

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS: RATES FOR  
EROSION AND DEPOSITION OF COHESIVE SEDIMENTS  
LITERATURE REVIEW AND EXPERIMENTAL DESIGN

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## ABSTRACT

Nationally sediment pollution exceeds all other types including those from municipalities and industries. Sediment is recognized as a dangerous multiple pollutant since it may carry other contaminants such as herbicides, pesticides, toxic metals, and plant nutrients adsorbed on particle surfaces. Evaluation of water quality improvements which might be derived from alternative control techniques will require methodologies for predicting the transport and distribution of sediments and associated contaminants in alluvial channels on agricultural and silvicultural watersheds.

The mechanisms of hydraulic erosion and deposition of cohesive sediments are extremely complex and depend not only upon the hydraulic regime, but also upon the physicochemical forces between sediment particles. The strength and number of bonds between particles of cohesive sediment are influenced by the sediment mineralogy, mode of deposition, and the chemical quality of the pore and eroding fluids.

A review of the literature has been conducted to describe the progress toward understanding the mechanisms of hydraulic erosion and deposition of cohesive sediments. At the present time there are no methods for predicting rates of erosion or deposition which do not require field or laboratory erosion or deposition studies.

An experimental tilting recirculating flume has been designed to acquire data which can be used in empirical models for rates of erosion and deposition of cohesive sediments. It can also be used to develop more detailed mechanistic models. Factors which must be considered in

the design of a flume which will handle sediment suspensions are discussed, and guidelines for experimental procedures for erosion and deposition studies are outlined.

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## INTRODUCTION

Nationally, sediment pollution exceeds all other types, including those from municipalities and industries. Erosion depletes natural soil resources and leads to degradation of hydraulic channels and structures. Resulting sediment causes millions of dollars damage every year in clogged drainage systems and polluted water in streams, sewers, lakes, and reservoirs. Sediment may also carry other pollutants such as pesticides, herbicides, heavy metals, and plant nutrients adsorbed on the soil particles. These pollutants may become incorporated to a considerable depth in a stream bed through the processes of scour and fill which occur during storm flows. Little information is available concerning the fate and behavior of many pollutants which may be associated with stream bed sediments. However, it will be necessary to develop the methodology to describe the spatial and temporal distributions of sediments in alluvial channels before the movement of contaminants associated with these sediments can be described.

Sediment, both as bed material and suspended load, is generally divided into two categories: (1) cohesionless material consisting primarily of sand and gravel; and (2) cohesive material composed of mixtures of silts and clays which may possess various degrees of cohesion. These two classes of sediments differ substantially in their interactions with flow-induced hydrodynamic forces. For cohesionless



sediments the primary resistance to erosion is provided by the submerged weight of the particles, or gravity forces. Many empirical and semi-theoretical relationships have been developed for reasonable quantitative analysis; none of which are applicable to cohesive sediments. The resistance to erosion of cohesive soils is generally attributed to the net attractive surface forces, or electrochemical forces, between clay particles. In a flocculated suspension, the basic solid units are not individual particles, but aggregates of particles called flocs. The size and settling velocity of the flocs depend on the intensity of turbulence, sediment concentrations, and salinity.

This report presents a review of the literature related to the erosion and deposition of cohesive sediments, most of which has been published during the last thirty years. A great deal of progress has been made toward understanding the mechanisms of erosion and deposition of cohesive sediments. At the present time, however, there are no methods for predicting rates of erosion or deposition for cohesive sediments which do not require field or laboratory erosion or deposition studies.

An experimental titling, recirculating flume has been designed and is described in this report. Factors which must be considered in the design of a flume which will handle sediment suspensions are discussed, and guidelines for experimental procedures for erosion and deposition studies are outlined.

## LITERATURE REVIEW

There are several ways of organizing a review of previous studies of the erosion and deposition of cohesive sediments. For example, studies can be categorized by soil properties investigated, the type of experimental apparatus, the mode of deposition and compaction, etc. The approach used in this report is to discuss selected studies in a more or less chronological order to gain some insight into the historical development of the state-of-the-knowledge of hydraulic erosion of cohesive soils. This development has been fairly dynamic, particularly during the last two decades.

Early studies of the erosion of cohesive soils were directed toward the development of design criteria for stable channels. Empirical correlations of scouring velocity and/or bed shear stress were formulated in terms of the bulk physical properties of cohesive soils, such as porosity, bulk density, plastic limits, vane shear strength, and particle size. Das (1970) reported that prior to 1962 the only data available for bed shear stress in canals in cohesive soils were those of Etcheverry (1915) and Fortier and Scobey (1926) together with the data from a Russian article reported by Lelivasky (1950).

Carlson and Enger (1963) conducted studies to develop better design criteria for both lined and unlined canals in cohesive soils. Samples from canals which had been in operation for a number of years were tested in the laboratory to determine bulk densities, compaction characteristics, vane shear strength and Atterberg limits. Water was circulated with a rotating impeller over samples set flush in the bottom

of a circular tank. Correlations between boundary shear and the soil properties were obtained and recommendations were made for general use in the design of unlined canals in soils similar to those tested.

Enger (1964) studied the erosion of cohesive soil samples in a boundary shear flume and found that the boundary shear necessary to cause erosion was dependent upon the moisture content of the sample.

Dunn (1959) used a submerged vertical jet of water directed perpendicular to remolded soil samples and proposed a method for estimating the tractive resistance for cohesive soils. A semi-theoretical equation was derived for the critical shear stress in terms of vane shear strength, particle size distribution, and plasticity index.

Smerdon and Beasley (1959) remolded cohesive soils in the bottom of a flume and flowed water over the bed until there was a general movement of the bed material. For the soils tested, the critical tractive force was correlated to soil properties such as plasticity index, dispersion ratio, mean particle size, and percentage of clay. Laflen and Beasley (1960) extended this work to develop a linear relationship between critical tractive force and soil voids ratio. However, the tractive force varied with the soil and indicated that the void ratio was not a proper characteristic influencing the resistance of cohesive soils to erosion.

Moore and Masch (1961) also used a vertical submerged jet to erode remolded and undisturbed samples of cohesive soils. A scour rate index was correlated with the jet Reynolds number in an attempt to develop a test for comparing the potential erodibility between soils. They also developed an apparatus in which cylinders of remolded cohesive soils

could be rotated at various speeds in a test chamber. Masch, Epsey, and Moore (1961) discussed the results of experiments using this device and outlined test procedures to evaluate the critical shear stress for cohesive soils.

Rektorik (1964) also used the rotating cylinder apparatus in an attempt to correlate bulk soil properties with critical shear stress. For the five remolded clays used in the study, correlation of critical shear stress with moisture content and void ratio was poor; and there was no correlation of critical shear stress with plasticity index, percentage of clay, or exchangeable calcium-sodium ratio.

Flaxman (1963) presented the concept that the resistance of cohesive soils to erosion can be determined from unconfined compressive strength tests on saturated, undisturbed samples. He plotted "tractive force" (the product of channel slope, hydraulic radius, specific weight of water, and average velocity) as a function of unconfined compressive strength and defined an approximate boundary between eroding and stable channels.

Grissinger and Asmussen (1963) discussed the influence of antecedent moisture content and the length of time compacted soil samples were permitted to age before being subjected to erosive forces. Data indicated that the rate of erosion decreased with increasing age. The increase in resistance to erosion was attributed to the development of adsorbed layers of water molecules on the clay surfaces.

Abdel-Rahman (1962) conducted studies on the erodibility of remolded clay beds in an open channel to determine the relationships between critical shear stress, the velocity distribution, and various

properties of the clay beds. He also measured the depth of erosion as a function of time and suspended sediment concentration and developed an empirical correlation for the average depth of erosion at steady state conditions. The two factors assumed to affect erosion were the tractive shear stress induced by the flowing water and the vane shear strength of the bed material. A significant phenomenon observed in this study was the ability of the bed to stabilize after some erosion had taken place.

Partheniades (1962) also investigated the influence of shear stress, suspended sediment concentration, and vane shear strength on rates of erosion of cohesive beds in an open channel. Two beds of a silty-clay (San Francisco Bay mud) were tested. The first was remolded at field moisture content, and the second was a flocculated bed deposited directly from suspension. The most important conclusion of the investigation was ". . . for the tested range of bed strength the erosion rates were independent of the shear strength of the bed and the concentration of suspended sediment . . . ." This suggested that the overall resistance to erosion of a cohesive bed is independent of the macroscopic shear strength of the bed measured by any conventional means. Also the fact that erosion occurs at shear stresses which are negligible compared to the bulk shear strength indicates that the mechanism of erosion is different than that for deep shear failure of the bed.

Partheniades (1962, 1965) also proposed the following mechanistic model for rates of erosion:

$$E = \frac{A' D_s \gamma_s}{t (\tau_o)} \left[ 1 - \frac{1}{(2\pi)^{1/2}} \int_{-c/k\bar{\tau}_o r_o - 1/r_o}^{c/k\tau_o r_o - 1/r_o} \text{EXP}\left(-\frac{u^2}{2}\right) du \right]$$

where

- $E$  = erosion rate,
- $D_s$  = average diameter of clay particles or clusters,
- $C$  = cohesion due to interparticle forces,
- $k$  = proportionality factor,
- $A'$  = a dimensionless shape factor,
- $t(\tau_0)$  = time required for a stress to act to remove a particle or cluster of particles,
- $\gamma_s$  = specific weight of particles or clusters,
- $\tau_0$  = local instantaneous boundary shear stress,
- $\bar{\tau}_0$  = time, averaged local boundary shear stress,
- $r_0$  = dimensionless variable such that  $\bar{\tau}_0 r_0$  is the standard deviation of  $\tau_0$ , and
- $u$  = dummy integration variable.

This model attempts to separate the hydraulic parameters from the soil properties. The product  $A'D_s\gamma_s/t(\tau_0)$  is a function of the soil properties while  $r_0$  depends on the bed configuration and flow conditions. Christensen (1965) confirmed the validity of the interaction between the bed surface and fluid flow in Partheniades' mechanistic model. However the model has several constants which must be evaluated from experimental data.

Partheniades' (1962) original studies included measurements of the rate of deposition of cohesive sediments, and he found that the shear stress at which all suspended sediment deposits is considerably lower than the minimum shear stress for erosion. These preliminary deposition

studies and the later and more detailed investigations by Partheniades and Kennedy (1966) demonstrated that, for a particular flow, the concentration of suspended sediment decreases to a constant equilibrium concentration. The ratio of the equilibrium concentration to the initial suspended sediment concentration was constant for constant flow conditions and was a strong function of average bed shear stress. These last two observations tend to preclude the occurrence of simultaneous erosion and deposition.

Grissinger (1966) undertook a study to qualitatively evaluate the soil properties that control the erodibility of cohesive soils. Soil properties which were investigated included bulk density, antecedent moisture content, type and percentage of clay minerals, orientation of clay particles, and eroding fluid temperature. Samples were remolded in the bed of a small flume and subjected to a constant hydraulic shear stress. The more important results of this systematic study are:

- 1) Resistance to erosion increased slightly with increasing bulk density, but the relationship was confounded by concurrent changes in clay particle orientation;
- 2) The influence of antecedent moisture depended upon the type and orientation of clay minerals. Resistance to erosion decreased with increasing antecedent water for unoriented samples, but increased with increasing antecedent water for oriented samples;
- 3) Resistance to erosion increased with increasing clay mineral content at the optimum antecedent moisture content for stability;

- 4) Resistance to erosion increased with decreasing particle size and increasing surface activity of clay particles;
- 5) Erosion rates increased with increasing temperature of the eroding fluid; and
- 6) Aging the samples had a significant influence on erosion rates.

Perhaps the most important conclusion of Grissinger's study is that the results demonstrated the extreme complexity of the process of erosion of cohesive materials.

The experimental evidence gained throughout the early and middle 1960's demonstrated the complexity of the interparticle physicochemical forces involved in the erosion and deposition of cohesive sediments. The objectives of the investigations which have been discussed were to identify the important hydraulic parameters and soil properties which control the initiation, degree, and rates of erosion. Efforts were made to establish quantitative relationships between the erosion and deposition characteristics and the flow parameters and soil properties. Most of the work through the late 1960's focused on the role of hydraulic parameters. However, many of the studies also demonstrated and explained why bulk soil properties, such as macroscopic vane shear strength, cannot be used as a unique measure of the interparticle forces which resist boundary erosion.

Erosion studies in the Soviet Union appear to have proceeded along a different line during the late 1950's and early 1960's. Mirtskhulava (1966) reported the results of a somewhat novel approach to the evaluation of the resistance of cohesive soils to erosion. High speed photography was used to study the process of erosion of cohesive soils



depending upon their composition, structural peculiarities, moisture content, and the "degree of cohesion." A spherical punch pressed into the soil--similar to the Brinell hardness test in metallurgy--was reported to provide the best method for measuring cohesion.

Mirtskhulava developed a relationship based on theoretical arguments for the average non-eroding velocity of a flat turbulent flow for cohesive soils. The approach is novel in that it considers erosion of aggregates from the bed rather than individual soil particles. The size of the aggregate was reported to indicate the influence of velocity, friction, and turbulence on the bed. Mirtskhulava's equation for the average non-eroding velocity is

$$V_{ne} = \frac{2gm}{2.6\gamma_0 n} \left[ (\gamma_k - \gamma_0)d + 1.25 (C_f K + \beta \gamma_0 H) \right]^{1/2} \log_{10} \frac{8.8 H}{D}$$

where

$V_{ne}$  = average non-eroding velocity,

$d$  = mean diameter of spherical aggregates,

$D$  = diameter of the coarsest aggregates constituting 5 percent of the total aggregates composing the bottom surface,

$C_f$  = minimum tensile resistance of cohesive soil,

$H$  = depth of flow,

$g$  = acceleration of gravity,

$m$  = a working conditions coefficient which determines the effect of changing conditions on the aggregates,

- n = an overload coefficient which considers the pulsating character of flow as well as other probable cases of actual loads exceeding their calculated values,
- $\beta$  = ratio of dry contacts to the total thrust area of the aggregate,
- K = a homogeneity coefficient determined from cohesion measurements,
- $\gamma_k$  = specific weight of aggregates, and
- $\gamma_0$  = specific weight of water.

Mirskhulava reported that "A comparison of the calculated values of eroding and permissible velocities with data obtained in laboratory and fluid research [references] carried out on canals of various irrigation systems of the USSR has shown their sufficient coincidence. . . ."

Unfortunately, original sources underlying much of the development could not be obtained, and the basis for selecting values of some parameters in the equation cannot be determined. For example, it is not quite clear what Mirskhulava means by "aggregates" in the erosion process or how the size of the aggregates ". . . may be predetermined with the help of a specifically prepared and specially treated bed surface. . . ."

The accumulated field and laboratory experience of the late 1950's and the 1960's demonstrated that the erosion of cohesive sediments was controlled by physicochemical forces at the eroding surface rather than by the bulk properties of the deep soil matrix. As a result, the line of experimental study shifted toward gaining an understanding of the effects of eroding and pore fluid chemistry and the crystalline structure of clay minerals on rates of erosion for cohesive soils.

Liou (1967, 1970) studied the influence of chemical additives on the erosion of kaolinite and montmorillonite clays. Before the erosion tests,  $\text{Na}_2\text{CO}_3$  and  $\text{Ca}(\text{OH})_2$  were added to soil suspensions to permit ion exchange to take place. Attempts to correlate erosion with vane shear strength for different amounts of chemical additives were successful only with  $\text{Na}_2\text{CO}_3$ . Liou concluded that a higher potential swell pressure (which would result in a high total vane shear strength) would also result in a lower resistance to hydraulic erosion. There was no correlation between vane shear strength and the critical shear stress with  $\text{Ca}(\text{OH})_2$  added. Liou suggested that the variation in erodibility between the sodium and calcium montmorillonites is a result of the structure, flocculated or dispersed, which is established by the quantity of salt added.

Arulanandan, et al. (1973) used a modification of the Masch, Espey, and Moore (1961) rotating cylinder apparatus to study the effects of the chemical composition of the pore and eroding fluids and the types of clay minerals on the critical shear stress for erosion of cohesive soils. They found that, for the soil tested, critical shear stress could be correlated with the electrical conductivities of the pore and eroding fluids and the sodium absorption ratio of the soil. The authors concluded that erosion depended upon the osmotic pressure gradient between the pore and eroding fluids.

Raudkivi and Hutchison (1974) conducted a set of experiments with a saturated kaolinite clay-water system to investigate the dependence of erosion rates on the bed shear stress, salinity, temperature, zeta potential, and ion exchange capacity. Their results demonstrated that the time-dependence of erosion rates may greatly influence the

interpretation of experimental results. Erosion rates increased with increasing particle size. However, for less than 1 micron particle sizes erosion rates were very sensitive to salinity, and erosion started as soon as flow started, i.e., no critical shear stress was observed. In distilled, deionized water the fine kaolinite actually diffused through the fluid by molecular action at no flow. Neither ion exchange capacity nor zeta potential were found to be a useful parameter in the erosion studies which were conducted.

Raudkivi and Hutchison (1974) analyzed the temperature dependence of erosion rates by means of a rate process theory which emphasized the important role of viscosity and molecular kinetic energy in the erosion of deflocculated soils. The influence of temperature was reduced with increasing salinity and decreasing particle size. The approach, however, is an example of the application of physical chemistry concepts to the behavior of cohesive soils in a macroscopic sense.

Christensen and Das (1973) investigated erosion in clay-lined brass tubes to gain a better understanding of the role of test duration and shear stress, density and moisture content, and the temperature of the eroding fluid in the erosion of cohesive soils. Their results confirmed those of many previous investigators, i.e., erosion rates are dependent on soil composition, surface roughness, flow rate, duration of flow, and temperature. A major contribution of the study was the use of a rate process theory to analyze the data from a series of erosion tests at various temperatures.

Christensen and Das (1973) found that the rate of erosion increased significantly with increasing temperature and that the response of erosion to temperature changes was typical of a thermally activated

process. Their test results were also similar to those which might be obtained from creep tests on saturated cohesive sediments under a constant shear stress. They postulated that a rate process theory similar to that proposed by Mitchell, et al. (1968, 1969) for steady-state creep could be used to explain the hydraulic erosion of saturated cohesive soils.

Christensen and Das (1973) used the following rate equation for erosion:

$$E = \beta_E \text{EXP} (\alpha \tau_H)$$

with

$$\beta_E \sim T \text{EXP} \left( - \frac{\Delta F}{RT} \right)$$

and

$$\alpha = \frac{\lambda}{2SkT}$$

where

E = erosion rate,

$\Delta F$  = free energy of activation,

k = Boltzman constant,

R = universal gas constant,

S = number of flow units per unit area,

T = absolute temperature,

$\lambda$  = separation distance between successive equilibrium positions, and

$\tau$  = hydraulic shear stress.

The rate equation is of the general form of the Arrhenius equation for temperatures dependent reactions, or

$$E = C_1 \text{EXP}(-A/RT)$$

where A is the activation energy and  $C_1$  is the frequency factor. Values of the rate process parameters can be obtained through careful experimental design.

Gularte (1978) conducted erosion studies on a clay (Grundite) in a temperature-controlled water tunnel to test the applicability of a rate process theory to the erosion of cohesive materials and to gain insight into the basic mechanisms controlling erosion. Temperature was found to be the dominant factor. Experimental activation energies were essentially the same as those obtained by Christensen and Das (1973). In addition, the erosion rates were comparable between the two studies which used the same cohesive material, even though the test methods were different (Kelly, Gularte, and Nacci, 1979).

### Summary

This brief review of some of the laboratory and field studies on the erosion of cohesive soils gives some indication of the complexity of the problem and explains the tendency to draw false conclusions in the past.

Early empirical studies attempted to relate a critical erosion velocity or tractive force to general soil classifications, i.e., particle size distribution and bulk density. As the fields of soil science and hydrology advanced, a considerable number of field and laboratory investigations focused on relationships between the erosion resistance and a variety of mechanical properties of cohesive soils. Table 1 summarizes selected soil properties which have been studied as parameters influencing erosion. Das (1970) listed the following soil characteristics as controlling the erosional and depositional behavior.

- a. Physical characteristics
  - 1. soil types (mineral composition)
  - 2. percent clay
  - 3. plasticity index (activity)
  - 4. specific gravity
  
- b. Physico-chemical characteristics
  - 1. cation exchange capacity
  - 2. (quality of fluid)
  
- c. Mechanical properties
  - 1. shear strength (surface and body)
  - 2. cohesion
  - 3. thixotropy

These soil characteristics reflect the historical association of hydraulics and soil science, and some explanation of these characteristics is warranted.

TABLE 1

## SUMMARY OF SELECTED STUDIES ON THE EROSION OF COHESIVE SOILS

Investigator	Soils Properties Studied	Sample Preparation	Erodibility Measurements
Anderson (1951)	Dispersion ratio	In place topsoils	Correlation of erodibility with shear measurements
Arulanandan, Loganathan and Krone (1975)	Sodium adsorption ratio, salt concentration	Molded in ring	Weight comparisons
Arulanandan, Sargunam, Loganathan, and Krone (1973)	Sodium adsorption ratio, salt concentration, type of clay	Molded in ring	Weight comparisons
Christensen and Das (1973)	Molding moisture content and temperature	Remolded in tube	Weight comparisons
Flaxman (1962)	Unconfined compressive strength	Natural soils	Correlation of unconfined compressive strength and permeability with natural erosion
Grissinger (1966)	Bulk density temperature, antecedent water type of clay, orientation of clay materials	Natural samples remolded in flume	Rate of erosion by weighing
Kelly, Gularte, and Nacci (1979)	Shear stress and temperature	Remolded illite in water tunnel	Concentration of suspended sediment by laser and photocell
Liou (1970)	Influence of electrolyte concentration, pH, and temperature on hydraulic erodibility of pure clays	Remolded in flume	Point-gage measurement of erosion depth
Lutz (1934)	Physical properties of soils that affect permeability and dispersion	Comparison of physical tests with erosive properties of natural soils	Use of qualitative physicochemical analysis
Masch, Espey, Moore (1965)	None	Unspecified but trimmed as a hollow cylinder	Weight loss versus rotating shear, visual correlation with shear
Moore and Masch (1962)	Scour index as a function of Reynolds number	Remolded and trimmed natural soils	Measurement of jet scour depth and weight loss
Parthenaides (1965)	Shear strength and mode of deposition	Remolded in flume and naturally sedimented and compacted in duct	Measurement of suspended sediment concentration with time
Raudkivi and Hutchinson (1974)	Temperature and salinity	Remolded kaolinite in water tunnel	Weight comparisons



A cohesive soil typically contains a sufficient amount of clay minerals, with the associated large surface area, so that the bulk behavior is dominated by particle surface forces rather than by gravitational forces. The more common clay minerals in soils are kaolinite, illite, and montmorillonite. Kaolinite is relatively inert and has little ability to absorb water; thus it does not swell to a great extent. Montmorillonite, on the other hand, can absorb large quantities of water and swells. Illites are of the same form as montmorillonites, but have less ability to absorb water. Swelling increases the distance between clay particles and reduces the interparticle forces resisting erosion. Thus, clay mineralogy has a significant influence on the erosion of cohesive soils. Since swelling also increases the void ratio, or porosity, correlations with erodibility might be expected.

The percentage of clay in a soil can be interpreted as an indication of the degree of surface activity. As the clay percentage increases the strength of the soil becomes more dependent on the physicochemical forces between clay particles.

Das (1970) interpreted the plasticity index as a measure of the percentage of clay and clay mineral content of the sediment. The resistance to erosion increases with increasing plasticity index. Parthenades and Paaswell (1968) pointed out that this characteristic may not be a primary parameter for erosion. However, plasticity index may serve as a means of classifying soils with regard to their erodibility.

The cation exchange capacity is one of the most important physicochemical characteristics of cohesive soils. The parameter reflects surface activity and is a measure of the relative amount of

adsorbed cations on the clay surface which can be exchanged in solution. Cation exchange capacity can be a useful indicator of the effect of cohesion on shear strength. Krone (1963) developed a relationship between cation exchange capacity and the Bingham shear strength of cohesive sediments.

Cohesion is a measure of the interpartical forces and is a function of clay mineralogy and mode of deposition and compaction. Thixotropy is the tendency of compacted or disturbed clay to regain cohesive strength with time. Partheniades and Paaswell (1970) discussed the processes involved in the development of a flocculated clay bed.

There are a large number of soil properties which influence the erosion of cohesive soils. Many conventional soil tests to determine these properties actually reflect the interactions or influence of more basic physicochemical phenomena which cannot be measured directly, or which may not be identified to date. However, there appears to be a trend toward interpreting the erosion of cohesive sediments in terms of the physical chemistry of surfaces.

The experimental results of Christensen and Das (1973) and Gularte (1978) indicated that a rate process theory may be applicable to the hydraulic erosion of cohesive soils. The strength of particle contacts probably involve a number of bonds and will depend on the magnitude of the attractive forces. These forces, in turn, will depend upon the microcrystalline structure and physicochemical parameters such as salinity, pH, and temperature.

The phenomenon of erosion is observed when the fluid flow-induced shear stress at a sediment/water interface becomes great enough to remove a particle from the surface. There are two main difficulties in

modeling and predicting this behavior. The true state of the stress induced by the flowing fluid at the sediment/water interface in the flow field must be determined, and the parameters of the sediment that control its susceptibility to erosion must be established.

Bulk soil properties, such as plasticity index, can serve as a group index indicating whether one class of soils is likely to be more susceptible to erosion than another. All other conditions being equal, a sediment with a high plasticity index will probably be more resistant to erosion than a sediment with a low plasticity index. Seldom are all things equal, and a given sediment with a fixed plasticity index may or may not be erosion resistant depending upon its structure. Therefore plasticity index (or other bulk parameters such as vane shear strength, voids ratios, etc.) are not primary indices of erosion potential, but serve as a means of identification only. Parameters or indices which describe the physicochemical behavior, such as sodium adsorption ratio, salinity, and temperature, should give better information of sediment and fluid structure required to interpret potential behavior.

The generally used soil classification structures have not proven to be useful as parameters in predicting rates of erosion or deposition. Structural indices which reflect particle orientation, separation, previous stress history, and the strength and number of interparticle bonds are required.

Both the internal and external force systems must be evaluated to determine the initiation and rate of erosion. Contrary to the case of coarse sediments, erosion and deposition of cohesive sediments belong to two distinctly different hydraulic regimes. Hydraulic shear stresses for erosion are considerably higher than the shear stresses at which

eroded sediment deposits. This observed phenomenon precludes the simultaneous erosion and deposition of cohesive sediments.

The few investigations reviewed in this report, as well as many others listed in the bibliography, demonstrate the complexity of the cohesive soil erosion and deposition problems. Continued developments on sediment fabric analysis, physicochemical analysis, and mechanistic models for rates of erosion and deposition of cohesive sediments have continued to develop. The state-of-the-art has shown a great deal of progress over the last two decades, but methods for predicting the rates of erosion and deposition of cohesive sediments still require the laboratory evaluation of various constants and parameters for both empirical and mechanistic models.

## EXPERIMENTAL DESIGN

A prerequisite in any experimental design is the identification of the data required. Two general categories of problems requiring experimental data on the rates of erosion and deposition of cohesive soils have been considered in the design of the specialized equipment described in this report.

One area of application is the modeling of cohesive sediment transport in canals and streams which requires expressions for the rates of erosion and deposition of sediment in terms of readily defined hydraulic variables. Relatively simple empirical expressions have been used quite successfully in numerical models including a cohesive sediment transport component (Ariathurai and Krone, 1976; Onishi, 1977a, 1977b). For example, Partheniades (1962) presented the following empirical equation for erosion:

$$\left(\frac{dm}{dt}\right)_e = M \left( \frac{\tau_b}{\tau_{ce}} - 1 \right)$$

where  $(dm/dt)_e$  is the mass rate of erosion per unit area,  $\tau_b$  is the bed shear stress,  $\tau_{ce}$  is the critical shear stress for erosion, and  $M$  is an erodibility constant. The model parameters  $M$  and  $\tau_{ce}$  must be determined experimentally. For deposition, Krone (1962) found that

$$\left(\frac{dc}{dt}\right)_d = \frac{V_s C}{d} \left( 1 - \frac{\tau_b}{\tau_{cd}} \right)$$

where  $(dC/dt)_d$  is the rate of change in suspended sediment concentration,  $V_s$  is the particle settling velocity,  $\bar{d}$  is the average depth through which particles settle, and  $\tau_{cd}$  is the critical shear stress for deposition. Assuming a four-thirds power law for the settling velocity (Krone, 1962), or

$$V_s = KC^{4/3}$$

where  $K$  is an empirical constant, still requires the field or laboratory evaluation of two deposition model parameters,  $\tau_{cd}$  and  $K$ . Thus, even relatively simple empirical models for rates of erosion and deposition require the experimental evaluation of two parameters for each rate expression.

The other category of erosion and deposition data requirements is the development and/or verification of more complex mechanistic models for erosion and deposition of cohesive sediments. Examples include the critical shear stress model proposed by Partheniades (1962, 1965) and the rate-process models of Christensen and Das (1965) and Gularte (1978). These mechanistic models are discussed in the literature review section of this report, and require much more detailed experimental data than the simple empirical models.

The most dependable erosion tests appear to be those carried out in open channels in which the sediment forms either the entire bed or a significant portion of the bed (Partheniades and Paaswell, 1970). Flume studies of the erosion and deposition of cohesive sediments are also the most difficult. The cohesive bed should be deposited in a state as representative of the natural bed as possible. Forming a bed several

feet or yards long from undisturbed materials is no easy task. Preparing a remolded bed of cohesive materials may require handling large quantities of sediments or soils, even for channels which would be considered small from a hydraulic viewpoint. The chemical quality of the eroding and pore fluids should also be representative of prototype conditions.

Problems are also encountered in recirculating systems. The turbulence induced by bends and pumps in the return lines can shear flocs and/or aggregates of the cohesive bed material, resulting in a decreased particle size distribution and settling velocities. These effects are particularly important in deposition studies. The dead volume of the return duct system should also be minimized to control the loss of sediment by deposition in the return lines/system. Minimum velocities in the return line system should also be sufficient to transport the largest particles to prevent sedimentation in recirculation systems.

The abrasive nature of the fine particles of sediment suspensions can lead to mechanical failure of pump seals and the erosion of pump volutes, impellers, and metering orifices. These mechanical problems can be minimized through careful design and selection of materials of construction.

The flume must be designed for hydraulic performance as well as the ability to handle sediments and sediment suspensions. Hydraulic considerations should include the provision to adjust the channel slope to obtain uniform depth of flow and head-box and tail-box construction to minimize entrance and exit effects. The ideal flume would operate

with steady uniform flow over the entire length of the channel for a range of discharges and bed friction coefficients.

#### Tilting Recirculating Flume

Considerable time and funds are involved in the design and fabrication of a laboratory flume, let alone a system which will handle suspended sediment. Therefore, a flexible system which will provide a variety of operating conditions is desirable. An experimental laboratory flume has been designed to acquire data for the erosion and deposition of cohesive sediments. These data could be used to evaluate parameters in empirical models as well as to develop and test mechanistic models. The tilting recirculating flume is shown in Plates 1 and 2.

The size of the flume represents a compromise between several factors which must be considered in conducting erosion and deposition studies. These include (1) the quantity of sediment or soil required to prepare a bed in the channel, (2) the difficulties expected in remolding cohesive materials into a uniform bed, (3) control of the chemical quality of the eroding fluid, (4) the lengths of the channel which might be influenced by entrance and exit effects, and (5) standard lengths of materials of construction.

The rectangular channel is 0.5-foot wide, 1.0-foot deep, and 24-feet long. The sides and bottom of the channel are 0.25-inch thick plate glass. Glass was selected because it is chemically inert with respect to eroding fluids and transparent to light. In addition, glass is more abrasion resistant and less expensive than acrylic plastic. Three eight foot sections are cemented together with silicon adhesive and mounted in an aluminum framework. The glass channel is thermally



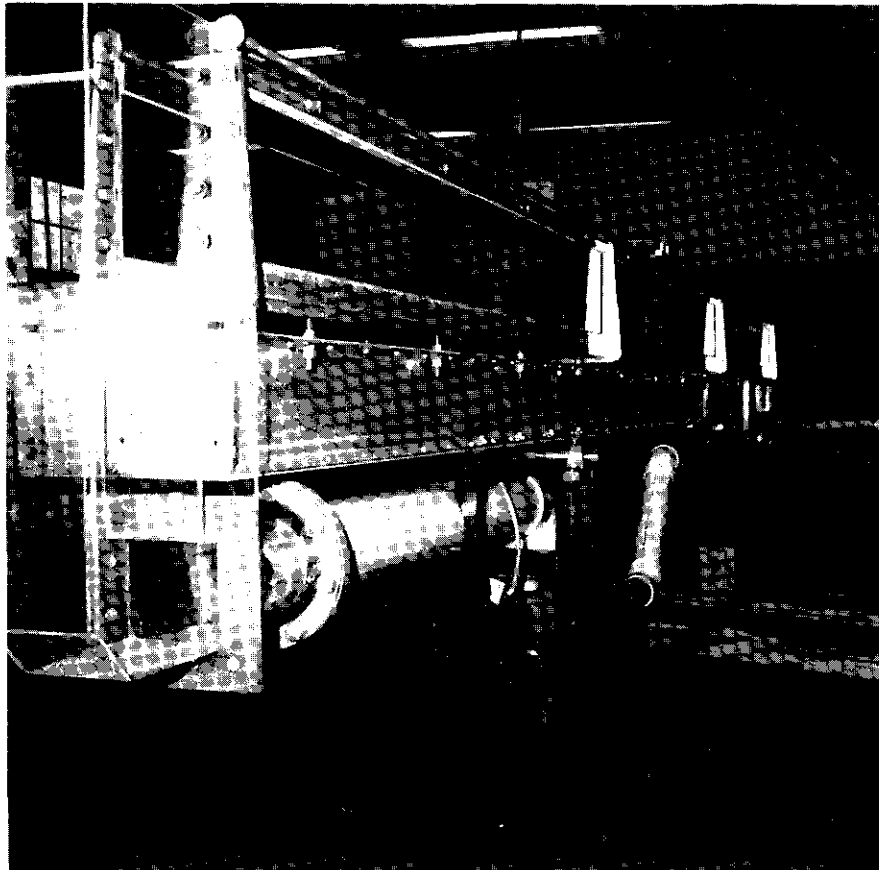


Plate 1 - Tilting Recirculating Flume Showing Tail-Box and Recirculating Pump.

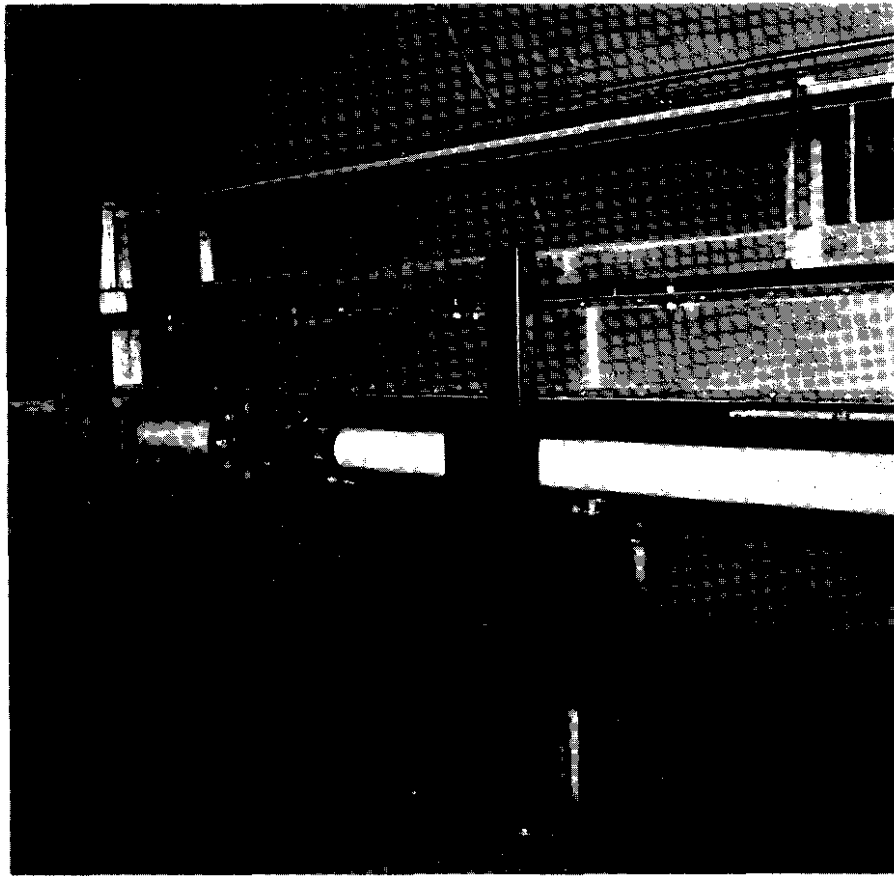


Plate 2 - Tilting Recirculating Flume Showing Jack, Venturi  
Meter, and Head-Box.

insulated from the aluminum to minimize temperature gradients in the bed and to relieve thermal stresses which might result from differential expansion under controlled temperature conditions. The glass channel is free to float on 3/16-inch thick cork sheet.

Twelve manometer taps are mounted along the channel bottom on 2-foot centers. These manometer taps can be used to measure the peizometric head along the length of the channel. The taps may not be effective, depending upon the nature of the bed material. However, the glass channel bottom would be very difficult to drill after installation.

Rails made of aluminum rod were mounted along the top of the channel to carry an instrumentation platform which travels the length of the channel. The elevation of the rails was adjustable so that they could be aligned parallel with the bottom of the channel. The rails formed a reference plane for the measurement of elevations in the channel.

The head-box was fabricated from 304 stainless steel sheet and included a transition from a 4-inch diameter circular section to a 6-inch wide by 8-inch high rectangular entrance to the channel. In addition to providing a transition from circular to rectangular geometry, the head-box is also used to reverse the flow direction and to decelerate the velocity of flow by a factor of approximately 3.8. Stainless steel was used to reduce the potential formation of iron oxides (or hydroxides) which can serve as binding agents in cohesive beds (Partheniades, 1962).

Acrylic plastic was used as the material of construction for the tail-box because it is relatively inert and fairly easy to machine and

fasten. The tail-box includes a transition section from a 6-inch square section to a 6-inch diameter circular section.

The return line from the tail-box to the recirculating pump is 6-inch schedule 40 polyvinylchloride (PVC) flanged pipe. Immediately downstream of the pump the return line is reduced to 4-inch diameter PVC pipe. The reduction in cross-sectional area is intended to increase the velocity and, therefore, minimize sedimentation in the return line.

A 4-inch short-form venturi meter with a throat to entrance ratio of 0.57 is installed in the return line just upstream of the entrance to the head-box. An 8-foot long meter run to the venturi meter was provided to eliminate entrance effects on meter performance. The venturi meter itself was fabricated by laying up fiberglass-reinforced epoxy resin over a two piece machined steel plug mold. This relatively soft material was selected to minimize erosion of the throat by suspended sediment. Flange mounting permits the venturi meter to be pulled for inspection.

The recirculating pump can pose very difficult problems for a flume of this size. Volumetric recirculation rates can be on the order of 1 CFS (450 gal/min), but head requirements may be only a few feet of water. These operating conditions call for a mixed-flow or axial-flow pump. Commercial units in this capacity range and a suitable configuration are not available as stock items. Custom fabrication or modification by a commercial pump manufacturer were prohibitively expensive for this project (estimates ranged from \$4,000 to \$6,000 plus driver). The only alternative was to design and fabricate a recirculating pump in-house.

A 6-inch elbow pump was designed to recirculate sediment suspensions at rates up to 450 gal/min at total head of 6 feet of water. The basic principles outlined by Lazarkiewicz and Troskolanski (1965) were followed for sizing the impeller and pump volute. The pump volute was machined from a short length of 6-inch schedule 80 steel pipe. The housing was fabricated from a 6-inch schedule 40 forged steel elbow and 150 pound forged steel flanges. The impeller shaft, shaft bearing, and end face shaft seal were designed as a carriage unit so that the pump could be serviced without having to remove the entire pump assembly from the return line. A carbon-ceramic end face shaft seal was recommended for this service (Smail, 1980). The pump impeller was obtained from the Worthington Pump Corporation, Taneytown, Maryland, and was cast in bronze as an impeller for a Worthington 6KLD-6 Axial Flow Pump. The pump parts and assembly are shown on Plates 3 and 4.

The pump driver is a 1.5 Hp DC motor with a variable speed controller. The motor is coupled to the pump shaft through a 2:1 V-belt drive to increase the maximum speed to approximately 3400 rpm. By adjusting the speed of the motor, the desired flow rate can be obtained.

The channel, with head-box, tail-box, return lines, and recirculating pump with driver are mounted on a 6-inch wide by 8-inch deep aluminum box-type beam. The channel is attached by adjustable studs and can be leveled with the beam deflected by a nominal load.

The beam was fabricated using two 24-foot long sections of 8-inch by 0.25-inch 6061-T6 aluminum channel with a 10 gauge 6061-T6 aluminum skin riveted top and bottom. With a uniform load of 75 lb/ft and two supports, the maximum deflection of the beam was estimated to be less than 0.020 inches. This load corresponds to the weight of the beam,

Plate 3. - Parts Assembly for Recirculating Pump

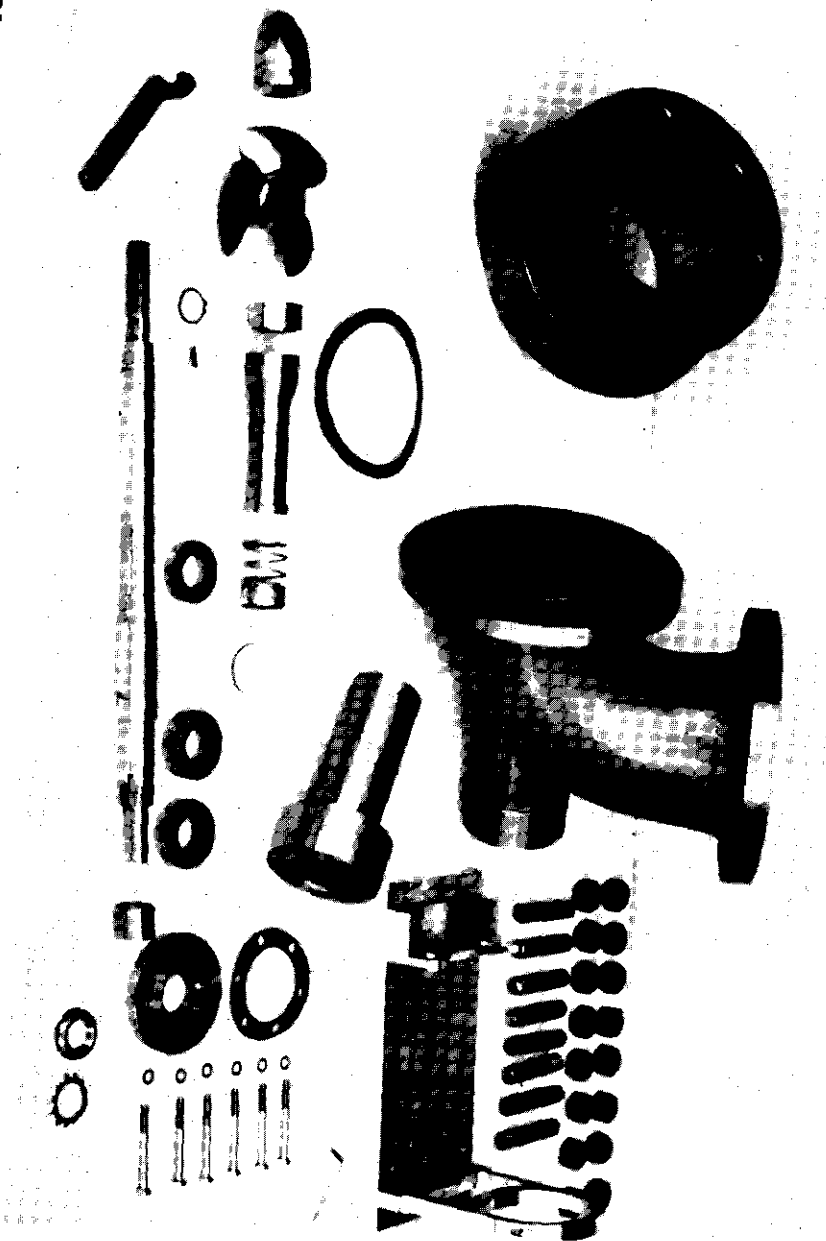
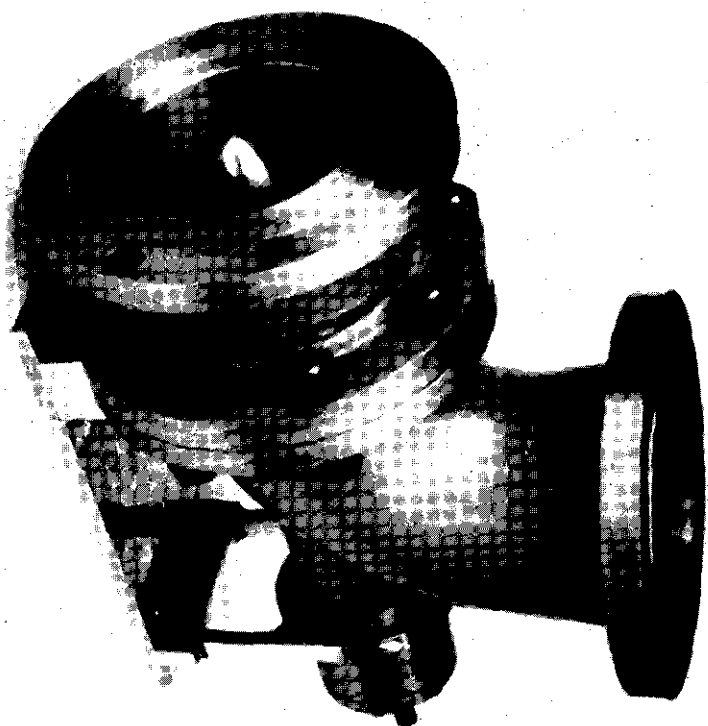


Plate 4. - Assembled Recirculating Pump



return lines, and the channel filled with 6 inches of water and 2 inches of sediment.

The beam supports were located to minimize deflection as outlined by Hopkins (1970). The support nearest the tail-box was pivoted and carried the weight of the recirculating pump and motor. The other support was mounted between vertical guides on a worm gear jack driven by a reversible gear motor. This arrangement permits the slope of the channel to be adjusted from a horizontal position to a maximum slope of approximately 0.07 ft/ft while the flume is in operation. The idealized slope-discharge relationships for two values of Manning "n" are shown in Figures 1 and 2.

For constant temperature operation, cooling/heating coils must be added in the return line downstream of the recirculating pump. For operation at 30°F below ambient condition, the estimated rate of heat loss for an uninsulated system is approximately 10,000 BTU/hr and probably represents worse case conditions.

This discussion of the tilting recirculating flume is intended to provide a narrative description of the system and to point out mechanical and construction difficulties which must be considered in the design and fabrication of a laboratory flume. Shop drawings and sketches for this system can be obtained by contacting Jan Wagner, School of Chemical Engineering, Oklahoma State University, Stillwater, OK, 74078.

### Experimental Procedures

The exact experimental procedures which are followed in an erosion or deposition study are dependent upon the type of information to be



acquired. The following discussion is intended to identify general areas which might be considered common to many studies.

Bed preparation. The preparation of a cohesive bed in the flume using undisturbed samples is very difficult under the best of circumstances. Special equipment would be required to collect and transport somewhere between 10 and 12 square feet of natural, undisturbed cohesive sediment at field moisture conditions. Placing the material in the flume in an undisturbed state would also require ingenuity. If an undisturbed bed is required, the test section of the channel should probably be restricted to a relative short section of the channel.

Cohesive sediments and soils can be remolded in the flume, realizing, of course, that observed erosion rates would be somewhat higher than those expected in the field. Bulk soil properties generally cannot be used to quantify rates of erosion, but mechanical testing of the bed material can provide valuable information. Particle size analysis can be used to classify the soil and may indicate potential problems in suspended sediment concentration measurements, such as the plugging of filters. As discussed in the literature review, the plasticity index can be used to characterize the activity of the soil. One of the most valuable tests for dry soils is a compaction test which yields the optimum moisture content for compaction. These results can be extremely valuable in remolding a uniform bed of cohesive soils and should help in reproducing experiments. The results of these types of tests for three silty-clay subsoils are included in the Appendix.

Rates for Erosion and Deposition. Erosion rates in a closed recirculating system can be measured by monitoring the suspended sediment

concentration of the recirculating fluid. Suspended sediment concentrations can be measured using a filtration method or by using optical techniques such as a calibrated laser and photocell system (Gularte, 1978).

Actual procedures for conducting erosion and deposition studies to acquire data for empirical critical shear stress models have been outlined in detail by Partheniades (1962). Rate process models require erosion tests at constant temperature with various shear stresses and at constant shear stress with various temperatures. Gularte (1978) outlined the experimental procedures and the analysis of the results.

Estimation of Bed Shear Stress. Bed shear stress cannot be measured directly in the experimental laboratory flume described in this report. To calculate the bed shear stress from channel geometry and hydraulic parameters, the effects of side-wall friction must be considered. Johnson (1942) suggested a method for accounting for the wall effects in channels of this type. The method is based on the assumption that the cross-sectional flow area can be divided into two subareas: an area,  $A_b$ , affected by bottom friction, and an area,  $A_w$ , affected by wall friction. The average velocity,  $V_a$ , and friction slope,  $S$ , are assumed to be the same in both subareas. The total area,  $A$ , is defined as

$$A = A_b + A_w$$

and the wetted parameter,  $P$ , is calculated as

$$P = 2d + b$$

where  $d$  is the depth of flow and  $b$  is the width of the channel. In terms of the hydraulic radius,  $R$ ,

$$A = bR_b + 2dR_w.$$

The two side walls are glass and the friction factor for turbulent flow in pipes can be used to estimate the side-wall friction, or

$$(\tau_w/\rho)^{1/2} = V_a (f/8)^{1/2}$$

where  $\tau_w$  is the wall shear stress expressed as

$$\tau_w = \rho g R_w S$$

and  $\rho$  and  $g$  are the fluid density and the acceleration of gravity, respectively. For flow along the side walls,

$$(gR_w S)^{1/2} = V_a (f/8)^{1/2}$$

and  $R_w$  can be estimated using a trial-and-error procedure.

A value of  $R_w$  is assumed and the Reynolds number defined as

$$R_e = 4R_w V_a / \nu$$

is calculated, where  $\nu$  is the kinematic viscosity of the fluid. This Reynolds number is then substituted into the Prandtl-von Karman equation to estimate the friction factor, or

$$(1/f)^{1/2} = 2 \log (R_e f^{1/2}) + 0.4$$

If this friction factor does not satisfy the relationship for side-wall friction with the assumed value of  $R_w$ , a new value of  $R_w$  is assumed; and the procedure is repeated.

Once the value of  $R_w$  has been determined, the hydraulic radius,  $R_b$ , is calculated from the expression for the total cross-sectional area. The average bottom shear stress is then calculated as

$$\tau_b = \rho g R_b S.$$

The bed shear stress can also be evaluated from a detailed description of the velocity distribution within the channel. However, the above procedure should give estimates of average bed shear stress which are adequate for most applications.

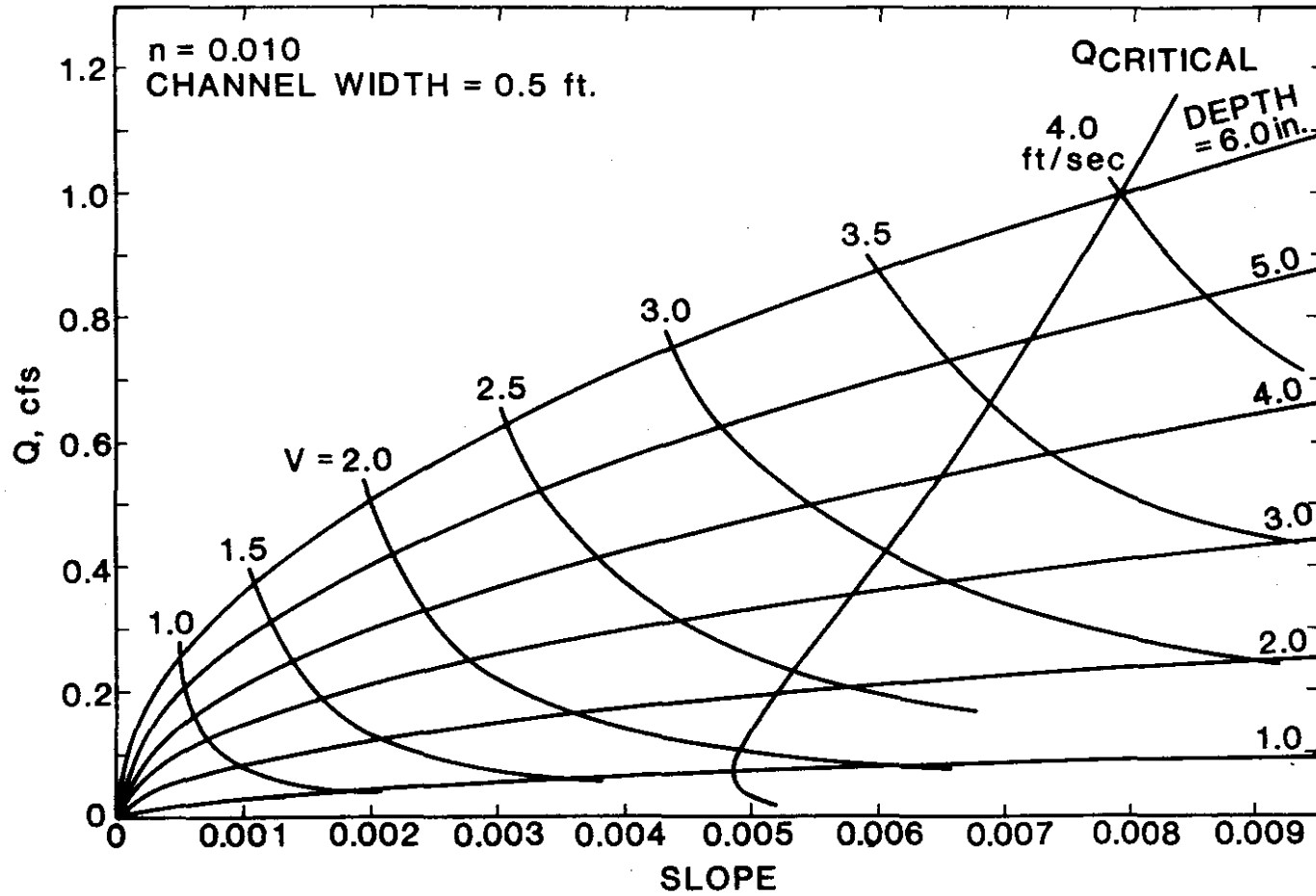


Figure 1. - Idealized Channel Performance for Manning  $n = 0.010$ .

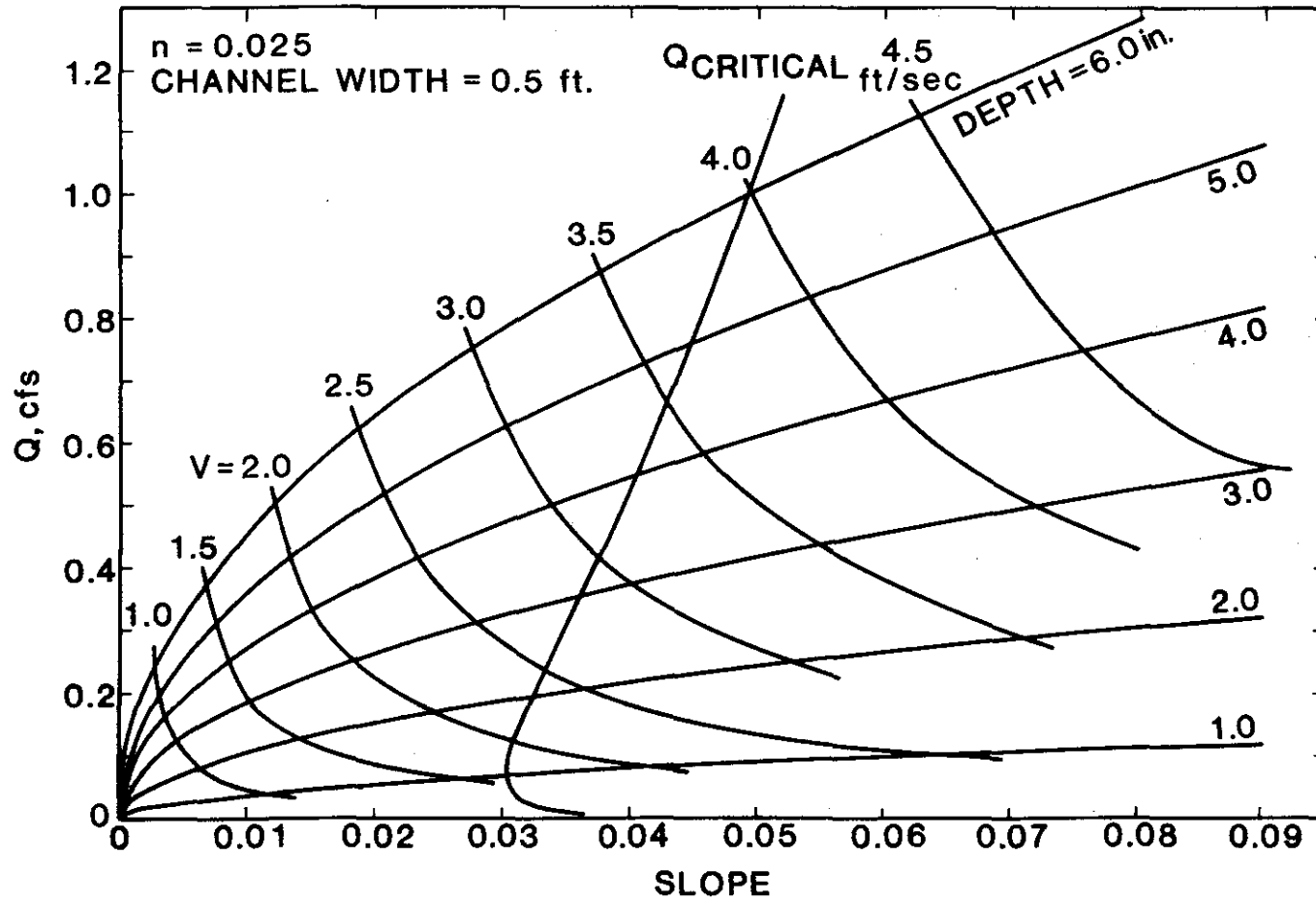


Figure 2. - Idealized Channel Performance for Manning  $n = 0.025$ .

## SUMMARY

The hydraulic erosion and deposition of cohesive sediments is an extremely complex process. The numerous field and laboratory investigations over the last three decades have provided a great deal of insight into the fluid and soil characteristics which influence the processes as well as the mechanisms of erosion and deposition.

Early investigations focused on correlating rates of erosion with bulk soil properties such as the plasticity index, vane shear strength, and particle size distribution. Experimental results published during the 1960's demonstrated that the erosion of cohesive sediments must be considered as a surface phenomenon and that the generally used soil classification indices which reflect bulk properties are generally not useful as erosion prediction parameters. More attention began to be focused on the mechanisms of erosion and deposition of cohesive sediments. In particular, the physicochemical nature of interparticle bonds between sediment particles were considered.

During the late 1960's and early 1970's investigators began to study effects of the chemical quality of pore and eroding fluids. Sediment texture and behavior began to be interpreted in terms of clay mineralogy and the molecular structure of the system. Rate process theories which considered particle bond activation energies were introduced.

Recent studies have continued with the development and application of critical shear stress and rate process types of mechanistic models. Data have also been obtained to evaluate parameters in relatively simple

empirical models for the rates of erosion and deposition of cohesive sediments which can be used in conjunction with numerical sediment transport models.

At the present time there are no methods to predict the rates of erosion and deposition of cohesive sediments which do not require the field or laboratory evaluation of model parameters or constants. Laboratory flume studies are considered to be the most dependable tests for erosion. However, flume studies are also fairly difficult to conduct, and laboratory results must be carefully extrapolated to field conditions.

An experimental tilting recirculating flume which can be used to acquire data for empirical models of a specific sediment or to develop and/or test mechanistic models has been described in this report. Some of the important factors which must be considered in the design and construction of a flume for sediment studies have been discussed. Experimental procedures for conducting flume studies for rates of erosion and deposition of cohesive sediments will depend upon the type of data required. However, general guidelines have been presented.

It is hoped this report will provide an appreciation of the complexity of the processes involved for other investigators contemplating experimental studies on the erosion and deposition of cohesive sediments. Previous approaches to the problem have been reviewed and evaluated. The bibliography in this report should include most of the literature published over the last thirty years which is related to the hydraulic erosion and deposition of cohesive sediments.



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Engineering Properties and Three Oklahoma Soils

APPENDIX

SOIL MECHANICS LABORATORY

School of Civil Engineering  
Oklahoma State University

SPECIFIC GRAVITY DETERMINATION

Tested by GEISER Sample No. \_\_\_\_\_  
 Date 4/9/80 - 4/21/80 Test No. \_\_\_\_\_  
 Tested for DR. WAGNER Sheet No. \_\_\_\_\_ Of \_\_\_\_\_  
 Location of Sample \_\_\_\_\_  
 Position of Sample \_\_\_\_\_  
 Description of Sample NORGE SS CL NP

Trial No.					
Flask No.					
Method of Air Removal					
$W_{bws}$					
Temperature, T°C.					
$W_{bw}$					
Evap. Dish No.					
Wt. Sample Dry + Tare					
Tare (wt. of Dish)					
$W_s$					
$G_s$	2.63				

$W_{bws}$  = Weight of Flask + Water + Sample at T°C.

$W_{bw}$  = Weight of Flask + Water at T°C.

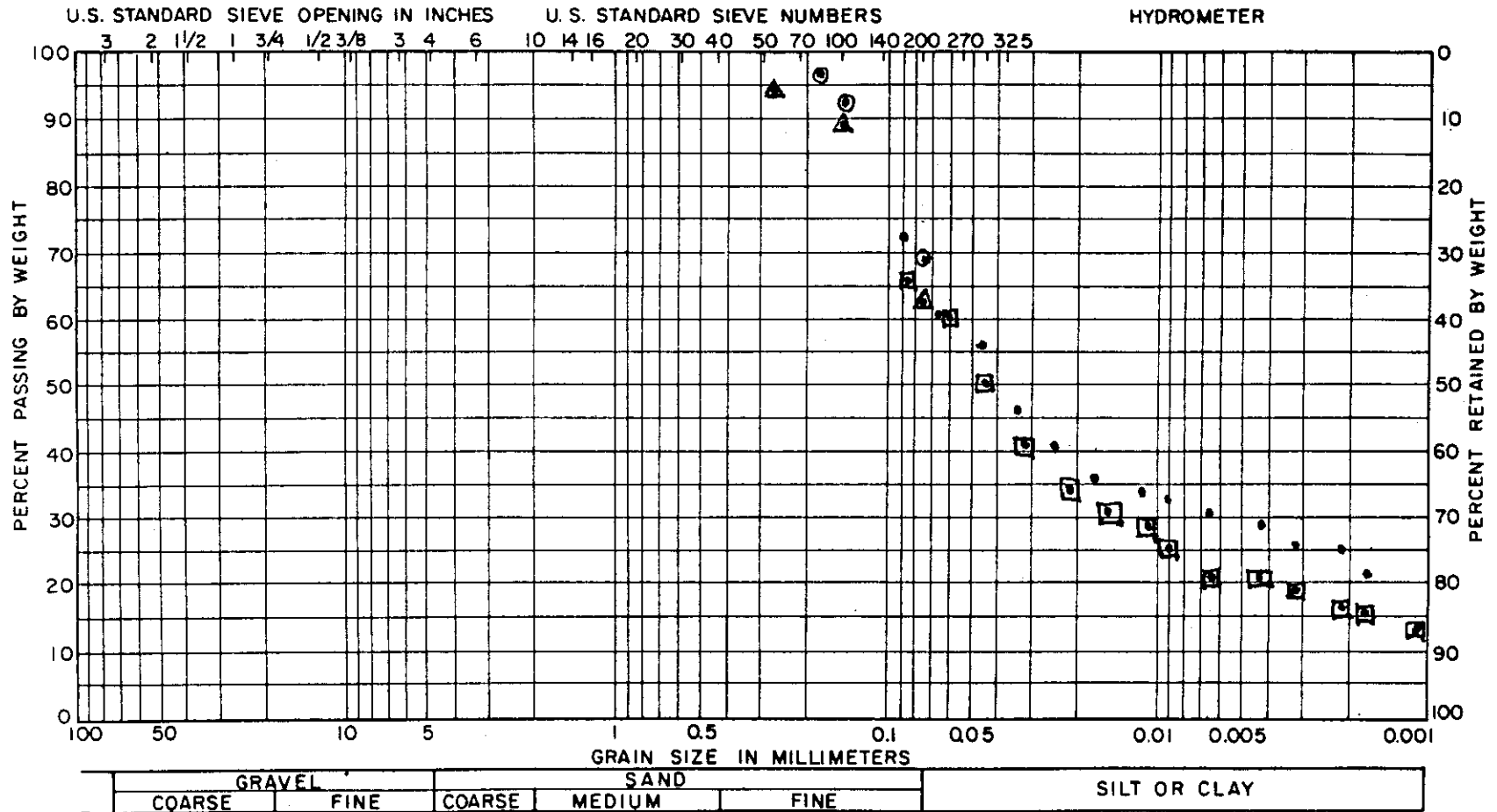
$W_s$  = Weight of Dry Soil

$G_s$  = Specific Gravity of Solids =  $\frac{W_s}{W_s + W_{bw} - W_{bws}}$

Remarks: \_\_\_\_\_

NORGE SS CL NP

MECHANICAL ANALYSIS CHART



SOIL MECHANICS LABORATORY  
 School of Civil Engineering  
 Oklahoma State University  
 Stillwater, Oklahoma

PLOT OF COMPACTED DRY DENSITY VS. MOISTURE CONTENT

Tested by GEKER Sheet \_\_\_\_\_ of \_\_\_\_\_

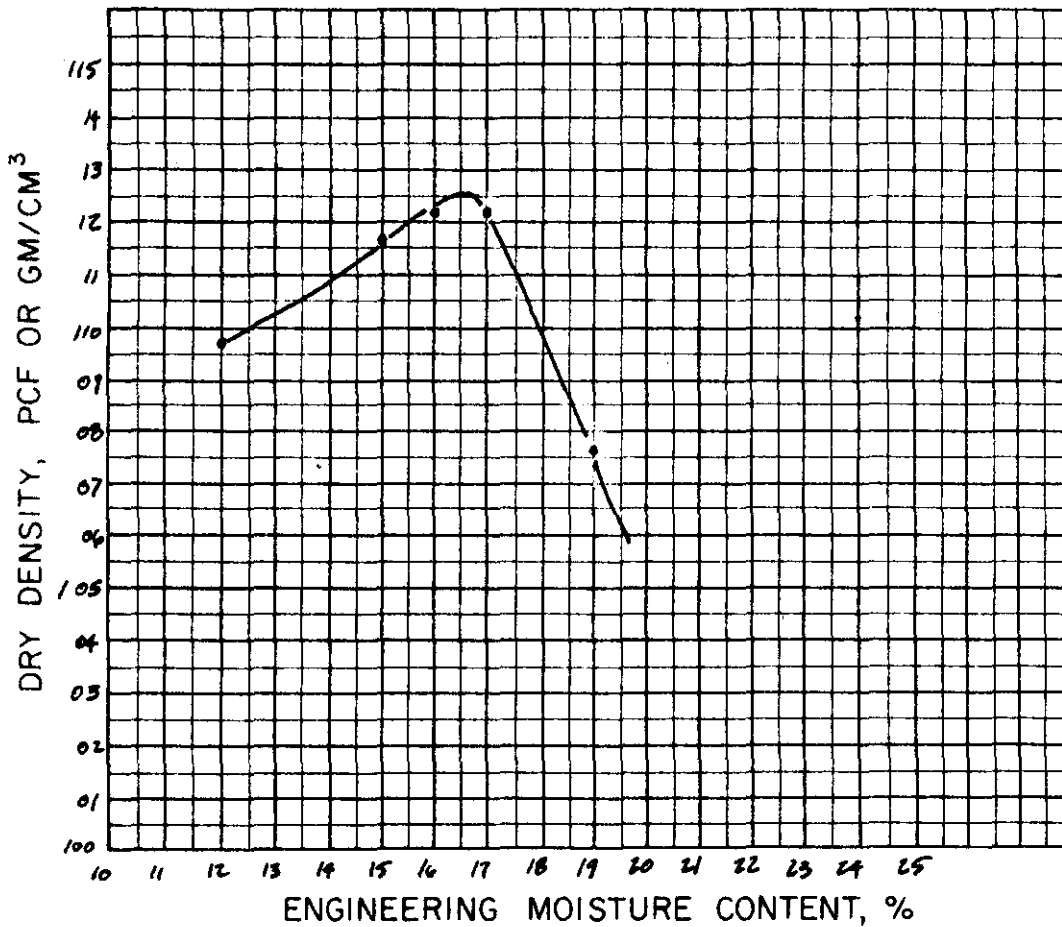
Date \_\_\_\_\_ Sample No. \_\_\_\_\_ Test No. \_\_\_\_\_

Description of Sample NORRIS SS CL NP

Method of Compaction:  Impact  Kneading  Static  Vibration

Mold Size:  4 in. ID  6 in. ID  1 5/16 in. ID  1.4 in. ID  Other

Compactive Effort \_\_\_\_\_



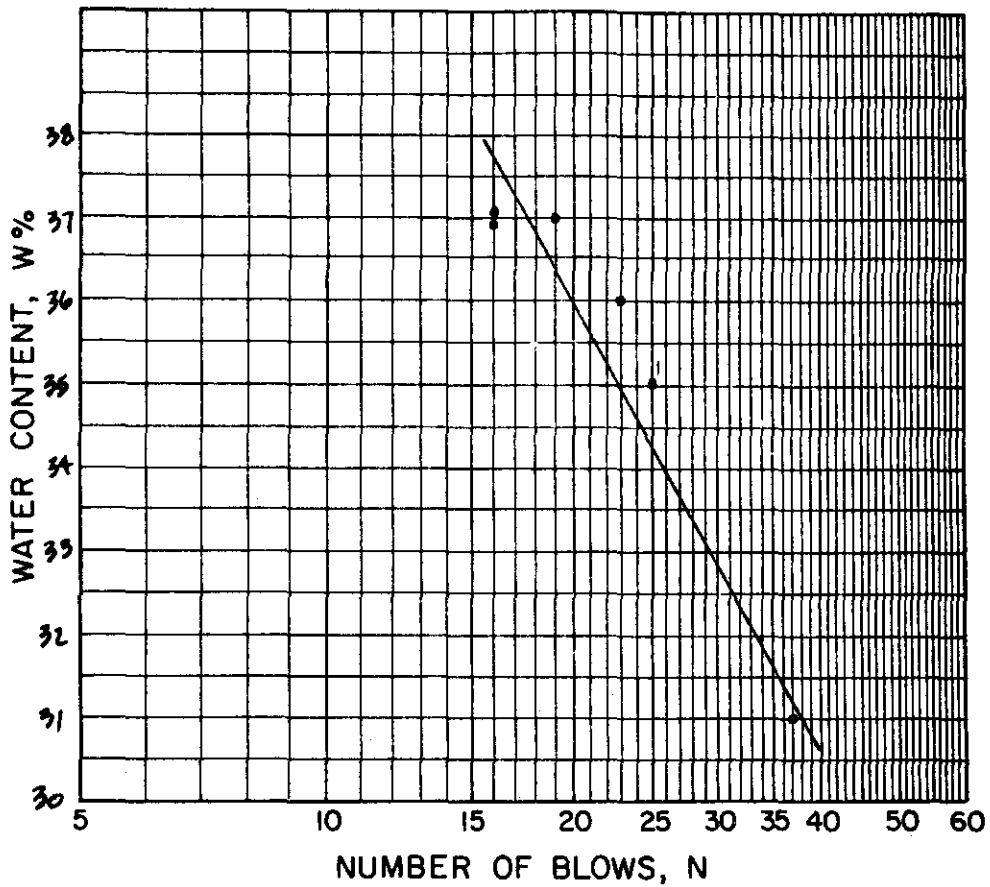
Remarks: \_\_\_\_\_

SOIL MECHANICS LABORATORY  
SCHOOL OF CIVIL ENGINEERING  
OKLAHOMA STATE UNIVERSITY

Name: CEYER Date: \_\_\_\_\_ Sheet \_\_\_\_\_ of \_\_\_\_\_

Description of Sample: NORGE SS CL NP

**WATER CONTENT AND LIMIT TESTS**  
**Flow Curve and Summary**



Summary

Nat. Water Content, $w_n$	Liquid Limit, $w_L$	Plastic Limit, $w_p$	Plastic Index, $I_p$	Flow Index, $I_F$	Toughness Index, $I_T$	Liquidity Index, $I_L$
16	34	19	15			

Remarks: \_\_\_\_\_



SOIL MECHANICS LABORATORY

School of Civil Engineering  
Oklahoma State University

SPECIFIC GRAVITY DETERMINATION

Tested by GEISER Sample No. \_\_\_\_\_

Date 4/21/00 - 4/1/00 Test No. \_\_\_\_\_

Tested for DR. WAGNER Sheet No. \_\_\_\_\_ Of \_\_\_\_\_

Location of Sample \_\_\_\_\_

Position of Sample \_\_\_\_\_

Description of Sample PORF SS SILT

Trial No.					
Flask No.					
Method of Air Removal					
$W_{bws}$					
Temperature, T°C.					
$W_{bw}$					
Evap. Dish No.					
Wt. Sample Dry + Tare					
Tare (wt. of Dish)					
$W_s$					
$G_s$	<u>2.64</u>				

$W_{bws}$  = Weight of Flask + Water + Sample at T°C.

$W_{bw}$  = Weight of Flask + Water at T°C.

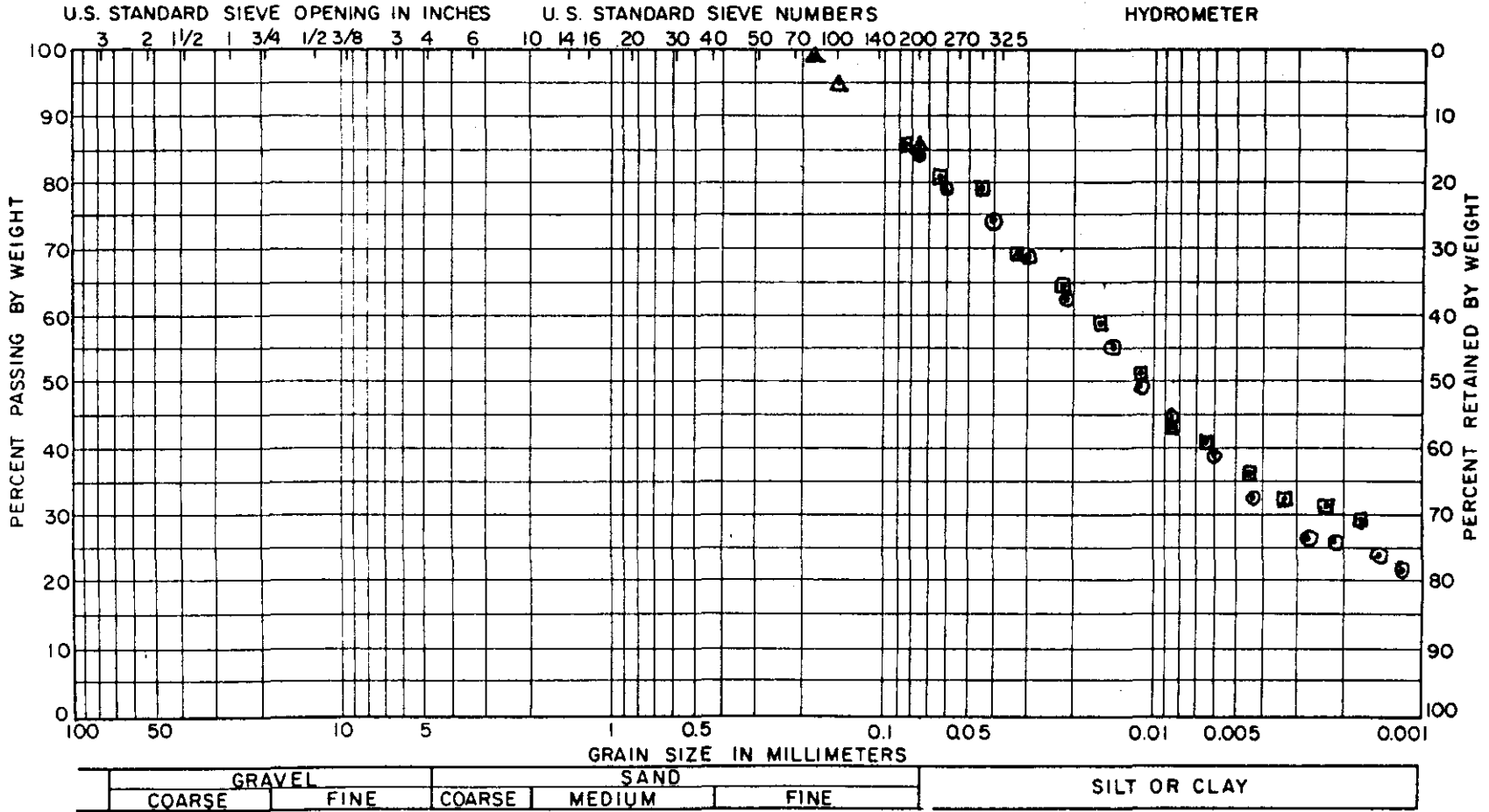
$W_s$  = Weight of Dry Soil

$G_s$  = Specific Gravity of Solids =  $\frac{W_s}{W_s + W_{bw} - W_{bws}}$

Remarks: \_\_\_\_\_

PORT 69 SIL

### MECHANICAL ANALYSIS CHART



SOIL MECHANICS LABORATORY  
 School of Civil Engineering  
 Oklahoma State University  
 Stillwater, Oklahoma

PLOT OF COMPACTED DRY DENSITY VS. MOISTURE CONTENT

Tested by GEISER Sheet \_\_\_\_\_ of \_\_\_\_\_

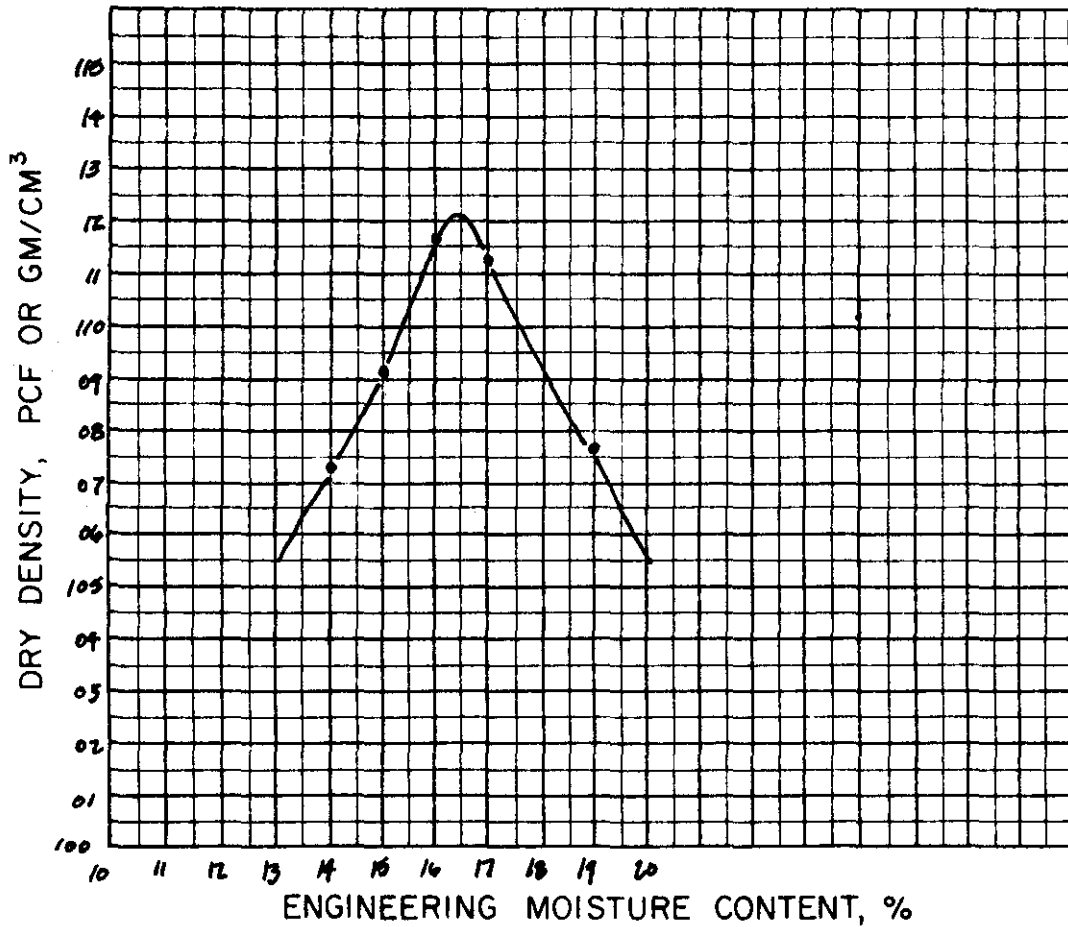
Date \_\_\_\_\_ Sample No. \_\_\_\_\_ Test No. \_\_\_\_\_

Description of Sample PORT SS SIL #2

Method of Compaction:  Impact  Kneading  Static  Vibration

Mold Size:  4 in. ID  6 in. ID  1 5/16 in. ID  1.4 in. ID  Other

Compactive Effort \_\_\_\_\_



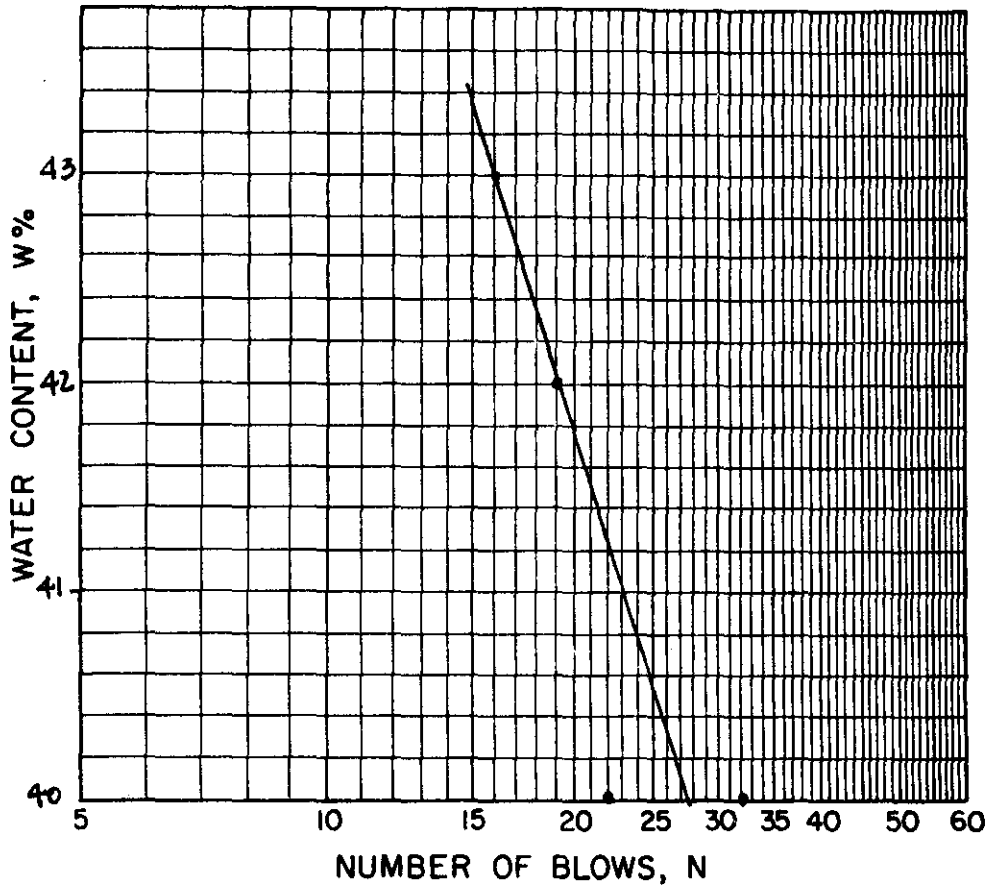
Remarks: \_\_\_\_\_

SOIL MECHANICS LABORATORY  
SCHOOL OF CIVIL ENGINEERING  
OKLAHOMA STATE UNIVERSITY

Name: FEISER Date: \_\_\_\_\_ Sheet \_\_\_\_\_ of \_\_\_\_\_

Description of Sample: PORT SS SIL

**WATER CONTENT AND LIMIT TESTS**  
Flow Curve and Summary



Summary

Nat. Water Content, $w_n$	Liquid Limit, $w_L$	Plastic Limit, $w_p$	Plastic Index, $I_p$	Flow Index, $I_F$	Toughness Index, $I_T$	Liquidity Index, $I_L$
17	40	19	21			

Remarks: \_\_\_\_\_

SOIL MECHANICS LABORATORY

School of Civil Engineering  
Oklahoma State University

SPECIFIC GRAVITY DETERMINATION

Tested by GEISER Sample No. \_\_\_\_\_

Date 4/9/80 - 4/10/80 - 4/14/80 Test No. \_\_\_\_\_

Tested for \_\_\_\_\_ Sheet No. \_\_\_\_\_ Of \_\_\_\_\_

Location of Sample \_\_\_\_\_

Position of Sample \_\_\_\_\_

Description of Sample MILLER SS SIL

Trial No.					
Flask No.					
Method of Air Removal					
$W_{bws}$					
Temperature, T°C.					
$W_{bw}$					
Evap. Dish No.					
Wt. Sample Dry + Tare					
Tare (wt. of Dish)					
$W_s$					
$G_s$	2.67				

$W_{bws}$  = Weight of Flask + Water + Sample at T°C.

$W_{bw}$  = Weight of Flask + Water at T°C.

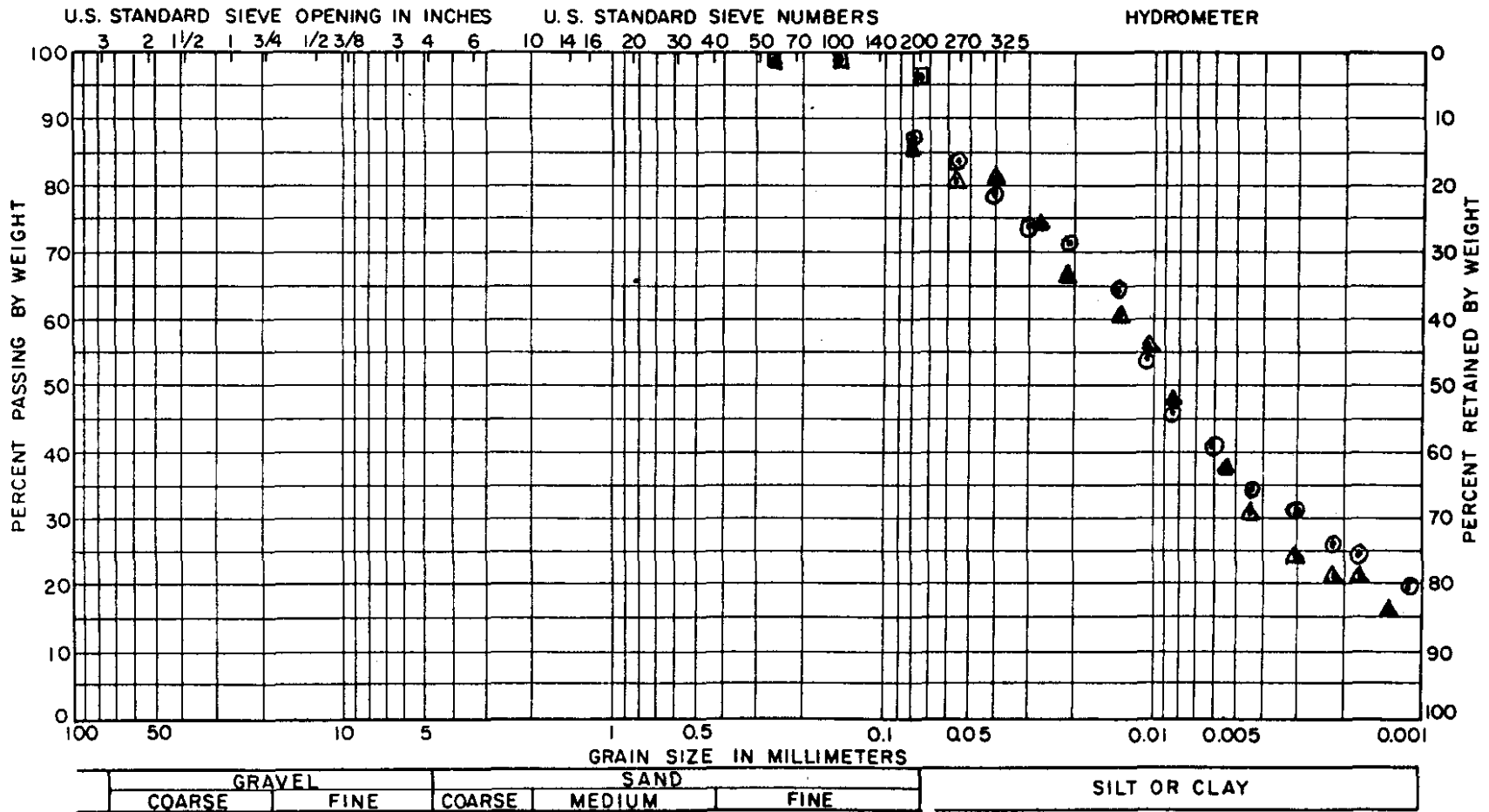
$W_s$  = Weight of Dry Soil

$G_s$  = Specific Gravity of Solids =  $\frac{W_s}{W_s + W_{bw} - W_{bws}}$

Remarks: \_\_\_\_\_

MILLER SS SILT

MECHANICAL ANALYSIS CHART



SOIL MECHANICS LABORATORY  
School of Civil Engineering  
Oklahoma State University  
Stillwater, Oklahoma

PLOT OF COMPACTED DRY DENSITY VS. MOISTURE CONTENT

Tested by HEWNER Sheet \_\_\_\_\_ of \_\_\_\_\_

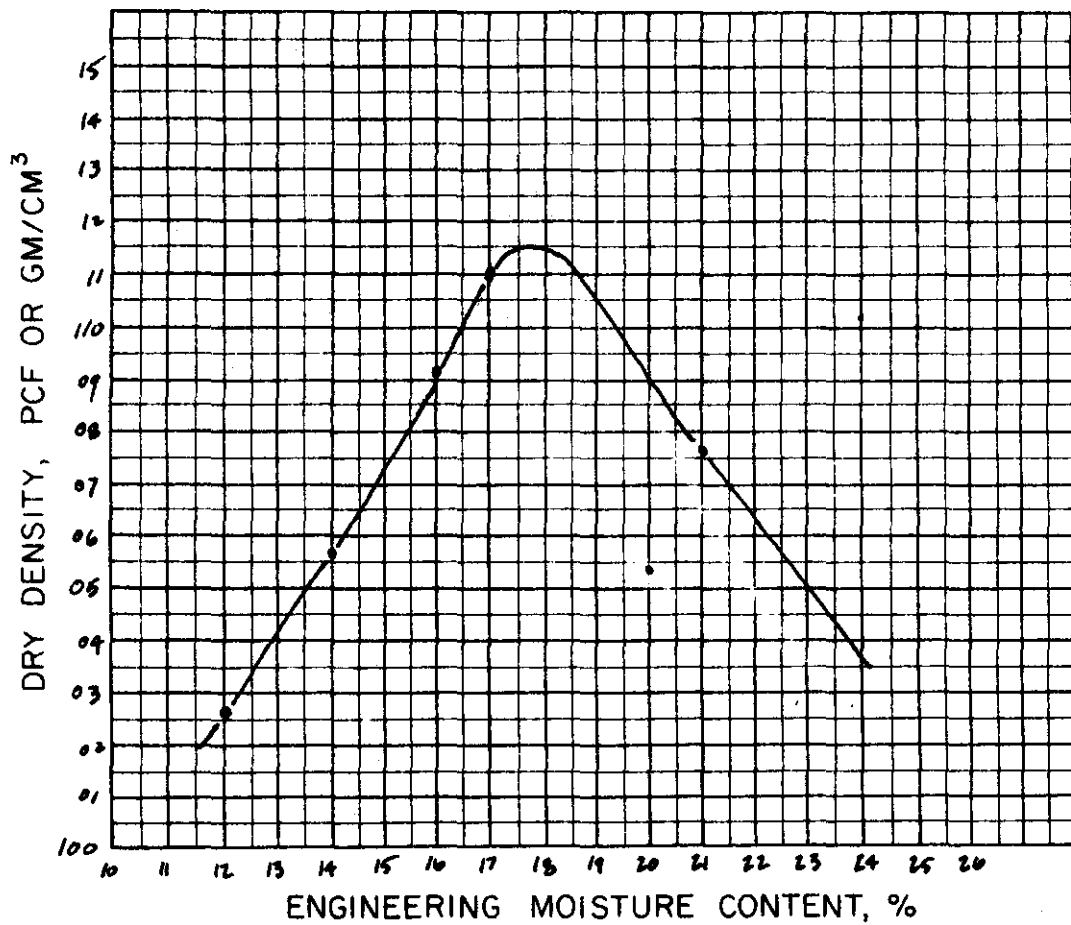
Date 4/23/80 Sample No. \_\_\_\_\_ Test No. \_\_\_\_\_

Description of Sample MILLER SS SIL

Method of Compaction:  Impact  Kneading  Static  Vibration

Mold Size:  4 in. ID  6 in. ID  1 5/16 in. ID  1.4 in. ID  Other

Compactive Effort \_\_\_\_\_



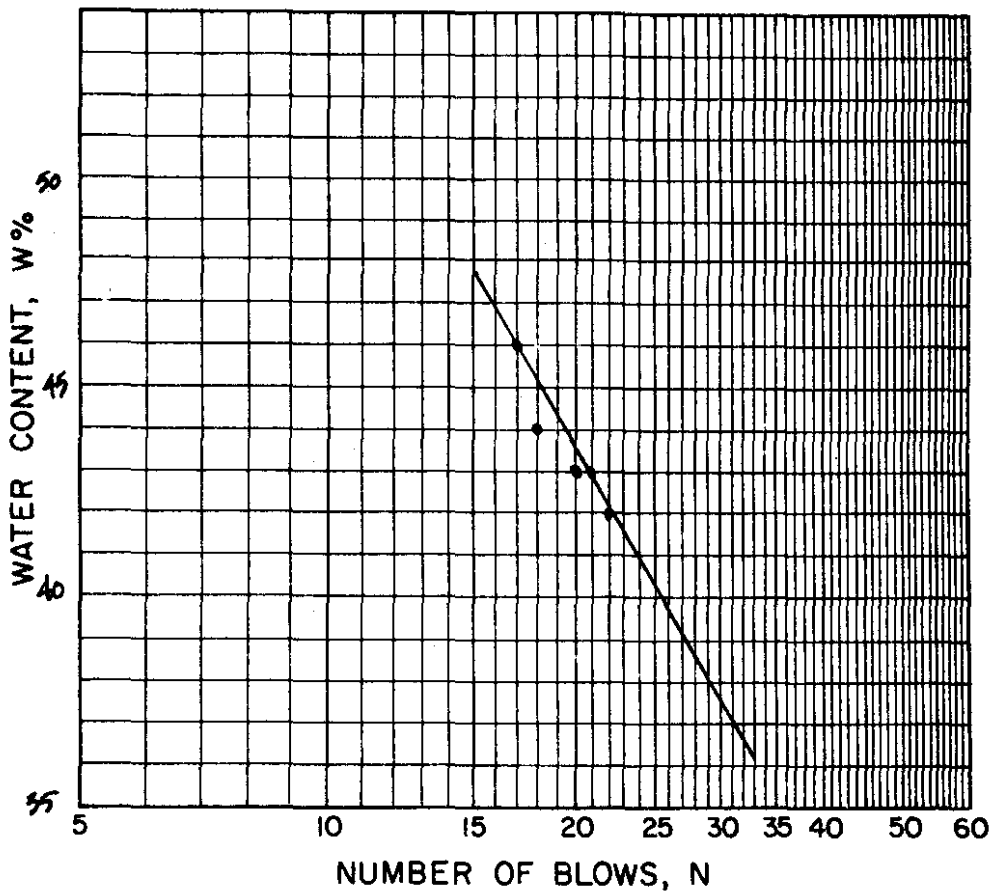
Remarks: \_\_\_\_\_

SOIL MECHANICS LABORATORY  
 SCHOOL OF CIVIL ENGINEERING  
 OKLAHOMA STATE UNIVERSITY

Name: GEKER Date: 4/19/80 - 4/20/80 Sheet \_\_\_\_\_ of \_\_\_\_\_

Description of Sample: MILLER SS SIL

WATER CONTENT AND LIMIT TESTS  
 Flow Curve and Summary



Summary

Nat. Water Content, $w_n$	Liquid Limit, $w_L$	Plastic Limit, $w_p$	Plastic Index, $I_p$	Flow Index, $I_F$	Toughness Index, $I_T$	Liquidity Index, $I_L$
19	40	17	23			

Remarks: \_\_\_\_\_