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PIPING IN EARTH DAMS CONSTRUCTED OF DISPERSIVE CLAY; LITERATURE REVIEW AND DESIGN OF LABORATORY TESTS

by

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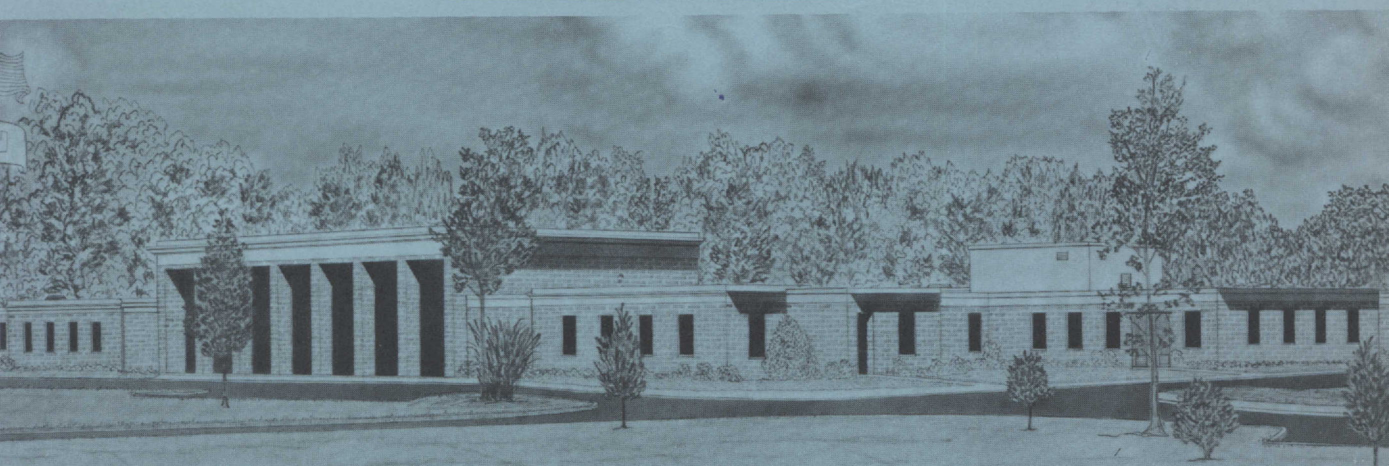

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It was assumed when empirical piping criteria were developed 25 yr ago that soil type and method of construction were the main parameters controlling the resistance of homogeneous earth dams to piping failure. Research on piping failure in earth dams constructed of dispersive clay (a particular type of soil in which the clay fraction erodes in the presence of water by a process of deflocculation) was initiated in Australia about 15 yr ago. This research has resulted in a method of analysis to assess the susceptibility of a
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20. ABSTRACT (Continued).

homogeneous earth dam, constructed of predominately illite or montmorillonite clay, to dispersive clay piping. The first study of dispersive clay in the United States, reported in 1972, developed a relationship between percent sodium and total soluble salts in the soil pore water extract and field performance of earth dams as evidenced by piping failure or rainfall erosion damage. This research has demonstrated the usefulness of the pinhole erosion test as a method of identifying dispersive clays, shown the feasibility of using filters to prevent piping in dispersive clays, and indicated that stabilization of dispersive clays is possible. A laboratory pinhole erosion apparatus has been designed and constructed at the Waterways Experiment Station (WES). A series of laboratory tests has been designed to standardize a procedure for use of the pinhole erosion test as a method of identifying dispersive clays, evaluate the effectiveness of filters in preventing piping in dispersive soils, and determine the influence of selected parameters on erodibility of dispersive clays. The procedure for conducting the Crumb Test is given in Appendix A, and Appendixes B and C present detailed drawings and photographs, respectively, of the WES laboratory erosion test apparatus.

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PREFACE

This study on piping in dispersive clay was funded by the Office, Chief of Engineers, U. S. Army, under CWIS 31173, Task 7, "Special Studies for Civil Works Soils Problems."

The study was conducted during the period July 1973-October 1974 at the U. S. Army Engineer Waterways Experiment Station (WES) by Dr. Edward B. Perry under the general supervision of Mr. Clifford L. McAnear, Chief, Soil Mechanics Division, and Mr. James P. Sale, Chief, Soils and Pavements Laboratory. This report was prepared by Dr. Perry.

BG E. D. Peixotto, CE, and COL G. H. Hilt, CE, were Directors of WES during the study and preparation of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
microns	0.001	millimetres
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	6.894757	kilopascals
pounds (force) per square foot	47.88026	pascals
tons (force) per square foot	95.76052	kilopascals
dynes per square centimetre	0.1000000	pascals
square feet per second	0.09290304	square metres per second
cubic feet per second	0.02831685	cubic metres per second
feet per second	0.3048	metres per second
degrees (angle)	0.01745329	radians

PIPING IN EARTH DAMS CONSTRUCTED OF DISPERSIVE CLAY; LITERATURE REVIEW AND DESIGN OF LABORATORY TESTS

PART I: INTRODUCTION

Background

1. Piping in an earth dam is the progressive internal erosion of the soil by the flow of water along preferred seepage paths such as cracks or sandy lenses traversing the width of the dam. Because of the frequency and the serious consequences of failures of earth dams due to piping, empirical piping criteria were developed before the mechanism of piping was understood. Laboratory studies of piping in cohesive soils were initiated to determine the mechanism of piping failure. Dispersive clays are a particular type of soil in which the clay fraction erodes in the presence of water by a process of deflocculation. This occurs when the interparticle forces of repulsion exceed those of attraction so that clay particles are detached and go into suspension. If the water is flowing, as in a crack in an earth dam, the detached clay particles are carried away and piping occurs. Research on piping failure in earth dams due to dispersive clay behavior was initiated in Australia. The first study of dispersive clay piping in earth dams in the United States was reported in 1972. It has been suggested that tests of clay dispersibility should be made as a routine part of studies for earth dam design.

Objective of the Study

2. The objective of the study was to design and construct the necessary laboratory equipment to (a) identify dispersive clays; (b) evaluate the effectiveness of filters in preventing piping in dispersive clays; and (c) conduct research on the influence of selected parameters on the erodibility of dispersive clays. The design of the laboratory equipment was preceded by a literature review on empirical piping

criteria and laboratory studies of piping, soil erosion, and dispersive clay.

Scope of the Study

3. When work on this study was undertaken in July 1973, various governmental organizations and universities were just beginning research on dispersive clays. In order to gain knowledge of existing research and to avoid duplication of effort in the work to be conducted at the U. S. Army Engineer Waterways Experiment Station (WES), visits were made to the University of California at Davis; Soil Mechanics Unit of the Soil Conservation Service in Lincoln, Nebraska; Oklahoma State University; and the United States Department of Agriculture Sedimentation Laboratory in Oxford, Mississippi, to discuss current research on dispersive clays. This report is limited to the literature review, design and construction of laboratory equipment, and the design of laboratory tests to identify dispersive clays, evaluate the effectiveness of filters in preventing piping in dispersive clays, and evaluate the influence of selected parameters on the erodibility of dispersive clays.

PART II: REVIEW OF PREVIOUS RESEARCH

Empirical Piping Criteria

4. In a study of the influence of soil properties and construction methods on the performance of homogeneous earth dams reported in 1952, Sherard[1] assumed that soil type and method of construction were the main parameters controlling the resistance to piping. In order to evaluate the piping resistance of the thirty-one dams studied, Sherard devised three categories. Category 1 represented the greatest resistance to piping. In this category, if failure occurred it would take place slowly, thus allowing time for remedial action to be taken. Although an embankment might eventually fail as a result of slowly progressive piping caused by a large (arbitrarily defined as 0.5 cfs*) concentrated leak, smaller leaks would heal themselves or continue to flow without an increase in quantity of flow. Category 2 represented intermediate resistance to piping. In this category, dams would safely resist saturation of the lower portions of the downstream slope indefinitely; a small concentrated leak for a long period of time could result in failure; and if a large concentrated leak through the embankment developed, complete failure would result in a short period of time. Category 3 represented the least resistance to piping. In this category, dams would fail completely within a few years after first reservoir filling if any water found its way to the unprotected downstream slope, and any small concentrated leakage on the downstream slope would cause failure within a short period of time.

5. Figure 1 shows the relationship between Atterberg limits of the embankment soils and the piping resistance. As shown in Figure 1, nearly all the dams constructed from soils with a plasticity index greater than 15 were in the piping resistance category 1 (highest resistance). All the dams which fell in piping resistance category 3

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* A table for converting U. S. customary units of measurement to metric (SI) units is given on page 4.

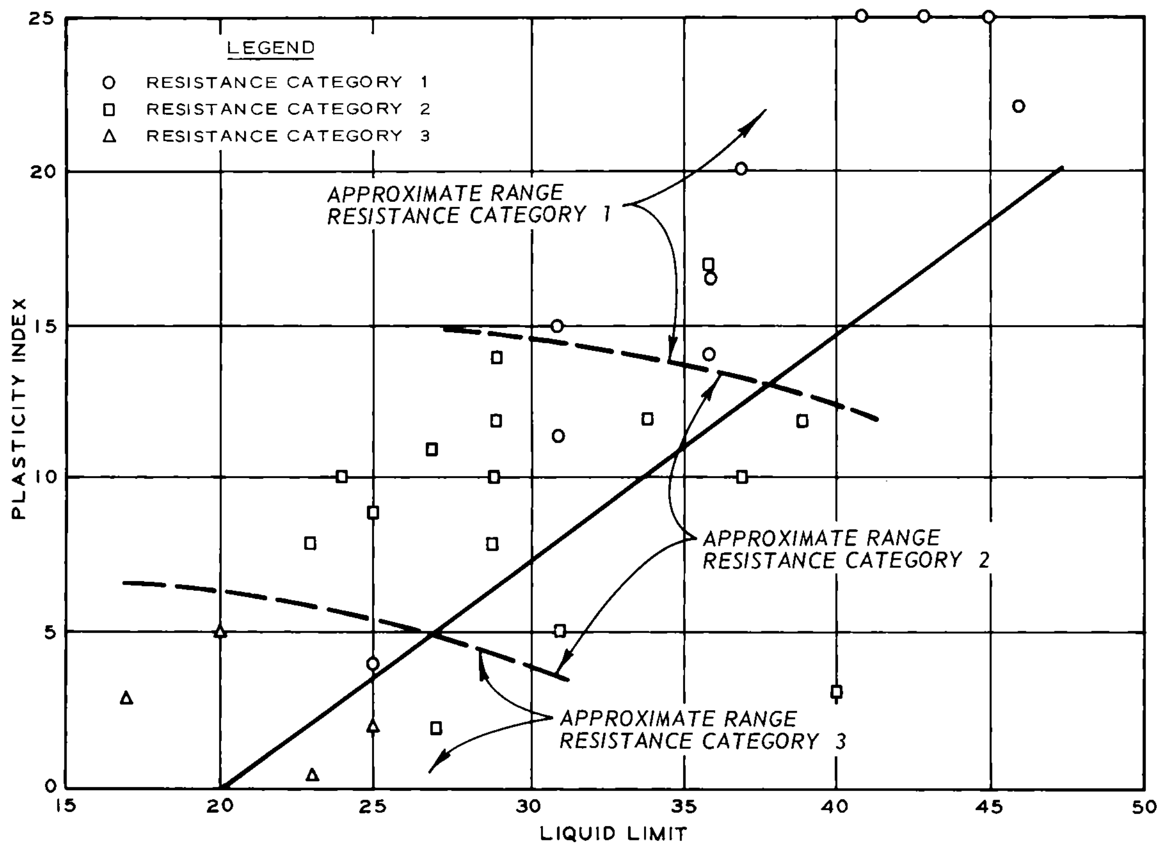


Figure 1. Relationship between Atterberg limits and resistance to piping (from Reference 1)

(least resistance) were constructed from soils with plasticity indexes less than 5. The data of Figure 1 also suggest that the higher the liquid limit for a given plasticity index, the higher the piping resistance.

6. Figure 2 shows the relationship between gradation of the embankment soils and the piping resistance. As shown in Figure 2, the soils in resistance categories 1 and 2 were fairly well-graded with category 1 containing the finer soils with the higher clay contents and category 2 containing the coarser material. Of the four dams whose resistance to piping was such that they were placed in category 3, all but one represent very fine, very uniform sands.

7. Study of the relationship between the method by which the dam was constructed and the piping resistance indicated that coarse

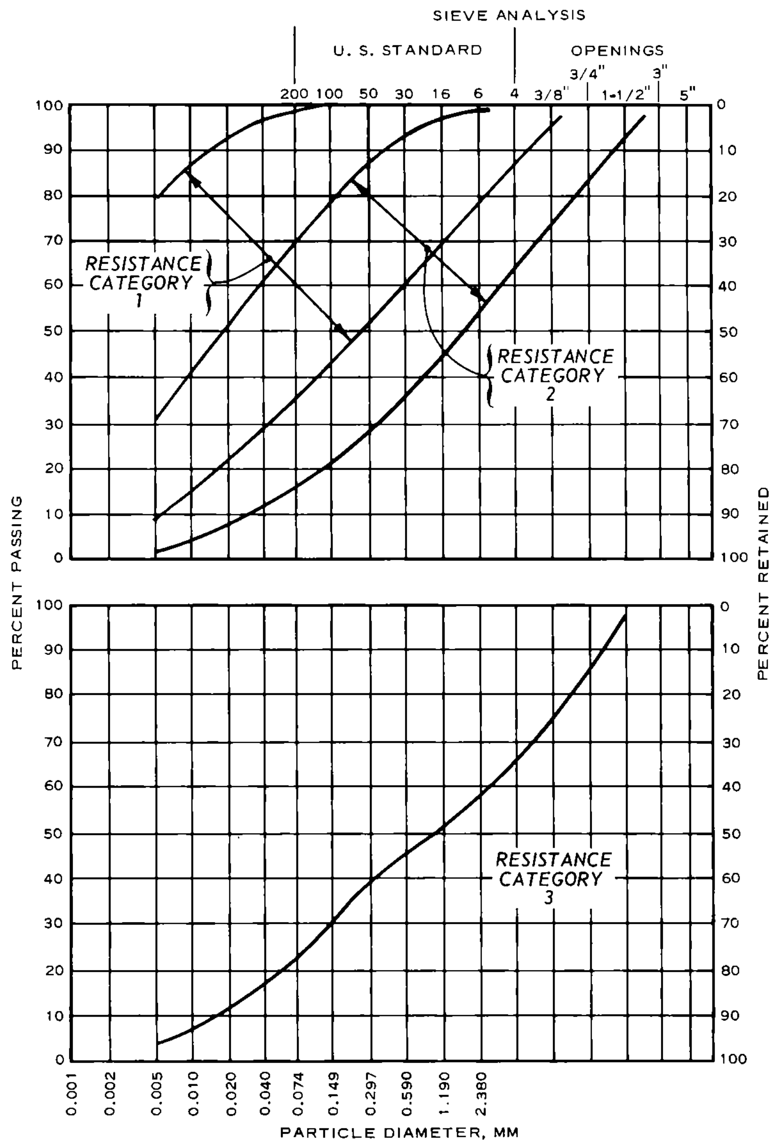


Figure 2. Relationship between gradation and resistance to piping (from Reference 1)

soils with nonplastic fines may have low piping resistance when lightly compacted and relatively high resistance when heavily compacted. For dams constructed of fine sands, no conclusions could be drawn regarding the relationship between the method of construction and the piping resistance because all three dams studied failed and all were relatively poorly compacted. For soils with a plasticity index greater than 15, the very poorest construction did not reduce the piping resistance.

8. The relationship between piping resistance, soil type, and construction method is summarized in Table 1. Sherard discusses the empirical relationships given in Table 1 in later publications.[2-4]

9. In connection with a study of the influence of the earthquake hazard on the design of embankment dams conducted for the California Department of Water Resources, Sherard[5] presented a classification of core materials on the basis of resistance to concentrated leaks as shown in Table 2.

Laboratory Studies of Piping

10. Davidenkoff[6] in 1955 reported on a theoretical and experimental study of the composition of filters in earth dams. Using simplified assumptions regarding the exit gradient, an approximate formula was derived relating the cohesive strength of the base soil to the size of the protecting filter material and hydraulic gradient averaged over the filter thickness. The experimental apparatus used in the laboratory studies is shown in Figure 3. A unique feature of the laboratory apparatus was the use of a hole in the lower plate supporting the soil specimen to simulate a filter material.

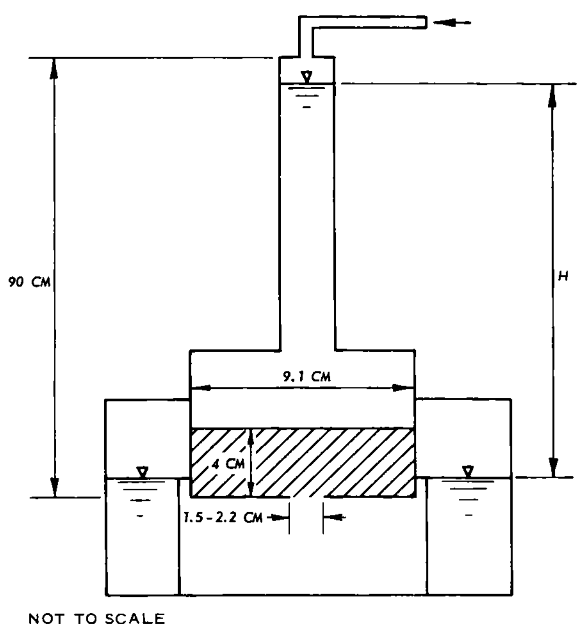


Figure 3. Experimental apparatus used by Davidenkoff to study piping in cohesive soils (courtesy of International Commission on Large Dams[6])

11. Czyzewski and coworkers[7] in 1961 reported on an experimental study of filter requirements for earth dams. Figure 4 shows the two types of filter tests which were conducted to represent conditions

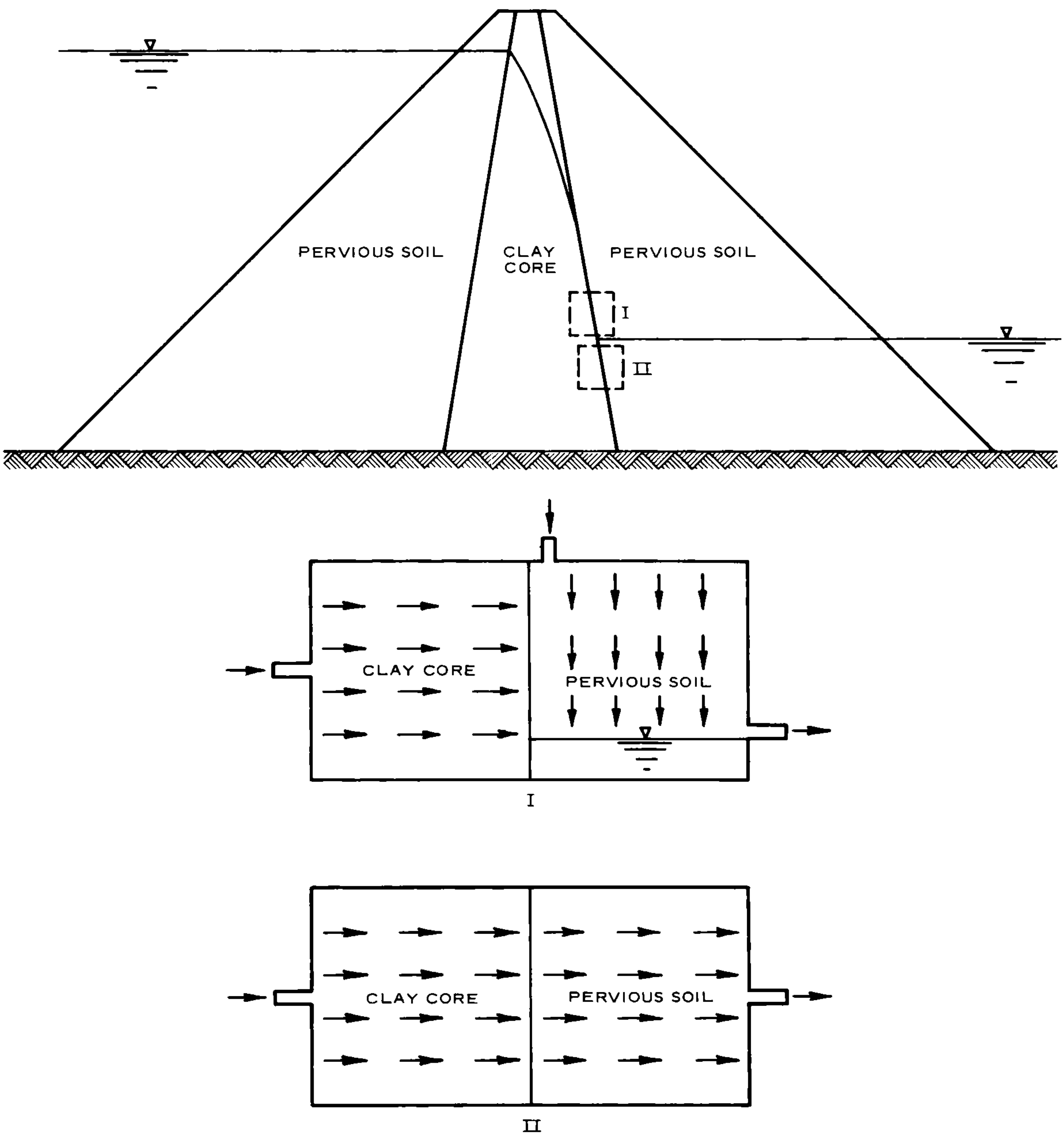


Figure 4. Modified permeameters used by Czyzewski and coworkers to study filter requirements for earth dams (courtesy of International Commission on Large Dams[7])

existing on the downstream face of the core of the dam. A novel approach used in one type of filter test was to introduce water into the top of the permeameter to simulate downward flow through the filter material on the downstream face of the core of the dam.

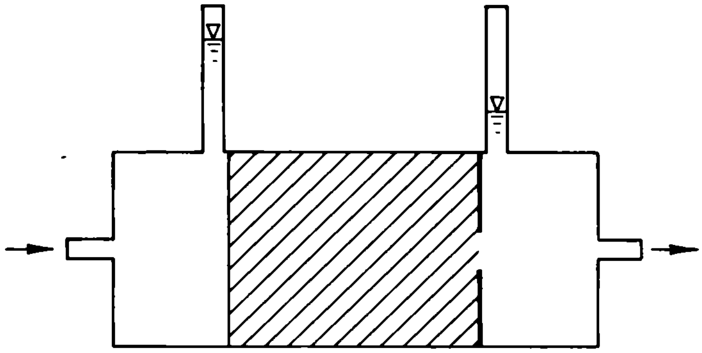
12. Zaslavsky and Kassiff[8,9] presented a theoretical formulation for piping in cohesive soils considering drag forces due to water flow, submerged weight, and soil tensile strength. Using an experimental apparatus similar to the one developed by Davidenkoff with a multiple-hole perforated base and spring-loaded surcharge, Kassiff and coworkers found the safety factor against piping to be inversely proportional to the size of the aggregate washed out.[10] The effect of surcharge was found to be significant. No failures were obtained for tests under a surcharge of 0.2 kg/cm^2 using hydraulic gradients up to 1000. Although the measured average gradients required to cause failure through the holes in the perforated base increased with decreased size of holes, an estimate of the actual exit gradient obtained from a flow net of the soil specimen was independent of the size of the holes.

13. Wolski[11] used an experimental apparatus similar to the one developed by Davidenkoff to study piping failure of a silty clay core of an earth dam. Piping failure, defined in terms of the hydraulic gradient at which a cylindrical hole was eroded through the soil specimen, occurred rapidly once the depth of the eroded zone penetrated two-thirds the length of the soil specimen.

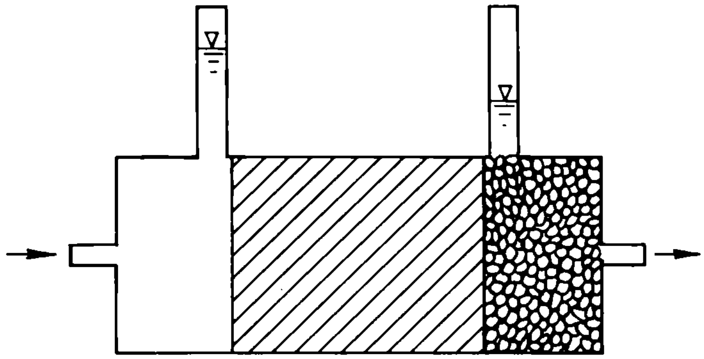
14. Ranganatham and Zacharias[12] in 1968 used an experimental apparatus similar to the one developed by Davidenkoff to study the effects of initial dry unit weight and hydraulic gradient on the piping resistance of cohesive soils. The critical hydraulic gradient was taken to be the gradient at which a dome-shaped portion of soil separated from the soil specimen. The tests were not continued until a cylindrical hole was eroded through the soil specimen. For the two soils tested, kaolinite clay and a local clay, the critical hydraulic gradient was found to increase with increasing initial dry unit weight.

15. In 1970 Wolski and coworkers[13] reported on an experimental study of cracking and piping of a silty loam core of an earth dam.

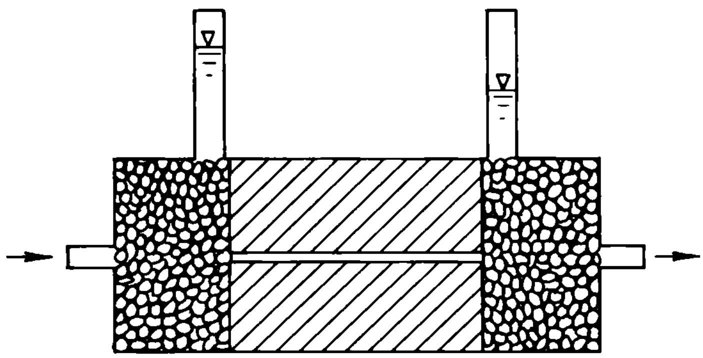
Figure 5 shows the different types of laboratory apparatus used to study piping in the earth dam. This is the first study, to the author's



a. DAVIDENKOFF - TYPE PIPING APPARATUS



b. CONVENTIONAL PERMEAMETER



c. PINHOLE EROSION APPARATUS

Figure 5. Laboratory apparatus used by Wolski and coworkers to study piping in earth dam cores (courtesy of International Commission on Large Dams[13])

knowledge, where the pinhole erosion apparatus, shown in Figure 5c, was used to study piping in soils. The results of the laboratory piping tests by Wolski and coworkers indicated that the filter criteria were dependent upon the plasticity index and geometry of the core of the earth dam. The potential usefulness of the pinhole erosion apparatus was recognized by Sherard[2] as early as 1959:

> The writer once considered attempting a research program directed at studying "piping" resistance for an earth dam material in the laboratory by forcing water through a cylindrical hole in a soil specimen compacted in a Proctor mold and measuring the weight of eroded soil as a function of various parameters of rate and time of water flow.

The first use of the pinhole filter apparatus, to the author's knowledge, was reported by Cole and Lewis[14] in connection with an investigation of piping failure of Lake Grace Dam in Australia. In describing the laboratory tests Cole and Lewis stated:

> The efficiency of a graded gravel and sand filter in restricting the development of "pipes" in soil was studied. A 5-in. layer of soil was loosely compacted over a graded filter layer in a 4-in. diam perspex tube. Under a constant head of 16 in. of water, seepage paths throughout the dry soil mass and along artificially induced 1/4-in. diameter "pipes" through the soil, were found to be quickly sealed off by the deposition, against the filter boundary, of clay particles carried down by the moving water.

16. A review of theoretical and experimental aspects of piping and filter requirements for cohesive soils was reported by Kulandaiswamy and coworkers[15] in 1971. Using the Davidenkoff-type piping apparatus, they developed analytical procedures to determine the critical exit gradient, taking into consideration the cohesion and tensile strength of the base soil and the dimensions of the filter pore opening. Flow conditions of seepage water through the base soil above the filter pore opening were determined from flownets. Two distinct types of failure were proposed, one based on plastic failure and the other based on brittle failure mechanism. For soils compacted wet of optimum water content, Mohr-Coulomb and Von Mises yield criteria were used to derive expressions for the critical exit gradient. For soils compacted dry of optimum water

content, Griffith-Brace and Griffith-Murrel failure criteria were used to derive expressions for the critical exit gradient. An experimental program, as shown in Table 3, was outlined to study the piping mechanism in cohesive soils and to verify the proposed methods for the determination of the critical exit gradient. The investigators were aware of the existence of dispersive clays, as a result of the research by Australian workers, and included physicochemical aspects of clays in the experimental program. The research program outlined in Table 3 has been completed and is in the process of being published.

Laboratory Studies of Soil Erosion

17. The influence of physicochemical factors on the erosion of soil was recognized by Middleton[16,17] in 1930. From the results of laboratory tests conducted on soils that had been observed in the field to be erosive and nonerosive, the dispersion ratio was found to be the best index of erosional behavior. In Middleton's studies the dispersion ratio was measured as follows:

> A sample of air-dry soil equivalent to 10 grams of oven-dry soil was placed in a tall cylinder of approximately 1200 cubic centimeter capacity fitted with a rubber stopper. Sufficient distilled water was added to make the volume a liter. The cylinder was closed with a stopper and was shaken end over end twenty times. The suspension was then allowed to settle until a 25 cubic centimeter sample, which was pipetted at a depth of 30 centimeters, consisted of particles of a maximum diameter of 0.05 millimeter. From the dry weight of the pipetted fraction, the total weight of silt and clay in the suspension was calculated. The ratio, expressed in percentage, of the silt and clay so determined to the total silt and clay obtained by mechanical analysis is called the dispersion ratio.

Soils with a dispersion ratio of less than 10 were classified as nonerosive. Middleton did not find any direct correlation between the chemical analysis of the soils tested and erosional behavior. Subsequent work by Lutz[18] published in 1934 confirmed the usefulness of the dispersion ratio as an index of erosional behavior.

18. In 1946 Straub[19] reported the results of a laboratory study to determine the erosive properties of undisturbed clay specimens taken from the vicinity of the spillway structure of the San Jacinto River damsite near Houston, Texas. Fifteen-inch-cube clay specimens were placed in a 3-ft-wide laboratory flume with the top surface of the clay at the same elevation as the bottom of the flume. The specimen was oriented so that the flow was in the same direction as in nature. The erosion of the clay was computed from measurements taken on the top surface of the clay before and after each test at points on a square grid system with 1-in. intervals. The length of each run was governed by the time required for measurable loss of clay to occur or until the sides of the box containing the clay specimen noticeably interfered with the flow of the water. The results of the tests indicated that erosion upstream of the spillway on the clay strata would amount to only a fraction of an inch per day for velocities over the clay as high as 8 fps where the material near the top surface was relatively homogeneous and uniform in texture. Where the clay was fractured and contained pockets of sand and sandstone, erosion rates would reach 1 ft per day for velocities up to 8 fps. For velocities of 10 fps or greater over the clay strata, potholes would be likely to develop in the clay if the velocity continued for any appreciable period of time. No soil property data were given other than a visual description of the soil samples.

19. In a study of south coastal California soils in 1950, Anderson[20] used multiple regression analysis to obtain equations relating physical soil characteristics to erosion measurements taken in the field from 14 watersheds. The dispersion ratio, as defined by Middleton, was found to be a useful expression of erosional behavior when compared with measured erosion from watersheds.

20. Since 1950 there have been a number of studies conducted to provide a rational method for the design of stable (nonscouring) channels in cohesive soils.[21] The need to measure the critical shear stress at which incipient cohesive bed movement began led to the development of specially designed laboratory apparatus.

21. In 1959 Dunn[22] reported on the results of a laboratory study

on remolded consolidated clay samples taken from canals in Nebraska, Wyoming, and Colorado. The soil samples were subjected to erosion by submerged vertical water jet impinging on the sample whose upper surface formed the bottom of a small cylindrical container. The magnitude of the shear stress for various jet heads was calibrated by measuring the force exerted on a shear plate located in the region of observed initiation of erosion. The critical flow was defined in the following way:

> The jet was then positioned above the soil sample and the head of water on the nozzle (H) was slowly increased.... With each additional increase in H , a small additional amount of soil was carried off the surface followed by clearing of the water in the container. When H reached the critical value, the rate of erosion increased, the water became cloudy, and no subsequent clearing occurred. The critical point was definite and reproducible in the clay samples.

The critical shear stress was related to the laboratory vane shear strength. The results of the study indicated that the most useful index property for estimating the critical shear stress was the plasticity index with an applicable range between five and sixteen. Methods based on characteristics of the particle size curves were also useful in the correlation.

22. Smerdon and Beasley[23] conducted erosion tests in a flume in an attempt to correlate critical tractive force with the physical properties of eleven Missouri soils ranging from a silty loam to a highly cohesive clay. The soils were placed in the flume and leveled without compaction. The critical condition was defined as the point at which the bed material was in general movement. The critical tractive force was found to correlate with the plasticity index, the dispersion ratio, the mean particle size, and the percent clay.

23. In a companion study to the one described previously, Laflen and Beasley[24] conducted erosion tests in a flume to determine the effect of void ratio on the critical tractive force. The soils were placed in the flume at approximately natural water content and compacted using hand tamping tools. After compaction, water was admitted into the flume. The

soil was then allowed to drain through the perforated bottom of the flume for 18 hr before conducting the test. The critical condition was defined as the point at which the soil aggregate movement did not increase appreciably with time. At the end of the test the soil was allowed to drain again, and undisturbed soil samples were taken for the determination of void ratio. A linear relationship was found to exist between the void ratio and critical tractive force for each soil tested.

24. The Bureau of Reclamation[25-27] conducted a field and laboratory study from 1960 to 1962 to determine the critical tractive force to be used in the design of canals in cohesive materials. Undisturbed soil samples were obtained from 46 straight test reaches of canals in cohesive soils in five of the seven regions of the Bureau of Reclamation. A laboratory tractive force testing apparatus, as shown in Figure 6, was developed to determine the critical tractive force of undisturbed samples of soil material obtained from each of the test reaches. The tractive force apparatus included a 35-in.-diam tank, a variable-speed air motor, a transparent lid, impeller blades, pressure gage, and a pressure regulator. Prior to testing, the soil samples were immersed in water for one week in an attempt to saturate the soil. Since a direct method for measuring boundary shear was not available, the rotational velocities required to move uniform sands and gravel were determined in the tractive force apparatus and correlated with known values of critical tractive force. The test procedure consisted of approaching the critical rotational velocity in systematic steps between which the velocity was held constant over specified intervals of time. Incipient erosion was judged by observation through the transparent tank lid. The tractive force which developed when general erosion of the surface of the soil sample began was considered to be the critical tractive force. The critical tractive force was correlated with plasticity index, liquid limit, dry unit weight, mechanical analysis (using a logarithmic probability analysis), shrinkage limit, vane shear values, and percent of maximum Proctor dry unit weight using a multiple linear correlation method. The plastic limit, liquid limit, and dry unit weight were found to correlate best with erosion characteristics obtained using the tractive force testing

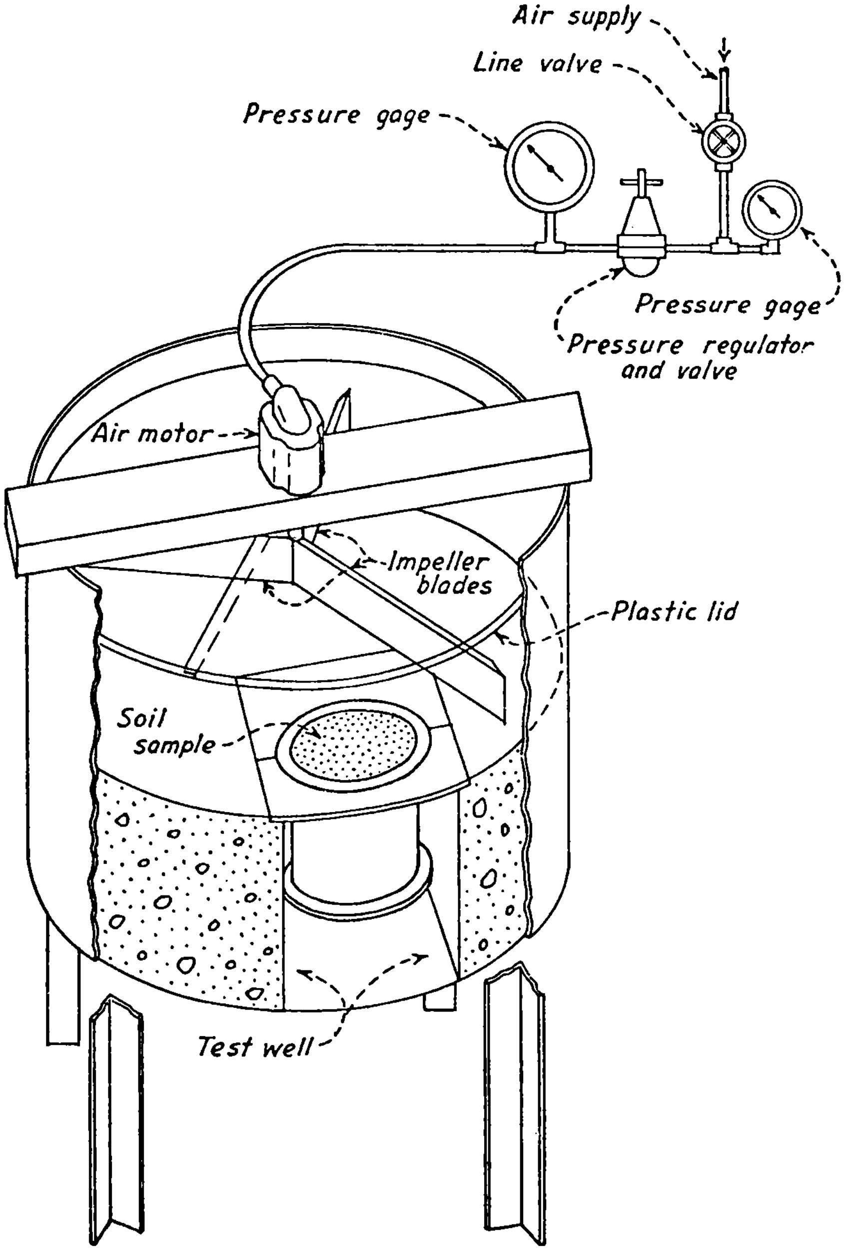


Figure 6. Bureau of Reclamation tractive force test apparatus (from Reference 25)

apparatus.[27] Figure 7 shows the correlation between plasticity and erosion characteristics from both laboratory tests and field observations.[26] As shown in Figure 8, natural dry unit weight has some effect on erosion resistance but not as pronounced an effect as does plasticity.[26]

25. The tractive force testing apparatus was used in a subsequent

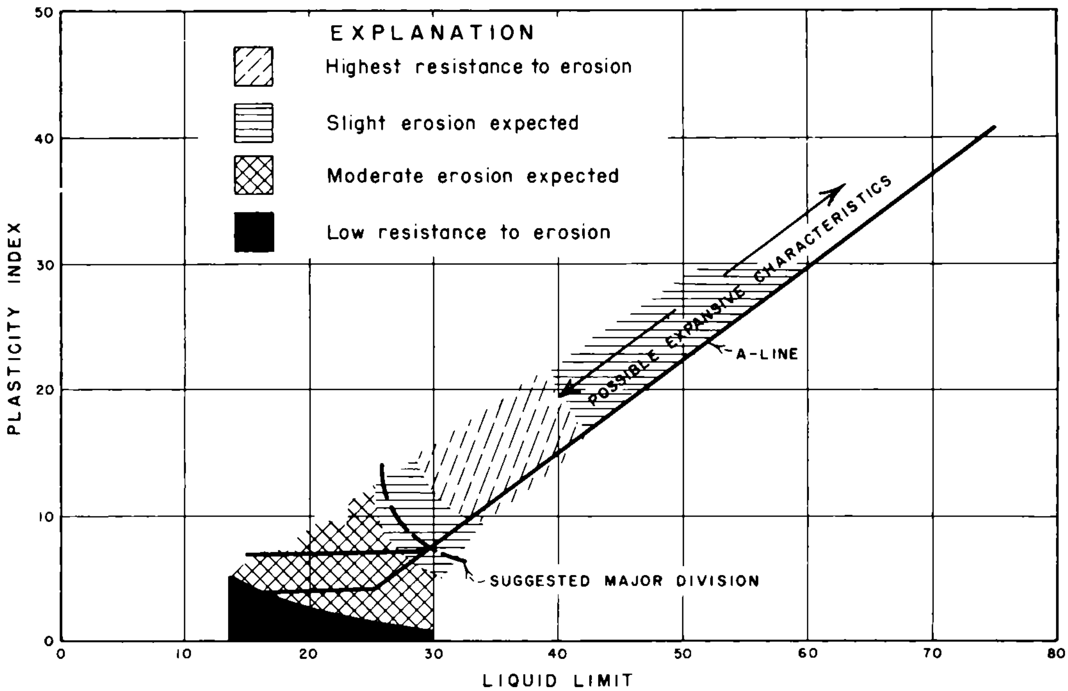


Figure 7. Relationship between plasticity and erosion characteristics from both laboratory tests and field observations (from Reference 26)

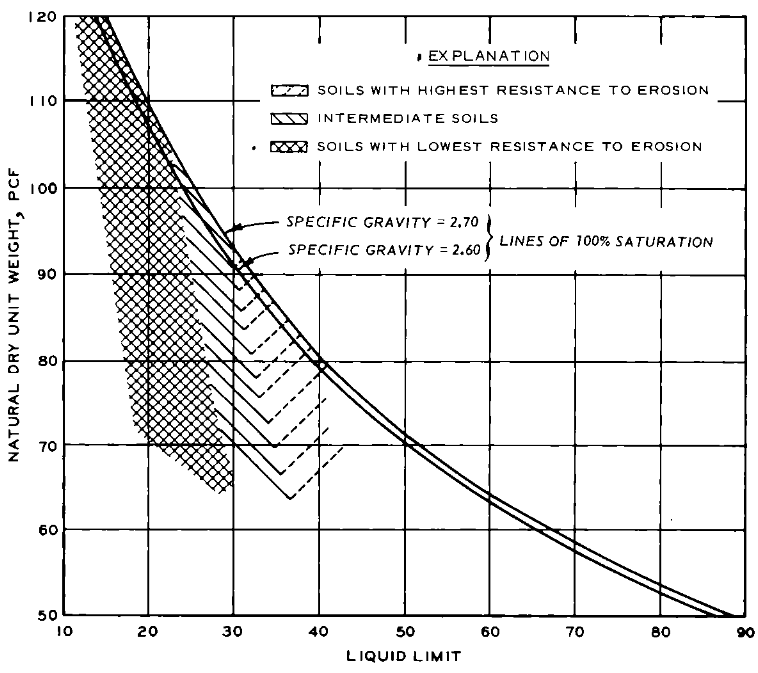


Figure 8. Relationship between natural dry unit weight and erosion characteristics (adapted from Reference 26)

study of the erodibility of a silty clay modified with both portland cement and asphalt emulsion.[28] Soil specimens containing 2.5 percent Type I portland cement by volume did not erode at tractive forces within the capacity of the testing apparatus (0.77 psf). Soil specimens containing 1 percent asphalt by dry weight of the soil eroded at a tractive force of 0.140 psf. Wetting and drying and natural weathering resulted in additional deterioration of the asphalt-modified specimens.

26. In a study reported in 1961, Wallis and Stevan[29] indexed the inherent erodibility of twenty California soils using Middleton's dispersion ratio and Anderson's surface-aggregation ratio. These erodibility indexes were related to the predominate exchangeable cations (calcium, magnesium, potassium, sodium) present in the soil. Using a regression analysis, the best fit to the data, with an arbitrarily selected 5 percent significance level, was given by the equation

$$\text{Erosion Index} = a + b\,(Ca^{++} + Mg^{++}) + c\,(Ca^{++} + Mg^{++})^2 \qquad (1)$$

where a, b, c = constants and Ca^{++}, Mg^{++} are expressed in milliequivalents per 100 grams of oven-dried soil. The soils contained relatively small amounts of potassium and sodium as compared with the calcium and magnesium present.

27. Moore and Masch[30] in 1962 used a jet test apparatus to measure the rate of erosion of undisturbed and remolded cohesive soils. The results obtained indicated that the erosion was proportional to the logarithm of time during which the erosion occurred. In an effort to minimize the effect of variation in shear stress acting on the soil surface with respect to time and location, Moore and Masch introduced the rotating cylinder test apparatus shown in Figure 9. This apparatus was built using rotating cylinder principle common to certain types of viscosimeters.[30,31] A cylinder of cohesive soil 3 in. in diameter and 4 in. long was mounted coaxially inside a larger transparent cylinder that can be rotated at speeds up to 2500 rpm. To transmit shear from the outer rotating cylinder to the surface of the soil specimen, the annular space between the soil specimen and the outer rotating cylinder was filled with

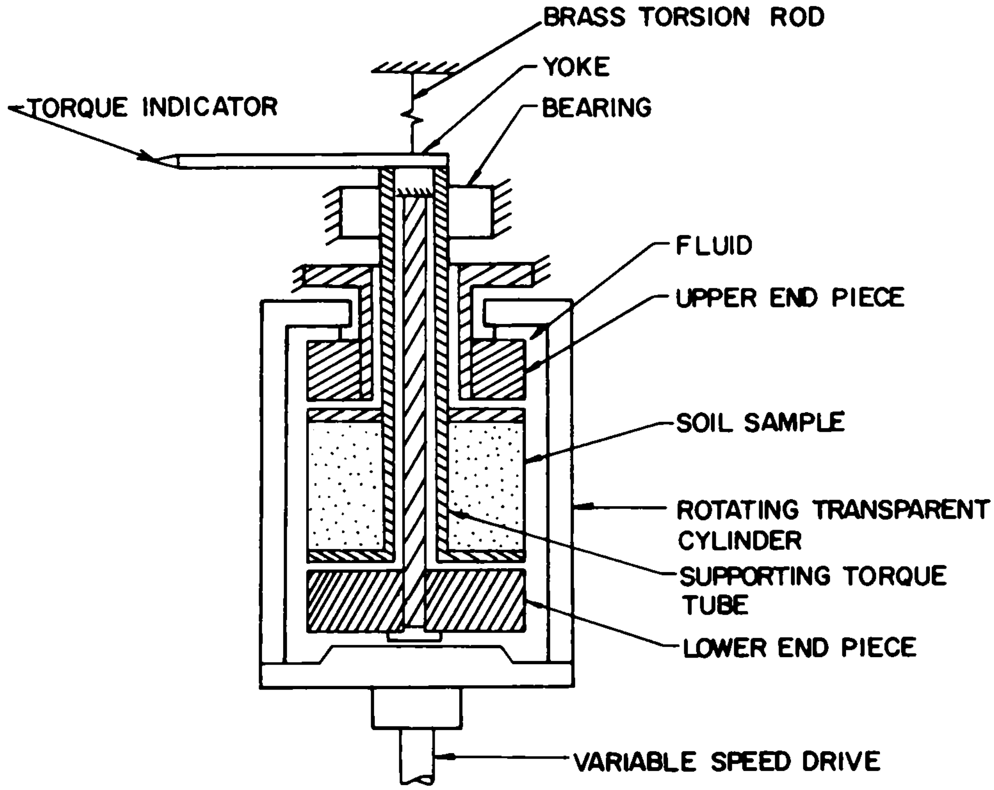


Figure 9. Cross-sectional view of rotating cylinder test apparatus (from Reference 31)

water. Since the distance between the surface of the soil specimen and the outer rotating cylinder was constant and there were no abrupt changes in roughness on the area in shear, the shear stress acting on the surface of the soil specimen was uniform. The soil specimen was stationary, but was mounted on a combination radial and thrust bearing so that the shear stress transmitted to the surface of the soil specimen resulted in a slight rotation of the supporting tube. This rotation was calibrated to measure the magnitude of torque on the soil sample and, thereby, the shear stress on the surface of the soil specimen. To minimize the variation in shear stress at the ends of the soil sample, end pieces were mounted independently of the sample so that the shear stress applied to their surfaces would not contribute to the measured torque for the soil sample. In a discussion of the paper by Moore and Masch, the significance of tensile strength, salt concentration, and water content was noted by Martin.[32]

28. Espey[33] conducted a pilot test series using the rotating cylinder test apparatus to determine the critical shear stress for remolded Taylor Marl clay. The soil samples were prepared by extrusion from a vacuum extruder resulting in samples with a high degree of saturation. Two different procedures were used to determine the critical shear stress. The first method consisted of loading the soil sample to a value of shear over a period of 1 min and allowing it to scour at this stress for 1 min. The soil sample was then removed from the rotating cylinder test apparatus and its weight loss determined. The soil sample was placed in the apparatus again, loaded to a higher value of shear in 1 min, allowed to scour for 1 min, and weight loss determined. This procedure was repeated with the weight loss plotted as a function of the shear stress noting the range of shear stress at which an appreciable quantity of soil was removed. The second method consisted of increasing the shear stress at a steady rate and visually observing the beginning of scour by viewing the soil sample through the transparent outer cylinder. The preparation of the soil sample was found to influence the test results. If any small cracks were present on the surface of the soil samples after molding, the samples, when tested in the rotating cylinder test apparatus, would fail prematurely along planes formed by the cracks.

29. Rektorik[34] used the rotating cylinder test apparatus in an attempt to correlate the critical shear stress with the moisture content, vane shear strength, void ratio, plasticity index, percent clay, and exchangeable calcium-sodium ratio for six cohesive soils. The soil samples were prepared using a vacuum extruder resulting in samples with a high degree of saturation. Correlation and linear regression analyses indicated that for five of the six soils tested, the critical shear stress increased with decreasing moisture content, increased with increasing vane shear strength, and decreased with increasing void ratio. No apparent correlation was found between critical shear stress and plasticity index, percent clay, or exchangeable calcium-sodium ratio for the soils when tested at a common moisture content equal to the liquid limit.

30. In 1962, Cecil and Karaki[35] reported on a laboratory study to determine the type of protective crushed rock cover required to

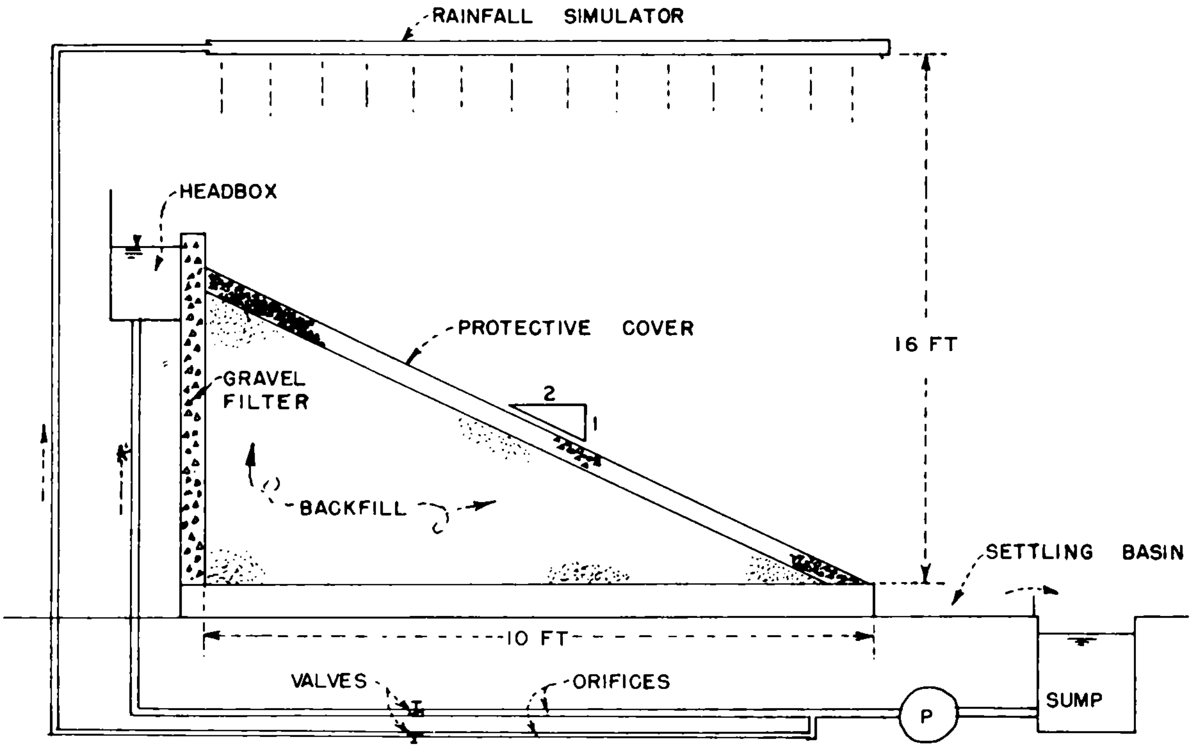


Figure 10. Schematic diagram of rainfall simulator (from Reference 35)

prevent earth embankment erosion due to rainfall. A laboratory rainfall simulator shown in Figure 10 was used in the study. A review of the literature on rainfall simulators was given by Parr and Bertrand[36] in 1959. More sophisticated rainfall simulators[37,38] have recently been developed. Preliminary tests made by Cecil and Karaki[35] on well-graded river sand and sandy loam topsoil indicated that erosion due to raindrop impact was of minor importance compared to erosion caused by runoff. The results of the study showed that 6-in. cover of nominal 0.75-in. crushed rock adequately protected both the sand and topsoil from rainfall erosion.

31. In a study reported in 1962, Partheniades[39-41] studied the erosion of San Francisco Bay soil in a straight flume with recirculating water at ocean salinity. The soil, which was composed of about equal amounts of silt and clay, was placed at natural water content with a resulting undrained shear strength of 40 psf. For this soft soil, the

erosion rate was found to be independent of the shear strength of the soil and of the concentration of suspended sediment in the flume.

32. The Bureau of Reclamation[42] in 1963 reported on the use of a recirculating flume to study the effects of water temperature, soil moisture content, and soil dry unit weight on the critical shear stress. Following static compaction, the 8-in.-diam samples of fine-grained cohesive soils were saturated by submergence in water for a minimum of 48 hr to simulate the conditions which would occur in an operating canal. Measurements on the soil sample top surface were used to determine the amount of erosion which occurred during a test. The critical boundary shear was taken as the shear at which the soil sample started to erode. As shown in Figure 11, the critical boundary shear increased with

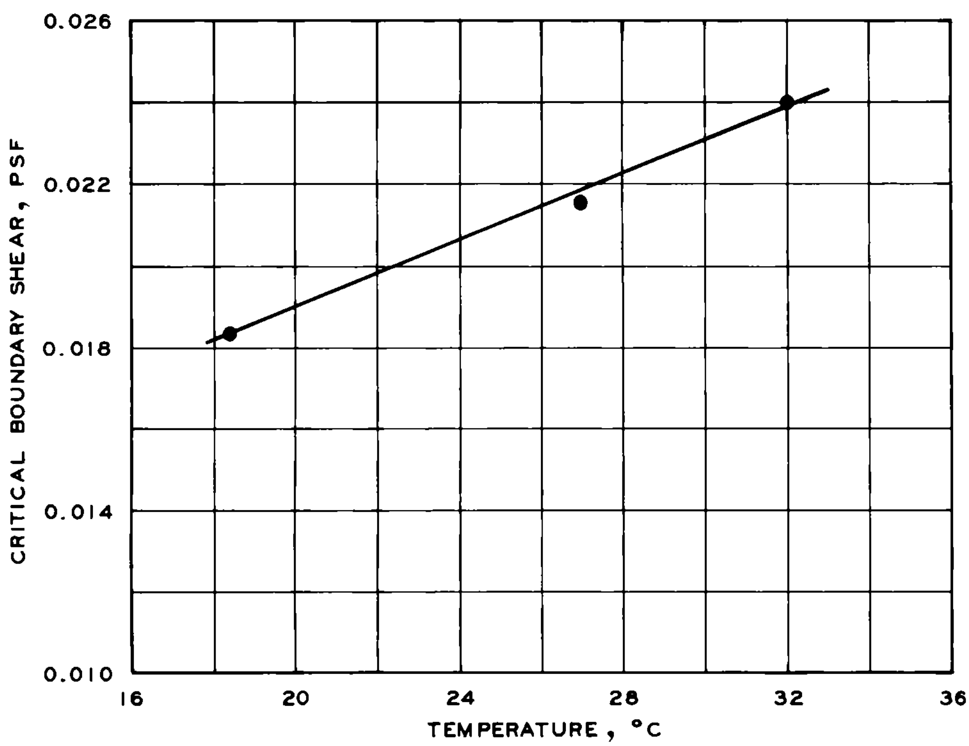


Figure 11. Effect of water temperature on critical boundary shear (after Reference 42)

increase in water temperature. As the moisture content at compaction increases, the critical boundary shear increases as shown in Figure 12. As shown in Figure 13, the critical boundary shear increased with

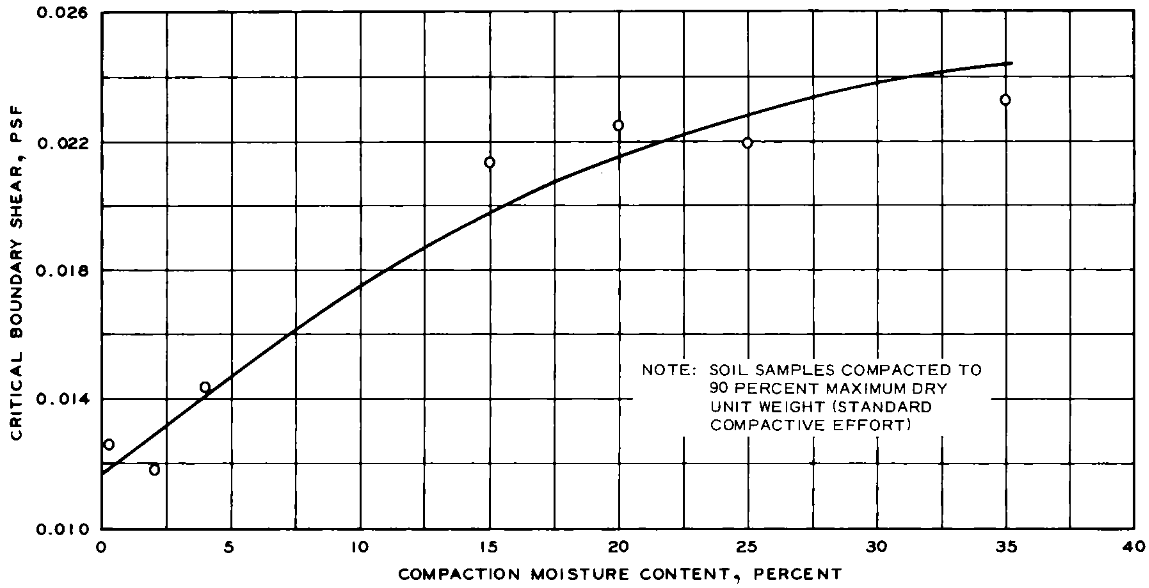


Figure 12. Effect of compaction moisture content on critical boundary shear (after Reference 42)

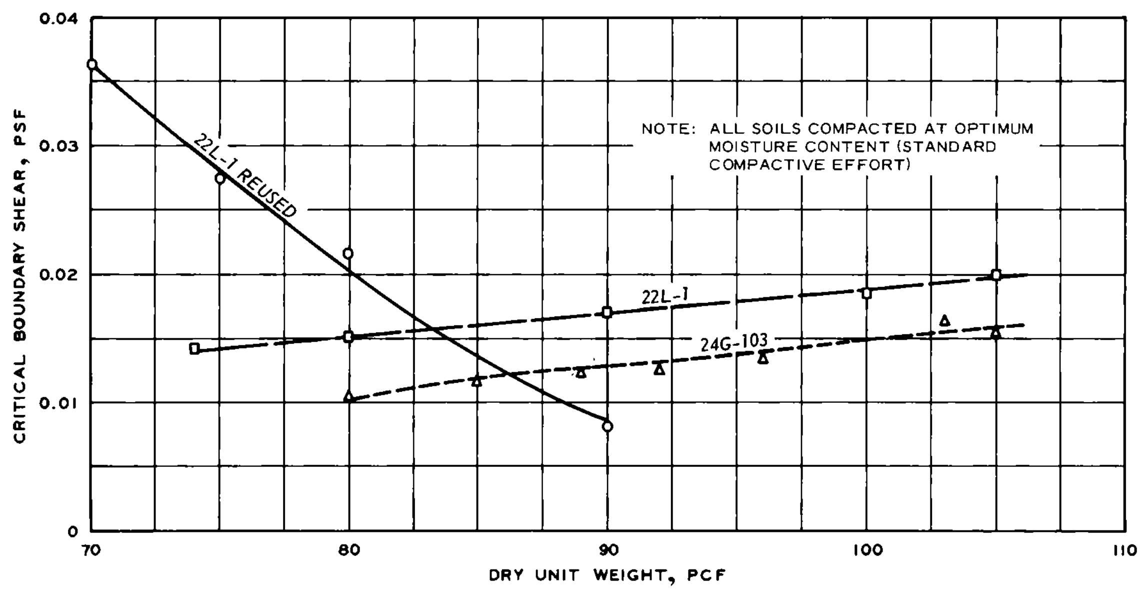


Figure 13. Effect of dry unit weight on critical boundary shear (after Reference 42)

increase in dry unit weight. When one of the soils tested was reused, it appeared to be less resistant to erosion as dry unit weight increased.

33. Lyle[43,44] used a laboratory flume to study the effect of compaction and selected soil properties on the erosion resistance of sand

and clay. The soil was hand tamped in the flume, wetted, and allowed to drain through a perforated bottom for 20-24 hr before the tests were conducted. The critical tractive force was determined by plotting the degradation rates of the channel bed versus the corresponding tractive force. The degradation rate increased linearly at a very slow rate up to a point. Above this point the degradation rate increased rapidly with increase in tractive force. Following this rapid change, the degradation rate again increased linearly, but at a more rapid rate. The critical tractive force was determined by extending the straight-line portions of the curves until they intersected. The critical tractive force for each soil tested was found to increase linearly with compaction as indicated by a decrease in the void ratio as shown in Figure 14. The straight-line functions of critical tractive force versus void ratio were assumed to extend over the range of void ratios from 0.8 to 1.6, and a regression analysis was run to analyze the regression of critical tractive force for particular void ratios on various soil properties. This regression was run on four separate plots of data, an arithmetic plot, two semi-logarithmic plots, i.e., taking the logarithm of the independent and dependent variable alternately, and a logarithmic plot. The regression analysis indicated that the plasticity index, as shown in Figure 15, was the most highly significant factor for determining critical tractive force. The dispersion ratio, as shown in Figure 16, gave higher correlation in the regression analysis for all values of void ratio than any other property considered. Other soil properties considered were vane shear strength, percent organic material, percent clay, mean particle size, calcium-sodium ratio, and cation exchange capacity. Comparison of the critical tractive force for a void ratio of 1.4 obtained by Rektorik[34] using the rotating cylinder apparatus with values obtained by Lyle[43] using the laboratory flume for two common soils (Houston Black clay and Lake Charles clay) indicates that the ratio of critical tractive force from the rotating cylinder apparatus was about twenty-five times higher than that obtained from the laboratory flume. This may be due in part to the increased resistance to erosion afforded by the spiral orientation of the soil particles[45] inherent in the vacuum extrusion

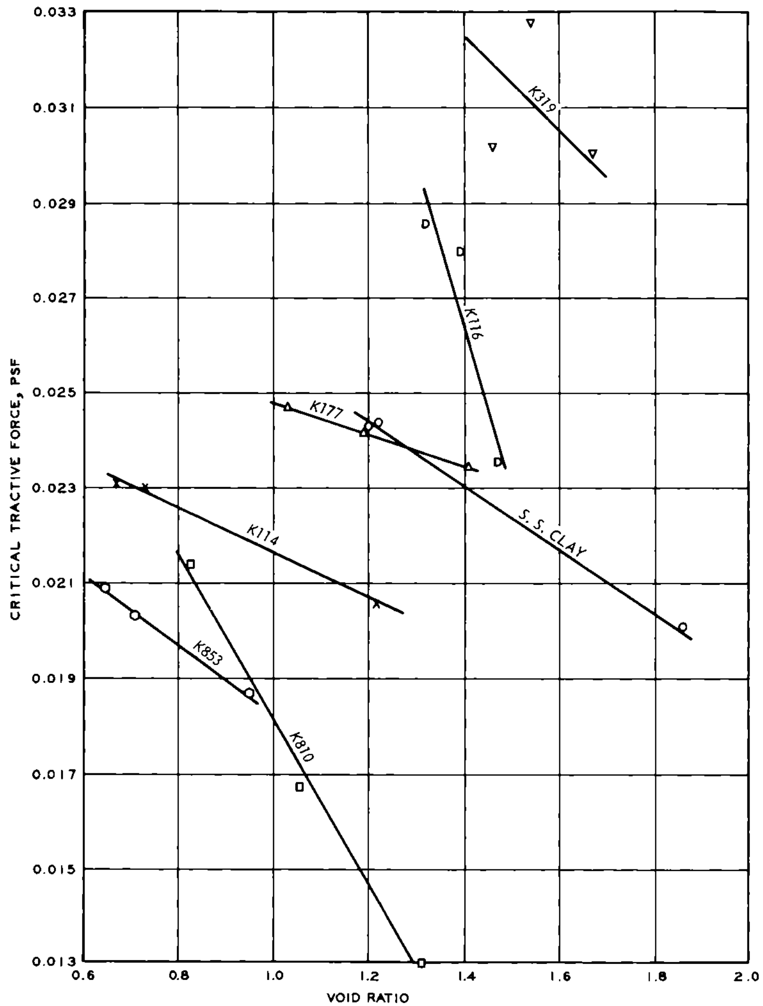


Figure 14. Effect of void ratio on critical tractive force (after Reference 43)

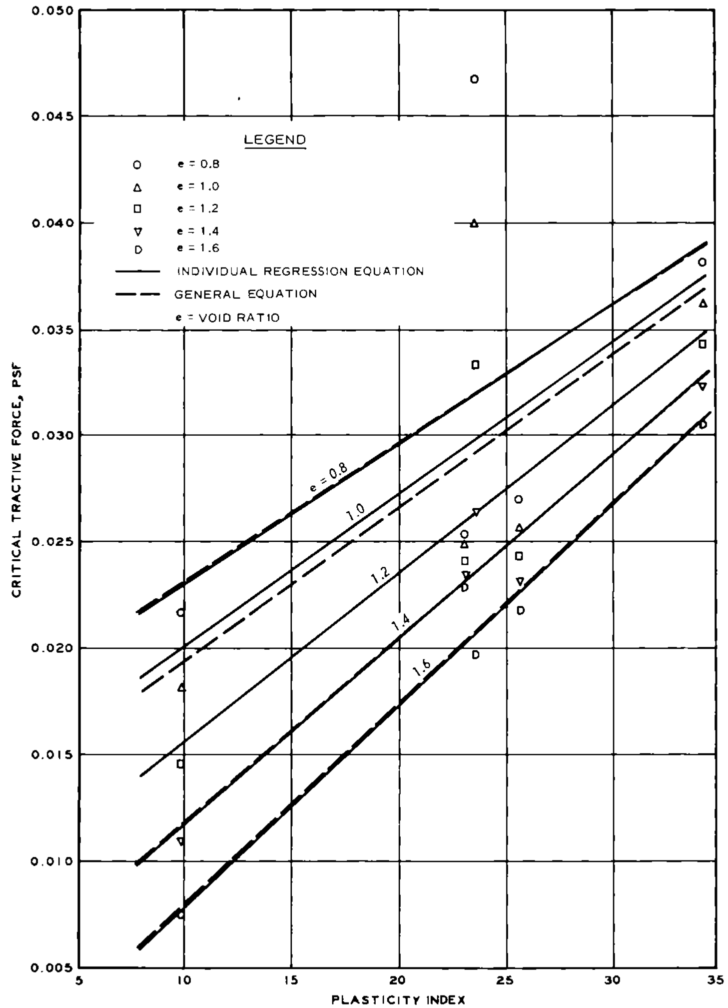


Figure 15. Effect of plasticity index on critical tractive force (after Reference 43)

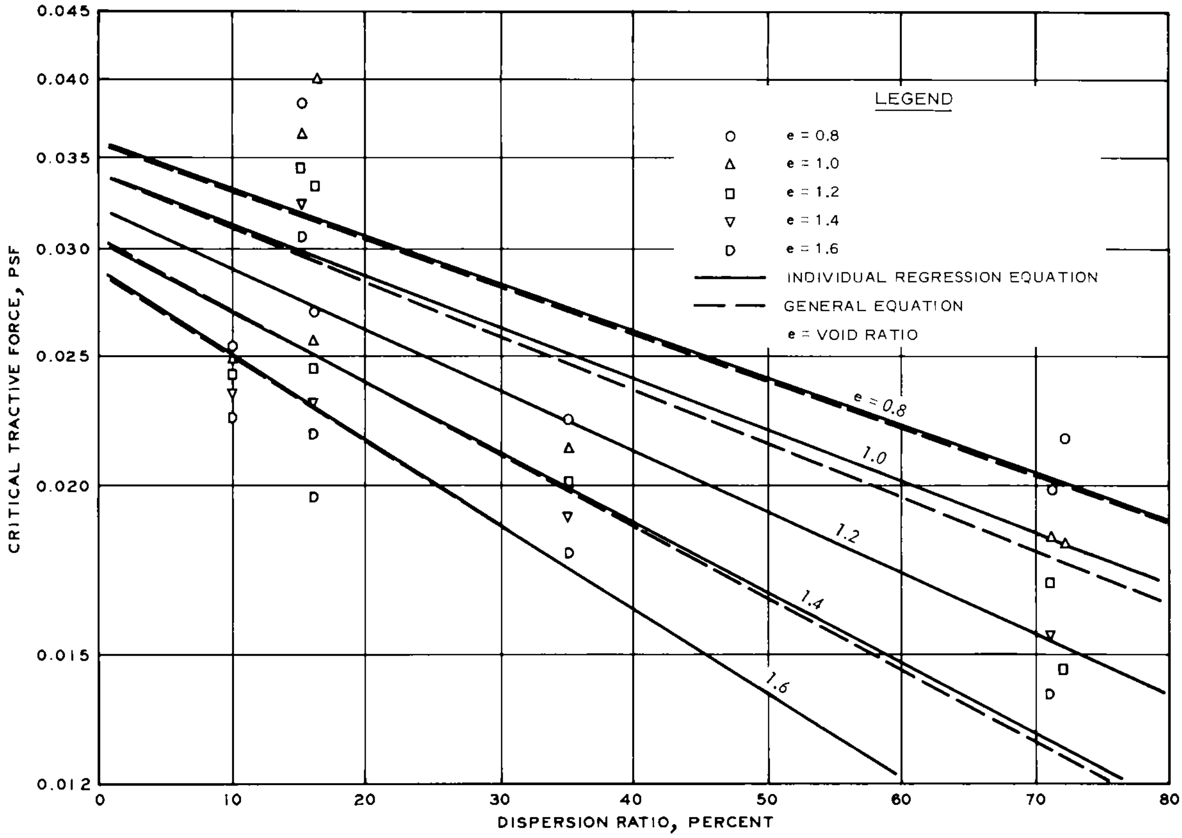


Figure 16. Effect of dispersion ratio on critical tractive force (after Reference 43)

method[46] used to prepare the soil specimens for the rotating cylinder apparatus. Additional testing of soil samples consolidated from a slurry in the rotating cylinder apparatus has shown that the rate of erosion, at "constant" shear stress, is considerably larger in the rotating cylinder apparatus than that obtained in laboratory flumes.[47]

34. Berghager and Ladd[48] conducted a laboratory flume study to relate erosion resistance to effective cohesion for a remolded lean silty marine clay. Visual observations of saturated overconsolidated soil samples failed to show any appreciable erosion at a shear stress equal to three times the critical shear predicted by techniques used by other investigators.

35. Most studies of soil erosion prior to 1962 were conducted with either tap water from a city water supply or tap water with salt added to simulate ocean salinity. Soderblom[49] conducted a laboratory study

in 1963 to determine the influence of dispersing agents on the erosion of glacial clay. The tests were of a qualitative nature with clay specimens exposed to dropping water for 24 hr. The results of the study indicated that the properties of the water significantly influence the amount of erosion exhibited by the clay. Water with dispersing ability was found to have a large eroding effect on the clay, while water with a coagulating effect was found to induce little erosion. The significance of Soderblom's work with respect to piping in earth dams was recognized by Altschaeffl[50] in 1965:

> In fact, it may be that erosion of clay, whether in the bed of a stream or at the sides of a crack that has developed in a compacted earth dam, can be severe, regardless of the state of soil compaction, if the proper fluid environment is present.

36. Partheniades and coworkers[51] in 1966 described an annular rotating channel apparatus, shown in Figure 17, developed to study the behavior of cohesive sediments in estuaries. The apparatus consists of a rotating annular channel containing the water and soil with an annular shear ring which just touches the water surface and rotates in a direction opposite to that of the channel. The concentration of suspended sediment samples is determined from samples of the water-sediment mixture extracted through stopcocks on the outside wall of the annular channel. A limited investigation was conducted to determine the feasibility of the annular rotating channel apparatus for study of erosion. Thoroughly mixed sediment of commercial kaolinite clay was allowed to deposit under quiescent conditions and form a flocculated bed which was subjected to erosion. The erosion tests were inconclusive because the runs were not conducted for a long enough period of time and no considerations were given to the bed strength characteristics. Although the authors concluded that the use of the annular rotating channel apparatus for erosion studies was feasible, subsequent work with the apparatus has been confined to depositional studies of cohesive sediments.[52-55]

37. Swanberg[56] reported in 1966 on the use of a laboratory flume to study the effect of compaction moisture content on the erosion of a Duluth red clay soil. The soil samples were prepared by kneading

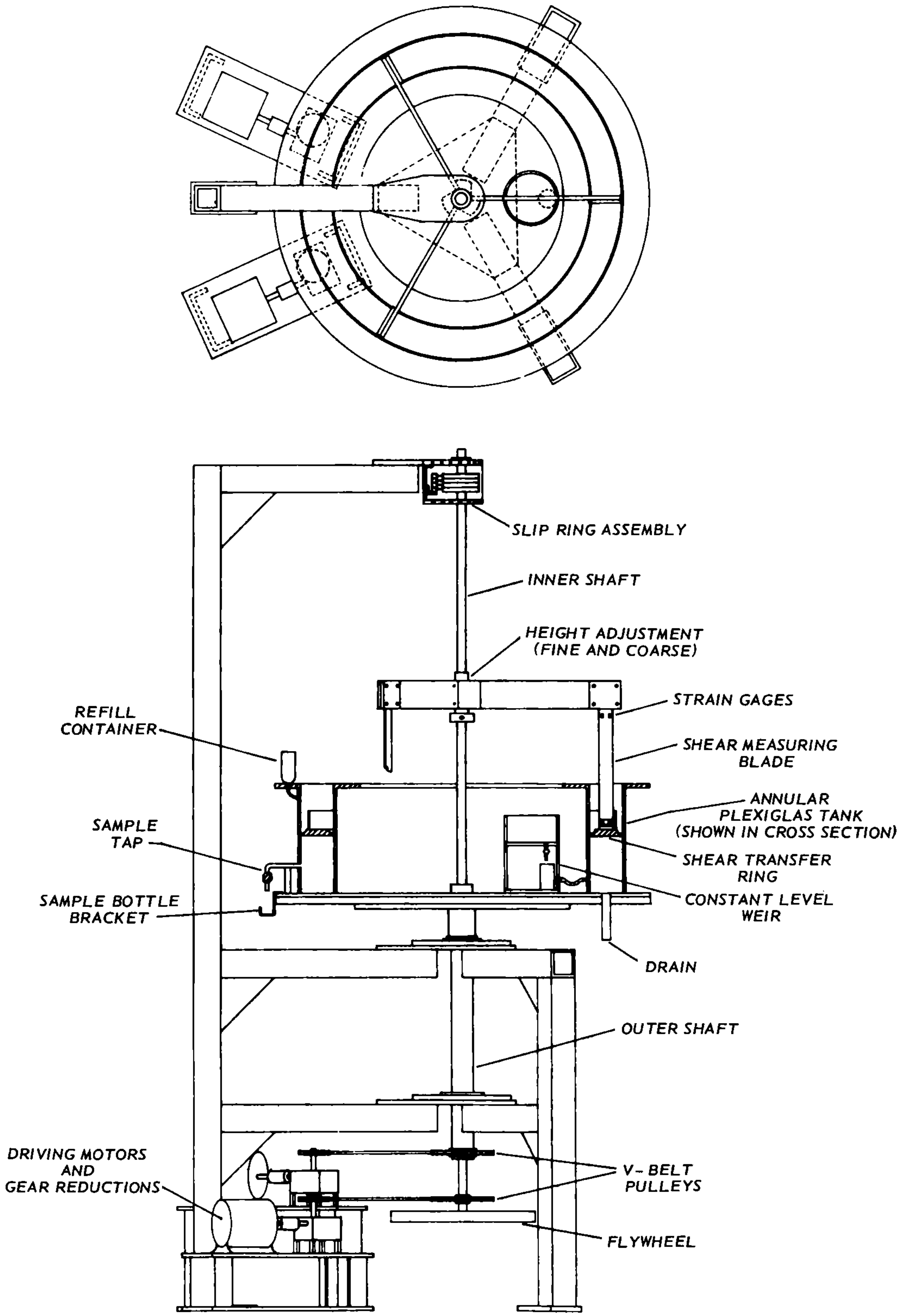


Figure 17. Schematic diagram of annular rotating channel apparatus (courtesy of Massachusetts Institute of Technology[51])

compaction and consolidated under 0.2 tsf for 24 hr prior to testing. Mississippi River water was used as the eroding fluid. The erosion resistance was found to increase with increase in compaction moisture content and then to decrease as compaction moisture content continued to increase as shown in Figure 18. The moisture content at which the

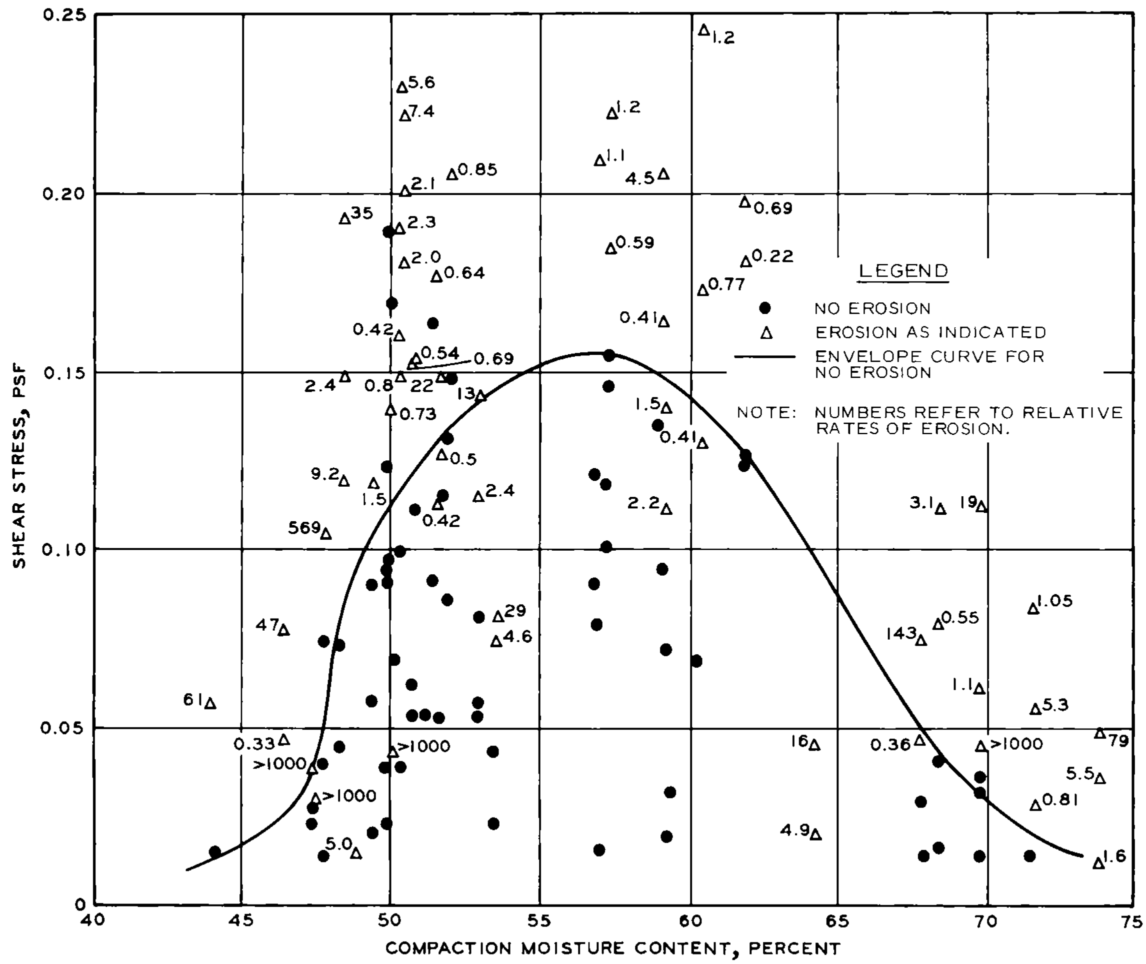
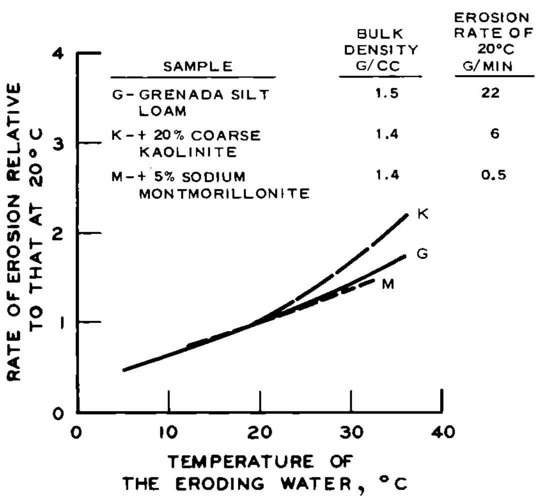


Figure 18. Effect of compaction moisture content on shear stress (after Reference 56)

change from increasing to decreasing erosion resistance occurred was approximately midway between the plastic limit (32 percent) and the liquid limit (65 percent) of the soil tested.

38. Grissinger[57-59] conducted a study to determine the properties of cohesive materials which contribute to the stability of the material when subjected to flowing water. Varying proportions of commercial

kaolinite, illite, calcium montmorillonite, and sodium montmorillonite were mixed with a loess soil to form samples of known mineralogy. Soil samples were prepared by static compaction, and orientation of the clay minerals was measured by X-ray diffraction procedures using the method developed by Mead.[60] Following compaction the soil samples were allowed access to water through a stainless steel filter used as the bottom of the compaction mold. After completion of this water sorption phase, which lasted from several minutes to several hours, the soil samples were aged for predetermined times prior to erosion testing. The soil sample in the mold was placed on the outside of an abrupt 5-deg turn of the side wall of a laboratory flume and subjected to a constant erosive force (flow velocity and depth of water were constant) with the rate of erosion being determined by weighing the soil sample after several minutes elapsed. The influence of temperature of the eroding water on the erosion rate is shown in Figure 19a. The influence of thixotropy on the erosion rate is shown in Figure 19b. A discussion of thixotropy,



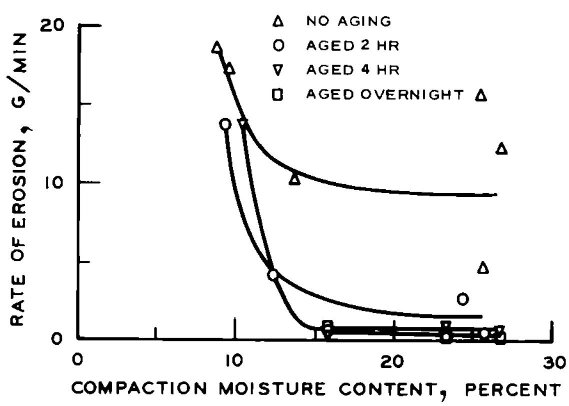


Figure 19. Influence of temperature and thixotropy on erodibility of Grenada loess (courtesy of American Geophysical Union[58])

including the influence of electrolyte concentration, was given by Kashmeeri.[61] Table 4 summarizes the results of the influence of compaction dry unit weight on rate of erosion for different soil mixtures tested by Grissinger.[58] The plasticity index was not a useful indicator of rate of erosion for the soil mixtures tested.

39. Mirtskhulava[62] reported in 1966 on a study of the erosion resistance of cohesive soils. He found that the most important properties of cohesive soils indicating resistance to erosion were the cohesion at 100 percent saturation and the size of the aggregates carried away. The cohesion was determined by a spherical punch and the size of the aggregates carried away by high-speed microfilm photography.

40. The effect of chemical additives on the erodibility of cohesive soil was reported by Liou[63] in 1967. Varying percentages of sodium carbonate (Na_2CO_3) were added to Marshall Lake montmorillonite clay and statically compacted into a hydraulic flume. The erosion was determined by measuring the amount of soil erosion after 4 hr of flow. The critical tractive force was defined as the tractive force required for zero erosion. The results of the study indicated that the critical tractive forces for sodium montmorillonite clay were lower than those for calcium montmorillonite clay. Figure 20 indicates that adding between 0.5 and

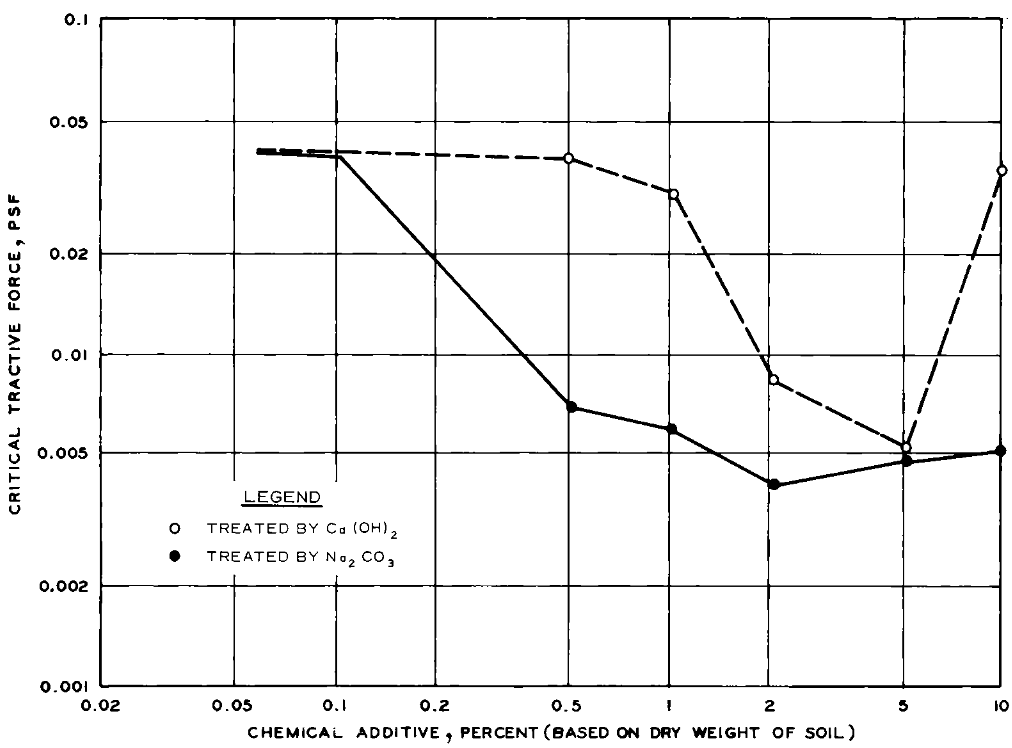


Figure 20. Effect of chemical additives on critical tractive force (after Reference 63)

10 percent sodium carbonate or calcium hydroxide to the montmorillonite clay actually increases the amount of erosion the soil mixture would exhibit. Figure 21 shows the influence of dispersed and flocculated clay structures on the equilibrium of the soil under flowing water.

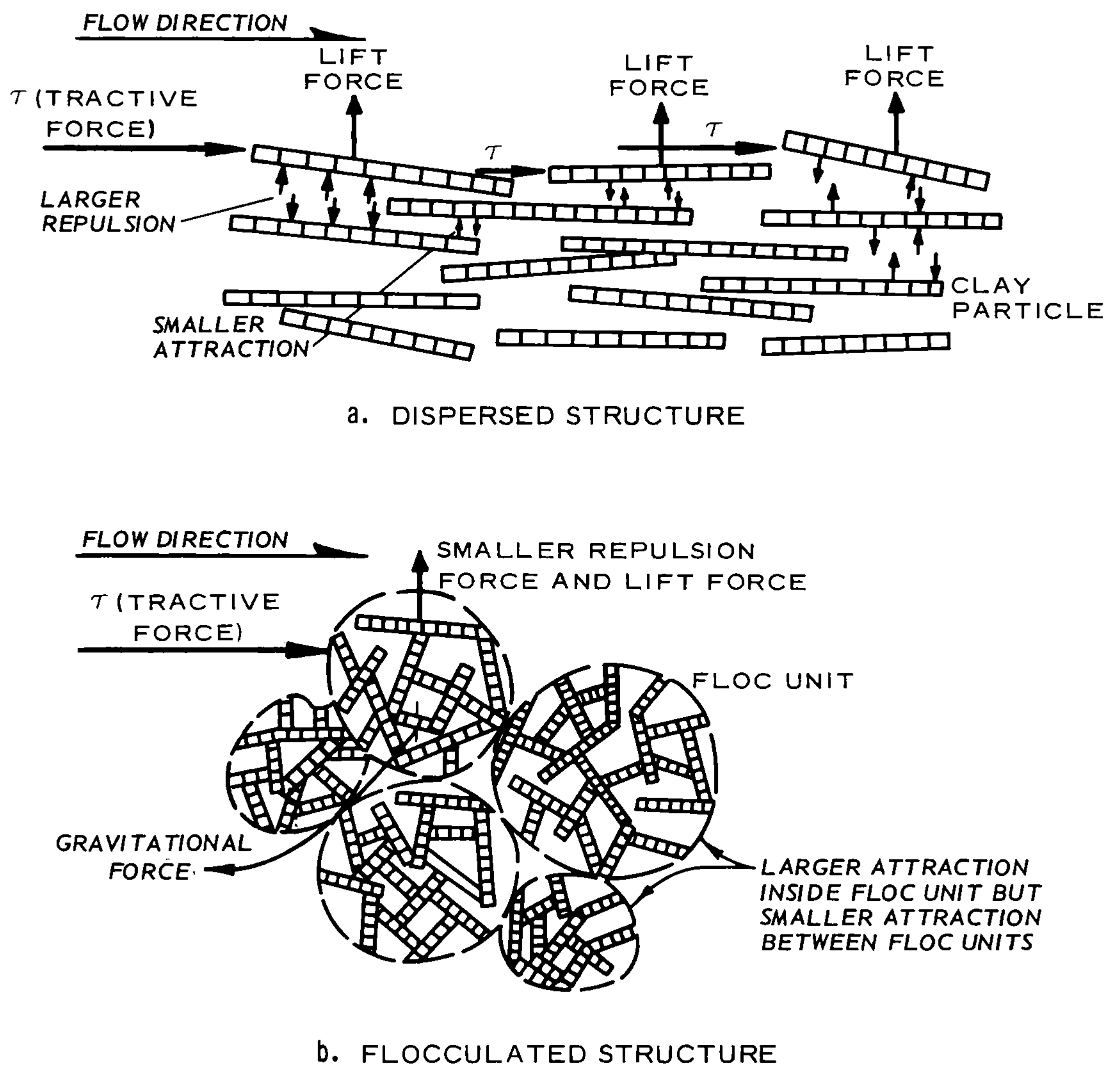


Figure 21. Influence of dispersed and flocculated clay structures on the equilibrium of soil under flowing water (after Reference 63)

41. In a study reported in 1968, Dash[64] investigated the influence of soil type, clay percentage, moisture content, and maximum consolidation pressure on the erosive behavior of cohesive soils. Commercial kaolinite and illite clays were mixed with Ottawa sand to obtain different

clay percentages. Erosion tests were conducted on saturated, consolidated soil samples in a vertical jet apparatus and on nearly saturated, statically compacted samples in a flume section. Dash derived an erosion index

$$I_e = \frac{1}{AS_f + B} \tag{2}$$

where

I_e = erosion index

A,B = defined functions of the erosion system

S_f = strength factor

The erosion index was found to increase with increase in water content and decrease in clay percentage. Dash's results confirmed those obtained by Partheniades[41] that erosion rates provide a better basis for comparison among different soils than afforded by the critical shear stress approach.

42. Bhasin,[65] using the vertical jet apparatus developed by Dash,[64] conducted a study to determine the erosive behavior of nearly saturated statically compacted sand-clay mixtures. Commercial illite was mixed with Ottawa sand to obtain different sand-clay ratios. The erosion rate was found to increase with increasing moisture content, sand to clay ratio, temperature of eroding water, and amount of suspended sand in the eroding fluid. The erosion rate was found to decrease with increase in duration of the time interval between mixing the soil and water and compaction of the soil.

43. In 1968 the American Society of Civil Engineers Task Committee on Erosion of Cohesive Materials, Committee on Sedimentation, Hydraulics Division[66] reported on research needs on the fundamentals of erosion and channel design in cohesive soils. Figure 22 relating the plasticity index of the soil to the product of the depth times the slope of the channel was suggested for the design of drainage ditches.[67] The Task Committee concluded that although a considerable amount of research had been conducted on the erosion of cohesive soils, the properties which control erosion had not been conclusively defined. It was suggested

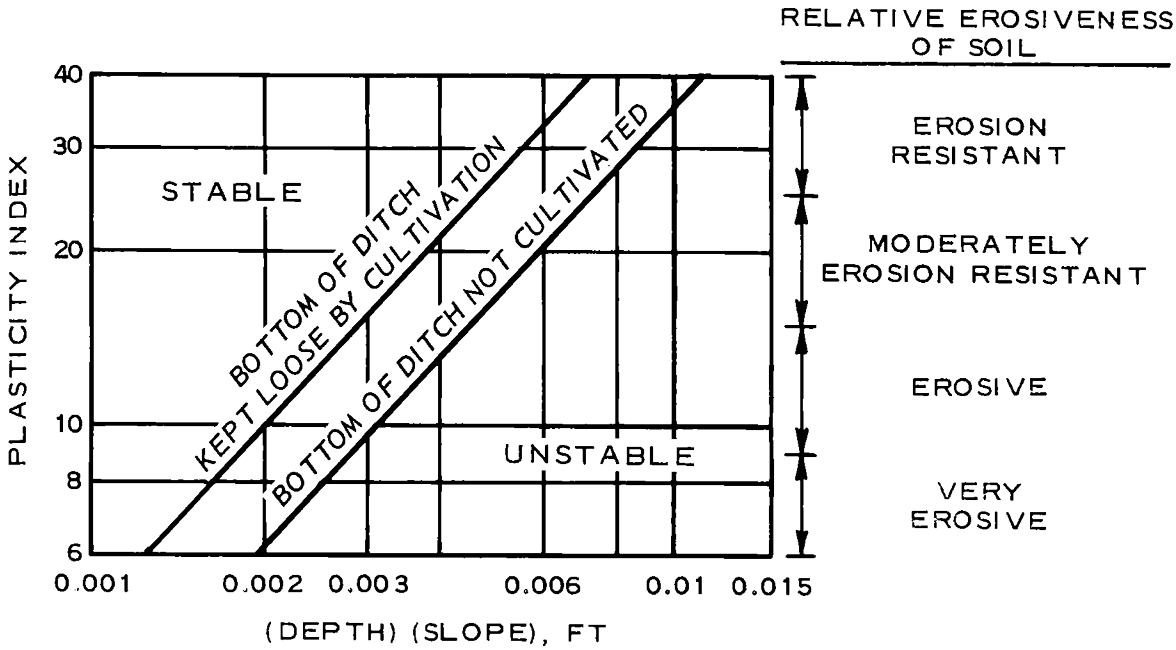


Figure 22. Design method for drainage ditches based on plasticity index of soil (after Reference 67)

that additional research was needed to define the influence of the mineralogy of the clay fraction, different cations, suspended sediment, and pore water quality on the resistance of cohesive soils to erosion.

44. Martin and coworkers[68,69] conducted a laboratory study to determine the effect of dry unit weight, slope angle, and rainfall intensity on the rate of erosion of a statically compacted, partially saturated clayey silt. The results of the study, which considered equal horizontally projected areas of sloping surfaces, indicated that the maximum erosion rate for the soil tested was a function of slope angle, dry unit weight of soil, and the depth of water flow over the soil. A method to estimate the pore water pressure in a soil under a given rainfall condition was presented by Kobashi.[70]

45. Liou[71] in a study reported in 1970 used a hydraulic erosion device shown in Figure 23 to determine the effect of moisture content, chemical additives, and water temperature on the erodibility of statically compacted commercial kaolinite and sodium montmorillonite. Rotation of the plastic disk mounted above the soil sample shown in Figure 23

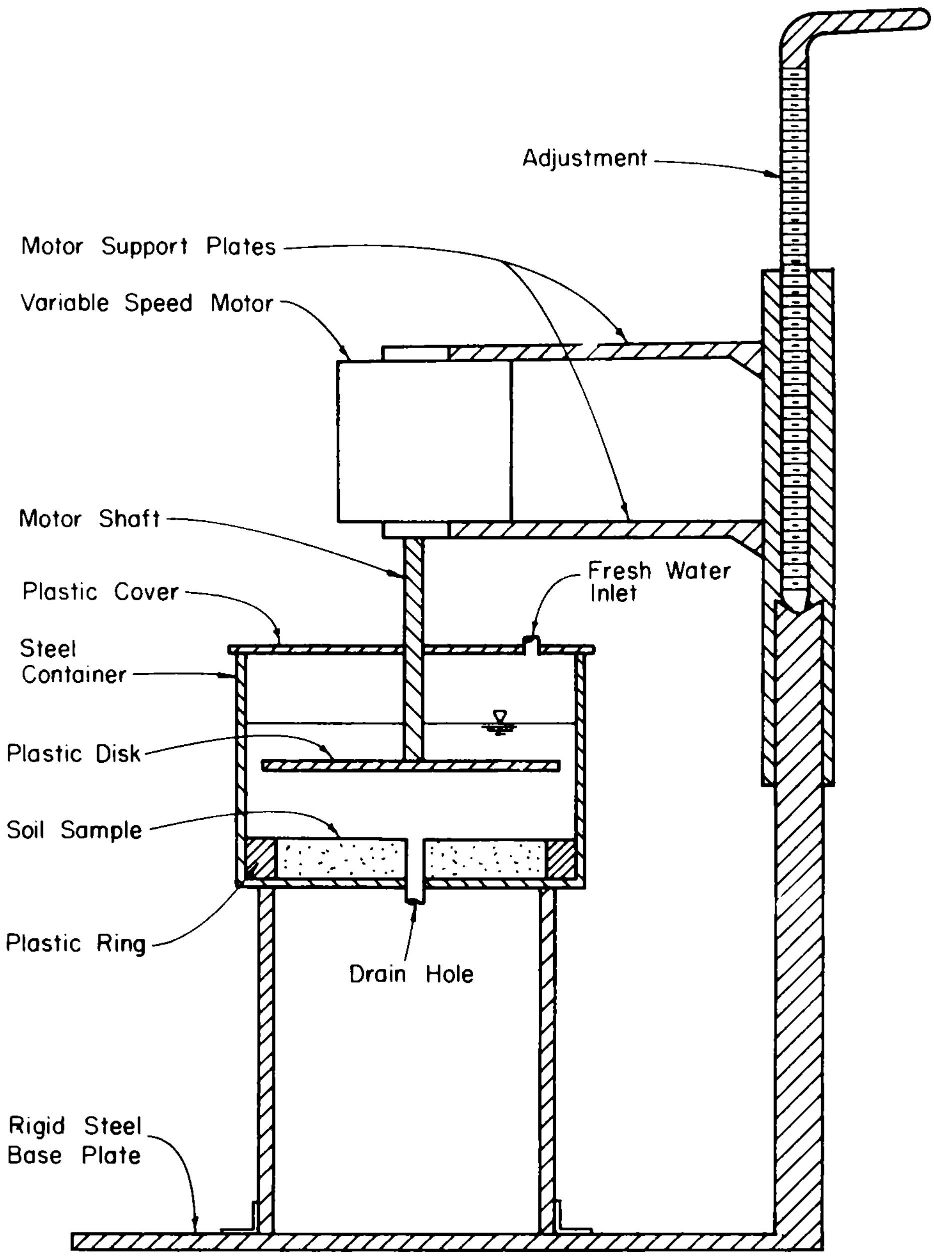


Figure 23. Hydraulic erosion device (from Reference 71)

exerted a known shear stress on the surface of the soil sample as shown in Figure 24. The critical erosion shear stress was taken to be the erosion shear stress which was constant over a certain period of time (about 30 min). No erosion was observed with or without chemical additives or at different water temperatures (15-50°C) within the limit of the erosion device (about 0.09 psf) on kaolinite samples with a moisture content

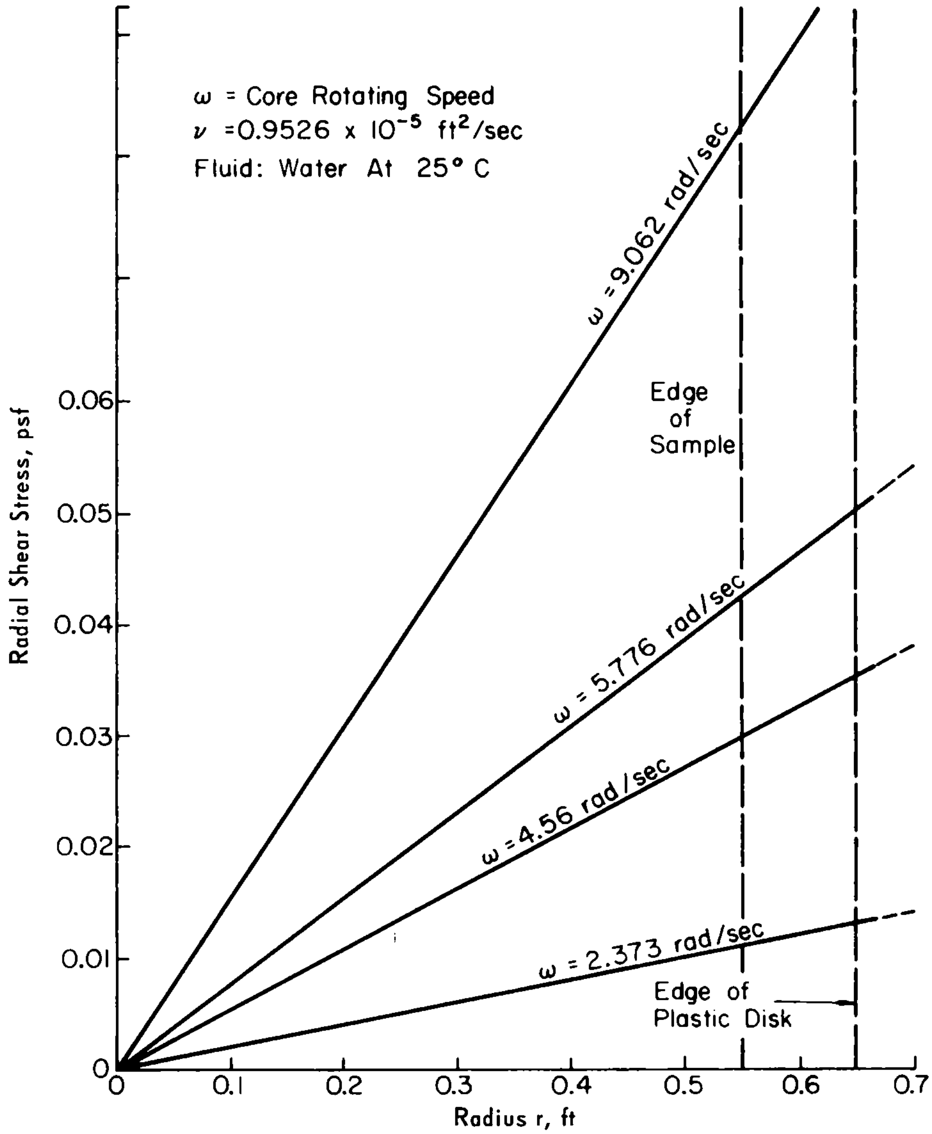


Figure 24. Radial shear stress versus radius of hydraulic erosion device (from Reference 71)

higher than 45 percent (10 percent below liquid limit). Kaolinite samples compacted at a moisture content below 32 percent (5 percent above plastic limit) slaked upon immersion in water. The rate of slaking was observed to increase with increase in water temperature. Figure 25 shows the effect of soil pH on erosion shear stress for kaolinite. For the sodium montmorillonite samples, Figure 26 shows the erosion shear stress increasing with decreasing moisture content. Figure 27 shows variations of erosion shear stress with erosion time of sodium montmorillonite

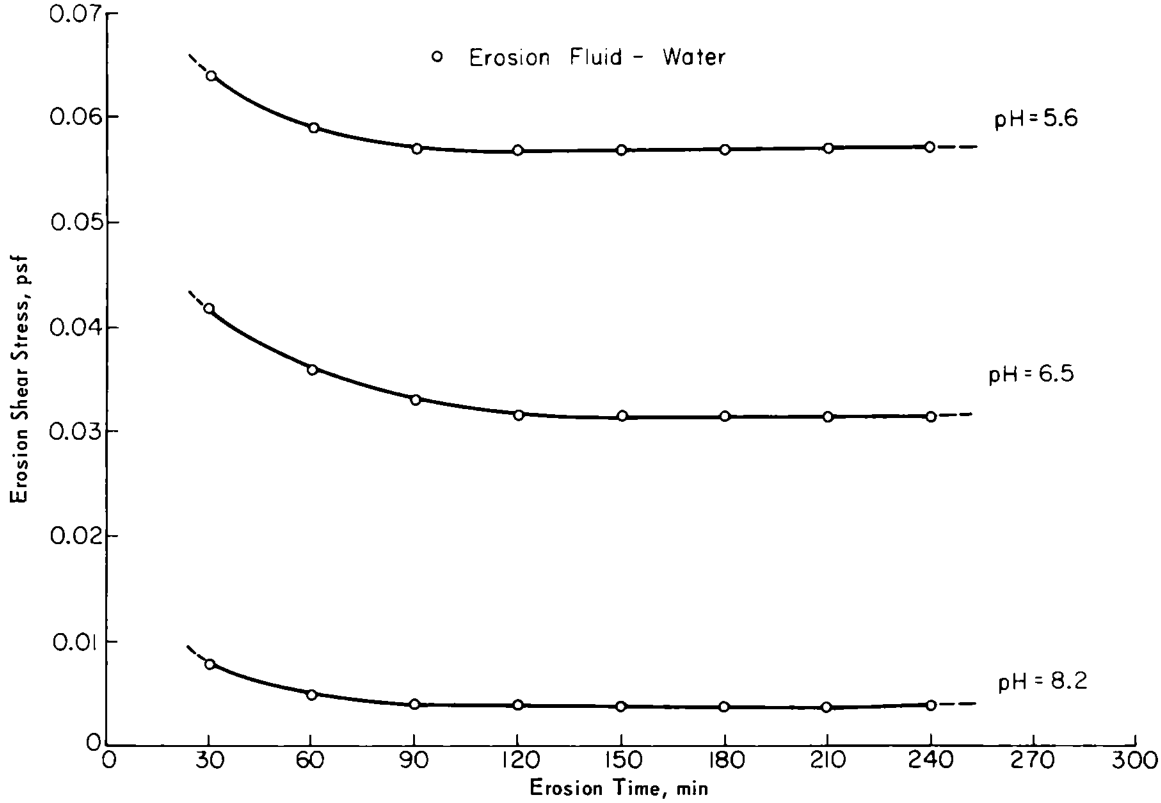


Figure 25. Effect of soil pH on erosion shear stress for kaolinite clay (after Reference 71)

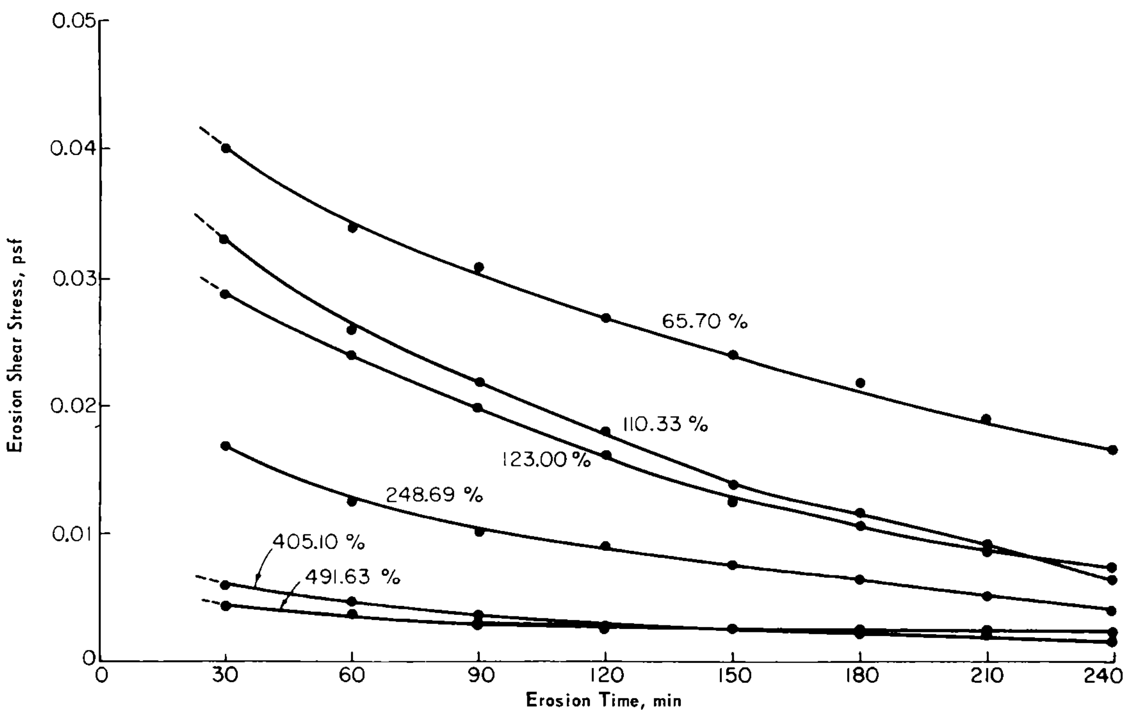


Figure 26. Effect of moisture content on erosion shear stress for sodium montmorillonite clay (after Reference 71)

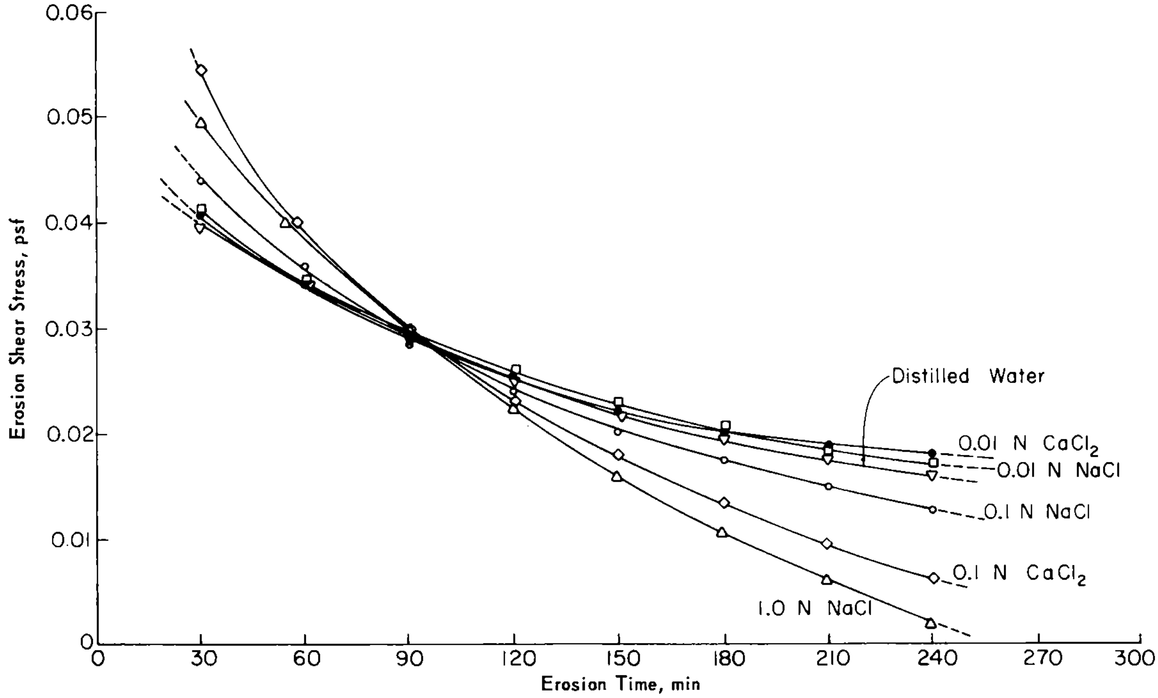


Figure 27. Effect of chemical additives to soil pore water on erosion shear stress for sodium montmorillonite clay at 65 percent moisture content (after Reference 71)

samples with selected concentrations of sodium chloride (NaCl) and calcium chloride ($CaCl_2$). As shown in Figure 28, the erosion shear stress increased with decreasing eroding water temperature.

46. Meeuwig[72] in 1971 reported results of a study on the effect of organic matter on the erodibility of soil. Measurements were taken of the amount of soil eroded from 460 small plots (20 by 30.5 in.) under 2.5 in. of water applied at a constant intensity of 5 in. per hour for 30 min using the Dortignac rainfall simulator.[73] Figure 29 shows relative erodibility as a function of organic matter, sand content, and clay content. Relative erodibility is the ratio of the calculated erosion corrected for organic matter, sand, and clay to calculated erosion at average organic matter, sand, and clay (8 percent, 30 percent, and 24 percent, respectively). As shown in Figure 29, organic matter decreases erosion of clay soils, but tends to increase erosion of sandy soils.

47. In a study reported in 1972 Riley and Arulanandan[74] describe

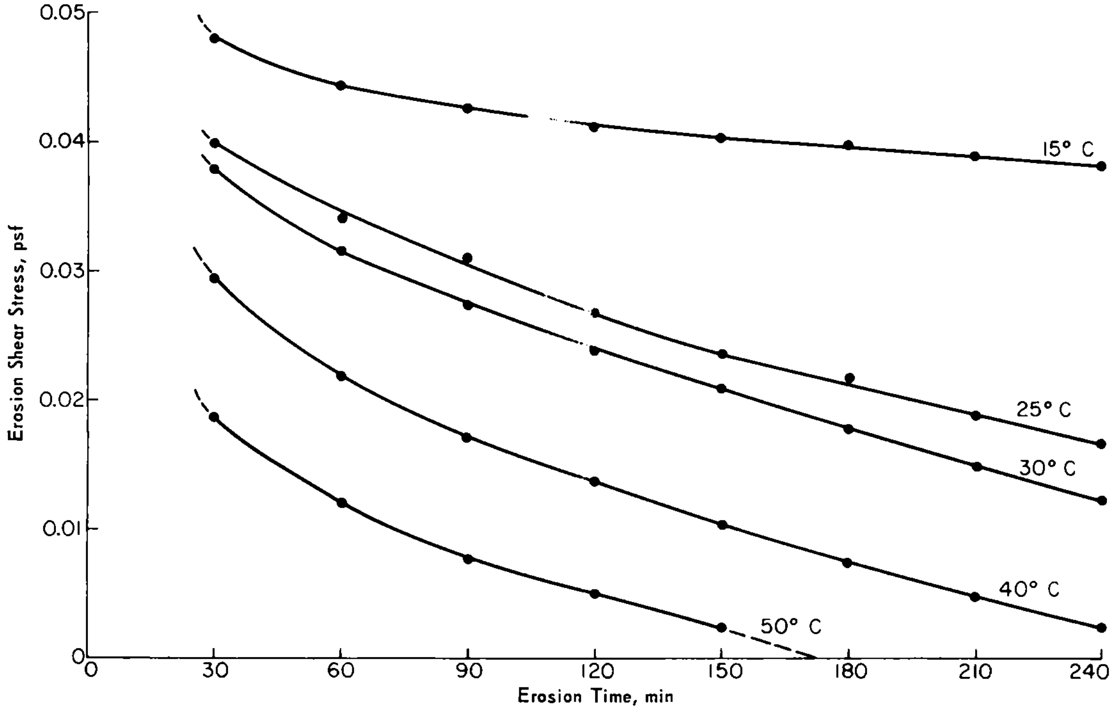


Figure 28. Effect of eroding water temperature on erosion shear stress for sodium montmorillonite clay at 65 percent moisture content (after Reference 71)

erosion tests conducted on consolidated soil samples using the rotating cylinder test apparatus developed by Moore and Masch.[30] Subsequent research by Arulanandan and coworkers on the influence of physicochemical factors on the erosion of cohesive soils will be discussed in paragraphs 74-79.

48. Akky and Shen[75-77] used the rotating cylinder test apparatus to study the erodibility of a cement-modified, kneading-compacted, uniformly graded, gravelly sand. Following compaction the cement-modified soil samples were cured in a moisture room for 7 days, subjected to various numbers of wet-dry or freeze-thaw cycles, and soaked in water for 1 hr prior to erosion testing. Erosion tests were conducted by determining the relationship between the weight of soil loss per unit surface area and the time of erosion for various applied shear stresses. The critical boundary shear stress was taken to be the shear stress at zero erosion rate. For samples subjected to various cycles

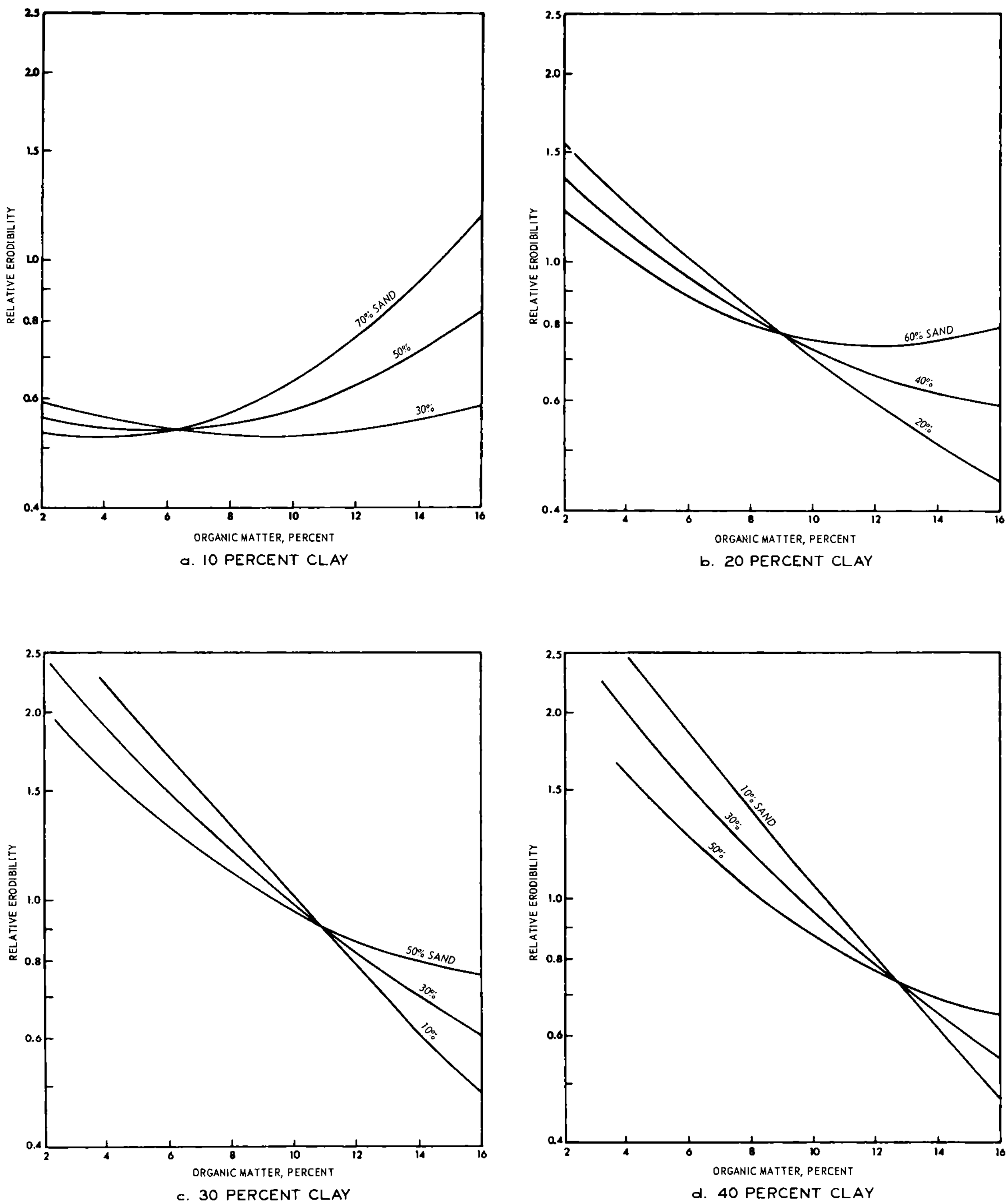


Figure 29. Influence of organic matter content on the erodibility of soil (from Reference 72)

of freeze-thaw, substantial weight loss occurred early in the test as a result of a weakened outer layer of soil formed during the first few freeze-thaw cycles. For a given cement content, the critical boundary shear stress decreased as the number of freeze-thaw cycles increased. For uncycled samples, the critical boundary shear stress was related to the 7-day-cured unconfined compressive strength as shown in Figure 30.

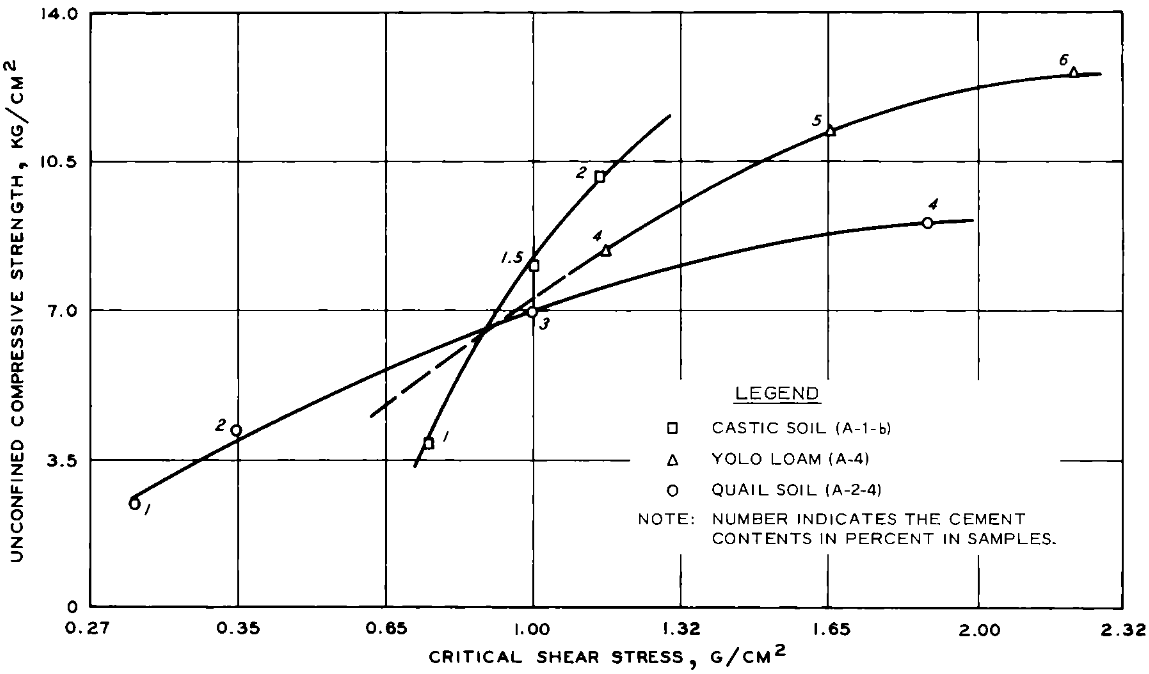


Figure 30. Relationship between critical shear stress and 7-day-cured unconfined compressive strength for cement-modified soils (from Reference 76)

The results of the study by Akky and Shen indicated that adequate slope protection could be achieved with less cement than is currently recommended by the Portland Cement Association[78] for stabilized soil located below the minimum water level. For samples subjected to freeze-thaw cycles, the erodibility could not be related to unconfined compressive strength.

49. Paaswell[79] in 1973 referred to research in progress by Coad[80] to study the influence of preconsolidation pressure on the rate of erosion of statically compacted kaolinite samples. The soil samples were

consolidated in the laboratory and subjected to flow in a 4-ft-long by 1-ft-wide test section of a 30-ft-long duct (closed flume). The erosion rate was measured from concentrations of fluid taken from the duct. Preliminary results indicated an initial period of high erosion rate followed by a steady-state erosion rate.

Dispersive Clay

50. The possibility of piping failure in earth dams due to dispersive clay behavior was recognized in Australia in 1960. Cole and Lewis[14] presented a paper relating Atterberg limits to susceptibility of an earth dam to piping failure as had been done by previous investigators.[1,26] In the discussion of this paper Aitchison[81] noted:

> Referring to the paper by Messrs. Cole and Lewis, I wonder whether the authors have taken into account the possible dispersion of the clay mineral at the exit point where it may be in the outer face or one of the small cracks in the dam. Piping failures in natural soils is a noticeable feature in Victoria, such failures being associated with the dispersion of the soils at points where free water comes into contact with readily dispersible clay - either a slightly sodium or hydrogen clay. The clay disperses very readily and can be moved under exceptionally low hydraulic gradients....It would be possible to detect (susceptibility to) deflocculation of the clay, and consequently its movement in groundwater, by tests of the exchange status and the salt concentration of the soil water.

Shortly thereafter, research on dispersive clay was initiated in Australia.

51. Two concepts, developed in the field of soil science, were utilized in the study of dispersive clay. The Crumb Test (see Appendix A) was found to be a good field indicator of potential problems with dispersive soils.[82-91] In the United States, the Soil Conservation Service (SCS) has employed the Crumb Test since 1971 as a routine test for soil dispersion as part of engineering investigations for earth dams and unlined flood channels.[92-97] It was found that if the Crumb Test indicates dispersion, the soil will almost always be dispersive,

but that about 30 percent of dispersive soils will give nondispersive reactions to the Crumb Test.[93]

52. The second concept, developed in the field of soil science, which was applied to the study of dispersive soils was deflocculation or dispersion as a function of the sodium adsorption ratio (SAR)*[97] of the soil and total cation concentration of the eroding water.[91,98-101] Figures 31-33 show deflocculation as a function of SAR and total cation concentration of the eroding water for a predominately montmorillonite clay, illite clay, and predominately kaolinite clay.[91,102,103]

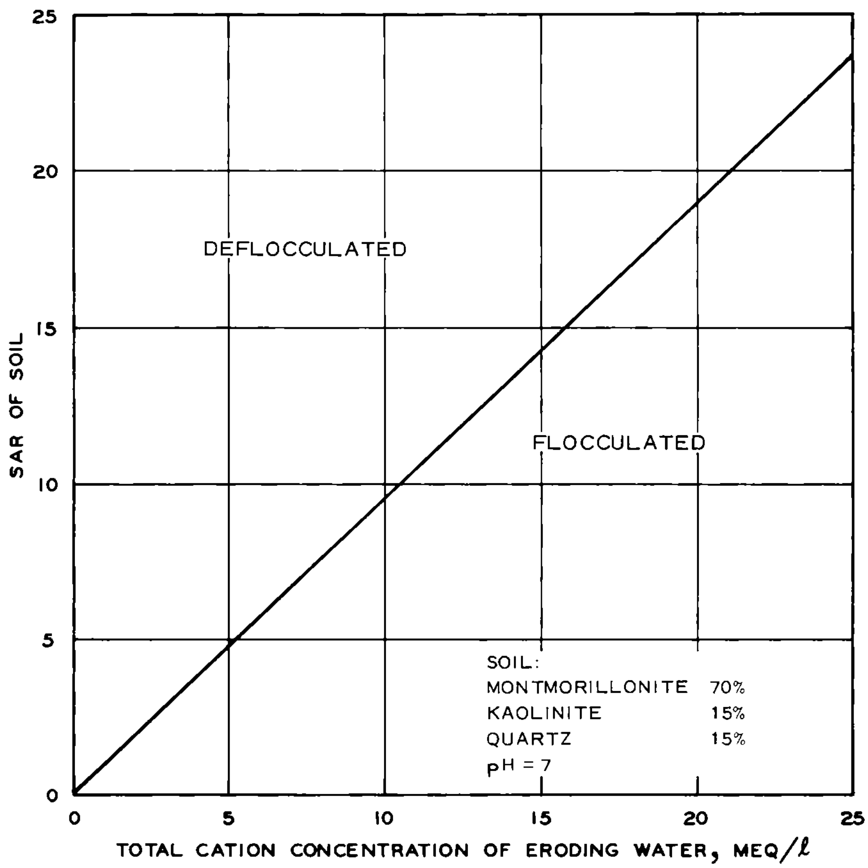


Figure 31. Deflocculation as a function of SAR and total concentration for a predominately montmorillonite clay (courtesy of Water Research Foundation of Australia[91])

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* $SAR = \dfrac{Na}{\sqrt{0.5\ (Ca + Mg)}}$

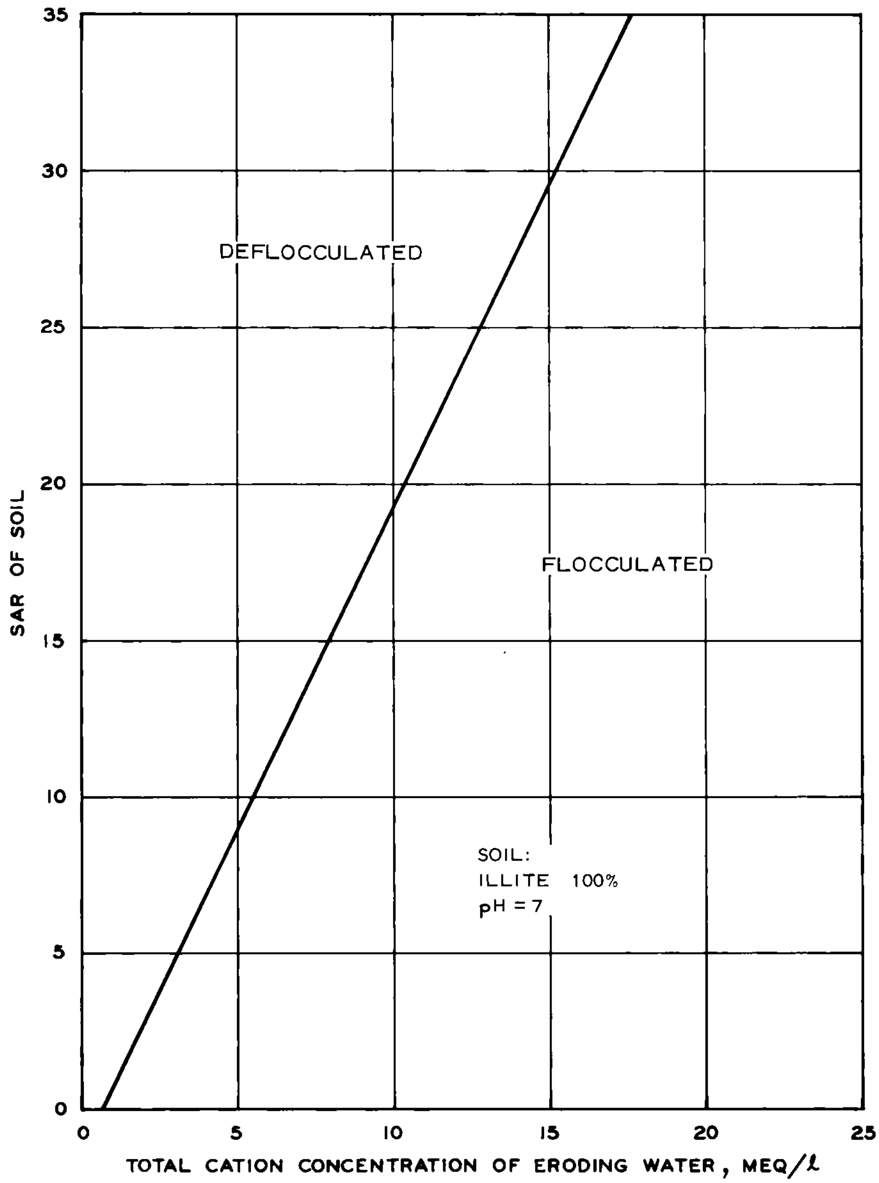

Figure 32. Deflocculation as a function of SAR and total cation concentration for an illite clay (courtesy of Water Research Foundation of Australia[91])

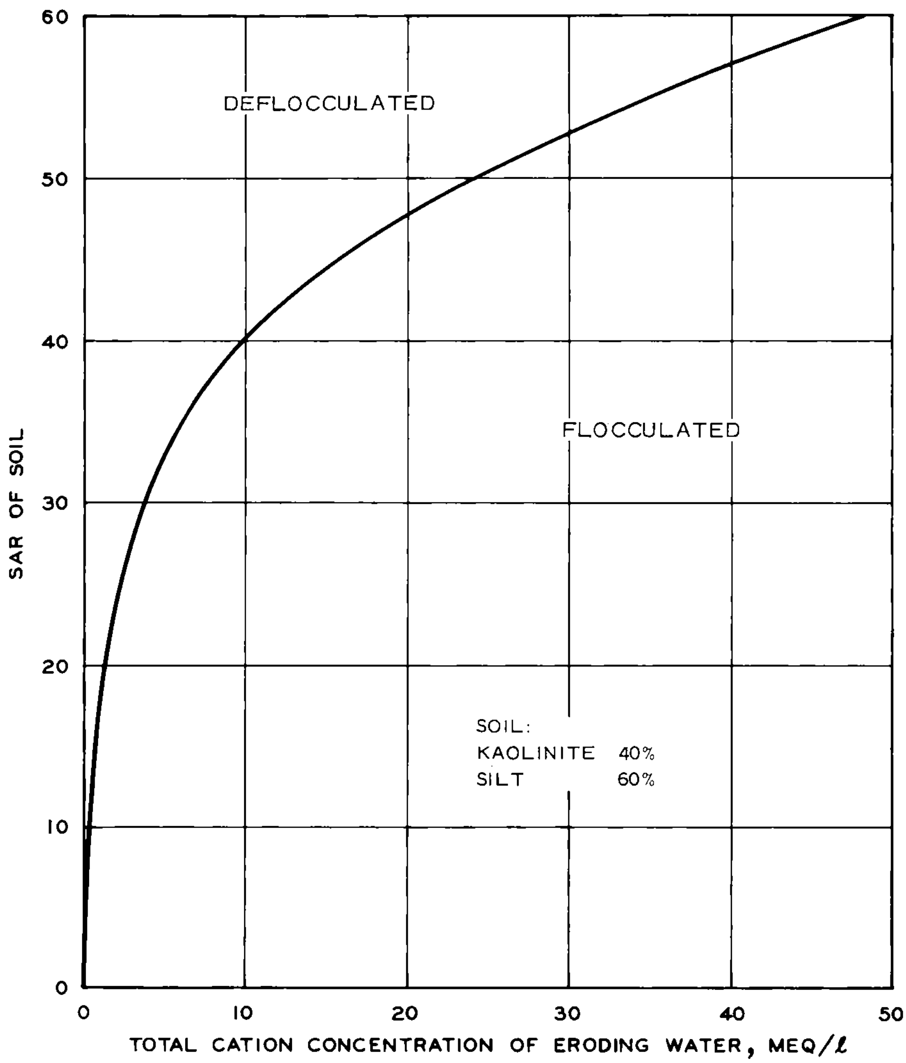

Figure 33. Deflocculation as a function of SAR and total cation concentration for a predominately kaolinite clay (after References 91, 102, 103)

Subsequent research by Kandiah,[104] as shown in Figure 34a, b, and c, indicates that the soil pH influences the flocculated-deflocculated behavior of soil.

53. Aitchison, Ingles, and Wood[105] in 1963 reported on a study to predict the piping failure of three earth dams in Australia. The cation exchange capacity (CEC)[97] was determined for soil samples from each dam. The exchangeable sodium percentage (ESP)*[97] was computed for each soil

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* $ESP = \frac{\overline{Na}}{CEC} (100)$

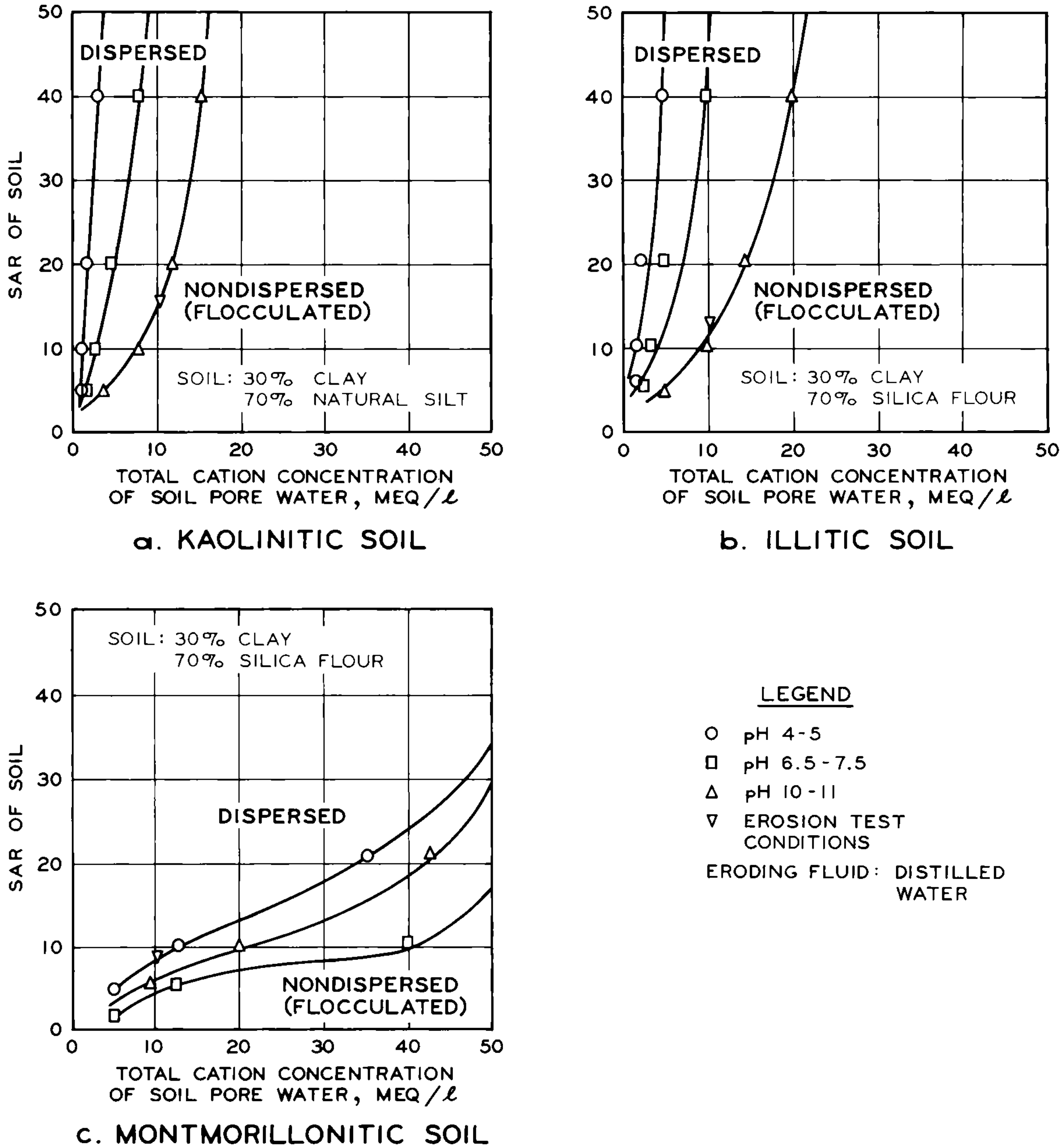

Figure 34. Influence of soil pH on deflocculation as a function of SAR and total cation concentration for kaolinitic, illitic, and montmorillonitic soil (after Reference 104)

sample. Then the total cation concentration was determined from water samples taken from the reservoir for each dam. At the time of this study (1963), the only available data on deflocculation as a function of the ESP of the soil*[97] and the total cation concentration of the eroding water were for predominately illite clay.[98,99] Quirk and Schofield[98] postulated that this relationship, similar to that shown in Figure 32, was unique for all soils of semiarid and arid regions with the possible exception of kaolinitic soils of low pH. Subsequent research[91,101,103] has shown that the relationship is at variance for montmorillonitic and kaolonitic soils. Although no information was given concerning the clay mineralogy of the soils from the three earth dams studied by Aitchison, Ingles, and Wood, subsequent work[106] indicated that one of the soils (Mansfield) contained montmorillonite with a trace of kaolinite. Using the relationship for deflocculation as a function of the ESP of the soil and the total cation concentration of the eroding water obtained by Quirk and Schofield[98] for a predominately illite clay, Aitchison, Ingles, and Wood were able to predict the piping failure for the three earth dams as shown in Figure 35. Aitchison and Wood[107] discussed the possibility of using filters in earth dams of dispersive clay:

> The exit velocity for seepage water emerging from clay is so low that the clay particles are not normally detached. However this is no longer true if deflocculation takes place....Under conditions of seepage flow through the dam, the deflocculated particles will move in suspension through the pore spaces within the soil....It is probable that any deflocculated clay particles suspended in water would not be retained by conventional filter zones.... In this case the seepage water leaving the dam may well contain a suspension of sub-micron clay particles. Piping failure can occur as a consequence of the enlargement of water conveying channels.

54. Ingles and Wood[108] in 1964 presented a case history of an earth dam in Victoria, Australia, which illustrates the soil-reservoir water interaction problem. The reservoir water was relatively high in dissolved salts. The dam was stable although continuous seepage losses

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* $$\text{ESP} = \frac{100\ (-0.0126 + 0.01475\ \text{SAR})}{1 + (-0.0126 + 0.01475\ \text{SAR})}$$

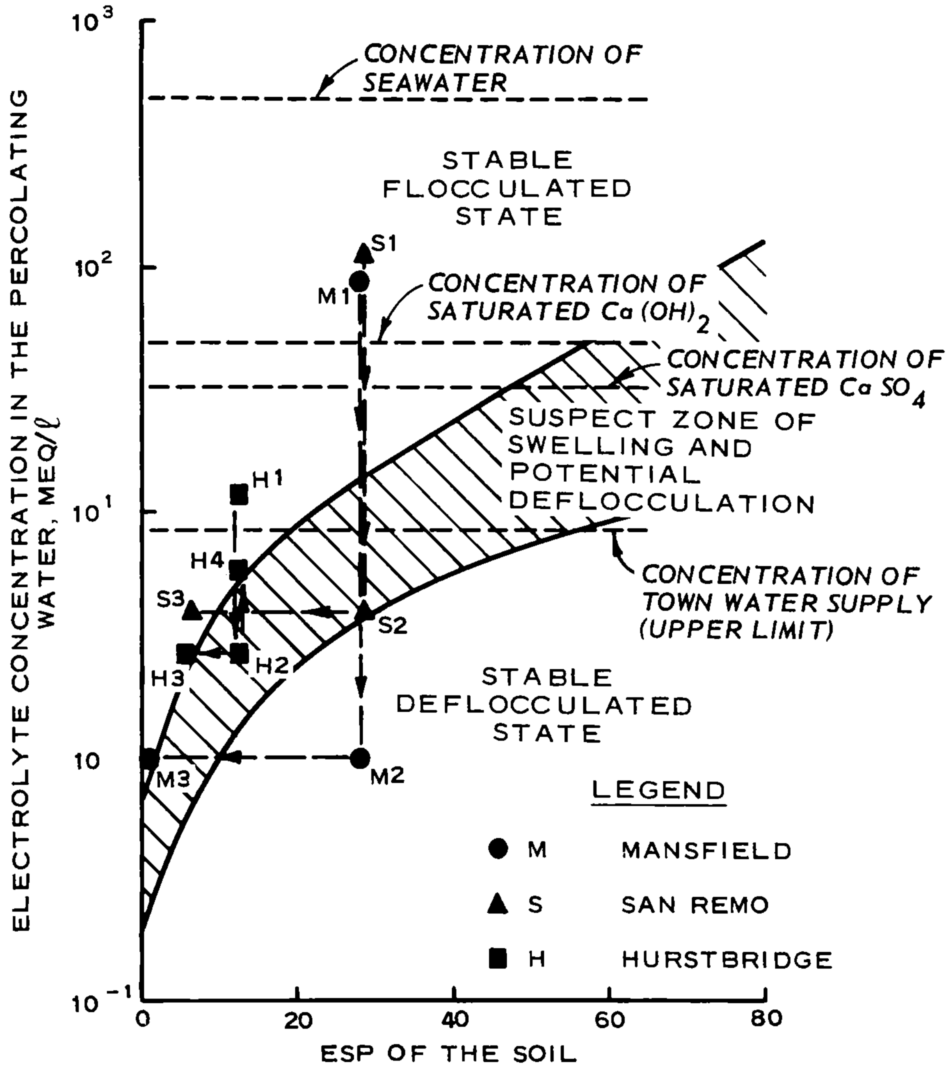

Figure 35. Prediction of piping failure in earth dams using the ESP of the soil and the total cation concentration of the eroding water (courtesy of Institution of Engineers, Australia[105])

were noted. Following completion of a 20-mile pipeline to bring river water of a good quality (relatively low in dissolved salts) from a distant source, the dam immediately failed by piping.

55. In 1964 Ingles and Wood[109] reported on an aerial survey flown over Victoria, Australia, which indicated that it was feasible to assess areas of troublesome soils for earth dam construction. The failure rate of earth dams due to piping was ten times as high when the reservoir storage water was observed to be turbid.

56. In November 1964 a colloquium on Failure of Small Earth Dams was convened by the Water Research Foundation of Australia, Ltd., and the Soil Mechanics Section* of the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia. The proceedings were to have been published by the Water Research Foundation of Australia, Ltd. Failure to publish these proceedings, which represented the state of the art of dispersive clays, isolated most of the world from a major portion of the research results on dispersive clays.

57. Aitchison and coworkers[107,110] reported on the results of a study of 20 earth dams chosen as being representative of a wide variety of climatic and soil conditions from four states of Australia. The field performance of the earth dams in terms of piping failure was correlated with the predicted deflocculation based on laboratory tests of the SAR of the soil and total cation concentration of the reservoir water from the earth dams. The type and amount of clay minerals were determined by X-ray diffraction of the -2μ fraction. Using the relationship developed by Quirk and Schofield[98] and confirmed by Collis-George and Smiles[100] for illite clay and the relationship developed by Rowell[101] for montmorillonite clay, Aitchison and coworkers were able to predict successfully the field behavior of 19 of the 20 dams as shown in Figure 36. All 14 of the earth dams that failed by piping plot on the deflocculated side of the relevant boundary (depending on whether the clay was predominately montmorillonite or illite) in Figure 36, whereas all but one of the six sound earth dams fall within the flocculated zone. The earth dam at Nambour (No. 7 in Figure 36) was in sound condition even though the soil and reservoir water characteristics indicated a susceptibility to deflocculation. This dam, however, differs from most of the other dams reported in that compaction was carried out at a moisture condition wet of optimum water content.

58. CSIRO[111] in 1966 reported on a study of the applicability of lime stabilization to the soils of Australia. It was reported that both laboratory[106] and field tests had shown that blending small amounts of

* Now Division of Applied Geomechanics.

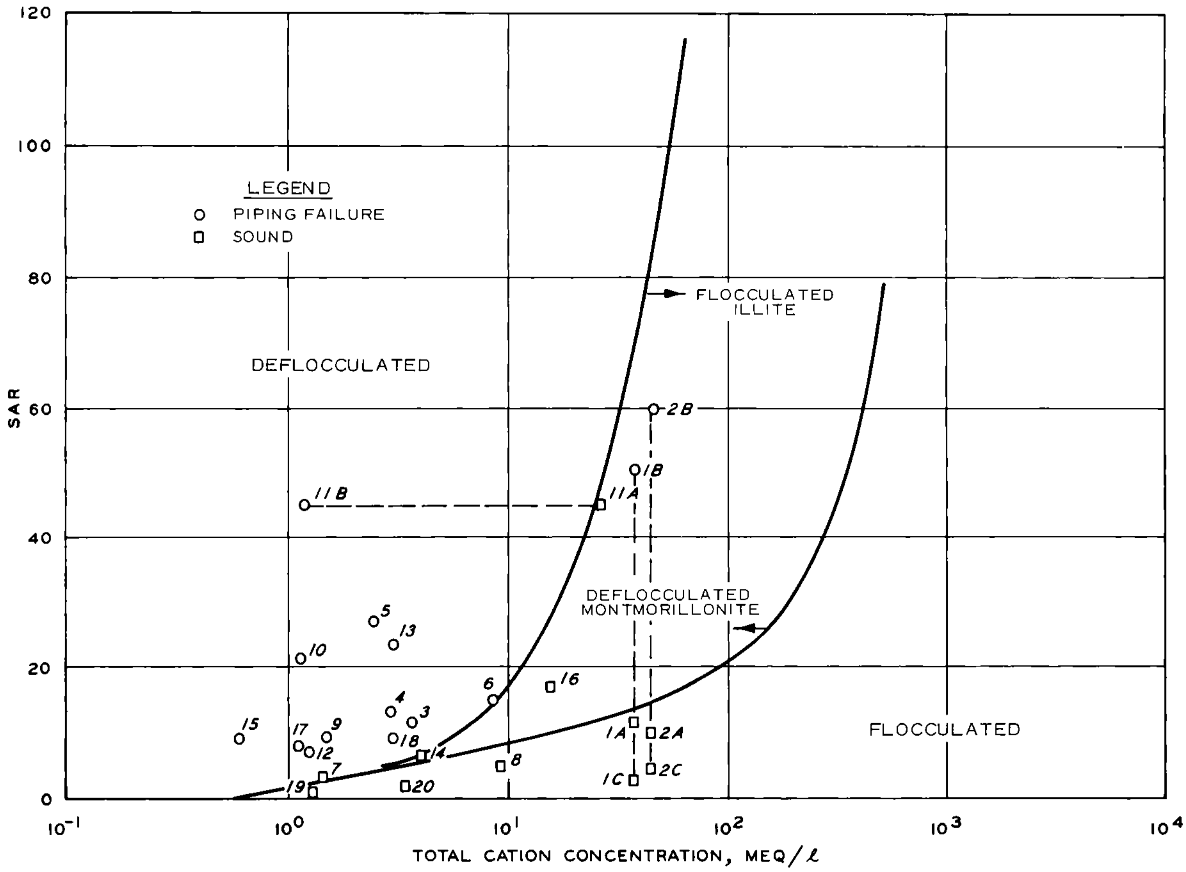

Figure 36. Correlation of field performance of earth dams in Australia with deflocculation based on laboratory tests of the SAR of the soil and the total cation concentration of the eroding water (courtesy of CSIRO[110])

hydrated lime (2 percent by dry weight) into the soil during construction would eliminate piping failure in earth dams. Subsequent work in the United States by SCS[96] has shown that rainfall erosion tunnels on the embankment slopes of earth dams constructed of dispersive clays could be prevented by plating the slopes with 12 in. of soil mixed with 2-3 percent of hydrated lime. The addition of hydrated lime to the reservoir water of an earth dam constructed of dispersive clay in an attempt to remedy an existing piping failure proved unsuccessful and a failure subsequently occurred.[112]

59. Rallings[91] in 1966 reported on a study conducted under the auspices of the Water Research Foundation of Australia, Ltd. The results of a survey of 498 farm dams in Queensland, Australia, compacted with

tractor and scoop or dozer and blade, revealed a failure rate of 33 percent with piping failure accounting for one-half of the failures. The farm dams were constructed in an arid climate with resulting field moisture contents in the range 4-10 percent dry of optimum moisture content at one-half standard compaction effort. A detailed investigation of 41 farm dams, of which 26 had failed by piping and 15 were sound dams, showed that the Crumb Test correlated well with field performance of the dams. The use of 0.001-normal sodium hydroxide in the Crumb Test was found to be more effective with soils of low pH and high ESP.

60. In 1967 Kassiff and Henkin[113] reported on a study of piping failure of low loess dams in the Negev. The clay fraction of the loess soil studied was predominately montmorillonite with small amounts of illite present. The results of the study by Kassiff and Henkin, as shown in Figure 37, indicated that the soil was susceptible to piping

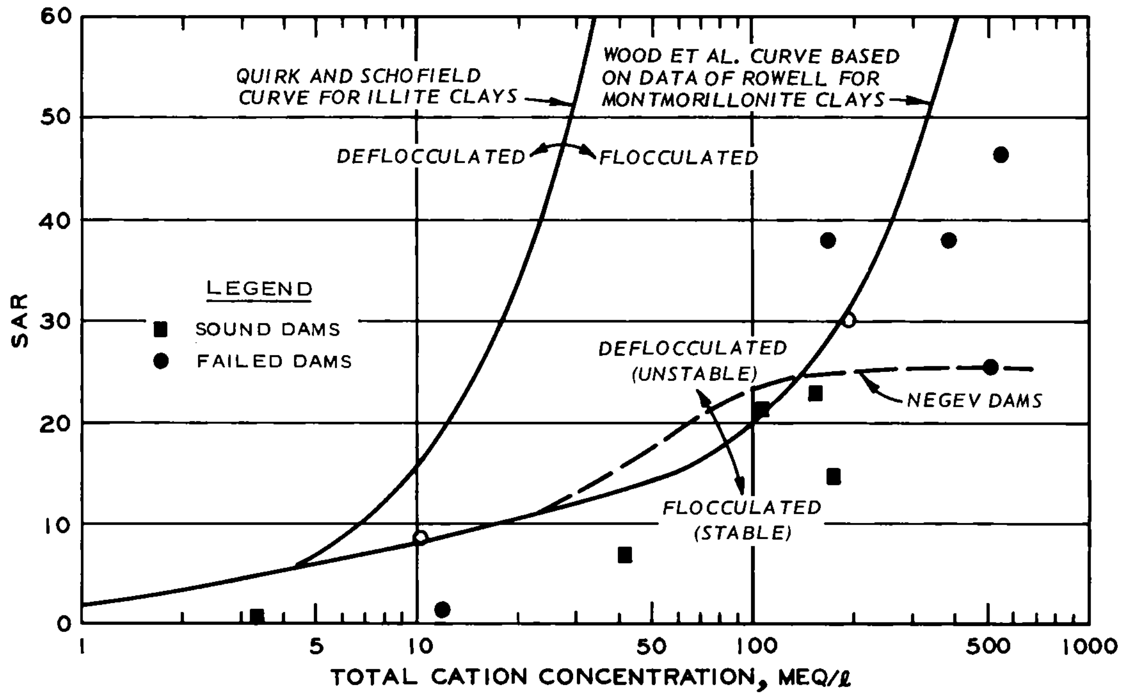

Figure 37. Correlation of field performance of loess dams in Negev with deflocculation based on laboratory tests of the SAR and total cation concentration from the soil pore water extract (From Reference 113. Courtesy of Prof. J. G. Zeitlen, Geotechnology, Technion City, Haifa, Israel)

failure whenever the SAR exceeded 25 and the total cation concentration exceeded 150 meq/ℓ. Kassiff and Henkin determined the total cation concentration from pore water extracted from the soil. The earth dams studied by Kassiff and Henkin were located in an arid climate where there was no permanent reservoir. Piping failures occurred in the earth dams immediately following filling of the reservoir during infrequent rainfall, indicating that the eroding water in the piping process was the reservoir water. It was, therefore, the reservoir water, instead of the pore water extracted from the soil, from which the total cation concentration should have been determined if the field performance of the earth dam was to be correlated with a laboratory relationship for deflocculation as a function of the SAR of the soil and the total cation concentration of the eroding water.

61. Ingles and coworkers[112,114-117] presented an important case history of a large earth-rock dam where the clay core was constructed of dispersive clay. Flagstaff Gully Dam, Tasmania, a town water supply reservoir, was constructed with upstream and downstream rockfills over filter zones on either side of the clay core, all on a rock foundation. The dam has a maximum height of 51 ft and a crest length of 600 ft. The properties of the clay core are given in Table 5. The clay core was placed at an average dry unit weight of 106 pcf and moisture content of 19 percent. Using the relationship given in Figure 31 for a predominantly montmorillonite clay, the upper and lower portions of the clay core with SAR's of 8 and 14 would deflocculate for total cation concentrations of the eroding water less than 8.5 and 14.5 meq/ℓ, respectively. Flagstaff Gully Dam was filled with water (total cation concentration = 1.4 meq/ℓ) from the Upper Derwent River some twenty miles away. Side drains around the perimeter of the reservoir prevented local runoff water from entering and increasing the salinity of the storage water. In July 1963, three weeks after first filling, a piping failure occurred at the junction of the clay core and bedrock foundation. Subsequent excavation revealed a major joint plane (joint width 1.5 - 3.0 mm) in the bedrock.[112] The initial leak leading to piping failure was believed to have been traveling in this joint in the bedrock surface just below

the clay-rock contact. Following reconstruction of the damaged portion of the dam, piezometers were installed to monitor changes in pore pressure and chemical composition of water within the clay core to investigate the possibility of further dispersive clay piping. Soil samples were taken from the clay core for determination of exchangeable cations to compute ESP. Water samples were taken from intake and storage waters, downstream toe seepages, and water entering the piezometer holes in the clay core for determination of total cation concentration.

62. Combining the results obtained by Quirk and Schofield[98] (soil containing 40 percent illite, 40 percent kaolinite, 20 percent vermiculite) and Rowell[101] (soil containing 100 percent montmorillonite), Ingles and coworkers[116] obtained the relationship shown in Figure 38 for

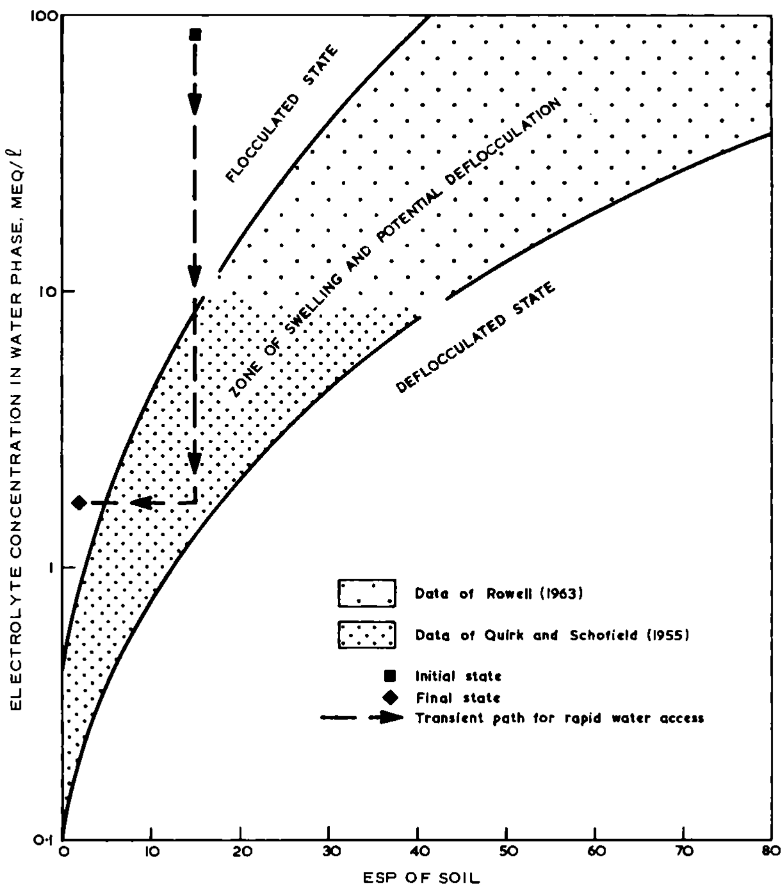

Figure 38. Postulated field performances of Flagstaff Gully Dam leading to piping failure following first filling of the reservoir (courtesy of CSIRO[116])

deflocculation as a function of ESP of the soil and electrolyte concentration (same as total cation concentration) of the eroding water. The band of data shown in Figure 38 reflects the difference between threshold (upper bound of data band) and turbidity (lower bound of data band) concentrations obtained in the permeameter tests by Quirk and Schofield.

63. The initial condition of soil and water chemistry of the clay core of Flagstaff Gully Dam prior to filling the reservoir is shown in Figure 38. Once the reservoir was filled, the storage water became the potential eroding water and the electrolyte concentration decreased by an order of magnitude. The joint plane in the bedrock surface beneath the clay core provided access for the reservoir water, with an electrolyte concentration of 1.4 meq/ℓ, to the lower portion of the clay core, with an ESP of 17 percent, precipitating piping failure of the dam following first filling of the reservoir. Following reconstruction of the damaged portion of the dam, over the 5-yr reporting period (1964-1968), the relationship between the electrolyte concentration in the seepage water and the ESP of the soil, as shown in Figure 39, has followed a path within the stable flocculated state. As shown in Figure 39, only in the final approach to equilibrium, where the soil ESP ≤ 7, does the transient state path approach the zone of swelling and deflocculation. The final state is being approached very slowly and is estimated to be at least 15 yr away. The slowness of the adjustment and the stable final equilibrium position indicate that the dam will be safe from dispersive clay piping provided the reservoir water is not permitted rapid egress from the clay core through a crack in the core of the dam. Should this occur, the only deterrence to failure by dispersive clay piping would be the ability of the core material to seal the flow channels by swelling and the possible beneficial action of silt size particles accumulating behind the sand filter and forming an impervious seal at the interface between the leakage channel and the filter.[118] Although the effectiveness of filters in preventing dispersive clay piping has been questioned by Australian investigators,[119] the results of recent laboratory tests[120] conducted at the SCS Soil Mechanics Unit in Lincoln, Nebraska, indicate that filters may provide

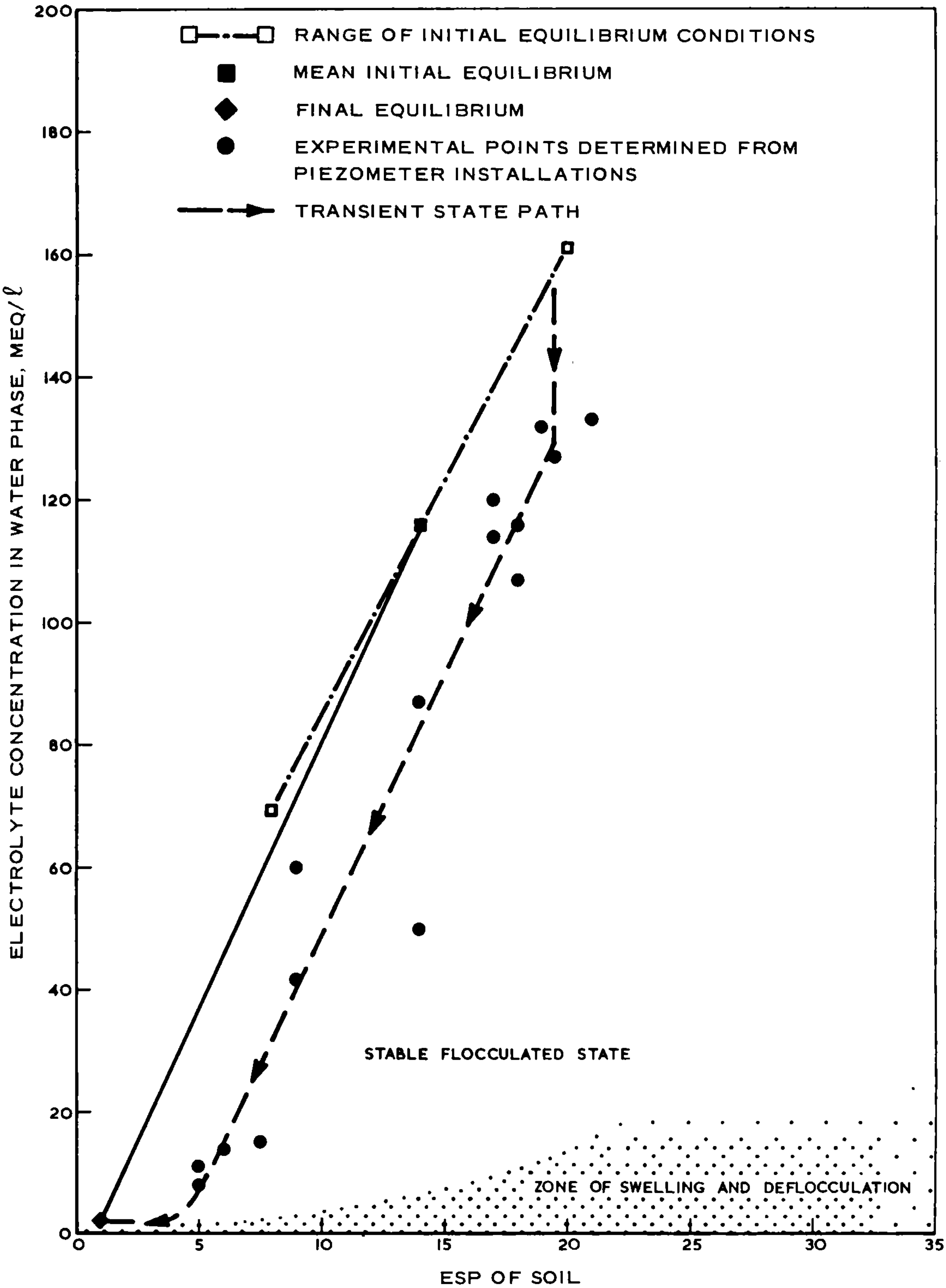

Figure 39. Observed field performance of Flagstaff Gully Dam following reconstruction of portion of embankment involved in piping failure after first filling of reservoir (courtesy of CSIRO[116])

an effective method of preventing dispersive piping when the soil contains a sufficient amount of silt size particles.

64. Carmichael[121] in 1970 referred to unpublished work by Fox using the Crumb Test to classify soils according to the readiness with which they dispersed. Fox used a range of calcium salt solutions, distilled water, and a range of sodium salt solutions. The solutions were given "dispersion numbers" starting with the strongest calcium solution, through distilled water, and then to the strongest sodium solution. A low dispersion number indicated that the soil would readily disperse and a high dispersion number indicated that the soil would not be dispersive. Using soil samples taken from earth dams in Queensland, Australia, Fox found that when dispersion numbers were high, irrespective of the initial moisture content of the material, all dams were successful. Low dispersion numbers resulted in failure if the initial water content at construction was low; but if the initial water content at construction was high, successful dams resulted. Following Australian practice, air-dried soil crumbs were used in these tests. Research by Sherard[92] has shown that wet (moisture content equal to one-half the plasticity index) soil crumbs will show a more positive reaction towards dispersion than will oven-dried soil crumbs 50 percent of the time. The work by Fox would have been more informative, particularly for the failed dams, if the Crumb Tests had been conducted at field moisture content and the relationship between moisture content and dry unit weight established in the laboratory simulating field compaction.

65. Ingles and coworkers[90,122] in 1973 presented a summary of their method to assess qualitatively the susceptibility of an earth dam to dispersive clay piping. The relationship between moisture content and dry unit weight is established in the laboratory using the appropriate compaction effort to simulate field compaction. The percent air voids is determined as shown in Figure 40. If the percent air voids ≤ 5 percent, no hazard of dispersive clay piping exists and no further testing is required (this is at variance with results presented by Sherard and coworkers,[96] who have documented dispersive clay piping in earth dams compacted near optimum water content). If the percent air

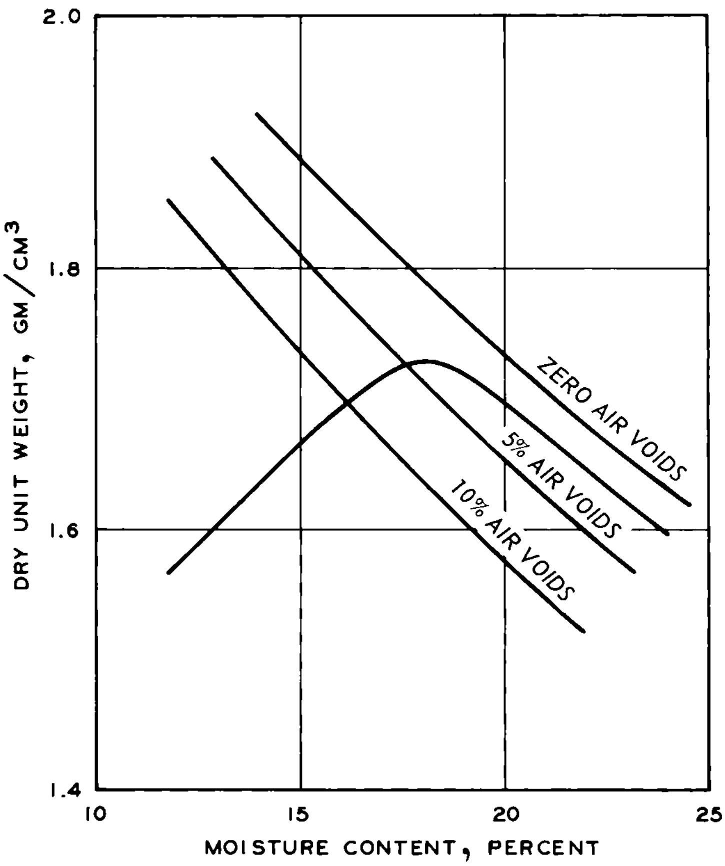

Figure 40. Typical dry unit weight versus moisture content relationship for soil (courtesy of the Publishers Butterworths, Sydney[90])

voids > 5 percent, the ESP of the soil is determined from conducting a CEC, computed from the SAR conducted on pore water extracted from a soil paste, or estimated from Figure 41 using the soil pH and the ionic ratio*[116] of water extracted from the saturated soil paste.

66. Prior to first filling of the reservoir, the ESP of the soil is in equilibrium with the total ionic concentration of the pore water of the soil. This will be the initial condition for the dam as shown in Figure 42 which shows deflocculation as a function of ESP of the soil, for predominately illite or montmorillonite clay, and total ionic

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* Ionic Ratio = $\frac{Na}{\sqrt{Ca + Mg}}$ (concentrations in molar units)

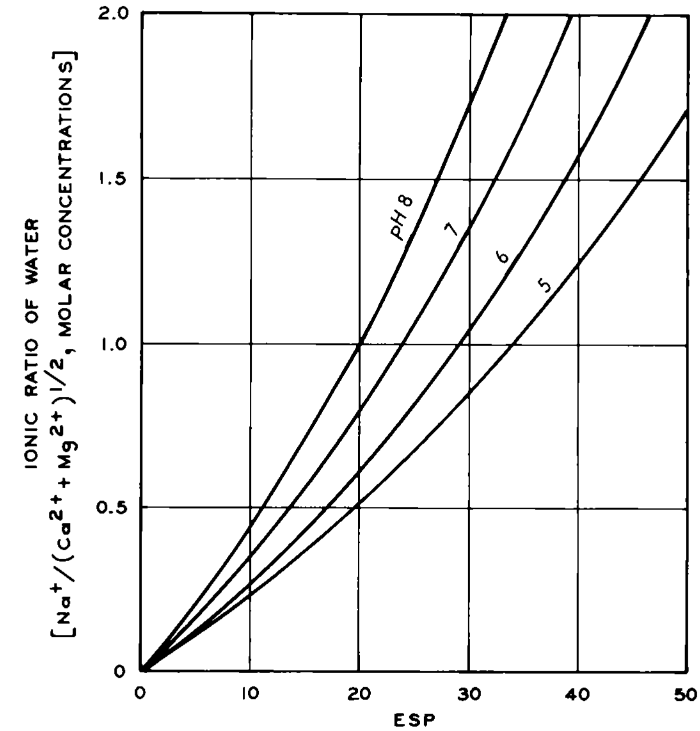


Figure 41. Equilibrium relationship between ionic ratio of water and exchangeable sodium percentage of soil for different soil pH values (courtesy of the Publishers Butterworths, Sydney[90])

concentration of the eroding water. Upon first filling of the reservoir, the susceptibility to dispersive clay piping may be predicted from Figure 42. If the earth dam is free from cracks or sandy lenses traversing the width of the dam, the final equilibrium state may be approached by a path which is safe from deflocculation as shown by dam A in Figure 42. It may take several years to reach the final equilibrium state. Soil samples are taken from the earth dam at various time intervals to determine the ESP of the soil and the total ionic concentration of the pore water of the soil to plot the curve shown for dam A in Figure 42. Some variation in total ionic concentration of the seepage water may result from chemical stratification with depth of the reservoir water. Cost and Naney[123] reported a variation in total ionic concentration of 100 meq/ℓ between the surface and bottom of the reservoir of Lake Chickasha Dam, Oklahoma. Chemical stratification increases with increasing

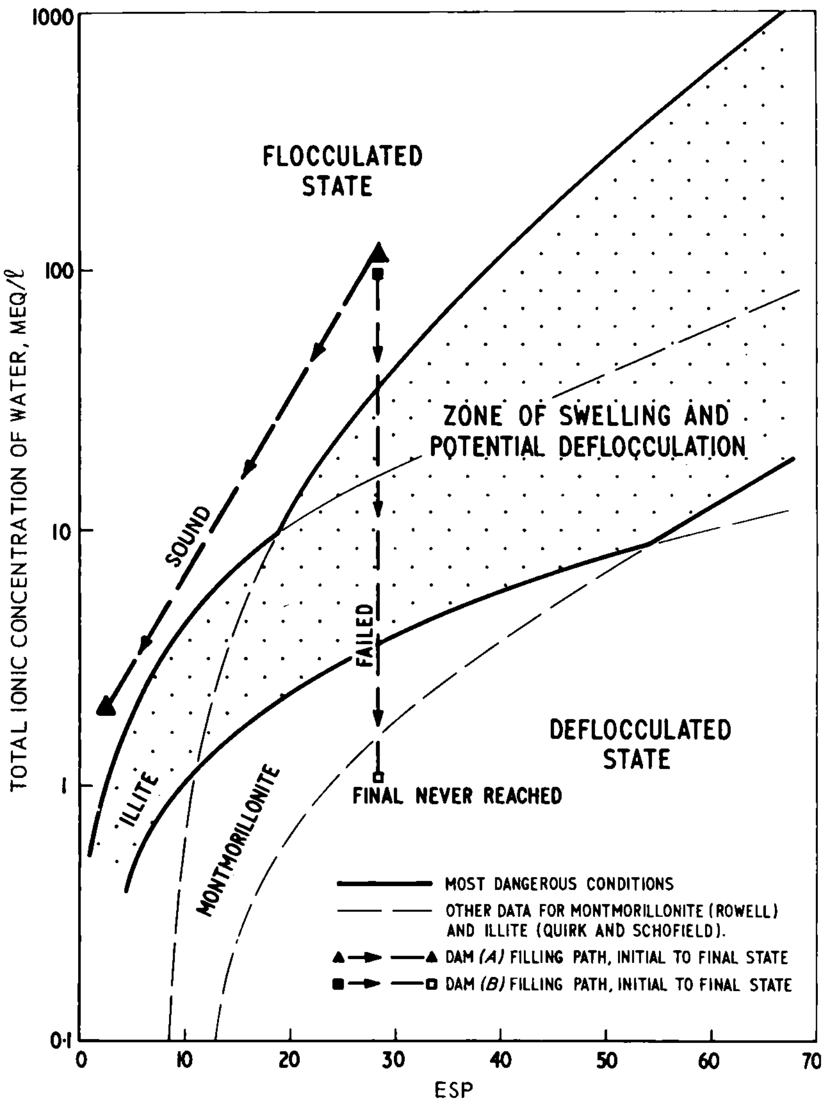


Figure 42. Prediction of piping failure in earth dams using the total ionic concentration of the eroding water and the ESP and predominate clay minerals of the soil (adapted from Reference 90 with the permission of the Publishers Butterworths, Sydney)

depth of the reservoir and decreases in wind activity. Aerial surveys[109,124] and the remote measurement of salinity of reservoirs[125] would not reflect this chemical stratification. If the earth dam does contain cracks or sandy lenses traversing the width of the dam, the reservoir water will have a path of rapid access across the earth dam. For this case the eroding water will be the reservoir water. The total cation concentration will change rapidly from the soil pore water (initial position of dam B in Figure 42) to the reservoir water (final position of dam B in Figure 42) while the ESP of the soil remains the same because it does not have time to change. If the final position of the dam plots in the deflocculated zone, as is the case for dam B in Figure 42, the dam may fail by dispersive clay piping upon first filling of the reservoir. The only deterrence to failure by dispersive clay piping for a homogeneous earth dam would be the ability of the embankment material to swell and seal the flow channels.

67. In 1972 Sherard[92] reported on a study conducted for SCS to investigate piping failures and rainfall erosion of earth dams in Oklahoma, Mississippi, and Arkansas. Soil samples were taken from shallow excavations on the dam slopes or old borrow pit areas from both earth dams which had failed by piping and/or been damaged by rainfall erosion and earth dams which had given satisfactory performance. Soil samples from these earth dams were tested for mechanical analysis, Atterberg limits, specific gravity, Harvard miniature standard compaction test, SCS Laboratory Dispersion Test,[96] Crumb Test, soil pH, SAR, and CEC. Water samples from the reservoirs of selected Oklahoma earth dams were tested for total dissolved salts. Figure 43 shows the relationship between percent sodium and total soluble salts in the soil pore water extract as a function of the SCS Laboratory Dispersion Test results for soil samples taken from earth dams which either failed by piping or were damaged by rainfall erosion. For soils low in potassium ($K \leq 1.1$ meq/ℓ in Sherard's study), the percent sodium is directly related to the SAR and the total soluble salts as shown in Figure 44. Figure 43 shows that the test results for a majority of the soil samples from the failed or damaged earth dams plot above the curved solid line, and all the soil samples with more than 67 percent dispersion plot above this line. Figure 45 shows the relationship between percent sodium and total soluble salts in the soil pore water extract including only samples which were taken from earth dams which were damaged by rainfall erosion. For this particular case, the eroding water involved in the erosion process would be rainfall and the total soluble salts would be less than

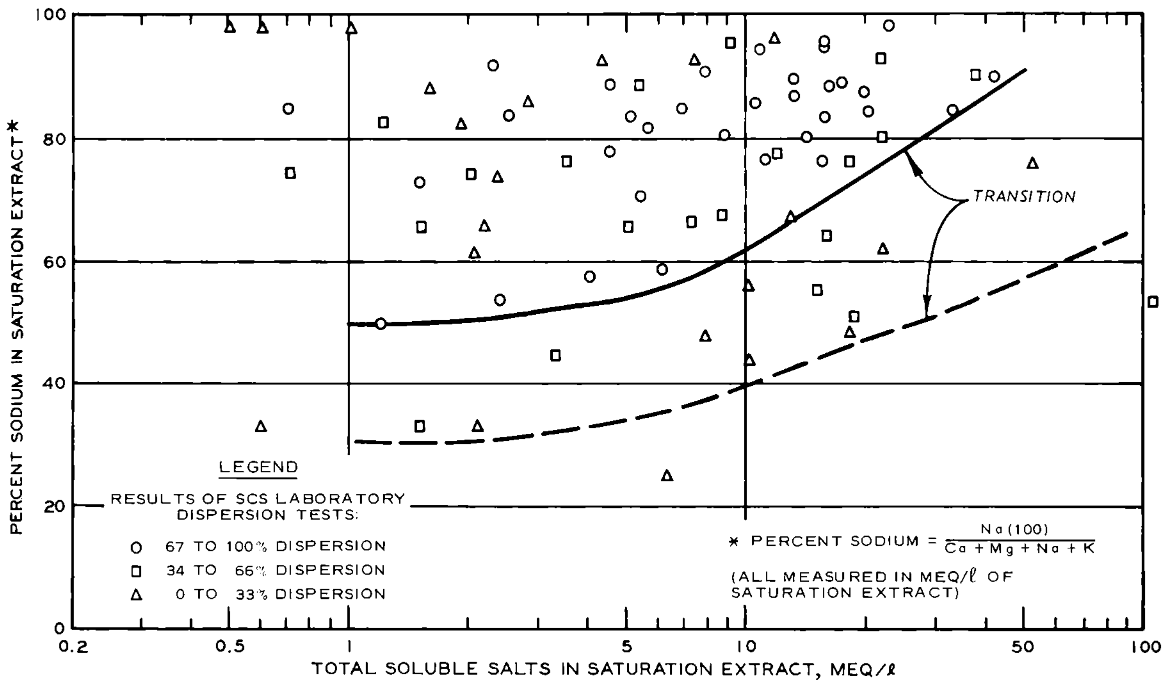


Figure 43. Results of soil chemistry tests on soil pore water extract from earth dams which failed by piping or were damaged by rainfall erosion (from Reference 92)

1 meq/ℓ. Figure 46 shows the relationship between percent sodium and total soluble salts in the soil pore water extract as a function of the SCS Laboratory Dispersion Test results for soil samples taken from undamaged earth dams which were included in the investigation as "control" dams. As shown in Figure 46, the test results for all but two of the control samples fall below the curved dashed line, and all but one of the control samples have less than 33 percent dispersion. Figure 47 shows a summary plot which correlates the results of chemical tests on the soil pore water extract with performance of the earth dams. Reservoir water samples from the earth dams in Oklahoma which failed by piping gave total dissolved salts in the range of 0.3-2.5 meq/ℓ with more than half the samples less than 1.0 meq/ℓ. As shown in Table 6, the dominant clay minerals for the samples tested were kaolinite and mica with lesser amounts of montmorillonite and vermiculite present. Subsequent documentation of the clay mineralogy of soil samples for the SCS study by Totrakool[126] and King[127] indicated that the dominant clay

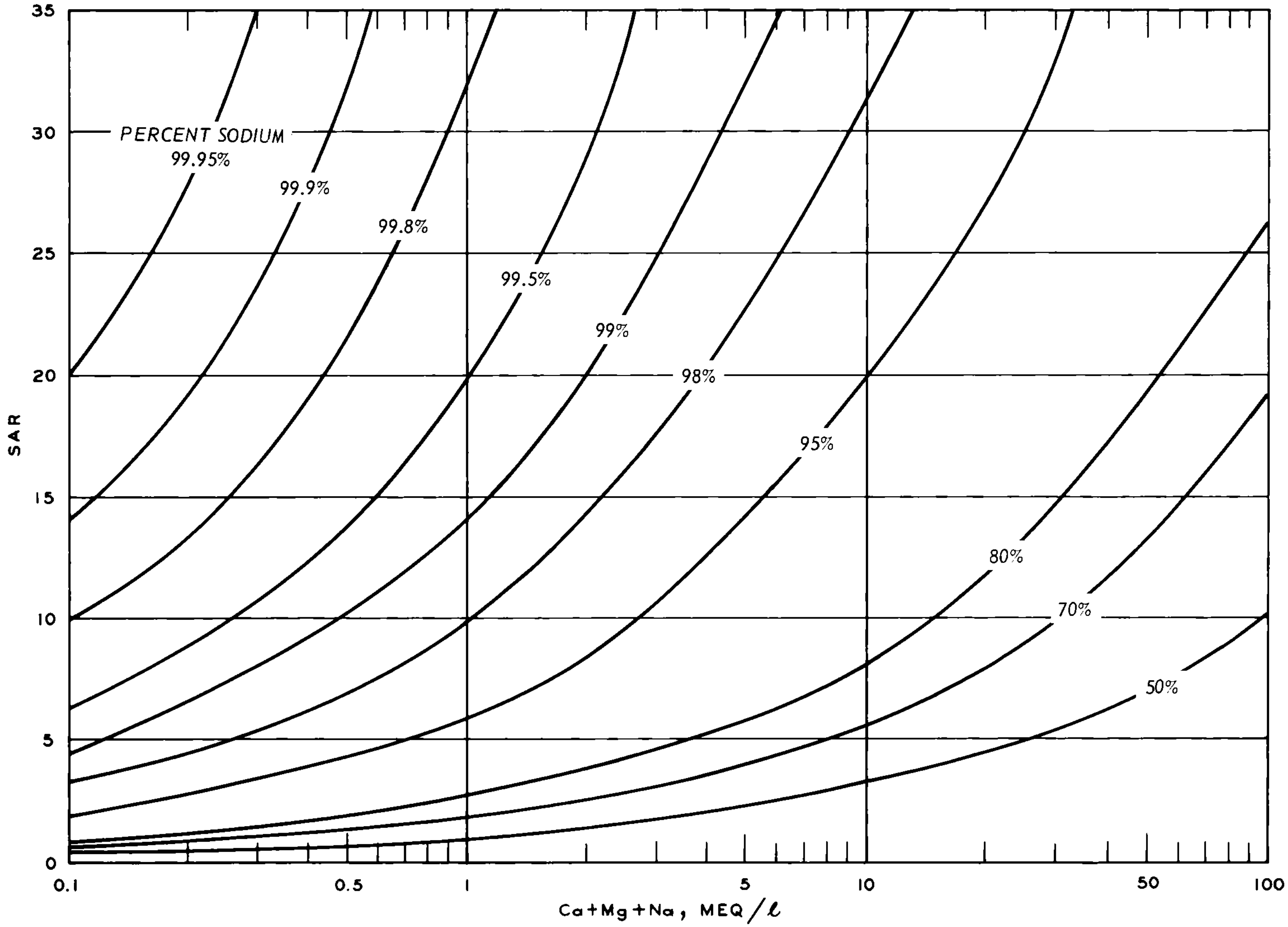


Figure 44. Percent sodium as a function of SAR and total soluble salts for low-potassium soil

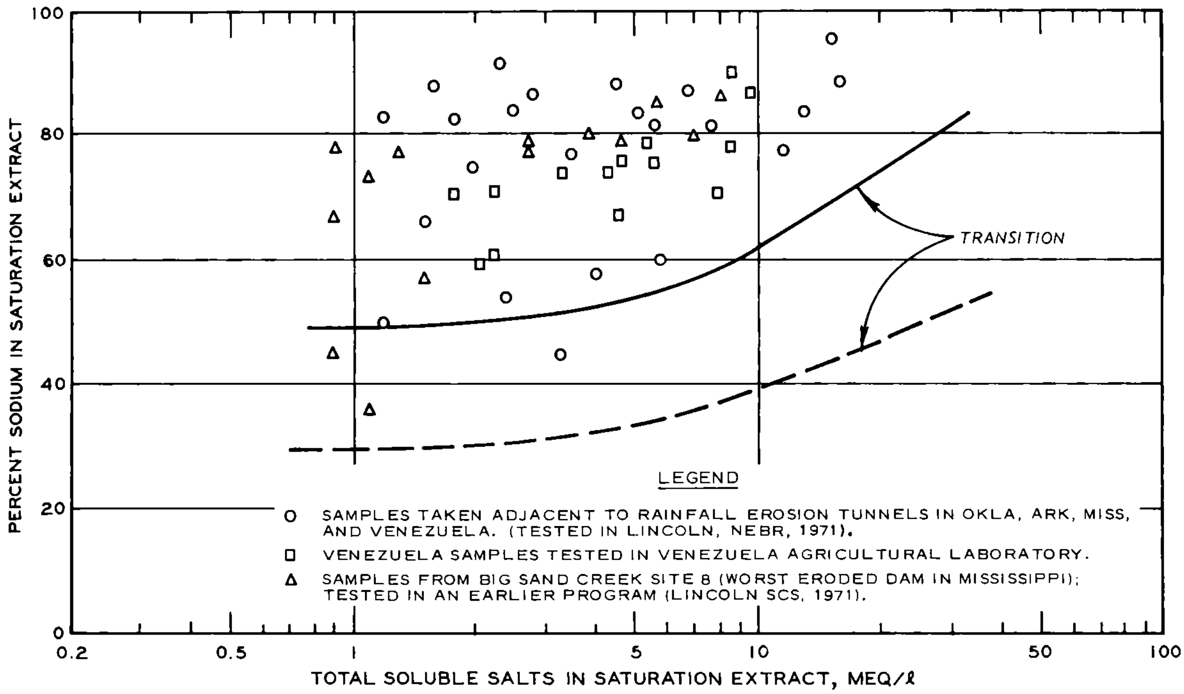


Figure 45. Results of soil chemistry tests on soil pore water extract from earth dams which were damaged by rainfall erosion (from Reference 92)

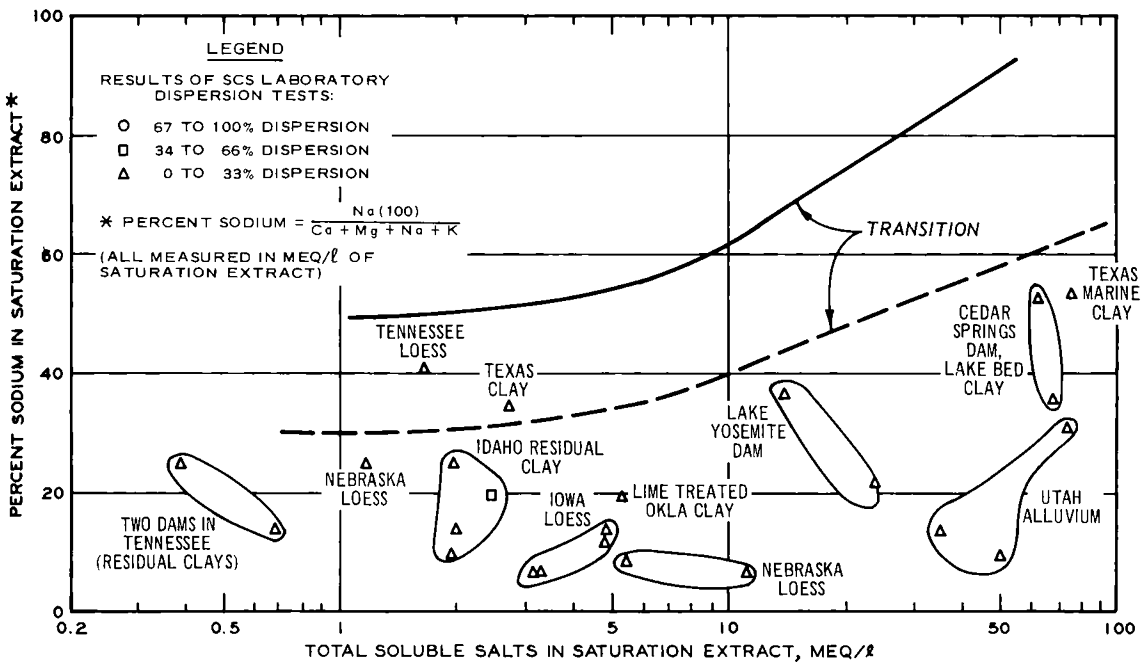
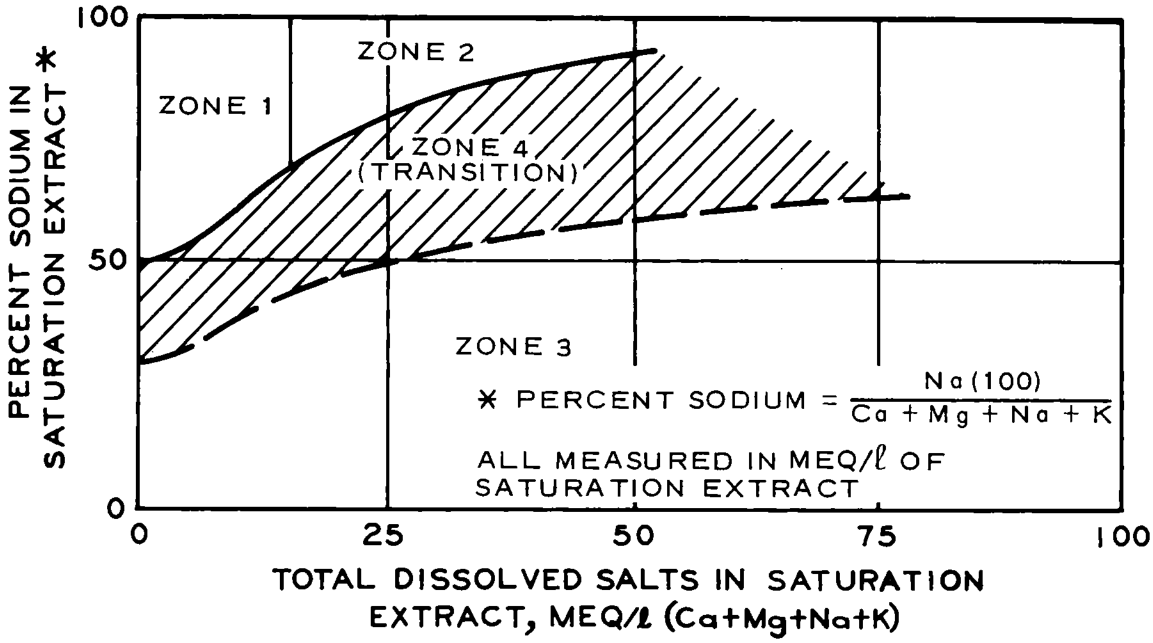


Figure 46. Results of soil chemistry tests on soil pore water extract from undamaged earth dams (from Reference 92)



ZONES 1 & 2 INCLUDE NEARLY ALL OF THE CLAY SAMPLES FROM DAMS WHICH FAILED BY BREACHING IN OKLAHOMA AND MISSISSIPPI. SAMPLES GENERALLY HAVE HIGH DISPERSION WHEN TESTED IN THE LABORATORY. HIGHLY ERODIBLE CLAYS.

ZONE 1 INCLUDES ALL SAMPLES FROM 16 CLAY DAMS WHICH WERE DAMAGED BY TUNNEL EROSION FROM RAINFALL IN VENEZUELA, OKLAHOMA, MISSISSIPPI, ARKANSAS, TENNESSEE, AND TEXAS.

ZONE 3 INCLUDES THE TEST RESULTS FOR MOST OF THE "CONTROL" SAMPLES. PROBABLE RANGE OF ORDINARY, EROSION RESISTANT CLAYS.

ZONE 4 IS THE TRANSITION ZONE. MOST SAMPLES IN THIS ZONE HAD LOW DISPERSION WHEN TESTED IN THE LABORATORY. THE LOWER BOUNDARY OF THE ZONE IS NOT WELL ESTABLISHED BY THE DATA.

Figure 47. Summary of correlation between soil chemistry tests on soil pore water extract and performance of earth dams (from Reference 92)

mineral was montmorillonite, illite was subdominant, and kaolinite was present in lesser amounts. For the one location for which comparative mineralogy data are available, Venezuela, as shown in Table 6, clay mineralogy was not found to be a deciding factor in identifying dispersive clays. All of the piping failures in this study occurred as the result of an initial leak which emerged at the downstream side of homogeneous embankments constructed without filters. In discussing the possible use of filters with dispersive clays Sherard noted:[92]

> If the initial leaks which led to failure of the Oklahoma and Mississippi dams had exited through sand filters, it is speculated that none of the dams may have failed....The very finest colloidal clay particles suspended in the leakage water would be carried at first through the voids of the sand filter....In order for an initially small leak to increase in volume rapidly by piping, the silt size particles and fine sands must also be carried out of the dam; however, these particles would not pass through the voids of a conventional sand filter. Therefore if the initial leak exited through a sand filter and if the dispersed clay particles passed through the filter, the silt size particles would back up behind the filter and remain in the dam. The silt size particles backing up against the filter would tend to keep the leakage channel filled with relatively impervious material so that the volume of the leak could not become very large, and would probably decrease gradually with time. Even if the leak did not gradually disappear because of the accumulation of silt size particles behind the filter, there can be little doubt that the volume of the leak would increase more slowly because of the existence of the sand filter than it would have without it. This being the case, the compacted clay material forming the walls of the leakage channel has more time to swell and to squeeze off a leakage channel. For these reasons, the writer has little doubt that filters of fine to medium sand, designed with adequate thickness and confinement so that the filter itself is stable, will be effective in the control of piping in dispersive clays.

68. The results of the study of dispersive clay conducted for SCS reached a wider audience through three papers by Sherard and coworkers in 1972.[96,118,128] In a discussion of these papers, Vizcaino and

Lattuada[129] describe a failure which occurred in June 1972 at the La Escondida Dam, Mexico. The embankment was a homogeneous clay placed at optimum moisture content and compacted with a sheepsfoot roller. Prior to completion of the spillway, a 9-in. rainstorm in the basin resulted in filling of the reservoir to a level 6 ft below the embankment crest. A few hours after the filling of the reservoir, the embankment failed by piping in approximately 50 locations. Preliminary investigations indicated that the embankment material was dispersive clay.[130]

69. Decker[95] in 1972 presented a paper on the identification and influence of dispersive clays on erosion. Using the American Society of Testing and Materials (ASTM)[131] classification for clay size particles (<0.005 mm), and the results from the SCS Laboratory Dispersion Test,[96] Decker defined the effective clay as

$$\text{Effective clay} = \% < 0.005\ \text{mm} - \left(\% < 0.005\ \text{mm} \times \frac{\%\ \text{Disp.}}{100\ \%}\right) \qquad (3)$$

where

$\% < 0.005$ mm = percent clay size particles

% Disp. = percent dispersion from SCS Laboratory Dispersion Test

Figure 48 shows the correlation between soil chemistry test on soil pore water extract and percent effective clay and field erosive performance. Figure 49 shows the correlation between percent effective clay and plasticity index and field erosive performance. The results shown in Figures 48 and 49 indicate that fine-grained soils with plasticity index $\geq$ 8 percent and effective clay $\geq$ 20 percent are nonerosive. Figure 49 indicates that nonerosive soils will have a percent effective clay equal to or greater than the plasticity index. Table 7 gives the critical dispersion from the SCS Laboratory Dispersion Test for different percentages of total clay size particles (< 0.005 mm) for fine-grained nonerosive soils containing 20 percent effective clay.

70. In 1973 Sherard[120] reported on a laboratory study of dispersive clays conducted at the SCS Soil Mechanics Unit in Lincoln, Nebraska.

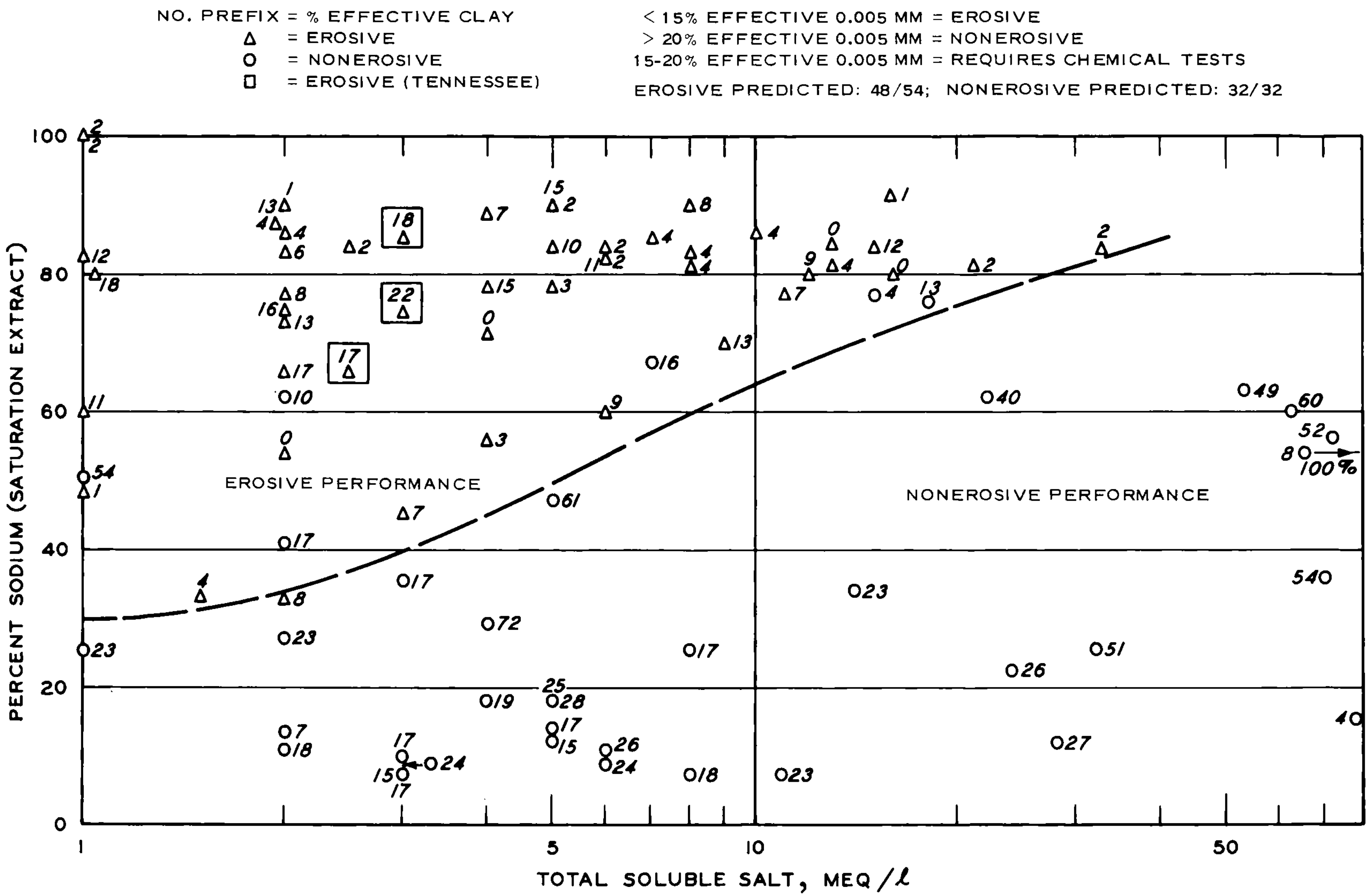


Figure 48. Correlation between soil chemistry tests on soil pore water extract and percent effective clay and field erosive performance (from Reference 95)

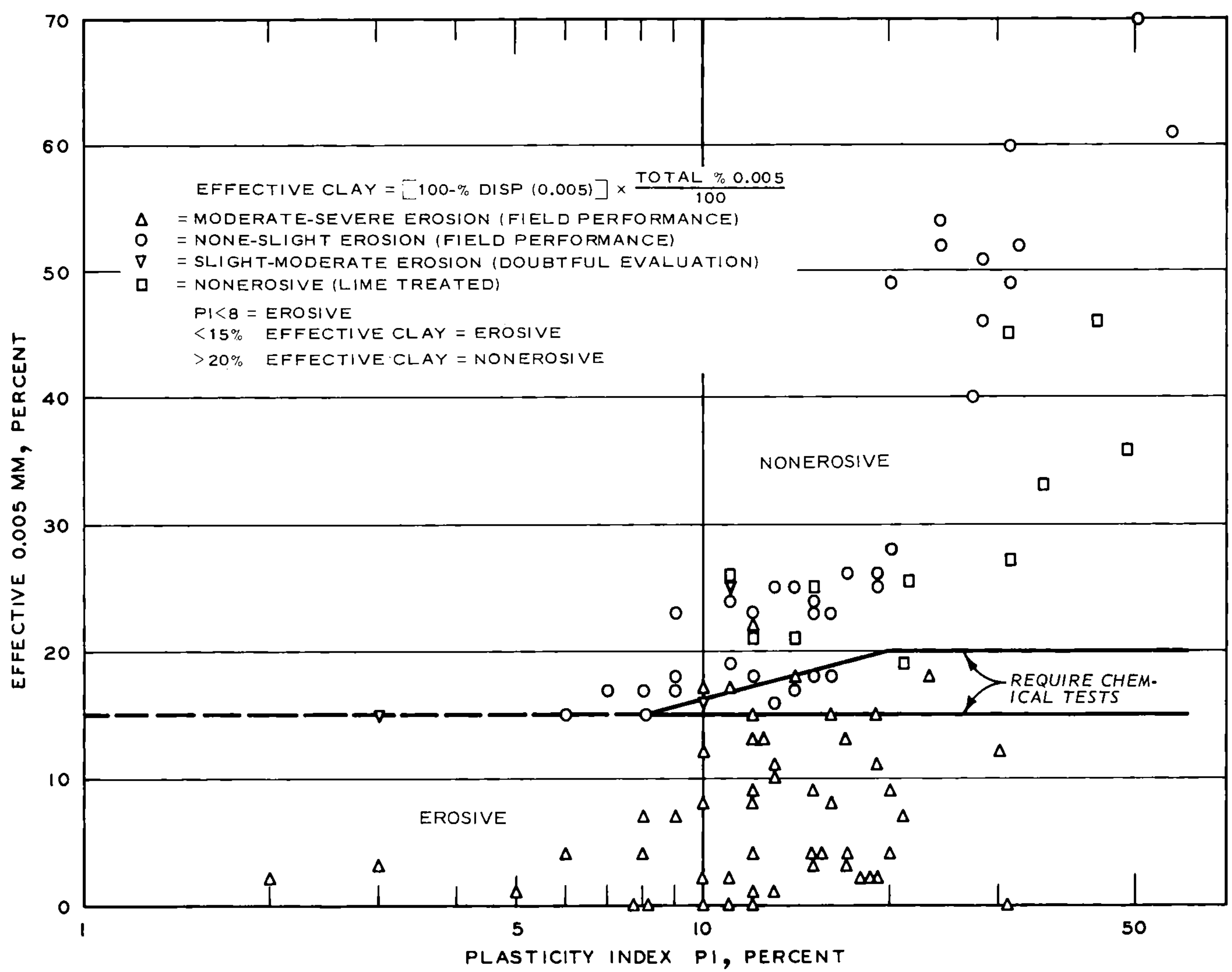


Figure 49. Correlation between percent effective clay and plasticity index and field erosive performance (from Reference 95)

Using a pinhole erosion apparatus similar to that shown in Figure 5c, filter tests were conducted using 8-in.-long specimens of compacted clay with 4 in. of sand filter in a 3-in.-diam clear plastic cylinder. All tests were made with distilled water. Coarse and fine filter sands were obtained by blending screened river sand to match the coarse and fine boundaries of ASTM fine aggregate.[132] The clay specimens used in the filter tests included both nondispersive and dispersive clays compacted at optimum water content ($\pm$1.5 percent) and 95 percent maximum dry unit weight (standard compactive effort). The size of the "pinhole" drilled or punched through the clay specimens varied from 0.1 to 0.5 in. in diameter. The hydraulic gradient used in the filter tests varied from 4 to 6. The pinhole erosion filter test conducted on the nondispersive clay indicated no erosion. The water flowing through the pinhole remained clear and the size of the pinhole remained constant. The rate of flow through the specimen was limited by the permeability of the sand filter. The pinhole erosion filter tests conducted on the dispersive clay indicated that erosion was occurring. The water flowing through the pinhole was cloudy and colloids were carried through the sand filter. Initially the rate of flow through the specimen was limited by the permeability of the sand. Immediately after the initiation of flow, silt sized particles (0.005-0.074 mm) began to deposit at the interface between the clay specimen and the sand filter. This silt skin became the hydraulic control. The flow through the specimen was gradually sealed by the action of silt sized particles backing up in the pinhole behind the sand filter. Striking the pinhole erosion apparatus with a carpenter's hammer broke the seal and formed a vertical crack between the clay specimen and the sand filter. The resulting flow through the pinhole was sealed again by the deposition of silt sized particles in the open cavity at the interface between the clay specimen and the sand filter. The number of pinhole erosion filter tests conducted was not sufficient to allow differentiation between the effectiveness of coarse and fine filter sand. Although the length of the clay specimens was not varied, it was postulated that the time required for the silt sized particles to form a seal at the interface between the clay specimen and the sand filter and back up in the pinhole behind the sand filter would decrease as the length of the clay specimens increased. The conditions imposed in the pinhole erosion filter tests, with the exception of the relatively low hydraulic gradients, were considered to be more severe than actual conditions which would occur in an earth dam.

71. A second series of tests was conducted by Sherard and coworkers[120] to study the behavior of intact specimens of dispersive clay under relatively high hydraulic gradients. Using a conventional permeameter apparatus similar to that shown in Figure 5b, tests were conducted using 1-in.-long specimens of compacted clay with 9 in. of filter material (coarse sand or pea gravel) in a 3-in.-diam clear plastic cylinder. All tests were made with distilled water. The clay specimens used included both nondispersive and dispersive clays compacted at optimum water content and 95 percent maximum dry unit weight (standard compactive effort). The hydraulic gradient used varied from 0 to 110. The results of the tests indicated that a 1-in.-thick specimen of compacted dispersive clay underlain by pea gravel showed no tendency towards piping when subjected to a hydraulic gradient of 110 for in excess of 4 months.

72. A third series of tests was conducted by Sherard and coworkers[120] to determine if the pinhole erosion apparatus could be used to differentiate between dispersive and nondispersive clays. Using a pinhole erosion apparatus similar to that shown in Figure 5c, erosion tests were conducted using 1-in.-long specimens of compacted clay with 9 in. of pea gravel in a 3-in.-diam clear plastic cylinder. The compacted clay specimens included both nondispersive and dispersive clays compacted at optimum water content ($\pm$1.5 percent) and 95 percent maximum dry unit weight (standard compactive effort). Erosion tests were also conducted on undisturbed samples of nondispersive and dispersive clays. All tests were made with distilled water. The size of the pinhole varied from 0.016 to 0.040 in. in diameter. The results of the tests indicated that using the pinhole erosion apparatus with a 1-in.-long clay specimen, an initial pinhole diameter of 0.040 in., and a hydraulic gradient of 6, it was possible to differentiate between dispersive and nondispersive clays. Dispersive clays erode to a hole of

0.25-in.-diam in a few minutes while nondispersive clays reach equilibrium without appreciable erosion.

73. In 1974 Sherard[133] reported on further laboratory study of dispersive clay conducted at the SCS Soil Mechanics Unit in Lincoln, Nebraska. Approximately 150 pinhole erosion tests were conducted on samples from various parts of the United States. The soil samples were tested for SCS Laboratory Dispersion, Crumb Test, SAR, and CEC. The results of the pinhole erosion tests have been used to redefine the boundaries of the chemical properties which define dispersive clays shown in Figure 47.[93] The results obtained in the pinhole erosion test were found to be highly reproducible. More recent pinhole erosion tests have shown that sample preparation procedure can influence the results obtained for certain nondispersive clays.* Some nondispersive clays, if allowed to dry in the laboratory, combined with distilled water to obtain optimum water content, remolded using kneading compaction, and tested immediately, will give the reaction of a dispersive clay in the pinhole erosion apparatus.

74. Arulanandan and coworkers[47,74,102,134-136] have conducted studies to correlate the physicochemical properties of soils with erosion. With a rotating cylinder apparatus similar to the one shown in Figure 9, research has been conducted to determine the influence of clay mineralogy, clay content, and pore and eroding water compositions on the erodibility of saturated statically compacted soils. Limitations of the rotating cylinder apparatus in testing partially saturated soils led to the utilization of laboratory flumes, with soil specimens mounted flush with the flume bottom, to study soil erosion. Comparison of the results obtained with the rotating cylinder apparatus and laboratory flume indicates good agreement for the critical shear stress, defined as the stress at which erosion is initiated. However, the rate of erosion at "constant" shear stress was larger in the rotating cylinder apparatus than in the laboratory flume.[47]

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* J. L. Sherard, personal communication, 12 June 1974.

75. Soil specimens for use in the rotating cylinder apparatus were prepared by mixing varying proportions of commercial clay minerals (kaolinite, illite, sodium montmorillonite), silt, and sand with solutions of various SAR and salt concentrations.[103] The exchange complex of the soil was brought into equilibrium with an appropriate concentrated salt solution and then changed by a series of percolating solutions of decreasing concentration while the same cation status was maintained. For samples of high SAR, the soil mixture was first equilibrated with a higher concentration of sodium chloride than the final concentration to displace as much calcium and magnesium as possible and then vacuum filtered and equilibrated with the proper concentration of sodium chloride. The soil mixture was then consolidated for 2 weeks with increasing loads up to 32 kg. The effluent from the consolidated sample was analyzed to determine the relative concentrations of sodium, calcium, and magnesium in the soil pore water. The operation of the rotating cylinder apparatus was the same as previously described in paragraphs 27 and 28. The amount of erosion was determined by weighing the sample following scour at a preselected value of shear stress acting on the surface of the soil specimen. The erosion rate was determined from a plot of weight loss per unit area versus time as shown in Figure 50. The critical shear stress was defined as the intercept on the applied shear axis corresponding to zero erosion rate as shown in Figure 51. The critical shear stress is the stress required to initiate surface erosion, which is defined as a slight flaking of material from the surface of the soil sample.

76. The influence of soil pore water concentration on the critical shear stress for kaolinitic, illitic, and montmorillonitic soils is shown in Figure 52a, b, and c, respectively. Distilled water was used as the eroding fluid. As shown in Figure 52, the critical shear stress increased with increasing soil pore water concentration. The increase in critical shear stress with increasing soil pore water concentration was more significant at low SAR values. Figure 53 shows the influence of clay mineral type on the critical shear stress versus SAR. For a given SAR the critical shear stress increased with increasing surface area and/or CEC of the clay mineral.

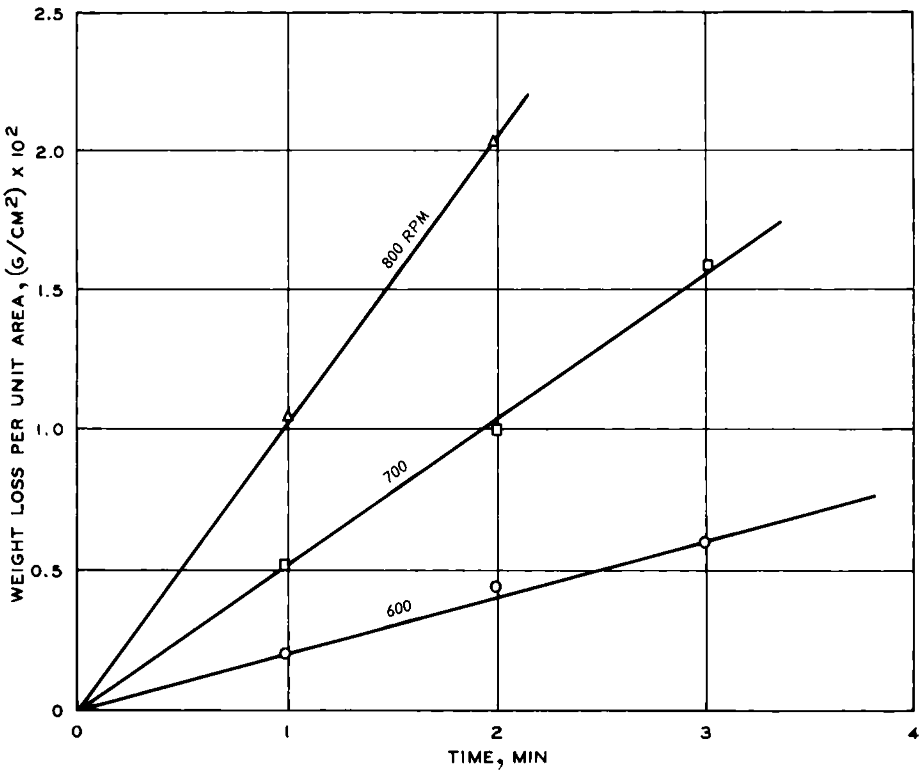


Figure 50. Weight loss per unit area versus time for various speeds of rotation for rotating cylinder apparatus (after Reference 103)

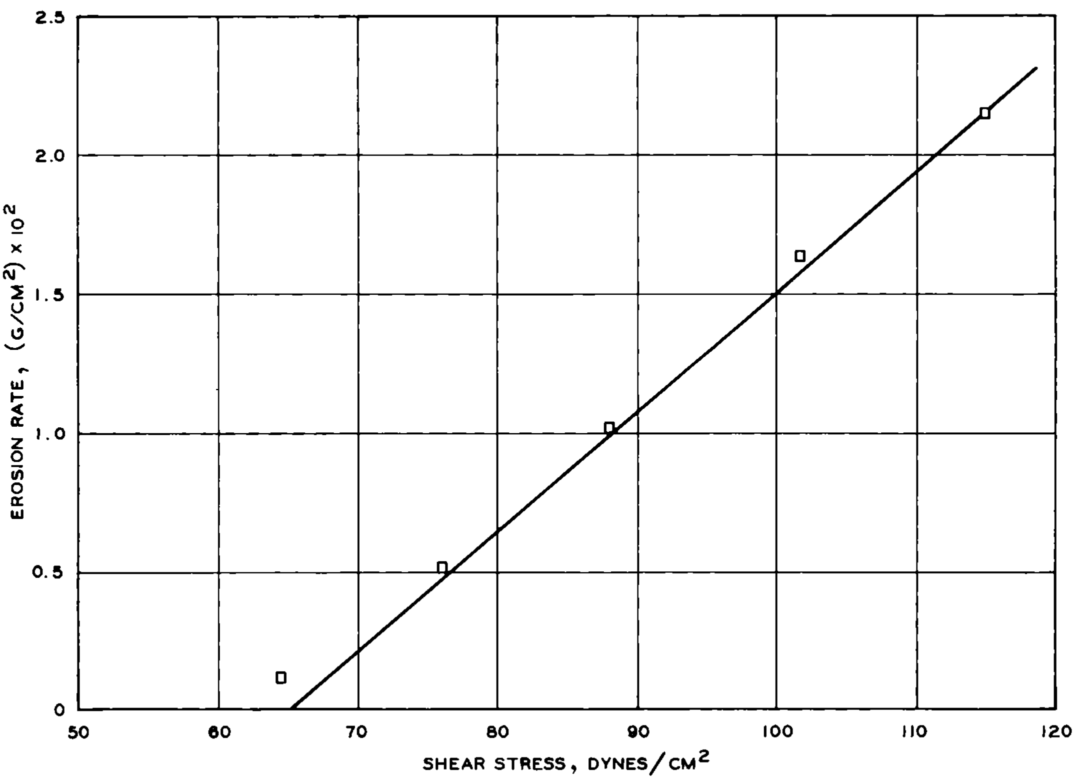


Figure 51. Erosion rate versus shear stress for kaolinitic soil (after Reference 103)

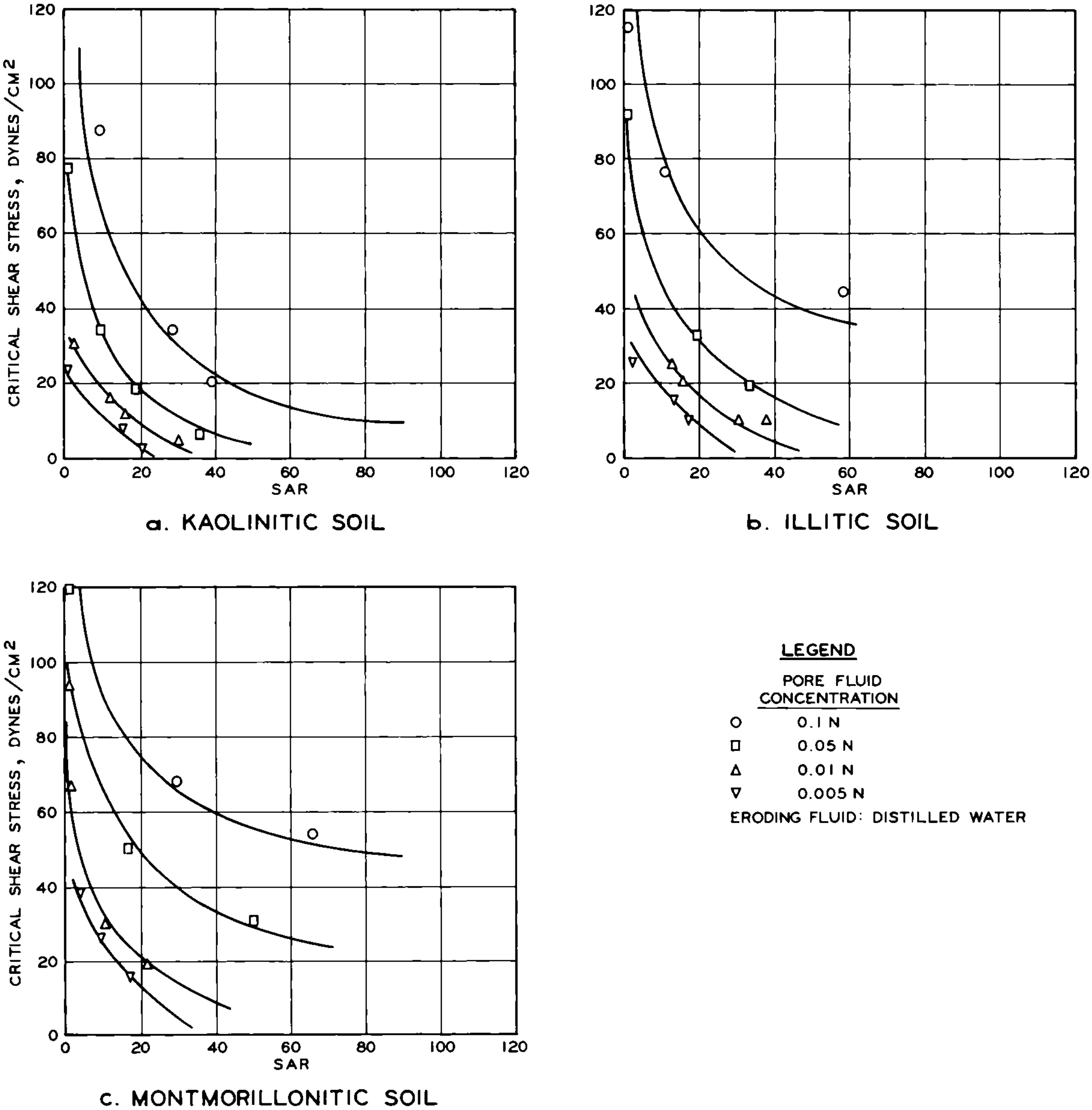


Figure 52. Critical shear stress versus sodium adsorption ratio for different soil pore water concentrations (after Reference 103)

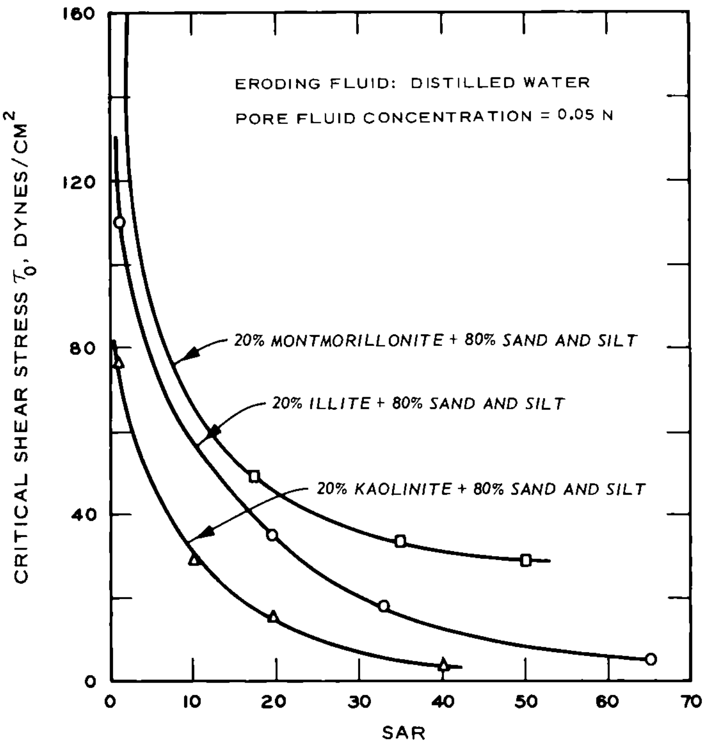


Figure 53. Influence of clay mineral type on the critical shear stress versus sodium adsorption ratio (after Reference 103)

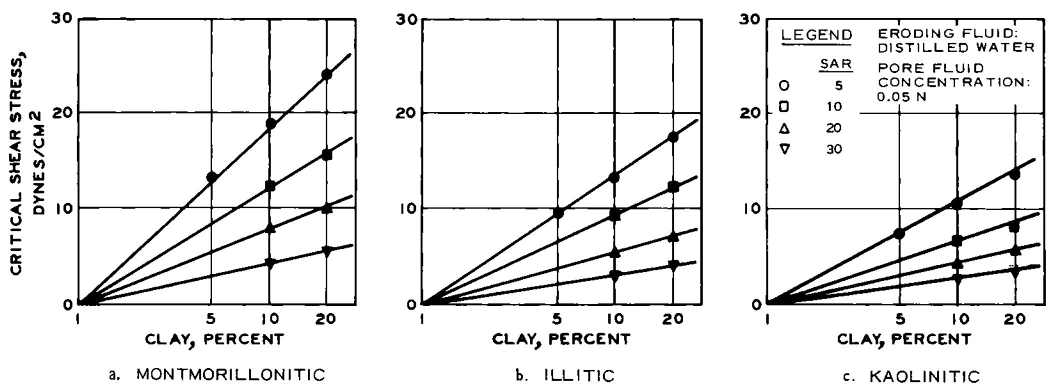


Figure 54. Influence of the amount of clay mineral on the critical shear stress as a function of SAR for clay soils (after Reference 137)

77. The influence of the amount of clay mineral on the critical shear stress, as determined by Alizadeh,[137] is shown in Figure 54. The critical shear stress increased with increasing amounts of clay

mineral present for kaolinitic, illitic, and montmorillonitic soils.

78. The influence of eroding fluid concentration on the erosion rate versus shear stress acting on the surface of the soil specimen for kaolinitic soil with a pore fluid concentration of 0.1-normal sodium chloride is shown in Figure 55. It was found that no erosion measurable

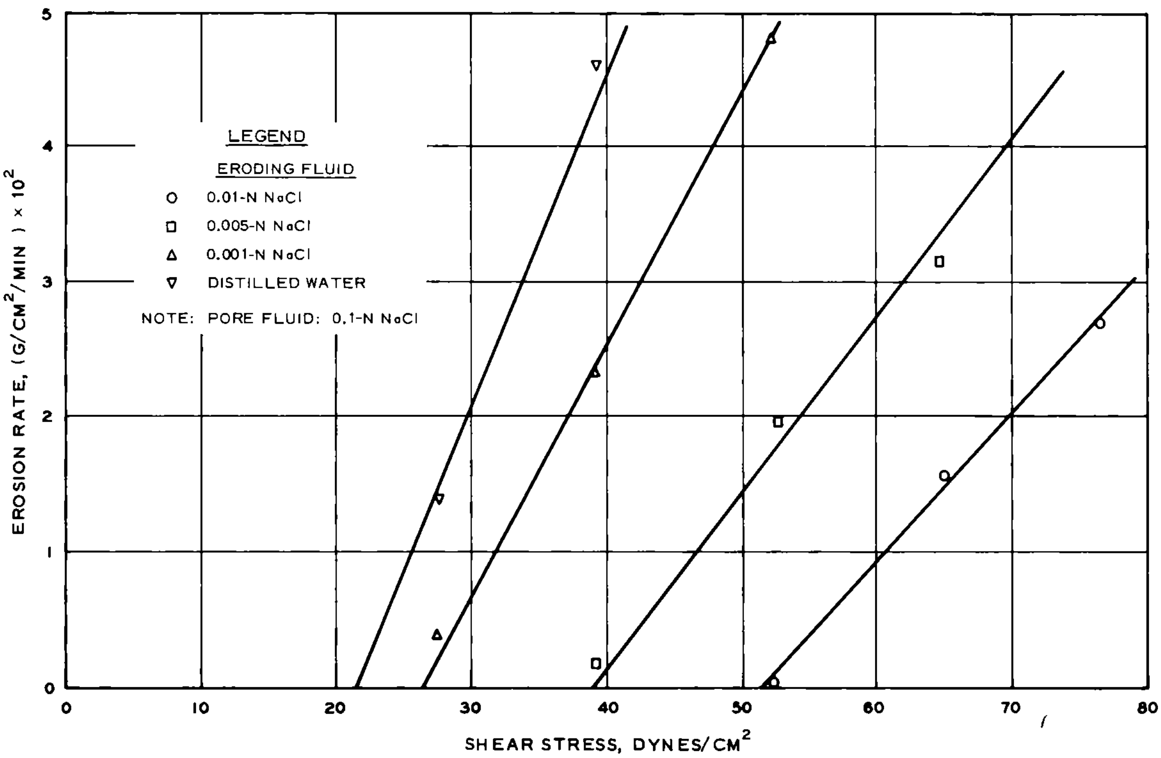


Figure 55. Influence of eroding fluid concentration on erosion rate versus shear stress for kaolinitic soil (after Reference 103)

within the limits of the rotating cylinder apparatus occurred when the eroding fluid concentration was equal to or greater than the soil pore water concentration. When the eroding fluid concentration was lower than that of the soil pore water, erosion was initiated. As shown in Figure 54, the erosion rate increased with increase in the concentration gradient between the soil pore water and eroding fluid. The critical shear stress, defined as the shear stress at zero erosion rate, decreased with increase in the concentration gradient between the soil pore water and the eroding fluid.

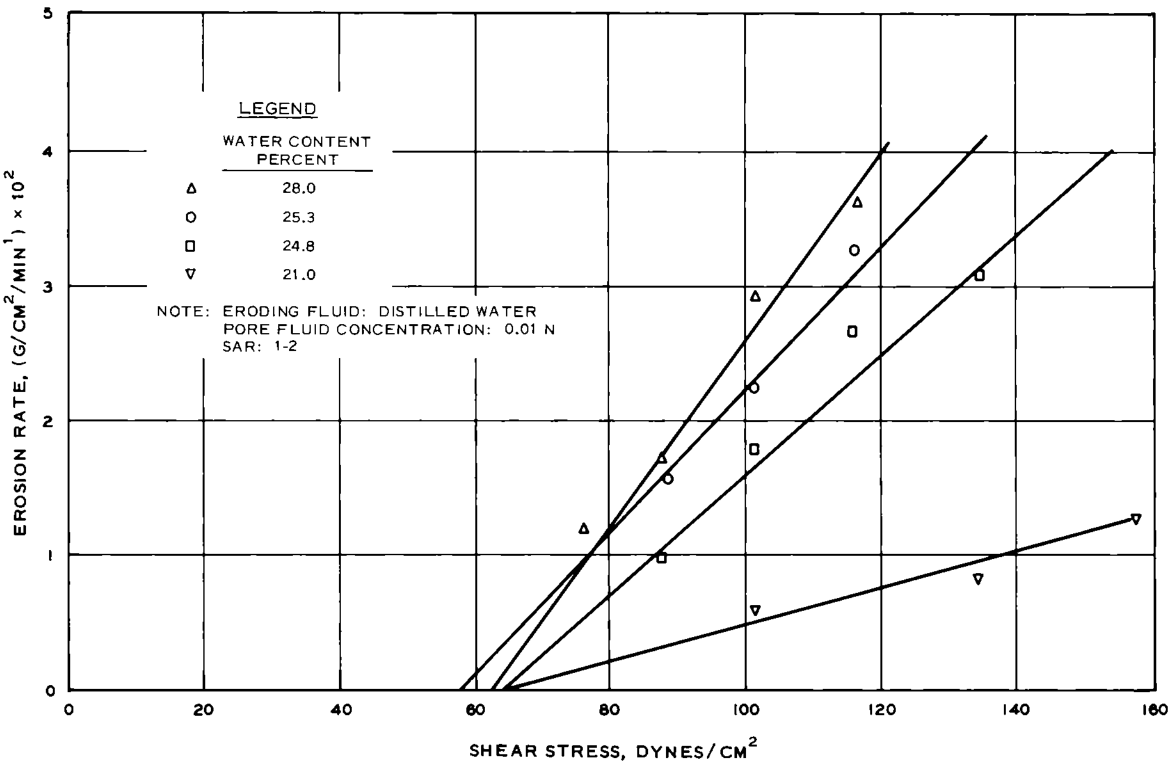
79. The influence of moisture content on the erosion rate versus

shear stress for kaolinitic soil at low (1-2) and high (36) SAR is shown in Figure 56a and b, respectively. The critical shear stress remained essentially constant over the range of moisture contents tested at low SAR, while increasing with increase in moisture content at high SAR. The influence of storage time (time between compaction and erosion testing) on erosion rate versus shear stress for kaolinitic soil is shown in Figure 57. As shown in Figure 57, there is a marked effect of storage time on both the critical shear stress and erosion rate. The relationship between critical shear stress, SAR, and total salt concentration of soil pore water extract for kaolinitic, illitic, and montmorillonitic soils is shown in Figure 58a, b, and c, respectively.

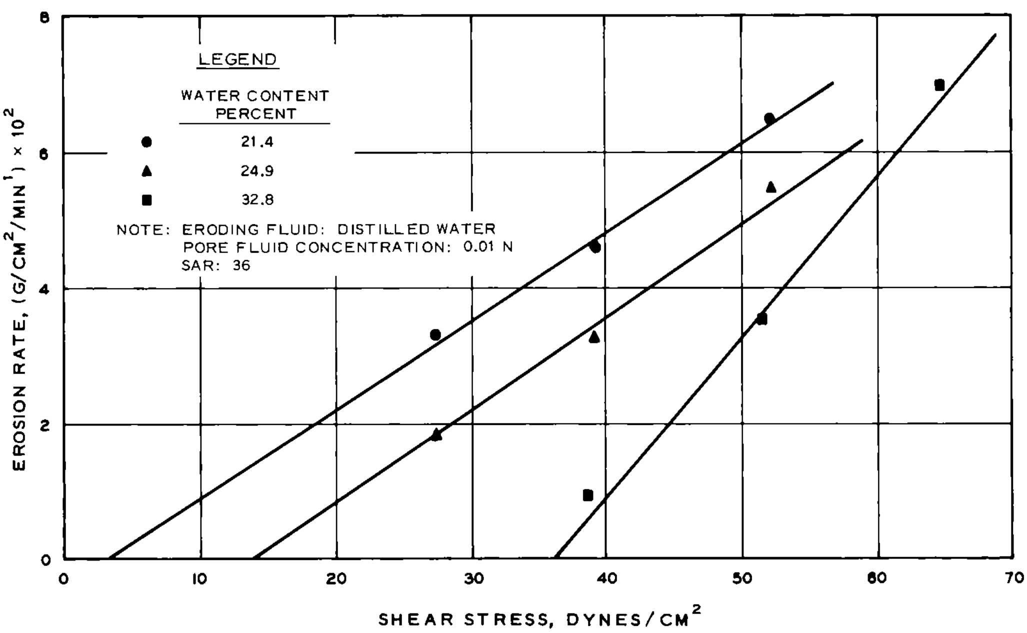
80. In 1973 Mitchell and Woodward[138] reported on a study to determine whether soil chemistry could be used to predict the susceptibility to slope failures. The soil chemistry of several of the slide sites studied was susceptible to dispersion using the relationship shown in Figure 47. The results obtained did not establish that the slope failures were caused by clay dispersion.

81. Petry and coworkers[139,140] reported on the development of a laboratory "physical erosion test" for the measurement of the erodibility of compacted dispersive clay soils. The physical erosion test (PET) device, shown in Figure 59, is somewhat similar to the pinhole erosion device developed at the SCS Soil Mechanics Unit in Lincoln, Nebraska. The PET employs a 1.31-in.-diam by 2.8-in.-long soil specimen with three 0.125-in.-diam longitudinal holes while the SCS pinhole erosion device employs a 1.31-in.-diam by 1.5-in.-long soil specimen with one 0.040-in.-diam longitudinal hole. The longitudinal holes in the PET device simulate cracks in the soil mass in the field. Although the theory of similitude was not used in the design of the PET device, Petry was concerned with the relationship between time in the laboratory and time in the field:

> It was believed that this method should provide reliable estimates of field behavior in a relatively short time; thus the internal erosion process had to be accelerated to provide, in hours of testing, results that took months to occur in the field....It



a. LOW SAR



b. HIGH SAR

Figure 56. Influence of moisture content on erosion rate versus shear stress for low and high SAR for kaolinitic soil (after Reference 103)

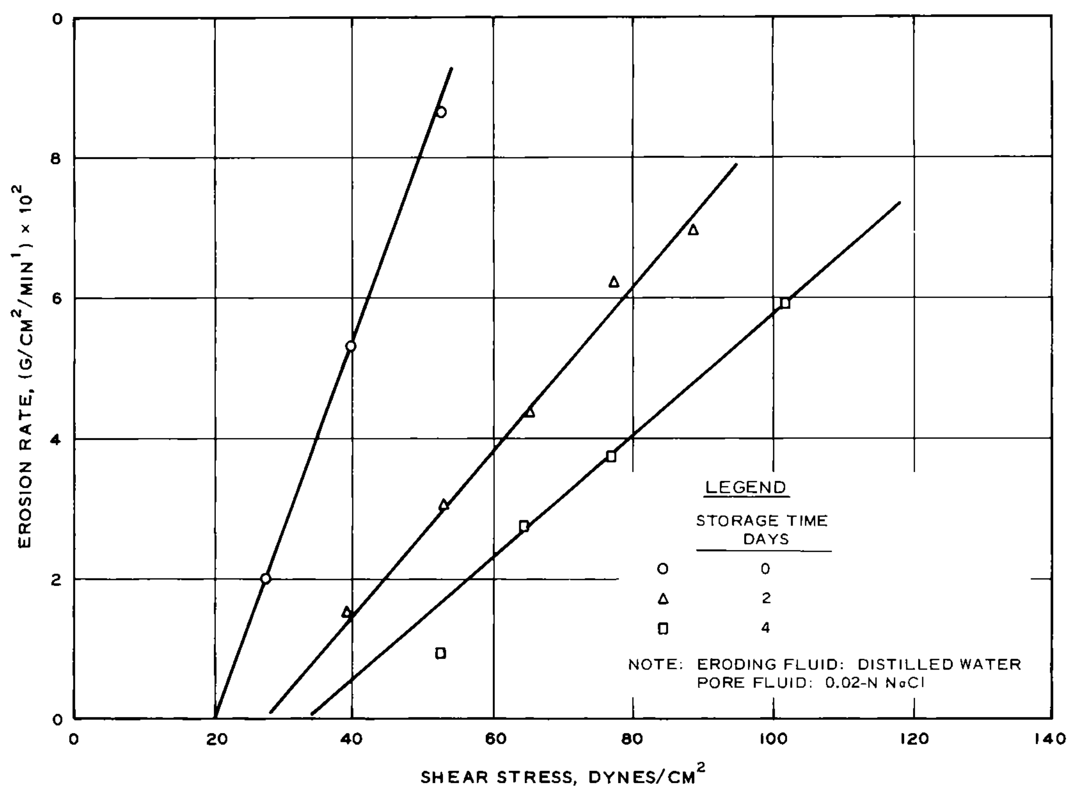


Figure 57. Influence of storage time on erosion rate versus shear stress for kaolinitic soil (after Reference 103)

> meant that back pressure was needed to reduce the time required for water movement into the soil mass surrounding each hole and to accelerate the disintegration of the soil cylinder.

After some preliminary testing, a back pressure of 15 psi was selected and used for all testing. The observed behavior of homogeneous earth dams subject to dispersive clay piping has indicated that failure of the dams may occur a few hours after first filling of the reservoir.[92,129] It would be difficult under these conditions to justify the use of back pressure in a pinhole type erosion test device to duplicate in the laboratory in a few hours what took months to occur in the field.

82. In the PET device used by Petry,[139] distilled water entered the three longitudinal holes in the soil specimen by gravitational flow, 15-psi back pressure was applied with no flow permitted, and the water was flushed and replaced for about 7 sec each 6 min for a period of 4 hr. The bottom of the soil specimen was supported on a U. S. No. 40 sieve.

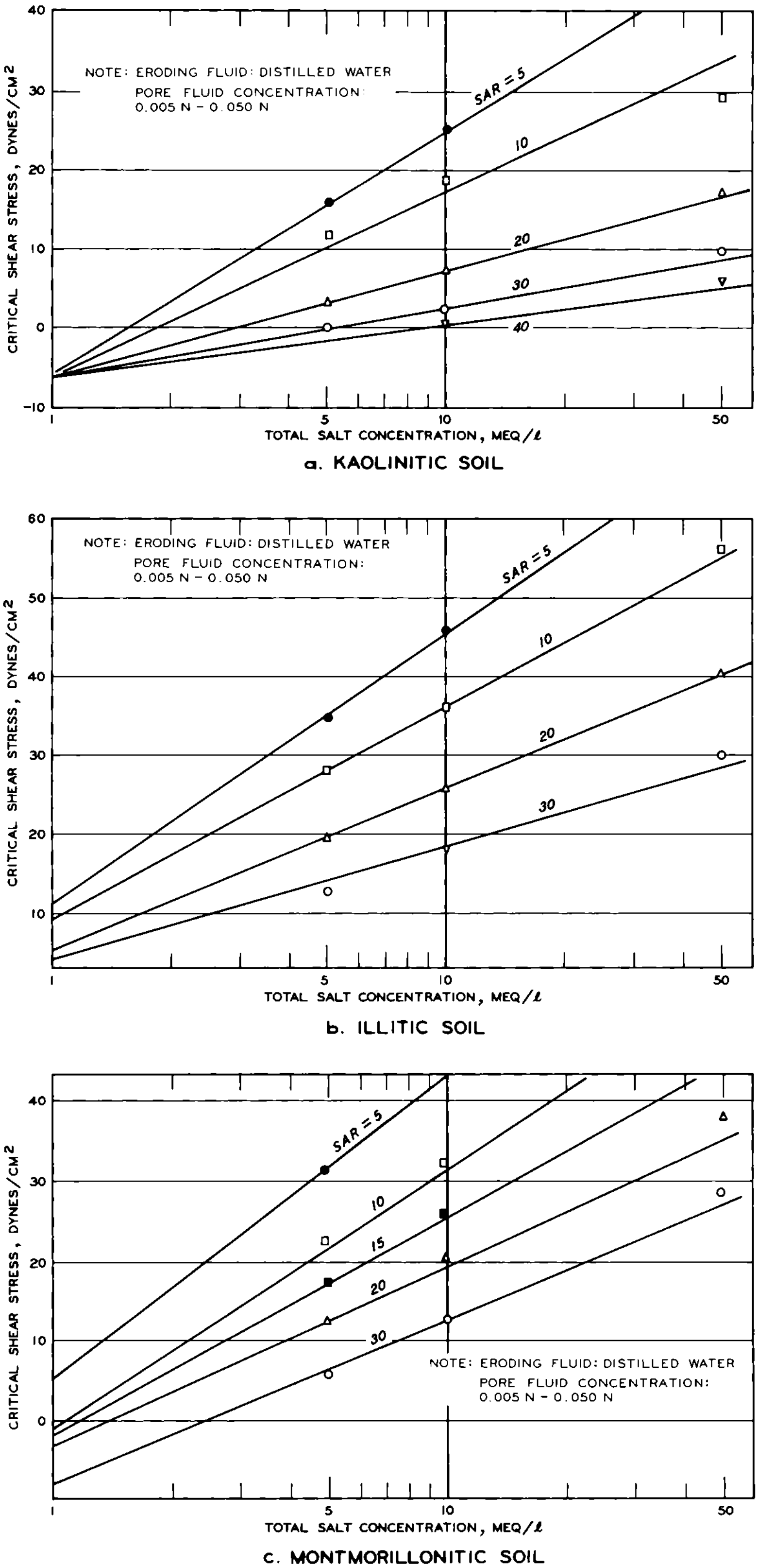


Figure 58. Relationship between critical shear stress, SAR, and total salt concentration of soil pore water extract for kaolinitic, illitic, and montmorillonitic soils (after Reference 103)

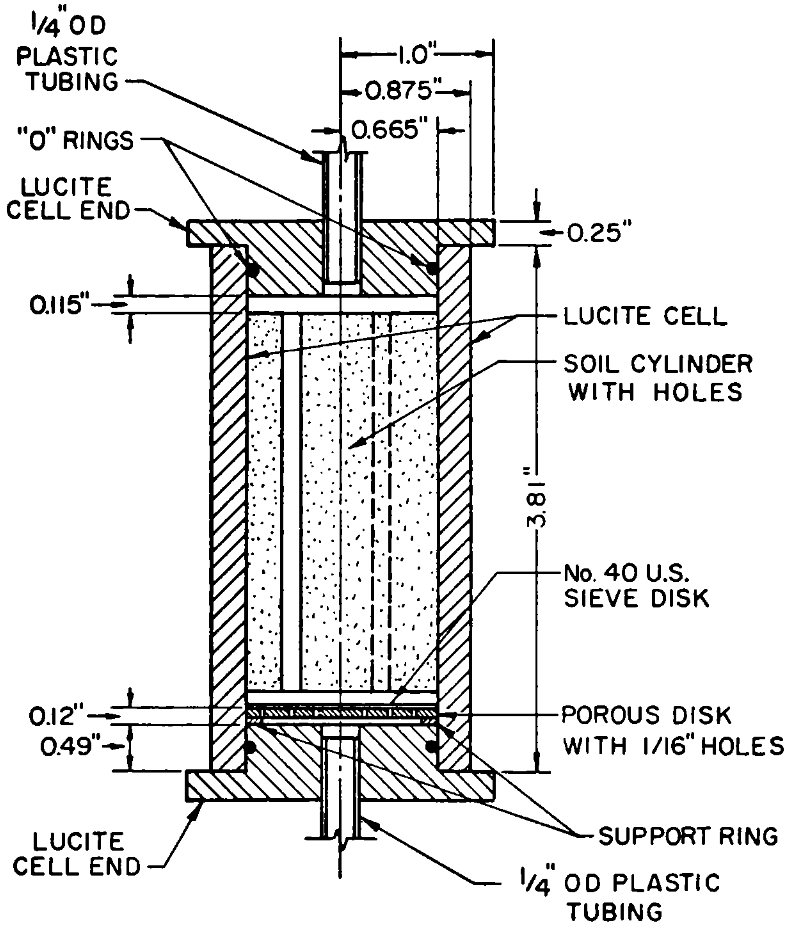


Figure 59. Physical erosion test device (courtesy of Thomas M. Petry[139])

The percent erosion was defined as the ratio of the weight of dry soil lost during the test to the initial dry weight of soil in the cell, expressed in percent. The soil samples tested by Petry included samples taken from natural slopes, samples taken from borrow pits and earth dam slopes, and a commercial kaolinite. The soils were mixed with distilled demineralized water, compacted with a mechanical impact compactor, and tested in the PET device with no postcompaction curing. Duplicate soil specimens were prepared for PET testing at standard and modified compaction efforts at optimum moisture content and 2 percent wet of optimum water content. No correlation was found between percent erosion and compaction effort. The percent erosion was found to increase with increase in moisture content for each compactive effort. No correlation was found between percent erosion and percent dispersion from the SCS Laboratory Dispersion Test as shown in Figure 60. No correlation was found between

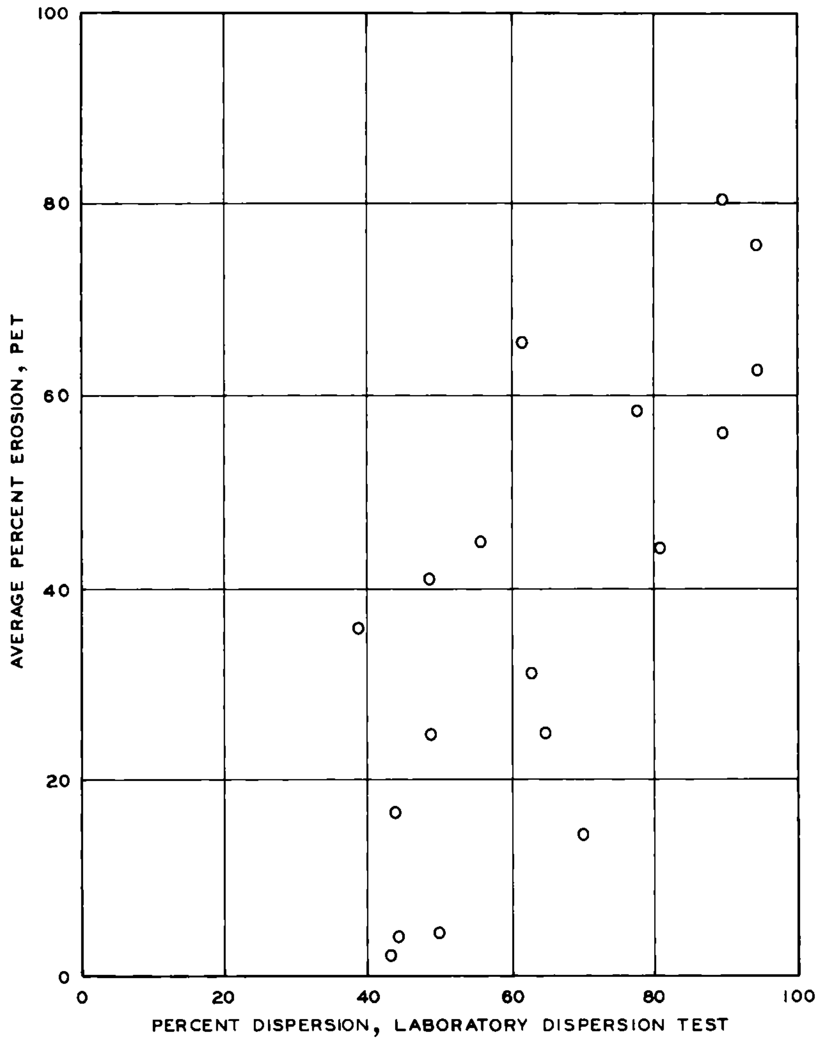


Figure 60. Percent erosion from PET device versus SCS laboratory dispersion (courtesy of Thomas M. Petry[139])

percent erosion and ESP of the soil as shown in Figure 61. Petry defined the ESP (clay) as

$$\text{ESP (clay)} = \frac{\text{ESP}}{\% < 0.002 \text{ mm}/100\%} \tag{4}$$

where

ESP = exchangeable sodium percentage of total soil sample

% < 0.002 mm = percent clay size particles

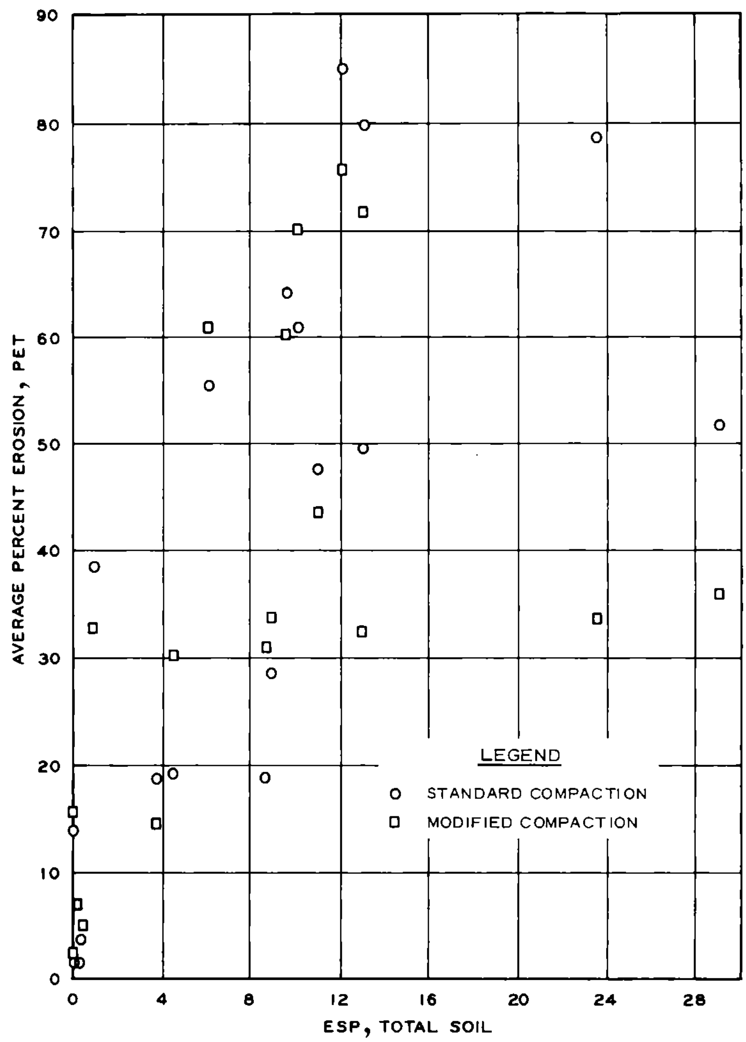


Figure 61. Percent erosion from PET device versus ESP (courtesy of Thomas M. Petry[139])

Figure 62 shows the correlation obtained between percent erosion and ESP (clay). Petry also correlated the percent erosion obtained in the PET with the relationship developed by Sherard and coworkers[92] between soil chemistry and performance of compacted soil in the field as shown in Figure 63. The majority (11 of 18) of the soil samples tested by Petry were taken from natural slopes where erosive behavior was observed in the field. All of the samples were remolded for laboratory erosion testing. No attempt was made to differentiate between the observed behavior of remolded laboratory soil specimens and the possible different

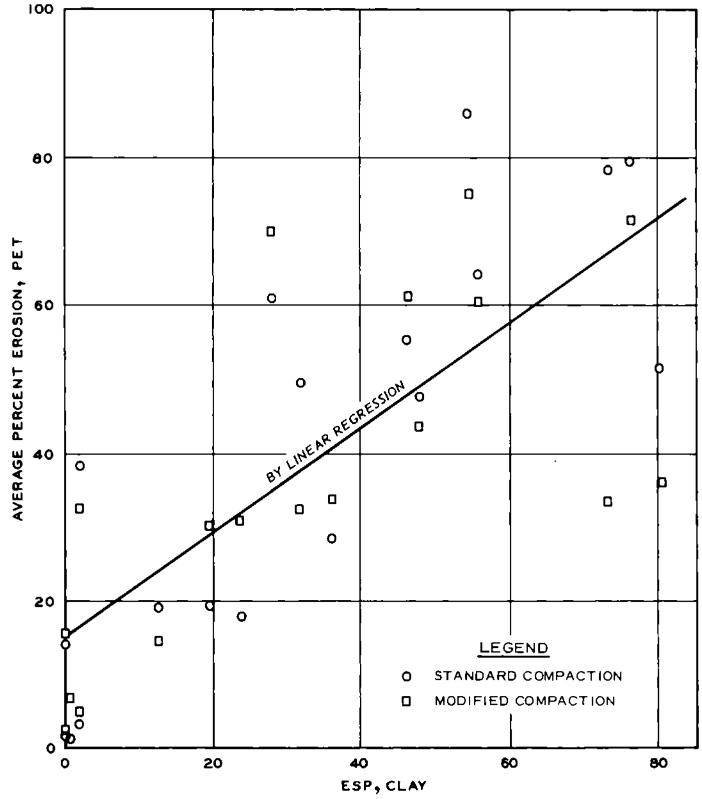


Figure 62. Percent erosion from PET device versus exchangeable sodium percentage (clay) (courtesy of Thomas M. Petry[139])

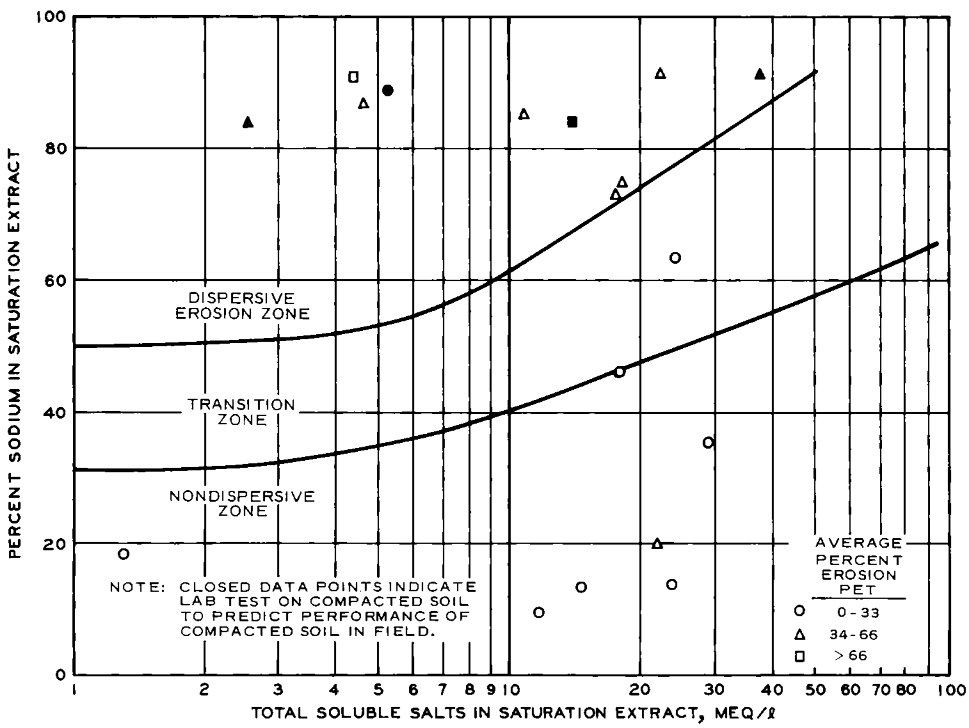


Figure 63. Correlation of PET results with Sherard and coworkers relationship between soil chemistry and performance of compacted soil in field (courtesy of Thomas M. Petry[139])

behavior of undisturbed laboratory soil specimens.

83. Landau[141] conducted a study to determine the effects of selected variables on the susceptibility of earth dams to dispersive clay piping. A Davidenkoff-type piping apparatus, shown in Figure 64, was

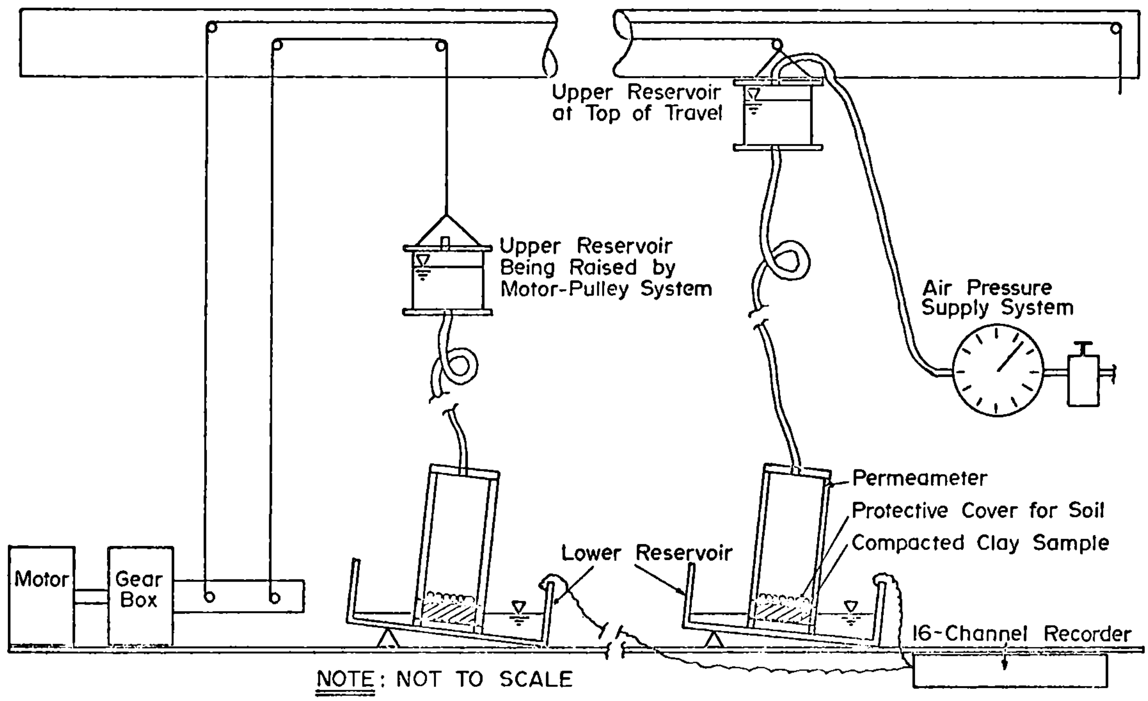


Figure 64. Schematic representation of erosion test apparatus used by Landau (courtesy of Henry G. Landau[141])

used to conduct erosion tests on remolded samples taken from borrow areas of two SCS dams located 40 miles southeast of Oklahoma City. The results of the study indicated that the ion concentration of the eroding water was of primary importance while the type of anion was of secondary influence. Soils compacted wet (+2 percent) of optimum moisture content were found to be more erosive than soils compacted dry (-3 percent) of optimum moisture content.

84. Many earth dams constructed of dispersive clays in Mississippi were damaged by heavy rains (in excess of 100-yr frequency) during the spring of 1973.[142] An extensive program of field and laboratory testing is being conducted by SCS using lime modification to repair the earth dams and to provide a basis for future evaluation of performance.

PART III: DESIGN OF LABORATORY TESTS

Overview of the Problem

85. There are three basic problems pertaining to piping in earth dams of dispersive clays:

- a. For earth dams to be constructed in the future, a method of identifying dispersive clays is needed.
- b. Once dispersive clays have been identified, they may be excluded from the earth dam or, if this is not possible, preventive measures such as filters or stabilization of the dispersive clay may be incorporated into the design of the earth dam to prevent piping failure.
- c. For existing earth dams constructed of dispersive clays, a method of analysis to assess the susceptibility of the earth dam to piping failure is needed.

Some progress has been made to date toward solving each of these problems. Research by Sherard and coworkers[94,120,133] has demonstrated the usefulness of the pinhole erosion test as a method of identifying dispersive clays, shown the feasibility of using filters to prevent piping in dispersive clays, and indicated that stabilization of dispersive clays is possible. Australian workers[90,122] have developed a method of analysis to assess the susceptibility of a homogeneous earth dam constructed of predominately illite or montmorillonite clay to dispersive clay piping.

General Approach to the Problem

86. A laboratory pinhole erosion test apparatus, shown in Figure 65a, has been designed and constructed at WES. Detailed drawings of the WES laboratory pinhole erosion test apparatus are given in Appendix B and photographs of the apparatus are shown in Appendix C. The method of differentiation between dispersive and nondispersive clays using the time rate of flow under various hydraulic gradients is shown in Figure 65b and c. Table 8 lists the independent and dependent variables involved in pinhole erosion tests on compacted soils. A series of tests will be conducted at WES to standardize a procedure for use of the

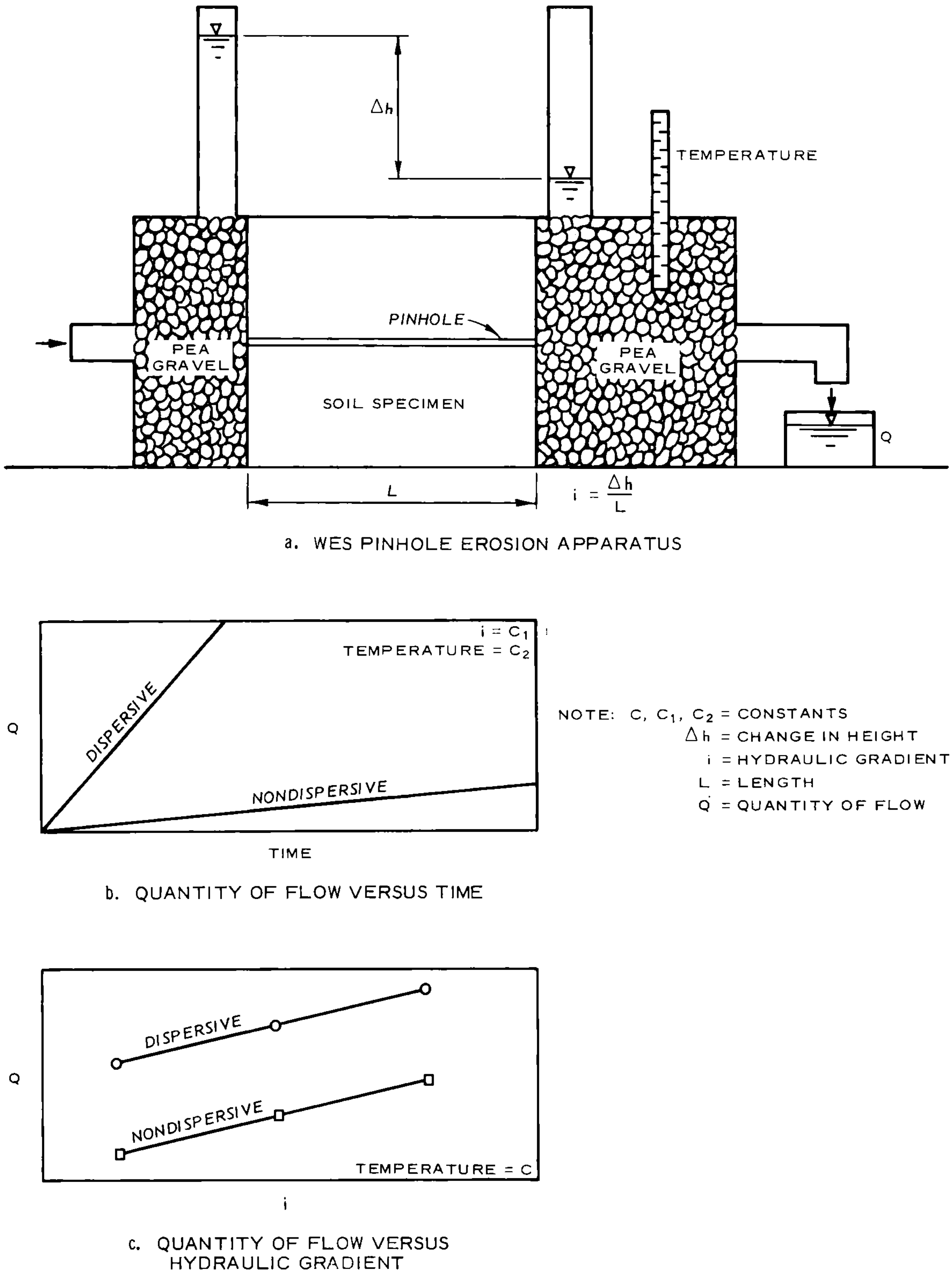


Figure 65. WES pinhole erosion apparatus and presentation of laboratory test results

pinhole erosion test as a method of identifying dispersive clays. These tests will supplement the previous work by Sherard and coworkers,[94,120,133] who demonstrated the usefulness of the pinhole erosion test as a method of identifying dispersive clays.

87. The WES pinhole erosion filter apparatus and method of presentation of test results are shown in Figure 66a and b, respectively. Table 9 lists the independent and dependent variables associated with

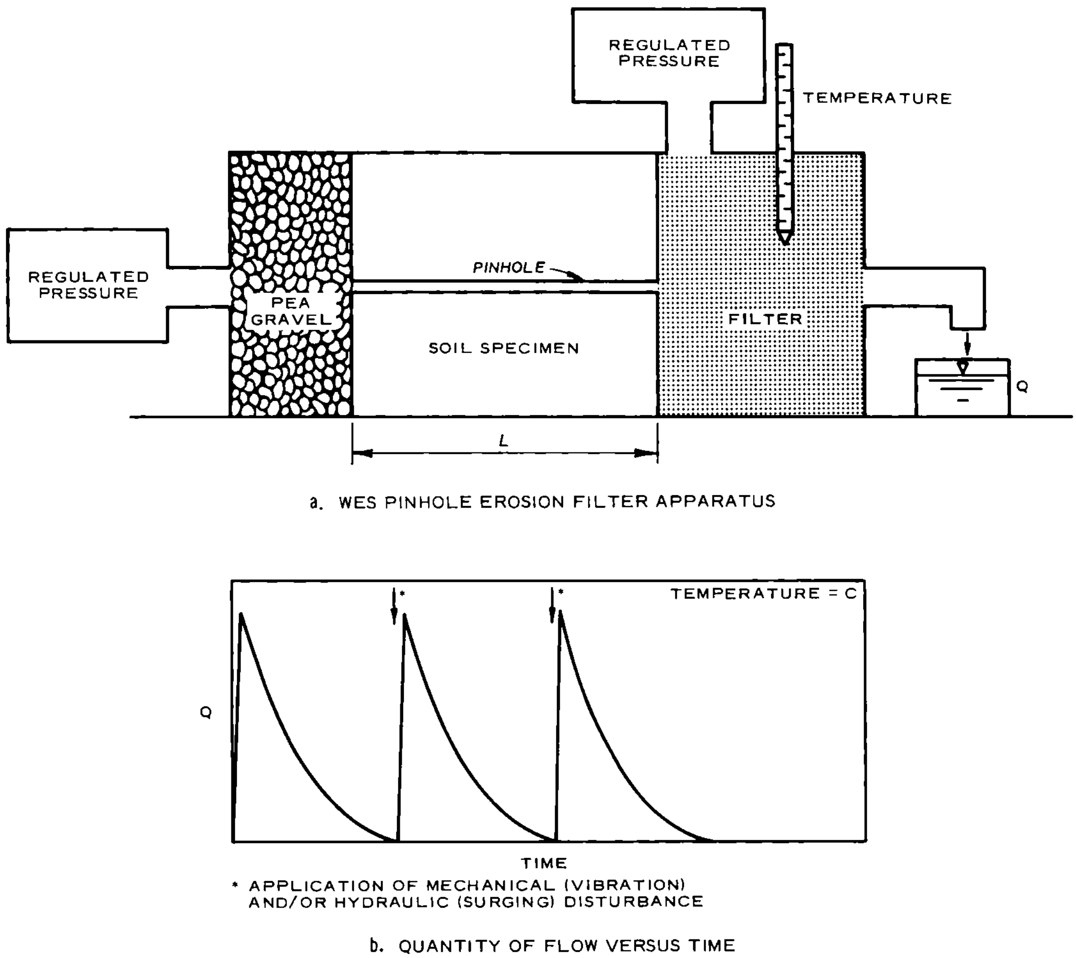


Figure 66. WES pinhole erosion filter apparatus and presentation of laboratory test results

the pinhole erosion filter test on compacted soils. A series of tests will be conducted at WES to evaluate the effectiveness of filters in preventing piping in dispersive soils. These tests will extend the preliminary pinhole erosion filter tests conducted by Sherard and coworkers[120] who demonstrated the feasibility of using filters to prevent piping in dispersive clays.

88. In addition to providing a laboratory test for identifying dispersive clays, the pinhole erosion test can be used to conduct both basic and applied research on dispersive clays. Table 10 lists parameters which should be considered in a research study of dispersive clays. The type of soil to be tested and reference to previous research are given for each parameter. A research study will be conducted at WES using the pinhole erosion test to determine the influence of selected parameters, taken from those given in Table 10, on the erodibility of dispersive clays. Continuing liaison will be maintained by WES with other investigators who are conducting research on dispersive clays to avoid duplication of effort.

PART IV: SUMMARY AND FUTURE WORK

Summary of Literature Review

89. Empirical piping criteria developed 25 yr ago were based on the assumption that soil type and method of construction were the main parameters controlling the resistance of homogeneous earth dams to piping. Dispersive clays cannot be identified by conventional index tests such as Atterberg limits, particle size distribution, and compaction characteristics. Some dispersive clays, such as those in Mississippi and Tennessee, cannot be identified by the SCS Laboratory Dispersion Test or the Crumb Test.[95] The type and amount of clay mineral present in the soil have been found to influence dispersive clay behavior. Australian workers have developed a method of analyses, shown in Figure 42, to assess the susceptibility of a homogeneous earth dam, constructed of predominately illite or montmorillonite clay, to dispersive clay piping. In research conducted for SCS, Sherard developed a relationship, shown in Figure 47, between percent sodium and total soluble salts in the soil pore water extract and field performance of earth dams as evidenced by piping failure or rainfall erosion damage. The relationship developed by Sherard could be used to predict piping failure for the cases in which the field situation was similar to those from which the original zones of behavior were developed. However, the relationship shown in Figure 42 is more general, taking into account the mineralogy of the clay and the total cation concentration of the eroding water involved in the piping process. Sherard and coworkers, using the laboratory pinhole erosion test, on both undisturbed and compacted, partially saturated soils, have shown that it was possible to differentiate between dispersive and nondispersive clays. Preliminary pinhole erosion filter tests conducted by Sherard and coworkers using relatively low hydraulic gradients indicated that dispersive soils containing silt sized particles could be retained by a filter of concrete sand.

Future Work

90. A series of tests will be conducted using the WES pinhole erosion apparatus to standardize a procedure for use in the pinhole erosion test as a method of identifying dispersive clays. A series of pinhole erosion filter tests will be conducted to evaluate the effectiveness of filters in preventing piping in dispersive clays and to study the influence of selected parameters, given in Table 10, on the erodibility of dispersive clays.

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Table 1

Relationship Between Piping Resistance, Soil Type, and Construction Method (from Reference 1)

Category 1. Greatest Piping Resistance

1. Plastic clay, plasticity index greater than 15, well compacted
2. Plastic clay, plasticity index greater than 15, poorly compacted

Category 2. Intermediate Piping Resistance

3. Well-graded material with clay binder, plasticity index between 6 and 15, well compacted
4. Well-graded material with clay binder, plasticity index between 6 and 15, poorly compacted
5. Well-graded cohesionless material, plasticity index less than 6, well compacted

Category 3. Least Piping Resistance

6. Well-graded cohesionless material, plasticity index less than 6, poorly compacted
7. Very uniform, fine cohesionless sand, plasticity index less than 6, well compacted
8. Very uniform, fine cohesionless sand, plasticity index less than 6, poorly compacted

Table 2

Classification of Core Materials on the Basis of Resistance to Concentrated Leaks (from Reference 5)

Very Good Material

1. Very well-graded coarse mixtures of sand, gravel, and fines. D_{85} coarser than 2 in., D_{50} coarser than 0.25 in. If fines are cohesionless, not more than 20% finer than the No. 200 sieve

Good Material

2. Well-graded mixture of sand, gravel, and clayey fines. D_{85} is coarser than 1 in. Fines consisting of inorganic clay (CL) with plasticity index greater than 12
3. Highly plastic tough clay (CH) with plasticity index greater than 20

Fair Materials

4. Fairly well-graded, gravelly, medium to coarse sand with cohesionless fines. D_{85} coarser than 0.75 in., D_{50} between 0.5 mm and 3.0 mm. Not more than 25% finer than the No. 200 sieve
5. Clay of medium plasticity (CL) with plasticity index greater than 12

Poor Materials

6. Clay of low plasticity (CL and CL-ML) with little coarse fraction. Plasticity index between 5 and 8. Liquid limit greater than 25
7. Silts of medium to high plasticity (ML or MH) with little coarse fraction. Plasticity index greater than 10
8. Medium sand with cohesionless fines

Very Poor Materials

9. Fine, uniform, cohesionless silty sand. D_{85} finer than 0.3 mm
10. Silt from medium plasticity to cohesionless (ML). Plasticity index less than 10

Table 3

Experimental Program to Determine Mechanism of Piping in Cohesive Soils*

Soil Type
1. Expansive soils (containing montmorillonite and illite minerals)
2. Nonexpansive clay soils
3. Sandy clay
4. Silty clay
Placement Condition
1. Method of compaction (static, dynamic, and kneading)
2. Compaction energy (similar to field compaction)
3. Dry unit weight
4. Initial and final water content and degree of saturation
Filter Characteristics
1. Material (crushed aggregates, natural aggregates, glass beads)
2. Variation of pore opening of filter
3. Filter thickness
Physicochemical Aspects
1. Type and amount of exchangeable ions
2. Type of seeping fluid (total and type of concentration of ions)
3. Sodium adsorption ratio
Failure Mechanism
1. Erosion
2. Heaving
Miscellaneous
1. Effect of experimental technique (pore pressure measurement, tracer techniques, strength characteristics of soil)
2. Size of washed out particles
3. Hydraulic gradient (initial, critical, and complete failure)

* Courtesy of Hydraulics and Water Resources Department, College of Engineering, Guimby, Madras, India.[15]

Table 4

Influence of Compaction Dry Unit Weight on Rate of Erosion for Soil Mixtures Compacted at 10 percent Moisture Content* (after Reference 58)

Soil Mixture	Compaction Dry Unit Weight pcf	Rate of Erosion g/min 2% Mix	5% Mix	10% Mix
Loess-fine kaolinite	74	15	12	10
	79	17	14	10
	85	18	15	9
	91	18	14	8
Loess-coarse kaolinite	74	21	19	18
	79	24	20	15
	85	22	20	10
	91	20	17	9
Loess-illite	74	21	13	6
	79	23	15	7
	85	23	14	7
	91	21	12	6
Loess-calcium montmorillonite	74	14	16	21
	79	16	17	20
	85	17	17	17
	91	17	16	14
Loess-sodium montmorillonite	74	5	1	<1
	79	7	1	<1
	85	7	<1	<1
	91	7	<1	<1

* Courtesy of American Geophysical Union.

Table 5

Average Properties of Clay Core Material for Flagstaff Gully Dam*

	Upper 25 ft of core	Lower 25 ft of core
Plastic limit (percent)	15	15
Liquid limit (percent)	75	40
Montmorillonite (percent)	80	70
Kaolinite (percent)	15	--
Quartz (percent)	--	30
CEC (meq/100 gr)	32	16
ESP (percent)	10	17
SAR	8	14
pH	7.4	6.1
Maximum dry unit weight (pcf)	98	110
Optimum moisture content (percent)	23	17

* Courtesy of Indian National Society of Soil Mechanics and Foundation Engineering.[115]

Table 6

Selected Soil Chemistry and Clay Mineralogy Data from SCS Study (from Reference 92)

Dam	Lab Sample	Soil Pore Water pH	ESP	Ionic Ratio*	Equilibrium Ionic Ratio**	Predominate Clay Minerals†
		Failed/Damaged Dams				
OK-17	S-1	6.6	8	2.34	0.25	K, MI, M
OK-29	S-11	7.6	13	7.45	0.60	MI, K, V
OK-Wister	S-42	4.4	5	2.24	0.10	K, MI
Venezuela	S-48	6.9	10	5.68	0.35	K, MI, V
AR-6	S-79	5.3	6	3.32	0.15	MI, M, K
MS-10	S-86	5.6	7	3.14	0.20	K, MI
MS-3	S-90	7.3	2	1.12	0.10	MI, K, M, V
		Undamaged Dams				
Venezuela	S-54	5.9	18	7.22	0.50	K, MI, V

Note: A detailed study of the clay mineralogy of the soil samples from the SCS study is given by Totrakool[126] and King.[127]

* Ionic ratio = $Na/\sqrt{Ca + Mg}$.

** From Figure 43.

† K = kaolinite, M = montmorillonite, MI = mica, V = vermiculite.

Table 7

Total Clay Size Particles and Critical Dispersion for Fine-Grained Nonerosive Soils Containing 20 Percent Effective Clay (from Reference 95)

Effective Clay percent	Total Clay Size Particles* percent	Critical Dispersion** percent
20	20	None
20	25	20
20	30	33
20	35	42
20	40	50
20	50	60

* <0.005 mm (ASTM designation).

** SCS Laboratory Dispersion Test.

Table 8

List of Variables for Pinhole Erosion Test on Compacted Soils

Independent Variables
Soil Pore Water
1. Type and amount of cations (calcium, magnesium, potassium, sodium)
Soil
1. Composition of soil (percentages of sand, silt, clay)
2. Type and amount of clay mineral (kaolinite, illite, montmorillonite)
3. Moisture content of soil
4. Dry unit weight of soil
5. pH of soil
Compaction
1. Type of compaction (impact, kneading, static)
2. Compactive effort (standard, modified)
3. Time between addition of compaction water and compaction
4. Time between compaction and testing
Eroding Fluid
1. Type and amount of cations (calcium, magnesium, potassium, sodium)
2. Temperature
3. pH of the eroding fluid
Testing
1. Rate of application and magnitude of hydraulic gradient
2. Duration of test
Dependent Variables
Quantity of flow through pinhole
Amount of soil erosion
Rate of soil erosion

Table 9

List of Variables for Pinhole

Erosion Filter Test on Compacted Soils

Independent Variables

Base Soil Pore Water

1. Type and amount of cations (calcium, magnesium, potassium, sodium)

Base Soil

1. Length of soil specimen
2. Diameter of pinhole through soil specimen
3. Composition of soil (percentages of sand, silt, clay)
4. Type and amount of clay mineral (kaolinite, illite, montmorillonite)
5. Moisture content of soil
6. Dry unit weight of soil
7. pH of soil

Compaction of Base Soil

1. Type of compaction (impact, kneading, static)
2. Compactive effort (standard, modified)
3. Time between addition of compaction water and compaction
4. Time between compaction and testing

Filter Soil

1. Grain shape (angular, rounded)
2. Gradation
3. Relative density

Eroding Fluid

1. Type and amount of cations (calcium, magnesium, potassium, sodium)
2. Temperature
3. pH of the eroding fluid

Testing

1. Rate of application and magnitude of hydraulic gradients (both through pinhole and at the interface between the base soil and the filter)
2. Surging (used to simulate the many variations of flow likely to occur during the lifetime of the filter system)

(Continued)

Table 9 (Concluded)

Independent Variables (Continued)

Testing (Continued)

3. Vibration (used to simulate disturbances from sources such as earthquakes, wave action, and nearby spillways which might occur over the lifetime of the filter system)

4. Duration of test

Dependent Variables

Quantity of flow through pinhole

Amount of soil erosion

Rate of soil erosion

Time to terminate initial flow through pinhole

Time to terminate flow following disturbance (vibration and/or surging)

Gradation of base soil penetrating the filter

Table 10

Parameters for Consideration in Research Study of Dispersive Clays Using the Pinhole Erosion Test

Parameter	Type of Soil to be Tested	Previous Research
1. Effect of soil pore water concentration (type and amount of cations) on erodibility of dispersive clay	Sand, silt, commercial clay mixture	71, 102, 103, 104, 134, 136, 137
2. Effect of composition of soil (percentages of sand, silt, clay) on erodibility of dispersive clay	Sand, silt, commercial clay mixture	65, 72, 95, 137
3. Effect of type and amount of clay mineral (kaolinite, illite, montmorillonite) on erodibility of dispersive clay	Sand, silt, commercial clay mixture	103, 137
4. Effect of moisture content on erodibility of dispersive clay	Remolded embankment sample	71, 103, 139, 140
5. Effect of dry unit weight on erodibility of dispersive clay	Remolded embankment sample	139, 140
6. Effect of pH of the soil on erodibility of dispersive clay	Sand, silt, commercial clay mixture	71, 104
7. Effect of type of compaction (impact, kneading, static) on erodibility of dispersive clay	Remolded embankment sample	None
8. Effect of eroding fluid concentration (type and amount of cations) on erodibility of dispersive clay	Remolded embankment sample	71, 103, 136, 140
9. Effect of temperature of eroding fluid on erodibility of dispersive clay	Remolded embankment sample	71, 104

(Continued)

Table 10 (Concluded)

Parameter	Type of Soil to be Tested	Previous Research
10. Effect of pH of the eroding fluid on erodibility of dispersive clay	Remolded embankment sample	None
11. Modification and/or stabilization of dispersive clay to reduce erodibility	Remolded embankment sample	133, 140
12. Effect of remolding on erodibility of undisturbed dispersive clay	Undisturbed natural soil sample	None

APPENDIX A: CRUMB TEST

1. The Crumb Test[87-89] is run using distilled demineralized water. Small (5-10g) crumbs of soil at natural moisture content are placed in 100-ml clear glass beakers filled with distilled demineralized water. The behavior of the soil crumb is observed and readings are taken after 10 and 30 min.

2. Dispersion is detected by the formation of a colloidal cloud which appears as a fine misty halo around the soil crumb. The Crumb Test is rated for reaction or colloidal cloud formation as follows:[92,95]

<u>a</u>. 1 = no sign of cloudy water caused by colloids in suspension.

<u>b</u>. 2 = bare hint of colloidal cloud formation at surface of soil crumb.

<u>c</u>. 3 = easily recognizable colloidal cloud covering one-fourth to one-half of the bottom of the glass container.

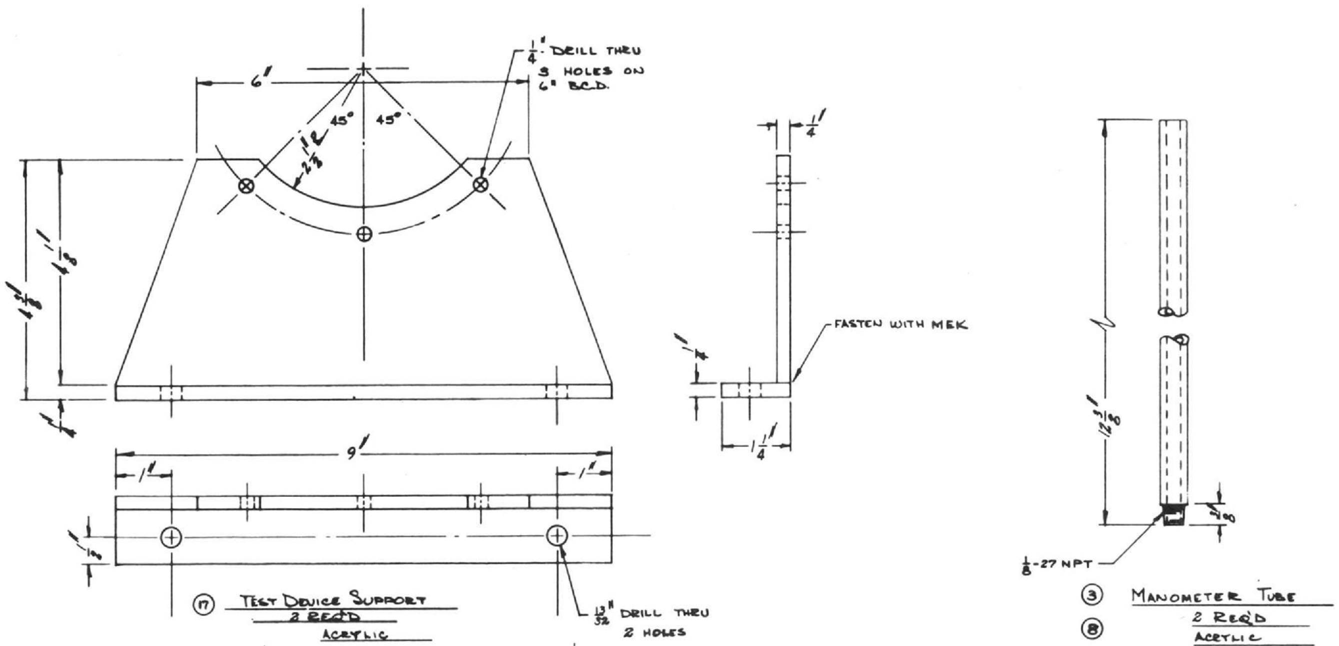
<u>d</u>. 4 = strong reaction with colloidal cloud covering most of the bottom of the glass container.

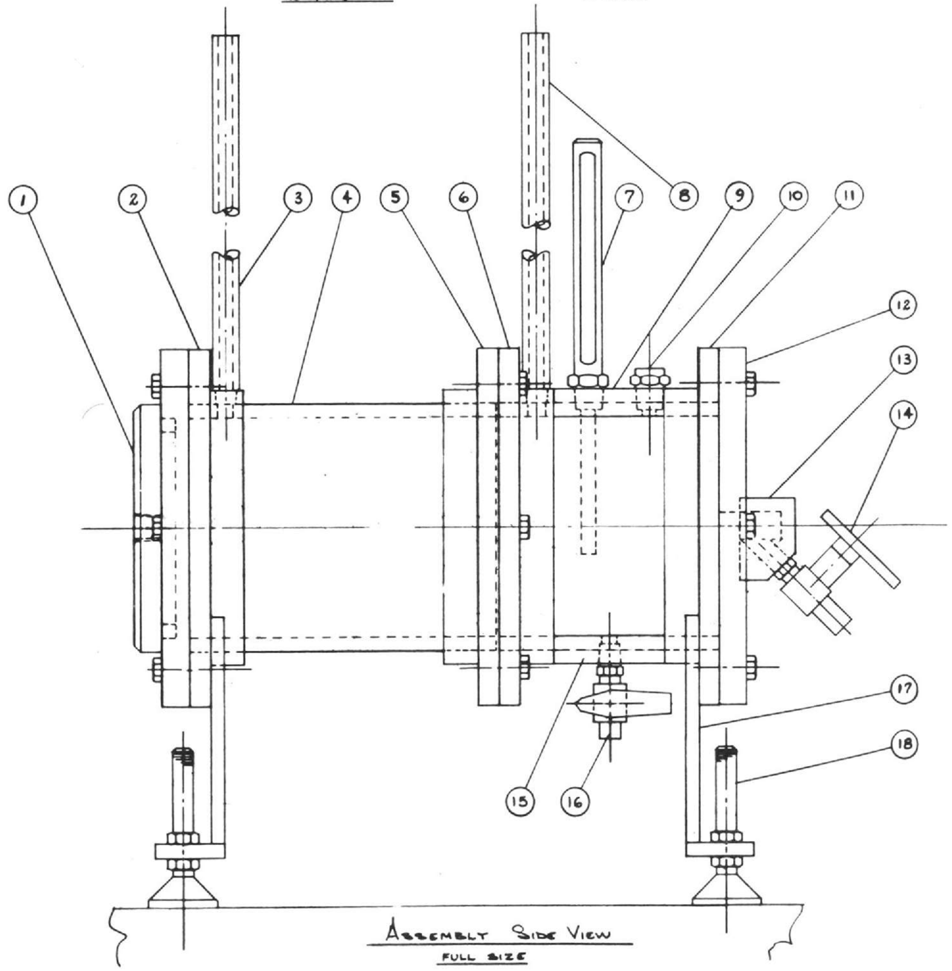
3. Since each Crumb Test involves a small quantity of soil, several tests should be run on each soil sample before making an evaluation. The Crumb Test may be used as an indicator of field performance of dispersive soils using the following evaluation of soil crumb reaction:[89]

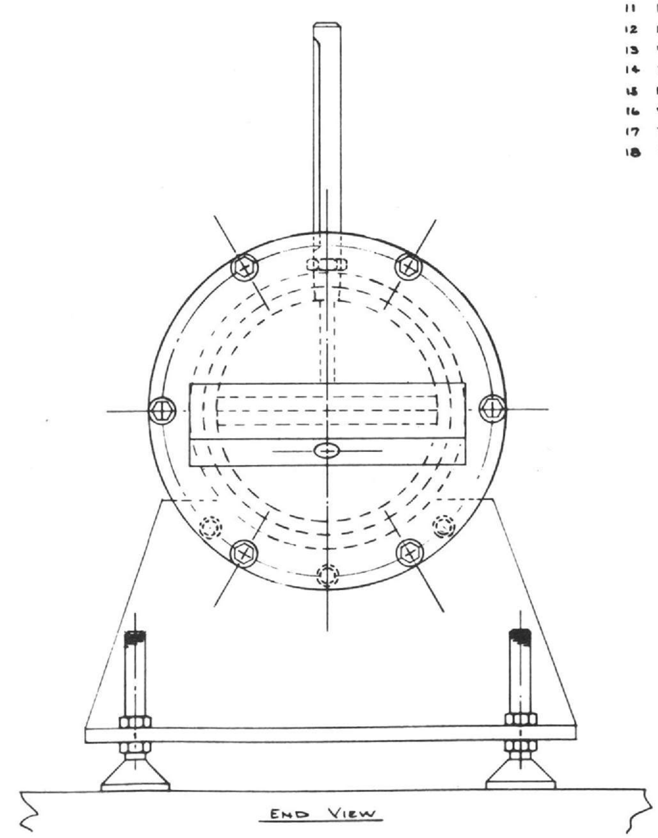
No dispersion problem = 1
Possible dispersion problem = 2
Definite dispersion problem = 3 or 4

4. Available data show that if the Crumb Test indicates dispersion, the soil will almost always be dispersive but that about 30 percent of dispersive soils will give nondispersive reactions to the Crumb Test.[93]

APPENDIX B: DETAILED DRAWINGS OF WES LABORATORY EROSION TEST APPARATUS







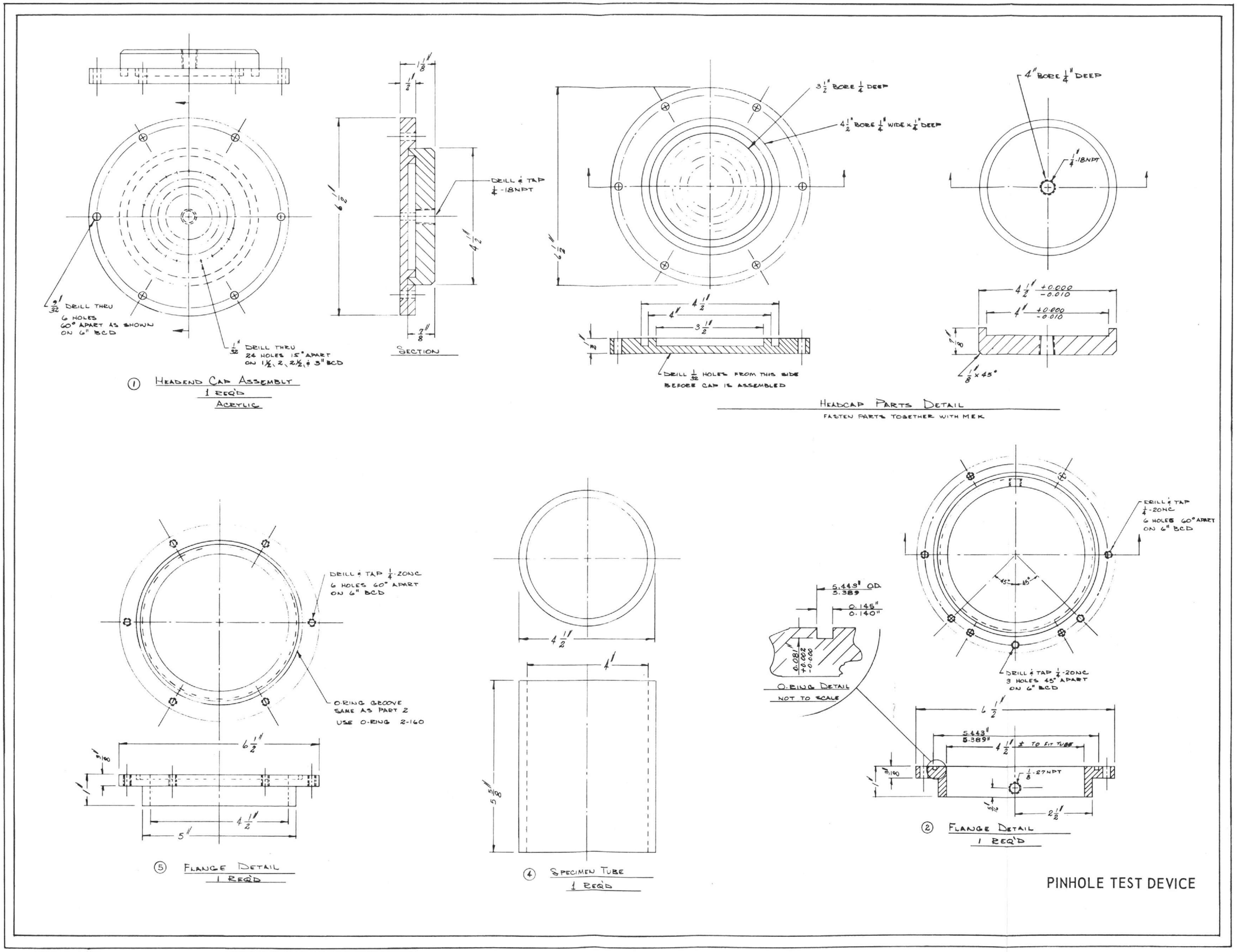
MATERIAL & PARTS LIST

1 HEADEND CAP — ACRYLIC - $6\frac{1}{2}$" O.D. x 1" THICK
2 HEADEND FLANGE - ACRYLIC - $6\frac{1}{2}$" OD. x 1" THICK
3 MANOMETER TUBE - ACRYLIC - $\frac{1}{2}$ OD. x $\frac{1}{4}$ I.D.
4 SPECIMEN TUBE - ACRYLIC - $4\frac{1}{2}$" O.D. x 4" I.D.
5 FLANGE (SAME AS PART 2) — ACRYLIC
6 FLANGE - ACRYLIC - $6\frac{1}{2}$" O.D. x 1" THICK
7 THERMO-WELL-METER — BROOKLYN THERMOMETER CO.
8 MANOMETER TUBE (SAME AS 3) - ACRYLIC
9 FILTER TUBE - ACRYLIC - $4\frac{1}{2}$" OD. x 4" I.D.
10 PIPE PLUG 1/4" - BRASS
11 FLANGE (SAME AS 2 & 5) - ACRYLIC
12 END CAP - ACRYLIC - $6\frac{1}{2}$" OD x $\frac{1}{2}$" THICK
13 WATER COLLECTOR - ACRYLIC - 1" x 2" x 5"
14 WHITEY VALVE NO. B-42FS
15 MOUNTING PLATE - ACRYLIC - $\frac{1}{2}$" x 2" x $2\frac{5}{8}$"
16 WHITEY VALVE (SAME AS 14)
17 TEST DEVICE SUPPORT - ACRYLIC - $\frac{1}{4}$"
18 STUD TYPE LEVELING PADS NO. TL-1 — REID TOOL CO.

O-RING NO. 2-160 - 3 REQ'D
NYLON SCREWS 1/4-20NC
NYLON SCREEN - 4 PCS 4" DIA.

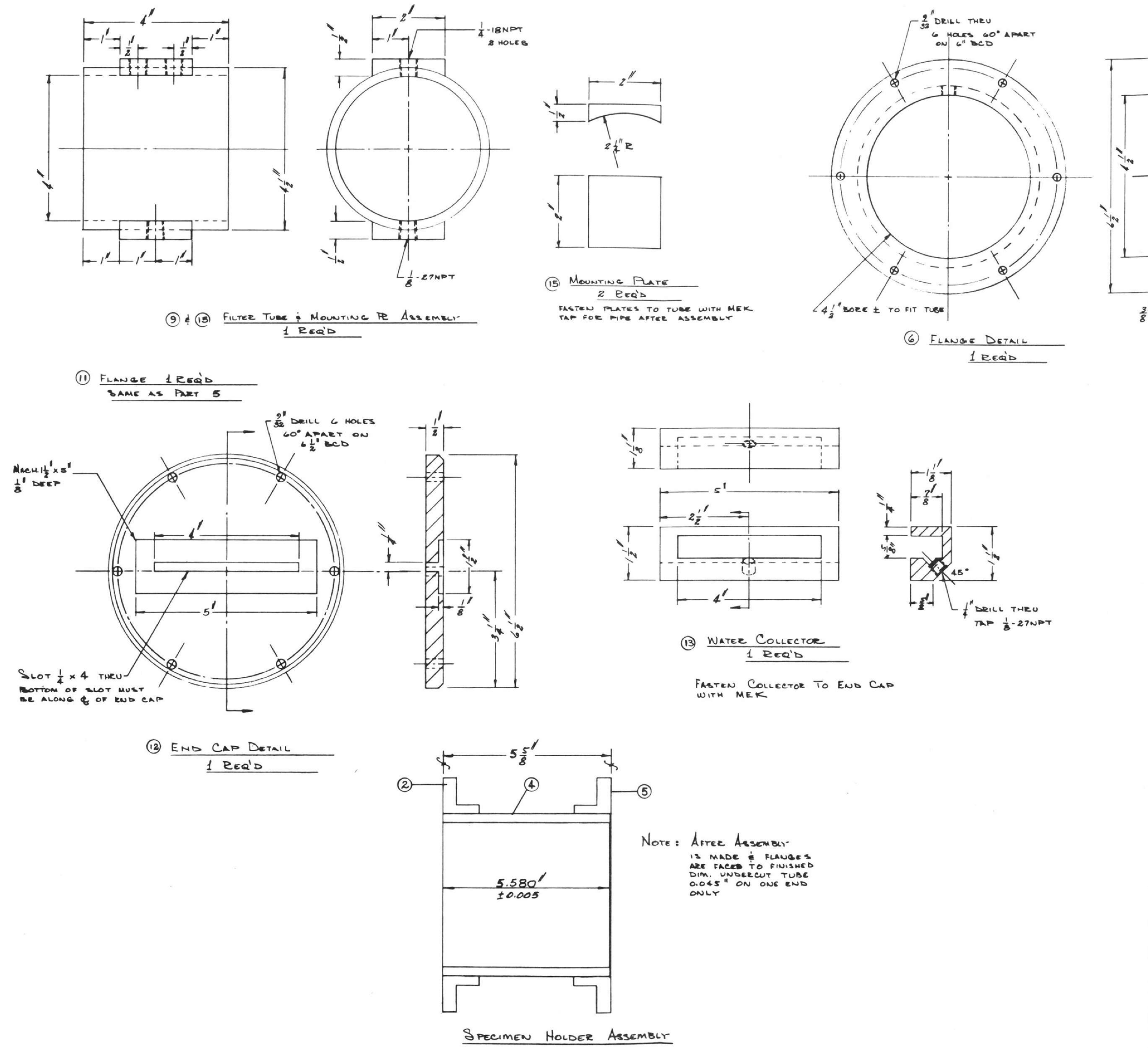
PINHOLE TEST DEVICE

PLATE B1a



PINHOLE TEST DEVICE

PLATE B1b



PINHOLE TEST DEVICE

APPENDIX C: PHOTOGRAPHS OF WES LABORATORY EROSION TEST APPARATUS

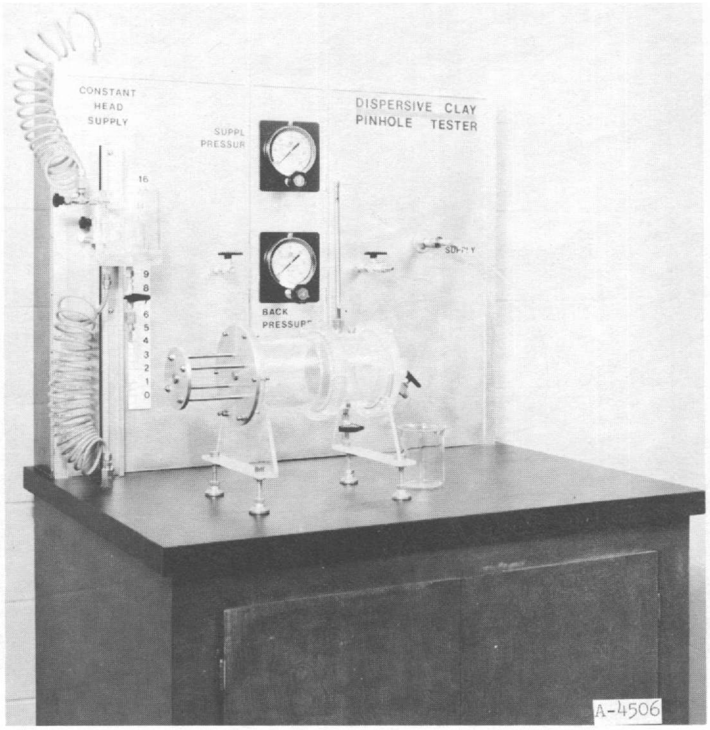


Figure C1. General view of WES laboratory erosion test apparatus

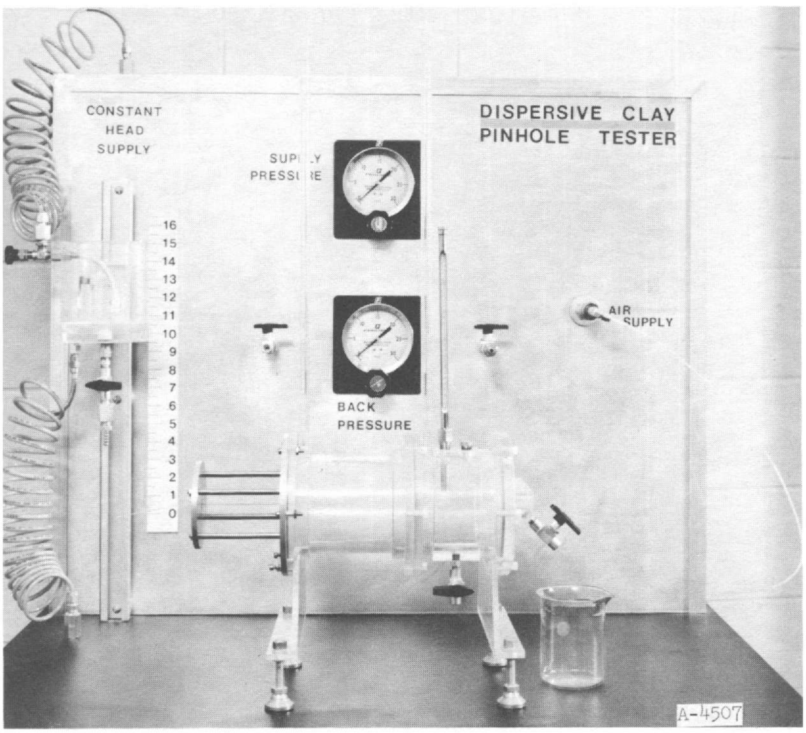


Figure C2. Console of WES laboratory erosion test apparatus

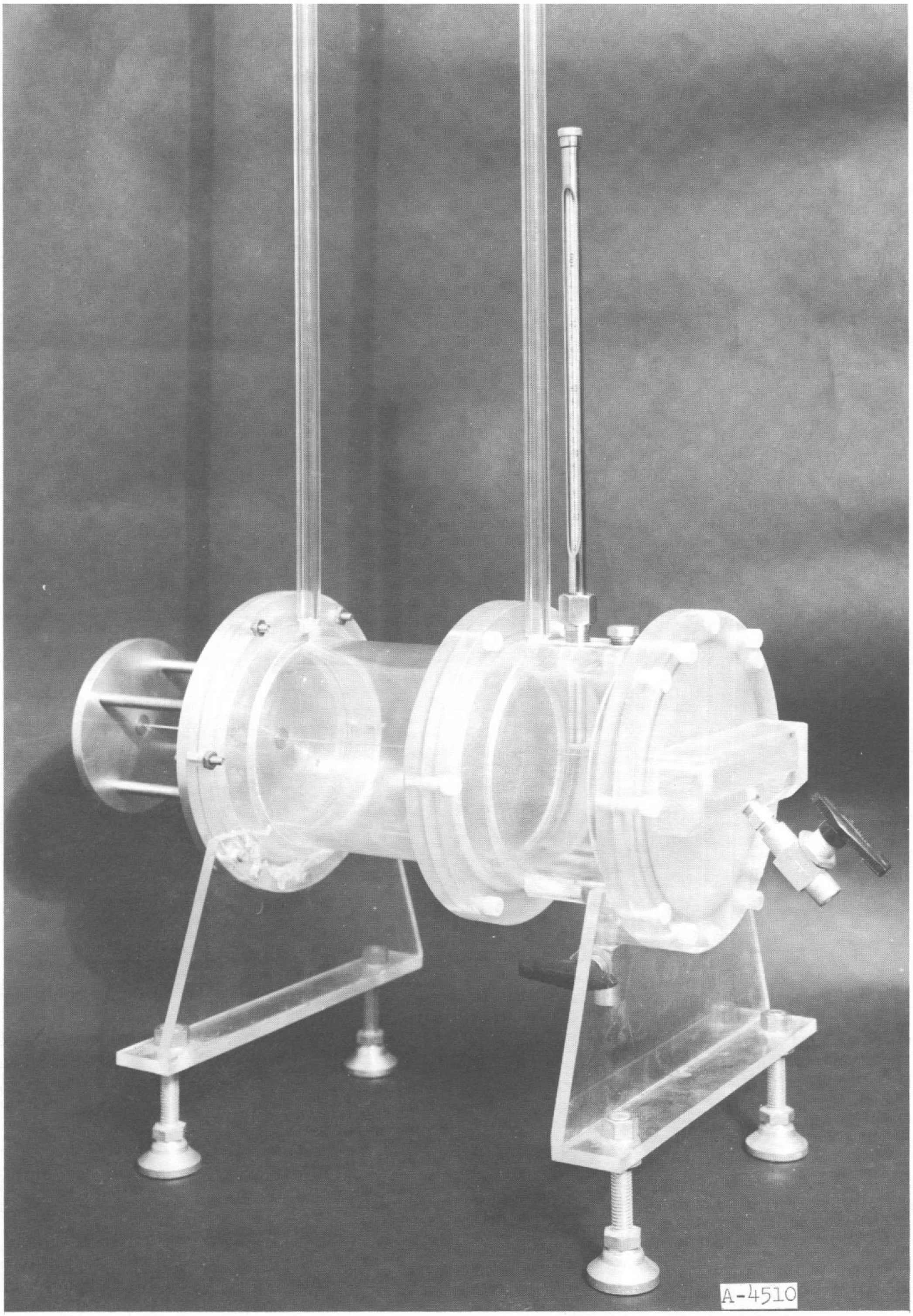


Figure C3. Detailed view of WES laboratory erosion test apparatus

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Perry, Edward Belk
Piping in earth dams constructed of dispersive clay; literature review and design of laboratory tests, by Edward B. Perry. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1975.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report S-75-15)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C.
Includes bibliography.

1. Clays. 2. Dispersive clay. 3. Earth dams. 4. Piping (erosion). I. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report S-75-15)
TA7.W34 no.S-75-15