EROSION OF COHESIVE SEDIMENTS

A report
prepared by the

Task Committee on Erosion of Cohesive Materials
Committee on Sedimentation
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INTRODUCTION

The Task Committee on Erosion of Cohesive Materials was formed by the Sedimentation Committee of the Hydraulics Division of ASCE to review the literature and to establish what has been done and what the research needs are relative to:

a. the fundamental understanding of principles and processes of erosion of cohesive sediments, and

b. the planning, design, construction and maintenance of channels in cohesive materials.

The need to define the fundamental principles involved in the erosion process and to develop criteria and guides applicable to field problems is indeed great. This has been clearly demonstrated by the numerous river, irrigation and drainage, and channel stability problems encountered when dealing with soils displaying varying degrees of cohesiveness.

From an abstracted bibliography prepared by the Task Committee [1]*, several trends of research on cohesive sediments can be noted. Most of the work on cohesive sediments has been carried on by hydraulic engineers, agricultural engineers and soil scientists. In general, research by each of these groups has been directed toward solutions of the problems most often encountered

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*Numbers in brackets correspond to similarly numbered entries in the bibliography, pages 64-70.

by the particular group. For example, hydraulic research efforts have been directed toward determination of tractive force, channel stability criteria and other data related to channel design. Many of these studies have involved either field observations, flume tests, or shear tests in specially designed apparatus. Usually, some measure of resistance to erosion or rate of erosion has been related to mechanical properties of the cohesive sediments, such as vane shear strength, compressive strength, Atterburg limits, dispersion ratio, etc.

Agricultural engineers have been more concerned with erosion control in irrigation channels and furrows and with raindrop erosion. In the agricultural discipline, rates of erosion have been related to furrow size and slope, time of irrigation, extent of vegetation and soil type. Research by soil scientists has proceeded along lines in which special study has been given to the chemical, mineralogical, and physical properties of the soil.

Estuarine sedimentation is another area in which engineers are concerned with cohesive sediments. In estuaries, sediment particles are mostly in the fine silt and clay-size range. In estuaries, however, the sediment problem is further complicated by the unsteady nature of the flow and by flocculation problems caused by reactions between sea water and clayey sediments. The problems of estuarine sedimentation were beyond the scope of the activities of this Task Committee, and are not discussed in this report.

Even from a cursory glance through the literature on cohesive sediments, one is struck immediately with the interdisciplinary nature of the erosion problem. As contrasted to noncohesive sediments in which the weight and size of the particles are the principle sediment factors controlling erosion, the resistance of cohesive sediments to erosion is related to the electrochemical bond between individual particles. This bond in turn depends on the ionic charge on the particles, the presence of electrolytes, the mineralogy, temperature, pH, ion exchange and absorption. These factors are usually not thought of in the realm of Civil Engineering, but rather are left to the soil chemists, mineralogists, and physicists. Still from an engineering standpoint, it is desirable to have simple and readily measurable properties to characterize the erosion resistance of cohesive sediments.

When considering the erosion of cohesive sediments, exclusive of the estuarine problem, four broad catagories of study are particularly significant. These are:

1. laboratory research on erosion resistance.
2. field observations in natural channels.
3. design of non-eroding channels.
4. problems of agricultural land and channels.

The following sections of this report are concerned primarily with each of these catagories. Much of the literature currently available is reviewed briefly and recommendations are made for practical application and for further research.

LABORATORY RESEARCH ON EROSION RESISTANCE

Much of the research undertaken in the laboratory has been directed toward determining relationships between a critical boundary shear stress or a tractive force above which scour of a cohesive material begins and pertinent soil properties and flow conditions. Studies in specially designed apparatus and laboratory flumes have attempted to define the mechanical soil properties which best characterize the erosion resistance of various cohesive soils.

When concerned with stable channel design or localized scour in beds of cohesive sediments, either a critical tractive force or a safe permissible velocity is selected so that no undesirable erosion occurs. These methods involve choosing the hydraulic variables such that certain critical tractive forces or velocities are not exceeded. While it is generally understood that the scour resistance of a cohesive sediment will depend in some fashion on the properties of the sediment, the complete significance of such parameters as density, moisture content, percent clay, vane shear strength, etc. is not fully known at this time.

In work on the Klaralven, Sundborg [2] proposed that the force resisting entrainment was proportional to the shear strength of the sediment. In a similar manner, Dunn [3] related critical tractive force at which erosion of a cohesive sediment was considered to have started to the vane shear strength of the soil. Dunn tested samples of cohesive soils taken from channels in Colorado, Nebraska and Wyoming. He subjected the samples to the erosive action of a submerged jet and measured the magnitude of the boundary shear stress causing scour by replacing the soil sample with a shear plate coated with soil particles. Dunn's equation for the critical tractive force, τ_c, is given by

$$\tau_c = 0.02 + \frac{S_v \tan \theta}{1000} + 0.18 \tan \theta \qquad (1)$$

in which S_v is the vane shear strength and θ is the inclination with the horizontal of the linear relation between critical tractive force and vane strength. Dunn then relates θ to the percent of soil finer than 0.06 mm, plasticity index, and to various statistical representations of the particle size distribution.

To help develop design criteria for unlined reaches of irrigation canals, Carlson and Enger [4] performed field and laboratory studies with various cohesive soils. Critical tractive forces were obtained from a test in which the soil samples were set into a well flush with the bottom of a circular tank and water circulated over the sample with a rotating impeller. Among the various properties measured were liquid limit, plasticity index, soil density, percent of maximum Proctor density, shrinkage limits, soil gradation, and vane shear strength values. Several correlations between the variables were obtained and recommendations for general use were made for soils displaying properties similar to those tested. Examples were also presented illustrating the use of the results in the design of unlined canals in cohesive soils.

Enger [5] also reports on studies made in a boundary shear flume. In these studies samples of cohesive sediments were tested by gradually increasing the boundary shear stress acting on a sample until the shear became critical and the sample began to erode. For the soils tested, the boundary shear required to produce erosion was found to be a function of the moisture content at which the soil was compacted.

Moore and Masch [6] made a series of tests using a vertical submerged jet to determine the relative scour resistance of various kinds of sediments. In these tests, the characteristics of the scour surface were observed on remolded and natural sediments, and the rates of scour were measured by the weight loss from the sample. Results from these tests indicated that the mean depth of erosion was proportional to the logarithm of the time during which scour occurred. This is a result similar to that found in experiments on noncohesive sediments.

A number of flume tests also have been performed to determine the relationship between critical tractive force and various soil properties. Among the most notable are those by Smerdon and Beasley [7] and more recently by Abdel-Rahman [8]. In the Smerdon and Beasley studies, data from hydraulic and physical tests on soils were analyzed statistically to determine the apparent correlation between critical tractive force and pertinent soil properties. For the soils tested, the critical tractive forces computed from the energy slope and channel properties were found to correlate with plasticity index, dispersion ratio, mean particle size and percent clay. These correlations are illustrated in Figures 1 through 4. For the soils tested, the critical tractive forces τ_c, were found to be best correlated with plasticity index and dispersion ratio, the

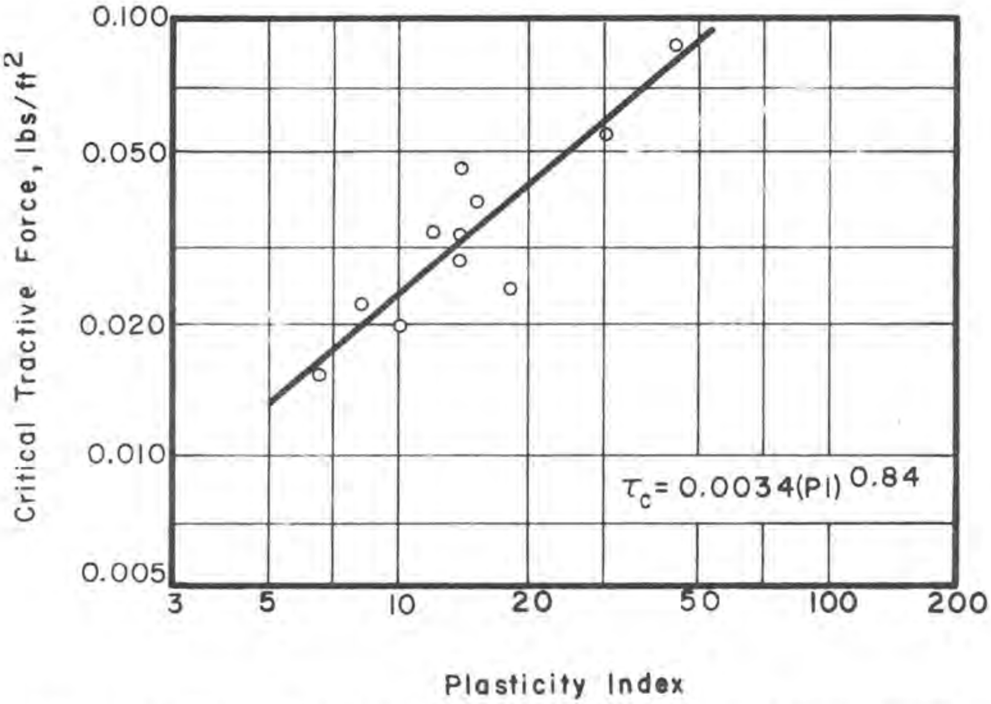

FIG. 1 CRITICAL TRACTIVE FORCE DETERMINED FROM ENERGY SLOPE VS. PLASTICITY INDEX. (after Smerdon and Beaseley [7])

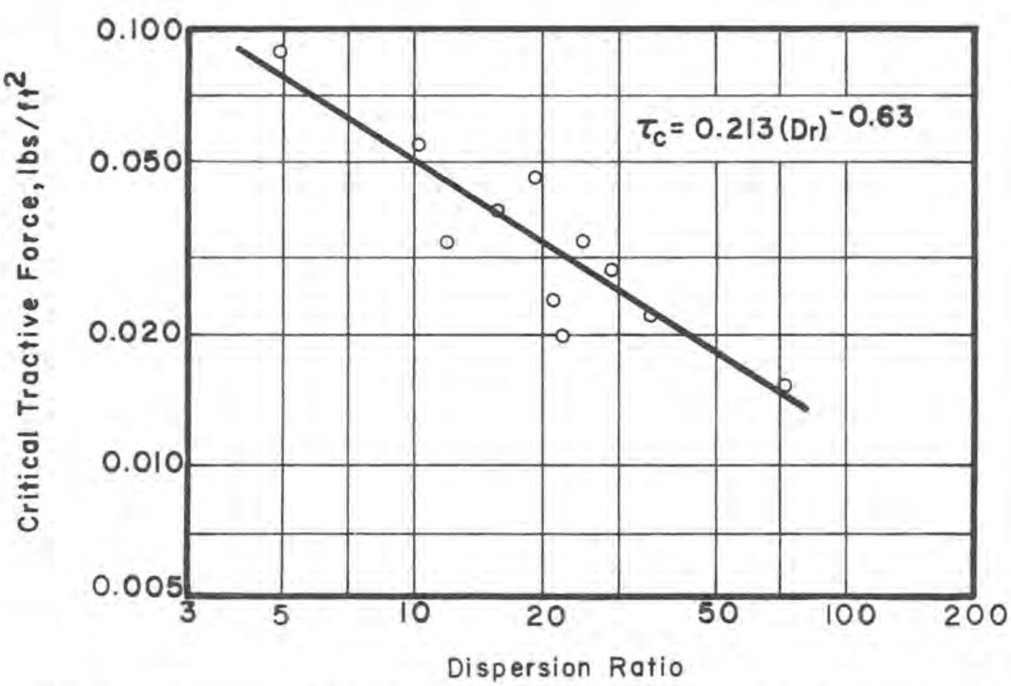

FIG. 2 CRITICAL TRACTIVE FORCE DETERMINED FROM ENERGY SLOPE VS. DISPERSION RATIO. (after Smerdon and Beaseley [7])

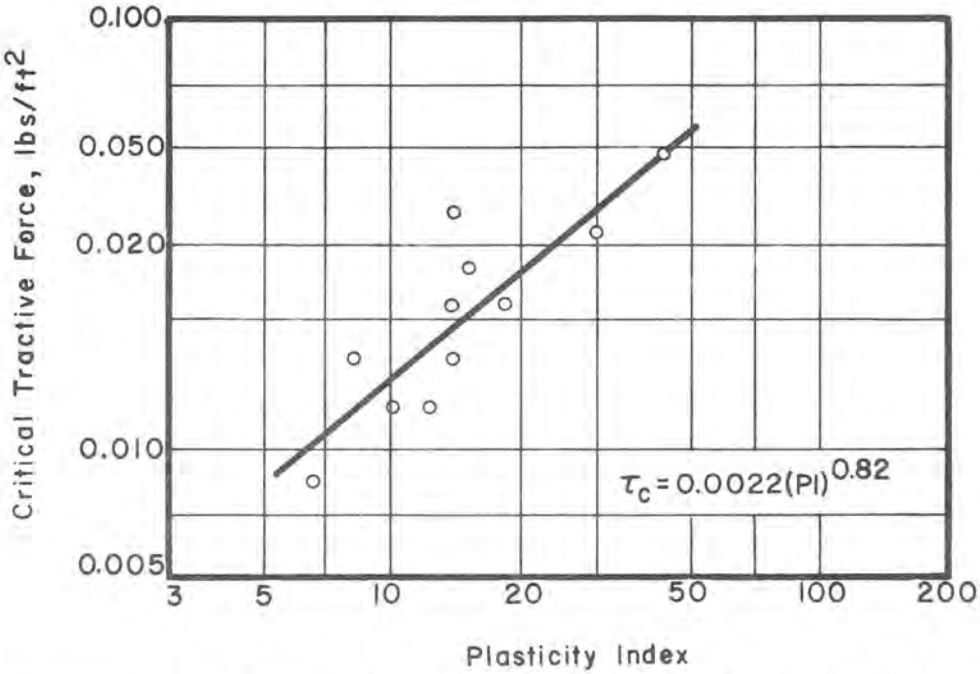

FIG. 3 CRITICAL TRACTIVE FORCE DETERMINED FROM VELOCITY PROFILE VS. PLASTICITY INDEX. (after Smerdon and Beaseley [7])

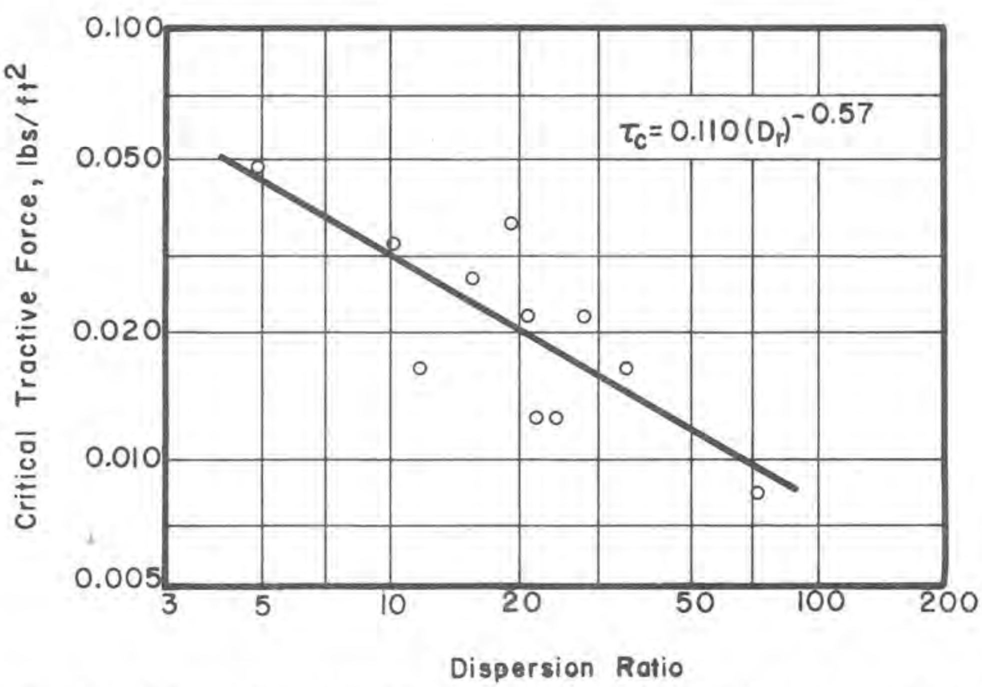

FIG. 4 CRITICAL TRACTIVE FORCE DETERMINED FROM VELOCITY PROFILE VS. DISPERSION RATIO. (after Smerdon and Beaseley [7])

relations being given by:

$$\tau_c = 0.0034\,(PI)^{0.84} \tag{2}$$

and

$$\tau_c = 0.213\,(D_r)^{-0.63} \tag{3}$$

Calculating the tractive force from the velocity profile, the relations are:

$$\tau_c = 0.0022\,(PI)^{0.82} \tag{4}$$

and

$$\tau_c = 0.110\,(D_r)^{-0.57} \tag{5}$$

in which PI is the Plasticity Index and D_r is the dispersion ratio. Smerdon and Beasley consider equations (2) and (3) more reliable than equations (4) and (5) because of accuracy of measurements. A less significant correlation was also found to exist between critical tractive force and the phi mean particle size.

Abdel-Rahman [8] made laboratory flume measurements of the soil properties of clay beds, the velocity distribution, the erosion depth as a function of time and the suspended load in the water. Based on his test, an equilibrium state or termination of erosion was found to occur. Empirical equations were determined for beds of Opalinuston clay that give information on the mean depth of erosion, t_m, at steady state conditions and on the bed roughness, ϵ_m. These equations are:

$$\frac{(\gamma_w R S_e)^2}{S_v} = p + b' \gamma_w t_m \tag{6}$$

and

$$\frac{\rho u_*^2}{S_v} = 0.83 \times 10^{-4} + 2.90 \times 10^{-6} \left[\frac{\gamma_s'' \epsilon_m S_o}{u_*/\epsilon_m}\right] \tag{7}$$

in which R is the hydraulic radius; S_e the energy slope; p a pressure dependent on viscosity of flow and mineralogy of the soil; S_v the vane shear strength of the bed material after the flow of water; ρ the density of water; γ_w the specific weight of water; u_* the friction velocity; γ_s'' the submerged volume weight of the bed material; S_o the bed slope; μ the viscosity; and b' is a constant. Abdel-Rahman's tests on mean erosion depth versus time show similar characteristics to those determined by Moore and Masch [6] in tests with the submerged jet. Flume test with salt water and estuarine sediments have also been reported by Partheniades [9] who, contrary to the work of others, reports that shear strength is not a factor in determining the resistance of cohesive sediments.

It is not entirely clear whether tractive force measurements made on soil samples set into a section of a smooth-bottom flume or tank are totally representative of the boundary shear stress which could cause erosion of a cohesive bed. As the flow over the bottom suddenly encounters the soil sample, there is abrupt change in the bed roughness which in turn can affect the velocity distribution. This is particularly true when the surface of the soil sample is eroding. Under these conditions, the average tractive force is not uniformly distributed over the sample, and determinations of critical tractive force from average channel and flow properties are not necessarily representative of the boundary shear on the sample.

If the relationships between critical tractive force and various properties of cohesive soils are to be investigated, there is a necessity to measure a mean shear stress or tractive force that is nearly constant over the entire surface of the sample tested. With this in mind, Moore and Masch [6] developed a small rotating cylinder apparatus, Figure 5, which is useful in determining factors that control the erosion resistance of cohesive sediments. In this appa-

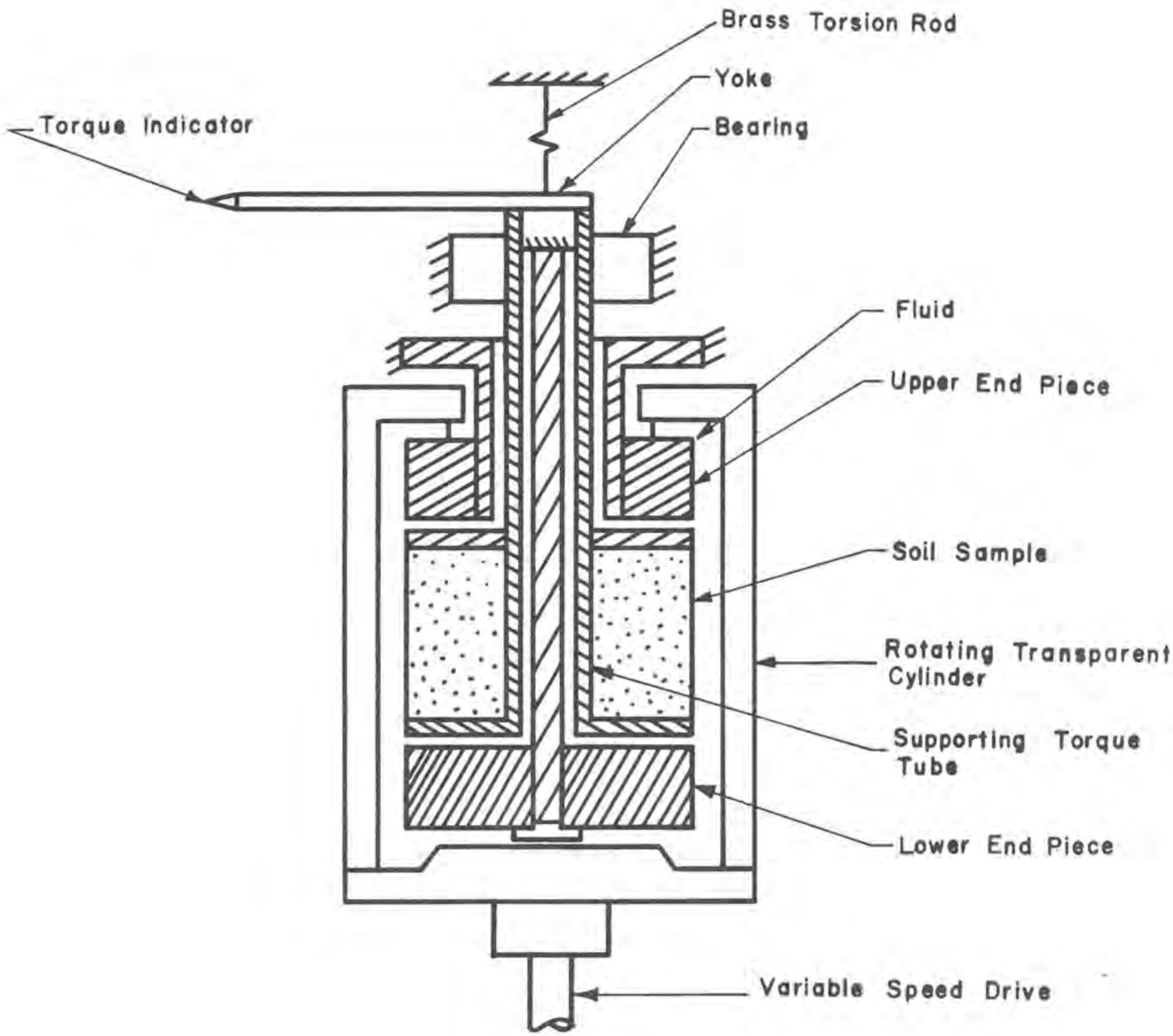

FIG. 5 DIAGRAM OF MODIFIED ROTATING CYLINDER TEST APPARATUS.
(after Moore and Masch [6])

ratus, a cylindrical sample of cohesive soil is placed concentrically into another cylindrical container. Water fills the annular space between the sample and the outer cylinder. The outer cylinder is then rotated at a uniform speed and the torque transmitted to the soil sample is measured to determine the shear stress on the surface of the sample. The quantity of erosion may also be determined in the apparatus by weighing the sample at fixed intervals of time. Detail studies on the apparatus and its use have been reported by Espey [10], Rektorik and Smerdon [11], and by Masch, Espey, and Moore [12]. Figure 6 illustrates relations between vane shear strength and critical tractive force as measured by the rotating cylinder apparatus for several different clay materials, some properties of which are tabulated in Table 1. Because of the interrelationship between various physical soil properties, tests were run also to determine the affect of moisture content on critical tractive force. Results from the Espey and Rektorik and Smerdon tests are shown in Figure 7. With the exception of the San Saba Clay, these data all illustrate the same general trends with the critical tractive force decreasing with increasing moisture content, as also reported by Enger, and increasing with increasing vane shear strength. Data obtained for San Saba clay displayed a great

TABLE 1. PHYSICAL PROPERTIES OF SOME CLAY-TYPE SEDIMENTS
(after ESPEY [10] AND REKTORIK AND SMERDON [11])

Soil Name and Number	Lake Charles K319	Lufkin K116	Houston K177	Houston K177A	Houston K177B	San Saba	Taylor Marl
Texture	Clay or Silty Clay	Clay or Clay Loam	Clay or Silty Clay	Clay or Silty Clay	Clay or Silty Clay	Silty Clay	
Liquid Limit	56.4	49.4	43.7	44.7	48.7	47.7	47
Plastic Limit	22.0	15.9	20.5	17.7	18.0	22.0	21
Plasticity Index	34.4	33.5	23.2	27.0	30.7	25.7	26
Percent Clay	46.2	40.3	55.5	55.5	55.5	44.7	50
Mean Particle Size, mm	0.0019	0.0084	0.0033	0.0033	0.0033	0.0020	0.0048

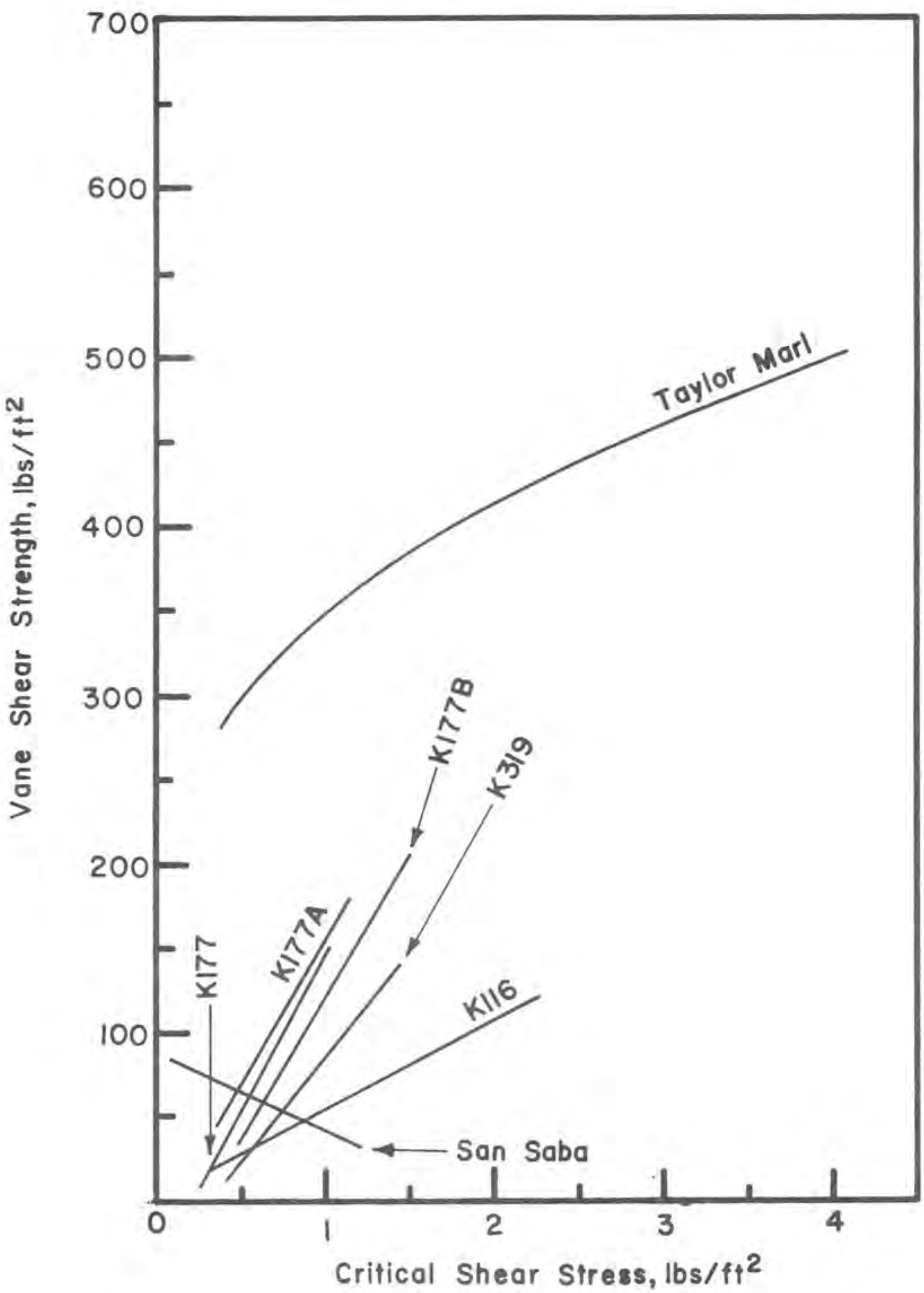

FIG. 6 VANE SHEAR STRENGTH VS. CRITICAL SHEAR STRESS.

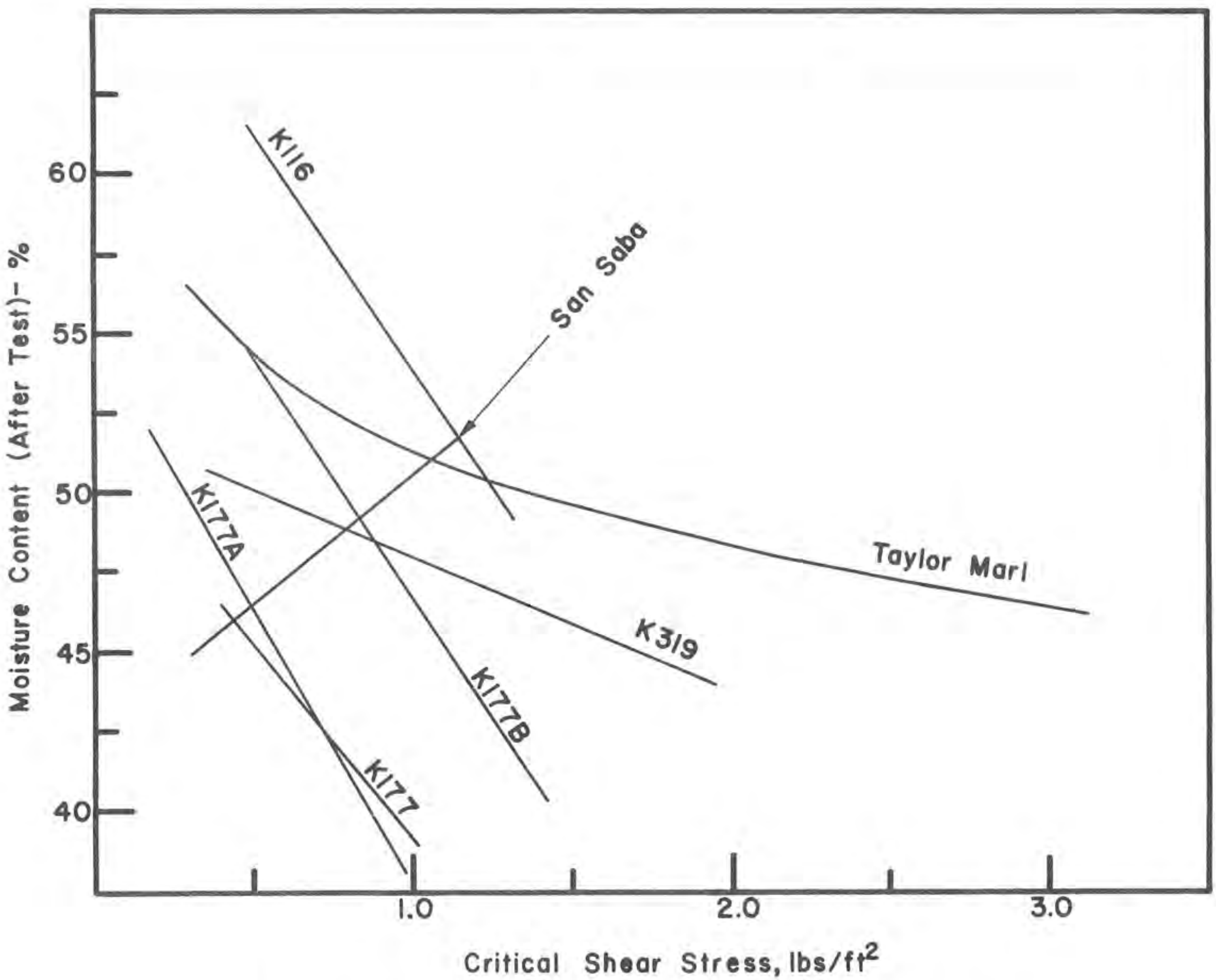

FIG. 7 CRITICAL SHEAR STRESS VS. MOISTURE CONTENT.

amount of scatter and when fitted with a least squares regression, the resulting relation showed an opposite trend to those found for the other soils. No explanation has been offered for the reverse behavior of this particular soil.

Martin [13], Grissinger [14], and others have reported on the effects of chemical and physical properties on erosion resistance. Martin discusses the effect of clay type and electrolyte on compressive strength and notes that a change in kinematic viscosity results as clay material goes into suspension during erosion and that this in turn is a factor which may affect the tractive force. Data are presented by Grissinger and Asmussen [15] on the effects of the quantity of water within the soil and the length of time the soil sample has been at a given water content before testing. The results show that the rate of erosion decreases with wet age at the time of the test, but increases with the time after erosion begins. Berghager and Ladd [16] conclude that previous investigators had not adequately controlled the engineering properties of the clays being eroded and that relative soil properties were not measured. They discuss drawbacks regarding the concept of the critical tractive force and stress the importance of clay fabric and inner particle forces.

FIELD OBSERVATIONS IN NATURAL CHANNELS

Generally, erosion or deposition occurring in a natural water channel depends on the local forces exerted by the flowing water, the geology and properties of the material over which the water flows, and on the sediment load being transported. Seasonal changes may occur, and local scour or deposition may result due to man-made or natural structures.

Sediment Load

The importance of sediment load in influencing the characteristics of natural streams has been recognized by most researchers. Considerable study has been conducted to establish sediment erodibility and predict sediment loads. Anderson [17,18] obtained data from 14 watersheds on the west side of the Coast Range in Southern California. From regression analysis he found that the sediment yields of watersheds depend on the watershed characteristics, land use and condition, and the nature of storms and streamflow. Results of Anderson's analysis were presented by five equations, which are summarized in Table 2. Correlation coefficients for these equations vary from about 0.85 to 0.89.

TABLE 2

EQUATIONS RELATING PHYSICAL CHARACTERISTICS OF SOIL AND COVER DENSITY TO EROSION (after ANDERSON [17])

Equation	Correlation coefficient
$\log E_8 = 3.073 - 2.430 \log C + 3.427 \log D_r$	.888
$\log E_8 = 4.786 - 2.486 \log C + 2.473 \log ER$	.878
$\log E_8 = 11.461 - 2.524 \log C + 2.189 \log S - 3.288 \log (si + cl)$	.849
$\log E_8 = 2.127 - 2.341 \log C + 3.861 \log D_r + 1.353 \log \frac{Coll}{ME}$	.890
$\log E_8 = 10.279 - 1.788 \log C + 1.151 \log S - 3.164 \log Coll$	.854

In Table 2, E_8 is the average suspended sediment content of stream flow in ppm; C, the average cover density on watershed in percent; D_r, the dispersion ratio; ER, the erosion ratio; S, the suspension; (si + cl), the ultimate silt plus clay; Coll, the colloid, and ME, the moisture equivalent.

Zernial and Laursen [19] used an empirical formula to predict the sediment load from five western streams for comparison with field measurement data collected from the streams by the U. S. Geological Survey. The formula used for the prediction was:

$$\bar{c} = \sum p_d \left(\frac{d}{y_o}\right)^{7/6} \left(\frac{\tau_o'}{\tau_c} - 1\right) f\left(\frac{\sqrt{\tau_o/\rho}}{w}\right) \tag{8}$$

in which $\bar{c}$ is the mean sediment concentration, in percentage by weight; p_d is the fraction of the bed material having a mean particle size d in feet; y_o is the depth of flow in feet. τ_o' describes that part of the total tractive force associated with the sediment particles; τ_c refers to the critical tractive force, in pounds per square foot, and is evaluated for each fraction, p_d, as equal to 4 d; τ_o is the tractive force acting on the bed, in pounds per square foot, and is evaluated as equal to $\gamma_w \, y_o \, S$ where S is taken as the slope of the water surface assuming uniform flow; γ_w is the specific weight of water; ρ is the density of water; and w denotes the fall velocity, in feet per second of a quartz sphere of diameter d.

Some of the predicted and measured values were in good agreement, in Figure 8, but several cases indicated some variation, Figure 9. The variability of the load-discharge characteristics was assessed, and the effects of changes in channel instability, temperature and bed-material for the five streams were presented. Tables 3, 4 and 5

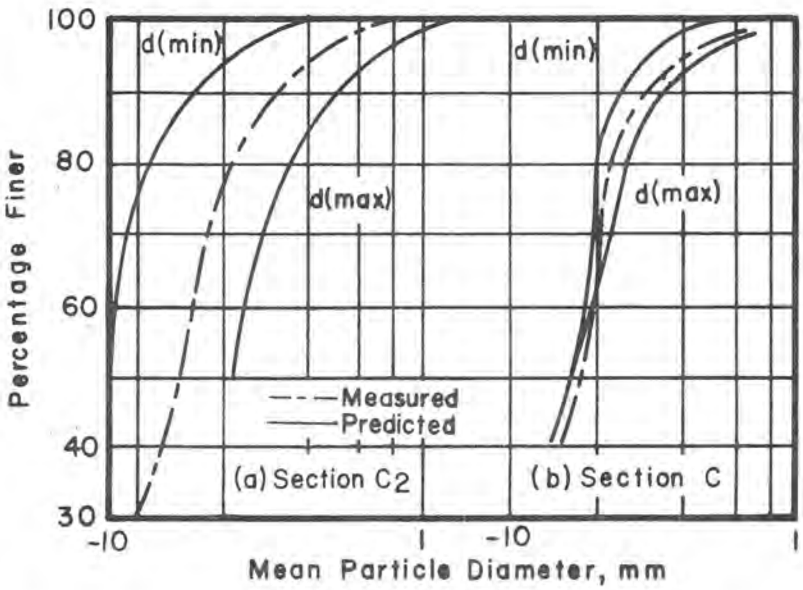

FIG. 8. PREDICTED AND MEASURED COMPOSITION OF SUSPENDED LOAD ON MIDDLE LOUP RIVER. (after Zernial and Laursen [19])

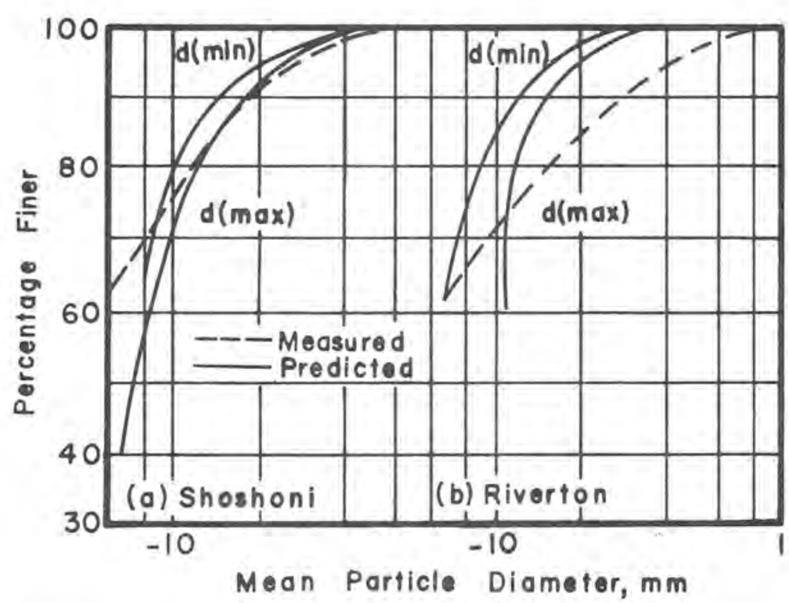

FIG. 9. PREDICTED AND MEASURED COMPOSITION OF SUSPENDED LOAD ON FIVEMILE CREEK. (after Zernial and Laursen [19])

show these effects. It was concluded that the sediment load is a unique function of the flow, fluid, and bed material characteristics and that the watershed and stream characteristics can be used to evaluate the sediment yield.

Shapes of Natural Channels

Schumm [20, 21, 22] collected data at over 40 cross sections located near Geological Survey gaging stations throughout the Western United States. The channels were considered stable and information collected included: channel width (b), maximum channel depth (y), mean annual discharge (Q), mean annual flood or the total discharge with a recurrence interval of 2.33 years (Q_b), and percent silt-clay in the bed (S_c) and the banks (S_b). From this information, a width-depth ratio (F) and the percent silt-clay in the perimeter of the channel (M) was calculated. M was calculated as:

$$M = \frac{(S_c)(b) + (S_b)(2y)}{b + 2y} \tag{9}$$

Streams from which the data were collected varied in width-depth ratio from about 2.5 to 138, in percent perimeter silt-clay from about 1.4 to 89, and in mean annual discharge from about 5.8 to 5,200 cfs.

TABLE 3. EFFECTS OF CHANNEL INSTABILITY

(after ZERNIAL AND LAURSEN [9])

Location	Approximate effects on Q_s, in percentage				
	Change in y_o	$\left(\frac{d}{y_o}\right)^{7/6}$	$\frac{\tau_o'}{c} - 1$	$f\left(\frac{\sqrt{\tau_o/\rho}}{w}\right)$	Total effects
Middle Loup, Section C	+10	-10	-25	+12	-23
Middle Loup, Section C_2	+24	-22	-55	+22	-57
Fivemile-Shoshoni	+55	-40	-70	+55	-72
Fivemile-Riverton	+27	-24	-55	+29	-56
Rio Grande-Bernalillo	+20	-19	-34	+21	-35

TABLE 4. EFFECTS OF TEMPERATURE CHANGES

(after ZERNIAL AND LAURSEN [9])

Location	Change in percentage		
	Change in temperature	Change in w	$f\left(\frac{\sqrt{\tau_0/\rho}}{w}\right)$
Middle Loup, Section C	-54	-42	+236
Middle Loup, Section C_2	-54	-38	+190
Fivemile-Shoshoni	-59	-43[a] -50[b]	+230 +110
Fivemile-Riverton	-58	-46[a] -55[b]	+294 +135
Rio Grande-Bernalillo	-24	-17[a] -25[b]	+ 51 + 88

[a]Maximum probable size of bed material. [b]Minimum probable size of bed material.

TABLE 5. EFFECTS OF BED-MATERIAL VARIATIONS

(after ZERNIAL AND LAURSEN [9])

Location	Approximate effects on Q_s, in percentage					
	Change in d	Change in w	$\left(\frac{d}{y_o}\right)^{7/6}$	$\frac{\tau_o'}{\tau_c} - 1$	$f\left(\frac{\sqrt{\tau_o/\rho}}{w}\right)$	Total effects
Middle Loup, Section C	-13	-24	+13	-13	+ 84	+ 84
Middle Loup, Section C_2	-49	-68	+59	-30	+1160	+1300
Fivemile-Shoshoni	-49	-71	+59	-29	+1400	+1600
Fivemile-Riverton	-33	-52	+39	-23	+ 415	+ 450
Rio Grande-Bernalillo	-49	-65	+59	-24	+ 490	+ 610

Analyses of the data indicated that the mean annual flood and the weighted mean percent silt-clay are most significantly related to the width and a multiple correlation analysis yielded the equation:

$$b = 5.76 \frac{Q_b^{0.45}}{M^{0.36}} \tag{10}$$

for the channel width.

Neither mean annual discharge nor the mean annual flood was found to significantly affect the width-depth ratio. A regression line was determined graphically for the data in Figure 10, resulting in the equation:

$$F = 255\,M^{-1.08} \tag{11}$$

for the width-depth ratio.

Effects of Structures

Frequently the upsetting of natural conditions by man causes a cohesive channel to change its shape, erode, or degrade. Often comprehensive plans and manmade structures are necessary to alleviate this problem. Miller and Borland [23] reported on a study and stabilization program on Fivemile and Muddy Creeks in central Wyoming. Due to manmade changes, the discharge had increased from less than 5,000 acre-feet to over 90,000 acre-feet on Fivemile Creek and over

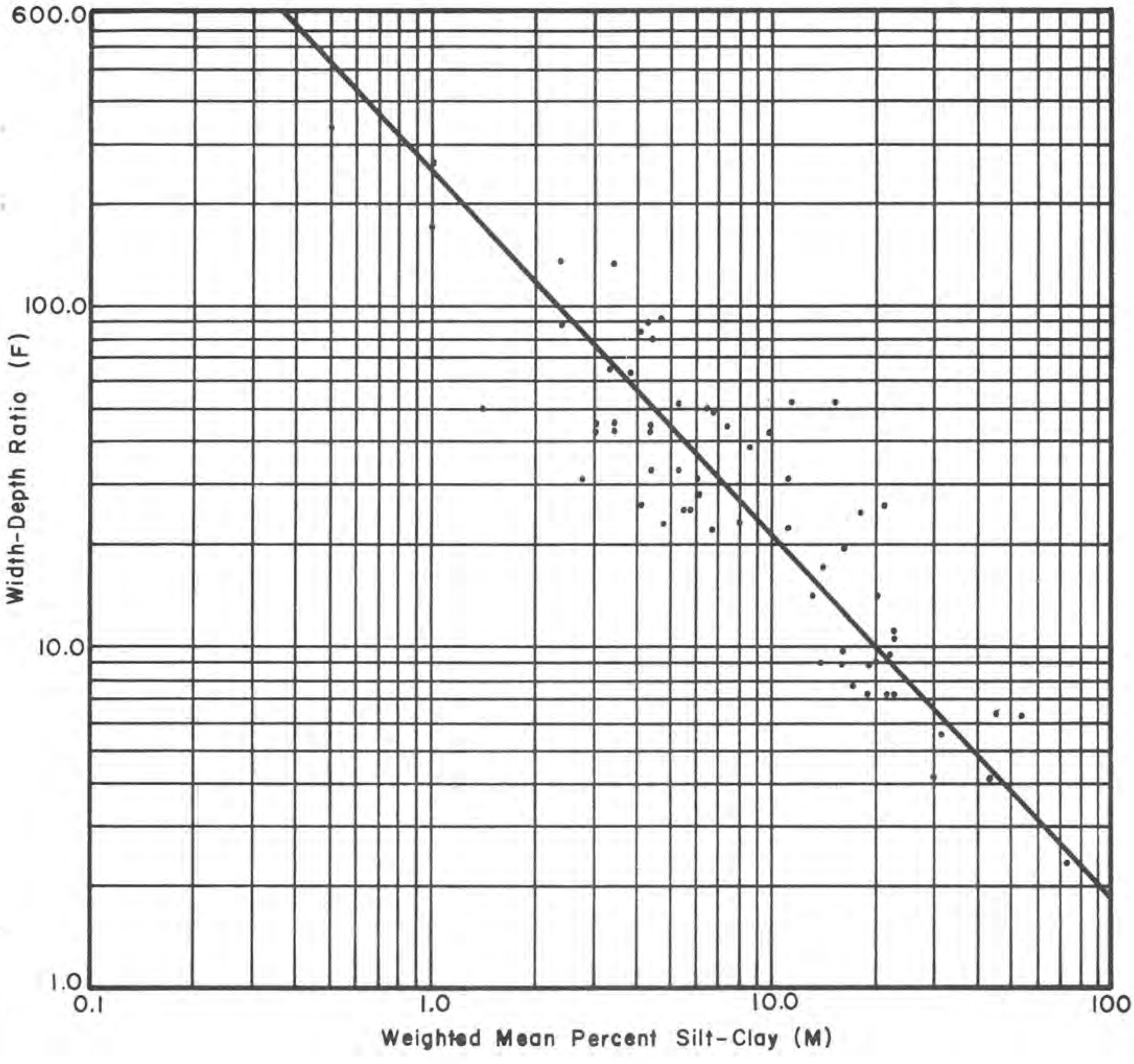

FIG. 10 WIDTH-DEPTH RATIO VS. MEAN PERCENT SILT-CLAY. (after Schumm [22])

20,000 acre-feet on Muddy Creek in a period of about 25 years. Due to the increase in flow, erosion had greatly accelerated, and the streams were contributing over 50 percent of the sediment being deposited in Boysen Reservoir. A detailed field investigation was undertaken to collect geologic, hydrologic and hydraulic data. Using the data collected, control measures, including wooden and concrete jacks, groins and jetties and vegetation, were designed. These measures proved successful and resulted in a stabilized channel and a ninety percent reduction of sediment inflow into Boysen Reservoir.

Woolheiser and Miller [24] present the results of a study of channel erosion above and below gully control structures. This study was intended to document present and past conditions and experiences at several gully control structures in order to provide data which would aid in the design of these structures. The study concentrated primarily on the scour hole development at the principle spillway outlet and changes in the channel bed profile downstream from the structure along the line of maximum depth of flow in the stream.

Climate and Temperature Effects

Wallis and Willen [25] obtained 0 to 6-inch samples of soil from 258 locations in northern California's mountain lands. A part of their analyses included relating climatic parameters to textural and erodibility measures of the soil. Although correlation was not highly significant, they found from regression analysis that for the soils, a predicition of total clay ($clay_{ce}$) could be made, based on the climate, from the equation:

$$\begin{aligned} clay_{ce} = {} & 0.343 + 0.06201\,(P) + 0.4213\,(K_w) \\ & - 0.05764\,(K_w P) - 0.0003761\,(P)^2 \\ & - 0.0002589\,(K_w)^2 + 0.0001781\,(K_w P)^2 \end{aligned} \tag{12}$$

in which P is the mean annual precipitation in inches and K_w is the dissociation constant of water summed for 12 months by using the mean monthly temperatures calculated for each site.

It was found that for the mountain soils the surface aggregation ratio (S/A), which expresses the amount of surface area of the particles greater than sand size relative to the amount of aggregated silt and clay that is available for aggregate formation, was an effective measure of the soil erodibility. Predictions of the surface aggregation ratio were made from the climate variables as:

$$\begin{aligned} S/A = {} & 322.6 - 6.39\,(P) - 7.52\,(K_w) + 2.42\,(K_w P) + \\ & 0.0404\,(P)^2 + 0.0553\,(K_w)^2 - 0.00693\,(K_w P)^2 \end{aligned} \tag{13}$$

Wolman [26] found severe erosion in winter months when bankfull flow attacked channel banks that were previously wet. He also noted significant erosion from combinations of cold periods, wet banks, frost action, and rises in stage, and that crystallization of ice and frequent thawing without a change of stage also produced some erosion.

Predicting Erosion or Deposition

In a study on channel deterioration of natural and artificial drainageways in Nebraska and Iowa, Schroeder [27] classified 121 test reaches as being (1) stable, (2) fairly stable or questionable, and (3) deteriorating channels. Using the mean annual peak discharge and stage-discharge relationships, the depth was obtained and tractive forces were computed from:

$$\tau = k \gamma_W y_o S \qquad (14)$$

where k is a variable dependent on the bed-depth ratio and the side slope of the channel, γ_W the specific weight of water, y_o the depth of water in the channel, and S is the slope of water surface or canal bed. The percent density of vegetative cover was recorded for the channels, and soil tests of the channel material were conducted.

Curves were developed, Figures 11 and 12, showing limiting tractive forces for the bed and banks of the channels. Curves of tractive force versus plastic index are shown for no vegetal cover

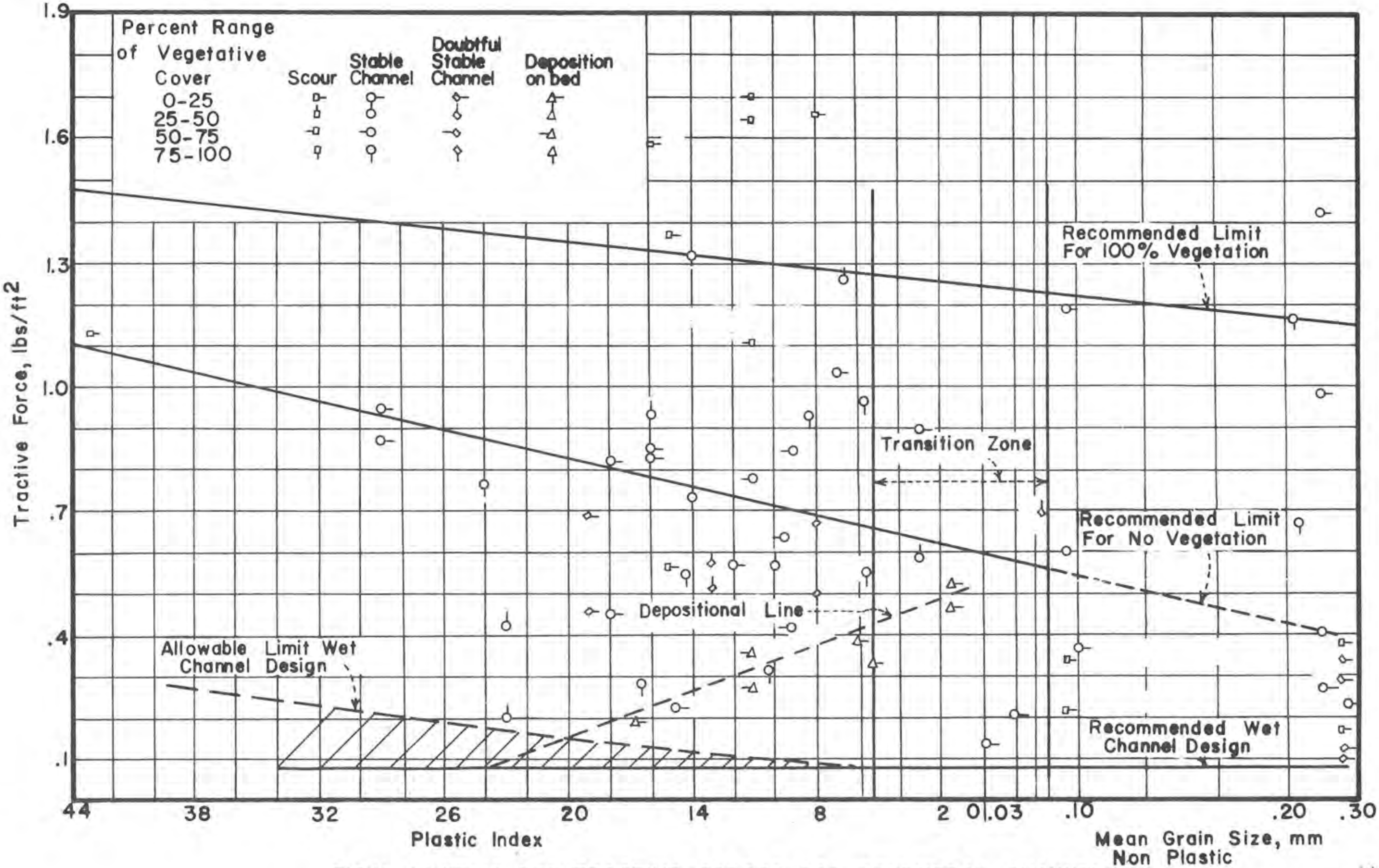

FIG.11 LIMITING BED TRACTIVE FORCES FOR EPHEMERAL CHANNELS (after Schroeder [27])

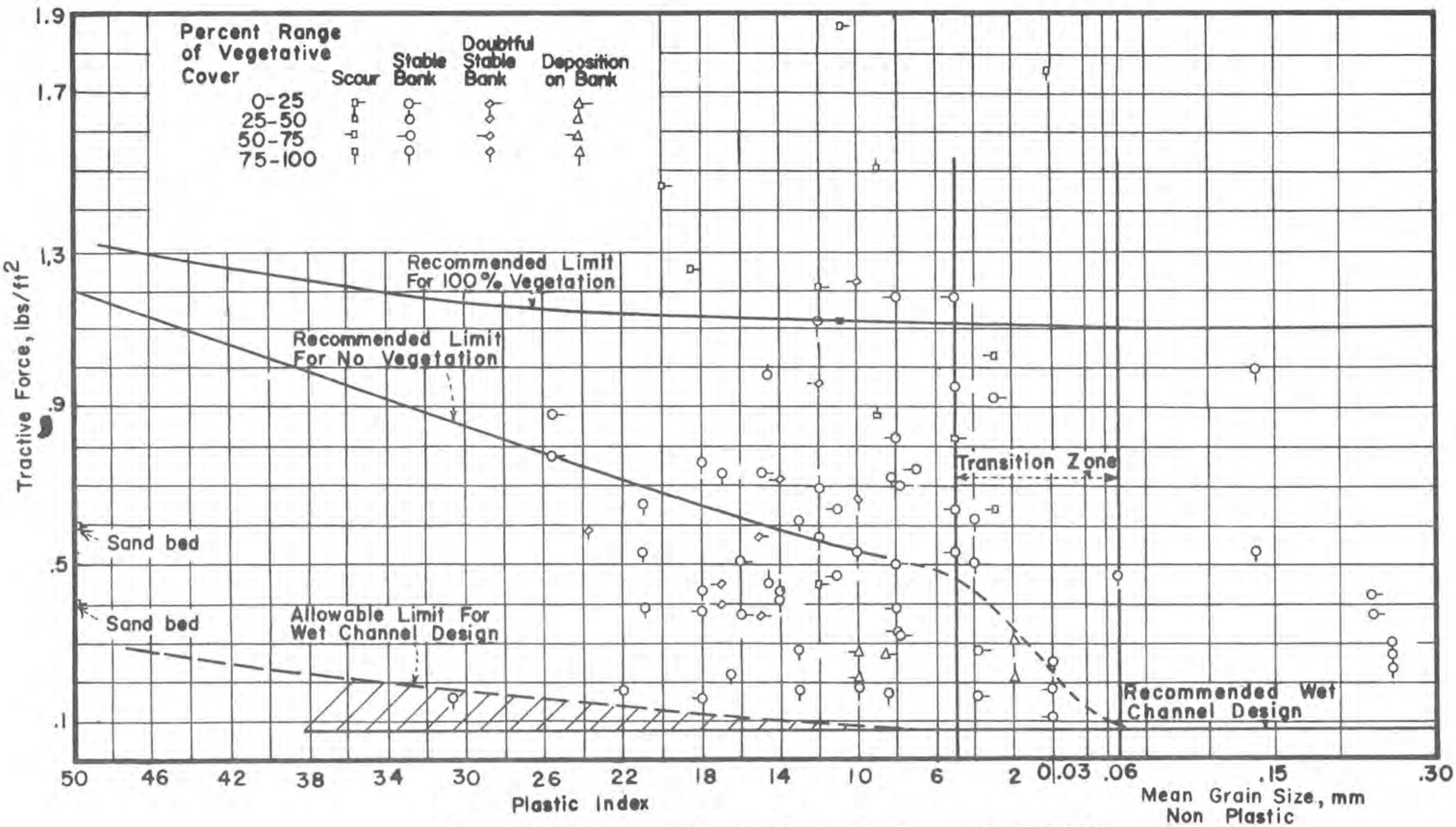

FIG. 12 Limiting Bank Tractive Forces For Ephemeral Channels (after Schroeder [27])

and 100 percent vegetal cover. Although there is a wide scatter of points, these curves may be used as a guide for predicting conditions of erosion or deposition. Where banks are flatter than a 5 to 1 slope they should be considered essentially the same as a bed condition, and where channels are quite sinuous, vegetation should not be considered a limiting factor. The wet channel design limits shown on Figures 11 and 12 were obtained from limited data and, therefore, were not advocated for use in design.

Hjulstrom [28] has presented a curve relating grain size and erosion velocity from studies of the River Fyris. Much of the information available for designed channels is also of considerable benefit in predicting erosion conditions of a natural stream.

DESIGN OF NON-ERODING CHANNELS

Observations and Tests

Observations, tests, and data collection have been conducted on several canal systems with the objectives of developing satisfactory design methods. The U. S. Bureau of Reclamation observed and tested 46 channel test reaches located throughout the Western United States [4, 29, 30, 31, 32]. The canals and laterals had been in operation for a number of years and discharges varied from 2 to 3,000 cfs. Field data were obtained on both the hydraulics and soils, and several soil samples were obtained from each test site. Both soils and hydraulic tests were conducted on the samples obtained from the test reaches. An electronic digital computer was used to investigate about 40 data correlations from the reaches. These correlations were reported by Carlson and Enger [4]. Correlation coefficients for the data correlations varied from "imaginary" to greater than 0.9. Thomas and Enger [32] reported a correlation from this data which gave satisfactory results within certain limits. Their equation is presented as equation (18) in the following section, Design Information Available.

Simons and Albertson [33] have used information collected from field observations to develop design criteria. The design information developed also is reported in the section, Design Information Available.

Flaxman [34] conducted field observations along existing channels, and obtained soil samples from the channels for laboratory analysis. He concluded that the unconfined compressive strength of soils is a good indicator of erosion potential, and "that soils of low strength are easily susceptible to erosion in channel flow while those of high strength resist hydraulic stresses of considerable magnitude."

Design Information Available

In 1926, Fortier and Scobey [35] presented the final report of the Special Committee on Irrigation Hydraulics on Permissible Canal Velocities. The Special Committee had submitted questionnaries to a number of engineers whose experience qualified them to make estimates of the maximum mean velocities allowable in canals of various materials. Constructive replies and suggestions were received from 10 engineers. From this and other available material, the values in Table 6 were recommended as maximum permissible mean velocities.

In an attempt to more adequately predict channel behavior, two other design theories, the regime theory and the tractive-force theory, have been studied. Simons and Albertson [33] have presented considerable information on design by the regime theory. This theory has evolved from the empirical equation of R. G. Kennedy:

$$V = C\, y^{m} \tag{15}$$

where C and m were thought of as constants, V represents the critical mean velocity in feet per second for which no silting or scouring of the channel occurs, and y is the depth in feet. The original value suggested for C was 0.84, and for m, 0.64. Other values have been

TABLE 6

PERMISSIBLE CANAL VELOCITIES
(after FORTIER AND SCOBEY [35])

Original material excavated for canal	Velocity in feet per second, after aging, of canals carrying:		
	Clear water, no detritus	Water transporting colloidal silts	Water transporting non-colloidal silts, sands, gravels, or rock fragments
(1)	(2)	(3)	(4)
Fine sand (non-colloidal)................	1.50	2.50	1.50
Sandy loam (non-colloidal)................	1.75	2.50	2.00
Silt loam (non-colloidal)..................	2.00	3.00	2.00
Alluvial silts when non-colloidal	2.00	3.50	2.00
Ordinary firm loam.....................	2.50	3.50	2.25
Volcanic ash.........................	2.50	3.50	2.00
Fine gravel..........................	2.50	5.00	3.75
Stiff clay (very colloidal)................	3.75	5.00	3.00
Graded loam to cobbles, when non-colloidal	3.75	5.00	5.00
Alluvial silts when colloidal..............	3.75	5.00	3.00
Graded silt to cobbles, when colloidal......	4.00	5.50	5.00
Coarse gravel (non-colloidal)..............	4.00	6.00	6.50
Cobbles and shingles....................	5.00	5.50	6.50
Shales and hard-pans....................	6.00	6.00	5.00

suggested for these constants.

Using data obtained from canals in India and the Western United States, Simons and Albertson [33] presented several plots to aid in the design of canals. Reproductions of several of these plots are presented in Figures 13 through 19.

The curves shown in Figure 13 provide a means of estimating the wetted perimeter for a given discharge. After the wetted perimeter has been found, the average channel width may be determined from Figure 14, and the top width from Figure 15. For the given discharge, the hydraulic radius may be found directly from the curves of Figure 16, and as the hydraulic radius and depth are closely related, the average depth may be determined from Figure 17.

The required cross-sectional area may be determined from the curves in Figure 18, and knowing the discharge and area, an average velocity may be determined. Using the average velocity, a value of R^2S may be estimated from the curves of Figure 19, and utilizing the hydraulic radius found from Figure 16, the slope may be evaluated.

Utilizing this method, Simons and Albertson stated that canals in the four following groups could be designed:

1. Canals formed in coarse non-cohesive material (charge $<$ 500 ppm)

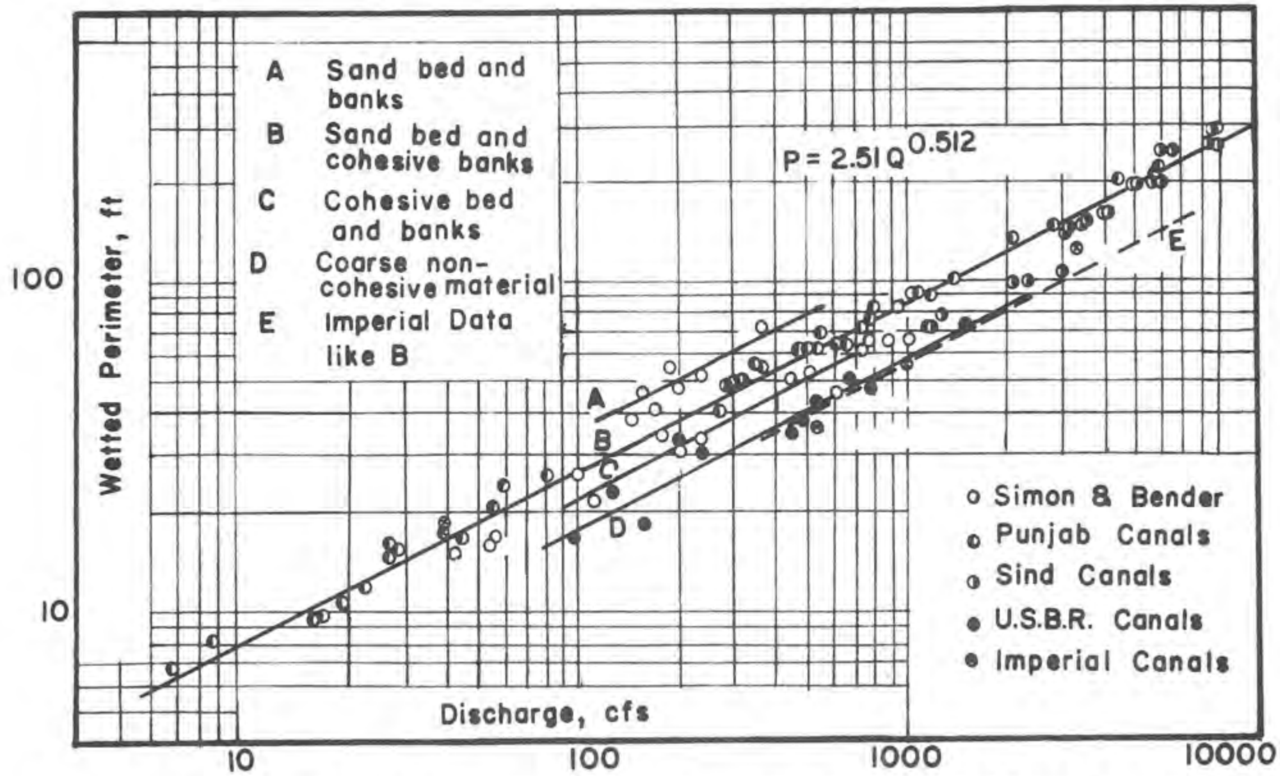

FIG. 13 VARIATION OF WETTED PERIMETER WITH DISCHARGE AND TYPE OF CHANNEL. (after Simons and Albertson [37])

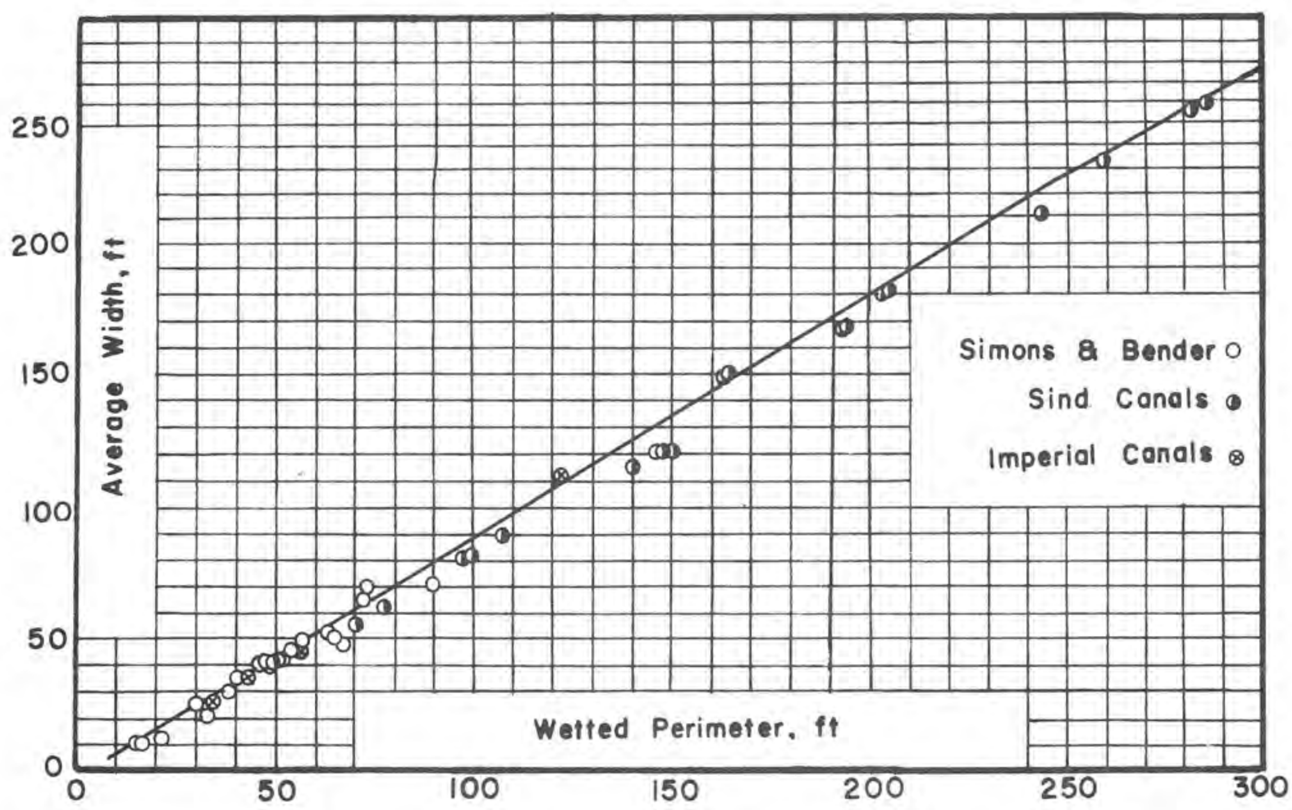

FIG. 14 VARIATION OF AVERAGE WIDTH WITH WETTED PERIMETER. (after Simons and Albertson [37])

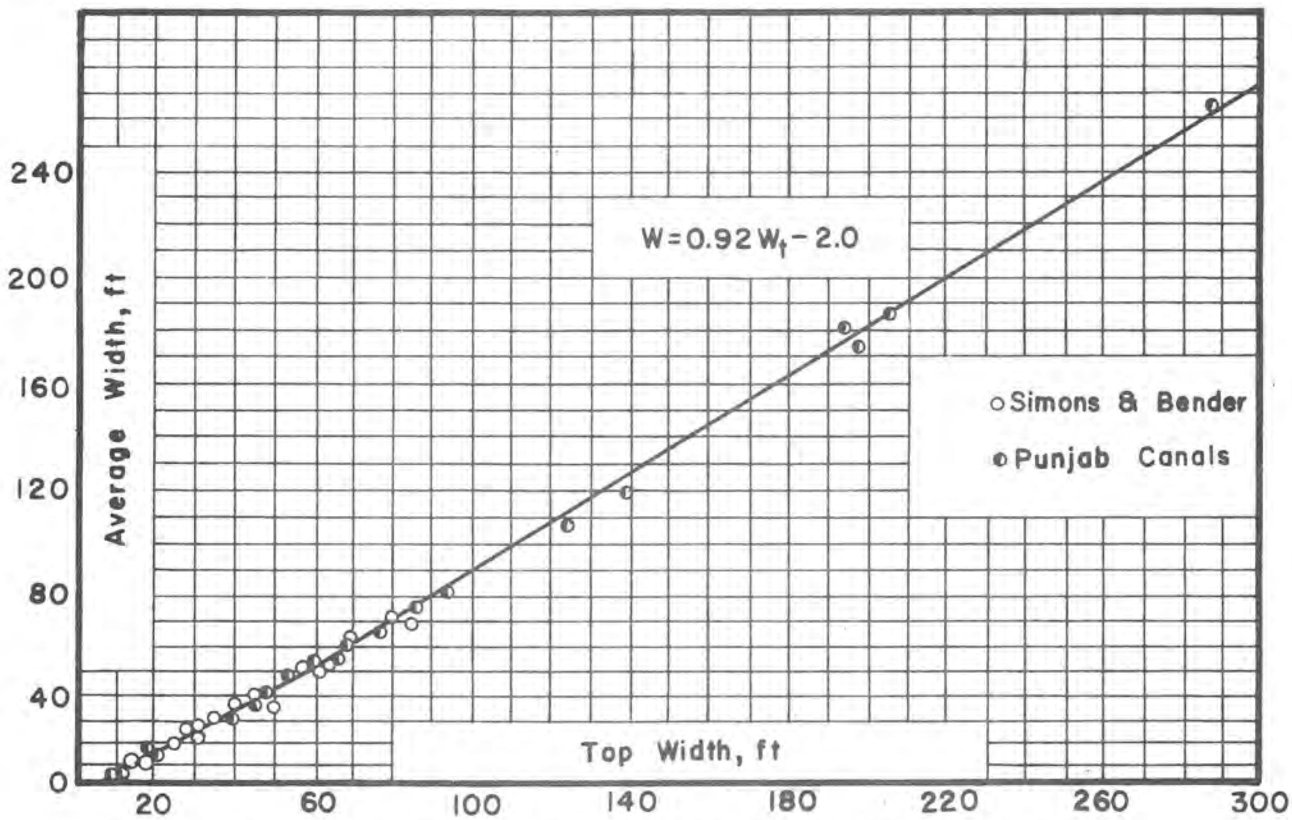

FIG. 15 VARIATION OF AVERAGE WIDTH WITH TOP WIDTH. (after Simons and Albertson [37])

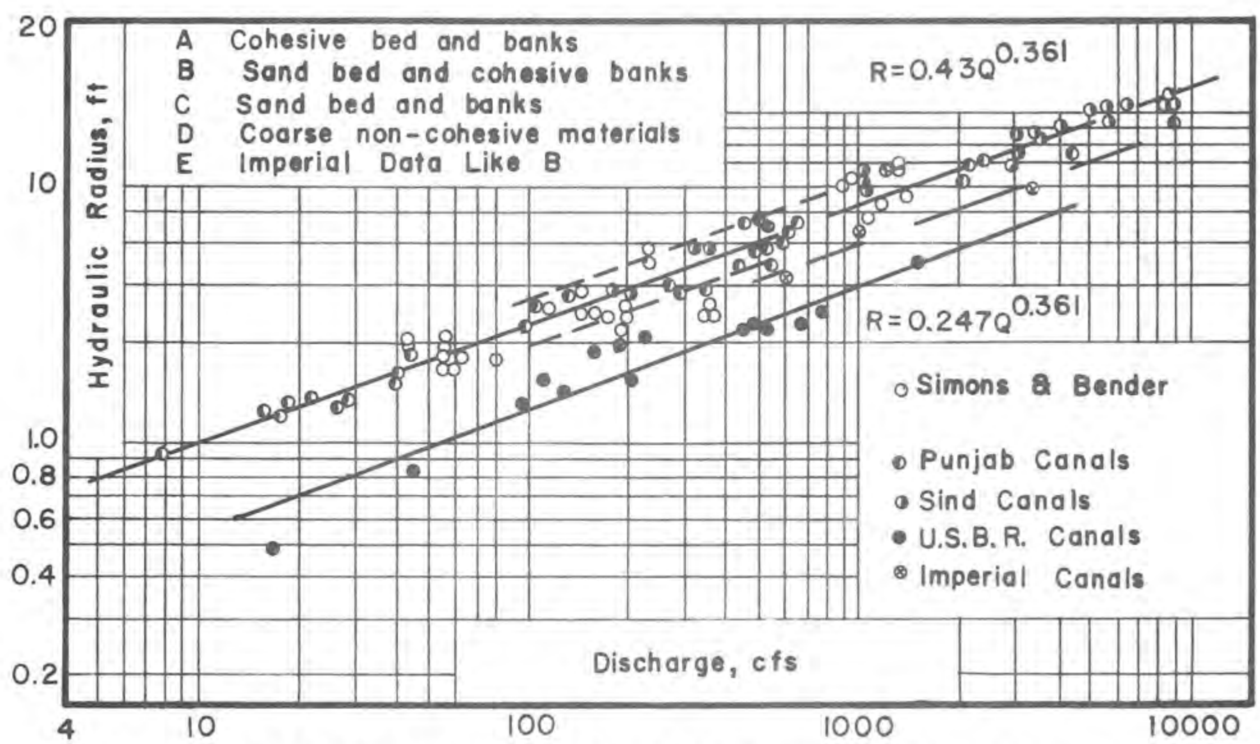

FIG. 16 VARIATION OF HYDRAULIC RADIUS WITH DISCHARGE AND TYPE OF CHANNEL, ALL DATA. (after Simons and Albertson [37])

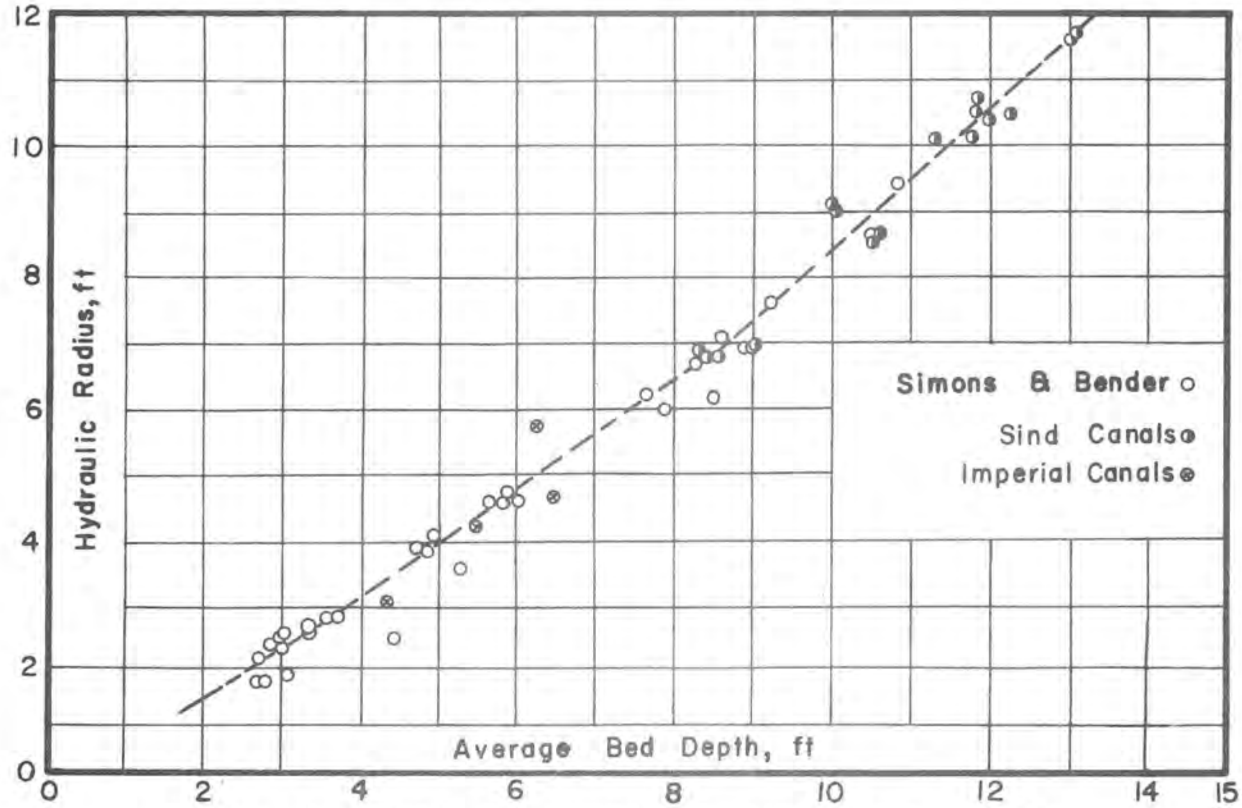

FIG. 17 VARIATION OF HYDRAULIC RADIUS WITH DEPTH. (after Simons and Albertson [37])

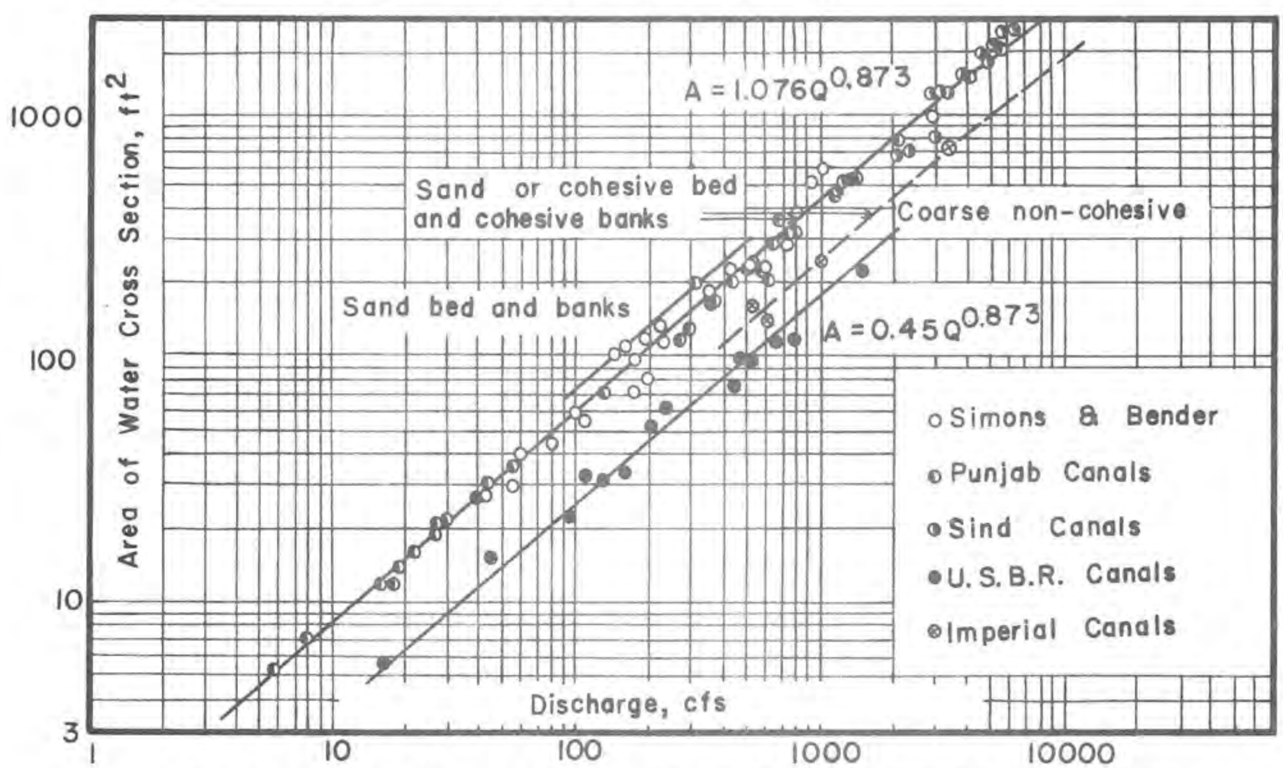

FIG. 18 VARIATION OF AREA OF WATER CROSS-SECTION WITH DISCHARGE AND TYPE OF CHANNEL. (after Simons and Albertson [37])

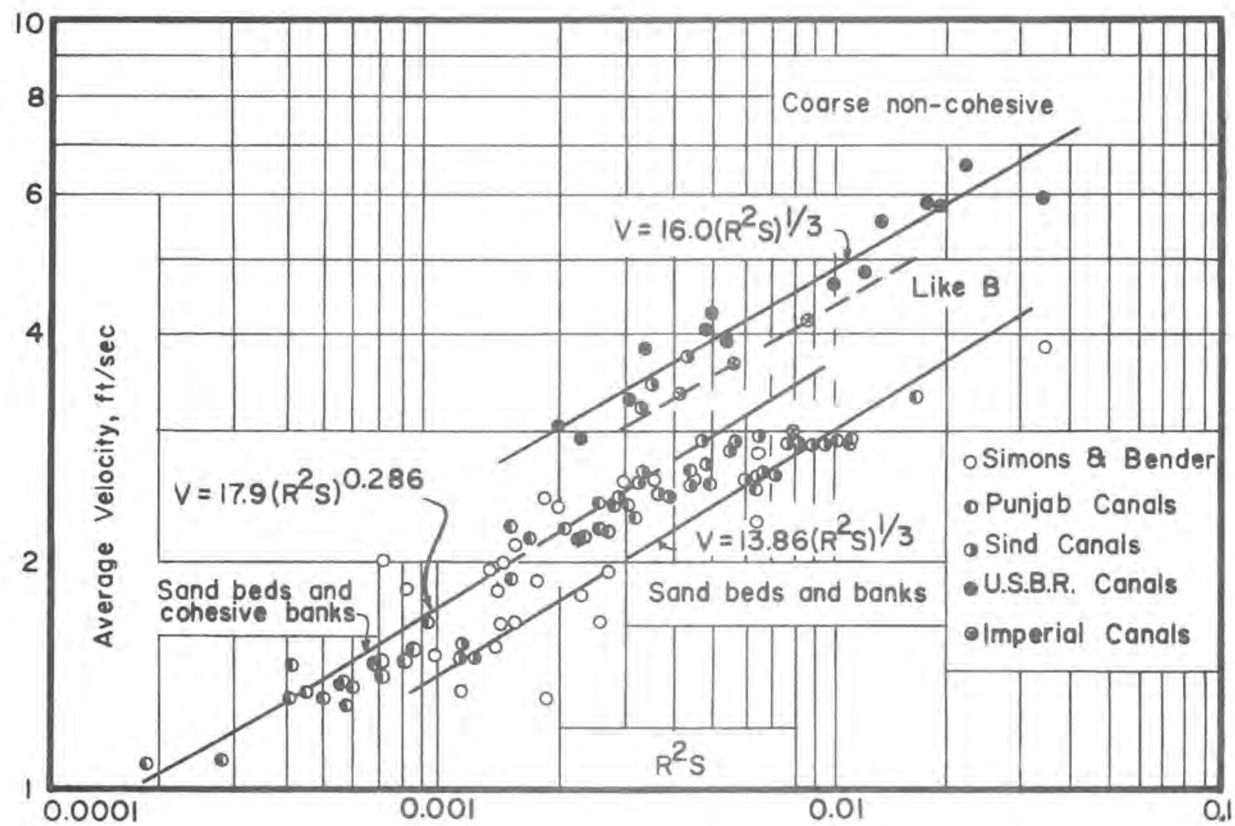

FIG. 19 VARIATION OF AVERAGE VELOCITY WITH R^2S AND TYPE OF CHANNEL. (after Simons and Albertson [37])

2. Canals formed in sandy material with sand beds and banks (charge < 500 ppm)

3. Canals possessing sand beds and slightly cohesive to cohesive banks (good results when charge < 500 ppm, qualitative results when charge > 500 ppm)

4. Canals having cohesive beds and banks (charge < 500 ppm).

A method of design by the tractive-force theory has been presented by Doubt [36]. The method involves three phases: (1) a channel is first designed to meet the capacity (maximum discharge) requirement, (2) the channel is checked to determine if it meets the requirements for stability, and (3) the economical proportions of the channel and its associated structures are checked. When necessary, the original design is altered, thus resulting in a trial solution.

The average unit frictional forces on the wetted perimeter (which are equal to the average unit tractive forces but are oppositely directed) are computed from:

$$f = R \gamma_w S_t \tag{16}$$

where f is the average unit frictional force in pounds per square foot, γ_w the specific weight of water in pounds per cubic foot, R the actual hydraulic radius in feet, and S_t is the rate of energy loss at the interface of the earth material and the flowing body of water, foot-pounds per pound of water per foot of channel.

The value of S_t is computed from:

$$S_t = \frac{n_t^2 \, Q^2}{(1.486)^2 \, A^2 \, R^{4/3}} \tag{17}$$

where Q is the actual discharge in cubic feet per second; A the actual flow area in square feet; and n_t is the Manning's roughness-coefficient for the earth material in the wetted perimeter (not to be confused with Manning's coefficient n, which is usually larger than n_t). Lane [37] suggested the relation $n = D_{75}^{1/6}/36$, in which D_{75} is the size of earth material in the wetted perimeter of which 75 percent is smaller expressed in inches.

As the tractive forces are not distributed evenly around the wetted perimeter of a channel, the maximum actual tractive force is usually obtained from experimental data such as that also presented by Lane [37], Figure 20.

Several methods have been suggested to determine the allowable tractive force, or the maximum tractive force that the channel materials can safely withstand before erosion occurs. Thomas and Enger [32] found that, within given limits, the following equation provided satisfactory results for critical tractive force.

$$\tau_c = 0.00124 + 0.00081\,PI + 0.00030\,D\% + 0.00022\,M_\phi \sigma_\phi k_\phi' \tag{18}$$

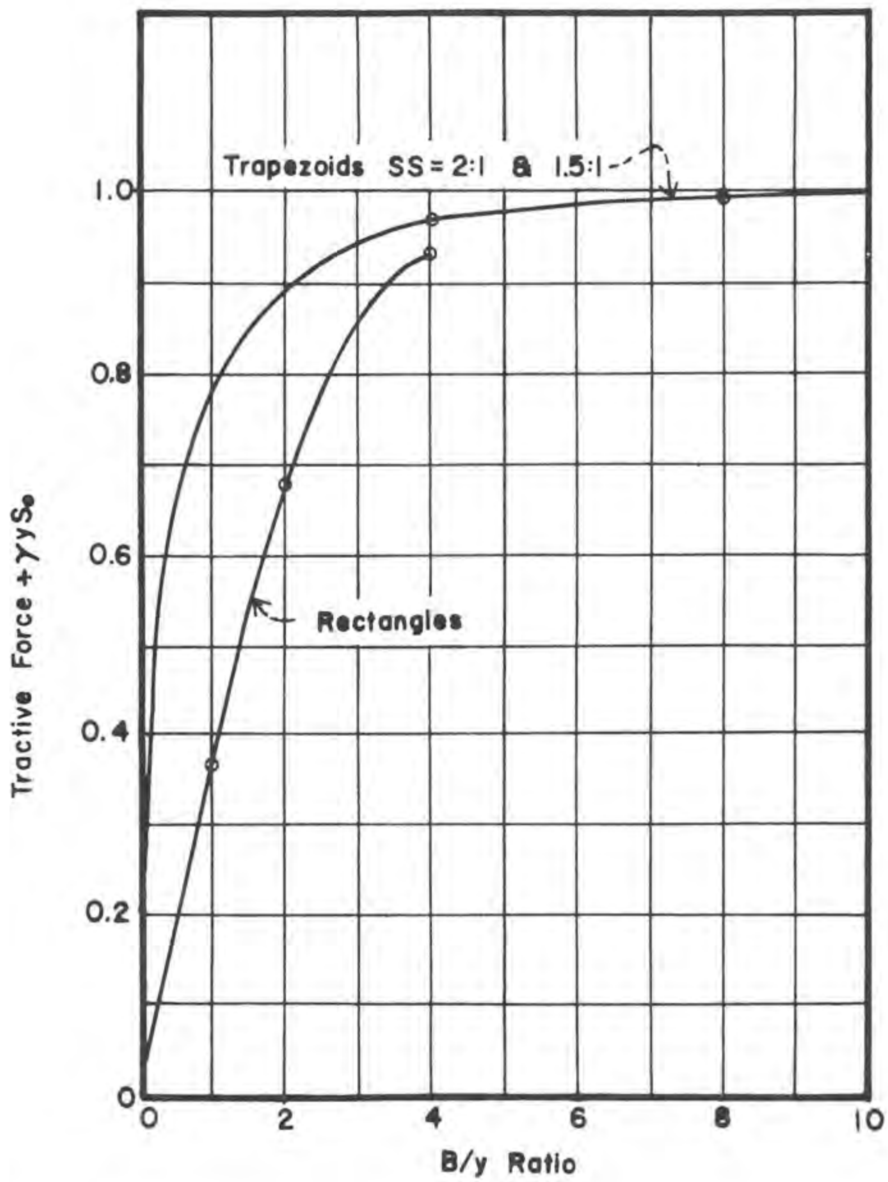

FIG. 20 MAXIMUM TRACTIVE FORCES IN TERMS OF $\gamma y S_o$ ON BOTTOM OF CHANNELS. (Lane [37])

where τ_c is the critical tractive force in pounds per square foot, PI the plasticity index, D% the in-place percent maximum soil density, and $M_\phi \sigma_\phi k'_\phi$ is a description of soil gradation. The limits of equation (18) are:

$$0 < PI < 22$$

$$65 < D\% < 100$$

$$-12 < M_\phi \sigma_\phi k'_\phi < 40$$

$$13 < LL < 42$$

in which LL is the liquid limit.

Dunn [3], Smerdon and Beasley [7] and Schroeder [27] have also found the plasticity index to be a measure of the allowable tractive force. However, to date, only empirical relations are available for determining the allowable tractive force.

PROBLEMS OF AGRICULTURAL LAND AND CHANNELS

The problem of erosion of cohesive materials as related to agricultural land can be divided into two general catagories: The first pertains to land erosion from rainfall and has historically been viewed from the point of view of the damage that erosion does to the productivity and value of agricultural land. Much less concern has been focused on the ultimate disposal of the eroded sediments. The second erosion category is related to design, operation and maintenance of earthen water conveyance structures in agriculture. These include field ditches and channels such as drainage ditches, farm irrigation channels, terrace and diversion channels and irrigation furrows.

Land Erosion

Erosion is generally thought of as a slow process, but figures representing the annual loss of soil are staggering. It is estimated that the annual rate of soil loss for the Mississippi River Basin is about 400 tons per square mile [38]. An annual rate as high as 97,740 tons per square mile was measured from a small watershed in western Iowa. Each year one billion tons of suspended sediment are estimated to be transported to the oceans from the United States. In addition, vast quantities of eroded soil never reach the ocean, but are deposited in the flood plains, in river channels, and in reservoirs.

It is estimated that 380 million cubic yards of sediment are dredged each year from the nation's harbors and waterways to keep them clean [39]. The annual cost for this dredging is about $125 million. Reservoir capacity lost each year as a result of sedimentation is difficult to determine accurately, but conservative estimates place this loss at 1.5 billion cubic yards. This amounts to an annual loss of nearly one million acre-feet of reservoir storage due to sedimentation--much of which is eroded soils from agricultural and forest lands.

In 1966, Smith [40] reported that uncontrolled erosion in the United States produced nearly 4 billion tons of sediment each year. Considering the 1955 estimate of one billion tons reaching the sea, then approximately 3 billion tons of eroded material is deposited at some point between the point where erosion occurs and the sea. Smith also reports that there is evidence that the principle means of water pollution from agricultural chemicals may be from erosion of cohesive soils with the chemicals adsorbed on the clay and organic fraction of the soil.

The importance of erosion of cohesive soils from agricultural land is obvious. Much research has been accomplished but much remains to be done if the erosion and resultant pollution from eroded sediments are to be controlled. Smith summarizes research on erosion of agricultural land and suggests some promising approaches to erosion control.

Erosion Loss Equation. In 1961, the Agricultural Research Service of the USDA published a special report entitled "A Universal Equation for Predicting Rainfall-Erosion Losses" [41]. This report presented an empirical equation to predict soil losses by erosion from agricultural land derived from statistical analysis of erosion measurements in the field and under natural and simulated rainfall conditions. The equation is:

$$A = (RF)\,(K)\,(LS)\,(C)\,(PF) \qquad (19)$$

in which A is the average annual soil loss in tons per acre predicted by the equation, RF the rainfall factor, K the soil erodibility factor, LS the length and steepness of slope factor, C the cropping and management factor, and PF is the supporting conservation practice factor (terracing, strip-cropping, contouring).

The rainfall factor, RF, in equation (19) was found to be dependent on two measurable rainfall characteristics. One was the rainfall energy which could be expressed in terms such as foot-tons per acre-inch. Another index was rainfall intensity. The product of the rainfall energy times its maximum 30 minute intensity was found to represent the rainfall in the erosion equation. This product was called the rainfall erosion index. The rainfall erosion indices have been calculated for 181 locations in the United States and were found to vary as follows: Southeastern States, 142 to 779; Northeastern States, 62 to 220; and North Central States, 64 to 261.

The soil erodibility factor, K, is of primary importance in the erosion of cohesive soils by rainfall. The factor was said to depend on many soil characteristics. Values of this soil erodibility factor, which measures the relative erodibility of soils, are being determined for so-called "benchmark" soils where erosion losses have been measured. Wischmeier and Smith [42] have indicated that values of the soil erodibility factor range from 0.50 for soil high in silt content with a weakly-formed and unstable structure, to 0.10 or less for soils with a high sand content and nearly permanent structural stability. Soil erodibility factors average about 0.33 for silty loams and about 0.25 for sandy loams. The higher soil erodibility factor indicates a more erosive soil.

The length and steepness of the slope factor, LS, increases as slope length increases or steepness of slope increases, but not at uniform rates. Increases in slope length of the fields is much more critical where the slope is great. The factor, LS, can be estimated by the empirical equation:

$$LS = 0.0177\,(0.43 + 0.30S + 0.043S^2)\sqrt{f} \qquad (20)$$

in which f is the slope length in feet and S is the predominent field slope expressed as percent [43].

The cropping management factor, C, depends on such management practices as crop rotations and the kinds of crops grown. Some crops provide more protection against erosion than others. Factors such as seasonal distribution of rainstorms, dates of plowing, seeding and harvesting, residue management practices, seeding methods and tillage procedures all must be known to calculate C.

The conservation practices factor, PF, depends on the conservation practices used in farming. Such practices as contour farming and strip cropping reduce the factor, PF. Values of PF range from 0.90 for contouring on steep slopes to 25 for contour strip cropping on gentle slopes [42]. Terraces, while being a conservation practice, are accounted for by reducing the slope length from that of the entire field to the horizontal distance between terraces.

The equation for estimating soil loss is a valuable tool to determine conservation practices needed to control erosion. Conservation and management practices may be designed which will keep erosion to a tolerable level, perhaps 1 to 5 tons per acre per year. The equation may also be used to estimate sediment yield although the actual sediment yields from the field may be much less than the calculated erosion because of deposition in terrace channels or at the bottom of slopes.

The equation for estimating soil losses is constantly being revised as additional erosion data are available. But the method is quite easily used and the procedure is outlined and curves and tables for the various factors are presented in most Soil Conservation Service Handbooks and in a recent text by Schwab, et. al. [43].

Soil Erodibility. In the 1930's, researchers attempted to relate soil erodibility to measurable physical characteristics of the soil. Middleton [44], in 1930, found the dispersion ratio (a measure of the stability of aggregates of cohesive soils in water) and what he called the erosion ratio to be the most significant soil characteristics influencing soil erodibility. His erosion ratio was the dispersion ratio divided by the ratio of the total weight of silt and clay sized aggregates in the nondispersed sample to the total weight of silt and clay in the dispersed sample. Middleton also suggested that organic matter, the silica-sesquioxide ratio, and the total exchangeable bases influenced the erodibility of soils. Middleton et. al. [45, 46] grouped soils from the ten original USDA erosion stations according to the above criteria.

Lutz [47] in 1934, Yoder [48] in 1936, Peele [49] in 1937, and Peele et. al. [50] in 1945, also investigated aggregate stability and other soil properties including the clay in the soil and found them to be related to soil erosion.

In more recent investigations, Anderson [17, 51] found Middleton's dispersion ratio to be statistically significant in soil erosion. Anderson [51] and Andre and Anderson [52] also defined the surface-aggregation ratio as another useful erosion index. Wallis and Stevan [53] have shown these erosion indexes to be related to the cation exchange capacity of the soil and found calcium and magnesium to be particularly important.

In flumes or other special apparatus to simulate erosion forces where cohesive soils were used, investigators have determined that many soil properties are statistically correlated with erosion resistance of cohesive soils [11, 7, 14, 54, 55, 56]. Yet these tests have all been run with disturbed soils and do not give information which can readily be used in design. This is exemplified by the fact that no design procedures for water conveyance structures consider all the individual soil properties which have been suggested from past research. Most often the designs consider only the soil texture or a single measure of the strength of cohesive forces such as the plasticity index or the dispersion ratio. These measures do, however, assist in making estimates of the relative erodibility of soils.

Scour in Agricultural Channels

Most often the flow in agricultural channels is intermittent and relatively shallow. The channel bed may have a vegetative covering or may be tilled leaving the physical condition of the bed in different states of erodibility at the time of a potential erosion producing event.

Stable channel design is quite critical in these channels, but the definition of channels stable against scour may be slightly different for an intermittently flowing channel than for one flowing continuously. Sometimes low rates of scour during short periods of peak flow may have the effect of cleaning sediments deposited in the channel during low flow periods. Nonetheless, reasonable design criteria are needed and some suggested procedures from the literature are given.

Design of Farm Drain Ditches and Terrace Channels

Most farm drain ditches are designed on the basis of limiting velocity. Typical suggested values are [57]:

Stiff clay soils - 4 feet per second

Sandy loam soils - 2.5 feet per second

Fine sandy soils - 1.5 feet per second

Published data on allowable tractive forces in cohesive soil have not been used to any extent in the design of farm drains. However, the use of tractive force data (or depth-slope product) for the design of drain ditches which are stable against scour has been suggested [58].

The suggested procedure considers that some shallow farm drain ditches are cultivated, and this leaves the soil in a more erodible state. The suggested design curves are shown in Figure 21. The product of depth of flow and slope of the ditch should not exceed the values given. These results can be converted to critical tractive force values by multiplying the (y) (S) values by the specific weight of water.

Channel type terrace design is generally based on limiting velocities with values being about 1. 5 feet per second for erosive soils and 2. 0 feet per second for most soils and 2. 5 feet per second for soils with high organic content [59]. Using tractive force data, McCool and Beasley [60] have presented a method for the design of channel type terraces considering the spatially varied flow in the channel. The left curve in Figure 21, where the channel bottom is cultivated, could likely be used for the design of channel type terraces.

Design of Farm Irrigation Systems

Most surface irrigation systems are designed on the basis of experience with similar soils as far as erosion is concerned. In 1946, data were presented by Gardner, et. al. [61] on critical furrow stream

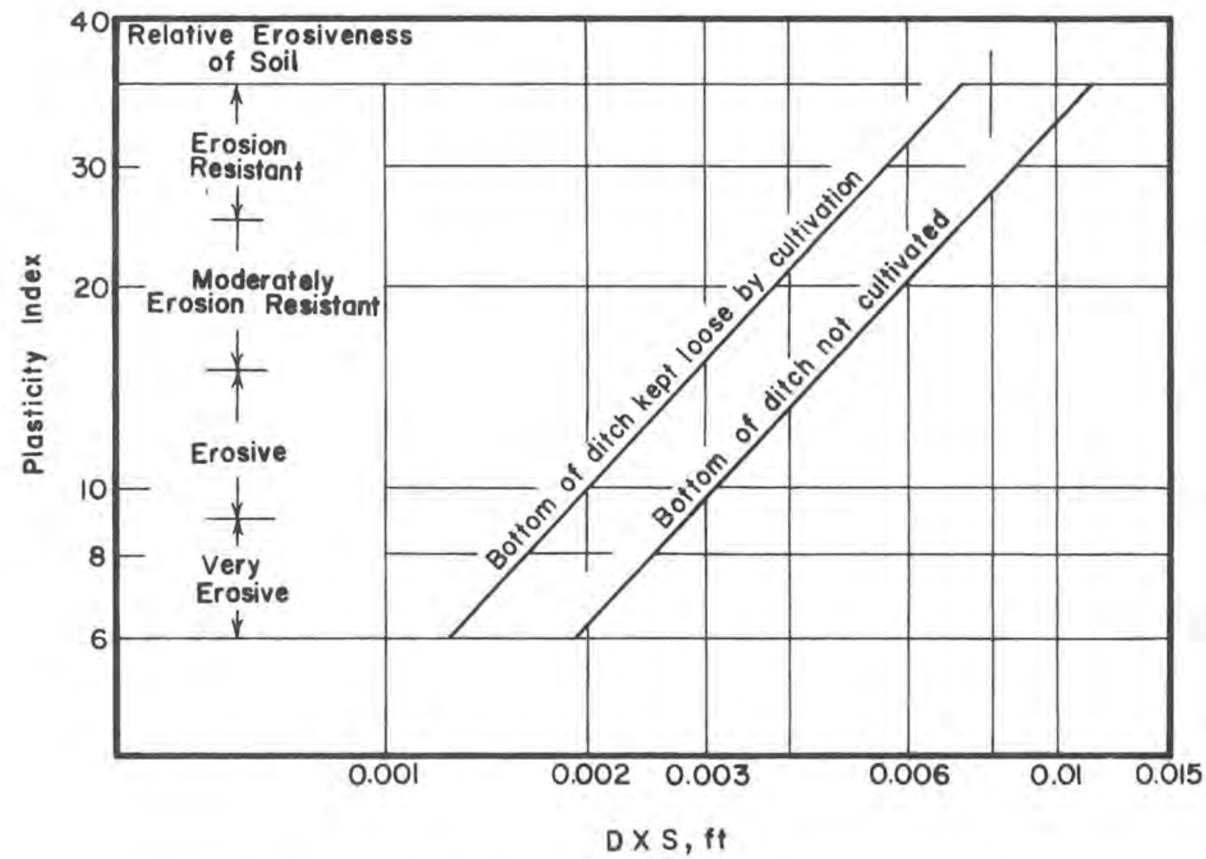

FIG.21 DEPTH X SLOPE OF DITCH VS. PLASTICITY INDEX.

sizes for different furrow slopes. The curves do not take into account the relative erodibility of the soil. A rule-of-thumb suggested to determine the maximum nonerosive furrow stream discharge in gallons per minute is 0.10 divided by the furrow slope in feet/feet [62]. For border strips the maximum allowable nonerosive stream is suggested as $Q = 0.0019\ S^{-0.75}$ where Q is in cubic feet per second per foot of border width and S is border strip slope in feet/feet [63]. Again, variations in soil erodibility are not considered in these guidelines.

Assuming Chezy's equation can be used to determine the rate of flow in a furrow, then $Q = CA\sqrt{RS}$. If the channel is broad and shallow, the hydraulic radius, R, is approximately equal to the depth of flow, y. Therefore, the stream size, Q, is proportional to $y^{3/2}\ S^{1/2}$. The Soil Conservation Service rule-of-thumb for maximum furrow stream size converted from gallons per minute to cubic feet per second is:

$$Q_{max} = \frac{0.10}{449\,S} = 0.00023/S \tag{21}$$

Using the Chezy equation for wide shallow channels

$$Q = K_1\, y^{3/2}\, S^{1/2} \tag{22}$$

in which K_1 is a constant representing the product of the Chezy C and

A/D. Equating equations (21) and (22) to determine the relationship of y and S for the maximum nonerosive stream in irrigation furrows gives:

$$0.00023/S = K_1 \, y^{3/2} \, S^{1/2} \tag{23}$$

or

$$y^{3/2} \, S^{3/2} = \frac{0.00023}{K_1} = K_2 \tag{24}$$

and

$$yS = (K_2)^{2/3} = K_3 \tag{25}$$

in which K_2 and K_3 are also constants. Therefore, the maximum nonerosive stream occurs for some constant value of the product y and S. In other words, there is a maximum value of tractive force for nonerosive irrigation furrow streams since tractive force is proportional to the product of y and S. This would correspond to the critical tractive force.

At this time no finalized values of limiting tractive force can be given for small agricultural channels in cohesive soils. The values of limiting tractive force which can be used for the channels which flow intermittently will be greater than can safely be used in continuously flowing larger channels. The reason for this is possibly because slow rates of scour are not objectionable for the short periods of time when peak flow occurs in these channels.

CONCLUSIONS AND NEEDED RESEARCH

A great deal of research has been conducted into the basic aspects of scour resistance of cohesive sediments. Still the properties which control erosion resistance of cohesive sediments have not been conclusively defined. The Task Committee considers that a major research effort must be undertaken to define those properties whether chemical, physical or environmental that determine the resistance of a cohesive sediment to flowing water. The porperties of these sediments which influence their ability to resist erosion need to be better understood. The mineralogy of the clay fraction and the role of different cations associated with the clays needs investigating. Also, the influence of suspended sediment and its effect on the viscosity of the water producing erosion needs to be better understood.

Much progress has been made on apparatus to simulate the erosion forces on cohesive soils. Problems in translating the results to design criteria are still essentially unsolved and more study is needed. Simple laboratory devices which permit soil conditions to be easily controlled or undisturbed samples to be used need to be further developed.

Cohesive soils have bonds which are related to the soil mineralogy and chemistry. Consequently, water quality can play an important role in changing these bonds by chemical action. This is also important in estuarine erosion where some research has been conducted, but still more work is needed.

The immediate necessity of stable channel design does not allow the designer to wait for the development of a complete method of analysis. For practical purposes, though, design methods should be complete enough to allow economical and useful designs to be made. The methods should be sufficiently logical and simple to be readily understood and used and should not require so much work as to make their use impractical. For very light sediment loads, sufficient design information to meet these requirements is probably available. However, this information should be assembled and presented in a simple and logical manner, with design examples.

Additional research which may be of benefit for design purposes is studies on stable channel shapes and the influence of heavy sediment loads. Also, research into the stability of mixtures, such as cohesive sediments and gravels, may prove valuable.

More basic research, which may eventually provide information to improve design criteria, should be conducted on the effect of the mineralogical characteristics of very fine particles on cohesion. The remarkable variety of properties exhibited by the very fine fractions may be the clue to the many varieties of results obtained from past tests on cohesive soils.

A great deal of research has also been conducted on the erosion of agricultural soils. Efforts to correlate the erodibility of soils to soil properties have been attempted but the results are still not readily useable in routine design of water conveyance structures in farm operations. Often the structures are shallow and relatively flat bottomed and are tilled as a part of agricultural operations. This changes the structure and resistance of the soil to erosion. The soil is often not saturated when the flow event occurs so soil moisture becomes an important variable. Flow is seldom uniform, but has lateral inflow (as in channel type terraces or drainage ditches) or lateral outflow (as in infiltration from irrigation furrows), so flow is spatially varied and more complex to analyze. The flow is shallow and rainfall on the surface of the flow may affect the resultant channel erosion in unexpected ways.

From these and other factors, some critical areas of research needed in agriculturally related problems include study of effects of prior physical disturbances and research on shallow flow hydraulics. The effect of physical activity on a soil prior to a potential erosion producing event needs study. Among these effects are physical compacting forces such as traffic, tillage operations, freezing and thawing, or effect of soil moisture variations and stress. Also, most agricultural erosion occurs as a result of splash erosion or channel erosion with relatively shallow flow. The importance of rain energy has not been sufficiently considered in shallow channel flow and needs study.

Finally, the design of on-farm water conveyance structures is based on empirical relationships and experience. Research is needed to develop useful design procedures for these channels taking into account variability in soil conditions and vegetative cover.

ACKNOWLEDGEMENTS

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