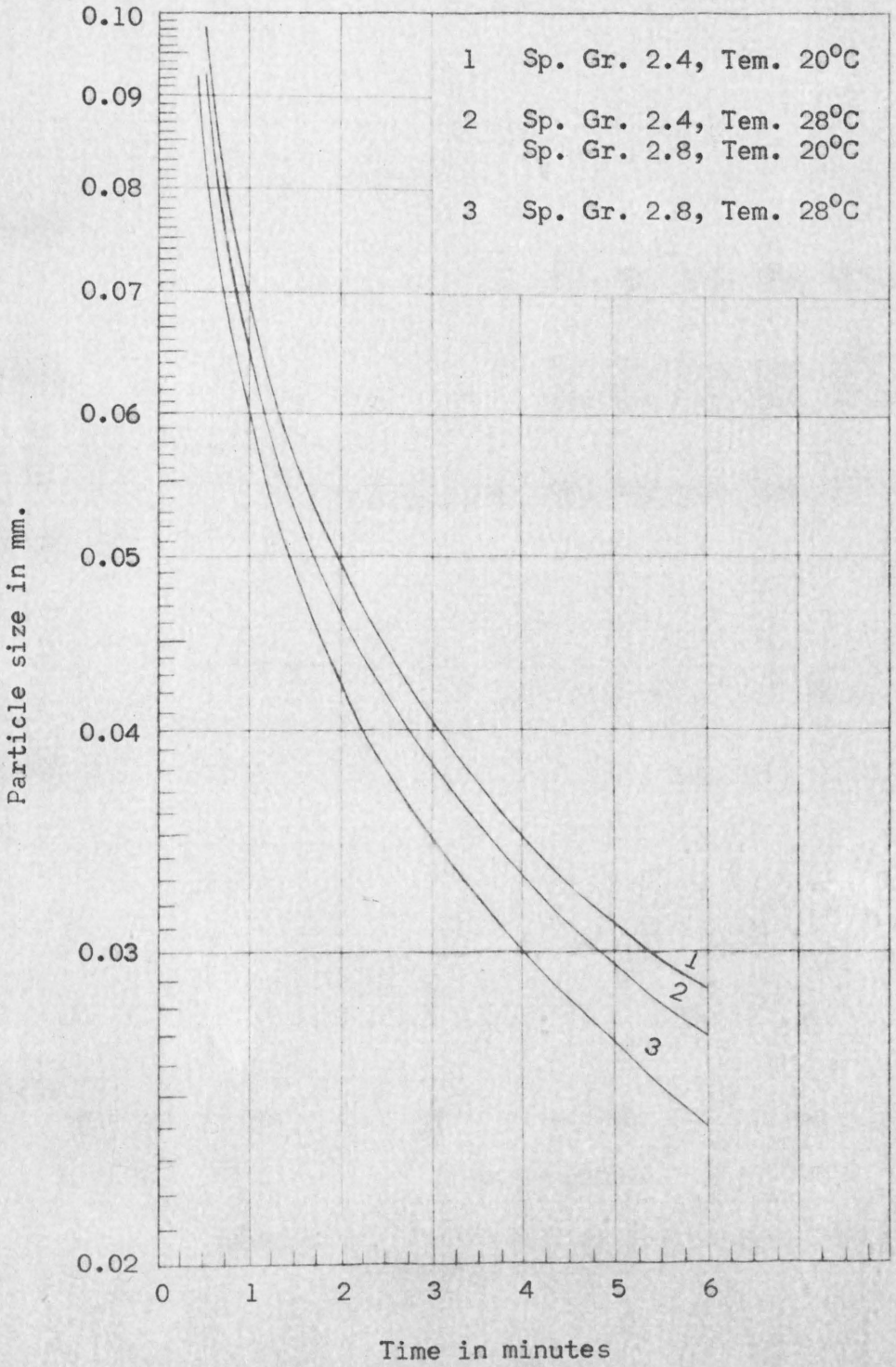

Figure 4a. Particle Size vs. Falling Time
(15 seconds to 6 minutes)

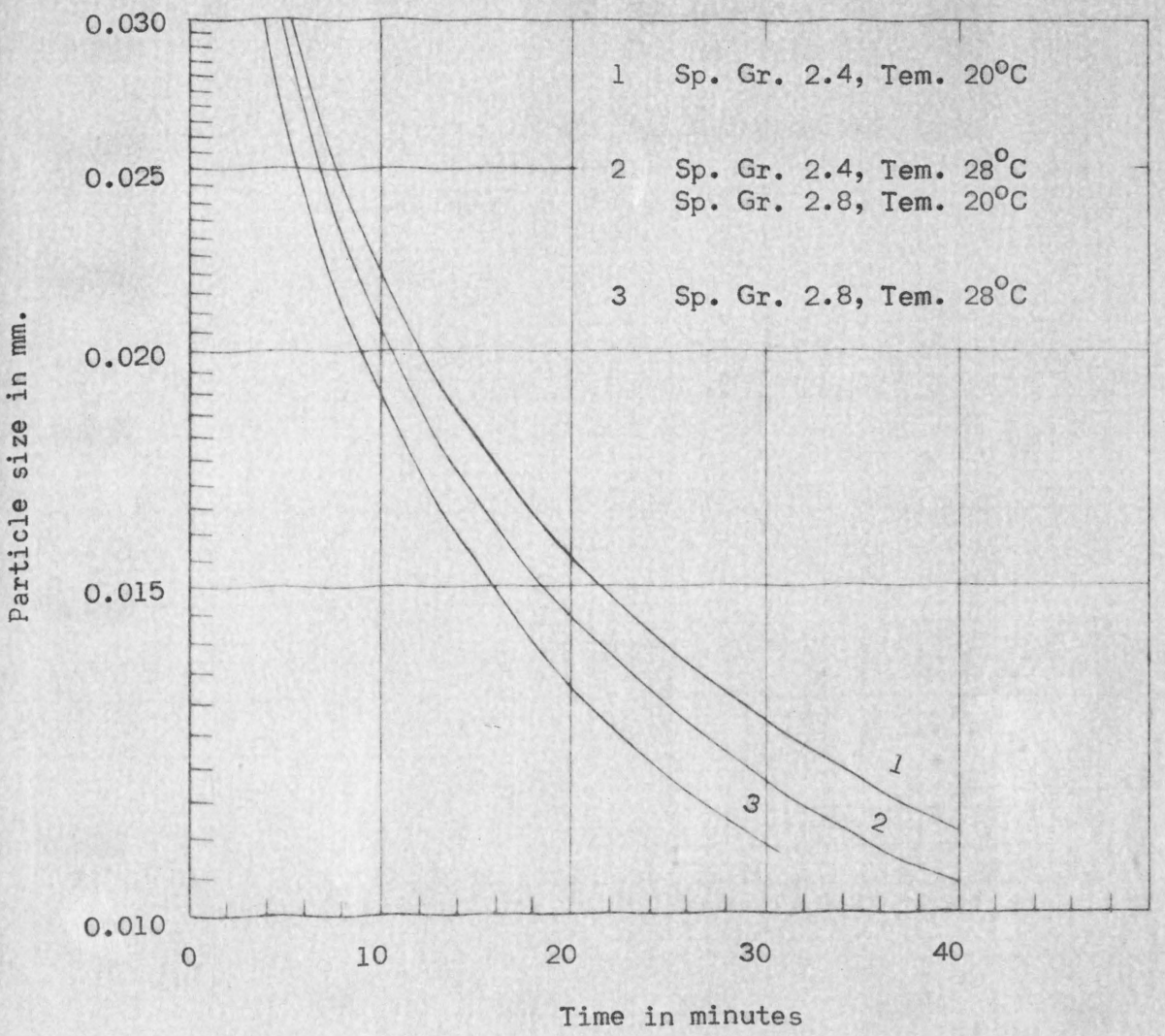

Figure 4b. Particle Size vs. Falling Time
(6 minutes to 40 minutes)

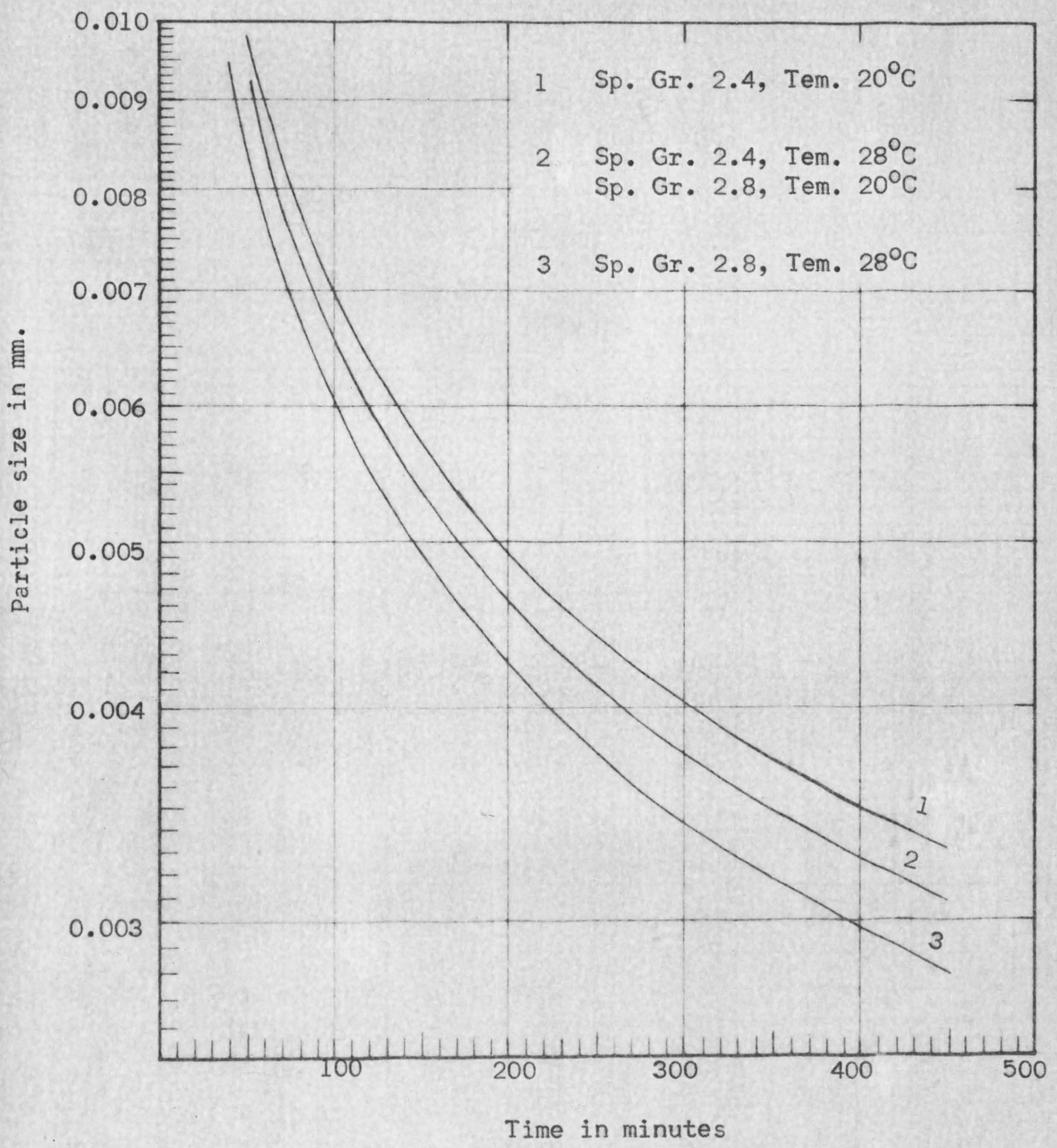

Figure 4c. Particle Size vs. Falling Time
(40 minutes to 500 minutes)

I.B.M. PROGRAM FOR STOKES' LAW

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100 FORMAT ( E14.7)
101 FORMAT ( 15HREAD VISCOSITY. )
102 FORMAT ( 14HREAD DISTANCE. )
103 FORMAT ( 16HREAD SP GR SOIL. )
104 FORMAT ( 15HREAD SP GR H20. )
105 FORMAT ( 10HREAD TIME. )
106 FORMAT ( 12HVISCOSITY =  , E14.7)
107 FORMAT ( 11HDISTANCE =  , E14.7)
108 FORMAT ( 13HSP GR SOIL =  , E14.7)
109 FORMAT ( 12HSP GR H20 =  , E14.7/)
110 FORMAT ( 7HTIME =  , E14.7)
111 FORMAT ( 7HDIAM =  , E14.7/)
    PRINT 50
  1 PRINT 101
    READ 100,VIS
    PRINT 102
    READ 100,S
    PRINT 103
    READ 100,GS
    PRINT 104
    READ 100,GW
    PRINT 106,VIS
    PRINT 107,S
    PRINT 108,GS
    PRINT 109,GW
 10 PRINT 105
    READ 100,T
    PRINT 110,T
    D = SQRT ((18.*VIS*S)/((GS-GW)*T*980.))
    PRINT 111,D
    GO TO 10
    END
```

Figure 5. Sieves for Sample Release and Dispersion

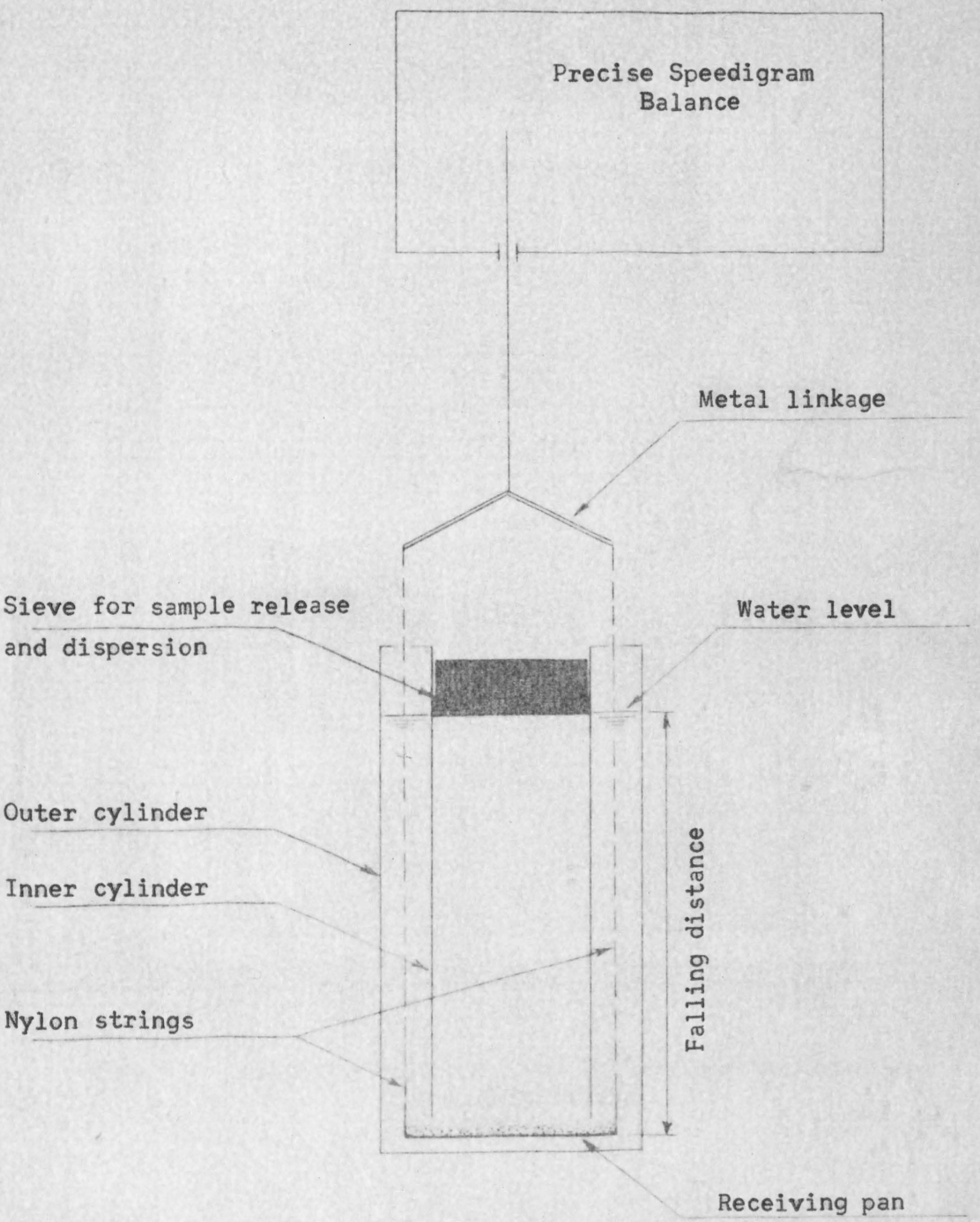

Figure 6. Sedimentation Apparatus for Time-Weight Accumulation

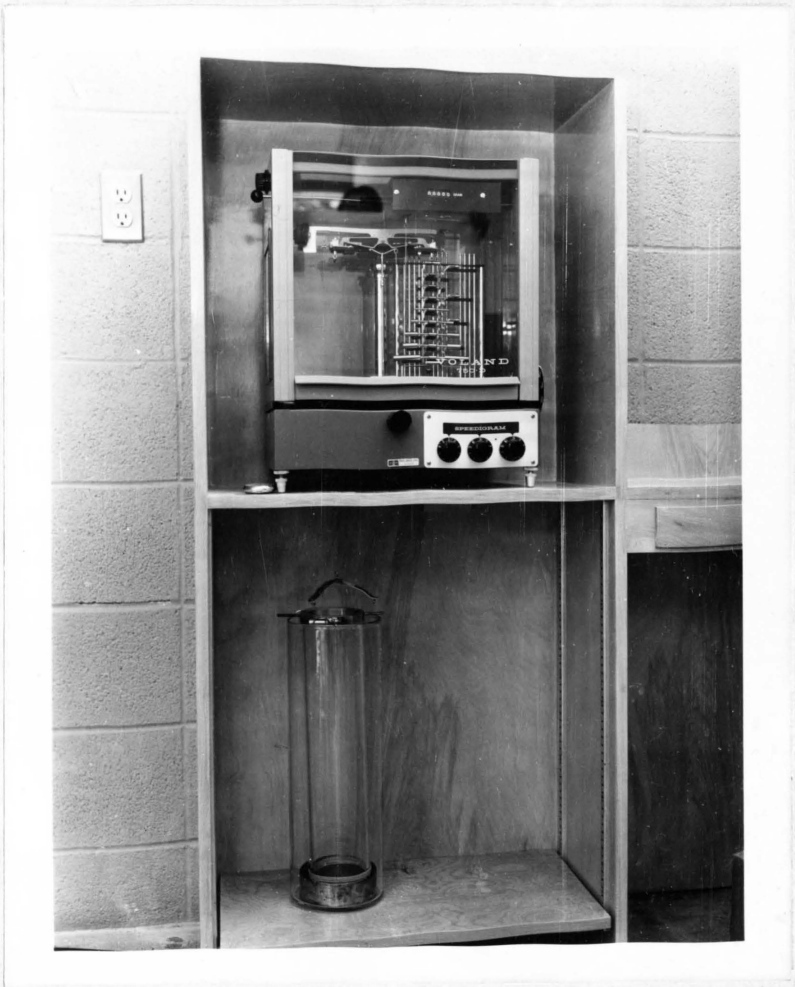

Figure 7. Complete Apparatus for Time-Weight Accumulation of Sedimentation