UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

STUDIES OF TRACTIVE FORCES OF COHESIVE SOILS IN EARTH CANALS

Hydraulics Branch Report No. Hyd-504

DIVISION OF ENGINEERING LABORATORIES

OFFICE OF ASSISTANT COMMISSIONER AND CHIEF ENGINEER
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STUDIES OF TRACTIVE FORCES OF COHESIVE SOILS IN EARTH CANALS*

SUMMARY AND CONCLUSIONS

A field and laboratory study was made to develop a method for determining critical tractive forces of cohesive earth materials for the design of unlined and earth-lined canals. It is desirable to know the critical tractive force value of proposed earth canal materials and to use critical tractive force as a criterion in designing earth canals. Critical tractive force is a more precise value on which to base the design than estimated permissible canal velocities. When the critical tractive force value is known, the methods of design outlined in References (1), (2), and (3) can be used to give the most efficient design for the canal.

Soil samples were obtained from 46 test reaches in various sizes of canals and laterals constructed on Bureau projects. Soil and hydraulic tractive force properties were measured and computed in the laboratory. The properties measured or computed were: critical tractive force from the hydraulic erosion machine, liquid limit, plasticity index, soil density, percent of maximum Proctor density, shrinkage limit, soil gradation using the logarithmic probability method of analysis and unit vane shear values.

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A multiple linear correlation was made using values of the variables obtained from the erosion and soil tests. The availability of an electronic digital computer and a program for making multiple linear correlations made it possible to use many groupings of the variables, obtain their equations, and determine correlation coefficients. The critical tractive force is the dependent variable and the measured soils properties are independent variables. The independent variables represent values obtained from standard tests that are easily made in the laboratory.

Data are arranged in four zones parallel to the "A" line on the soils plasticity chart. Correlations were made for data in each zone and for all data together. Some correlations within zones give the highest correlation coefficients. The correlations show that plasticity, gradation, and density are all important soils properties when considering erosion from hydraulic tractive forces.

Seven correlations which have high correlation coefficients for all the data, and also for the separate zones, were selected as the best correlations and are recommended for general use. For specific cases it may be desirable to use a correlation in a separate zone.

The dependent variable, critical tractive force, was measured on a soil erosion machine. The machine was calibrated to give critical tractive force values using uniform sands and gravels. The critical tractive forces for noncohesive sands and gravel materials are known from many laboratory and field measurements. The critical tractive forces of cohesive soil samples were related to critical tractive forces of noncohesive sands and gravels by calibration curves described in Appendix I.

The logarithmic probability method of plotting and defining mechanical analysis of soils was used because it defines the properties on a statistical basis. This method of defining size analysis lends itself to mathematical treatment better than other methods.

Examples are given showing the practical application of determining critical tractive forces of cohesive soils for design of earth canals.

INTRODUCTION

In 1950 the Bureau of Reclamation began an investigation of methods of improving the design of unlined canals constructed in earth materials. (1), 1/ A method for designing stable channels was developed which was based on distributing the tractive forces along the side slopes and bottoms of the channels, so that the force magnitude at all points on the perimeter would be sufficiently large to prevent sediment deposits in objectionable quantities and small enough to prevent objectionable scour. The method included the determination of channel slopes in coarse noncohesive materials which would result in a minimum of excavation. (2) Prior to this study, canals in earth materials were designed using limiting velocities as the main criteria. A summary of this work is given in Reference (3).

A similar method may be used in the design of canals in cohesive soils when the safe tractive force for the cohesive material can be determined. The distribution of tractive forces around the perimeter of canals is considered, but the rolling down effect and angle of repose of particles on the side slopes is not applicable for cohesive materials. The main factors considered are the cohesion of the particles and the critical tractive forces for the cohesive materials. (4)(5)(6)

The purpose of this report is to present a method for determining tractive force values which can be used in the design of canals in cohesive materials.

Smerdon and Beasley(7) made a study relating the critical tractive forces of 11 cohesive soil samples, measured in a 2.5-foot hydraulic flume, with plasticity index, dispersion ratio, mean particle size, and percent clay. They concluded that "the problem of the stability of open channels in cohesive soils can logically be approached on the basis of the tractive force theory." For the soils tested, Smerdon and Beasley maintained--"the critical tractive force is best correlated with the plasticity index and the dispersion ratio, although excellent correlation also exists with the mean particle size and percent clay." Correlations were made using only two variables at a time.

Moore and Masch(8) made tests on cohesive earth materials to determine scour resistance from hydraulic forces. Their tests were made with a water jet impinging on the surface of a 5-inch circular sample submerged in a 3-foot-square tank. They assumed

1/Numerals in parentheses--thus (1)--refer to corresponding items in the Bibliography.

the depth of scour to be proportional to the logarithm of the time of exposure and developed other relationships for depth of scour and a proportionality constant which was a measure of the rate of scour. Plots from their scour tests showed the proportionality factor to be related to the logarithm of the Reynolds number of the jet. Different ratios of height of jet to diameter of jet were used. The soil variables were lumped into a single constant called "the scour resistance of the sediment," and this single constant was related with the hydraulic variables. A rotating cylinder test apparatus for making scour tests was described, but no test results were given.

Dunn(9) studied the resistance to scour of cohesive soils using (a) a hydraulic jet flowing vertically downward on a soil surface and (b) a vane shear test on operating canal surfaces and on laboratory samples taken from the field. He determined the relationship between the critical hydraulic shear stress of the cohesive soil samples and the soil strength determined from the vane shear tests. He indicated that the vane shear strength, and consequently the critical hydraulic shear stress, varied with the percent of fine particles in the samples, the plasticity index, and the logarithmic probability characteristics of the particle size curves. He concluded that (a) the most accurate method of estimating critical hydraulic shear stress, for soils with plasticity index between 5 and 16, is by use of his derived formula which includes the term "plasticity index," (b) that predictions of critical tractive forces for cohesive soils can be based on the percent of silt and clay in the soil when the soil contains sand, and (c) that "correlation of soil properties with grain size gave good results in this investigation because the effect of changes in strength due to differences in chemical and mineralogical content, and due to differences in soil structure, are accounted for by the vane test."

EXPERIMENTAL WORK AND DATA OBTAINED FROM FIELD TEST SITES

Data Obtained

The 46 test reaches selected on canals and laterals of varying size and discharge were located in five of the seven regions of the Bureau of Reclamation. A search was made in each case to locate a straight reach of canal in cohesive soil. From each of the selected test reaches soil samples were obtained for making laboratory tests. The samples included disturbed samples, 3-inch drive tube samples, 8-inch undisturbed hand cut samples, and deposited sediment samples (in the reaches where deposition had occurred). The disturbed soil samples were used to determine gradation, plastic properties, and the compaction characteristics of the soil materials. The 3-inch drive tube samples were used in unconfined compression tests. The 8-inch hand cut soil samples were used as erosion test specimens.

During operation at near peak discharge of the canals and laterals the following data were obtained from the test sections: canal water surface slopes; canal cross sections at the middle of the reach; velocity contours at the middle of the reach including velocities near the canal boundary; amount of sediment being carried in suspension; temperature of the water; and shear resistance of the bank and bottom of the canal in place and in saturated condition. The shear resistance was determined by the vane shear tester shown in Figure 1. (10)

Photographs were made of each test reach showing the condition of the channel, both when it was flowing at near peak discharge and when there was no water in the test reach.

Water surface slopes were obtained using a water surface gage, Figure 2, and an engineer's level. Velocity measurements were made using a Type A current meter. A pigmy-type current meter was used to measure velocities near the boundary. A DH-48 hand sediment sampler was used for obtaining samples of suspended sediment flowing in the canal.

Records of the highest sustained flow (maximum sustained discharge) for each year in each test section for a period of several years, were obtained from the project offices. It was assumed that the maximum sustained discharge would produce the most severe erosion or would expose the earth material to the most severe hydraulic forces. Cross sections of each canal test reach were obtained and used to determine whether the original shape had changed during operation.

Tractive Force Testing Apparatus

A laboratory tractive force testing apparatus was developed to measure tractive forces of undisturbed samples of soil material obtained from each of the test reaches. Appendix I describes the equipment and procedures used to determine critical tractive forces of cohesive materials. The critical tractive force values obtained were used as the dependent variable in analyzing the results of this study.

The tractive force apparatus includes a 35-inch-diameter tank, a variable speed air motor, a transparent lid, impeller blades, pressure gage, and a pressure regulator. An 8-inch round saturated soil sample is placed in the tank with only the surface exposed on the bottom of the tank, and covered with 12 inches of water. The impeller is started, and rotating slowly, forces water to flow across the sample to create a tractive force of low value on the soil sample. After subjecting the sample to a low initial tractive force for 3 minutes, the speed of rotation is increased and the corresponding increased tractive force is allowed to act on the soil for another 3 minutes. This procedure is repeated, raising the speed of rotation in steps, until erosion begins. The speed of rotation of the impeller in revolutions per minute is recorded at the time erosion begins. Incipient erosion is judged by observation through the transparent tank lid. The tractive force occurring on the surface of the sample, in terms of the velocity of rotation of the impeller in revolutions per minute was determined from calibration curves explained in Appendix I. Notes on the behavior of the soil undergoing the test and sketches of the eroded area are made when the sample has reached a point of general erosion. Photographs of the soil sample before and after the test are taken for comparison purposes. After completion of the erosion test, soil density and vane shear strength are determined for the sample in the saturated condition. Mechanical analysis and standard soils Atterberg limits tests are also made on the same soil sample.

The tractive force developed when general erosion of the soil sample begins is considered to be the critical tractive force, and is the value used in the analysis presented in this paper.

Standard Soils Characteristics

Soil tests, including plasticity index, liquid limit, density, gradation factors, shrinkage limit, and percent maximum density were performed in conformance with procedures presented in the First Edition of the Bureau of Reclamation Earth Manual, July 1960.(11) Results are summarized in Table 2. Unconfined compression tests were performed on a few samples but the test results indicated that sufficient additional information could not be obtained to justify continuing this test. Density values (Column 4, Table 2) were obtained from the tractive force test specimens after they had been subjected to erosion tests in the tractive force machine. Vane shear values (Column 10, Table 2) were obtained using a vane shear apparatus having a four-bladed vane 4 inches high and 2 inches in diameter, Figure 1.(10) Vane shear tests were also performed on tractive force test specimens after the erosion tests were completed.

Mechanical Analysis of Soils

The logarithmic probability analysis was used to explain the gradation of the soils. In this statistical method the particle size distribution is assumed to follow a logarithmic normal probability curve. Mechanical analysis of soils can be described by deviations from this curve.

A special graph ruling, developed in the Bureau of Reclamation, provided a simple and rapid method of determining soils characteristics in relation to the logarithmic normal probability curve. By plotting a standard soils size analysis on the special graph paper, values of $M\phi$, $\sigma\phi$, and $k'\phi$ are quickly determined. $M\phi$ is a measure of the mean particle diameter. $\sigma\phi$ is the standard deviation of the sample giving a measure of the particle distribution or scatter of particles about the mean size, and the value of $k'\phi$ gives a measure of the amount of fine particles in the soil.

In general, the mean particle size decreases as the value of $M\phi$ becomes greater; as $\sigma\phi$ increases the spread or range of distribution of particles about the mean increases; and as $k'\phi$ becomes greater the percentage of fine material in the sample increases. These three values were used in the multiple linear correlations obtained from the electronic digital computer.

A detailed description of the logarithmic probability method for describing the gradation of soils is given in Appendix II.

ANALYSIS OF LABORATORY DATA

Data obtained in the laboratory were analyzed by correlating the soils properties with the critical tractive force values obtained from the tractive force machine tests. The soils properties used were plasticity index, liquid limit, soil density, mechanical analysis, shrinkage limit, vane shear values, and percent of maximum Proctor density.

Analysis of the laboratory data was first made using the method of deviations described by M. Ezekiel in his book, "Method of Correlation Analysis."(12) In this method, many hand calculations are required and a complete analysis is very time consuming. To make the analysis of many factors more practical, an electronic digital computer was used. A multiple linear correlation method, programed for the computer, was adapted for this study. The resulting computations provided the best linear equation, standard deviations from the linear equation, a correlation coefficient, and standard deviations for the coefficients of each of the variables.

The correlation coefficient is a measure of the combined importance of the several independent factors as a means of explaining the differences in the dependent factor. In general for a linear correlation, the closer the correlation coefficient approaches unity the better the correlation becomes between the dependent variable and the independent variables. A coefficient of 1.0 would show perfect correlation and a coefficient of zero would show no linear correlation.

Numerous correlation computations were made for all data together. Correlations were also made with the same data divided into zones which were arbitrarily drawn parallel to the "A" line on the plasticity index-liquid limit chart shown in Figure 3. This chart has been accepted for use in the unified soils classification procedure and is a guide for estimating the erodibility of soils. The first correlations were made without using the liquid limit as a variable. It was believed that this property would not affect the correlation because it had been included in the plasticity index factor.

In the first analysis, 21 different correlations, Table 3, were made using tractive force as the dependent variable. Plasticity index, density, gradation factors $k'\phi$, $\sigma\phi$, $M\phi$, their product $k'\phi\sigma\phi M\phi$; shrinkage limit, vane shear strength, and percent maximum density were the independent variables. Seven of these correlations, Numbers 1, 2, 6, 7, 9, 10, and 13, gave the highest correlation coefficients of 0.69 to 0.74 for all data, and also had high coefficients for the data in the separate zones.

It was decided to investigate the effect of the property liquid limit on the correlations. Additional multiple linear correlations were then made including the liquid limit as an independent variable.

Because of the computer program, it was comparatively simple to make additional correlations by utilizing the initial computations and the already punched cards. Consequently, correlations for all of the data in a group and for the data divided into four zones parallel to the "A" line on the liquid limit plasticity index chart were made adding the variable liquid limit. Seventeen additional correlations were made, Table 3A.

Higher correlation coefficients for all data were obtained than for the first analysis. This showed that even though plasticity index is the most important characteristic of plastic soils, the liquid limit is also important. Correlations Numbers 22 through 38 include liquid limit as an independent variable, Table 3A.

With the variable liquid limit added, the correlation coefficients for the best seven correlations were 0.71 to 0.79. The seven correlations, Table 3A, which give the highest correlation coefficients for all data are numbered 31, 32, 34, 35, 36, 37, and 38. The table below shows which variables are used to give these correlations.

Correlation Numbers	Dependent Variables									
	PI	Density	k'_ϕ	σ_ϕ	M_ϕ	$k'_\phi \sigma_\phi M_\phi$	SL	VS	Percent maximum density	LL	Correlation coefficient for all data
31	x	x	x	x	x					x	.78
32	x		x	x	x				x	x	.76
34	x	x				x		x	x	x	.79
35	x	x						x	x	x	.71
36	x	x				x			x	x	.78
37	x					x			x	x	.76
38	x	x	x							x	.78

PRACTICAL APPLICATION

An example of the determination of a critical tractive force value for a given soil, using the multiple linear correlation method, is given below:

Using Correlation Number 34 for all data, the general equation given at the top of Table 3 would be written:

$TF = -0.03414 + 0.00001\ PI + 0.00031\ D + 0.00029\ k'_\phi \sigma_\phi M_\phi + 0.00325\ VS + 0.00004\ D\% + 0.00102\ LL$ The numerical values are taken from Table 3A, Correlation Number 34, where

- TF = critical tractive force for beginning general erosion
- PI = plasticity index
- D = density of the natural soil, pounds per cubic foot
- k'_ϕ = phi skewness
- σ_ϕ = phi standard deviation
- M_ϕ = phi arithmetic mean diameter
- VS = vane shear value, pounds per square foot
- D% = percent of maximum Proctor density
- LL = liquid limit

A typical plastic soil may have the following values for soils properties:

PI = 12.0
D = 91.0 pounds per cubic foot
$k'\phi$ = 0.60, $\sigma\ \phi$ = 3.07, $M\phi$ = 5.70, $k'\phi\ \sigma\ \phi M\phi$ = 10.5
VS = 0.90 pound per square foot
%D = 85.3 percent
LL = 32.7

Inserting these values in the above equation and solving results in a computed critical tractive force, TF = 0.037 pound per square foot.

If all the soil properties used in the above computation are not known, a correlation can be chosen which includes the soil property data which is available. For the above soil, for example, if only the plasticity index, density and gradation factors were known, Correlation Number 38 for all data could be used to determine a critical tractive force value. For this case, the general equation at the top of Table 3 would become:

$$TF = -0.03477 + 0.00037\ PI + 0.00038\ D + 0.00548\ k'\phi + 0.00095\ LL$$

Inserting the values for the typical plastic soil in this equation results in a computed critical tractive force, TF = 0.039 pound per cubic foot. This value is probably not quite as reliable as the one from Correlation Number 34 but the two values are still very similar.

All of the correlations are given in Tables 3 and 3A. Whether to use the correlations for individual zones or the ones for all data is a matter of judgment, depending on the exact knowledge of the soil in question.

A study of the correlations shows that the plastic properties, the gradation properties, and the density properties of the soils are all important when determining the safe tractive force of cohesive soils.

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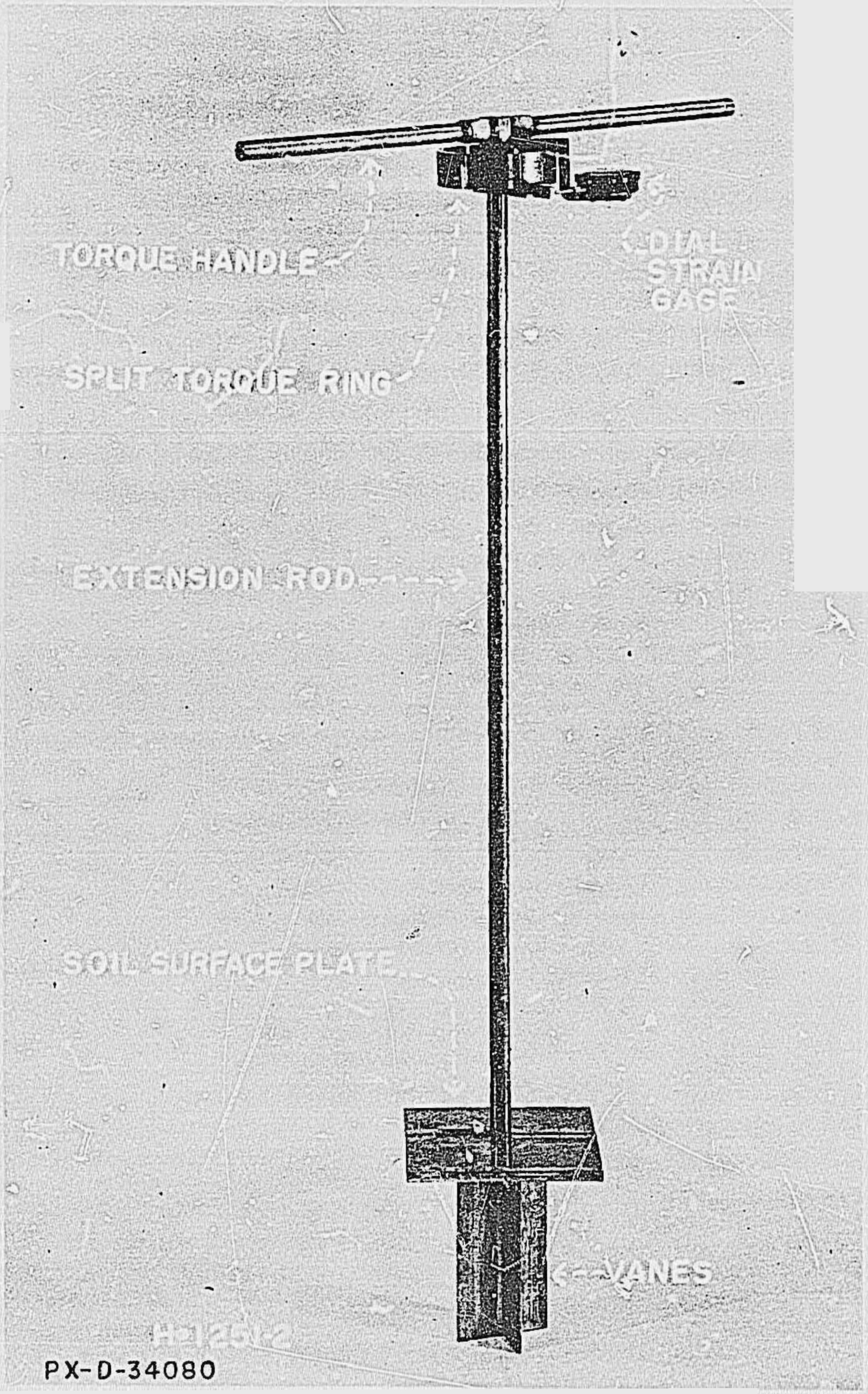
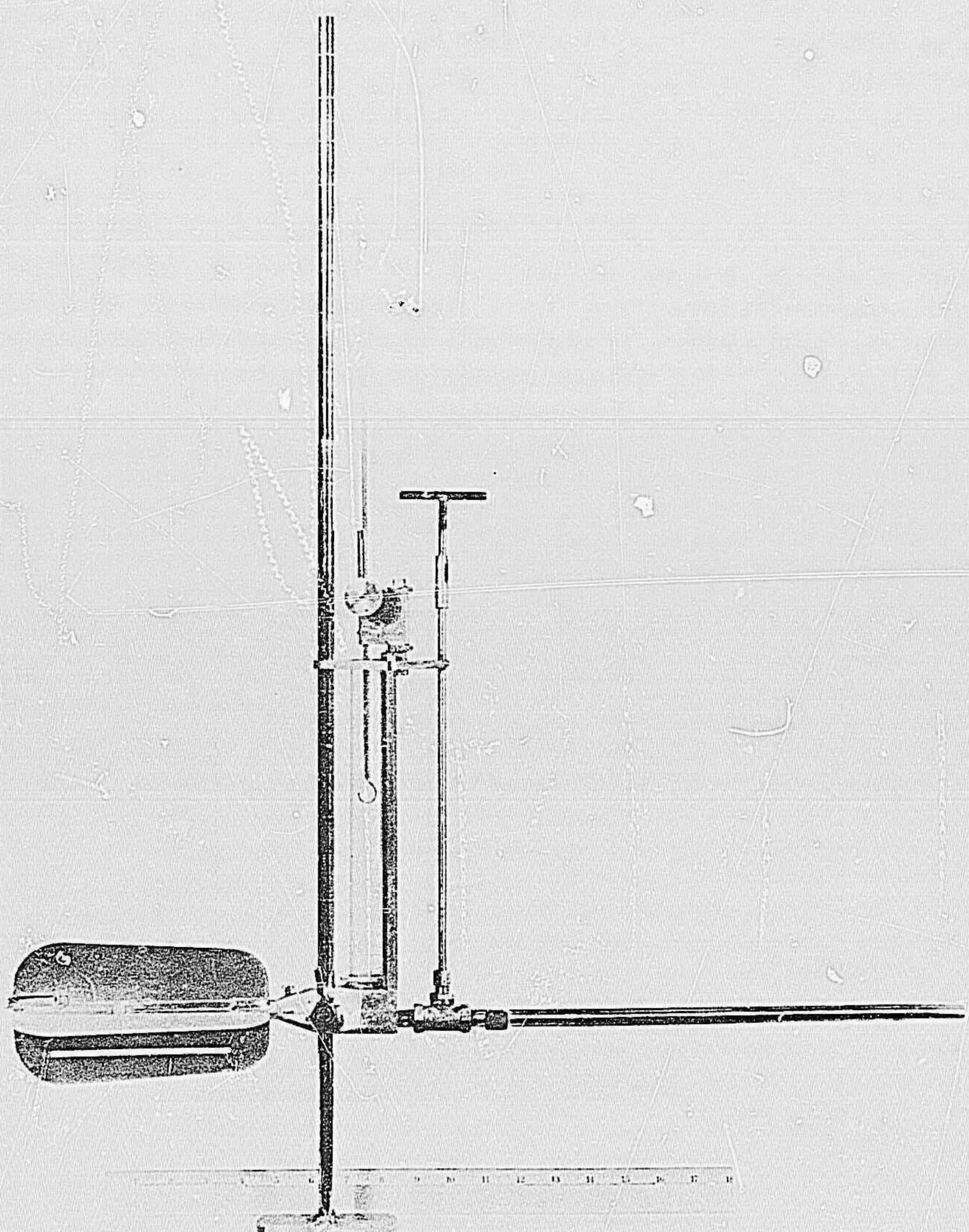
Figure 1



HYDRAULIC LABORATORY
VANE SHEAR TESTER

Figure 2



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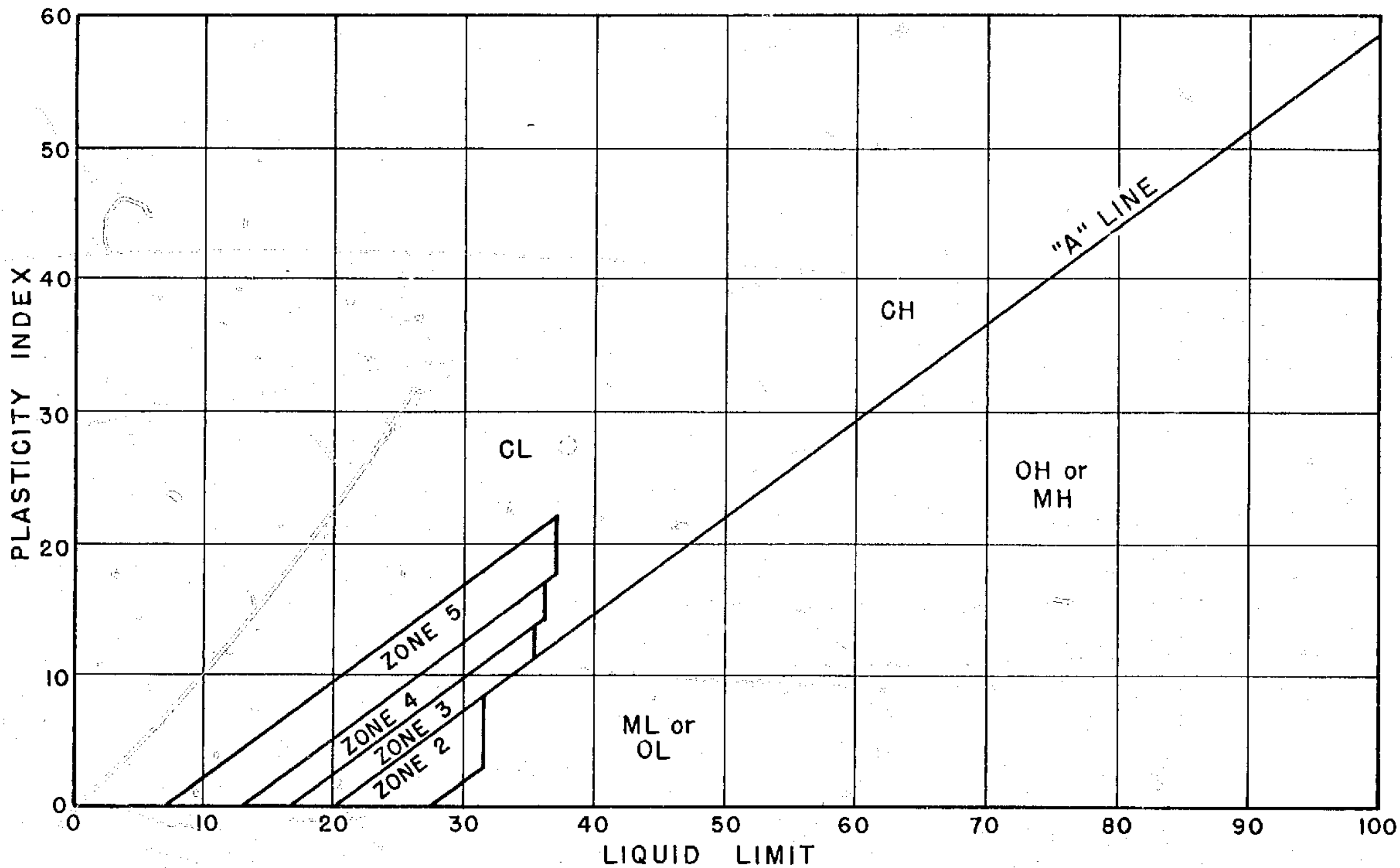
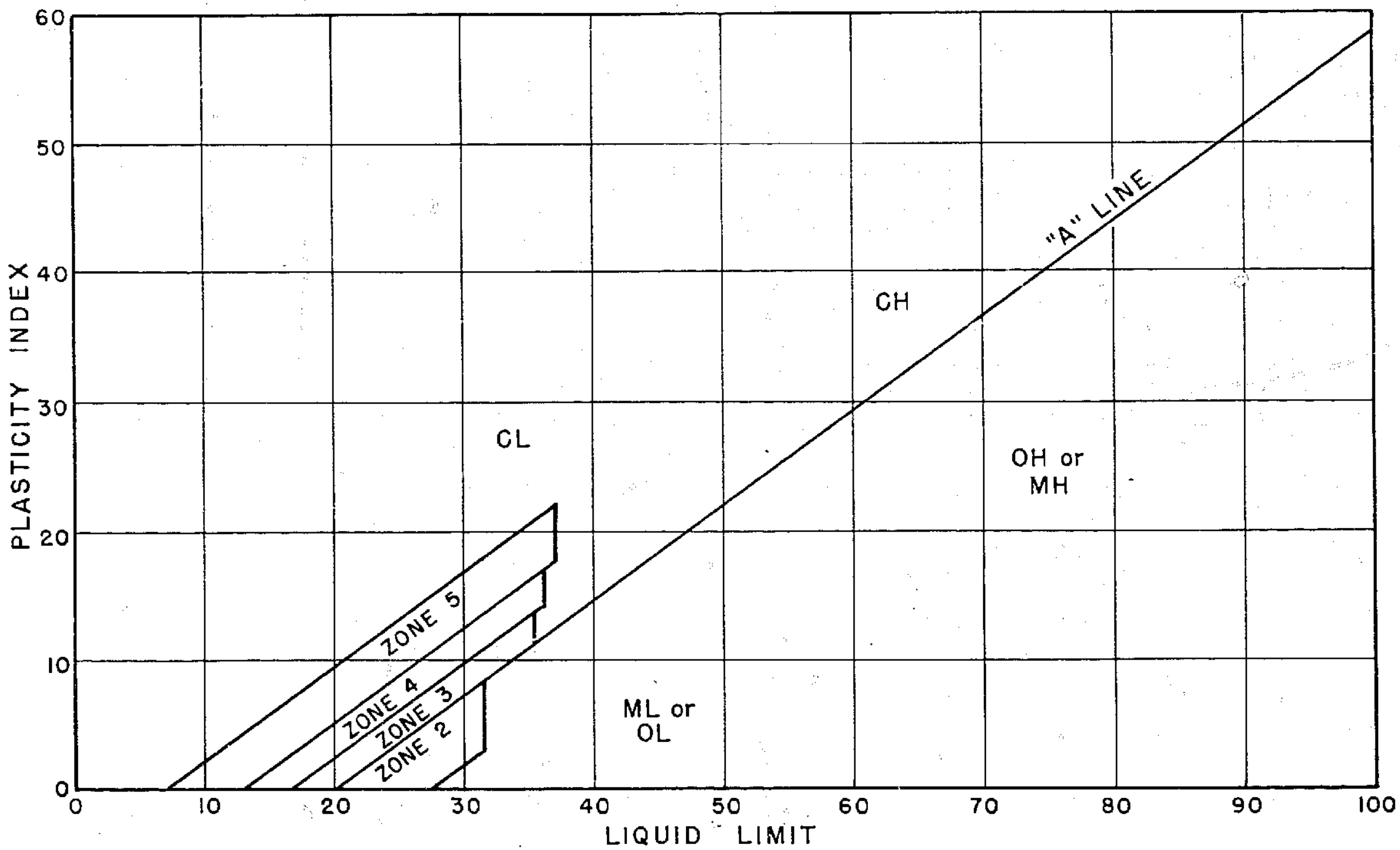
GAGE FOR MAKING WATER
SURFACE SLOPE MEASUREMENTS



TRACTIVE FORCE FIELD AND LABORATORY STUDY

RANGE OF SOILS TESTED

FIGURE 3



TRACTIVE FORCE FIELD AND LABORATORY STUDY

RANGE OF SOILS TESTED

FIGURE 3

Table 1

LOWER-COST CANAL LINING
TRACTIVE FORCE FIELD AND LABORATORY STUDY
CANAL AND LATERAL REACHES

Samples No. 18F-	Region: reach	Project	Canal or lateral	Station or mile at center of reach	Test discharge cfs	Soil type
625-633	1-1	Minidoka	Lateral PL 10-A-824S	33+00	3.79	ML
634-642	1-2	Minidoka	Milner-Gooding Canal	374+00	1,540	ML
643-651	1-3	Minidoka	PA Lateral (North Side Pumping Co.)	19+42	67.7	ML
652-660	1-4	Yakima	PL No. 14 (Lateral)	152+50	18.6	ML
661-669	1-5	Yakima	PL No. 13 (Lateral)		18.4	SM
670-678	1-6	Yakima	Roza Main Canal	*59.1	514	ML
679-687	1-7	Columbia Basin	WC Lateral W27B	24+90	26.4	ML
688-696	1-8	Columbia Basin	WC Lateral W26A	378+90	47.1	ML
697-705	1-9	Columbia Basin	EL Lateral 68T5	185+00	5.81	ML
435-439	2-1	Klamath	Lateral M-2-A	6+85	20.2	MH
440-443	2-2	Klamath	Lateral M-2-A	92+30	5.6	MH
444-449	2-3	Klamath	Lateral J-1-B	6+50	18.1	SM
450-455	2-4	Klamath	Lateral J-13	15+00	27.4	ML
456-459	2-5	Central Valley	Friant-Kern Canal	*37.49	2,910	CL-CH
460-465	2-6	Central Valley	Friant-Kern Canal	*39.82	2,620	CL
466-471	2-7	Central Valley	Madera Lateral 32.2	455+40	59.1	ML-SM
472-475	2-8	Central Valley	Madera Canal	*11.35	692	SC-CL
476-481	2-9	Central Valley	Madera Canal	*31.50	488	SC
510-517	4-1	Eden	Means	24+17	289	CL
518-521	4-2	Eden	Means	102+00	253	SP
522-533	4-3	Eden	Means	265+00	188	SM
534-542	4-4	Eden	Eden	348+50	176	SM
543-554	4-5	Eden	Eden	355+83	160	SC-CL
555-566	4-6	Eden	Eden	464+95	176	CL-SC
567-578	4-7	Eden	Eden	645+00	129	CL-SC
579-586	4-8	Eden	Eden	834+00	125	SM
597-605	4-9	Paonia	Fire Mountain	419+00	86.3	CL
606-614	4-10	Paonia	Fire Mountain	648+25	79.8	CL
615-624	4-11	Paonia	Fire Mountain	1341+50	55.2	CL

Table 1--Continued

Samples No. 18F-	Region: reach	Project	Canal or lateral	Station or mile at center of reach	Test discharge cfs	Soil type
799-807	5-1	Tucumcari	Conchas	3215+00	68.6	CL
814-822	5-2	Tucumcari	Conchas	3962+86	57.4	CL
808-813	5-3	Tucumcari	Conchas	4056+00	39.0	CL-with Gravel Blanket
823-832	5-4	Tucumcari	Hudson	274+57	138	CL
833-841	5-5	Tucumcari	Hudson	1091+00	61.7	SC-CL
772-780	5-6	W. C. Austin	West	188+00	78.5	CL
781-789	5-7	W. C. Austin	Altus	799+50	160	CL-CH
790-798	5-8	W. C. Austin	Ozark	316+00	41.2	CL-CH
382-388	7-1	Missouri River Basin	Bartley	263+00	72.6	ML
389-397	7-2	Missouri River Basin	Bartley	762+36	36.1	ML-CL
406-414	7-3	Missouri River Basin	Cambridge	1003+22	132.5	ML-CL
359-367	7-4	Missouri River Basin	Franklin Pump	215+57	18.0	ML
350-358	7-5	Missouri River Basin	Superior	1053+72	65.3	ML-CL
368-374	7-6	Missouri River Basin	Franklin	947+24	99.1	ML-SM
375-381	7-7	Missouri River Basin	Franklin	1949+24	54.6	ML-CL
398-405	7-8	Missouri River Basin	Cambridge	1240+00	54.6	ML-CL

*Mile point

Table 2

DATA OBTAINED FROM LABORATORY
TEST SAMPLES

Zone 2

	1	2	3	4	5	6	7	8	9	10	11	12
Region and reach	Sample No. (18F-)	Most prob T.F.	PI	Density	k'_ϕ	σ_ϕ	M_ϕ	$k'_\phi \sigma_\phi M_\phi$	SL	V.S.	% Max. density	LL
7-2	361-1	0.053	7.2	93.4	1.60	2.88	7.54	34.8	20.72	2.20	85.0	30.7
4-4	537	0.027	0.2	91.7	0.07	1.16	5.12	0.416	22.97	1.33	84.6	22.2
4-4	539	0.038	4.9	95.7	1.00	2.72	4.48	12.2	20.32	1.15	88.4	26.7
4-6	571	0.038	4.1	96.6	0.50	2.16	4.10	4.43	24.51	1.07	85.2	29.3
4-6	572	0.042	6.7	89.3	1.20	2.14	4.20	10.8	24.53	1.48	78.7	29.3
1-6	673	0.023	0	86.6	0.80	1.26	5.48	5.52	22.21	1.10	80.7	21.3
1-8	691	0.028	0.4	95.3	0.10	1.59	5.24	0.833	25.11	0.66	91.6	23.1
2-3	445	0.030	0	94.5	1.04	2.22	3.84	8.87	22.85	0.82	90.4	23.2
2-4	450	0.020	0	75.3	2.00	1.41	4.25	11.99	26.70	0.90	71.5	21.8
2-7	468	0.033	0	100.1	1.40	1.93	3.90	10.54	24.5	0.66	95.3	20.1
4-3	525	0.018	0	91.4	1.55	1.64	3.44	8.87	28.31	0.98	83.6	27.2
4-3	526	0.027	0	88.9	2.00	1.15	3.72	8.56	24.36	0.90	81.2	23.1
1-2	637	0.029	0	91.8	2.00	1.30	5.20	13.52	24.64	0.66	100	25.4
1-2	638	0.017	0	78.3	0.80	1.34	5.34	5.72	28.16	0.57	85.7	26.8
1-3	647	0.024	0	78.6	2.00	1.20	5.20	12.5	27.08	0.84	73.8	24.5
1-4	656-1	0.032	0	93.8	2.00	1.54	5.50	16.94	22.71	1.48	92.0	23.5
1-4	657-1	0.045	0	96.6	1.50	1.45	5.10	11.09	22.18	1.93	94.8	23.8
1-5	664	0.030	0	92.5	1.50	1.68	4.94	12.45	21.19	0.49	86.5	21.5
1-5	665	0.030	0	93.9	2.00	1.10	4.40	9.68	21.43	0.90	87.7	22.3
1-5	666	0.017	0	74.0	1.40	1.08	4.20	6.35	24.71	0.66	69.2	22.0
1-6	673-2	0.028	0	88.2	1.50	1.39	5.40	11.26	22.21	1.10	81.9	21.5
1-6	674	0.029	0	86.6	1.10	1.36	5.25	7.85	21.59	0.66	80.6	22.0
1-7	682	0.024	0	87.6	0.50	2.05	5.79	5.93	25.87	1.31	82.8	25.5
1-7	683	0.020	0	80.7	0.69	1.88	5.68	7.38	23.26	0.98	78.7	23.0
1-7	684	0.025	0	86.8	0.81	1.48	5.79	6.95	29.59	1.39	79.4	24.0
1-8	692	0.022	0	84.8	0.28	1.76	5.51	2.72	22.69	0.66	81.5	24.2
1-8	693	0.025	0	89.5	0.70	1.56	5.15	5.61	25.9	0.98	86.0	25.1
1-9	700	0.021	0	85.3	-0.25	1.92	6.10	-2.93	27.9	1.64	86.4	28.0
*	709-1	0.018	0	84.5	1.00	1.38	5.60	7.73	26.36	1.18	81.1	24.5
*	710-1	0.026	0	85.0	1.40	1.39	5.48	10.7	25.88	0.90	82.3	25.8
*	710-2	0.028	0	90.0	1.30	1.24	5.40	8.69	25.88	1.31	86.3	25.5
*	711	0.022	0	82.2	0.85	1.52	5.75	7.42	26.32	1.31	78.8	27.4
*	711-2	0.025	0	85.8	1.30	1.28	5.42	9.00	26.32	1.23	82.3	20.8

Notes:
- T.F. = most probable tractive force (pound per square foot) determined from tractive force machine
- PI = plasticity index
- $k\phi$ = phi skewness
- $\sigma\phi$ = phi standard deviation
- $M\ \phi$ = phi arithmetic mean diameter
- SL = shrinkage limit
- VS = vane shear--pound per square foot
- LL = liquid limit

*Field data not obtained because of construction.

Table 2

DATA OBTAINED FROM LABORATORY
TEST SAMPLES

Zone 3

Region and reach	1 Sample No. (18F-)	2 Most prob T.F.	3 P.I.	4 Density	5 $k'\phi$	6 $\sigma\phi$	7 $M\phi$	8 $k'\phi\,\sigma\phi\,M\phi$	9 S.L.	10 V.S.	11 % max. density	12 LL
7-5	352-2	0.036	10.8	76.0	1.20	1.90	6.46	14.73	23.92	1.80	67.9	31.5
7-5	359	0.043	11.3	76.2	2.10	1.66	6.14	21.40	27.12	2.20	70.1	34.7
7-6	370-1	0.025	0.8	85.7	1.55	2.24	5.19	18.02	15.45	1.45	82.3	19.7
7-1	382	0.033	6.4	72.1	1.50	2.18	5.50	17.99	17.71	1.80	69.8	26.0
7-2	391-1	0.042	10.2	82.9	1.50	1.91	6.15	17.62	16.15	1.80	79.1	30.8
7-8	400-1	0.043	8.6	81.9	2.00	2.21	6.60	29.17	19.60	1.50	74.1	31.0
7-3	407-1	0.039	5.4	92.5	2.00	1.88	6.21	23.35	18.04	1.90	88.3	26.7
7-3	407-2	0.040	5.6	84.2	2.00	2.07	6.49	26.87	18.04	1.90	80.2	27.5
4-1	514	0.037	9.7	73.4	1.57	2.76	5.88	25.48	19.31	0.41	69.0	31.8
4-3	527	0.040	8.5	91.6	2.00	2.46	4.54	22.34	20.98	0.90	83.8	29.5
4-8	582	0.049	4.8	99.3	1.40	2.41	3.98	13.43	18.3	1.64	84.5	24.3
1-1	629	0.033	5.3	85.3	1.00	1.81	6.08	11.0	19.62	1.43	81.3	24.4
1-1	630	0.041	3.3	78.8	1.8	2.22	6.68	26.69	20.15	1.43	75.2	22.6
1-3	646	0.028	5.6	78.7	0.90	2.81	4.31	10.9	19.67	0.74	74.0	25.5
1-3	648	0.040	3.5	91.6	1.10	1.58	5.70	9.91	22.01	0.98	85.8	24.2
2-4	451-1	0.023	0	76.5	1.90	1.31	3.29	8.19	22.64	0.57	73.2	18.8
2-7	467	0.029	0	99.3	0.60	2.20	3.60	4.75	24.5	0.98	94.1	19.5

Table 2

DATA OBTAINED FROM LABORATORY TEST SAMPLES

Zone 4

	1	2	3	4	5	6	7	8	9	10	11	12
Region and reach	Sample No. (18F-)	Most prob T.F.	P.I.	Density	k'_ϕ	σ_ϕ	M_ϕ	$k'_\phi \sigma_\phi M_\phi$	S.L.	V.S.	% max. density	LL
7-5	351-2	0.045	11.3	99.5	1.75	1.78	6.27	19.6	19.6	1.80	88.8	31.3
7-7	375-1	0.042	6.7	102.0	2.00	2.00	4.55	18.2	21.2	1.45	94.3	22.1
7-2	389-1	0.050	10.8	112.9	1.90	2.40	6.25	28.5	25.1	1.80	100	29.5
7-2	389-2	0.042	10.9	72.7	2.00	2.36	6.60	31.2	25.1	1.80	69.6	29.1
7-8	398-1	0.046	10.5	86.1	2.00	2.75	6.98	38.4	19.7	1.50	83.1	28.1
7-8	398-2	0.042	9.9	84.4	1.56	2.05	6.30	20.2	19.7	1.50	81.8	29.2
7-8	399-1	0.053	16.0	73.7	1.70	3.00	7.38	37.6	18.1	1.50	70.6	35.2
7-3	406-2	0.057	15.4	81.6	1.70	3.10	7.53	39.7	15.2	1.90	79.5	35.2
7-3	408-1	0.046	16.8	76.2	1.10	2.02	6.56	14.6	21.1	1.90	72.9	36.2
2-1	435	0.016	9.9	50.8	0.08	2.34	6.44	1.21	19.2	0.61	48.1	29.3
2-8	472	0.030	5.4	93.2	0.50	3.26	4.55	7.42	18.4	0.57	86.3	21.7
2-9	478	0.037	4.4	110.1	0.60	3.01	3.67	6.64	17.7	0.57	98.4	19.5
4-1	513	0.045	12.0	91.0	0.60	3.07	5.70	10.5	17.1	0.90	85.3	32.7
4-4	538	0.050	7.9	103.8	2.00	3.08	4.76	29.3	16.5	1.33	95.7	23.9
4-4	546	0.049	15.1	68.2	1.45	3.08	5.71	25.5	18.7	0.57	65.0	35.1
4-4	547	0.032	6.5	98.7	1.10	2.85	5.85	18.4	15.8	0.82	93.8	25.4
4-9	600	0.044	13.3	112.2	-0.6	4.5	5.1	-13.8	20.2	2.05	99.8	33.1
4-9	601	0.040	16.9	81.9	-0.28	3.14	6.44	-5.66	19.8	0.98	74.6	36.5
4-10	610	0.042	13.6	96.2	0.4	2.40	6.80	6.53	20.2	2.30	89.9	31.7
1-1	628	0.030	4.4	82.8	1.40	1.84	6.10	15.7	14.4	1.15	79.0	22.4
5-5	836-1	0.015	2.5	99.0	-0.9	2.70	4.61	-11.2	15.5	1.32	89.3	17.9
5-5	838-2	0.025	1.3	104.8	1.4	2.60	5.01	18.2	14.2	1.32	89.0	17.6
7-7	377-2	0.027	0	101.1	2.00	1.71	3.57	12.2	13.0	1.45	84.0	14.0

Table 2

DATA OBTAINED FROM LABORATORY
TEST SAMPLES

Zone 5

	1	2	3	4	5	6	7	8	9	10	11	12
Region and reach	Sample No. (18F-)	Most prob T.F.	P.I.	Density	k'_ϕ	σ_ϕ	M_ϕ	$k'\sigma_\phi M_\phi$	S.L.	V.S.	% max. density	LL
7-5	351-1	0.032	13.6	87.4	1.70	1.90	6.26	20.22	19.6	1.80	78.0	31.1
7-5	350-1	0.046	14.0	88.1	2.50	2.78	7.22	50.2	20.8	1.80	79.0	30.8
7-6	368-2	0.034	7.5	98.0	2.0	3.20	4.21	26.94	13.7	1.45	92.0	21.6
7-6	368-3	0.040	10.1	93.9	2.0	3.75	5.40	40.5	13.7	1.45	85.5	24.4
7-6	369-1	0.028	9.6	97.4	0.09	2.78	6.22	1.56	17.8	1.45	85.7	25.3
7-3	406-1	0.041	17.3	74.0	2.00	3.30	7.62	50.3	15.2	1.90	73.0	33.9
2-5	457	0.051	21.0	81.2	1.4	3.68	4.68	24.1	16.4	0.41	79.0	36.4
2-6	461	0.036	10.0	106.1	0.80	3.03	4.75	11.5	16.5	0.82	94.0	25.5
2-6	462	0.034	10.0	103.6	0.50	3.06	4.76	7.28	16.5	0.61	92.0	25.5
2-8	473	0.029	10.2	97.1	0	3.02	3.22	0	21.9	0.66	93.0	25.8
4-6	559	0.027	10.2	85.6	0.62	3.98	6.40	15.8	18.4	0.82	82.2	25.1
4-6	560	0.039	13.0	95.5	1.2	3.60	5.49	23.7	18.4	1.10	91.7	27.9
4-7	570	0.031	13.5	85.2	1.50	2.50	3.98	14.9	23.3	2.05	75.2	28.6
4-11	618	0.039	12.5	95.9	1.1	2.38	6.24	17.82	15.7	0.82	92.4	29.3
4-11	620	0.053	16.5	118.3	0.60	2.21	6.90	9.15	17.7	1.97	100	33.6
5-6	775-1	0.030	24.8	73.6	0.80	4.15	8.18	27.2	8.5	0.90	71.3	42.9
5-6	777-1	0.042	22.8	97.7	0.66	3.94	7.54	19.6	11.4	0.82	94.6	40.6
5-7	785-1	0.042	14.2	89.8	0.86	3.61	7.61	23.6	16.3	0.39	83.0	29.4
5-7	785-2	0.039	14.9	89.8	0.74	3.61	7.35	19.6	16.3	0.41	83.0	30.1
5-7	786-1	0.031	14.8	82.2	1.4	2.84	6.40	25.4	16.1	0.39	75.9	29.0
5-8	793-1	0.032	12.7	109.2	0.89	3.89	6.70	23.2	17.8	0.82	91.2	25.2
5-1	799-1	0.042	6.1	102.9	1.30	6.30	8.68	71.1	15.0	0.41	83.4	17.1
5-2	817-1	0.040	8.2	105.6	1.8	3.85	6.15	42.6	14.2	0.84	91.0	22.0
5-2	817-2	0.034	9.4	103.7	1.1	4.00	6.32	27.81	14.2	0.84	88.9	22.0
5-2	818	0.039	5.3	103.5	1.8	3.30	5.61	33.3	14.5	1.05	88.5	18.3
5-4	826-1	0.034	11.4	86.9	1.8	3.68	6.18	40.9	18.3	0.74	74.6	25.0
5-4	827-2	0.027	7.5	88.7	2.0	3.20	7.08	45.3	16.1	1.25	76.3	19.4
5-4	828-1	0.021	10.0	80.9	0.9	3.10	5.68	15.85	13.9	1.25	69.5	23.1
5-5	837-1	0.033	15.1	88.9	0.7	3.00	5.50	11.6	15.0	1.25	80.0	30.7
5-5	837-2	0.030	8.2	106.4	1.5	3.00	5.36	24.1	15.0	1.32	95.7	20.3
5-5	837-4	0.022	7.5	92.8	1.8	3.10	5.48	30.6	15.0	1.32	83.6	20.1
5-5	838-1	0.039	9.2	91.7	1.50	3.30	5.62	27.8	14.2	1.32	82.7	22.4
5-5	838-3	0.028	9.6	88.6	1.8	2.85	5.20	26.7	14.2	1.32	79.9	22.8
7-7	377-1	0.029	0	117.2	2.00	1.68	3.54	11.9	13.0	1.45	98.0	13.0

Table 3

MULTIPLE LINEAR CORRELATION VALUES USING ELECTRONIC COMPUTER

Values in General Equation: $TF = a+b_1 PI+b_2D+b_3K'_\phi+b_4\sigma_\phi+b_5M_\phi+b_6K'_\phi\sigma_\phi M_\phi+b_7SL+b_8VS+b_9D\%$

σ_n = standard deviation of variable

Correlation	PI b_1	PI σ_1	Density b_2	Density σ_2	k'_ϕ b_3	k'_ϕ σ_3	σ_ϕ b_4	σ_ϕ σ_4	M_ϕ b_5	M_ϕ σ_5	$k'_\phi\sigma_\phi M_\phi$ b_6	$k'_\phi\sigma_\phi M_\phi$ σ_6	SL b_7	SL σ_7	VS b_8	VS σ_8	% maximum density b_9	% maximum density σ_9	a	Standard deviation	Correlation coefficient
1. Zone 2	0.00246	0.00046	0.00074	0.00010	0.00337	0.00106	-0.00122	0.00223	0.00223	0.00077									-0.05296	0.00336	0.91
Zone 3	0.00111	0.00041	0.00052	0.00015	0.00412	0.00280	0.00077	0.00308	0.00190	0.00133									-0.03268	0.00460	0.76
Zone 4	0.00202	0.00020	0.00025	0.00004	0.00802	0.00079	0.00366	0.00125	-0.00106	0.00096									-0.01559	0.00282	0.97
Zone 5	0.00125	0.00027	0.00046	0.00011	0.00530	0.00178	0.00182	0.00143	0.00007	0.00098									-0.03654	0.00552	0.66
All data	0.00099	0.00015	0.00029	0.00006	0.00432	0.00096	-0.00138	0.00102	0.00129	0.00070									-0.00880	0.00658	0.72
2. Zone 2	0.00311	0.00061			0.00306	0.00135	-0.00053	0.00282	0.00104	0.00094							0.00055	0.00012	-0.02937	0.00422	0.86
Zone 3	0.00127	0.00054			0.00404	0.00339	0.00110	0.00371	0.00124	0.00159							0.00048	0.00022	-0.02450	0.00556	0.62
Zone 4	0.00203	0.00018			0.00782	0.00069	0.00324	0.00109	-0.00142	0.00081							0.00031	0.00004	-0.01597	0.00244	0.98
Zone 5	0.00094	0.00024			0.00533	0.00180	0.00162	0.00143	0.00079	0.00099							0.00056	0.00013	-0.04102	0.00555	0.66
All data	0.00099	0.00015			0.00461	0.00096	-0.00074	0.00096	0.00116	0.00068							0.00036	0.00007	-0.01399	0.00652	0.73
3. Zone 2			0.00062	0.00015	0.00425	0.00143	0.00669	0.00212	0.00218	0.00105			-0.00066	0.00039					-0.03788	0.00455	0.83
Zone 3			0.00046	0.00018	0.00578	0.00341	0.00489	0.00392	0.00397	0.00145			0.00056	0.00051					-0.05478	0.00560	0.61
Zone 4			0.00016	0.00011	0.00799	0.00191	0.00923	0.00268	0.00454	0.00175			0.00076	0.00050					-0.04971	0.00677	0.80
Zone 5			0.00019	0.00011	0.00192	0.00209	0.00083	0.00185	0.00210	0.00117			0.00046	0.00046					-0.00883	0.00716	0.23
All data			0.00022	0.00007	0.00478	0.00118	0.00302	0.00122	0.00283	0.00078			0.00018	0.00023					-0.01877	0.00779	0.57
4. Zone 2					0.00399	0.00168	0.00888	0.00237	0.00114	0.00119			-0.00108	0.00043			0.00031	0.00015	0.00330	0.00534	0.76
Zone 3					0.00556	0.00404	0.00535	0.00467	0.00347	0.00168			0.00059	0.00061			0.00033	0.00024	-0.04028	0.00655	0.38
Zone 4					0.00783	0.00189	0.00891	0.00267	0.00438	0.00161			0.00075	0.00049			0.00022	0.00013	-0.05067	0.00667	0.80
Zone 5					0.00294	0.00200	0.00100	0.00173	0.00257	0.00111			0.00058	0.00043			0.00042	0.00015	-0.03302	0.00667	0.42
All data											No correlation										
5. Zone 2	0.00190	0.00077			0.00353	0.00168	0.00379	0.00333	-0.00032	0.00137					0.00589	0.00312			0.01151	0.00529	0.76
Zone 3	0.00069	0.00056			0.00257	0.00386	0.00260	0.00445	0.00038	0.00199					0.00412	0.00389			0.01526	0.00636	0.44
Zone 4	0.00179	0.00028			0.00856	0.00108	0.00589	0.00168	-0.00312	0.00126					0.00436	0.00181			0.00903	0.00390	0.94
Zone 5	0.00061	0.00029			0.00286	0.00232	0.00097	0.00217	0.00035	0.00126					-0.00070	0.00340			0.01964	0.00704	0.29
All data	0.00073	0.00016			0.00363	0.00102	0.00161	0.00102	-0.00002	0.00071					0.00518	0.00153			0.01437	0.00684	0.69
6. Zone 2	0.00162	0.00042	0.00059	0.00018							0.00035	0.00011			0.00320	0.00175	0.00003	0.00017	-0.03593	0.00339	0.91
Zone 3	0.00072	0.00040	0.00111	0.00037							0.00037	0.00016			0.00232	0.00215	-0.00084	0.00046	-0.00512	0.00404	0.82
Zone 4	0.00188	0.00020	0.00027	0.00025							0.00041	0.00005			-0.00153	0.00175	0.00012	0.00029	-0.01935	0.00347	0.95
Zone 5	0.00104	0.00023	0.00016	0.00023							0.00025	0.00006			0.00061	0.00194	0.00039	0.00029	-0.03375	0.00526	0.70
All data	0.00077	0.00011	-0.00009	0.00013							0.00021	0.00005			0.00502	0.00130	0.00040	0.00017	-0.00631	0.00636	0.74

Table 3--Continued

Correlation	PI b_1	PI σ_1	Density b_2	Density σ_2	k'_ϕ b_3	k'_ϕ σ_3	σ_ϕ b_4	σ_ϕ σ_4	M_ϕ b_5	M_ϕ σ_5	$k'_\phi \sigma_\phi M_\phi$ b_6	$k'_\phi \sigma_\phi M_\phi$ σ_6	SL b_7	SL σ_7	VS b_8	VS σ_8	% maximum density b_9	% maximum density σ_9	a	Standard deviation	Correlation coefficient
7. Zone 2	0.00216	0.00044	0.00053	0.00020											0.00412	0.00197	0.00011	0.00019	-0.03520	0.00388	0.88
Zone 3	0.00104	0.00044	0.00035	0.00043											0.00336	0.00245	-0.00071	0.00053	0.00076	0.00471	0.75
Zone 4	0.00170	0.00039	-0.00040	0.00046											0.00157	0.00338	0.00085	0.00055	-0.01318	0.00692	0.79
Zone 5	0.00095	0.00028	0.00032	0.00027											0.00000	0.00234	0.00001	0.00033	-0.00871	0.00638	0.50
All data	0.00093	0.00011	0.00001	0.00014											0.00531	0.00140	0.00025	0.00018	-0.00121	0.00686	0.69
8. Zone 2			0.00090	0.00020							0.00054	0.00012			0.00506	0.00205	-0.00023	0.00019	-0.04341	0.00414	0.86
Zone 3			0.00136	0.00038							0.00047	0.00016			0.00339	0.00224	-0.00126	0.00043	0.00758	0.00439	0.78
Zone 4			-0.00085	0.00053							0.00034	0.00013			0.00620	0.00371	0.00114	0.00066	0.00718	0.00836	0.66
Zone 5			-0.00036	0.00025							0.00022	0.00008			0.00011	0.00248	0.00081	0.00035	-0.00529	0.00675	0.40
All data			-0.00001	0.00016							0.00034	0.00005			0.00603	0.00156	0.00025	0.00020	0.00119	0.00766	0.59
9. Zone 2	0.00183	0.00042	0.00062	0.00019							0.00039	0.00011					0.00002	0.00017	-0.03432	0.00353	0.90
Zone 3	0.00084	0.00039	0.00112	0.00038							0.00041	0.00016					-0.00081	0.00046	-0.00615	0.00407	0.82
Zone 4	0.00179	0.00017	0.00022	0.00024							0.00039	0.00005					0.00016	0.00029	-0.01850	0.00345	0.95
Zone 5	0.00104	0.00023	0.00017	0.00022							0.00025	0.00006					0.00038	0.00028	-0.03256	0.00518	0.71
All data	0.00081	0.00011	-0.00005	0.00014							0.00022	0.00005					0.00037	0.00018	-0.00169	0.00678	0.70
10. Zone 2	0.00249	0.00042									0.00035	0.00013					0.00051	0.00011	-0.02053	0.00408	0.87
Zone 3	0.00130	0.00045									0.00033	0.00020					0.00046	0.00020	-0.01361	0.00513	0.69
Zone 4	0.00172	0.00015									0.00038	0.00005					0.00042	0.00006	-0.01896	0.00343	0.95
Zone 5	0.00094	0.00019									0.00026	0.00006					0.00057	0.00012	-0.03192	0.00514	0.71
All data	0.00081	0.00011									0.00022	0.00005					0.00030	0.00007	-0.00124	0.00675	0.70
11. Zone 2			0.00067	0.00014							0.00059	0.00013	-0.00060	0.00039					-0.02229	0.00449	0.84
Zone 3			0.00038	0.00017							0.00069	0.00021	0.00051	0.00049					-0.01831	0.00571	0.59
Zone 4			0.00013	0.00011							0.00045	0.00012	0.00124	0.00058					-0.00293	0.00848	0.65
Zone 5			0.00016	0.00011							0.00016	0.00008	0.00028	0.00044					0.01126	0.00717	0.22
All data			0.00017	0.00007							0.00033	0.00006	-0.00007	0.00020					0.01386	0.00820	0.51
12. Zone 2											0.00060	0.00016	-0.00110	0.00044			0.00038	0.00015	0.01736	0.00546	0.74
Zone 3											0.00064	0.00024	0.00049	0.00056			0.00025	0.00022	-0.00476	0.00635	0.44
Zone 4											0.00044	0.00012	0.00123	0.00057			0.00020	0.00014	-0.00756	0.00831	0.67
Zone 5											0.00021	0.00008	0.00035	0.00042			0.00036	0.00015	-0.00707	0.00679	0.38
All data											No correlation										
13. Zone 2	0.00243	0.00035	0.00066	0.00010	0.00276	0.00107													-0.03570	0.00372	0.89
Zone 3	0.00140	0.00035	0.00049	0.00015	0.00473	0.00270													-0.02071	0.00461	0.76
Zone 4	0.00207	0.00016	0.00032	0.00005	0.00657	0.00083													-0.01749	0.00347	0.95
Zone 5	0.00126	0.00025	0.00045	0.00011	0.00505	0.00175													-0.02875	0.00555	0.66
All data	0.00098	0.00010	0.00023	0.00005	0.00455	0.00097													-0.00005	0.00666	0.71

Table 3--Continued

Correlation	PI		Density		k'_ϕ		σ_ϕ		M_ϕ		$k'_\phi \sigma_\phi M_\phi$		SL		VS		% maximum density		a	Standard deviation	Correlation coefficient
	b_1	σ_1	b_2	σ_2	b_3	σ_3	b_4	σ_4	b_5	σ_5	b_6	σ_6	b_7	σ_7	b_8	σ_8	b_9	σ_9			
14. Zone 2	0.00252	0.00042	0.00056	0.00022													0.00010	0.00020	-0.03297	0.00410	0.87
Zone 3	0.00128	0.00042	0.00095	0.00044													-0.00065	0.00054	0.00008	0.00486	0.73
Zone 4	0.00179	0.00034	-0.00037	0.00045													0.00083	0.00054	-0.01391	0.00678	0.80
Zone 5	0.00095	0.00027	0.00032	0.00027													0.00001	0.00032	-0.00871	0.00627	0.52
All data	0.00099	0.00011	0.00005	0.00015													0.00021	0.00019	0.00393	0.00729	0.64
15. Zone 2			0.00098	0.00025											0.00786	0.00244	-0.00025	0.00024	-0.04662	0.00521	0.77
Zone 3			0.00131	0.00047											0.00558	0.00263	-0.00134	0.00053	0.02422	0.00546	0.64
Zone 4			-0.00135	0.00057											0.00826	0.00415	0.00168	0.00071	0.01037	0.00957	0.52
Zone 5			-0.00018	0.00026											-0.00039	0.00271	0.00044	0.00036	0.01485	0.00739	Imaginary
All data			0.00020	0.00018											0.00693	0.00178	-0.00007	0.00023	0.01318	0.00882	0.37
16. Zone 2	0.00181	0.00037	0.00064	0.00010							0.00039	0.00011							-0.03422	0.00347	0.91
Zone 3	0.00120	0.00036	0.00049	0.00014							0.00037	0.00017							-0.01869	0.00438	0.78
Zone 4	0.00183	0.00016	0.00036	0.00005							0.00040	0.00004							-0.01753	0.00338	0.95
Zone 5	0.00114	0.00022	0.00044	0.00010							0.00022	0.00006							-0.02630	0.00525	0.70
All data	0.00078	0.00011	0.00021	0.00006							0.00020	0.00005							0.00577	0.00688	0.69
17. Zone 2	0.00242	0.00038	0.00066	0.00011															-0.03247	0.00405	0.87
Zone 3	0.00153	0.00037	0.00045	0.00015															-0.01061	0.00493	0.72
Zone 4	0.00199	0.00033	0.00030	0.00010															-0.00773	0.00701	0.78
Zone 5	0.00096	0.00025	0.00034	0.00011															-0.00853	0.00617	0.54
All data	0.00096	0.00011	0.00021	0.00006															0.00807	0.00730	0.64
18. Zone 2	0.00306	0.00040															0.00054	0.00012	-0.02054	0.00446	0.84
Zone 3	0.00160	0.00044															0.00044	0.00021	-0.00753	0.00544	0.64
Zone 4	0.00192	0.00030															0.00040	0.00012	-0.01271	0.00672	0.80
Zone 5	0.00076	0.00023															0.00037	0.00014	-0.00584	0.00632	0.51
All data	0.00100	0.00011															0.00028	0.00008	0.00356	0.00726	0.65
19. Zone 2													-0.00168	0.00049			0.00038	0.00018	0.03697	0.00645	0.61
Zone 3													-0.00003	0.00062			0.00002	0.00025	0.03524	0.00756	Imaginary
Zone 4													0.00144	0.00072			0.00014	0.00018	0.00050	0.01062	0.31
Zone 5													0.00012	0.00044			0.00023	0.00015	0.01346	0.00733	0.08
All data													-0.00060	0.00020			0.00013	0.00009	0.03427	0.00910	0.29

Table 3--Continued

Correlation	PI		Density		k'_ϕ		σ_ϕ		M_ϕ		$k'_\phi \sigma_\phi M_\phi$		SL		VS		% maximum density		a	Standard deviation	Correlation coefficient
	b_1	σ_1	b_2	σ_2	b_3	σ_3	b_4	σ_4	b_5	σ_5	b_6	σ_6	b_7	σ_7	b_8	σ_8	b_9	σ_9			
20. Zone 2			0.00068	0.00017									-0.00114	0.00046					-0.00465	0.00563	0.73
Zone 3			0.00019	0.00021									-0.00001	0.00060					0.02080	0.00736	Imaginary
Zone 4			0.00005	0.00014									0.00143	0.00074					0.00809	0.01076	0.27
Zone 5			0.00011	0.00011									0.00011	0.00045					0.02228	0.00746	Imaginary
All data			0.00011	0.00008									-0.00055	0.00020					0.03445	0.00909	0.29
21. Zone 2	0.00306	0.00050			0.00274	0.00159													0.02238	0.00552	0.74
Zone 3	0.00099	0.00043			0.00326	0.00349													0.02569	0.00603	0.52
Zone 4	0.00161	0.00024			0.00634	0.00140													0.01674	0.00586	0.85
Zone 5	0.00066	0.00025			0.00260	0.00202													0.02390	0.00681	0.38
All data	0.00094	0.00011			0.00417	0.00103													0.02216	0.00714	0.66

<u>Notes</u>: PI = plasticity index.
D = density, lbs per square foot.
$k\phi$ = phi skewness.
6ϕ = phi standard deviation.
$M\phi$ = phi arithmetic mean diameter.
SL = shrinkage limit.
VS = vane shear, pounds per square foot.
D% = percent maximum density.

TABLE 3 A

CONTINUATION OF TABLE 3 -- MULTIPLE LINEAR CORRELATION VALUES USING ELECTRONIC COMPUTER
(LL) Liquid Limit is Added as an Independent Variable
Values in General Equation $TF = a+b_1PI+b_2D+b_3k'_\phi+b_4\sigma_\phi+b_5M_\phi+b_6k'_\phi\sigma_\phi M_\phi+b_7SL+b_8VS+b_9D\%+b_{10}LL$
σ_n = Standard Diviation of the Variable

Independent Variable

Correlation		PI		Density		k'_ϕ		σ_ϕ		M_ϕ		$k'_\phi\sigma_\phi M_\phi$		SL		VS		% Maximum Density		LL		a	Standard Deviation	Correlation Coefficient
		b_1	σ_1	b_2	σ_2	b_3	σ_3	b_4	σ_4	b_5	σ_5	b_6	σ_6	b_7	σ_7	b_8	σ_8	b_9	σ_9	b_{10}	σ_{10}			
22.	Zone 2	0.00376	0.00066																	-0.00077	0.00048	0.04402	0.00556	0.73
	Zone 3	-0.00091	0.00208																	0.00159	0.00160	-0.00011	0.00601	0.53
	Zone 4	0.00400	0.00200																	-0.00187	0.00151	0.05254	0.00803	0.70
	Zone 5	-0.00017	0.00126																	0.00059	0.00097	0.02154	0.00695	0.33
	All data	0.00074	0.00018																	0.00027	0.00020	0.02145	0.00761	0.60
23.	Zone 2	0.00286	0.00050	0.00063	0.00011															-0.00046	0.00035	-0.01926	0.00400	0.87
	Zone 3	0.00023	0.00179	0.00043	0.00016															0.00101	0.00135	-0.02804	0.00501	0.71
	Zone 4	0.00352	0.00177	0.00028	0.00010															-0.00119	0.00135	0.01214	0.00705	0.78
	Zone 5	0.00070	0.00117	0.00033	0.00011															0.00019	0.00089	-0.01032	0.00627	0.52
	All data	0.00050	0.00017	0.00031	0.00006															0.00072	0.00021	-0.01683	0.00696	0.68
24.	Zone 2	0.00361	0.00066			0.00244	0.00162													-0.00061	0.00049	0.03744	0.00548	0.74
	Zone 3	-0.00043	0.00231			0.00216	0.00397													0.00115	0.00183	0.00532	0.00617	0.49
	Zone 4	0.00335	0.00145			0.00615	0.00139													-0.00133	0.00109	0.03708	0.00579	0.86
	Zone 5	-0.00035	0.00124			0.00238	0.00206													0.00081	0.00097	0.01413	0.00685	0.36
	All data	0.00068	0.00017			0.00447	0.00103													0.00039	0.00019	0.01326	0.00703	0.67
25.	Zone 2	0.00299	0.00071									0.00039	0.00017							-0.00060	0.00046	0.03692	0.00522	0.77
	Zone 3	-0.00024	0.00221									0.00024	0.00026							0.00088	0.00178	0.01043	0.00604	0.52
	Zone 4	0.00335	0.00152									0.00035	0.00008							-0.00152	0.00114	0.04357	0.00608	0.84
	Zone 5	-0.00154	0.00128									0.00021	0.00008							0.00171	0.00100	0.00262	0.00641	0.49
	All data	0.00032	0.00019									0.00026	0.00005							0.00057	0.00020	0.01220	0.00701	0.68
26.	Zone 2	0.00243	0.00076											-0.00135	0.00047					0.00010	0.00053	0.05660	0.00500	0.79
	Zone 3	-0.00131	0.00220											-0.00035	0.00052					0.00193	0.00171	0.00049	0.00613	0.50
	Zone 4	0.00399	0.00213											0.00001	0.00066					-0.00186	0.00157	0.05221	0.00824	0.68
	Zone 5	-0.00008	0.00132											0.00012	0.00044					0.00052	0.00102	0.02030	0.00706	0.28
	All data	0.00061	0.00030											-0.00015	0.00027					0.00039	0.00029	0.02253	0.00764	0.60
27.	Zone 2	0.00340	0.00063													0.00668	0.00268			-0.00106	0.00046	0.04412	0.00513	0.78
	Zone 3	-0.00100	0.00202													0.00405	0.00299			0.00150	0.00156	-0.00277	0.00584	0.57
	Zone 4	0.00339	0.00205													0.00422	0.00357			-0.00150	0.00153	0.04261	0.00795	0.70
	Zone 5	-0.00036	0.00137													-0.00103	0.00274			0.00073	0.00105	0.02116	0.00705	0.28
	All data	0.00076	0.00017													0.00532	0.00149			0.00016	0.00020	0.01806	0.00721	0.65

Correlation	PI		Density		K'_ϕ		σ_ϕ		M_ϕ		$K'_\phi \sigma_\phi M_\phi$		SL		VS		% Maximum Density		LL		a	Standard Deviation	Correlation Coefficient
	b_1	σ_1	b_2	σ_2	b_3	σ_3	b_4	σ_4	b_5	σ_5	b_6	σ_6	b_7	σ_7	b_8	σ_8	b_9	σ_9	b_{10}	σ_{10}			
28. Zone 2	0.00385	0.00049															0.00056	0.00011	-0.00087	0.00036	-0.00092	0.00414	0.86
Zone 3	0.00029	0.00203															0.00041	0.00022	0.00100	0.00151	-0.02391	0.00555	0.62
Zone 4	0.00346	0.00169															0.00038	0.00012	-0.00119	0.00129	0.00711	0.00675	0.80
Zone 5	0.00092	0.00124															0.00038	0.00015	-0.00012	0.00094	-0.00496	0.00642	0.49
All data	0.00069	0.00017															0.00032	0.00008	0.00047	0.00020	-0.01058	0.00710	0.66
29. Zone 2			0.00085	0.00015															0.00086	0.00037	-0.06893	0.00569	0.72
Zone 3			0.00042	0.00015															0.00118	0.00027	-0.03080	0.00484	0.73
Zone 4			0.00031	0.00011															0.00145	0.00027	-0.02915	0.00755	0.74
Zone 5			0.00031	0.00011															0.00071	0.00019	-0.01399	0.00620	0.54
All data			0.00037	0.00006															0.00119	0.00013	-0.03093	0.00719	0.65
30. Zone 2			0.00085	0.00014	0.00356	0.00156													0.00102	0.00036	-0.07652	0.00533	0.76
Zone 3			0.00045	0.00015	0.00371	0.00284													0.00107	0.00028	-0.03591	0.00472	0.75
Zone 4			0.00033	0.00006	0.00677	0.00101													0.00154	0.00015	-0.04129	0.00424	0.93
Zone 5			0.00042	0.00010	0.00518	0.00177													0.00096	0.00019	-0.03703	0.00556	0.65
All data			0.00042	0.00005	0.00578	0.00090													0.00131	0.00011	-0.04604	0.00611	0.77
31. Zone 2	0.00278	0.00052	0.00072	0.00010	0.00315	0.00106	-0.00089	0.00222	0.00239	0.00077									-0.00039	0.00031	-0.04250	0.00331	0.91
Zone 3	0.00154	0.00191	0.00053	0.00016	0.00446	0.00327	0.00076	0.00322	0.00194	0.00141									-0.00034	0.00150	-0.02777	0.00482	0.73
Zone 4	0.00241	0.00075	0.00025	0.00005	0.00793	0.00083	0.00372	0.00128	-0.00082	0.00107									-0.00033	0.00061	-0.01148	0.00288	0.97
Zone 5	-0.00113	0.00122	0.00044	0.00010	0.00611	0.00174	0.00372	0.00166	-0.00014	0.00093									0.00188	0.00094	-0.06271	0.00524	0.70
All data	0.00007	0.00023	0.00037	0.00006	0.00579	0.00092	0.00152	0.00108	0.00059	0.00064									0.00110	0.00022	-0.04354	0.00591	0.78
32. Zone 2	0.00379	0.00064			0.00258	0.00127	-0.00026	0.00263	0.00142	0.00089							0.00056	0.00011	-0.00082	0.00036	-0.01248	0.00393	0.88
Zone 3	0.00143	0.00238			0.00416	0.00400	0.00109	0.00389	0.00125	0.00168							0.00049	0.00024	-0.00012	0.00183	-0.02275	0.00583	0.57
Zone 4	0.00236	0.00064			0.00775	0.00072	0.00329	0.00112	-0.00122	0.00091							0.00031	0.00005	-0.00027	0.00052	-0.01249	0.00249	0.97
Zone 5	-0.00066	0.00131			0.00574	0.00181	0.00288	0.00174	0.00061	0.00099							0.00052	0.00013	0.00126	0.00101	-0.05543	0.00550	0.66
All data	0.00026	0.00023			0.00573	0.00095	0.00178	0.00112	0.00049	0.00066							0.00039	0.00007	0.00003	0.00022	-0.03687	0.00613	0.76
33. Zone 2	0.00258	0.00081			0.00296	0.00162	0.00417	0.00317	-0.00011	0.00131					0.00689	0.00301			-0.00093	0.00047	0.03164	0.00503	0.79
Zone 3	-0.00094	0.00248			0.00133	0.00436	0.00273	0.00457	0.00017	0.00206					0.00448	0.00402			0.00133	0.00196	-0.00803	0.00652	0.39
Zone 4	0.00162	0.00110			0.00860	0.00114	0.00587	0.00173	-0.00323	0.00149					0.00443	0.00194			0.00014	0.00089	0.00719	0.00402	0.93
Zone 5	-0.00224	0.00156			0.00422	0.00234	0.00293	0.00234	0.00014	0.00121					-0.00173	0.00331			0.00227	0.00122	-0.01257	0.00675	0.39
All data	0.00007	0.00025			0.00460	0.00102	0.00398	0.00123	-0.00067	0.00071					0.00532	0.00146			0.00074	0.00023	-0.00405	0.00655	0.72

Correlation	PI		Density		K'_ϕ		σ_ϕ		$M\phi$		$K'_\phi \sigma_\phi M_\phi$		SL		VS		% Maximum Density		LL		e	Standard Deviation	Correlation Coefficient
	b_1	σ_1	b_2	σ_2	b_3	σ_3	b_4	σ_4	b_5	σ_5	b_6	σ_6	b_7	σ_7	b_8	σ_8	b_9	σ_9	b_{10}	σ_{10}			
34. Zone 2	0.00238	0.00055	0.00042	0.00019							0.00029	0.00011			0.00441	0.00177	0.00018	0.00018	-0.00066	0.00033	-0.01801	0.00322	0.92
Zone 3	0.00046	0.00170	0.00111	0.00039							0.00036	0.00019			0.00236	0.00227	-0.00085	0.00048	0.00020	0.00130	-0.00822	0.00424	0.80
Zone 4	0.00287	0.00089	0.00024	0.00025							0.00040	0.00005			-0.00173	0.00174	0.00015	0.00029	-0.00076	0.00067	-0.00665	0.00344	0.95
Zone 5	-0.00094	0.00117	0.00029	0.00023							0.00030	0.00006			-0.00104	0.00210	0.00019	0.00030	0.00160	0.00092	-0.04723	0.00509	0.72
All data	0.00001	0.00019	0.00031	0.00015							0.00029	0.00005			0.00335	0.00124	0.00004	0.00017	0.00102	0.00022	-0.03414	0.00580	0.79
35. Zone 2	0.00308	0.00053	0.00030	0.00021											0.00556	0.00187	0.00029	0.00019	-0.00091	0.00035	-0.01064	0.00353	0.90
Zone 3	-0.00070	0.00176	0.00101	0.00043											0.00336	0.00245	-0.00081	0.00054	0.00132	0.00129	-0.02048	0.00470	0.75
Zone 4	0.00333	0.00179	-0.00044	0.00047											0.00113	0.00342	0.00087	0.00055	-0.00125	0.00134	0.00735	0.00695	0.78
Zone 5	0.00063	0.00142	0.00035	0.00030											-0.00028	0.00267	-0.00002	0.00038	0.00025	0.00111	-0.01025	0.00648	0.47
All data	0.00055	0.00019	0.00026	0.00017											0.00438	0.00142	0.00002	0.00020	0.00056	0.00023	-0.01556	0.00671	0.71
36. Zone 2	0.00231	0.00060	0.00052	0.00020							0.00036	0.00012					0.00010	0.00019	-0.00037	0.00034	-0.02384	0.00352	0.90
Zone 3	0.00077	0.00168	0.00112	0.00039							0.00041	0.00018					-0.00081	0.00048	0.00006	0.00130	-0.00707	0.00425	0.80
Zone 4	0.00269	0.00087	0.00019	0.00024							0.00039	0.00005					0.00019	0.00029	-0.00070	0.00066	-0.00685	0.00344	0.95
Zone 5	-0.00068	0.00103	0.00026	0.00022							0.00029	0.00006					0.00024	0.00028	0.00139	0.00081	-0.04709	0.00502	0.73
All data	-0.00008	0.00019	0.00040	0.00015							0.00031	0.00005					-0.00002	0.00017	0.00119	0.00021	-0.03621	0.00596	0.78
37. Zone 2	0.00323	0.00053									0.00030	0.00013					0.00053	0.00010	-0.00073	0.00034	-0.00404	0.00384	0.88
Zone 3	0.00138	0.00209									0.00033	0.00023					0.00046	0.00021	-0.00006	0.00164	-0.01266	0.00534	0.66
Zone 4	0.00272	0.00086									0.00037	0.00005					0.00041	0.00006	-0.00077	0.00065	-0.00605	0.00340	0.95
Zone 5	-0.00053	0.00103									0.00030	0.00006					0.00055	0.00012	0.00116	0.00079	-0.04375	0.00505	0.73
All data	0.00017	0.00017									0.00031	0.00005					0.00040	0.00007	0.00088	0.00018	-0.02952	0.00613	0.76
38. Zone 2	0.00268	0.00048	0.00064	0.00011	0.00254	0.00111													-0.00026	0.00034	-0.02783	0.00374	0.89
Zone 3	0.00145	0.00189	0.00049	0.00016	0.00476	0.00320													-0.00003	0.00147	-0.02017	0.00479	0.74
Zone 4	0.00279	0.00088	0.00031	0.00005	0.00648	0.00084													-0.00055	0.00067	-0.00807	0.00350	0.95
Zone 5	0.00067	0.00105	0.00044	0.00011	0.00517	0.00178													0.00046	0.00080	-0.03349	0.00561	0.65
All Data	0.00037	0.00015	0.00038	0.00005	0.00548	0.00088													0.00095	0.00018	-0.03477	0.00596	0.78

APPENDIX I

EQUIPMENT AND PROCEDURE FOR PERFORMING TRACTIVE FORCE TEST ON COHESIVE MATERIALS

Tractive force or boundary shear may be defined as the force per unit area exerted by a fluid flowing past a stationary boundary. The force, acting on the surface of the boundary in the direction of flow, is dependent on flow conditions and the roughness characteristics of the boundary material. In an earth canal, tractive force is a primary agent tending to cause erosion.

For every earth material there is a critical tractive force or range of tractive forces above which erosion will occur and below which the material will remain essentially stable.

The magnitude of this critical tractive force is dependent upon the properties of the soil, including cohesion, size and shape of soil particles, range and distribution of particle sizes, and various unknown physical and chemical properties. The determination of critical tractive forces has, in the past, depended to a considerable extent on the judgment of the observer. In some cases, initial movement of individual grains has been the criterion, whereas in other cases the criterion has been the beginning of general bed movement. In calibrating the tractive force tank, the experimenters tended toward the latter criterion.

During the last two decades, numerous experiments have established for noncohesive materials a fairly consistent relationship between critical tractive force and the mean diameter of particles composing the bed material. The majority of these experiments have been performed with uniform sand and gravels. However, no satisfactory relationship between tractive force and soil properties has been obtained for cohesive materials, although it has been conceded that cohesive soils are generally more resistant to erosion than are noncohesive soils.

The primary purpose of this laboratory investigation was to obtain data to assist in development of canal design criteria for cohesive soils based on the tractive force theory. However, the test may be adopted as a standard test for determining the erosion resistance of soils, especially those soils proposed for use as canal lining material. The test may also be used to evaluate the stabilizing effect of chemical or other additives.

TEST APPARATUS

Description of Equipment

The tractive force test apparatus, including tank, motor, plastic lid, impeller, pressure gage, and pressure regulator is shown in Figure 1. Water is circulated in the cylindrical tank through rotation of the impeller. The plastic lid was added to confine the water surface and improve visibility. Pertinent data regarding basic components are:

1. Tank

   a. Diameter = 35 inches

   b. Total height = 24 inches

   c. Height from sample surface to tank top = 13-3/8 inches

   d. Height from sample surface to bottom of plastic lid = 9 inches

   e. Depth of water used = 12 inches

2. Three-blade impeller

   a. Blade width = 3 inches

   b. Blade length = 17 inches

   c. Distance from sample surface to bottom of blade = 4-1/2 inches

3. Sample test well

   a. Width = 12 inches

   b. Length = 15 inches

   c. Depth = 10 inches

4. Sample container is a standard 8-inch-diameter plastic percolation test cylinder.

5. Plastic lid is made of 3/8-inch clear plastic.

6. Pressure gage reads from 0 to 100 pounds per square inch.

7. Pressure regulator variable from 0 to 70 pounds per square inch.

8. The power source is a converted compressed air drill.

Additional equipment required for this test includes two stopwatches, one for accurate determination of the rotational velocity and the other for determining the time required for testing at each velocity increment. A thermometer for reading the water temperature and various tools such as trowels, screwdrivers, etc., also are needed.

Calibration of Test Apparatus

A bank of four pitot tubes, mounted as shown in Figure 2, was used to determine magnitude and distribution of velocities occurring near the surface of the sample. The sample surface was represented by a smooth plastic plate set flush with the floor of the tank. It was assumed the logarithmic velocity distribution law applies in the immediate vicinity of the boundary.

Static pressures were read from static pressure taps in the pitot tubes and at piezometer taps across the plastic lid. At given verticals there was close agreement between measured static pressures.

From preliminary tests the tendency of sand and gravel particles to deposit near the center of the tank indicated a secondary circulation similar to that found in open channel flow around curves. The resultant direction of velocity components was checked by means of short lengths of string fastened at three levels at various points across the sample. The levels ranged from 0 to 1-3/4 inches above the sample surface. Figure 3 shows the strings oriented along lines closely following arcs from the center of the tank. Orientation of the strings remained essentially the same over the entire range of rotational velocities. It was concluded that effects of secondary currents were minor in comparison to primary currents. Pitot tubes were alined with the mean direction of flow indicated by the strings.

Readings on the pressure gage were correlated with rotational velocities of the impeller. The purpose of this correlation was to provide a basis for immediate determination of rotational velocities. Results of the correlation are plotted in Figure 4.

As a direct method for measuring boundary shear was not available, the rotational velocities required to move uniform sands and gravel were determined. The tractive force required to move these sands and gravels was known. The procedure followed was essentially the same as that presented under the heading "Performing the Test".

Figure 5 is a photograph of sands and gravels used in the tests. Table 1 shows their source location and size range. Results of these calibration tests are plotted in Figure 6.

Analysis of Calibration

Relation of critical tractive force to mean diameter of material is given in Figure 7. A relationship between rotational velocity of the impeller blade and resulting tractive force was established by combining calibration results shown in Figure 6 with this critical tractive force. The combination results in the equation $T_o = 0.000146\ V_r^2$

where

T_o = tractive force acting on sample, lb/ft^2

V_r = rotational velocity of impeller blade, rpm

It is apparent that tractive force varies with distance from the center of the tank. During calibration runs with noncohesive materials, erosion was concentrated near the outer edge of the sample at a distance of approximately 1.15 feet from the center of the tank (1.75 inches from outer edge of sample). Therefore, the equation applies only for the radial distance (r) equal to 1.15 feet.

As shear varies with the square of the velocity, distribution of shear across the sample was determined with the aid of the velocity distribution obtained from the pitot banks. The distribution indicated that at r = 1.15 feet, velocity of the water near the boundary was approximately 0.85 times the velocity of the blade, or $V_w = 0.85\ V_b$. Combining equations with the V_w/V_r ratio for r = 1.15 feet results in:

$$V_b = \frac{1.15\ (2\pi)}{60}\ V_r$$

and

$$T_o = 0.000146\ (8.30)^2\ V_b^2$$

as

$$V_b = \frac{V_w}{0.85}$$

$$T_o = 0.000146\ \frac{(8.30)^2}{(0.85)^2}\ V_w^2$$

and

$$T_o = 0.0140\ V_w^2$$

where

> V_w is the velocity of flow in ft/sec near the boundary as determined by the pitot tubes

letting

$$C = 0.0140\ \left(\frac{V_w}{V_r}\right)^2$$

and combining with the preceding equation results in $T_o = CV_r^2$. C is a factor which varies with the radial distance.

The variation of C across the sample is shown in Figure 8, in which the radial distance is expressed in terms of x, the distance in inches from the outer edge of the sample.

Figure 9 may be used to estimate the magnitude of the tractive force at any point on the sample area for various rotational velocities. The zones corresponding to 2-inch increments of the x distance are as defined on the figure. It is doubtful whether the tractive force should be estimated to more than two significant figures.

TEST PROCEDURE

The procedures recommended for performing the tractive force test on samples of cohesive soil are based primarily on experience gained from preliminary tests. Consequently, the recommended procedures should be considered as tentative and subject to revision pending the gaining of additional experience. The foregoing reservation applies particularly to some of the quantitative testing criteria.

The recommended procedure together with a sample data sheet are presented in the following pages.

Preparation for Test

Preparation of the sample involves saturation of the material and smoothing the surface prior to beginning the test. Approximately 1-week total immersion should be sufficient to saturate most samples. After removing the sample from the immersion tank, the surface should be smoothed off so as to be flush with the flange of the 8-inch percolation settlement cylinder. A trowel, putty knife, straight edge, or other suitable instrument may be used for this purpose. The cylinder may now be placed in the sample well of the tractive force tank. Care should be taken to fill cracks such as those between the cylinder flange and the sample well cover with modeling clay in order to obtain a smooth transition between the floor of the tank and the sample surface.

The tank is next filled with water to the level indicated by the black line on the wall of the tank. At this point, the water temperature is taken.

Performing the Test

The ultimate aim of the test is to determine, in terms of the rotational velocity of the impeller blade, the tractive force required to cause erosion of the sample. The test procedure consists essentially of approaching the critical rotational velocity in systematic steps between which the velocity is held constant over specified intervals of time. Rotational velocities are expressed in revolutions per minute and are determined by counting the number of revolutions of the impeller blade occurring in a period of from 30 to 60 seconds as timed with a stopwatch. A second stopwatch is used to provide a continuous time record of the test. The rotational velocity may be set fairly accurately to a predetermined magnitude by means of the pressure-regulator valve and pressure gage in accordance with the calibration curve shown in Figure 4. Velocities should always be varied by turning the pressure-regulator valve. The line valve is left open during the test.

The way in which the critical rotational velocity is approached constitutes an important part of the test. Increasing the velocity by large steps precludes the possibility of accurately determining the critical rotational velocity. However, if the velocity increments are too small, excessive time is consumed in performing the test. It is recommended that velocity increments be varied from a maximum of 5 to a minimum of 1 revolutions per minute, with increments becoming progressively smaller as the critical condition is approached. Between steps, the velocity should be increased gradually, as a sudden acceleration may prematurely precipitate an unstable condition. Upon attainment, the desired rotational velocity should be held constant for a period of from 5 to 10 minutes before increasing the velocity another step.

When the critical rotational velocity is reached, erosion tends to begin quite suddenly and to progress rapidly. This is true for sandy clay, lean clay, and plastic clay. There should be little question as to whether or not the critical condition has been reached.

When it becomes apparent that critical rotational velocity has been attained or surpassed, the test should be stopped. The valve should be closed, the tank drained, and the lid removed. The distance from the outer edge of the sample to the center of the eroded area should be measured in inches and recorded as shown on the sample data sheet.

Summary of Procedure

In performing a laboratory test, it is easy to overlook details or to omit steps which may have a significant bearing on the outcome of the test. Errors or omissions can sometimes be avoided by frequent reference to a check list which summarizes test procedures. It is recommended the following outline be used as such a check list.

A. Preparations for test

1. Preparation of sample

a. Saturate (1-week immersion)

b. Smooth surface of sample

c. Place cylinder in sample well

d. Insure smooth transition between tank floor and surface of sample by filling cracks with modeling clay

2. Fill tank to indicated level

3. Take temperature of water

B. Performing the test

1. Open line valve

2. Start Stopwatch No. 2

3. Open pressure regulator valve (gradually until gage registers 3 pounds per square inch) (about 10 revolutions per minute)

a. Check revolutions per minute with Stopwatch No. 1

b. Observe sample 5 to 10 minutes, writing down pertinent observations

c. Record cumulative time registered on Stopwatch No. 2 and increase velocity gradually to next step

4. Repeat Step 3, each time increasing the velocity by increments varying from 5 down to 1 revolutions per minute, as many times as necessary until critical condition is reached and general erosion begins

5. Record time on Stopwatch No. 2, shut off valve, drain tank, and remove lid

6. Measure x distance (from outer edge of sample to center of eroded area)

SAMPLE DATA SHEET

Material Description--CL Mod. Plasticity
Laboratory Sample No. ________
Temperature, 16.5° C

Revs. / secs.	V_r rpm	P psi	Cum. time, min.	Observations
10/56.0	10.7	3.0		No perceptible movement
10/55.4			5	
10/41.3	14.5	4.0		Not much change. A few loose sand particles leaving at first. Surface of sample still stable
10/41.0	14.6		10	
10/31.1	19.3	6.0		No significant change. A few loose sand particles left at first
10/32.0	18.8		18	
20/52.2	23.0	8.0		No perceptible movement. All loose sand particles seem to have left
20/51.9	23.1		26	
20/48.8	24.6	9.0		No perceptible change
20/48.8	24.6		36	
20/45.8	26.2	10.0		No perceptible change
20/46.0	26.1		46	
20/43.8	27.4	10.8		Surface of sample appeared stable at first. Small chunk broke loose after 3 minutes. Chunks continued to leave. Water becoming cloudy. Sizable cavity formed after 5 minutes at this speed. Past critical tractive force. Test stopped after 6 minutes
20/43.6	27.5		52	
				Critical V_r = 27 rpm

Upon completion of a tractive force test, the critical rotational velocity and the x - distance are known. Critical tractive force may be determined with the aid of Figure 9. Suppose, for example, the critical rotational velocity for a particular sample was 34 revolutions per minute, and the distance from the outer edge of the cylinder to the center of the eroded area measured 3 inches. According to the foregoing definitions, V_r = 34 revolutions per minute and x = 3 inches. The value of C in Figure 8 corresponding to x = 3 inches is 0.00013. Using Equation 1, the critical tractive force would then be:

$$T_o = CV_r^2$$

$$= 0.00013 \times (34)^2 = 0.15 \text{ lb/ft}^2$$

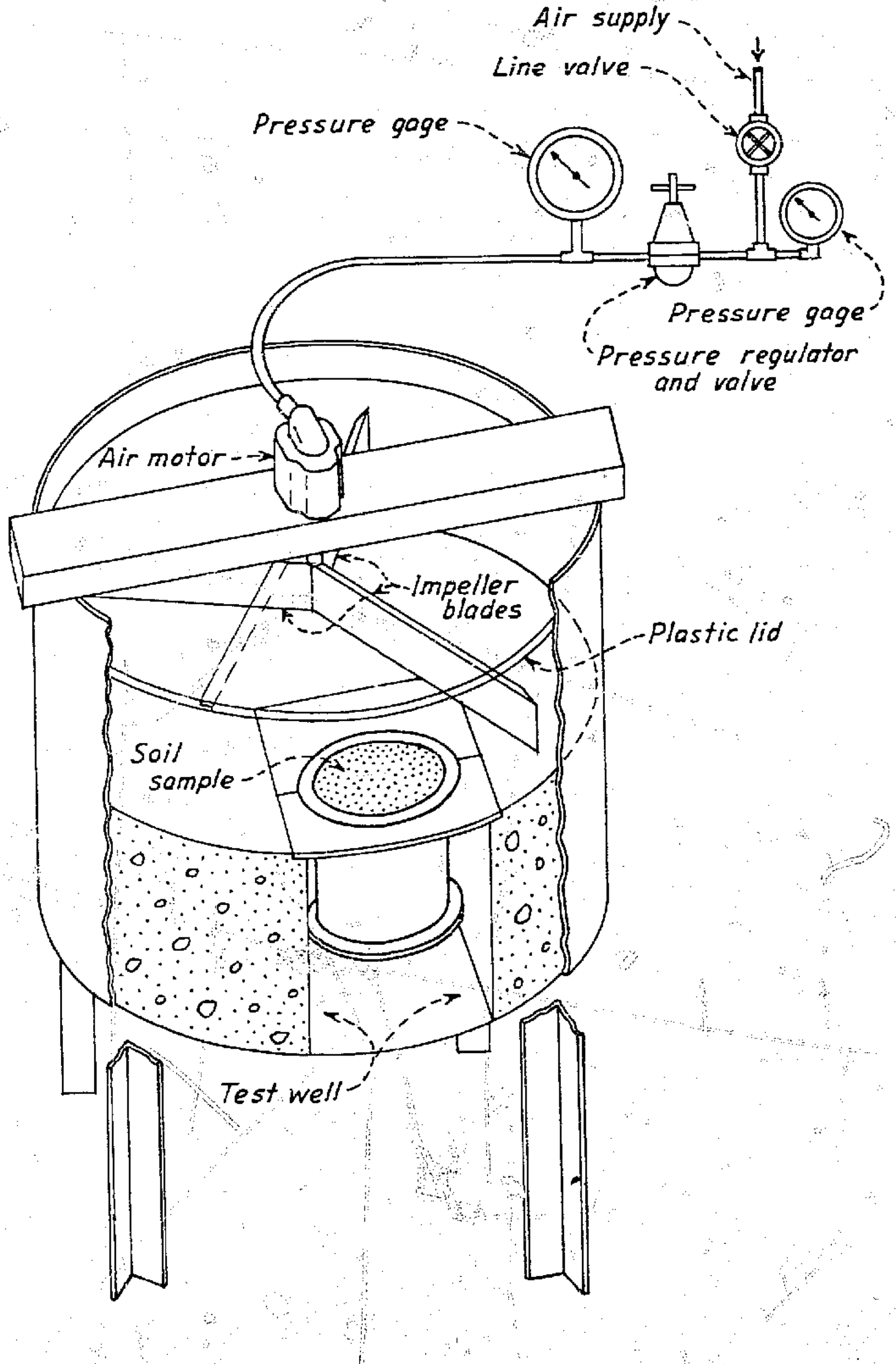
Figure 9 may be used for a direct estimation of the critical tractive force. In Figure 9, the sample is divided into four zones which correspond closely to 2-inch increments of the x - distance. Repeating the above example with V_r = 34 revolutions per minute and x = 3 inches, it is seen that the center of the eroded area lies in the center of Zone 2. Entering Figure 4 with V_r = 34 revolutions per minute, the tractive force at the center of Zone 2 is seen to be 0.15 pound/foot^2 which agrees with the method based on Figure 8. Considering assumptions made in evaluating calibration data, it would seem the critical tractive force can be estimated with sufficient accuracy from Figure 4.

Table 1

SANDS AND GRAVELS USED IN CALIBRATING TRACTIVE FORCE TANK

No.	Source	Particle diameter, mm
1	Clear Creek	0.59 - 0.71
2	Clear Creek	1.19 - 1.41
3	Clear Creek	2.38 - 2.83
4	Colorado River	2.38 - 2.83
5	Clear Creek	4.00 - 4.76
6	Colorado River	4.00 - 4.76
7	Clear Creek	7.93 - 9.42
8	Colorado River	7.93 - 9.42
9	Clear Creek	15.9 - 19.1
10	Colorado River	15.9 - 19.1

FIGURE I



TRACTIVE FORCE FIELD AND LABORATORY STUDY

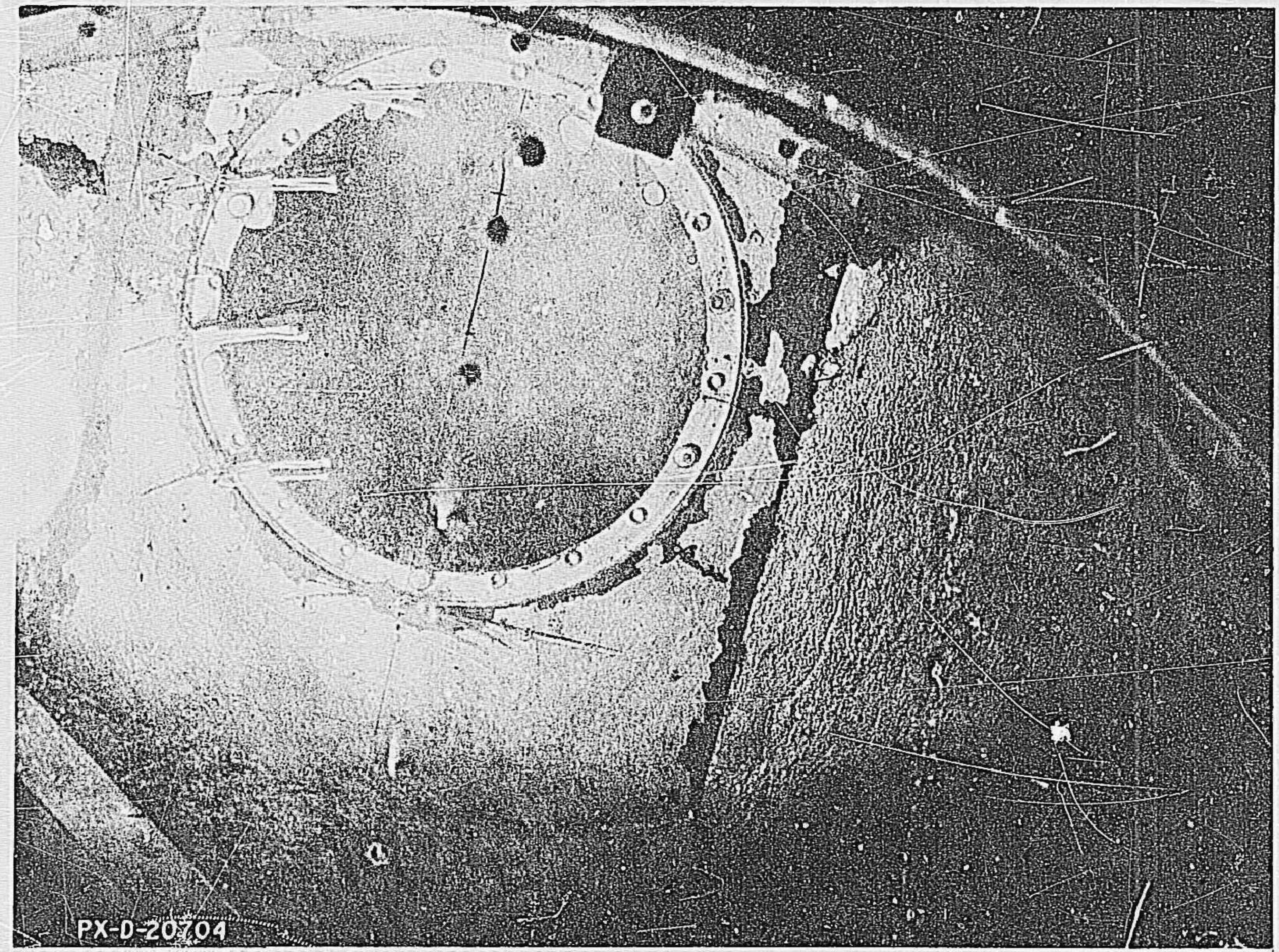
TRACTIVE FORCE TEST TANK

550

Figure 2

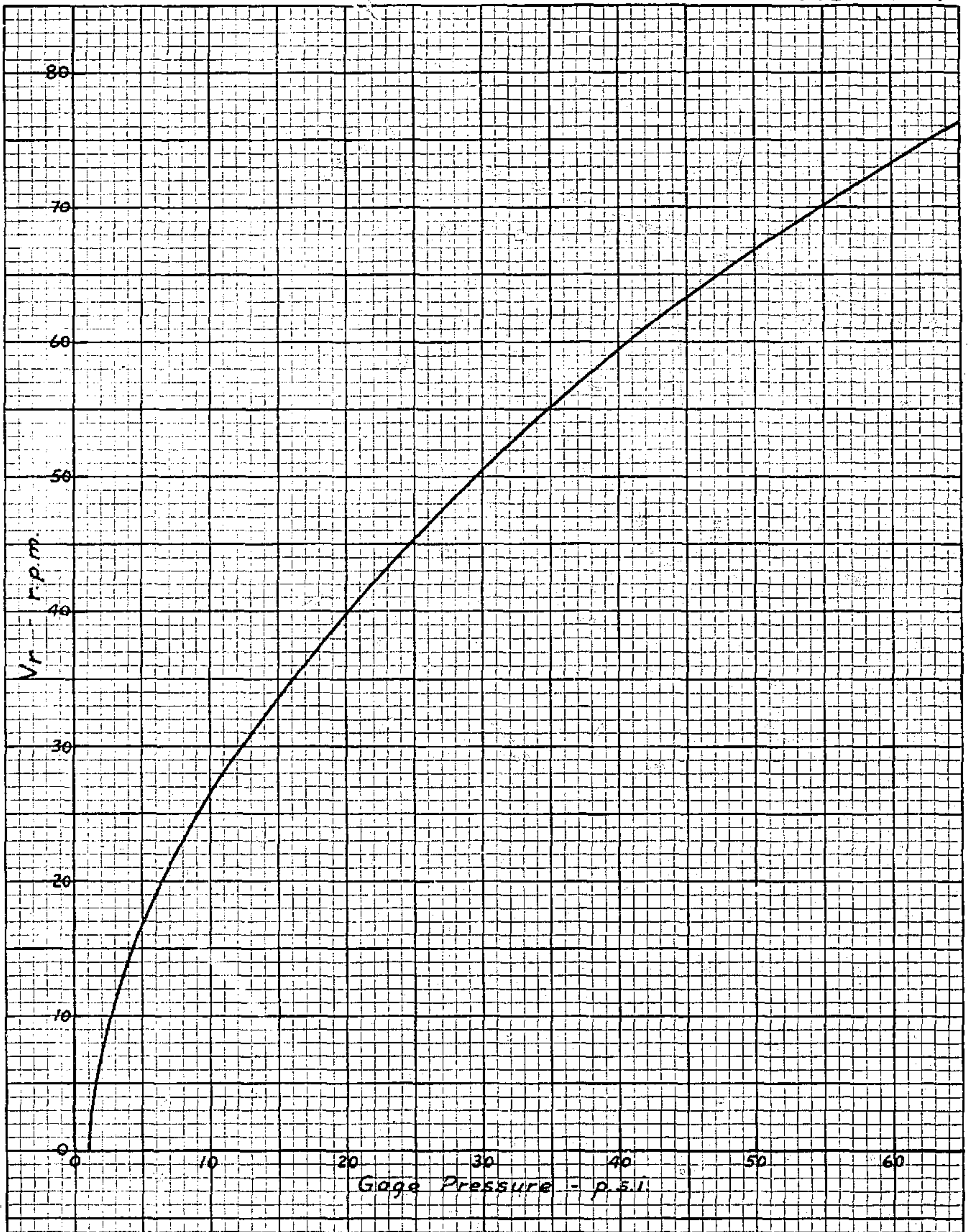
TRACTIVE FORCE FIELD AND LABORATORY STUDY
ARRANGEMENT FOR CALIBRATING TRACTIVE
FORCE TANK

Figure 3



TRACTIVE FORCE FIELD AND LABORATORY STUDY
STRINGS SHOWING DIRECTION OF FLOW ACROSS SAMPLE IN
TRACTIVE FORCE TANK - V_r = 24.5 rpm

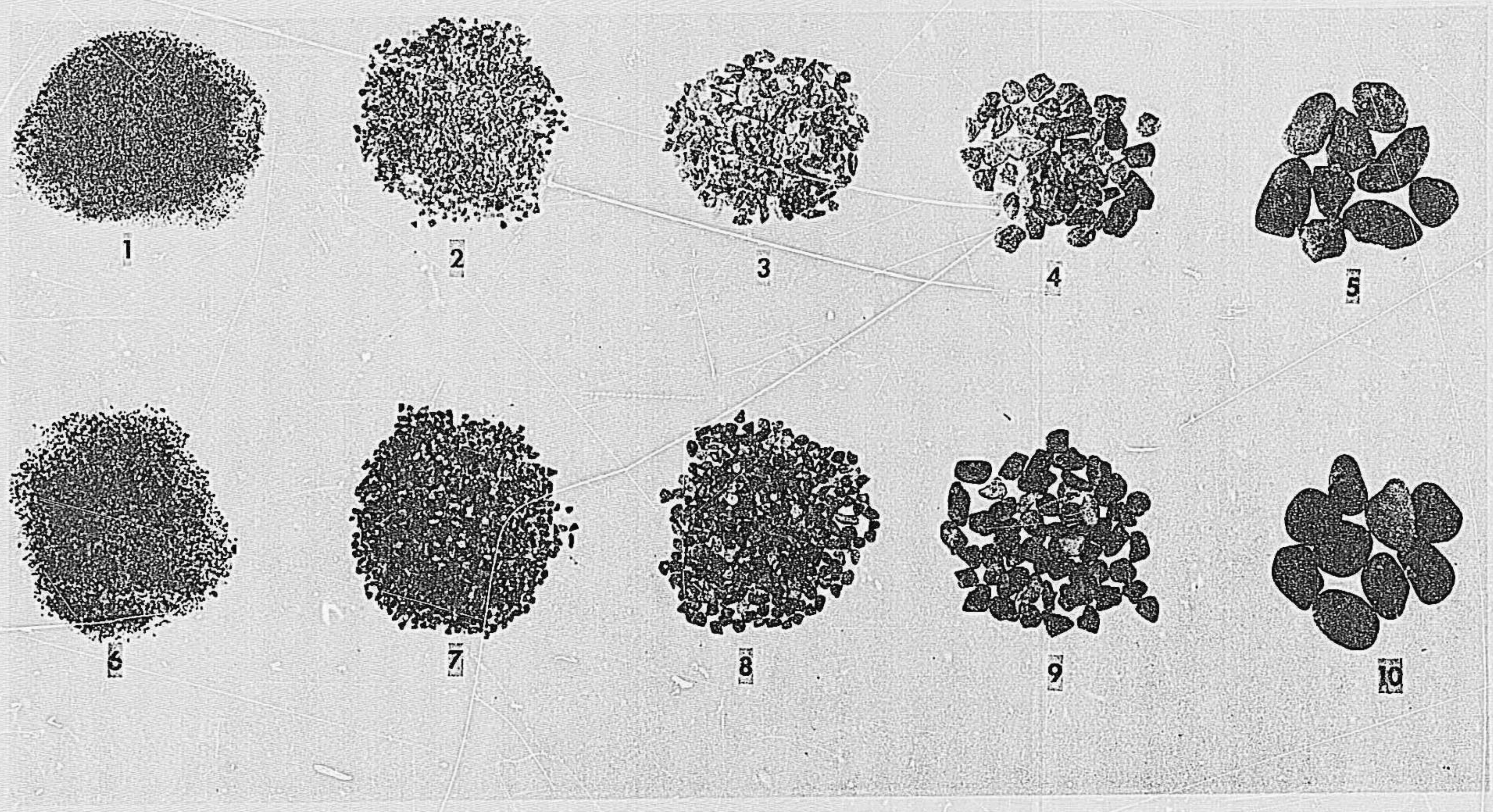
FIGURE 4



TRACTIVE FORCE FIELD AND LABORATORY STUDY

VARIATION OF IMPELLER BLADE SPEED WITH GAGE PRESSURE

Figure 5



TRACTIVE FORCE FIELD AND LABORATORY STUDY
SANDS AND GRAVELS USED IN CALIBRATING THE TRACTIVE FORCE TANK

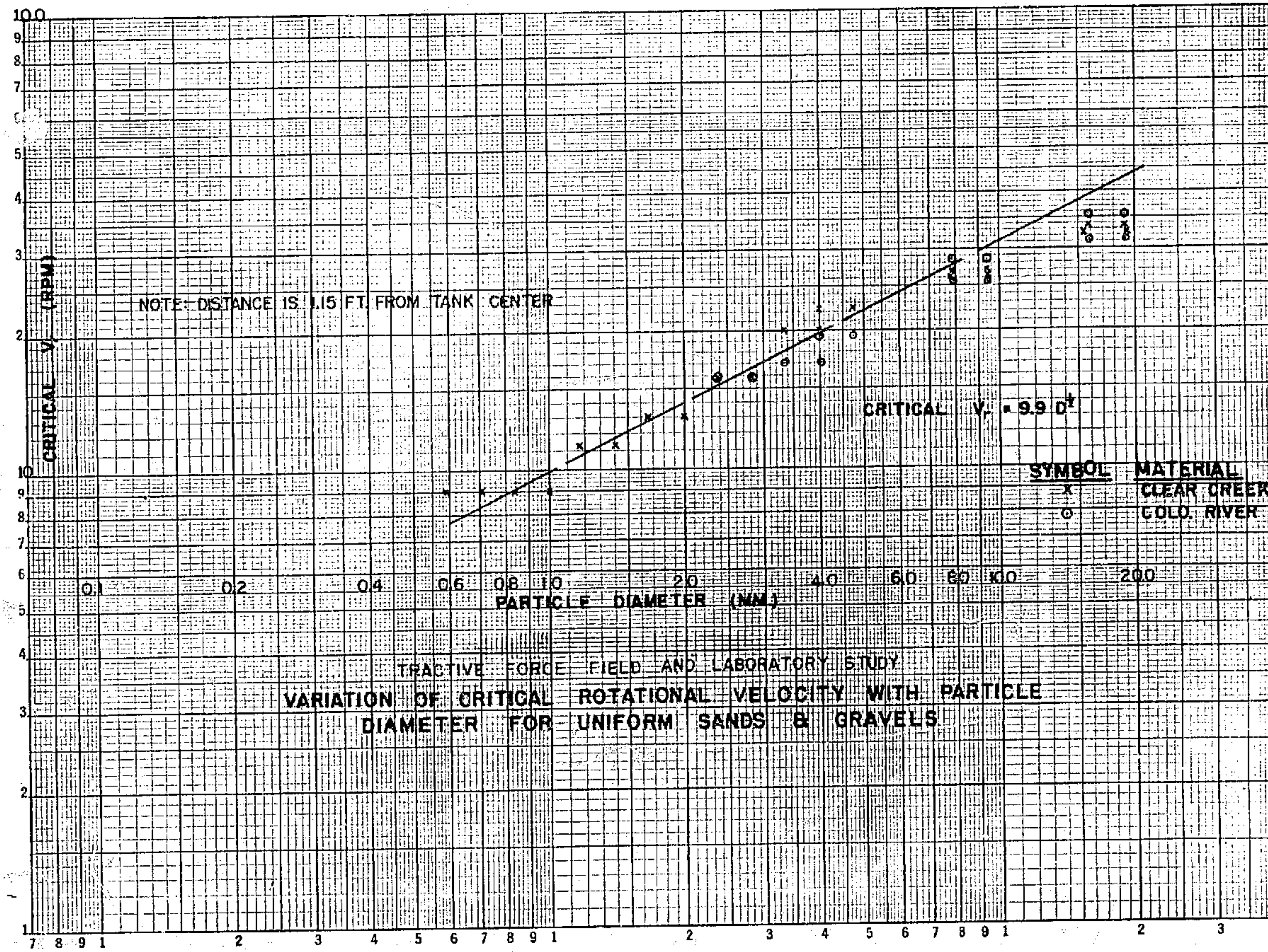
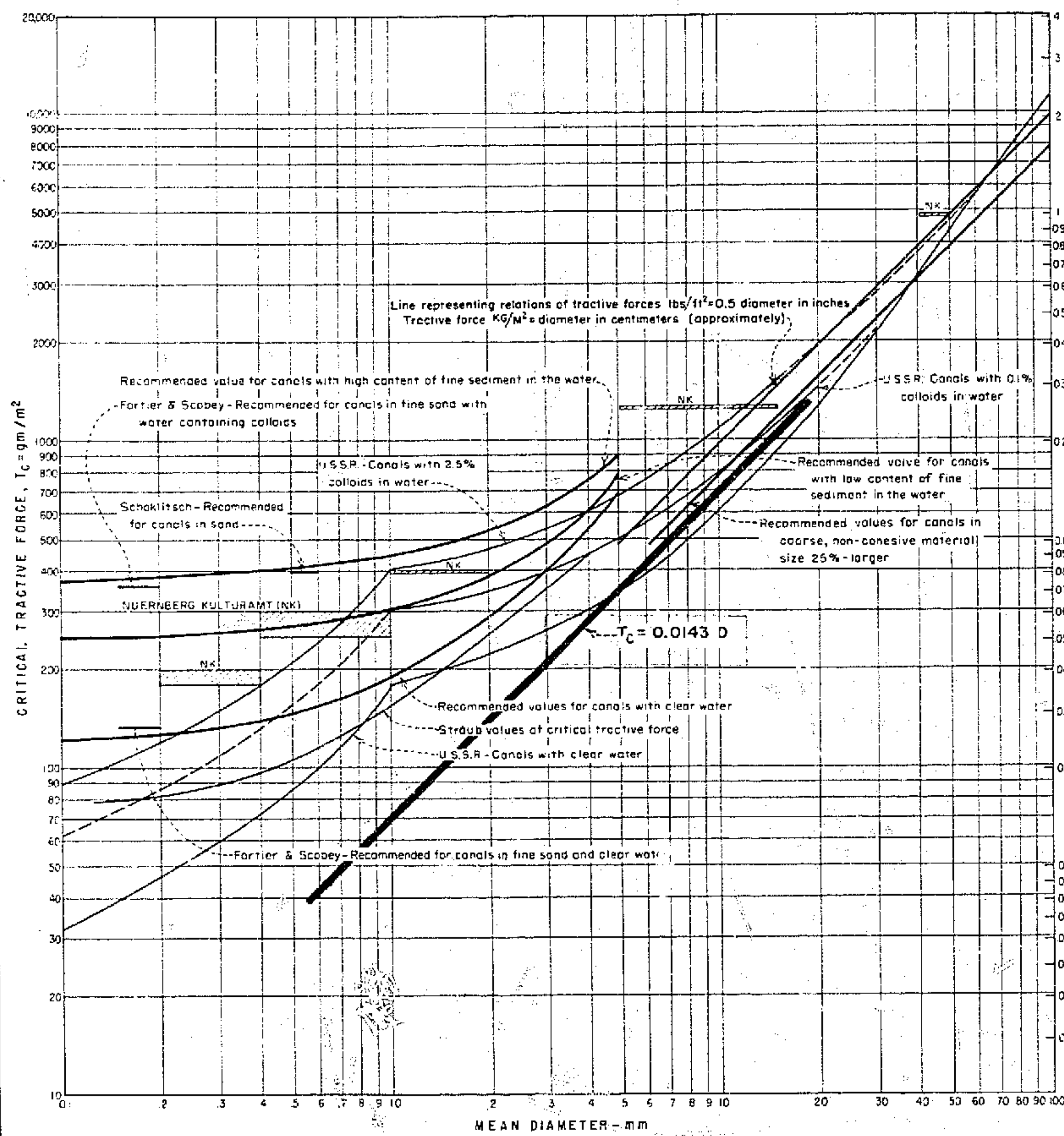

CRITICAL V, (RPM)
NOTE: DISTANCE IS 1.15 FT. FROM TANK CENTER
CRITICAL V, = 9.9 D¼
SYMBOL MATERIAL
X CLEAR CREEK
⊙ COLO. RIVER
0.1 0.2 0.4 0.6 0.8 1.0 2.0 4.0 6.0 8.0 10.0 20.0
PARTICLE DIAMETER (MM.)
TRACTIVE FORCE FIELD AND LABORATORY STUDY
VARIATION OF CRITICAL ROTATIONAL VELOCITY WITH PARTICLE
DIAMETER FOR UNIFORM SANDS & GRAVELS

FIGURE 6

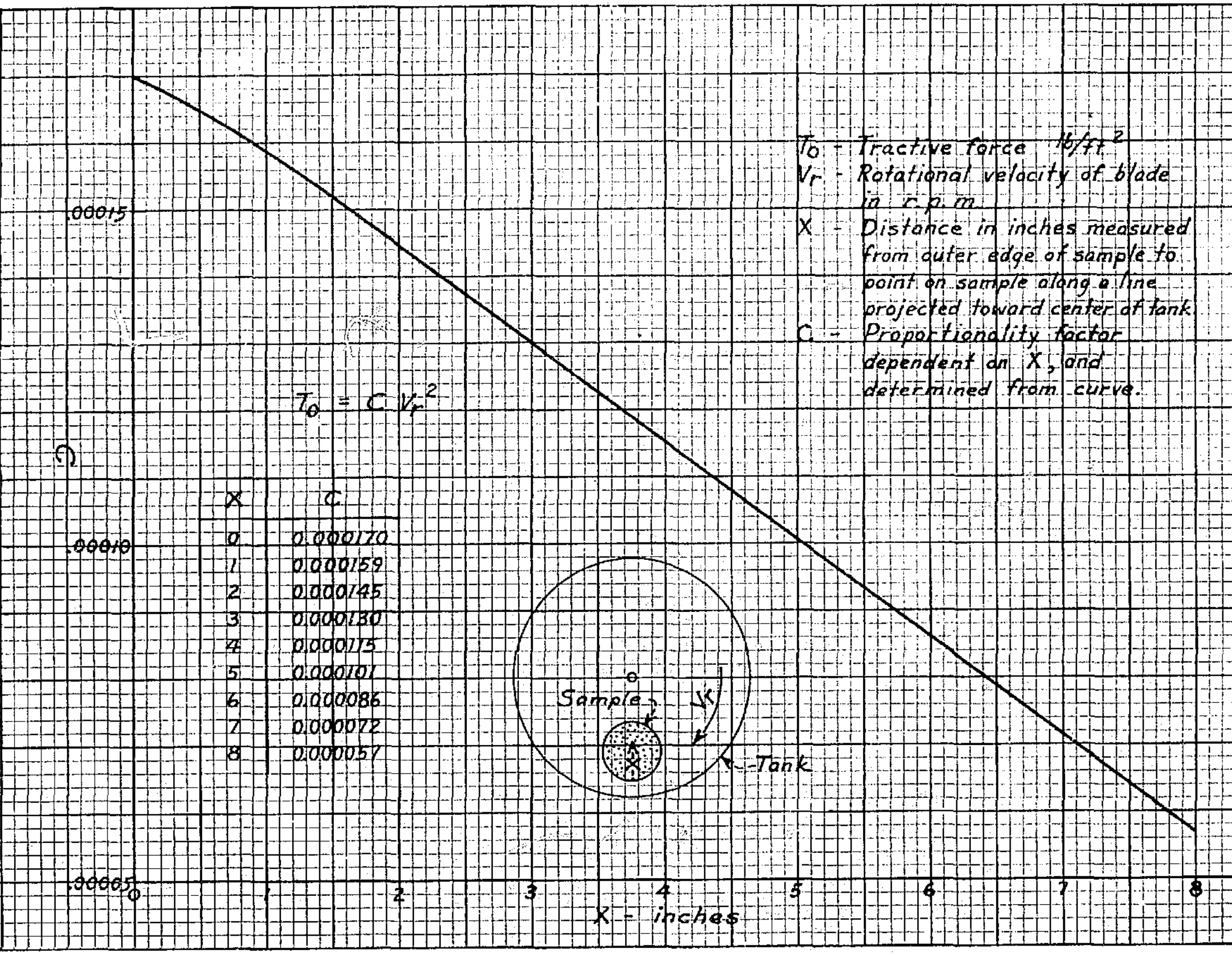


TRACTIVE FORCE FIELD AND LABORATORY STUDY

LIMITING TRACTIVE FORCES

RECOMMENDED FOR CANALS

FIGURE 8

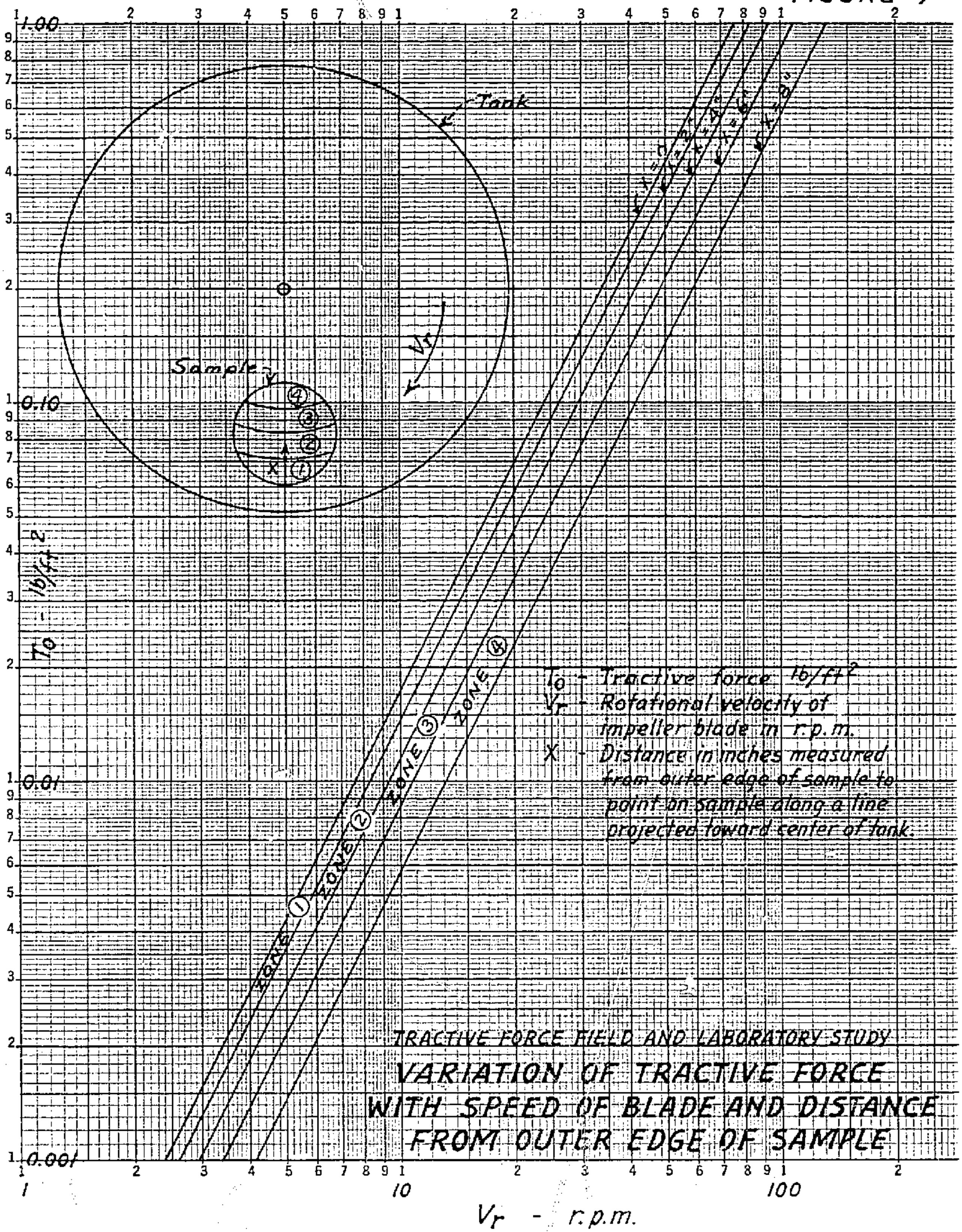


X	C
0	0.000170
1	0.000159
2	0.000145
3	0.000130
4	0.000115
5	0.000101
6	0.000086
7	0.000072
8	0.000057

TRACTIVE FORCE FIELD AND LABORATORY STUDY

DISTRIBUTION OF TRACTIVE FORCE ACROSS SAMPLE

FIGURE 9



TRACTIVE FORCE FIELD AND LABORATORY STUDY

VARIATION OF TRACTIVE FORCE WITH SPEED OF BLADE AND DISTANCE FROM OUTER EDGE OF SAMPLE

APPENDIX II

A LOGARITHMIC-PROBABILITY GRAPH METHOD FOR DESCRIPTION OF MECHANICAL ANALYSIS OF SOILS USED IN TRACTIVE FORCE STUDY

Particle sizes of cohesive soils are not uniform. Generally, a sample is analyzed and the results are plotted on standard paper as percent in weight passing a given sieve size versus particle size. By inspection, it is intuitively felt there is some law which governs the variability of sizes. Listing a few generalities regarding a given soil sample, we find: 1. Particle sizes are usually confined to a certain range. 2. Some size intervals contain many grains, while other size intervals contain only a few grains. 3. There is always one size interval which contains the largest number of particles. 4. For all other size intervals there will be fewer particles, their numbers decreasing toward the ends of the size ranges. A mathematical law which describes these generalities is immediately recognized as the mathematical probabilities normal density function or normal frequency curve (1)*. The problem is to find a fast and convenient way of expressing this law with regards to size analysis. While the function may be expressed in several ways, one given by Krumbein (2) in terms of the ordinate y and the independent variable x is

$$y = \frac{1}{\sigma_x \sqrt{2\pi}} e^{\frac{-(x-M_x)^2}{2\sigma_x^2}} \qquad (1)$$

where M_x is the arithmetic mean of the x values and σ_x is their standard deviation. A general plot of a curve of this nature is shown in Figure 1.

By general observations, we see that if the number of particles belonging to a general area is large, the effect of a misclassification of a particle is small. However, if the number of particles belonging to an area is very small, as is the case near the ends of the curve, the effect of misclassification of a particle may be very large. We also note that the Normal Frequency Curve is bell shaped and symmetrical about its mean value, M_x.

*Numbers in parentheses refer to Bibliography at end of Appendix.

In 1938, Krumbein (2) introduced a new variable into the normal frequency curve:

$$\phi = -\log_2 \xi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where

ξ = the diameter in mm

ϕ = a new variable = the negative $\log_2$ of ξ

M_ϕ = its arithmetic mean (the phi mean)

σ_ϕ = its standard deviation (the phi standard deviation)

These were substituted into Equation 1, and a normal phi curve was defined as:

$$y = \frac{1}{\sigma_\phi \sqrt{2\pi}} e^{\frac{-(\phi - M_\phi)^2}{2\sigma_\phi^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Krumbein then treats this curve similar to the Gaussian curve (Normal Frequency Curve). The negative logarithm to the Base 2 was chosen to simplify the geometric grade scales; i. e., if class intervals are of the range 2-1, 1-1/2, 1/2-1/4, 1/4-1/8 millimeter, etc., then $-\log_2 2 = -1$, $-\log_2 1 = 0$, $-\log_2 1/2 = +1$, $-\log_2 1/4 = +2$, etc. The negative log was used in the definition of ϕ because there are more fine-grained than coarse-grained soils.

Using the idea of Krumbein, and a method presented by Otto (5), the Hydraulic Laboratory designed a modified logarithmic probability graph for the interpretation of mechanical analyses of sediments in 1950. The mechanical analysis shown on Figure 2, is plotted as Curve 1, on a sheet of the special graph paper in Figure 3. The curve in Figure 3 is plotted in a manner similar to that in Figure 2; the sieve size, or geometric mean diameter is plotted against the percentage finer or percentage coarser. The percentage finer or coarser scale is a probability scale and the geometric mean size a logarithmic scale. The method of determining parameters from the graph paper follows.

DETERMINATION OF PARAMETERS IN PHI PROBABILITY GRAPH
Refer to Figure 3

To Obtain M_ϕ: (phi arithmetic mean diameter)

Draw a straight line AB connecting the intersections of the fitted curve and the 15.9 and 84.1 percent dotted lines. 68.2 percent of the weight of the material falls between the values 15.9 to 84.1. This is the range for one standard deviation each side of the geometric mean or two standard deviations. Where the 50 percent line crosses the line AB, draw a horizontal line CD intersecting the diameter scale used in plotting the analysis. Read off the value of M = 1.11, on the arithmetic phi scale and the corresponding geometric mean diameter, 0.469 millimeter, from the geometric scale.

ϕ is any diameter defined by the expresssion
$\phi = -\log_2 \xi$ where ξ is the diameter in millimeters

To Obtain $\sigma\phi$: (phi standard deviation)

Draw a line HF parallel to AB through the center of the small circle near the middle of the graph. Extend the line HF to the phi standard deviation scale on the same side of the graph as the scale used for plotting the analysis. The σ_ϕ scale is the slant scale along the lower left corner of the graph. Read the value of σ_ϕ, = 1.2, at the intersection of line EF with the scale.

To Obtain k_ϕ: (phi skewness)

Set a pair of dividers to the length GH on the vertical 4 percent line between its intersection with the EF and the horizontal line passing through the circle at the middle of the graph. Next, lay off the distance DI, equal to GH, on the 50 percent line starting at its intersection with the line AB. From Point I draw a horizontal line IJ intersecting the fitted curve. Read the percentage 91.2 percent at the intersection. On the k_ϕ scale near the lower right corner of the graph read the value of skewness -1.6, corresponding to the percentage just obtained. Similarly, locate I' and J' and determine the k_ϕ' value, -0.84, from the left corner of the graph.

INTERPRETATION OF ANALYSES

The value of M_ϕ is an indication of the position of the curve on the graph. For the sample in Figure 2, M_ϕ = 1.11 and the corresponding geometric mean diameter = 0.469 millimeter. It will be noted that the geometric mean diameter is not the diameter at which 50 percent by weight is larger and 50 percent smaller. As the mean size becomes smaller, the value of M_ϕ becomes greater and as the value of the mean particle size increases M_ϕ approaches zero or becomes negative. On standard gradation charts, an increase in value of M_ϕ will move the gradation curve to the left, while a decrease in value of M_ϕ will move the curve to the right.

As may be seen from a close study of the phi probability graph, a variation in σ_ϕ is a measure of distribution, or scatter of the particles about the median. In other words, σ_ϕ is a measure of the frequency of size range of particles present. For the example σ_ϕ = 1.2 This value is shown plotted on Figure 2, as 1.2 to each side of the mean. As the size range present between 84.1 and 15.9 percent becomes smaller, the numerical value of σ_ϕ decreases, and as the size range between 84.1 and 15.9 percent becomes greater, σ_ϕ increases.

Variation in the k_ϕ values describe changes in the shape of the curves. k_ϕ describes the tail of the curve in the region where particle size is largest. In general, as the percentage of coarse material increases k_ϕ tends to relatively large negative values. On standard gradation analysis paper, this would result in a flattening of the upper end of the curve, and the curve above the 50 percent size would tend to have a more pronounced S shape. As the percentage of coarse material decreases, k_ϕ tends to a relatively large positive value, and on standard paper, the curve tends to become straighter above the 50 percent size range.

k'_ϕ values describe the tail of the curve in the region of small particles. Generally, as the percentage of fine material increases, k'_ϕ tends to relatively large positive values. On the standard gradation paper, this would result in a flattening of the lower end of the curve, and the curve would tend to have a more pronounced S shape below the 50 percent size. As the percent of fine material decreases, k'_ϕ tends to negative values, and on standard analysis paper, the curve tends to become straighter. It may also be observed that if a straight line fits all the plotted points, the skewness is zero or k_ϕ and k'_ϕ equal zero. Values of k_ϕ for the example are shown on Figure 2.

Obviously, these data are not directly applicable to every type curve, but from the previous discussion, it is evident that if phi probability data are known the gradation curve on standard gradation paper can usually be rapidly sketched.

BIBLIOGRAPHY TO APPENDIX II

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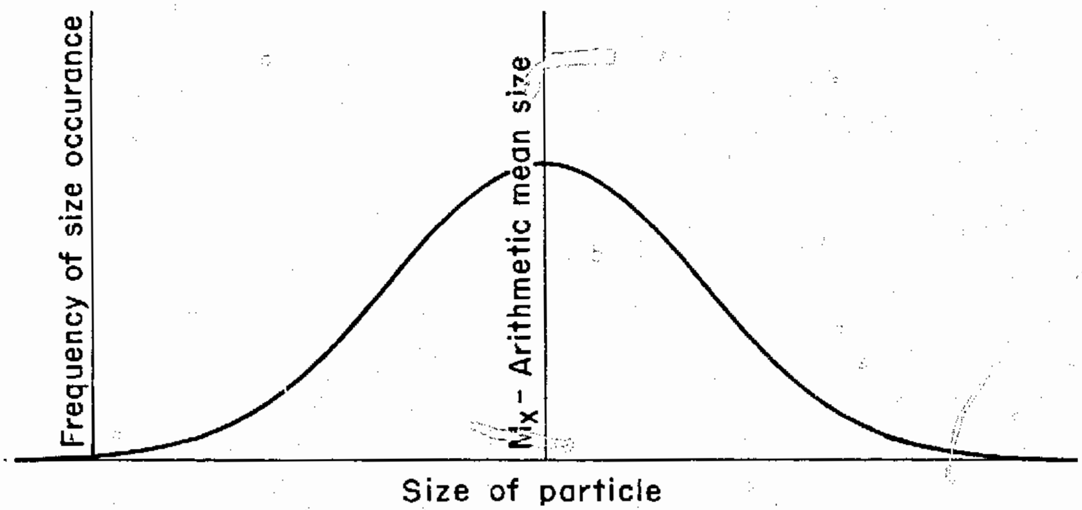
Table 1

TABLE FOR PLOTTING SIZE ANALYSIS OF SEDIMENTS USING LOG-PROBABILITY METHOD

Size mm	U. S. Standard sieve series	Ø units $-Log_2$ (size in mm)
0.001		9.97
0.002		8.96
0.005		7.65
0.009		6.80
0.019		5.71
0.037		4.76
0.074	200	3.75
0.149	100	2.77
0.297	50	1.75
0.590	30	0.76
1.19	16	0.253
2.38	8	-1.25
4.76	4	-2.25
9.52	3/8 inch	-3.25
19.1	3/4 inch	-4.26
38.1	1-1/2 inches	-5.26
76.2	3 inches	-6.26
127.0	5 inches	-6.99
152.0	6 inches	-7.26
200.0	8 inches	-7.66

FIGURE I



NORMAL FREQUENCY CURVE

(3-53)
Bureau of Reclamation

FIGURE 2

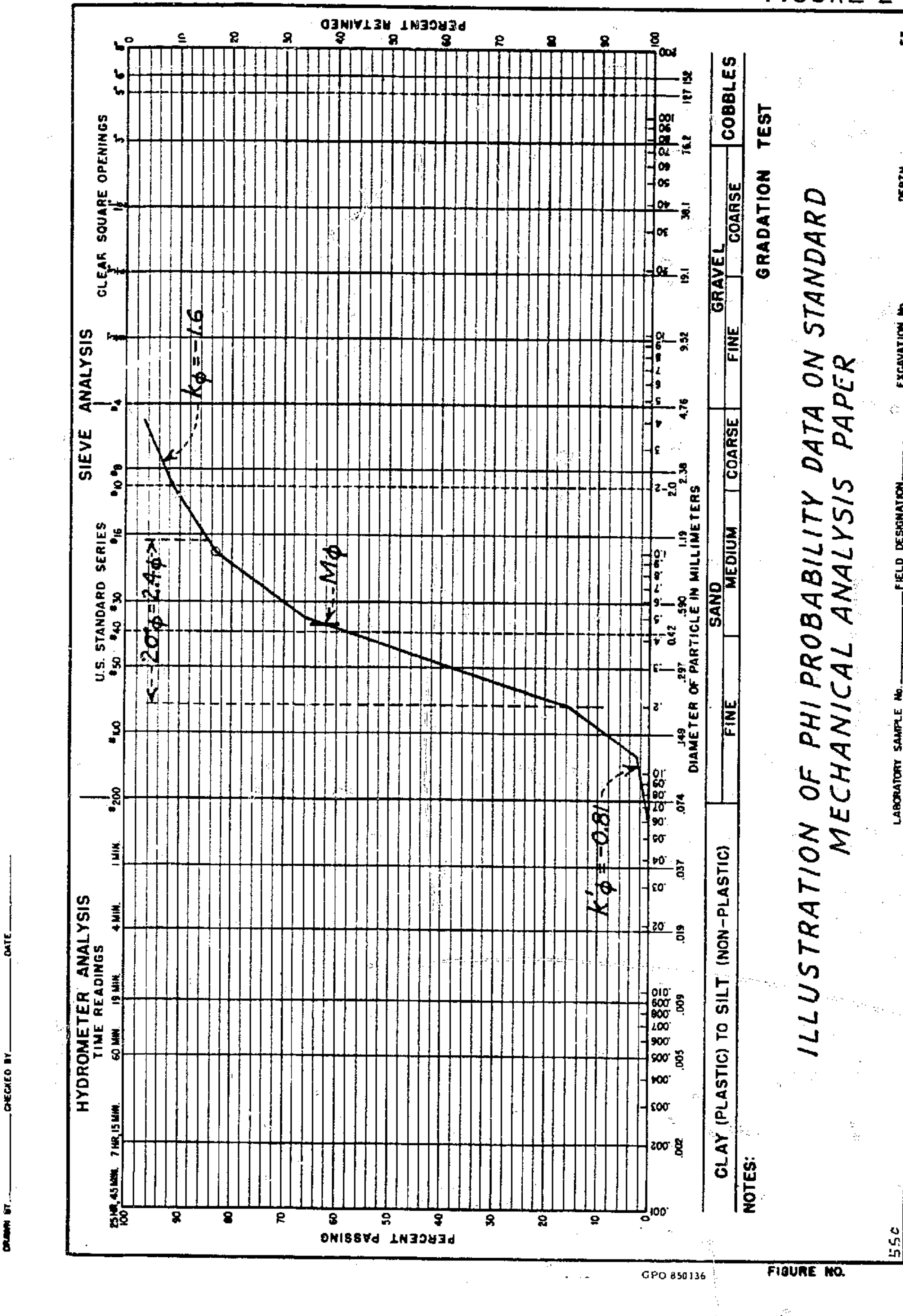


ILLUSTRATION OF PHI PROBABILITY DATA ON STANDARD MECHANICAL ANALYSIS PAPER

GPO 850136

FIGURE NO.

EL-103
(2-59)
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PHI PROBABILITY GRAPH

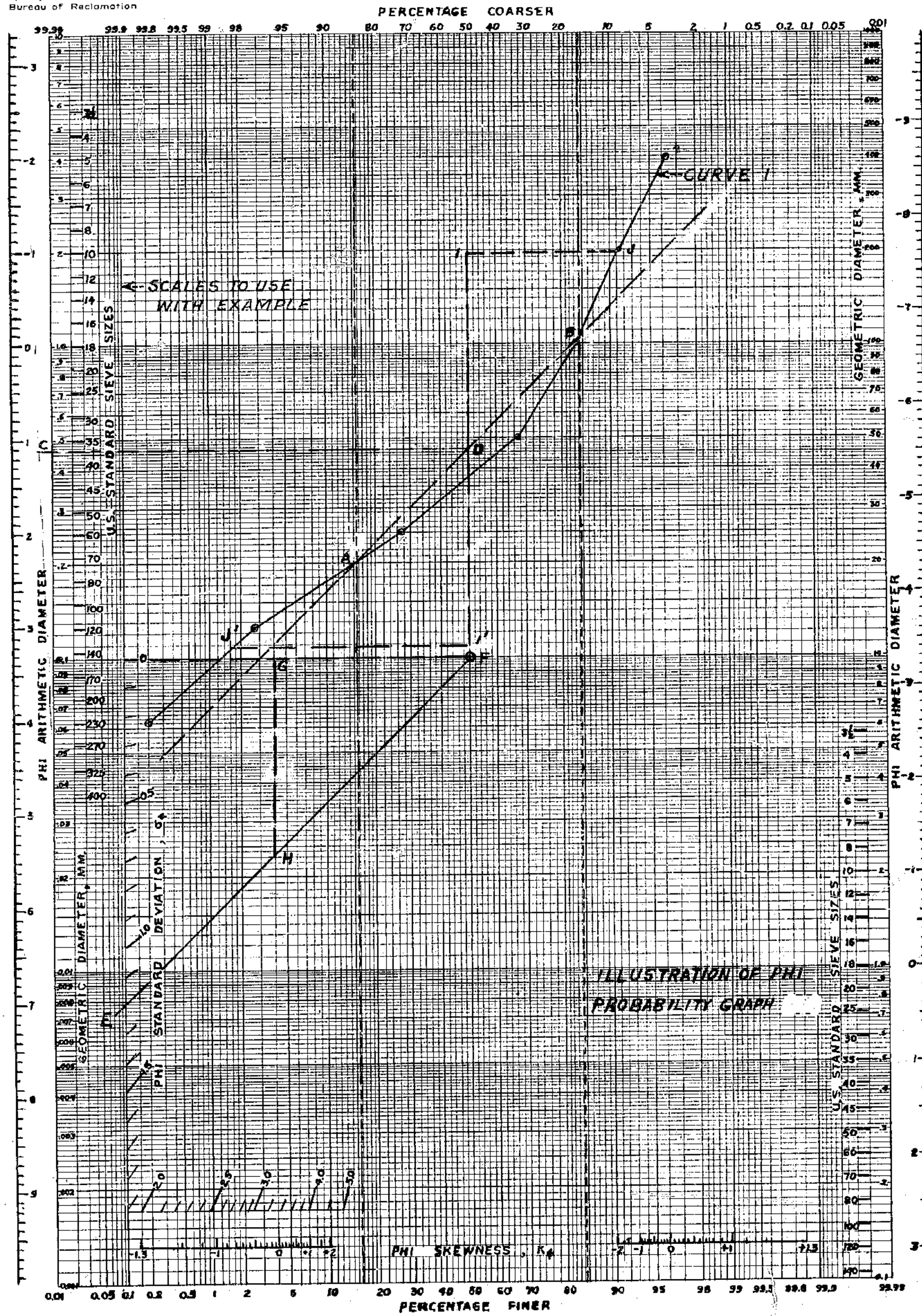

FIGURE 3