UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

# PROGRESS REPORT NO. 3 CANAL EROSION AND TRACTIVE FORCE STUDY (CORRELATION OF LABORATORY TEST DATA)--LOWER-COST CANAL LINING PROGRAM

General Report No. Gen.-26 

DIVISION OF ENGINEERING LABORATORIES

COMMISSIONER'S OFFICE
DENVER, COLORADO

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UNITED STATES
DEPARTMENT OF THE INTERIOR
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Commissioner's Office--Denver
Division of Engineering Laboratories
Hydraulic Laboratory Branch
Earth Laboratory Branch
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# PROGRESS REPORT NO. 3-CANAL EROSION AND TRACTIVE FORCE STUDY (CORRELATION OF LABORATORY TEST DATA)--LOWER-COST CANAL LINING PROGRAM--

## INTRODUCTION

To establish better design criteria for earth-lined and unlined canals, field and laboratory studies of erosion and tractive forces on fine, cohesive soil materials are being conducted under the Lower-cost Canal Lining Program. Forty-six test reaches, Figure 1, were selected and data and soil materials from them have been analyzed. Test reaches were selected on canals and laterals that had been in operation for a number of years. The maximum operating discharges vary from approximately 2 cubic feet per second to 3,000 cubic feet per second, Table 1. Three channel conditions were studied; these included: (1) canals where deposition was occurring, (2) stable canals, and (3) moderately scoured canals.

Investigations herein reported have been conducted under the Lower-cost Canal Lining Program. The program is intended to extend over a period of years, and include earth-lined and unlined canals with a variety of soil types which have been subjected to different climatic and hydraulic conditions. The purpose of this report is to present analyses of data which are complete at this time and is not intended to present final conclusions. All methods of analysis are tentative and subject to modification as more data become available.

The purpose of the program is to establish better design criteria for earth-lined and unlined canals. To establish behavior of soils under hydraulic forces, physical properties of soils are compared to hydraulic forces and the degree of soil erosion.

*See Laboratory Reports No. Hyd-464 and EM-576.

Data in this report are considered tentative and cover only a limited range of soil types. However, the soils studied were in the range of greatest interest in present canal designs.

A total of 46 test sites were selected in Regions 1, 2, 4, 5, and 7, Figure 1. Soil samples were obtained from each site when the canals were not operating. Hydraulic data were obtained during a period of near maximum sustained flow.

Canal and lateral reaches for the study were selected by a field inspection party consisting of an engineer from the Earth Laboratory, an engineer from the Hydraulic Laboratory, and a regional representative. An engineer from the Canals Branch was either present during selection of the test reaches, or he reviewed and approved the reports of those who did select the reaches.

Two trips were made to each site. A field inspection party selected the sites and obtained soil samples when canals were dry. The second trip was made to obtain hydraulic data and to make vane shear tests on the soils when the canals were operating near maximum discharge.

The soil samples were classified and tested to determine dry densities, gradations, Atterberg limits, and compaction characteristics. A tractive force and erosion test apparatus, Appendix I, was developed in the laboratories and tests were conducted on 8-inch undisturbed soil samples obtained from the field sites.

Hydraulic data obtained in the field were analyzed to determine velocity profiles, average velocities, discharge, hydraulic radius, average tractive forces, tractive force distributions, Manning's "n" values, and suspended sediment concentrations. The procedure followed is described in General Report No. 21, Progress Report No. 1, March 1957.

An IBM 650 electronic digital computer was used for analysis of laboratory data. This analysis has shown a number of promising multiple correlations. The laboratory correlations are reviewed in this report. A report covering the relation of laboratory correlations to field data will be compiled.

## FIELD DATA FROM TEST SITES

### First Trip to Sites

The limits of each test reach selected were set by placing hubs, guard stakes and flags at the upper end, center, and lower end of the reach.

Soil samples for laboratory testing were taken from each test reach. These samples included: sack samples, 3-inch drive samples, 8-inch undisturbed hand-cut samples, and sediment samples (in reaches where present).

The sack samples were taken to determine the gradation, plastic properties, and the compaction characteristics of the materials. The 3-inch drive samples were taken to obtain unconfined compression values. The 8-inch hand-cut samples were obtained for use as erosion test specimens.

Second Trip to Sites

The second trip was made during the time the canals and laterals were operating near peak discharge. Data recorded from all test sections included: 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, where possible; amount of sediment being carried in suspension; temperature of the water; shear resistance of the banks and bottom of the canal, in place and in the saturated condition; and photographs showing the condition of the test reaches.

To record water surface slopes, an engineer's level and a water surface gage were used. A Price Type A current meter was used to measure velocities at 0.2 and 0.8 of the depth for discharge measurements, and a pygmy current meter was used to measure velocities near the boundary. A DH-48 hand sampler was used to obtain samples for suspended sediment analysis, and a vane shear tester* was used to determine in-place shear values of the soils.

Records Obtained from Field Offices

Records of the highest sustained flow each year for at least a 1-week period over the past few years were obtained from project offices, and cross sections of the canal, in previous years, were obtained when available.

Summary of Test Sites

Short descriptions of conditions in each test reach during the first visit are given below.

Region 1

Minidoka Project, Lateral PL 10A-824S, Stations 28+00 to 38+00. Slight erosion on banks. Thin deposits on bottom. Section appears stable.

Minidoka Project, Milner-Gooding Canal, Stations 369+00 to 379+00. Moderate erosion.

*Design, assembly and use of a portable vane shear tester, Hydraulic Laboratory Report Hyd-434, USBR, June 1957

Minidoka Project, PA-lateral (North Side Pumping Company). Moderate erosion during past years. Considerable erosion on banks. Considerable amounts of moss and weeds in the canal.

Yakima Project, PL No. 14 (lateral), Stations 16+55 to 22+30. Reach is stable. Heavy weed growth on banks. Moss growing in lateral.

Yakima Project, PL No. 13 (lateral), Stations 149+50 to 155+50. Reach is stable. Heavy weed growth on banks. Moss growing in lateral.

Yakima Project, Roza Main Canal, Mile 59.1. Slight erosion. Heavy weed growth on upper banks. Moss, and aquatic weeds growing in local areas.

Columbia Basin Project, WC lateral W 27 B, Stations 21+90 to 27+90. Heavily eroded. Grass and weed growth on banks of lateral.

Columbia Basin Project, WC lateral W 26 A, Stations 374+90 to 382+90. Stable. Weed growth on banks.

Columbia Basin Project, EL lateral 68T5, Stations 180+00 to 190+00. Stable. Near critical conditions for scour.

Region 2

Lateral M-2-A, Klamath Project, Reach 1, unlined. Aquatic weeds, pondweeds, and moss growing across entire section of lateral. Lateral had eroded in past. Channel boundary well defined and solid. Pondweeds appeared to grow denser at center of lateral which created higher velocities in the area away from the center.

Lateral M-2-A, Klamath Project, Reach 2, compacted earth lining. Heavy weed growth at water surface edge. Moss covered boundary of section. Reach appeared stable.

Lateral J-1-B, Klamath Project, Reach 3, unlined. Lateral was full of moss and weeds. There were relatively clear channels along sides of section where water velocities were higher than in the center of the section. There appeared to have been scour in the past.

Lateral J-13, Klamath Project, Reach 4, unlined. Reach was clear of aquatic growth. There was a heavy growth of weeds at the water surface edge. There appeared to have been some erosion in the past.

Friant-Kern Canal, Reach 5, compacted earth lining. Aquatic weeds grew on the boundary to a height of approximately 1 foot. Sloughing had occurred on side slope of canal in this reach. Reach appeared stable with the exception of bank sloughing.

Friant-Kern Canal, Reach 6, compacted earth lining. Aquatic weeds on boundary to height of approximately 1 foot. Reach appeared stable.

Lateral 32.2, Madera Canal, Reach 7, compacted earth lining on slopes. Aquatic weeds growing along edges of lateral. Deposition occurring in area of weed growth.

Madera Canal, Reach 8, unlined. No weeds were growing in this reach. Erosion was occurring.

Madera Canal, Reach 9, unlined. No weeds growing in this reach. Slight erosion was evident.

Region 4

Eden Project, Means Canal, Stations 19+17 to 29+17. Deposition was occurring in bottom of canal and slight erosion on side slopes.

Eden Project, Means Canal, Stations 98+00 to 106+00. Deposition occurring. Deposition appeared to be due to material eroded from side slopes.

Eden Project, Means Canal, Stations 260+00 to 270+00. Stable. Slight erosion on side slopes.

Eden Project, Eden Canal, Stations 345+00 to 352+00, unlined. Stable.

Eden Project, Eden Canal, Stations 352+00 to 359+65, lined. Stable.

Eden Project, Eden Canal, Stations 459+95 to 469+95. Deposition on canal bottom. Slight erosion on side slopes. Bad erosion on sides - may be due to wind waves.

Eden Project, Eden Canal, Stations 640+00 to 650+00. Light deposition on bottom. Slight erosion on side slopes. Erosion near water surface due to wind waves.

Eden Project, Eden Canal, Stations 829+00 to 839+00. Deposition occurring on bottom. Slight erosion on side slopes.

Paonia Project, Fire Mountain Canal, Stations 414+00 to 424+00. Stable. Weeds and brush growing on canal banks. A few rocks to 6-inch diameter in canal bottom near toe of slopes.

Paonia Project, Fire Mountain Canal, Stations 643+00 to 653+50. Slight erosion. Weeds and brush growing on canal bank, 6-inch plus or minus dumped clay lining.

Paonia Project, Fire Mountain Canal, Stations 1338+00 to 1345+00. Stable.

Region 5

Tucumcari Project, Conchas Canal, Stations 3210+00 to 3220+00. Deposition occurring on bottom. Slight erosion on side slopes due to wind waves.

Tucumcari Project, Conchas Canal, Stations 3957+86 to 3967+86. Stable. Weeds and grass growing on banks.

Tucumcari Project, Conchas Canal, Stations 4051+00 to 4061+00. Stable. Scoured about 0.8 foot before gravel blanket placed to create stability.

Tucumcari Project, Hudson Canal, Stations 269+57 to 279+57. Bottom stable. Heavy erosion on the side slopes, probably due to wind waves.

Tucumcari Project, Hudson Lateral, Stations 1086+00 to 1096+00. Stable. Heavy weed growth on side slopes above water line.

W. C. Austin Project, West Canal, Stations 183+00 to 193+00. Slight deposition occurring.

W. C. Austin Project, Altus Canal, Stations 794+50 to 804+50. Stable. Heavy weed growth on banks.

W. C. Austin Project, Ozark Canal, Stations 311+00 to 321+00. Slight erosion occurring.

Region 7

Bartley Canal, Reach 1, compacted earth lining. Slight erosion from wave action near water surface. Three to five inches of loose silt on canal bottom.

Bartley Canal, Reach 2, unlined. Weeds generally grew on banks above water surface and extended into water. Reach appeared stable, with slight deposition near toe of side slope.

Cambridge Canal, Reach 3, unlined. Weed growth near water surface. Reach appeared stable, with some deposition on bottom.

Franklin Pump Canal, Reach 4, unlined. Cross section rounded but stable. Considerable weed growth near water surface.

Superior Canal, Reach 5, unlined. Erosion taking place on banks above water surface due to surface drainage. Wave erosion near water surface edge. Small deposits near toe of slope. Slight erosion on bottom.

Franklin Canal, Reaches 6 and 7, unlined. Slight erosion from wave action near water surface. Sediment deposits near toe of slope.

Cambridge Canal, two adjacent curved reaches, unlined. Weed growth near water surface edge. Deposition occurring on inside of curves.

## ANALYSIS OF LABORATORY DATA

To obtain more closely controlled data to correlate with field tests, a laboratory tractive force testing apparatus was developed, Appendix I. The apparatus was used to test the undisturbed 8-inch soil samples. Results from the machine tests have been used in this analysis.

As shown in Appendix I, the tractive force apparatus includes a 35-inch-diameter tank, a variable-speed air motor, a plastic lid, impeller blades, pressure gage, and pressure regulator. An 8-inch saturated sample is placed in the apparatus and covered with 12 inches of water. The impeller is started to rotate slowly. This action forces water to flow across the soil sample, thereby creating tractive forces of low value. After subjecting the soil to these tractive forces for 3 minutes, the speed of rotation is increased, and the increased tractive force is allowed to act on the soil for another 3 minutes. This procedure is followed until the soil begins to erode. The revolutions per minute at the time erosion starts is recorded. The tractive force is related to the revolutions per minute by calibration curves. The total time of test is recorded, as is the time the machine operated at the speed which caused erosion. Notes on behavior of the soil tested and sketches of the eroded area are included in the data. Photographs taken of the soil sample before and after the test permit comparison of all samples tested. Upon the completion of the erosion test, the soil density and vane-shear strength are determined. Samples of the soil are taken for mechanical analysis and Atterberg Limits tests.

The tractive force developed at the time the soil first began to erode is considered the critical tractive force and is the value used in the analysis presented in this report. No corrections are made for suspended sediment in the water, however, in no test was suspended sediment concentration very high in the tractive force apparatus.

Results of laboratory tests performed on soil samples are summarized in Table 2.

Standard laboratory test values, such as plasticity index, liquid limit, gradation factors , shrinkage limit and percent maximum density (Columns 3, 12 [5, 6, 7, 8], 9, and 11, respectively), were obtained from tests performed in conformance with procedures presented in the first edition of the Bureau's Earth Manual, July 1960. Unconfined compression tests were performed on a few samples, but preliminary study indicated that the test results would not give sufficient additional information to justify continuing these tests.

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. These tests were performed on tractive force test specimens after erosion tests were performed.

A log-probability method, Appendix II, was used to explain gradations of soils. By this method, the mean size of soil, scatter of particles about the mean, and a function of the amount of fines in the material were used to explain the mechanical analysis.

Laboratory data were analyzed by plotting soil properties against the critical tractive force obtained in the laboratory. Soils properties used were: plasticity index, liquid limit, soil density, mechanical analysis, shrinkage limit, vane-shear values, and percent of maximum Proctor density.

Initial analysis was made using the method of deviation described by M. Ezekial in "Methods of Correlation Analysis", second edition, Wiley, New York, 1941. To make analysis of many factors more practical, a program for an IBM 650 electronic computer was used. A multiple linear correlation method previously programed for the computer, was used for this study. Computed data resulted in the best fit linear equation, a correlation coefficient, and standard deviations for all variables. Numerous correlation computations were made for all data combined. Correlation computations were also made where the data was divided into zones, parallel to the A line on the plasticity index-liquid limit chart, Figure 2. As may be seen, only a limited range of soils were tested. Results of the correlations are presented in Table 3. As shown by the table, data in zones generally showed a higher correlation coefficient than when all data were combined.

While many of the deviations are small, it should be noted that the data cover only a limited range, and that some soils unexplainably deviated from general conditions.

## SUMMARY AND CONCLUSIONS

A field and laboratory study was made to develop a method for determining critical tractive forces of cohesive materials in connection with 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 this value to help determine the best designs of earth canals. The critical tractive force of the earth material is a more practical property on which to base design than estimating permissible velocities. When a critical tractive force value is known, the methods of design as outlined in Hydraulic Laboratory Report Hyd-352 can be used to give the most efficient characteristics for the canal.

Samples were obtained from several canals on Bureau projects and soil and hydraulic properties were measured in the laboratory. The properties measured or computed were: liquid limit, plastic limit, plasticity index, soil density, percent maximum density, shrinkage limit, soil gradation using the logarithmic probability method of analysis, unit vane-shear values, and critical tractive force from the erosion machine.

A multiple linear correlation was made using values of the variables listed. The availability of an IBM 650 electronic computer and a program for making multiple linear correlations made it possible to use many groupings of the variables and obtain their correlation equations and determine correlation coefficients. The critical tractive force is the dependent variable. Table 3 lists all correlations made. Equations can be written by inserting proper coefficients. Correlation coefficients and standard deviation coefficients are given. They give a measure as to the degree of relationship and feasibility of the equations. In general, it can be stated that the higher the value of the correlation coefficient, the better the linear correlation exists between variables.

Data are arranged in four zones parallel to the "A" line on the soils plasticity chart. Correlations were made for values in each zone and also for all values combined. Some correlations within zones give the highest correlation coefficients. However, before recommendations are made for the use of equations for determining critical tractive force on cohesive materials, it is believed experience should be gained on application of this method to typical design problems.

The dependent variable, critical tractive force, was measured on the erosion machine. The machine was calibrated to give critical tractive force values using samples of sands and gravels. The critical tractive forces for these noncohesive materials are known from many laboratory and field measurements.

The independent variables are values obtained from standard tests that are easily made in the laboratory. The log-probability method of plotting and defining grain size analysis 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. Log-probability size analysis has been used for many years in the sediment hydraulics field.

In some areas of the accumulated data, there is a lack of sufficient values to cover the range of soil conditions encountered in Bureau canals. It is planned to obtain additional values by making soil samples having properties in the areas needed.

Measurements in the field on canal reaches selected have been made to correlate values of tractive force and canal conditions on operating canals with critical tractive force values measured in the laboratory. Further study of operating and design conditions of test reaches will be made. It is planned to make some practicable application paper studies to arrive at the best methods of applying this tractive force study to design of earth canals. A practical application will be worked out and a canal will be designed which will test the proposed method in the field.

Until the laboratory values for allowable tractive force presented in this report have been correlated with field data, they should not be used in design.

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. | P.I. | Density | $k'_\phi$ | $\sigma_\phi$ | $M_\phi$ | $k'_\phi \sigma_\phi M_\phi$ | S.L. | 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

P.I. = plasticity index

$k'_\phi$ = phi skewness

$\sigma_\phi$ = phi standard deviation

$M_\phi$ = phi arithmetic mean diameter

S.L. = shrinkage limit

V.S. = vane shear--pound per square foot

*Field data not obtained because of construction.

**Table 2**

**DATA OBTAINED FROM LABORATORY TEST SAMPLES**

Zone 3

| | 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 | $k'\phi$ | $\sigma\phi$ | $M\phi$ | $k'\phi\,\sigma\phi\,M\phi$ | S.L. | V.S. | % max. density | 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

| 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 | 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 | $k'_\phi$ | $\sigma_\phi$ | $M_\phi$ | $k'_\phi \sigma_\phi M_\phi$ | 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: $TF = a + b_1 PI + b_2 D + b_3 k'_\phi + b_4 \sigma_\phi + b_5 M_\phi + b_6 k'_\phi \sigma_\phi M_\phi + b_7 SL + b_8 VS + b_9 D\%$

$\sigma_n$ = standard deviation of variable

| Correlation | PI | | Density | | $k'_\phi$ | | $\sigma_\phi$ | | $M_\phi$ | | $k'_\phi \sigma_\phi M_\phi$ | | SL | | VS | | % maximum density | | a | Standard deviation | Correlation coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $b_1$ | $\sigma_1$ | $b_2$ | $\sigma_2$ | $b_3$ | $\sigma_3$ | $b_4$ | $\sigma_4$ | $b_5$ | $\sigma_5$ | $b_6$ | $\sigma_6$ | $b_7$ | $\sigma_7$ | $b_8$ | $\sigma_8$ | $b_9$ | $\sigma_9$ | | | |
| 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 | | Density | | $k'_\phi$ | | $\sigma_\phi$ | | $M_\phi$ | | $k'_\phi \sigma_\phi M_\phi$ | | SL | | VS | | % maximum density | | a | Standard deviation | Correlation coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $b_1$ | $\sigma_1$ | $b_2$ | $\sigma_2$ | $b_3$ | $\sigma_3$ | $b_4$ | $\sigma_4$ | $b_5$ | $\sigma_5$ | $b_6$ | $\sigma_6$ | $b_7$ | $\sigma_7$ | $b_8$ | $\sigma_8$ | $b_9$ | $\sigma_9$ | | | |
| 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 | 0.00096 | 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 | | | | | -0.00298 | 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 | | $k'_\phi$ | | $\sigma_\phi$ | | $M_\phi$ | | $k'_\phi \sigma_\phi M_\phi$ | | SL | | VS | | % maximum density | | a | Standard deviation | Correlation coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $b_1$ | $\sigma_1$ | $b_2$ | $\sigma_2$ | $b_3$ | $\sigma_3$ | $b_4$ | $\sigma_4$ | $b_5$ | $\sigma_5$ | $b_6$ | $\sigma_6$ | $b_7$ | $\sigma_7$ | $b_8$ | $\sigma_8$ | $b_9$ | $\sigma_9$ | | | |
| 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 |

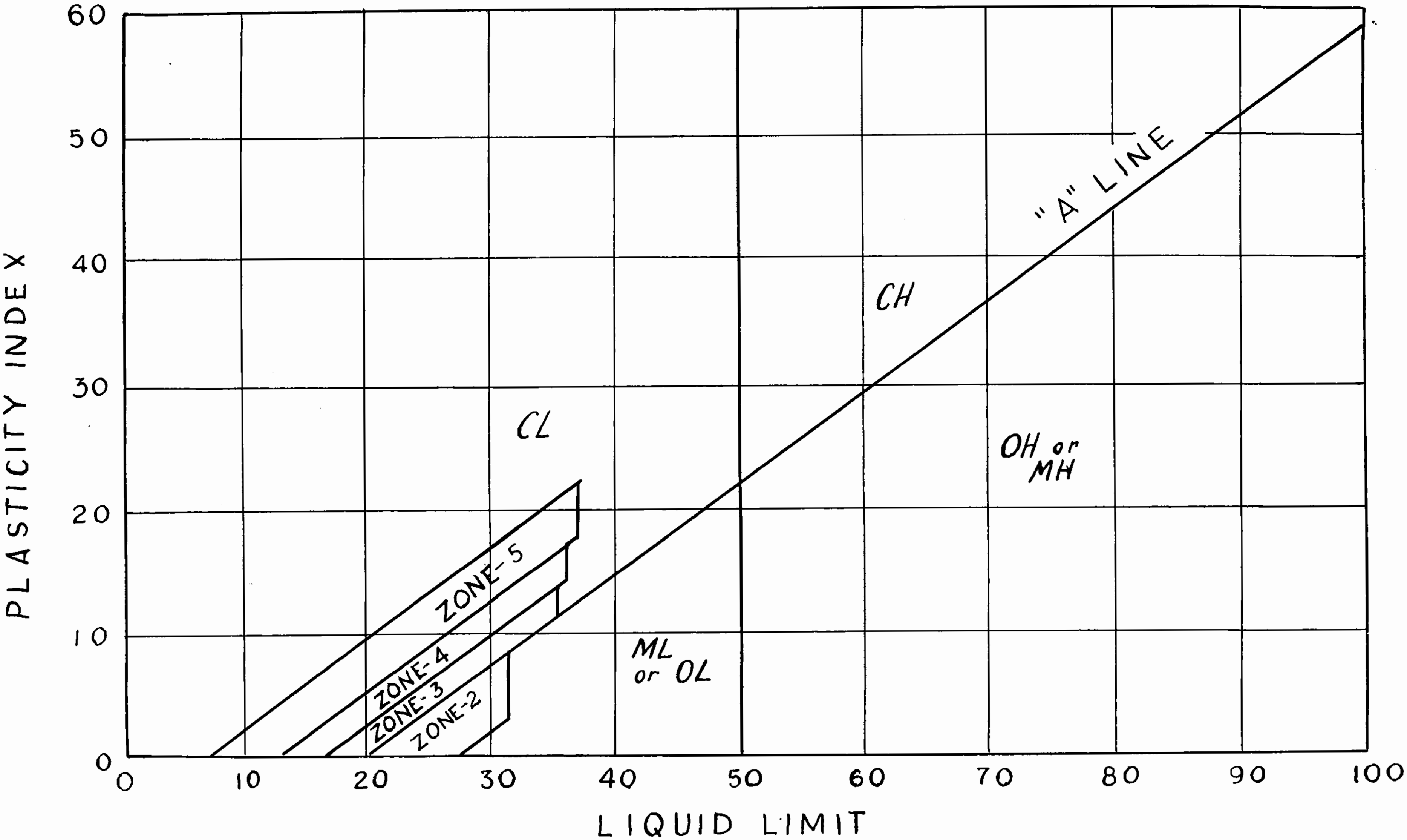
Table 3--Continued

| Correlation | PI | | Density | | $k'_\phi$ | | $\sigma_\phi$ | | $M_\phi$ | | $k'_\phi \sigma_\phi M_\phi$ | | SL | | VS | | % maximum density | | a | Standard deviation | Correlation coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $b_1$ | $\sigma_1$ | $b_2$ | $\sigma_2$ | $b_3$ | $\sigma_3$ | $b_4$ | $\sigma_4$ | $b_5$ | $\sigma_5$ | $b_6$ | $\sigma_6$ | $b_7$ | $\sigma_7$ | $b_8$ | $\sigma_8$ | $b_9$ | $\sigma_9$ | | | |
| 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 |

Notes: PI = plasticity index.
D = density, 16 per square foot.
$k_\phi$ = phi skewness.
$\sigma_\phi$ = phi standard deviation
$M_\phi$ = phi arithmetic mean diameter.
SL = shrinkage limit.
VS = vane shear, pound per square foot.
D% = percent maximum density.


LOWER COST CANAL LINING PROGRAM
TRACTIVE FORCE FIELD AND LABORATORY STUDY
GENERAL LOCATION
OF TEST SITES

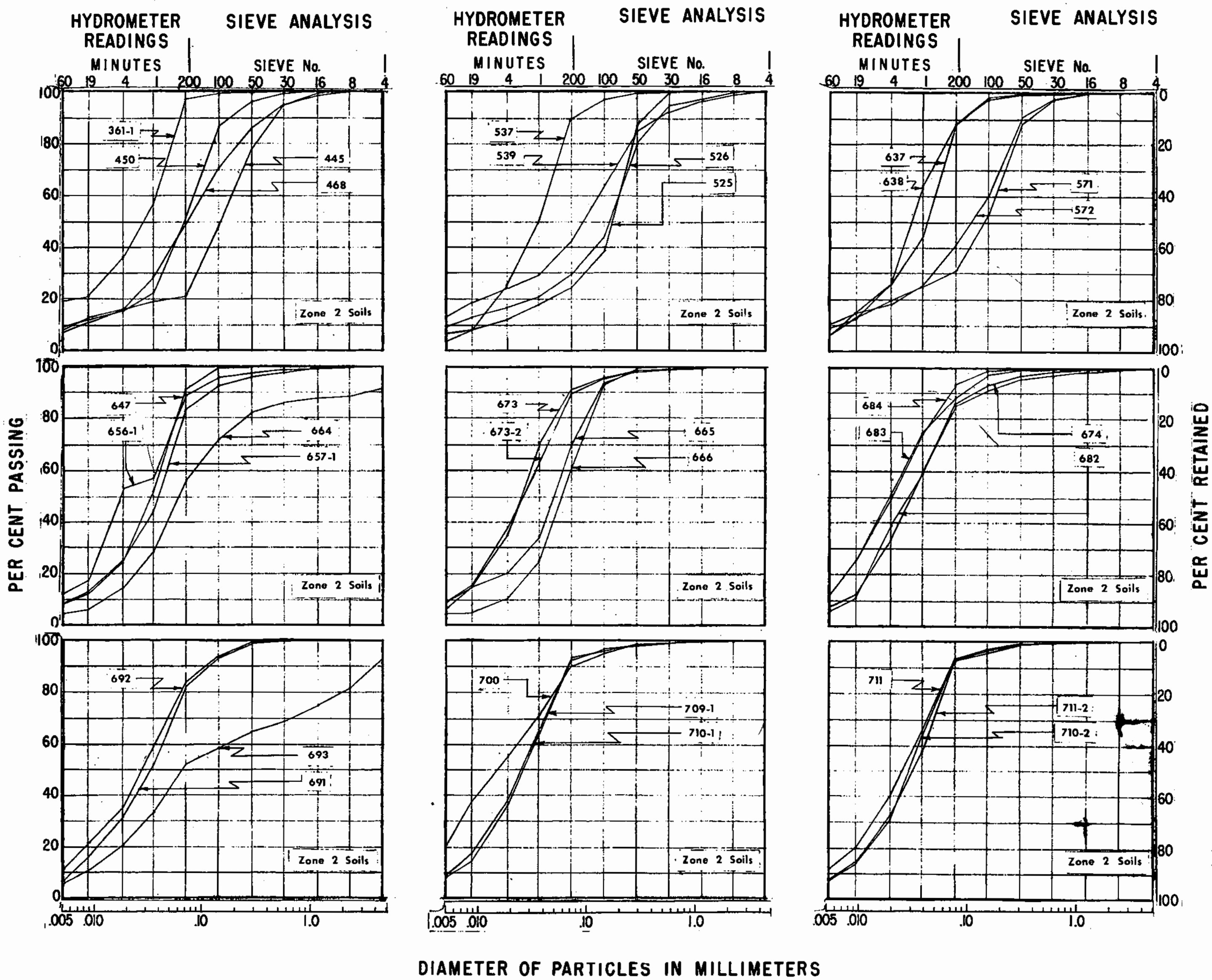
Figure 1




LOWER COST CANAL LINING
TRACTIVE FORCE FIELD & LABORATORY STUDY

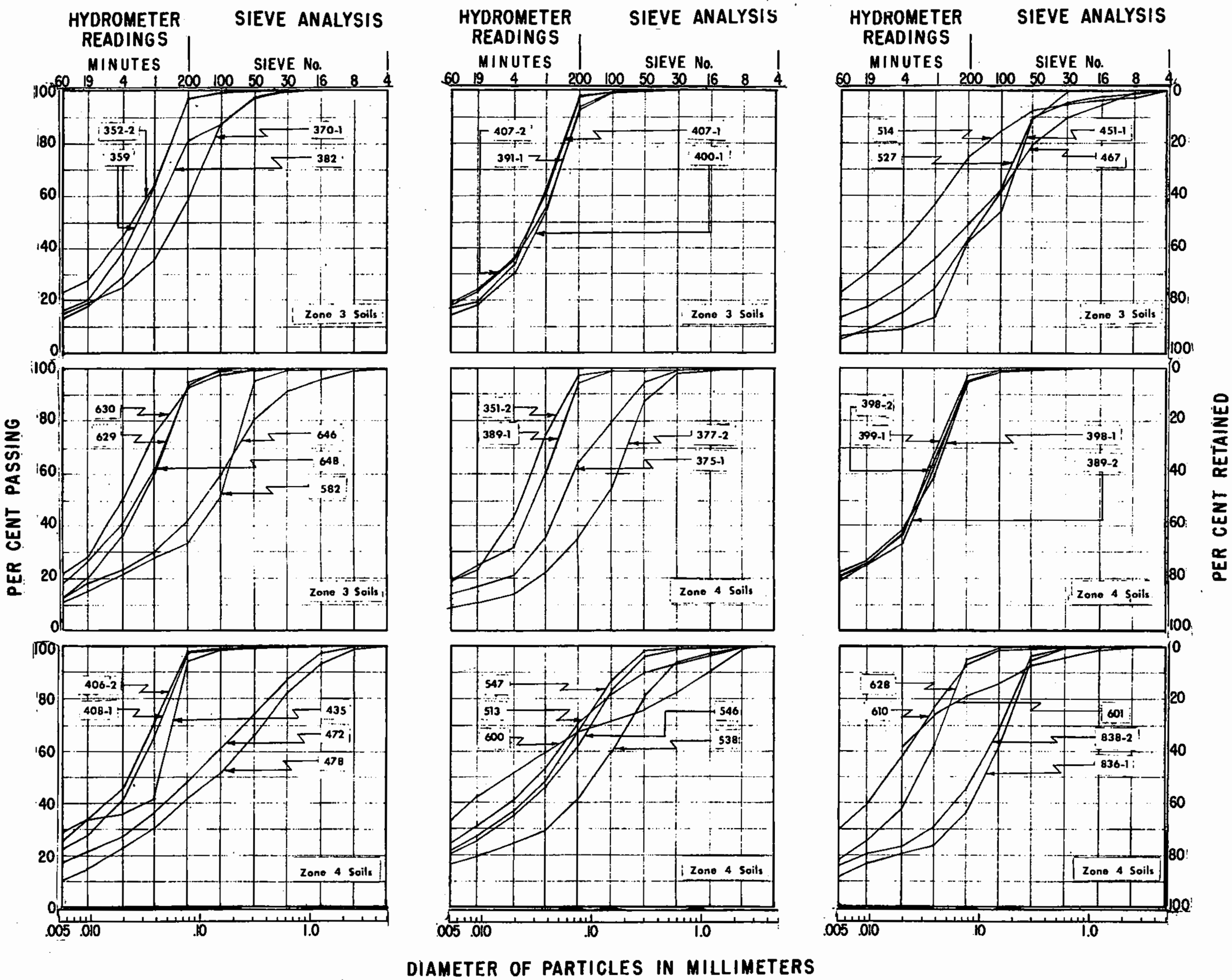
RANGE OF SOILS TESTED

FIGURE 2

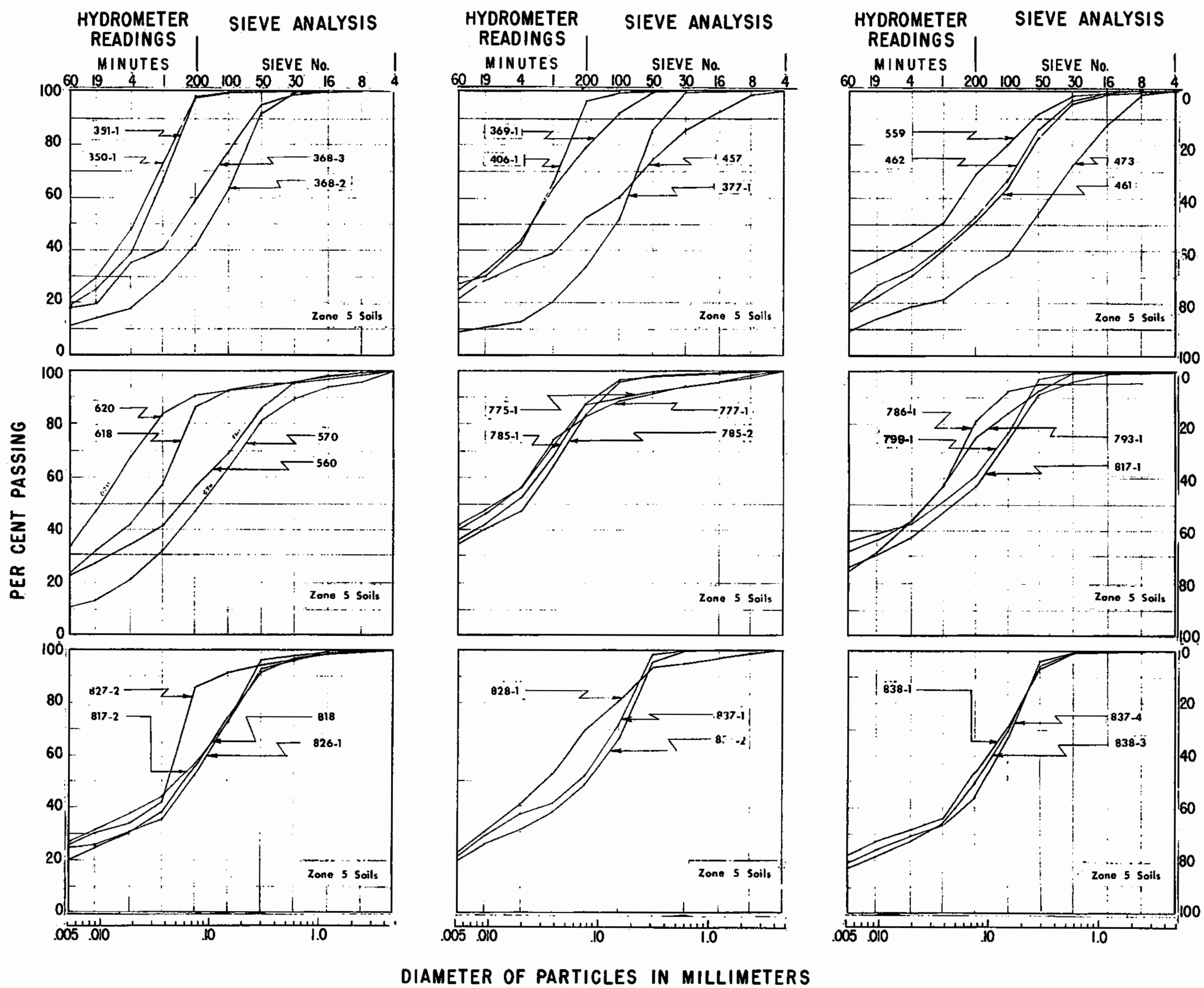



**MECHANICAL ANALYSIS OF SOIL SAMPLES OBTAINED FROM THE FIELD. EACH CURVE IS IDENTIFIED BY A SAMPLE NUMBER**

FIGURE 3
PAGE 1 OF 3




**MECHANICAL ANALYSIS OF SOIL SAMPLES OBTAINED FROM THE FIELD. EACH CURVE IS IDENTIFIED BY A SAMPLE NUMBER**




MECHANICAL ANALYSIS OF SOIL SAMPLES OBTAINED FROM THE FIELD.
EACH CURVE IS IDENTIFIED BY A SAMPLE NUMBER

FIGURE 3

# APPENDIX I

## EQUIPMENT AND PROCEDURE FOR PERFORMING TRACTIVE FORCE TEST ON COHESIVE MATERIALS

## SUMMARY

To improve design criteria for earth canals, a laboratory test was developed for determining the relative resistance of various soils to erosion from moving water. Tests are conducted in a covered cylindrical tank 3 feet in diameter. A 3-bladed impeller, powered by a compressed air motor forces water to flow across the surface of an 8-inch-diameter earth sample. The velocity of the blades is increased gradually until erosion of the sample occurs. The velocity of the blade is related to the tractive force acting on the sample by a combination of experimental and theoretical analysis.

## INTRODUCTION

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 was developed in Report Hyd-352 and 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

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

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:

$$T_o = CV_r^2$$

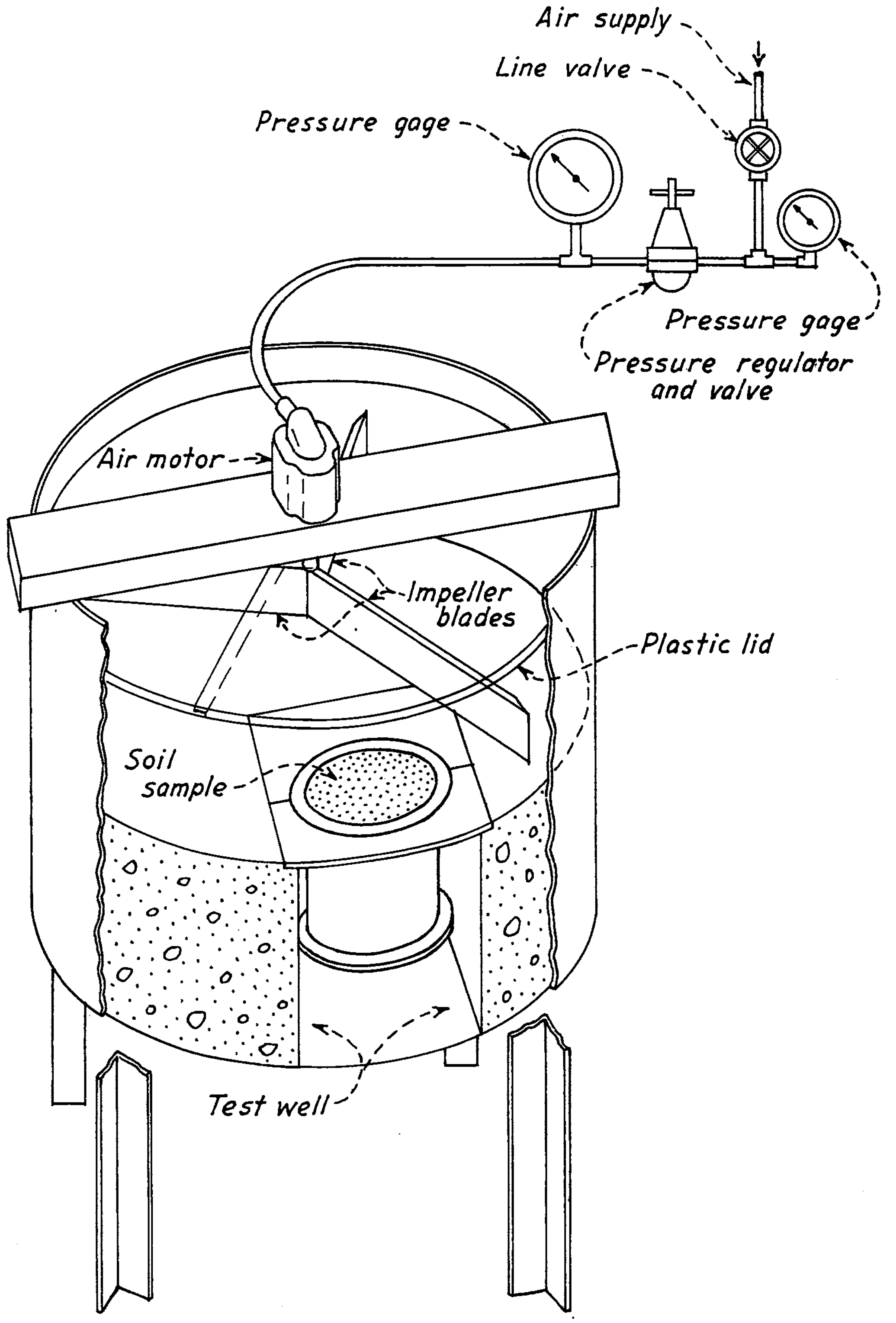
$$= 0.00013 \times (34)^2 = 0.15 \text{ lb/ft}^2$$

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 |




LOWER COST CANAL LINING
TRACTIVE FORCE FIELD AND LABORATORY STUDY

# TRACTIVE FORCE TEST TANK

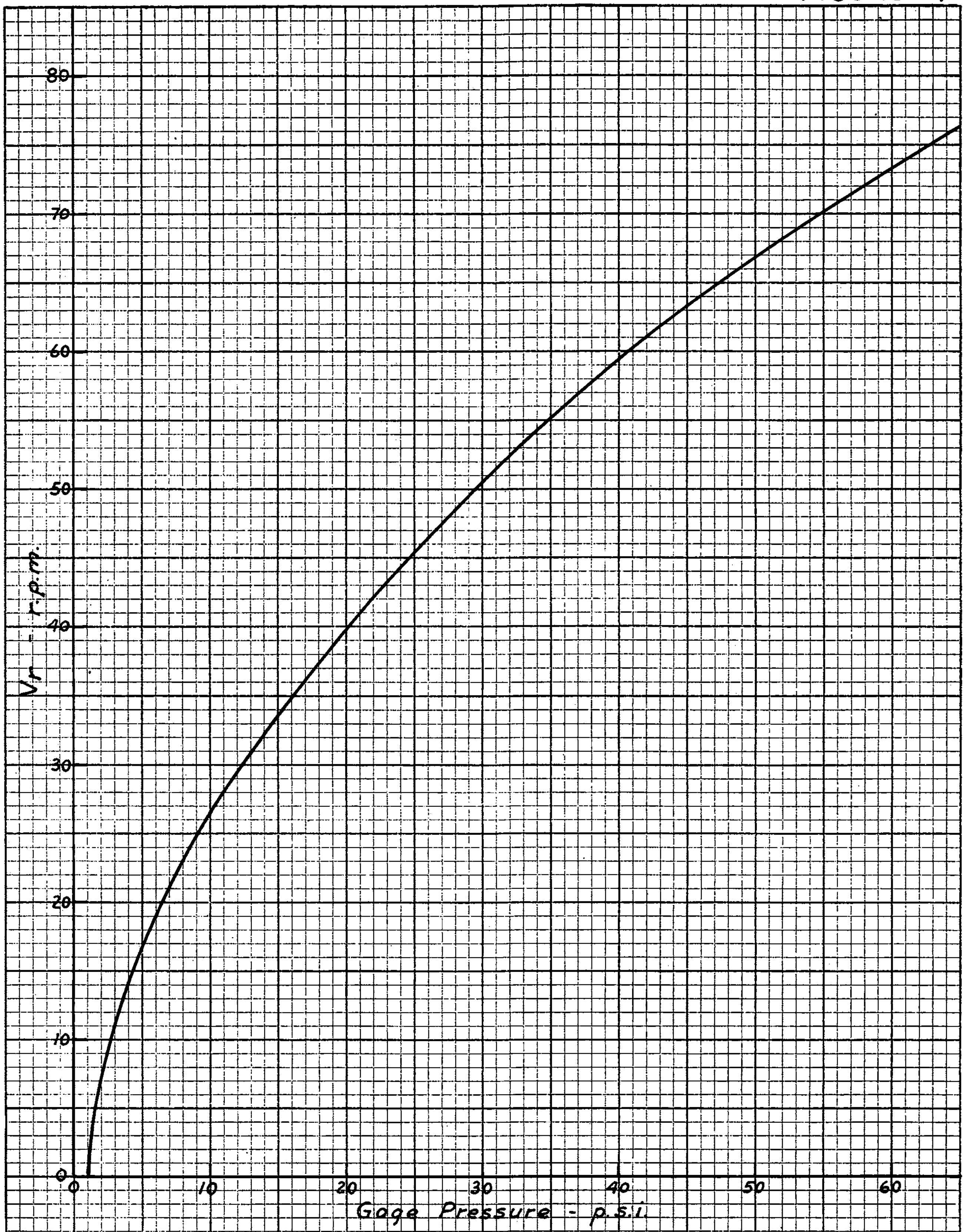
550


LOWER COST CANAL LINING
TRACTIVE FORCE FIELD AND LABORATORY STUDY
ARRANGEMENT FOR CALIBRATING TRACTIVE
FORCE TANK


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

Figure 3

FIGURE 4

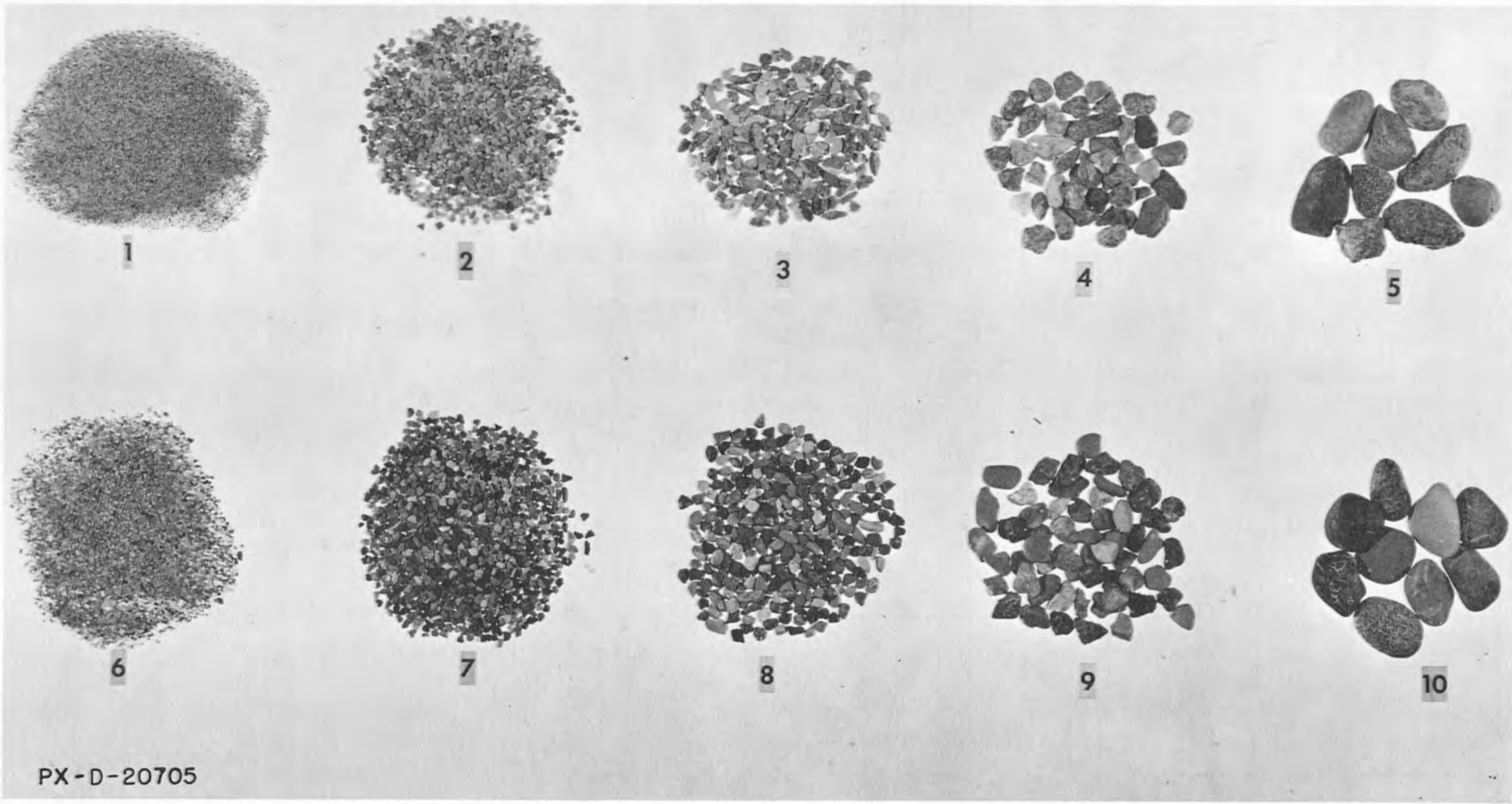



LOWER COST CANAL LINING

TRACTIVE FORCE FIELD AND LABORATORY STUDY

**VARIATION OF IMPELLER BLADE SPEED WITH GAGE PRESSURE**

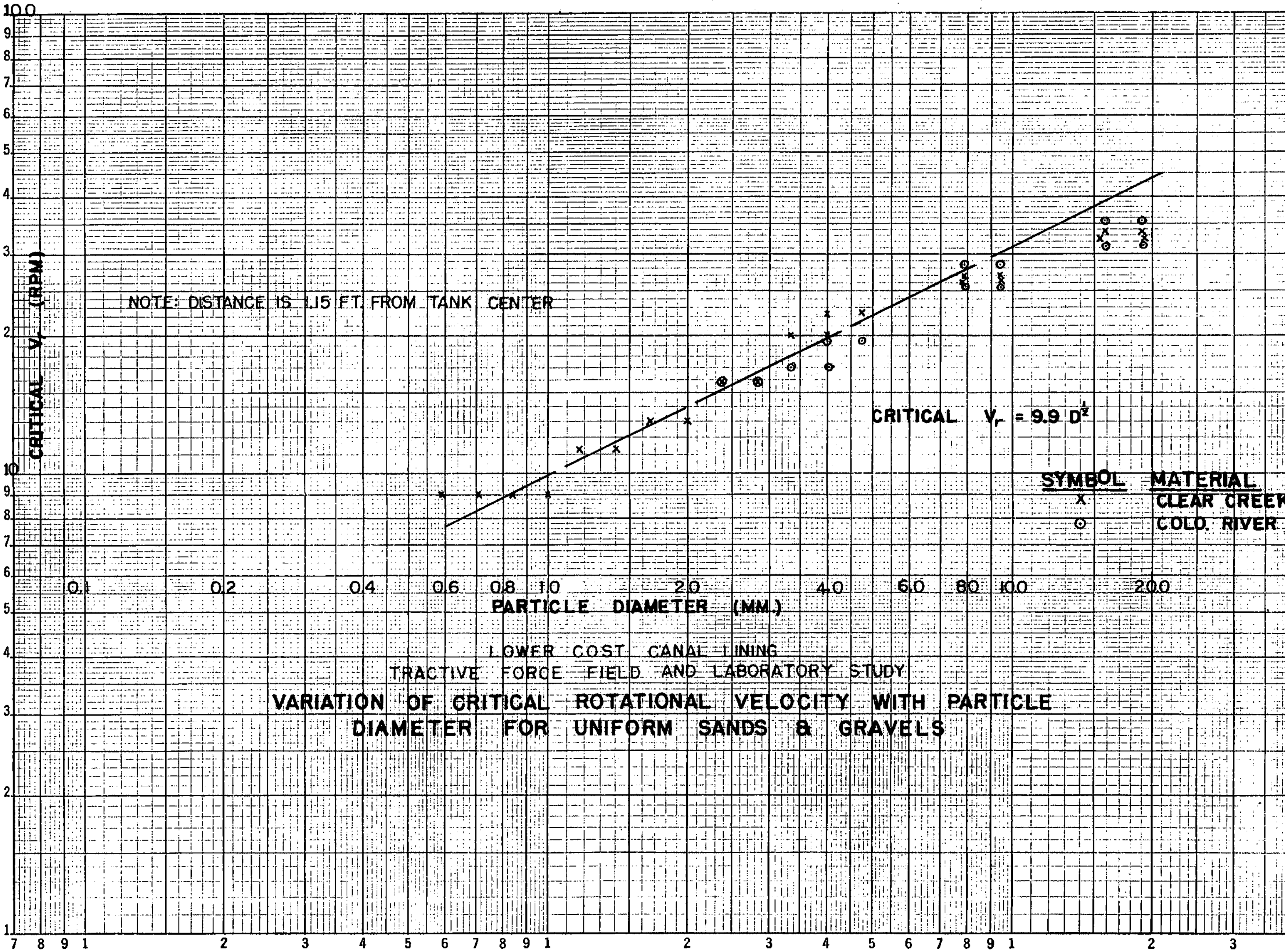
550




LOWER COST CANAL LINING
TRACTIVE FORCE FIELD AND LABORATORY STUDY
SANDS AND GRAVELS USED IN CALIBRATING THE TRACTIVE FORCE TANK

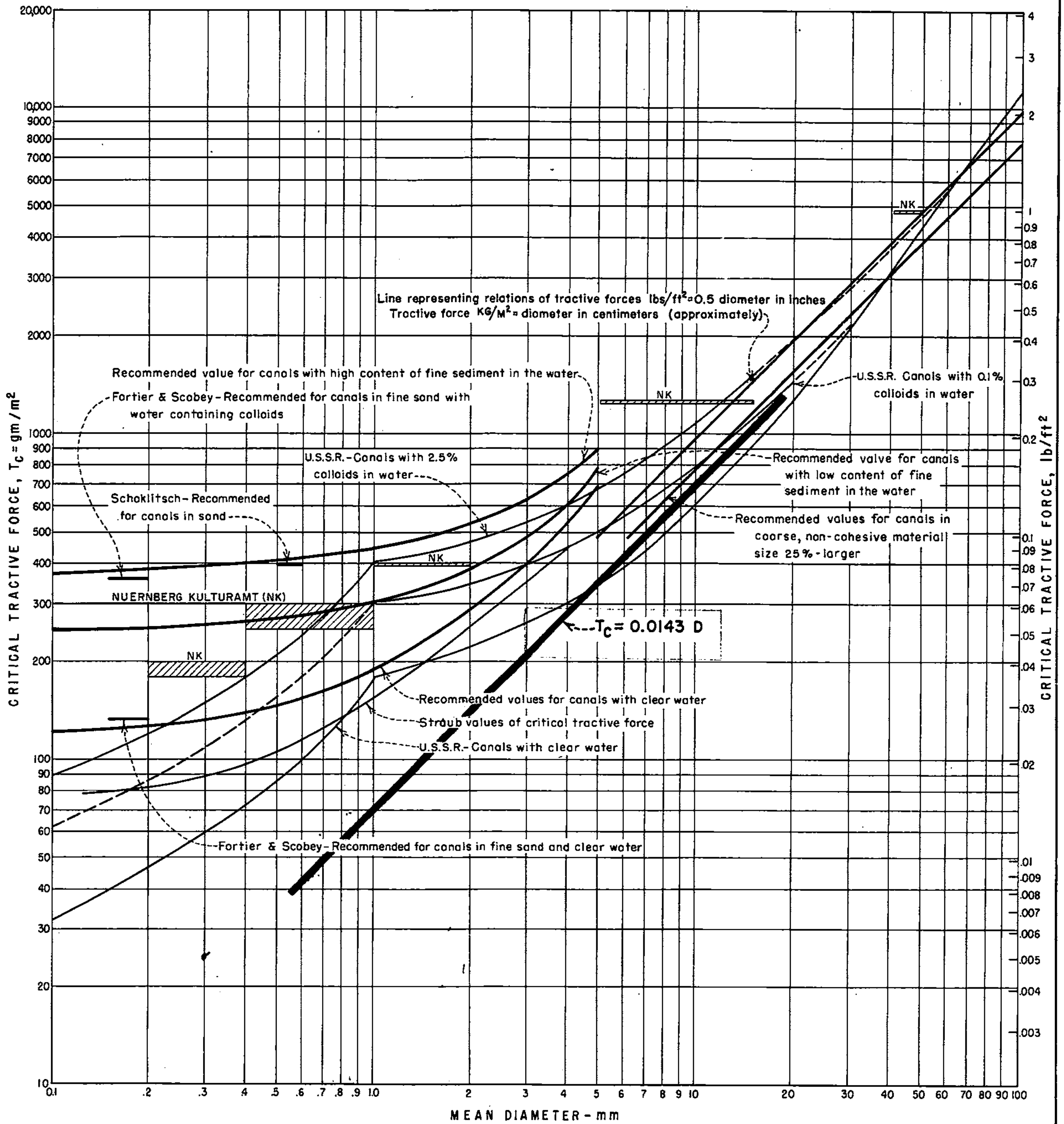
Figure 5

FIGURE 6




LOWER COST CANAL LINING
TRACTIVE FORCE FIELD AND LABORATORY STUDY

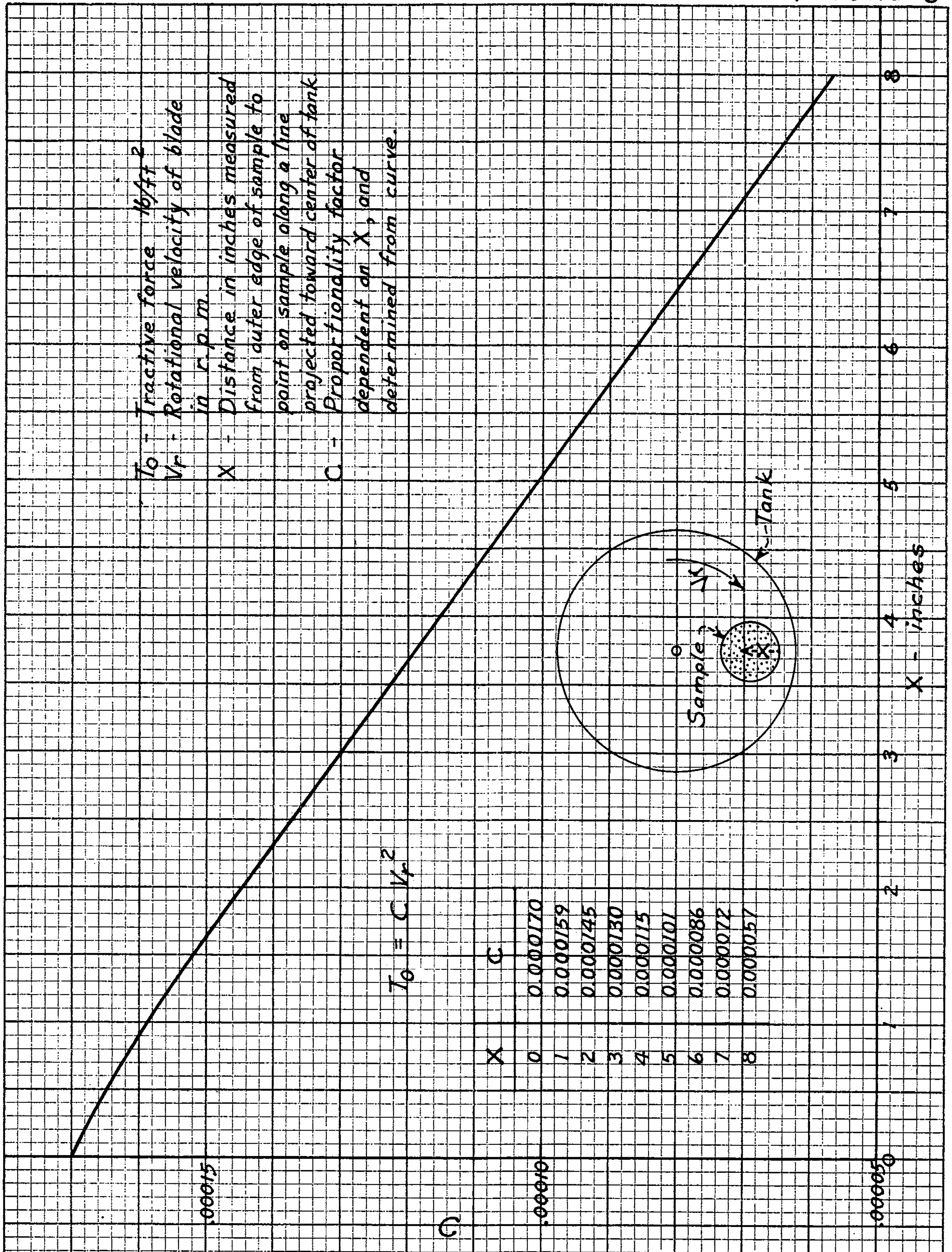
**VARIATION OF CRITICAL ROTATIONAL VELOCITY WITH PARTICLE DIAMETER FOR UNIFORM SANDS & GRAVELS**




LOWER COST CANAL LINING
TRACTIVE FORCE FIELD AND LABORATORY STUDY

## LIMITING TRACTIVE FORCES
## RECOMMENDED FOR CANALS

FIGURE 8



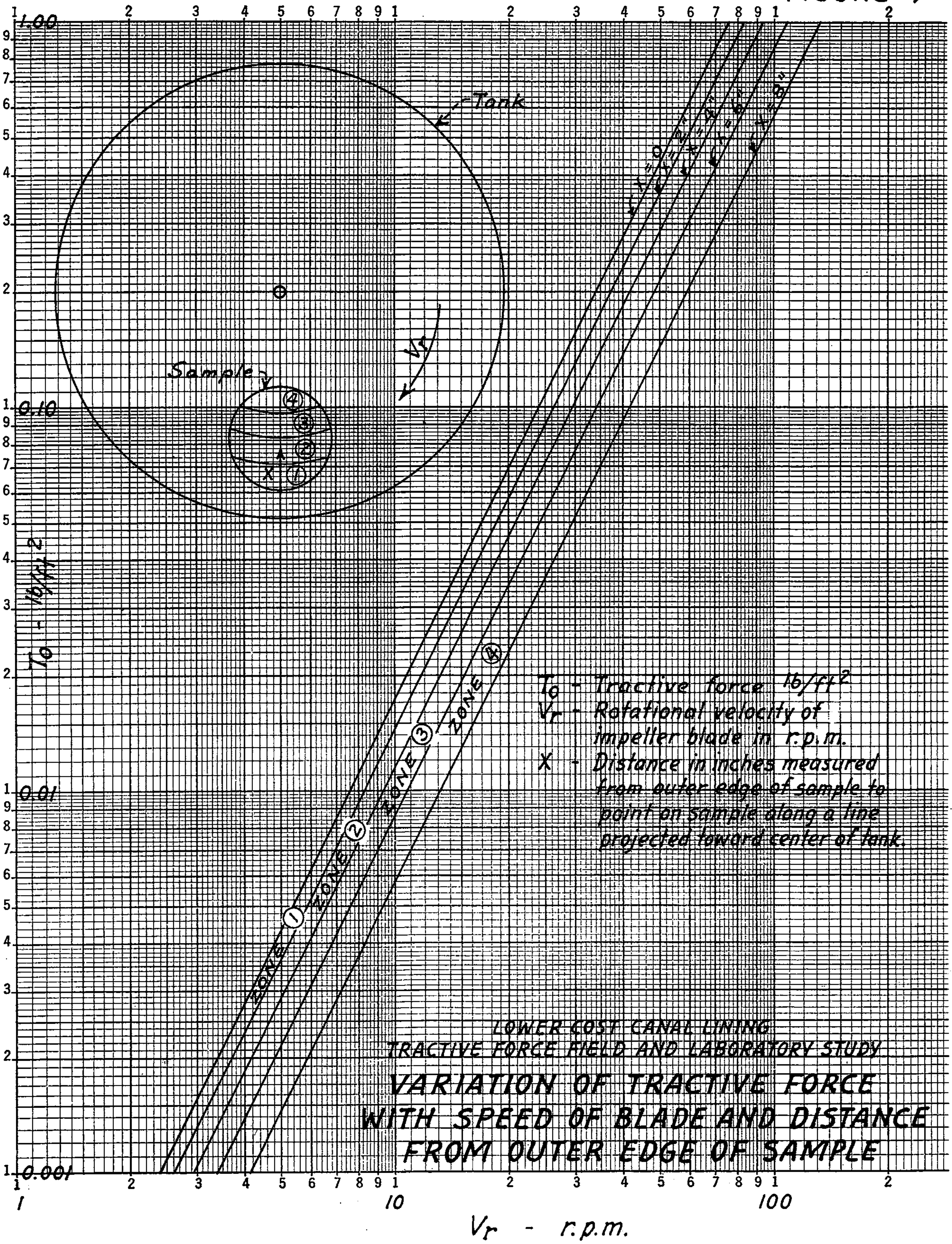

LOWER COST CANAL LINING

TRACTIVE FORCE FIELD AND LABORATORY STUDY

**DISTRIBUTION OF TRACTIVE FORCE ACROSS SAMPLE**

550

FIGURE 9




LOWER COST CANAL LINING
TRACTIVE FORCE FIELD AND LABORATORY STUDY

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

# APPENDIX II

## A LOG PROBABILITY GRAPH METHOD FOR DESCRIPTION OF MECHANICAL ANALYSIS OF SOILS USED IN TRACTIVE FORCE STUDY

## SUMMARY

A method is presented to describe the mechanical analysis curve of a soil by means of probability symbols. A log normal curve is used to replace the normal frequency curves and the analysis curve is represented by mean, a standard deviation and a skewness. The mean sets the location of the analysis curve on standard gradation test paper; the deviation sets the slope of the curve, and the skewness describes the shape of the curve. Method of use and interpretation of data are explained in the following description.


## INTRODUCTION

Particle sizes of cohesive soils are by no means 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

$$y = \frac{1}{\sigma_x \sqrt{2\pi}} \, e^{\frac{-(x-M_x)^2}{2\sigma_x^2}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

where $M_x$ is the arithmetic mean of the x values and $\sigma_x$ 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 references at end of Appendix.

There are several reasons why this law should not be directly applied to naturally occurring soils. One of the reasons was stated by Franics Galton (3) in 1879 when he warned, "* * * which may lead to absurdities. [The Normal Law] asserts that deviations in excess must be balanced by deviations of equal magnitude in deficiency; therefore, if the former be greater than the mean itself, the latter must be less than zero; that is, must be negative."

Another statement by Kottler (4) in analyzing size distributions of photograph emulsions "* * * the Normal Frequency Curve is symmetrical with respect to its peak, and hence the smallness of the frequencies near zero implies that the frequencies of the larger sizes beyond the mean will also be small. This, however, is contrary to observations, which show that the empirical size-frequency curve possesses a long, right tail in the region of the larger sizes."

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

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

where

$\xi$ = the diameter in mm

$\phi$ = a new variable = the negative $\log_2$ of $\xi$

$M_\phi$ = its arithmetic mean (the phi mean)

$\sigma_\phi$ = its standard deviation (the phi standard deviation)

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

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

Inspection reveals that every property of Equation 1 is present in Equation 3 in terms of the logarithmic variable $\phi$. 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 $\phi$ 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 $M_\phi$: (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 $M_\phi$, $1.11_\phi$, on the arithmetic phi scale and the corresponding geometric mean diameter, 0.469 millimeter, from the geometric scale.

$\phi$ is any diameter defined by the expression $\phi = -\log_2 \xi$ where $\xi$ 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 $\sigma_\phi$ scale is the slant scale along the lower left corner of the graph. Read the value of $\sigma_\phi$, $= 1.2_\phi$, at the intersection of line EF with the scale.

To Obtain $k_\phi$: (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 $k_\phi$ 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 $k_\phi'$ value, -0.81, from the left corner of the graph.

## INTERPRETATION OF ANALYSES

The value of $M\phi$ is an indication of the position of the curve on the graph. For the sample in Figure 2, $M\phi = 1.11\phi$ 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 $M\phi$ becomes greater and as the value of the mean particle size increases $M\phi$ approaches zero or becomes negative. On our standard gradation charts, an increase in value of $M\phi$ will move the gradation curve to the left, while a decrease in value of $M\phi$ will move the curve to the right.

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

Variation in the $k_\phi$ values describe changes in the shape of the curves. $k_\phi$ describes the tail of the curve in the region where particle size is largest. In general, as the percentage of coarse material increases $k_\phi$ tends to relatively large negative values. On our 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; $k_\phi$ tends to a relatively large positive value, and on our standard paper, the curve tends to become straighter above the 50 percent size range.

$k'_\phi$ values describe the tail of the curve in the region of small particles. Generally, as the percentage of fine material increases, $k'_\phi$ 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, $k'_\phi$ 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 $k_\phi$ and $k_\phi'$ equal zero. Values of $k_\phi$ for the example are shown on Figure 2.

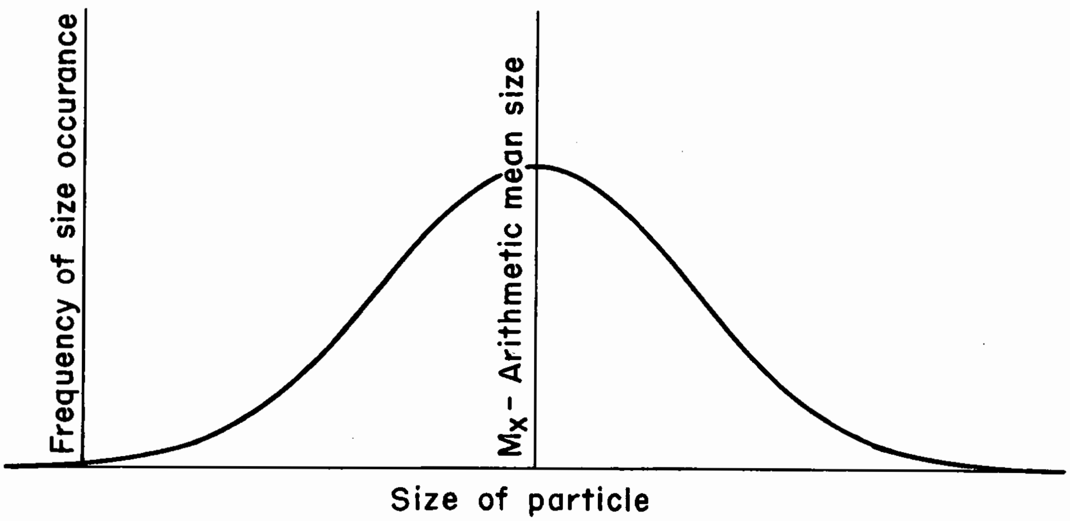
Obviously, these data are not directly applicable to every type curve, but from the previous discussion, it is evident that if phi probability data are known the gradation curve on standard gradation paper can usually be rapidly sketched.

Table 1

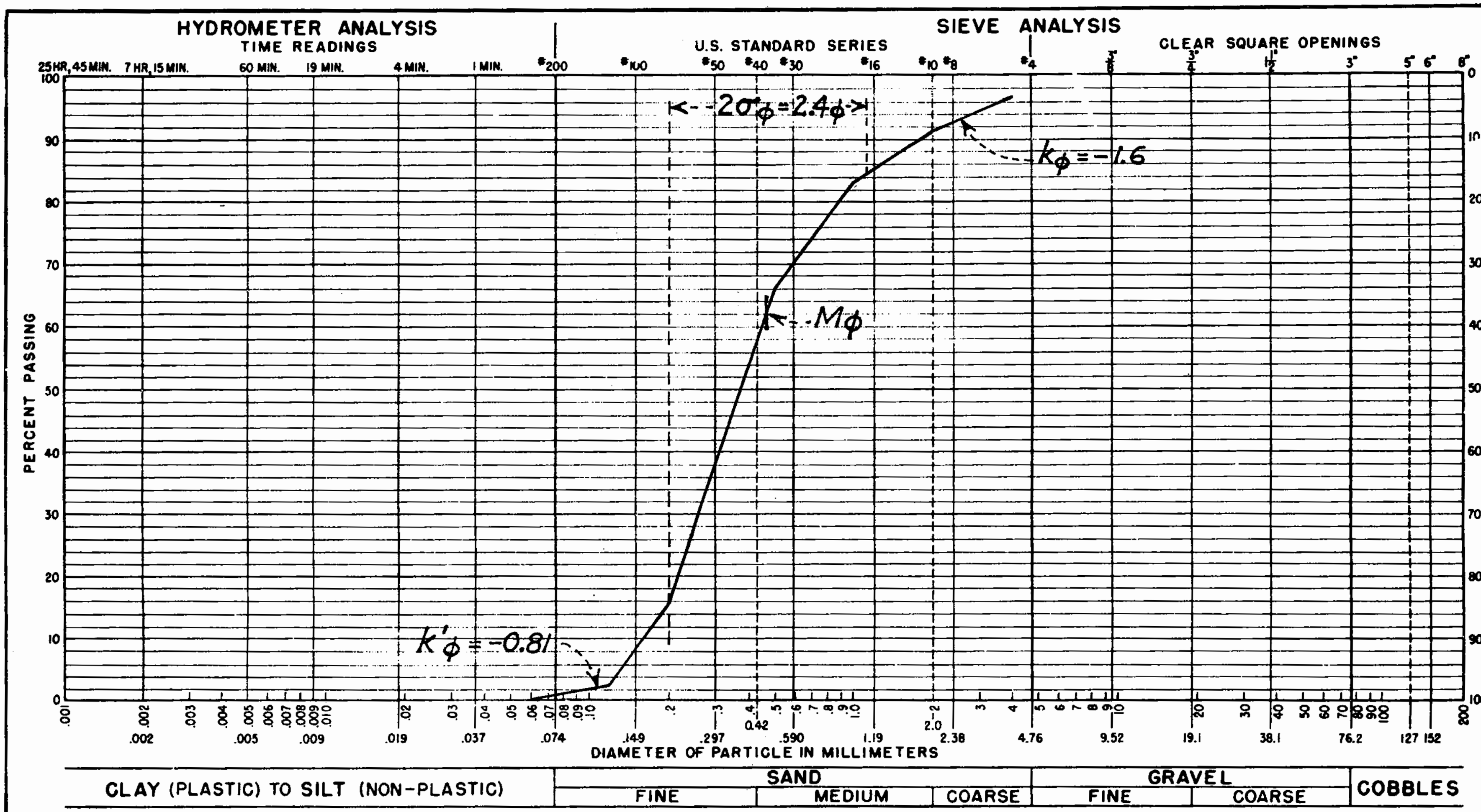
TABLE FOR PLOTTING SIZE ANALYSIS OF SEDIMENTS USING LOG-PROBABILITY METHOD

| 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




NOTES:

GRADATION TEST

FIGURE NO.

*ILLUSTRATION OF PHI PROBABILITY DATA ON STANDARD MECHANICAL ANALYSIS PAPER*

LABORATORY SAMPLE No.______ FIELD DESIGNATION______ EXCAVATION No.______ DEPTH______ FT.

FIGURE 2

EL-103
(2-59)
Bureau of Reclamation

# PHI PROBABILITY GRAPH

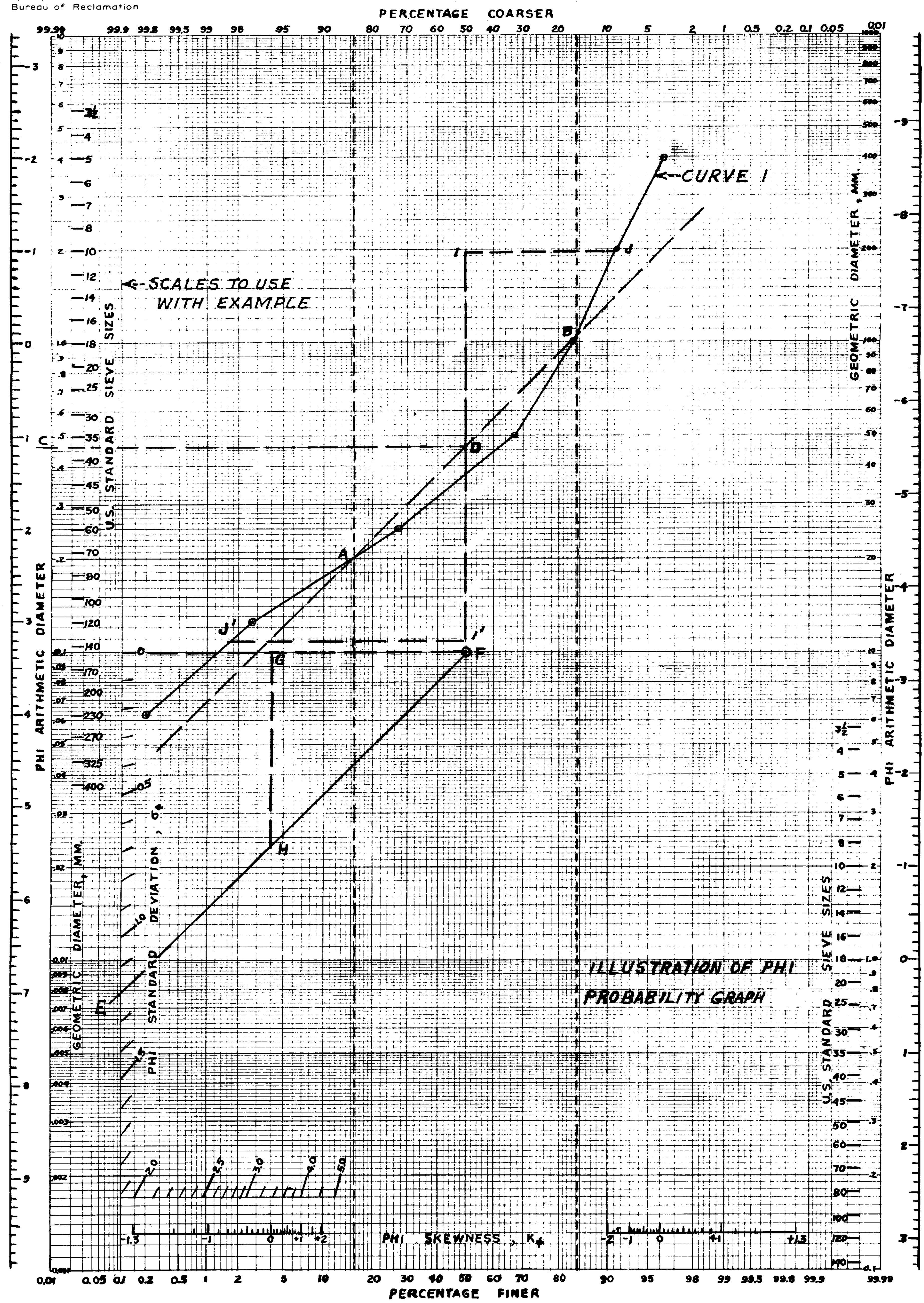



FIGURE 3

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2. Krumbein, W. C., Application of Logarithmic Moments to Size Frequency Distributions of Sediment, Journal of Sedimentary Petrology, Volume 6, pp 35-47, 1936

3. Galton, Francis, Proceedings Royal Society London, Volume 29, p 365, 1879

4. Kottler, F., Journal Franklin Institute, Volume 250, pp 339, 419, 1950

5. Otto, G. H., A Modified Logarithmic Probability Graph for the Interpretation of Mechanical Analyses of Sediments, Journal of Sedimentary Petrology, Volume 9, No. 2, pp 62-76, August 1939


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