

CAUSES AND MECHANISMS OF COHESIVE SOIL EROSION: THE STATE OF THE ART

The processes of erosion of cohesive soil are examined through a study of basic soil index properties, soil structure and fabric, and physicochemical interaction of soil and water. Reported studies are evaluated to determine the factors that initiate and sustain erosion. A wide variety of test procedures are studied, including jets, rotating cylinders, tube flow, flumes, and field data. It is found that generally used soil classification indexes have not proved useful as erosion predictors. Structural indexes and indexes describing the quality of the pore fluid and eroding fluid must be established for each case. Internal and external force systems are defined to establish the rate and initiation of erosion. The paper concludes with a brief study of some current methods used to stabilize erodible soils in the field.

In recent years as we invest more in our constructed environment, we turn our attention more to the quality of the land that we use and that is available. All too often we find that problems caused by water erosion coexist with other construction and land use problems. Of special concern are problems related to erosion of cohesive soils. Understanding the erosion process and defining ways to limit erosion are growing disciplines. Lyle and Smerdon (26) have stated, "The properties of a soil which govern or dictate its resistance to water erosion are numerous and difficult to understand." This paper is concerned with the influence of cohesive soil properties on the erosion process.

The phenomenon of erosion occurs when fluid flow-induced shear stresses on a surface reach values great enough to cause particle removal from that surface (Fig. 1). The difficulties in modeling and predicting this behavior can be classified as follows:

1. Defining the true state of stress induced by the fluid at the soil-water interface in the flow field, and
2. Establishing the parameters of the soil that control its behavior as a bed material potentially susceptible to erosion.

To develop valid theories of behavior or even to interpret currently available data on erosion requires that the characteristics of soil behavior be examined. This requires defining those parameters and properties involved with this problem. This paper is concerned with the following:

1. Basic soil properties currently noted in available literature are briefly defined and analyzed as to their relevance to the erosion phenomenon.
2. The distinction between natural and compacted states of soil is made in light of soil structure and fabric and influence of depositional mode. In addition, the importance of the electrolytic properties of fluid is discussed.
3. The nature of physicochemical interaction of soil and water influencing the water-particle force system is reviewed.
4. Analysis of possible erosion mechanisms is based on a critical review of the current state of knowledge of cohesive soil erosion.

The first three items lay the fundamentals for the last item. The purpose of the paper is to analyze the nature of control cohesive soil has on the erosion process by using reviews of previous studies.

BASIC SOIL PARAMETERS

Soil parameters of interest can be separated into those that define the physical characteristics of the soil and those that define aspects of mechanical behavior. These parameters, many of which have been postulated by researchers to have an effect on erosion, are given in Table 1 and discussed later in light of their relevance to the erosion phenomenon.

Vanoni (48) has stated that "shear strength and plasticity index and clay content have an important bearing on the phenomenon, but do not describe it completely. The chemical and environmental factors must also be considered." Because there are apparent disparities among previous workers in the field in measuring both the forces causing erosion and the rates of erosion under measurable flow, it became crucial to delineate all those properties of the soil that have some bearing on the observations in order to make comparisons in theory and also to design experiments that will give interpretable and reproducible results.

PHYSICAL CHARACTERISTICS

Naturally deposited soils are usually a mixture of soil types, i.e., clays, sands and silts, and clay minerals; artificially compacted soils can be controlled for variety and distribution of clay type. The first soil parameter examined in this study is the percentage of clay by weight in the soil investigated and the classification of this percentage according to mineralogical composition. Clay particles are of colloidal size, have large ratios of surface area to thickness, and are generally (for the most common clays) plate-like in shape (47). The mineralogical origin will specify the relative degree of activity of the clay, that is, whether the clay is a two- or three-layer clay and whether the clay lattice is expandable as noted below, this being an index of its ability to attract, hold, and replace surface ions.

The most common clays are two- or three-layer clays. These are bonded units of silica tetrahedra, T, and alumina octahedral, O, sheets. The most inert clay is two-layer OT, bonded together by hydrogen bonds, with strong attraction between O and T and with little isomorphous substitution within the lattice structures. These soils, kaolinites, are relatively inactive and show little or no ability to absorb water within the lattice, which can cause swelling.

Three-layer clays, TOT, that show such surface activity due to large-scale isomorphous substitution and that show great abilities to absorb water within the lattice are montmorillonites. Illites are of the same form as montmorillonites but, because of the large potassium ion present between the T and O sheets, strong bonding occurs and the swelling potential is greatly reduced. In these soils, swelling can occur as water enters the weakly bonded interlayers of the montmorillonite, whereas the strongly bonded interlayers of illite reduce the swell potential. The importance of swelling may briefly be envisioned if we consider an unsaturated embankment that exists at a given density (void ratio), which predetermines the structural (particle-to-particle) arrangement of the soil. If suddenly saturated, such an embankment, if composed of an active clay, would swell, thereby increasing the void ratio. This reduces the interparticle forces and makes the embankment more susceptible to erosion.

The isomorphous substitution of lower valence ions for higher valence ions within the lattice of the clays leaves charge deficiencies at the surface of the clay particle, resulting in a net negative charge at the surface. The magnitude of the charge depends on the degree and type (valence) of ionic substitution. Particles of colloidal size with highly charged surfaces respond to laws of electrical attraction and repulsion to an equal or greater degree than they do to ordinary Coulombic attraction (gravity) between layer bodies. The greater the percentage (by weight) of clay in a given soil is, the greater will be the overall effect of the surface behavior.

A widely used index for establishing the quality of the clay soil is the plasticity index (PI). PI is defined as the difference between the liquid limit (LL) and the plastic limit (PL) of a clay soil. Whereas the LL test is essentially a constant shear strength test, the PL test is not, showing higher limiting shear strengths as the plastic properties of the soil increase. Because the PI of sands and silts is zero, an increase in PI from zero indicates that the range of moisture contents over which a soil shows plastic behavior increases as the ability of the soil to absorb stress through deformation at specific values of shear stress (i.e., nonzero values, such as water) without brittle failure increases. This increase is due to (a) an increase in the percentage of clay mineral (by weight) of the total soil fraction and (b) the variance in the type of clay mineral. Both factors indicate that the strength of the soil becomes less dependent on the structure of the interparticle contacts and more dependent on the intercolloidal force structure as a function of such factors as surface charge density, arrangement of particles, and quality of the electrolyte.

Defining activity as follows (40, 41) gives more understanding to the significance of the concept of plasticity index:

$$\text{Activity} = \frac{(\text{change in}) \text{ plasticity index}}{(\text{change in}) \text{ percentage by weight of clay fraction}} \quad (1)$$

Activity as noted actually combines the two factors that influence the resultant limits of plastic behavior of the soil as noted above. By comparing activity with the swelling characteristics of clay soils, Seed (40) found this to be a "reasonably reliable index of... swelling coefficient." Proper use of the defined activity will allow this parameter to be a basic one in predicting regions of behavior for a given clay soil, for (40) "activity will accurately classify the soils with regard to their liquid limit versus clay content relationships, or with regard to their swelling potentials regardless of the clay mineral composition of the clay fraction."

It is important to establish certain aspects of soil behavior that the activity index does not cover. The PI is based on two tests at limiting moisture contents, neither of which has been generally used in erosion studies. In most erosion studies, the soil has been compacted or exists naturally at some moisture content other than the LL or PL. Furthermore, because the tests are based on soil remolded to existing conditions (19), they can in no way predict density or strength of the soil used. Activity serves to aid in classifying soil types, and thus its inherent value is its use as a comparative index or a grouping index to rate soil for its potential erosion resistance.

The structural indexes previously defined are indicators of the net interparticle force system that exists in the colloidal-size clay particles.

The true distribution of forces between individual clay particles has not yet been mathematically defined. Because of the highly complex geometry (even in the most disperse systems) and variations in structure (from flocs to pacs), plus the general level of the stability of the system, accurate mathematical formulation of the interparticle forces has been made nearly impossible.

This interparticle force system shall in the future be referred to as the internal system. This system is viewed on the atomic level and is defined as the resultant stresses established by the electrochemical behavior of the particle surface. The factors that control the strength of this potential field are valence and size of adsorbed ions, percentage and type of dissolved salts in the electrolyte, temperature, original particle orientation, and stress level (potential geometry).

The nature of the internal stress system can be illustrated if we consider the pressure between two parallel plates subject to a repulsive potential ψ (x) established by the existence of similar charge densities on each plate (47). The total excess pressure, p_e , between the plates is given by

$$p_e = p_d - p_w = 2nkT \left(\cos h \frac{V_e \psi_n}{kT} - 1 \right) \quad (2)$$

where

- p_d = pressure at a distance d midway between the plates,
- p_H = hydrostatic pressure of fluid not influenced by particles,
- v = valence,
- n = concentration of electrolyte,
- k = Boltzmann constant,
- ϵ = electrostatic unit of charge, and
- T = absolute temperature.

The attractive potential (A) is considered basically a Vanderwaal-London force and is dependent on the volume of the attracting mass, its geometry, and the distance of separation for clay plates and, compared to repulsive forces, can be assumed constant for a given environmental condition. The net force acting between particles is then more strongly dependent on the relative magnitude of the repulsive force (R) and can be illustrated for combinations of (R-A) as follows:

- (R-A) < 0, net attraction-tendency toward flocculation
- (R-A) > 0, net repulsion-tendency to dispersion
- (R-A) = 0, equilibrium position

This internal force system can be symbolized by a net force that is actually a difference between the R-forces and the A-forces acting between particles. The R-forces are highly susceptible to changes in the environment, whereas the A-forces are relatively stable. The net force is important in determining both initial structure and structural changes that occur when the soil is subject to applied stresses. This system itself is established by the type and distinction of the principal clay minerals, the net surface charge on these minerals, and the quality of the electrolyte surrounding them. Because of the ability of the net force to vary widely depending on the environment, the soil, during its process of formation, can assume a variety of structures. It is the nature of the geometry of these structures and their inherent stability that determine the ability of a soil to resist imposed stresses.

MODES OF DEPOSITION

There is evidence that the physical structure of the cohesive material plays a major role in erosion resistance, and the characteristics of that structure are determined by the initial mode of deposition or compaction. Deposition (natural) takes place through a body of water (sedimentary) where the particles are subject to Brownian motion and surface electrical forces as moderated by the quality of the water (character of dissolved salts, etc.). For example, Grissinger (14) found that the erosion rate of several clay soils was dependent on the formation technique, including the amount of moisture at compaction and the compaction method.

Interparticle orientation varies from highly random with many edge to force (EF) positions (flocculated) to highly oriented with parallelism of the particles and a parallel orientation to the bed surface (disperse) as the predominant structural pattern. Particles can also form packets first, which are groups of parallel-oriented particles held together by high local forces, and these packets can then form parallel or random structures. Residual soils, weathered in place from parent bed-rock, show different structural patterns, which are a function of the degree of weathering the rock has been subjected to. Compacted cohesive soils (man-made) have structural characteristics quite different from the others described.

Natural Deposition

In fresh water there is a large diffusion of low amounts of salts (if any) and of hydrogen ions in and out of the water surrounding the particle. This diffusion allows the zone of electrical force (or potential) to extend some distance away from the particle, resulting in a high degree of repulsion between adjacent particles. Fresh-water depositions result in a disperse interparticle structure, where the void ratio will decrease as the magnitude of the original surface charge decreases, allowing

particles to come closer together (30). The porosity of surface or near-surface deposits is also influenced by the rate of deposition and size of particle (30); porosity is greater for rapid deposition and less for greater particle size.

Nonsalt flocculation (20), most prevalent in kaolinite, can also occur as the strong positive edge charges are attracted by the negative force charges (EF). This gives a more or less perpendicular arrangement between the particle, resulting in an open structure with high porosity. Slight increases in the salt concentration reduce the magnitude of the face charge potential, resulting in a more disperse structure.

Saltwater deposition (NaCl , MgCl_2 , and CaCl_2) usually results in flocculated structures due to suppression of the repulsive force leaving a net attractive force between particles. This flocculation can be particle edge to face (EF) or face to face (FF) in an open network. Finer clays such as montmorillonite also form domains or pack clusters, and these domains then establish themselves as a flocculated system. During the process of deposition it is also possible for flocs to form during settling in the fluid. This total structure (Fig. 2) has a very high porosity (low total density) and is relatively weak. In all cases any loading of the sediment, due to either further deposition or some external physical loading, tends to create more parallelism between the particles, which breaks down the flocs.

The distance at which the particles are separated is a function of mineral type and fluid quality. If attractive forces predominate, it is possible to have actual EF contact, whereas with repulsive forces predominating it is most likely that the bound water layer will physically separate the particles. An understanding of the nature of particle-to-particle orientation and the associated surface force is essential for interpretation and evaluation of eroding forces.

Compacted Deposits

Soils that were deposited and then compacted in place, or natural deposits that are artificially compacted, have structural characteristics significantly different from soils that are naturally deposited and untouched. For soils that are remolded (or molded) and mechanically compacted, any natural interparticle bonding that occurred in the parent material is destroyed. The entire strength depends on the initial physical structure of the material created by compaction and to a lesser degree on subsequent bonding that may occur as the deposit is stressed. The structure that the soil will assume depends on the compacting moisture content (20). As the moisture content at compaction increases, the structure becomes more oriented. In addition, whereas it is possible to have flocculated structures (generally associated with low moisture contents of compaction), it is unlikely to form a structure composed of flocs that have the large void ratios (porosity) associated with naturally deposited materials. The nature of composition serves as an index of subsequent amounts of swelling (41), flocculated soils tending to swell to a much greater degree than the more oriented soils. Inasmuch as swelling reduces the structure (which increases the voids), if erosion is considered a surface phenomenon, it is evident that any swelling can only have an adverse effect on resistance to erosion.

Several basic studies that use both natural and artificially compacted soils (Table 2) have been made. As mentioned earlier, the variance in structure due to compaction state is the key to success or failure of a channel to resist erosion.

In both the deposited and compacted states, the structure of the sample has great influence on the relative erodibility of the sample. The structure reflects the interparticle force system and is established by the nature of the internal force system.

The erosion problem considered here is that of surface, and not deep-seated, shear. For this reason, any factors that minimize the surface interparticle forces and simultaneously minimize the stability of the surface layer (as realized through the geometry or potential energy configuration) maximize the erosive conditions. There are two distinct stress systems that control the resistive behavior: external and internal.

Figure 1. Mode of erosion.

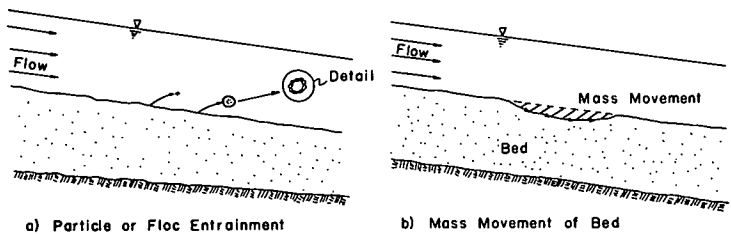


Table 1. Soil parameters used in evaluating erosion of cohesive beds.

Characteristic	Parameter
Physical	Soil type (clay mineral) Percentage of clay Liquid and plastic limits and activity Specific gravity
Physicochemical	Base exchange capacity Sodium adsorption ratio Pore fluid quality Pore fluid environment
Mechanical properties	Shear strength (surface and body) Cohesion Thixotropy Swelling and shrinkage properties
Conditions of environment	Weathering (wet-dry) Freezing and thawing Prestress history

Figure 2. Open network system formed by floc deposition.

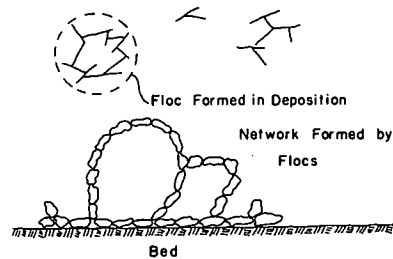


Table 2. Summary of selected studies on cohesive soil erosion.

Investigator	Mode of Placement of Sample	Mode of Measurement of Erodibility
Lutz (25)	Comparison of physical tests with erosive properties of natural soils	Use of qualitative physicochemical analyses
Peele (38)	In-place topsoils	Soil loss and runoff tables
Anderson (5)	In-place topsoils	Correlation of erodibility with shear measurements
Dunn (11)	Remolded, subjected to jet	Jet to produce erosion; visual measures
Smerdon and Beasley (45)	Slightly recompacted natural soil, top leveled	Visual observation of bed movement
Laflen and Beasley (18)	Remolded at unspecified percentage of water, then saturated	Visual correlation or erosion with calculated inactive stress
Flaxman (13)	Natural soils	Correlation of permeability and unconfined compressive strength with natural erosion (channel measures)
Moore and Masch (33)	Remolded and natural (trimmed) jet	Measurement of scour depth and weight loss
Abdel-Rahman (1964)	Remolded in duct	Visual; measurement of erosion depth
Partheniades (36)	Remolded natural deposited (salt water) in duct	Measurement of suspended sediment concentrating with time
Grissinger	Remolded in channel	Rate of erosion by weighing
McQueen (1965)	Remolded	Weight comparison
Masch, Espey, and Moore (28)	Unspecified but trimmed as hollow cylinder	Weight loss versus rotating shear; visual correlated with shear
Ben Zvi (1965)	Remolded in ring	Visual and measurement of sample surface
Mirtshkulava (31)	Remolded in flume	Weight of floc loss
Liou (22)	Remolded in flume	Point-gauge measurement of erosion depth
Liou (23)	Remolded in flume	
Coad and Paaswell (1968)	Naturally sedimented and consolidated in duct	Sediment concentration measurement
Akky and Shen (2)	Molded in ring; stabilized soil	Weight comparison
Arulanandan et al. (3)	Molded in ring	Weight comparison
Christensen and Das (9)	Remolded in tube	Weight comparison
Grissinger (15)	Natural samples remolded in channel	Rate of erosion by weighing
Wischmeier and Meyer (50)	Natural data	Weight of runoff

The external system is the stress system that is the total system imposed on the deposit during and subsequent to its formation. The previous stress history of the soil, if normally consolidated, is simply a function of the weight of overburden in place. If man-placed, the soil can be considered to have some properties that are functions of the energy input. The external system exerts much influence on the soil particle geometry, for, as the loads increase, the particles in the structure attain a higher degree of orientation and the interparticle spacing decreases. Under great loads there may be much interparticle contact with resultant formation of strong bonds. The influences of the structural geometry and location of the particles are shown in Figure 3. Particles on the surface are subjected to fewer net forces than are particles somewhat below the surface. Due to natural processes of compaction, the void ratio decreases with depth. A decreasing void ratio implies a more complicated structural matrix inasmuch as there would be greater physical particle interaction. Added to the fact that the soil surface is subject to constantly flowing water with fluctuating shearing stresses and the associated particle deformations is the fact that the surface particles would be in an energy state of less stability than particles below the surface.

In summary, the complexity of the forces holding a clay together can be seen through the historical development of the deposit. The type of mineral(s) determines the surface charge and then establishes the net repulsive force. The mode of deposition or compaction establishes the structural geometry as influenced by the net interparticle forces (internal system). Continual stressing (external system) causes further changes in the internal system through changes in interparticle spacing and orientation.

CHARACTERISTICS OF A CLAY BED FLUID AFFECTING EROSION RESISTANCE

The quality of the fluid during the process of deposit formation and the subsequent process of erosion must be accurately determined. This includes determination of dissolved salts (type and quantity), other impurities that may perhaps exist as cementing agents, and pH of the fluid.

A change in the ions in the electrolyte can lead to a change in the adsorbed ion and then to a change in the physical properties of the clay, i.e., liquid limit, plastic limit, and strength (47).

In a study of the erodibility of clay beds, Liou (22) demonstrated that pronounced changes in the stability of the soil deposit will occur when the type of chemical additive in the eroding and mixing fluid is changed. Partheniades (35) found that the presence of iron ions in the water was sufficient to cause cementing action on the surface of the bed, substantially changing the critical shear stress from values obtained when iron ions were not present.

MECHANICAL PROPERTIES OF CLAY BED

Measurement of mechanical properties is essential to establishing the specific stress deformation relationships that characterize clay soil behavior for a given set of environmental conditions.

Erosion is incipient when individual particle or small particle clusters (flocs) are worked loose from the parent mass and entrained in the moving fluid (Fig. 1). Note that in a geologic sense erosion is considered to take place even if large planes of the material are worked loose at once. The latter phenomenon is essentially a mass stability or mass movement problem and is different from the first.

The soil shearing strength is the resistance that the material can mobilize to imposed shearing stresses. In a clay soil it is, everywhere, a combination of interparticle assemblage (dilatation and friction components) and the net interparticle chemical forces as defined earlier. A plane of failure will develop when the shearing stress along that plane exceeds the mobilized shearing strength of the material, interparticle bonds are broken (N is exceeded), and particles are moved around or along each other. This plane can be readily visualized within a mass due to boundary stresses

acting on the mass. In the case of surface shear stresses (erosion stresses) where the nature of confining the total soil mass is quite different, the factors constituting the resistance to shear are not so readily defined. This is essentially resistance to shear at zero confining stress (7).

One parameter contributing to the net shearing resistance is cohesion. Cohesion can be considered as a measure of the actual interparticle bonds consisting of both chemical forces and cementing between particles. The amount of cohesive strength that can be developed is a function of original deposition conditions, minerals present, and the stress history of the soil. It is important to distinguish between normally consolidated and overconsolidated beds. A normal state is one in which the existing stress on the mass is the original stress on the mass and has never been exceeded. An overconsolidated state is one in which the current state of stress on the mass is less than some previous stress in the history of the material. The following examples illustrate the difference between the two states:

1. A bed whose surface has been recently deposited, whose deposition is continuing, and where no erosion has taken place (normal); and
2. A bed whose upper surfaces have been eroded away to some extent and whose current surface once existed some distance away from the previous surface (overconsolidated).

The resistance to erosion shear in these samples (even if of the same clay deposited initially under the same conditions) will be different.

Thixotropy is the strength regain with time of a compacted or disturbed clay and is due to particles being removed from an equilibrium condition (relative minimum energy position) and then reattaining a new equilibrium position under the imposed conditions. It is generally associated with the formation of flocs. A knowledge of the time-strength history of compacted clays is essential for evaluation of the bed and surface strength of the compacted clays at the time of erosion both in the laboratory and in man-made channels. According to Mitchell (32), thixotropy occurs as the excess of energy in the attraction term in the net internal force system is dissipated and equilibrium occurs through particle readjustment (slight) and changes on the structure of the adsorbed water.

An understanding of thixotropic behavior is important in using laboratory tests to predict field behavior. In laboratory testing, samples placed in ducts, flumes, or rotating devices are subject to thixotropic strength regain with time. This has been clearly shown by Grissinger (14, 15).

INFLUENCE OF SOIL STRUCTURE ON EROSION MECHANISMS

Although a most important variable of erosion control is soil structure, there is no one fundamental parameter that uniquely describes structure. Variables describing structure, such as void ratio, moisture content, percentage of clay, plasticity index (activity), and cohesion, must be isolated in any experimental analysis.

To interpret previous evaluations of variation of soil variables on erosion requires that critical shear, so widely used by hydraulic engineers as an index of inception of erosion, be defined. The critical shear stress τ_c is the empirically determined shear stress at which erosion is either imminent or actually taking place. In all equations defining τ_c , the velocity of flow is one essential factor that must be evaluated experimentally (6).

ISOLATION OF SOIL PARAMETERS INFLUENCING ERODIBILITY

To establish that any currently used soil parameters can be used as indexes to predict erosion, we must review previous studies made on a variety of soil types. In an early study, Lutz (25) compared two soils of different plasticities. These natural soils, one of high plasticity (D) and the other of lower plasticity (I), were noted to be quite different in their resistance to erosion. The high-plasticity soil was

nonerosive, whereas the lower one was highly erosive. In the analysis of erodibility it was noted that the permeability of the A horizon of the D soil was 34 times that of the I soil. It is also noted that in its natural state the soil is relatively friable. He concludes that the coefficient of permeability is a controlling variable in that it determines the rate of infiltration of water into the soil, resulting in less energy available for erosion. Inasmuch as the D soil does contain a higher percentage of clay, saturation of the soil subsequent to flow would reduce the friability, increase the surface activity, and increase the resistance to erosion. Chemical tests indicated that the D did not swell and that its suspension rapidly flocculated. I soil was more readily dispersed and exhibited swelling. These factors of swelling and flocculation are the most significant results reported with regard to soil influence on erosion. The measurement of permeability here is seen to be no index in the manner expected, inasmuch as the D had a coarse structure and higher permeability. Permeability can be used as an index of structure, and it is seen that a structure alone is not sufficient to predict the susceptibility. Permeability is a key to the rate at which a nonsaturated material can be wetted when subject to overland or channel flow.

Anderson (5) related the observed relative erodibility of six basic soil types to dispersion and erosion ratios. He measured erosion ratio by evaluating and comparing the quantity of suspended sediment of a specified size as a percentage of total silt and clay sizes in a very crude hydrometer type of test. Correlation is good inasmuch as the two comparisons are essentially the same. An increasing dispersion ratio implies that the fines as a percentage of the total soil in suspension at a given time increase. Dispersion ratio refers to a change in gross size of particle groups (clusters or aggregates, given as a ratio to the absolute quantity of soil and clay size). With this understanding, it becomes somewhat less than intuitive that critical shear stress will decrease as dispersion ratio increases. This correlation in fact is made by Smerdon and Beasley (45).

Smerdon and Beasley established from selected soils the following regression equation relating critical shear τ_c and dispersion ratio D_r :

$$\tau_c = AD_r^b \quad (3)$$

where A and b are constants and D_r is the dispersion ratio. Smerdon and Beasley for a group of 11 soils related τ_c to each of several soil properties including PI, mean particle size, and percentage of clay. The dependence of these parameters on each other can be shown by an example: According to the regression laws developed at a critical tractive force of 0.02 psf, a soil could have PI = 8 or a dispersion ratio of 40. Yet soil No. 1 has a greater PI (10.2) and a smaller τ_c (0.0199 psf). There is no question then that more insight into the relative cause and effect of the above-mentioned parameters on erosion can be provided if some form of multiple correlation is made. The essential problem is to correlate the internal force system that D_r and PI actually reflect.

The effect of the factors mentioned above that influence the net force system, hence surface stability of the material, has been noted by several investigators. Moore and Masch (33) noted the possibility that "...the shear producing fluid may influence the clay chemistry of the soil so as to affect the cohesive bond and thus the scour resistance." By using glycerine as the erosive fluid, they found that a scour-resistant layer of material was being formed on the surface. Exposed surfaces of increased stiffness could be attributed to the hygroscopic qualities of glycerine. A change in the surface adsorption characteristics of the soil with glycerine causes a change in the interparticle force system also. Moore and Masch's results may suggest that glycerine water may be used in erosion control, but they highlight the difficulties in substituting a liquid for water in the model tests. The viscosity and density of glycerine (100 percent glycerine has a specific gravity of 1.26 and viscosity of 1,400 at 20 C) are significantly different from water, which produces different flow properties (e.g., N_R , shear) at the same fluid velocities. Only at mixtures of 75 percent H_2O and 25 percent $C_3H_5(OH)_3$ can glycerine be used to model water with less than a 25 percent error in viscosity and density measurements. The difficulties in using a polar organic

compound to study flow (hydraulic) characteristics can be seen in the resultant change in soil characteristics.

In addition to the type of fluid, essential changes in erosive characteristics can be brought about by the type and quantity of dissolved salts in water. It is necessary to differentiate immediately between two roles water plays in the problem: (a) It is a medium for saturating the soil and plays the determinant role in its composition or consolidation, and (b) it is the erosion medium. It is quite possible that fluid characteristics in each of these cases are somewhat different. A soil may be deposited in a salt environment and may be eroded by fresh water. Thus, these roles must be completely distinguishable in any analysis. These roles were analyzed by Martin (27), who indicated that changing the salt concentration of the fluid surrounding the clay would have noticeable effect on the strength of the clay in both its natural and remolded states. If erosion is considered as a surface phenomenon and the characteristics of the eroding fluid are different from those of the saturating or depositional fluid, changes in the interparticle force system can be brought about by a displacement of the saturating by the eroding fluid.

The general effects of electrolyte replacement on strength were considered by Bjerrum and Rosenqvist (8), who established that clays deposited in a saline environment and then subsequently leached with pure water will suffer a decrease in shear strength and a reduction in the liquid and plastic limits. The strength change occurs although there is no further change in moisture content. Their analysis also indicated that changes akin to weathering occurred during a 2-month period in the laboratory, resulting in an increase in shear strength. The weathering effect, coupled with thixotropic effects, is a variable of great importance in the control of laboratory investigations. This effect may illustrate that freshly deposited samples (in the laboratory) are weaker and, hence, more subject to erosion forces than would be an identical sample in a natural channel that has existed for some period of time.

INFLUENCE OF INTERNAL STRUCTURE ON EROSION RESISTANCE

Studies of the influence of chemical additives on the erodibility of cohesive soil have been made by several investigators. In tests by Liou (23), Na_2CO_3 and $\text{Ca}(\text{OH})_2$ were added to soil to permit ion exchange before erosion took place. An attempt made to correlate vane shear strength of the soil with erodibility for different weights of chemical additives was successful only with Na_2CO_3 . Liou concluded that a higher potential swell pressure (see Eq. 2 for example), which would result in a high total vane shear strength, would also result in a low resistance to erosion under flow conditions. There was no correlation between vane shear and critical tractive force for the soil with $\text{Ca}(\text{OH})_2$ added. There is some indication that critical tractive force decreases rapidly to a minimum value as vane shear strength of the Ca-montmorillonite increases due to increasing availability of the Ca ion and then increases rapidly above this minimum as Ca availability increases. Further data points are needed to substantiate this trend. Liou described the physical process for erosion of the Na-montmorillonite as "the mixture of water dispersed small clay particles and some chemicals;... the soils were eroded away, layer by layer, approximately uniformly across the soil sample." For the Ca-montmorillonite, "... the soils treated with 2.0 percent and 5.0 percent $\text{Ca}(\text{OH})_2$ additives were eroded away in large flocs.... The soils were eroded away locally." The influence of the structure of the clay as evidenced by its particle orientation and potential swell characteristics is clearly seen in these tests through an analysis of erosion rates. The Na-montmorillonite displayed a sustained erodibility that increased as concentration of sodium ion increased. The Ca-montmorillonite showed erodibility over a range of a low-percentage additive but showed an abnormal peak at 5 percent Ca additive. This of course corresponds to the minimum critical tractive force required to erode the 5 percent Ca sample as described above. Liou suggests that the variation in erodibility between the Na- and Ca-montmorillonites occurs from the structure, flocculated or dispersed, that is established by the quantity of salt added. A further interpretation of the high Ca erodibility

peak may be that the structure is one of large flocs whose internal strength comes from suppression of the strong repulsive forces but whose interfloc strength is still weak enough to permit easy particle separation. As the percentage of Ca ion is increased, the interfloc repulsive forces are reduced, with the result of a regain in total structural stability or erosion resistance.

The relationship of erosion susceptibility to water quality is clearly shown in the study of Arulanandan et al. (34). Water quality of both the pore fluid and the eroding fluid was changed in a series of rotating-cylinder shear tests. The rate of erosion was measured under varying surface shears for soils in which the sodium adsorption ratio was varied and the internal structure of the soil was affected. The eroding fluid also had NaCl concentrations varying from 0 to 0.1 N. The results of these tests [shown in Figure 8, p. 47 (3)] can be interpreted in terms of the effects of fluid quality on external and internal force systems. As the adsorbed sodium ratio increases (i.e., as the replacement of calcium or magnesium ions or both by sodium increases), the critical shear stress decreases. The rate of decrease is a function of the salt concentration in the pore fluid. With low concentration of salt in the pore fluid, high shear stresses are resisted only when little of the original Ca or Mg ion has been displaced. When the pore fluid contains much salt (0.1 N) the resistance to initial erosion is sustained to much higher sodium adsorption ratios. Arulanandan et al. attribute this to the ability of the soil to form strong flocculated structures with either higher valence exchange ions or high concentrations of salt in the pore fluid. This affirms the mechanistic theories that relate erosion initiation to the surface conditions.

The eroding fluid can also be used to stabilize the soil [shown in Figure 9, p. 48 (3)]. Increasing concentrations of salt in the eroding fluid resulted in lower erosion rates. Thus, a quality of 0.005 N NaCl was enough to reduce the erosion rate to 20 percent of distilled water acting on the soil. The combined effect, that is, salt in both the eroding fluid and pore fluid, demonstrates the dynamic effects of the mechanism of erosion. In cases where the NaCl concentration in the pore fluid is greater than the eroding fluid, erosion can be expected; whereas, when the reverse is true, erosion is not expected. These show that the laws of diffusion cause surface changes affecting the internal force system. Reduction of salt concentration at the surface of the soil relaxes the internal forces and permits erosion to commence. There is one extremely important application apparent here. In many coastal areas and near many industrial sites, the quality of the groundwater is changing through diffusion of salts. Where channel erosion may have taken place prior to diffusion at low rates (pore and eroding fluids being of the same quality), erosion rates may be significantly changed, depending on the nature of the eroding fluid and the time allowed for erosion. Diffusion through the pores of soils under eroding conditions is a function of the concentration differences and the temperatures of the fluids. The conclusions of the work of Arulanandan et al. are particularly valid in field conditions where steady-state conditions can be developed.

Partheniades (36) found in flume tests using salt water that, after a period of 4 months and remolding of the soil bed, the erosion rates had significantly decreased (50 to 25 percent of corresponding rates for original bed and velocities of 1.32 and 2.31 ft/sec). This was attributed to a "possible increase of the electrochemical attraction and to the possibility of some cementation due to dissolved iron oxide in the water." The study by Bjerrum and Rosenqvist also suggests that particle weathering may account for increased stability of the soil. Partheniades' soil, a San Francisco Bay mud, was a highly plastic (PI = 55 percent) mixture of montmorillonite and illite clays, silt, and sand, with high ion and magnesium contents. Increased weathering of active particles will strengthen the interparticle bond (cohesion), creating an increase in total shear resistance.

Further study into the causal relationships, though examined on a macroscopic level, was made by Grissinger (14). Grissinger evaluated the relative erodibility of clays of various activity placed on a relatively small (5.04 × 12.5 cm) mold and subjected to flow normal to the orientation of the direction of packing of the material. The soil was compacted in either a flocculated or disperse nature, depending

on initial moisture content. The sample was allowed to adsorb water subsequent to compaction but did not necessarily reach a saturated state. The measured variable was rate of erosion (grams/min). The first study evaluated the effect of aging on erosion rate; and, as can be expected by thixotropic behavior, as aging time increased from no aging to overnight (12 to 24 hours), the rate of erosion decreased considerably. The various soils were made by mixing a predominantly silt soil with various mixtures of kaolinite, illite, Na-montmorillonite, and Ca-montmorillonite.

Grissinger found that, as the percentage of clay in the soil increased, the erodibility decreased with the exception of Ca-montmorillonite. The Ca-montmorillonite was the only soil in fact that showed (except at high density) decreasing stability with increasing clay content. This is consistent with Liou's results if the montmorillonite particles are forming large flocs loosely held together.

As the antecedent moisture content increases, resistance to erosion decreases. The soils were formed in a more disperse state with the main particle orientation parallel to the eroding water. In this manner, the particles are more resistant to shearing forces, inasmuch as the force system and structure are relatively well developed along the surface. As the antecedent water content increases to high values, the rate of erosion again increases, which indicates that swelling must be taking place. As swelling takes place, the net internal force system would decrease as the interparticle spacing increases. Swelling might also cause slight changes in the orientation: Small rotations of the particles occur, and the particles deviate from the generally horizontal disperse structure. In a less disperse form, the particles would be more susceptible to shearing forces than the more oriented particles as indicated by an increasing erosion rate.

Because of the wide range of PI and the overlapping of PI among the various sample mixtures, no correlation of PI with erodibility could be made.

Grissinger (15) later extended this test procedure to a wider range of natural soils. From these tests he related erosion rate to the rate of sample wetting. This empirical relationship is given by

$$ER = b_1 p (\Delta \text{ water/time}) \quad (4)$$

where

ER = erosion rate,

b = regression constant, and

p = sample porosity.

Molded samples were aged for a specified time and eroded in a small flume. The test results were presented in terms of erosion rates at fixed velocity. As noted the erosion force was not determined, so resistance to initial erosion or critical shear stress is not available. These can be thought of as tests on already eroding systems. The samples fell into classes that were established according to water pH, pH difference between water and clay, PI, and percentage of clay. The influence of differences in eroding fluid and clay quality is seen to have effect where the pH values are small for a slightly acid soil and where pH values are large for a water pH in the neutral to alkaline range. Grissinger applied this analysis to a field sample and developed a chart relating eroding velocity to eroding rate and delineating areas of stability.

FLUME STUDIES

Model tests of cohesive soils placed in a flume are worthy of extensive discussion because they clearly illustrate the strong influence of physicochemical forces acting in cohesive soils. The tests by Abdel-Rahman (1) were made on an expansive clay and clearly illustrate the influence of expandability in erosion. Mirtskhulava (31) studied the relationship between critical velocity and floc size and cohesion of soil in an attempt to define stability. Partheniades' tests (36) were also made on active clay but were different from previous tests inasmuch as they are deposited in water at ocean salinity.

Abdel-Rahman performed his tests on material compacted at a variety of moisture contents, varying first the fluid velocity for a series of tests at constant moisture content and then the moisture content for a series of tests at constant flow velocity. The material was compacted by a hammer, which tends to cause some orientation normal to the direction of the applied force, and the surface was subsequently trimmed to a desired level. Because the material was compacted at moisture contents less than the saturated moisture content, submergence in the flume caused additional amounts of water to be absorbed, generally resulting in swelling. The amount of swelling increased as the original moisture content decreased, which is of course expected for compacted materials (40). The swelling was of the order of 4 percent.

Because there were no moisture-density tests performed, it is difficult to determine whether the soil was compacted wet or dry of optimum moisture. The high moisture contents (30 percent) and, in the second series of tests, the large decrease in vane shear strength with increasing moisture content would imply that the material is near or greater than optimum. For this reason, the particle structure would tend more to be disperse than flocculated, this fact being somewhat borne out by the erosion pattern. The soil strength in each case was measured by the vane shear test. It should be noted that the soil tended to swell continually, usually reaching its maximum expansion after 60 to 100 hours after the test had proceeded. As moisture content increases and as the structure expands, the vane strength decreases. In series 2 the vane shear strengths varied initially from 1.026 t/m^2 (w percent = 36.05) to 7.260 t/m^2 (w percent = 24.40) and decreased to 0.90 t/m^2 (w percent = 37.8) to 2.814 t/m^2 (w percent = 29.94) respectively (Table 3).

As noted there are two basic series of tests in which the influence of the hydraulic parameters (velocity and bed shear) and soil parameters (shear strength and moisture content) are isolated. The time patterns of erosion in both are similar, and to relate the erosion phenomenon requires that the tests be discussed in some detail. For low values of hydraulic shear stress ($\tau \leq 1.54 \times 10^{-4} \text{ t/m}^2$; $S_r \approx 1 \text{ t/m}^2$) or for high values of vane shear strength ($S_r \geq 2$ percent; $\tau = 2.6 \times 10^{-4} \text{ t/m}^2$), swelling and erosion were of somewhat the same order of magnitude. Erosion apparently took place from time $t = 0$ and increased rapidly until a steady-state condition was reached. Finally a point of no erosion was attained. Abdel-Rahman cites continuing erosion until the water becomes "cloudy," which is an extremely vague term. The implication here is that there is some local surface shear initially and that after some time there is a greater large-scale surface shear more representative of the general surface condition. He notes that "the smaller the tractive stress, the larger the time needed for the water to become cloudy." This is consistent then with the concept of the time effect of shear. The nature of treatment of compaction and of leveling the surface causes a preferred orientation of the particles, especially on the surface, this orientation being parallel to the bed. Pulling the trimmer over the surface somewhat amplifies surface irregularities and inhomogeneities (mainly in density), causing the nature of erosion as shown in his photographs. The flat pieces are those clusters weakly held to the bed and easily removed by any surface shear force. Further breaking up of these particles is mainly a hydraulics problem. The greatest depths of erosion (hence greatest erosion rates) occur for minimum combinations of τ_c and S as mentioned above, indicating that the soil material possesses a certain inherent strength that will resist erosion below these values.

No scour or steady-state conditions were reached for specific values of stress. This indicated that, the more erodible the soil was, the longer the time necessary to reach steady state would be. Because the erosion mechanism is essentially the same, varying the hydraulic or soil parameters has the following effects: Increasing the tractive stress causes greater boundary shear and greater particle reorientation with surface disruption, thus permitting erosion to continue until the bed adjusts to the flow conditions; greater vane shear indicates a denser, more oriented bed. Thus, as the erosion process continues, more resistance is encountered below the surface, especially as the particles are oriented parallel to the direction of shearing, thus decreasing the time to steady state. In both cases steady state would

be reached because of a continued particle reorientation under the steady influence of the bed shear. This orientation tends to parallelism with the direction of shear. Furthermore, because erosion takes place below the surface, the internal system becomes greater because it has had more time to stabilize (thixotropic effect) and because it was initially in a position of greater stability. Of great interest would be the increase in velocity needed to sustain the maximum rate of erosion as the erosion depth increases. Abdel-Rahman also mentions a "gluey" substance forming on the bed (probably oxides of iron and other metals that become disoriented from the soil due to flow through the upper surface layer). However, the consistent time-depth pattern would tend to sustain the self-limiting aspects of erosion due to the limiting stability conditions of the material.

It may be concluded from Abdel-Rahman's study that, for a soil with a given PI, a wide range of erosion conditions is possible. The bed shear strength can serve as an index to a limiting amount of erosion possible for a given tractive stress. Conversely, for a given bed strength, there may be a lower limit to the tractive stress necessary to cause substantial erosion. Neither of these clarifies the conditions that initiate erosion. It would seem that the initial surface condition will determine the initial modes of erosion, and these of course will determine subsequent patterns; i.e., a naturally deposited material will behave somewhat differently from a compacted soil. Local inhomogeneities may precipitate erosion through the existence of weak planes between the inhomogeneity and the overall bed, which are susceptible to shear forces that will cause movement of the material and which are of orders of magnitude less than shear forces that cause general erosion. This was clearly shown by the flat plates being moved along the bed. Because overall surface erosion can only take place by increasing interparticle (or interfloc) distances, which reduces the interparticle strength, the time of clouding in Abdel-Rahman's tests would seem to represent the actual initiation of general erosion. This has already been discussed in some detail.

Erosion of flocs was also noted by Mirtskhulava in his study of erosional stability. Of significance was his relation of measurable soil parameters to velocity causing erosion. A plot of his data (Fig. 4) indicates that, as cohesion and particle mass (proportional to d^3) increase, the velocity to cause erosion also increases. As the internal stability increases, greater stresses (velocities) are needed to erode the particles. Mass erosion, i.e., large floc erosion, will occur as weak planes between the flocs develop. Cohesion and floc size would be interdependent, for greater cohesion is representative of a stronger internal force system or fewer potential weak planes.

Partheniades' tests examined the influence of velocity (surface traction) to other variables on erosion rate for a basically montmorillonitic clay deposited in salt water. Three series of tests were performed on a remolded sample, at field moisture, that had undergone some chemical change and on an artificially flocculated sample. (The relative shear strengths of the beds taken near the surface are given in Table 4.) Partheniades' significant findings were that the initiation of erosion occurred in all samples over a small range of water velocities, 0.6 to 0.8 fps. Thus, some yield stress must be overcome before erosion can be initiated. Data given in Table 4 also show that erosion rates decrease even though the shear strength of the bed decreases.

This would imply that there are essentially two controlling factors for the soil behavior in these tests. The first factor is that the initiation of erosion occurs by the same mechanism in each case, as explained by Partheniades. The second factor is that the substance of erosion at a constant velocity becomes more difficult as the test series goes from the naturally deposited soil to the artificially flocculated soil.

One explanation may be that the natural clay deposited through a greater depth of water may have had initially a more highly random structure than the artificially deposited clay, which under constant shearing stresses in the fluid develops a more preferred orientation, though perhaps a looser density. The natural clay over a long period of time would also develop strong interparticle bonds and would be more stable than the artificially deposited soil. However, the preferred orientation of the soils in test series 3 would tend to resist erosion more because the plane of the parti-

cles is more aligned with the direction of shear. Ladd (17) illustrated the formation of flocculent structures that consist of clusters of individual groups of particles, some of which have formed domains. He states that the factors that control the formation are the type of clay mineral and the fluid environment and notes that "domain formation is generally restricted to the montmorillonites and some illites. . . ."

The marine clay in its initial environment was probably deposited in an extremely dilute suspension, whereas the artificially sedimented material would be deposited in a more concentrated solution and would tend to form aggregated structures. The shear strength data give evidence that either the structure of the two materials is quite different or the internal force systems have evolved differently as noted. It is quite important to establish some criterion by which the surface orientation of the deposit can be established and to determine the surface strength at a given time as a function of its long time strength.

Flume studies have also been carried out on naturally consolidated laboratory samples (34). Kaolinite samples were deposited and consolidated in a 4-sq ft consolidometer (2×2 ft) to various levels of prestress and then subjected to flow in a 4-ft long by 1-ft wide test section of a 30-ft long duct. The test section is shown in Figure 5. Preliminary results (2) are consistent with other studies showing an initial period of high erosion rate, followed by a steady-state period. The erosion rate was measured using concentrations of fluid taken from the duct. Typical results are shown in Figure 6 where the preconsolidation pressure was 1,030 (10).

TRACTION FORCE AND EROSION IN OTHER MODELS

In an attempt to define a relationship between erosion and tractive force, several investigators worked with submerged jets acting on prepared surfaces, hoping to better define the relation of a relatively small area of tractive stress to erosion rate (or depth). Dunn (11) based his measurements on the assumption that the total force causing erosion consisted of, in his analysis, turbulent form drag and viscous drag, most of the force being caused by the latter. The force resisting shear was taken to be the Coulomb failure criterion in which it is necessary to assume some value of ϕ (friction angle) and c (cohesion), which have been shown to be approximations of some true failure criterion (9). By assuming that the Coulomb failure criterion is operative, Dunn postulated that the mechanism of erosion failure at the surface can be defined in the same manner as deep-seated failure criterion. By providing a subsequent redefinition of c , he reinterpreted the failure mechanism without redefining the law controlling this mechanism. The results indicate that the critical shear stress increases in some fashion with the vane shear strength of the bed (a deep-seated phenomenon). This would imply that the surface shear must also be linearly correlated with the vane shear, a fact that is yet to be demonstrated.

Dunn went on to relate erodibility to PI and percentage of fines, through the failure criterion, noting that, as PI and percentage of clay increase, resistance increases. It is necessary to examine his methodology before commenting on his results. The soils were remolded and subsequently consolidated in a saturated environment. No density measurements were made. The maximum PI was 15.6, and, of seven cohesive samples, three had PIs less than 10. This suggests that the samples consisted of relatively inert clay minerals and that the soil itself was not subject to adverse swelling. Dunn limited his correlation between PI and tractive resistance to those soils with $PI > 5$. Thus the correlation is made for soils with a range of PI of approximately 6 to 16.

The advantage of using activity instead of PI can be seen in a very brief examination of two studies. Reports by Dunn and Smerdon and Beasley isolate clay portion and PI and compare these with their defined critical shear stress. Whereas general relationships can be deduced from curve fitting, the resultant equations or curves are limited, in Dunn's case, to a very small range of soils with relatively low plasticity ($5 \leq PI \leq 16$) or a large degree of scatter, in the case of Smerdon and Beasley. Table 5 gives Dunn's data in terms of activity and shows the relatively small range of activity of soil investigated and, as would be expected, a small range of τ_c (critical

The figure consists of two main columns, (a) and (b), each illustrating a different system. Column (a) is labeled 'Disperse System' and column (b) is labeled 'Flocculated System'. Each column contains two diagrams. The top diagram in each column shows a 'Surface' with particles 'a' and 'b' below it. In the disperse system, particles are small and well-separated. In the flocculated system, particles are aggregated into flocs. The bottom diagram in each column shows a single particle 'a' with arrows pointing to it from the label '(R-A)', representing the reaction rate. In the disperse system, the reaction rate is higher due to the larger surface area. In the flocculated system, the reaction rate is lower due to the smaller surface area.

Test	w_1 (percent)	Δw (percent)	ΔS (percent)	S_r (t/m ²)	$t_{...}$ (cn)	τ_1/τ
1-1	33.55	3.45	14.72	1.000	0.450	1.00
1-2	34.10	2.88	14.30	1.080	0.300	1.57
1-3	34.50	2.88	14.00	1.085	0.391	2.06
1-4	34.10	2.75	14.00	1.085	1.345	3.46
1-5	34.16	2.44	13.50	1.110	3.990	5.90
2-1	36.03	1.77	12.30	0.90	1.410	1.00
2-2	30.50	3.51	51.00	1.31	1.045	1.00
2-3	27.56	3.16	55.50	2.00	0.610	1.00
2-4	24.40	5.54	61.50	2.81	0.493	1.00

Mean Velocity, V , m/s	Cohesion, d^3c , kg/cm
0.55	0.010
0.65	0.0105
0.75	0.0105
0.80	0.019
0.85	0.005
0.90	0.014
1.05	0.016
1.10	0.016

Test Series	Velocity of Flow (fps)	Erosion Rate (grams/ft ² /hour)	Apparent Shear Strength of Bed ÷ Shear Strength of Series I	Shear Stress on Bed (psf)
I	0.8	0.05	1.0	0.0023
I	1.34	0.338	1.0	0.0103
I	2.34	1.67	1.0	0.0278
II	1.32	0.174	0.6	0.0100
II	2.31	0.674	0.6	0.0272
III			0.0074	
III	1.27	0.506	0.0074	0.0091
III	1.46	0.252	0.0074	0.0120

Figure 5. Schematic diagram of duct and test section (34).

a) DUCT

b) FOUR FEET LONG TEST SECTION

Symbols

- 1 Head Tank
- 2 Pressure Taps
- 3 Venturi Meters
- 4 3" Brass Valves
- 5 4" Variable Speed Pump

shear stress). For these soils Dunn gets good correlation between tractive resistance and tractive force. If PI and vane strength are isolated, it must be assumed that there is a great deal of similarity in the structure of the soils and in the mechanism of erosion. The soils were recompacted and consolidated similarly and were most likely in a disperse state. In describing the manner of erosion, Dunn notes that the first material removed was that disturbed by the upper plate and that at a particular point, when the jet velocity was increased, the water became cloudy. Removal of the first particles would then be somewhat independent of the shear strength of the mass, inasmuch as these particles have been initially disturbed, have undergone some tensile stress, and evidently are not in a position of great stability. Under the tensile stresses, the bonds between particles (or particle groups) are weakened as the particles are moved further apart, making them more susceptible to erosive forces. Furthermore, removal of the cap would cause a geometric rearrangement in these upper particles so that their orientation is neither so uniform nor necessary predominantly in the same direction as the particles below the surface.

The erosive forces that act on the more stable layers are somewhat different in the case of parallel flow. The jet has components both tangential and normal to the bed so that with both components orientation of the bed particles becomes of less importance than it is for the case of just parallel flow. For a disperse system with particles oriented parallel to the surface of the bed, normal components of stress would tend to deform and cause rotations about the axis, and, coupled then with tangential components, through movement and rotation the bonds would loosen and erosion would occur (Fig. 7).

This is also shown in the tests of Moore and Masch who were able to cause scour to some depth in samples under jet tests. Under the influence of the jet they observed nonuniformities in scour because large pieces would be eroded away as the scour continued. This again can be attributed to a highly nonuniform force field acting on a surface that is somewhat nonuniform to begin with but whose degree of inhomogeneity increases under the influence of the surface forces.

Leitch and Yong (21) showed that under shearing stresses (deep-seated) there is marked reorientation of particles on the failure plane; the particles became aligned in the direction of movement of the plane. This is clearly shown in electron microphotographs taken of kaolin under shear (44).

Although the behavior of surface particles due to the shear forces of the fluid is different from deep-seated shear, the nature of reorientation of particles cannot be neglected. The reorientation or rotation at the surface, in order to cause erosion, must permit a general loosening of the structure. If the particles are subject to a tensile field (surface drag forces) or if under the influence of bending a particle separation can take place, the net interparticle energy field is reduced. Reorientation of a cluster will cause this same phenomenon along the small shear plane, allowing the entire cluster to be removed. This is shown schematically in Figure 8.

Moore and Masch presented many conclusions from their studies that can be extended to flume tests. Unfortunately, none of the plastic properties of the soils is given, nor is the method of preparing the sample for placing in the test apparatus given. The scour rate index, a measure of the rate of erosion, has an apparent linear relationship with Reynolds number N_R or velocity of flow, hence surface shear stress. Further, there is a limiting N_R below which scour does not take place. This in effect confirms the existence of a yield stress that the soil possesses, this yield stress being a function of the internal force system. For a given velocity and at an N_R sufficient to cause erosion, the rate (or depth) of erosion increases in some linear fashion with time. This is shown in Figure 9 for the three samples tested. If the data as presented are extended back to the time axis, it is seen that the initiation of erosion does not take place immediately and that, the lower the Reynolds number is, the longer is the time before initiation of erosion.

The large discontinuities in these curves are attributed to sudden erosion or large clusters of soil. It seems evident that two mechanisms are working simultaneously: first, the surface mechanism yielding a steady deterioration of surface resisting stresses due to general reorientation at the unconfirmed upper surface and,

Figure 6. Eroding soil concentration versus time (10).

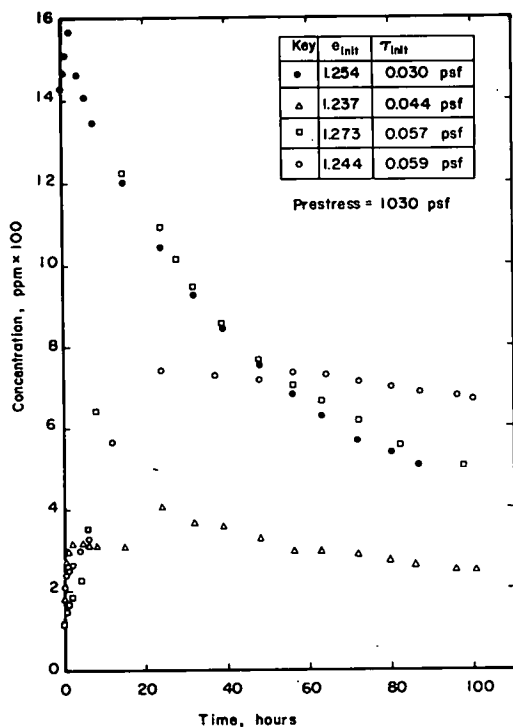


Table 5. Critical tractive stress versus activity (11).

Activity*	T_{cmin}	T_{cmax}
0.054	0.30	0.33
0.062	0.19	0.32
0.110	0.30	0.45
0.127	0.43	0.48
0.161	0.48	0.49
0.164	0.40	0.41
0.165	0.48	0.49

*Because soil is classified according to percentage of silt and clay (<0.06 min), the actual clay content (<0.002 min) will be less than given. This is an approximation, the true activity being greater for smaller percentages of clay.

Figure 7. Suggested mechanism of erosion in vertical jet tests.

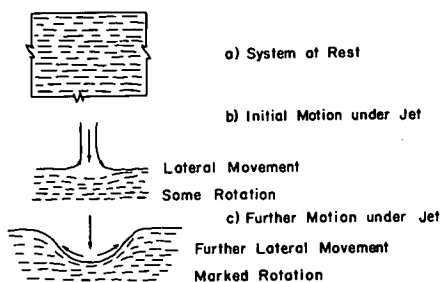


Figure 8. Mechanisms of erosion caused by reorientation or relocation of particles.

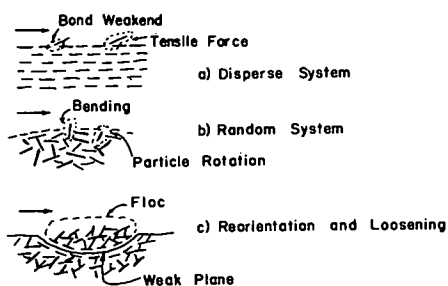
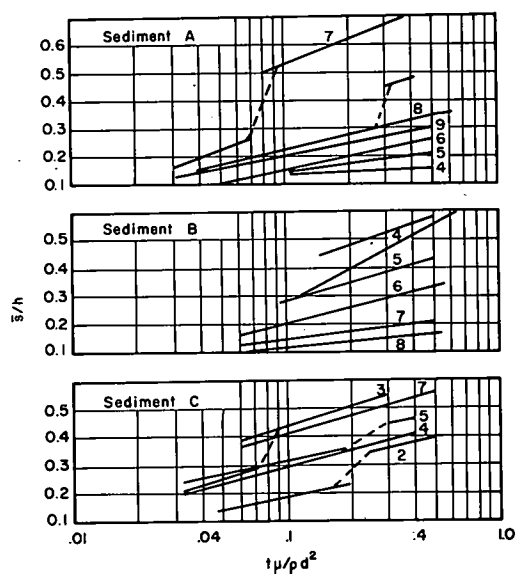


Figure 9. Scour depth versus time (33).



second, the deep-seated shear most likely acting along weak planes that may exist due to natural inhomogeneities in the soil. This would seem likely because there is no consistent pattern of deep-seated shear although in all cases the surface erosion proceeds for a given period of time $\left(t \geq 0.07 \frac{\rho d^3}{\mu}\right)$ before deep-seated shear occurs. This is entirely consistent with the fact that the shearing process in soil is highly time-dependent (21).

Christensen and Das (9) developed a unique test method in which samples were placed inside a brass tube as a lining. The clay was actually compacted by being squeezed into a tube [Figure 2, p. 10 (9)]. The surface was made smooth by removal of the inner tube, which also affected the orientation of the particles at the surface. It should be recognized that this technique allows comparison of erosion parameters for similar samples but would not be representative of field conditions. Molding moisture content, flow velocity, and temperature of the eroding fluid were varied. When eroded, the samples showed patterns consistent with other observers, i.e., an initial rate followed by steady-state conditions. After steady state, a rapid erosion again took place. This is due to the nature of the changing boundary forces as the surface becomes rougher and particle reorientation continues.

The significant contribution of these authors is their approach to a mechanistic model:

$$\dot{E} = \beta_e \exp(\alpha \tau) \quad (\tau < \tau_c) \quad (5)$$

and

$$\dot{E} = E_{CR} \exp \left[\alpha_1 (\tau - \tau_c) \right] \quad (\tau > \tau_c) \quad (6)$$

where

\dot{E} = steady-state erosion rate,

τ_c = critical stress, and

α and β = soil and test parameters.

This model makes possible the understanding of erosion as an internal/external energy system, where E can be a measure of the work done on the system, reflected in τ actual, and α and β represent measures of the internal energy developed by the samples. α is related to the bonding energy and β to the weight of the eroded particles. In the form of the relationships given, α , related by the authors to energy, is analogous to the term (constant/ T) in the activation process where increasing temperature loosens internal bonds. For erosion, as interparticle bonds are relaxed, external forces would have greater effect on changing particle geometry, thus intensifying the erosion process. The authors noted that, as molding moisture increased, total erosion weight decreased. It should be noted that, as molding water content (above optimum) increases, density or soil particles per unit volume decrease rapidly. Thus a plot of eroded soil in grams versus moisture content is not so meaningful as erosion weight in grams as a percentage of total original weight. If possible, reconstruction of this curve as particle volume lost per unit of area, as a function of original particles per unit area, would perhaps aid in the explanation and would most likely show results more consistent with other investigators.

The importance of the effects of temperature on erosion has also been amplified in a study made by Enger (12). The rate of increase on boundary shear of water from the city supply on the soil sample was 0.0036 psf/deg C. Because the critical boundary shear as measured in these tests ranged from 0.010 to 0.065 psf, the strong influence of temperature is clearly shown. However, other than a series of three tests evaluated to calculate temperature effects, no further temperature correlation was reported, although the report maintains that temperature records were kept.

APPLICATION TO FIELD CONDITIONS

The paper by Wischmeier and Meyer (50) relates the data developed since 1930 by the U.S. Department of Agriculture on runoff and erosion to properties of detachability and transportability of the soil. Dealing with field erosion, the erodibility factors are classified as: "those that influence the capability of the erosive forces, rainfall and runoff, to detach and transport soil material, and those that influence the capability of the soil surface to resist the erosive forces." The authors present the soil loss equation in terms of these factors, which is useful in predicting total weight of soil loss from climatic, geographic, and soil properties. In further multiple regression work, they found that significant parameters affecting erosion were soil texture, organic matter content, aggregation, surface pH, and permeability of surface seal. This was utilized in construction of an erodibility monograph. The monograph is of significance in predicting the erodibility of soil at construction sites from soil parameters easily obtained through surface sampling.

Akky and Shen (2) examine the influence that cement stabilization has on reducing the potential erodibility of a given soil. One to 3 percent cement was added to a sandy soil (nonplastic). Although they were concerned with cohesive soils, the implications of stabilization are important to understanding erosion control. The stabilized material was tested in a rotating cylinder apparatus. "Unweathered" samples showed increasing resistance to erosion with increases in unrefined sample strength. This is to be expected inasmuch as the bonding produced by the cement, which causes strength increases, would be reflected in surface resistance to erosion. This is analogous to increasing erosion resistance found in cohesive soils as percentage and activity of the clay material increase. The effects of weathering, freezing and thawing, or wetting and drying cause surface changes, again analogous to weathered clays. The process of weathering changes the surface through fissuring or bond relaxation through increased wetting. Greater surface areas exposed to the eroding forces make prediction of erosion on weathered surfaces more difficult than on non-weathered surfaces. The processes of stabilization of erodible surfaces need further research. Research in this area would give a needed link between understanding the theory of erosion mechanisms and the nature of control of erosion processes.

Stabilization by other methods including natural cementing agents such as iron oxide and the use of bentonite has been proposed by Partheniades and Paaswell (37).

CONCLUSIONS

It is possible here to summarize brief conclusions from the large amount of research. For example, PI (or activity) can serve as a group index telling whether a class of soils is more likely to be eroded than another class. That is, all other conditions being equal (fluid and density properties), it would be more likely that soils with a high PI would be less erodible than soils with a low PI. However, a given soil (i.e., PI fixed) may or may not be erodible depending on its structure. Thus, PI is not a primary index of erosion and actually serves the purpose of being a means of identification only. However, physicochemical indexes such as sodium adsorption ratio give better information on soil structure necessary to interpret potential behavior.

Other conclusions follow:

1. Generally used soil classification indexes have not proved useful as erosion predictors.
2. Structural indexes must be defined in order to establish relative erodibility of a given soil and comparison with other soils. This index should give an indication of particle orientation, separation (void ratio), stability (strength on a thixotropic scale), previous stress history, and ability to swell. These latter two items become extremely important when laboratory and field tests are compared. A soil that will swell appreciably may have done so in the natural stabilizing processes that take place. Thus such a soil may erode only at a higher velocity than that evidenced in the laboratory.

3. The external and internal force systems must be evaluated to determine rate and initiation of erosion. Surface erosion begins as a particle-by-particle phenomenon, due to the relative instability of a particle (or domain) compared with the remainder of the surface. This instability can arise from orientation, poor bonding, structural defects, or, when subject to a peak in a fluctuating shear field (or else after a time), being rotated in a fluctuating shear field and being subject to some stress less than the peak would be pulled away. Because the soil bed may not be everywhere parallel to the flow direction, the force vectors acting on the bed may have normal as well as tangential components. The normal stresses may have beneficial effects in that they cause more stabilization or harmful effects in that they cause re-orientation into the flow field. The internal force field is created by the initial mode of deposition, predominant clay mineral type, and previous stress history. Soils stabilized over a period of time, perhaps prestressed, with orientation parallel to the flow direction will obviously be less erodible than soils with more flocculated orientations of recent deposit.

The research cited here has shown how complex the cohesive soil erosion problem is, but continued developments on soil fabric analysis and more sophisticated techniques in physicochemical analysis should help in solving the aspects of soil behavior under flow.

REFERENCES

1. Abdel-Rahman, N. N. The Effect of Flowing Water on Cohesive Beds. Laboratory for Hydraulic Research and Soil Mechanics, Swiss Federal Institute of Technology, Zurich, thesis, 1962.
2. Akky, M., and Shen, C. K. The Erodibility of a Cement-Stabilized Sandy Soil. Published in this Special Report.
3. Arulanandan, K., Sargunam, A., Loganathan, P., and Krone, R. B. Application of Chemical and Electrical Parameters to Prediction of Erodibility. Published in this Special Report.
4. Arulanandan, K., Loganathan, P., and Krone, R. B. Effect of Pore Fluid Composition on the Erodibility of Soil. Dept. of Civil Engineering, Univ. of California, Davis, Paper 7215.
5. Anderson, H. W. Physical Characteristics of Soils Related to Erosion. Jour. Soils and Water Cons., July 1951, pp. 129-133.
6. Masch, F. D., Jr. Erosion of Cohesive Sediments. Jour. Hydraulics Div., Proc. ASCE, Vol. 94, No. HY4, Proc. Paper 6044, July 1968.
7. Berghager, D., and Ladd, C. C. Erosion of Cohesive Soils. Dept. of Civil Engineering, M.I.T., Res. Rept. R64-1, Jan. 1964.
8. Bjerrum, L., and Rosenqvist, I. Some Experiments With Artificially Sedimented Clays. Geotechnique, Vol. 5.
9. Christensen, R., and Das, B. Hydraulic Erosion of Remolded Cohesive Soils. Published in this Special Report.
10. Coad, R. Unpublished PhD data.
11. Dunn, I. S. Tractive Resistance of Cohesive Soils. Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 85, No. SM3, Proc. Paper 2062, June 1959.
12. Enger, P. F. Canal Erosion and Tractive Force Study—Analyses of Data Taken on Boundary Shear Flume. Bureau of Reclamation, Denver, Hydraulic Branch Rept. Hyd-532, Feb. 1964.
13. Flaxman, E. M. A Method Determining the Erosion Potential of Cohesive Soils. Internat. Assn. of Scientific Hydrology, Commission on Land Erosion, Pub. 59, Oct. 1962, pp. 114-123.
14. Grissinger, E. H. Resistance of Selected Clay Systems to Erosion by Water. Water Resources Research, Vol. 2, No. 1, 1966, pp. 131-138.
15. Grissinger, E. H. Ephemeral Erosion and the Stability of Cohesive Soils. Published in this Special Report.

16. Harr, M. Foundations of Theoretical Soil Mechanics. McGraw-Hill, New York, 1966, pp. 165-190.
17. Ladd, C. C. Physico-Chemical Analysis of the Shear Strength of Saturated Clays. M.I.T., PhD thesis, 1962.
18. Lafien, J. M., and Beasley, R. P. Effects of Compaction on Critical Tractive Forces in Cohesive Soils. Agricultural Exp. Station, Univ. of Missouri, Res. Bull. 749, Sept. 1960.
19. Lambe, T. W. Soil Testing for Engineers. John Wiley and Sons, ASI, pp. 22-28.
20. Lambe, T. W. The Structure of Compacted Clay. Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 84, No. SM2, May 1958.
21. Leitch, H., and Yong, R. The Rate Dependent Mechanism of Shear Failure in Clay Soils. McGill Univ., Montreal, Soil Mech. Series 21, Aug. 1967.
22. Liou, Y. D. Effects of Chemical Additives on Hydraulic Erodibility of Cohesive Soil. Colorado State Univ., MS thesis, Aug. 1967.
23. Liou, Y. D. Hydraulic Erodibility of Two Pure Clay Systems. Colorado State Univ., PhD thesis, 1970.
24. Liu, T. K., and Thornburn, T. M. Study of the Reproducibility of Atterberg Limits. Highway Research Record 63, 1964, pp. 22-30.
25. Lutz, J. F. The Physico-Chemical Properties of Soils Affecting Soil Erosion. Agricultural Exp. Station, Univ. of Missouri, Res. Bull 212, July 1934, 45 pp.
26. Lyle, W., and Smerdon, E. Relation of Compaction and Other Soil Properties to the Erosion Resistance of Soils. Trans. ASAE, 1965.
27. Martin, R. T. Discussion of Experiments on Scour Resistance of Cohesive Sediments. Jour. Geophysical Research, Vol. 67, No. 4, April 1962.
28. Masch, F. D., Jr., Espey, W. H., Jr., and Moore, W. L. Measurements of the Shear Resistance of Cohesive Sediments. Agr. Res. Service, Pub. 970, 1965, pp. 151-155.
29. McQueen, I. S. Some Factors Influencing Streambank Erodibility. Geological Survey Research, 1961, pp. B28-B29.
30. Meade, R. H. Factors Influencing the Early Stages of the Compaction of Clays and Soils—Review. Jour. Sedimentary Petrology, Vol. 36, No. 4, Dec. 1966.
31. Mirtskhulava, Ts. E. Erosional Stability of Cohesive Soils. Jour. Hydraulic Research, Vol. 4, No. 1, 1966.
32. Mitchell, J. R. Fundamental Aspects of Thixotropy on Soils. Jour. Soil Mech. and Found. Div., Proc. ASCE, Proc. Paper 2522, June 1960.
33. Moore, W. M., and Masch, F. D., Jr. Experiments on the Scour Resistance of Cohesive Materials. Jour. Geophysical Research, Vol. 67, No. 4, April 1962, pp. 1437-1499.
34. Paaswell, R., Partheniades, E., Coad, R., and Blinco, P. Experimental Study of Erosion of Cohesive Soils. Presented at 50th Annual Meeting of American Geophysical Union, April 1969.
35. Partheniades, E. A Study of Erosion and Deposition of Cohesive Soils in Salt Water. Univ. of California, Berkeley, PhD thesis, 1962.
36. Partheniades, E. Erosion and Deposition of Cohesive Soils. Jour. Hydraulics Div., Proc. ASCE, Vol. 91, No. HY1, Proc. Paper 4204, Jan. 1965, pp. 105-138.
37. Partheniades, E., and Paaswell, R. E. Erodibility of Channels With Cohesive Boundary. Jour. Hydraulics Div., Proc. ASCE, No. HY3, Proc. Paper 7156, March 1970, pp. 755-771.
38. Peele, T. C. The Relation of Certain Physical Characteristics to the Erodibility of Soils. Proc., Soil Science Soc. of America, Vol. 2, 1937, pp. 97-100.
39. Rektorik, E. J. Critical Shear Stresses in Cohesive Soils. Dept. of Agricultural Engineering, Texas A&M Univ., MS thesis, Jan. 1964.

40. Seed, H. B., Woodward, R. J., and Lundgren, R. Clay Mineralogical Aspects of the Atterberg Tests. Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 90, No. SM4, Proc. Paper 3983, July 1964.
41. Seed, H. B., and Chan, C. R. Structure and Strength of Compacted Clays. Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 85, Oct. 1959.
42. Seed, H. B., Woodward, R. J., and Lundgren, R. Fundamental Aspects of the Atterberg Limits. Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 90, No. SM6, Nov. 1964.
43. Skempton, A. W. The Colloidal Activity of Clay. Proc., 3rd Internat. Conf. on Soil Mech. and Found. Eng., Zurich, 1953.
44. Sloane, R., and Nowatzki, E. Electron Optical Study of Fabric Change Accompanying Shear in a Kaolin Clay. 3rd Pan-American Conf. on Soil Mech. and Found. Eng., Caracas, Vol. 1, 1967.
45. Smerdon, E. T., and Beasley, R. P. The Tractive Force Theory Applied to Stability of Open Channels in Cohesive Soils. Agricultural Exp. Station, Univ. of Missouri, Res. Bull. 715, Oct. 1959.
46. Smerdon, E. T., and Beasley, R. P. Critical Tractive Forces in Cohesive Soils. Agricultural Engineering, Jan. 1961.
47. Van Ophen, H. An Introduction to Clay Colloid Chemistry. Interscience, 1963.
48. Vanoni, V., et al. Sediment Transport Mechanics: Initiation of Motion. Jour. Hydraulics Div., Proc. ASCE, No. HY2, March 1966, pp. 291-314.
49. Veas, E., and Winterkorn, H. F. Engineering Properties of Several Pure Clays as Functions of Mineral Type, Exchange Ions, and Phase Compaction. Presented at HRB 46th Annual Meeting, 1967.
50. Wischmeier, W., and Meyer, L. D. Soil Erodibility on Construction Areas. Published in this Special Report.
51. Wu, T. H. Soil Mechanics. Allyn and Bacon, Dayton, 1966, pp. 395-398.