HYDRAULIC EROSION OF COHESIVE SOILS

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The mechanism of erosion of saturated and unsaturated soils was studied by examining the effect of initial water content on the critical shear stress required to initiate erosion. Erosion tests on saturated and unsaturated soils were carried out in a rotating cylinder and a flume apparatus respectively. To provide a valid comparison of the critical shear stresses obtained on two different measuring devices, identical saturated samples were tested in both to show that the critical shear stress is independent of the testing apparatus. Critical shear stresses obtained as a function of water content on saturated and compacted samples were compared. The mechanism causing erosion in both cases has been shown to be due to swelling. The mechanism causing swelling in the saturated samples is shown to be due to differences in concentration gradient. Test results are also presented to show the influence of structure and water content on the slaking of soils.

•IN recent years increasing emphasis has been placed on the study of erosion characteristics of soils. Knowledge of the factors influencing erosion is especially useful in the design of road cuts, drainage ditches, embankments, and other surfaces from which vegetation has been removed.

A significant body of information on the causes and mechanisms of cohesive soil erosion has been assembled (1) and presented at the Highway Research Board Soil Erosion Symposium held in 1973. One of the contributions made at the symposium was the successful adaptation of the modified rotating cylinder test apparatus of Masch, Espey, and Moore (2) for erosion measurement of saturated soils (3). At the panel discussion no general agreement was reached as to the validity of the critical shear stresses obtained by using the rotating cylinder apparatus. It may be argued that tests conducted in open flumes may give different critical shear stresses. The first objective of this paper, therefore, is to compare the results of critical shear stresses obtained on saturated samples of Yolo loam by using a flume and the rotating cylinder apparatus.

Numerous studies on the erosion of compacted clays have been carried out by various researchers (4, 5, 6). Evidence presented in previous studies has dealt mainly with erosion rates, and the testing conditions are not reported in sufficient detail in all cases to reach any definite conclusions. The erodibility index, which depends on the physicochemical and compositional properties of soils, is defined as the shear stress required for zero erosion rate, also called the critical shear stress τ_0. The influence of clay mineral type and pore and eroding fluid composition on the erodibility index τ_0 for saturated soils has been demonstrated earlier (3), but the influence of water content of saturated and unsaturated soils on the erodibility index of soils has not been reported. The second objective of the paper, therefore, is to examine the effect of water content on the erodibility index of soils in order to provide more insight into the mechanism of erosion of saturated and unsaturated soils. The third objective of the paper is to present some results to show the influence of structure and water content on the slaking of cohesive soil systems.

Publication of this paper sponsored by Committee on Physicochemical Phenomena in Soils.

SAMPLES FOR TESTING

Results reported in this study were obtained on a local natural soil called Yolo loam. Its composition is 40 percent sand, 49 percent silt, and 11 percent clay. X-ray analysis from the same soil group showed that montmorillonite, kaolinite, mica, and vermiculite were the clay minerals present.

Sample Preparation

For shear stress comparison, saturated soil samples were prepared by consolidating samples of Yolo loam from a slurry. Soil samples weighing 1.5 kg were mixed in 20-litre bottles containing 10 litres of solutions of various SAR and salt concentrations. Samples were agitated from time to time to obtain equilibrium between soil and solution. Samples were filtered and consolidated for 2 weeks with increasing loads up to a pressure of about 100 kPa. The effluent was used to determine the chemical composition of the pore fluid.

Compacted samples were prepared by mixing thoroughly a known weight of the soil with a given amount of water to obtain the desired molding water content. The sample was then allowed to equilibrate overnight in plastic bags placed in a humidity room. All samples were compacted according to the modified AASHO standard.

Measurement of Shear Stress

Lane (7) in his investigation on the design of stable channels used the following equation for determining the fluid-induced shear stress:

$$T_o = \gamma D S$$

where

T_o = critical shear stress,
γ = unit weight,
D = depth of flow, and
S = slope of the water surface.

For a two-dimensional flume or in the case of a very wide channel this equation is quite correct. However, for small, narrow flumes as used in this study the equation may give erroneous results because of varied nonuniform flow and turbulence.

Two kinds of instruments are currently available for the measurement of shear stress; one is the shear meter or shear balance and the other is the Preston tube.

The Preston tube consists of a circular tube with an outside diameter d_p resting on the surface and reading the total pressure P_t. Preston (8) showed that the total pressure p_t measured relative to the static pressure p_s depends on the independent variables ρ, v, T_o, and d_p. The equation developed by Preston takes the form

$$\log \frac{T_o d_p^2}{4\rho v^2} = -2.604 + \frac{7}{8} \log \frac{(p_t - p_s)}{4\rho v^2} d_p^2$$

where

ρ = mass density of fluid in slugs/ft^3;
v = kinematic viscosity of fluid in ft^2/second;
T_o = boundary shear stress in lb/ft^2; and
d_p = diameter of Pitot tube in feet.

If the left side becomes smaller than 4.5, then Preston's equation renders incorrect results; if larger than 6.5, no experimental data are available. Preston points out that for the equation to hold true the Pitot tube must lie in the laminal sublayer, which is expected to be about one-tenth of the boundary layer thickness.

The Preston tube has been successfully used to measure shear stress by several workers, including Ippen and Drinker (9); Gosh and Roy (10); and Hwang and Laursen

(11). Ippen and Drinker used the Preston tube to measure the shear stress distribution around bends in open channels. It was found that the shear stress distribution over the entire sample was reasonably uniform and that the Preston tube was a simple and accurate enough device to measure shear stress for erosion studies.

TESTING EQUIPMENT AND PROCEDURE

Erosion tests were performed in the rotating cylinder and a small flume. The rotating cylinder apparatus and testing procedure were described earlier by Arulanandan et al. (3).

The Flume

A small circulating flume, 8 ft (2.5 m) long, 6 in. (0.15 m) wide, and 12 in. (0.3 m) deep was modified to test the erosion of molded soil samples. The flume has three controls for varying the velocity of fluid flow: one discharge control valve with a pressure gauge and two controls for varying the slope of the flume. Figures 1 and 2 show the essential features of the flume. The soil samples were introduced from the bottom of the flume at a distance of 5 ft (1.5 m) from the tailgate. The sample was confined inside an aluminum ring and fitted to the bottom of the flume. A threaded screw was used to keep the surface of the sample flush with the bottom of the flume at any time during the erosion test.

Shear Stress Measurement

Shear stress is measured using a Preston tube (8) designed to suit the required condition of flume. Pressure differences are measured using two open inclined manometers. The flume was precalibrated by obtaining pressure differences for 0, 1, 2, and 3 percent slopes and two settings of headgate position, and the discharge control valve was operated to give the desired shear stress. After 1 minute of erosion, the sample was removed and weighed. The surface was trimmed and the sample was again soaked in water for 5 minutes before the next erosion test; 5 minutes of soaking was considered adequate for the surface to absorb sufficient water to produce maximum swell.

RESULTS OF EROSION MEASUREMENTS

Comparison of Erosion Rate Versus Shear Stress Measurements

The critical shear stresses obtained using the rotating cylinder and the flume are shown in Figure 3. Data shown indicate that the same critical shear stresses are obtained at different sodium absorption ratios (SAR) by the two methods. The results also show that τ_0, the critical shear stress, decreases with an increase in SAR. This result is expected because the degree of flocculation decreases with an increase in SAR at a given salt concentration (3, 12, 13).

The rates of erosion obtained by the two methods are different, however. Further study is necessary to provide a reasonable explanation for this behavior.

Effect of Water Content

The effects of varying the water content of a saturated sample of a silty clay containing 20 percent kaolinite (Hydrite R) and prepared at low SAR are shown in Figure 4. It may be observed that the water content has hardly any effect on the critical shear stress, even though it does affect the erosion rate, once the critical shear stress is exceeded. It is known, however, that samples at high SAR are less flocculated and hence would undergo particle orientation during consolidation. The critical shear stresses may thus be a function of water content. Conclusive results are not yet available to confirm this.

The relationships of erosion rate versus shear stress obtained on compacted samples of Yolo loam (see Fig. 5 for compaction curve) prepared at low SAR are shown in Figure 6. The samples were compacted in cylindrical molds and tested in the flume. The results show that the critical shear stress increases with increasing water content.

Figure 1. Schematic diagram of the flume.

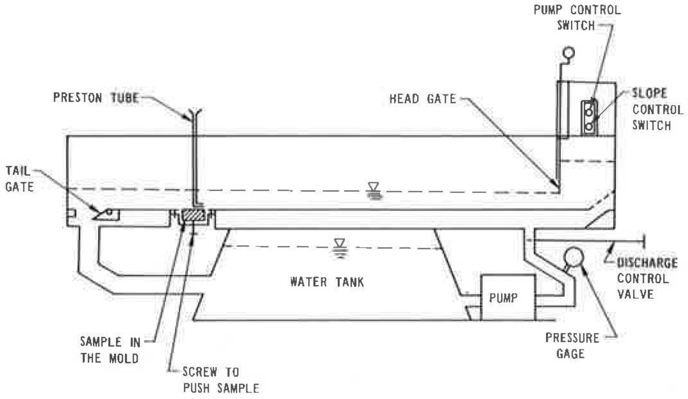


Figure 2. Photograph of the flume.

Figure 3. Plot of erosion rate versus shear stress for Yolo loam obtained from rotating cylinder apparatus and the flume.

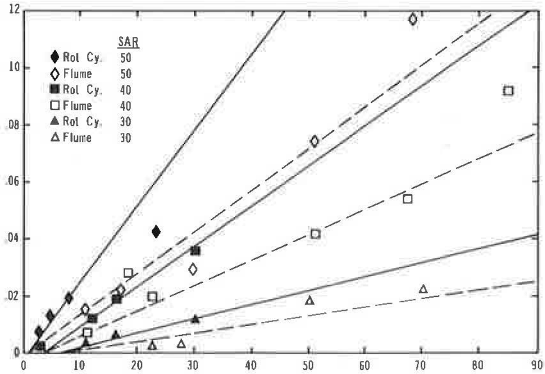
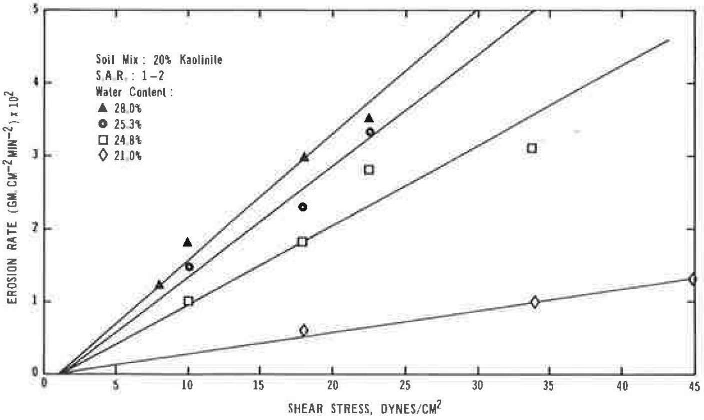


Figure 4. Effect of water content on critical shear stress and erosion rate in a kaolinitic soil at very low SAR (15).



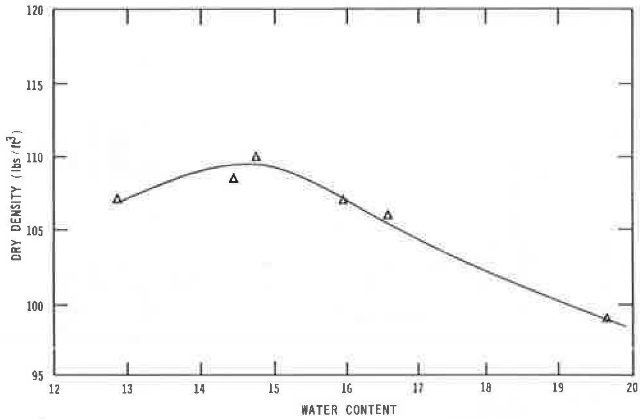


Figure 5. Compaction curve for Yolo loam.

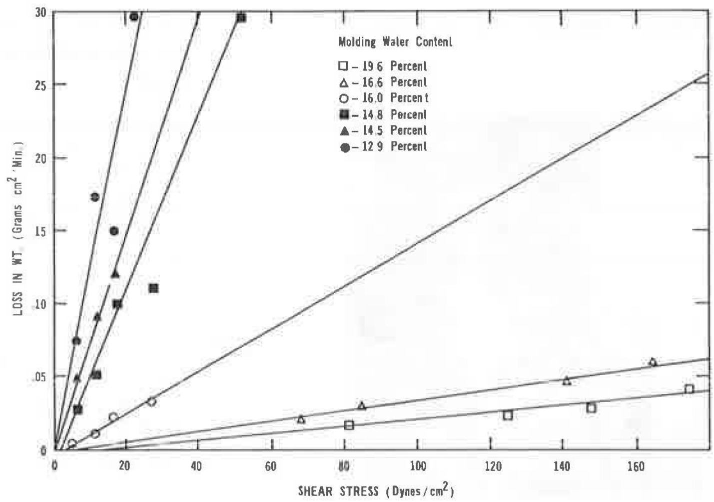


Figure 6. Shear stress versus loss in weight for compacted Yolo loam at various molding water contents.

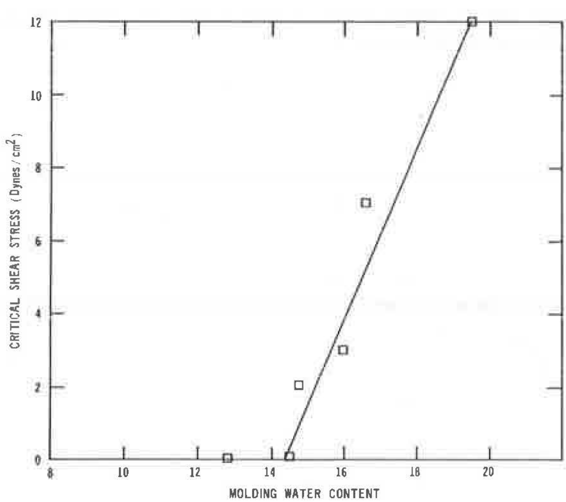


Figure 7. Influence of water content on the critical shear stress of compacted Yolo loam.

The amount of swelling is known to decrease with increase in water content. These results suggest that for a given soil the critical shear stress would increase with a decrease in the swelling of the soil and that for compacted soils the critical shear stress is a strong function of water content and density. A relationship between molding water content and critical shear stress is shown in Figure 7. At a water content of about 15 percent, which for this compaction curve is the optimum water content, the critical shear stress required to initiate erosion is zero. This result indicates that a different process of particle detachment is involved on the dry side of the line of optimum. This process is generally described as flaking.

Effect of Water Content and Structure on Flaking

Although the actual mechanism of flaking is complicated and not well understood, it is generally accepted that the flaking of dry cohesive soil when in contact with water is due to air pressure in the capillaries (17, 18). When a lump of dry soil is soaked in water, the dipolar water molecules are attracted by the clay particles and thus the water moves into the pores. The rate of water entry depends on the magnitude of the driving forces, which are a function of the matrix potential and osmotic potential. In the pore the water forms menisci, which react against the air in the pores of the dry soil. The entrapped air in the extremely small pores exerts enormous pressure and this breaks loose small bits of soil on the surface. This weakens the resisting forces of the dry soil system and suddenly the pressure in the soil is released and the expanding air throws the soil from the surface with explosive force.

Winterkorn (19) reported that the rate of slaking depends on the relative magnitudes of the driving and the resisting forces. Among the resisting factors are the resistance to water permeation, resistance of internal soil surface to wetting, electrochemical bonds, and cementing agents such as organic matter and other glutinous material. If the rate of water penetration exceeds that of the bond destruction, then the system fails slowly after a prolonged period. On the other hand, if the rate of bond destruction equals or exceeds the water penetration, the breakdown process is very orderly and sometimes instantaneous.

Flaking rate studies on compacted samples of Yolo loam indicate that flaking is instantaneous when samples are compacted on the dry side of the line of optimum. The flaking rates decreased with increased water content, and the flaking was practically negligible at 19.3 percent water content, as shown in Figure 8.

The influence of pore fluid composition on the structure of soils has been well documented (3, 12, 13). The higher the SAR and lower the concentration, the higher is the dispersion of clays, or at a given concentration an increase in SAR produces an increase in deflocculation. The influence of structure on erodibility of saturated soils has also been well demonstrated (3). The effect of structure on the flaking of soils was reported earlier (14, 15) and the results are discussed later. Samples of silty clay containing 20 percent kaolinite (Hydrite R), illite, or montmorillonite were prepared at low and high SAR at a concentration of 0.01 N. The samples were consolidated from a slurry under 100 kPa, allowed to air-dry, weighed, and then suspended in a beaker of distilled water. The flaking rates for the three different clays are shown in Figure 9.

The flaking times are shown to be greater for soils with more dispersed structure. A soil with a higher SAR in the saturated state develops a less flocculated structure than one with a low SAR. The air-dried soils appear to maintain the same structure. A more dispersed soil also has a low permeability and hence would require a longer time for the flow of water into the pores of the soil to produce the flaking observed.

The results also show the influence of minerology on the time of flaking. Montmorillonite with a lower permeability would take a longer time to flake than kaolinite, as shown by the results in Figure 9.

CONCLUSIONS

1. A comparison of the results of critical shear stresses obtained on saturated samples of Yolo loam using a flume and the rotating cylinder apparatus show that the critical shear stress is independent of the testing device. Compacted samples cannot,

Figure 8. Effect of water content on the flaking of compacted Yolo loam.

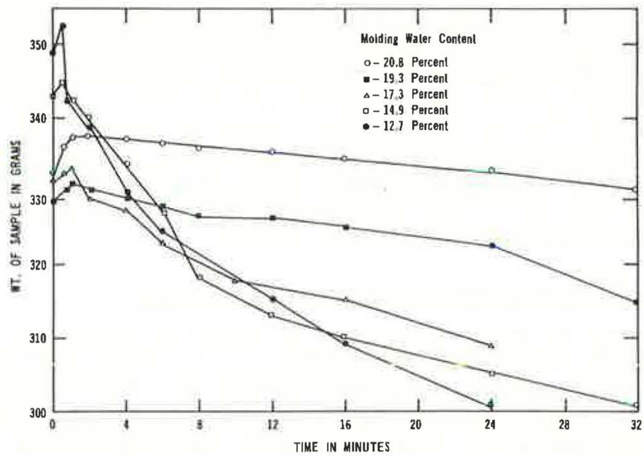


Figure 9. Effect of soil type and pore fluid composition on the slaking of dry soil samples.

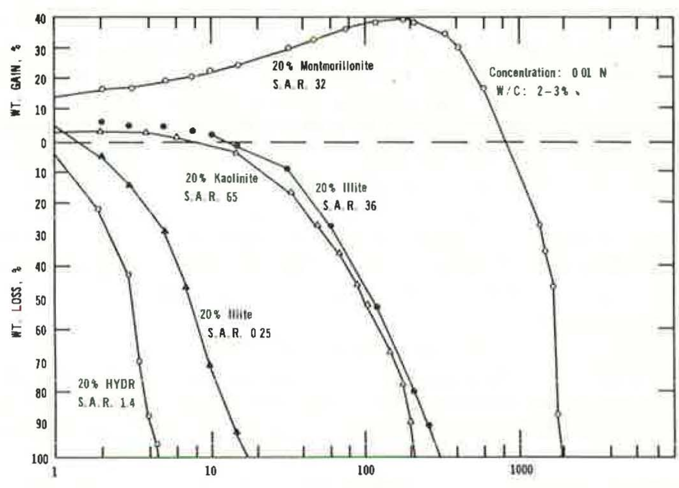
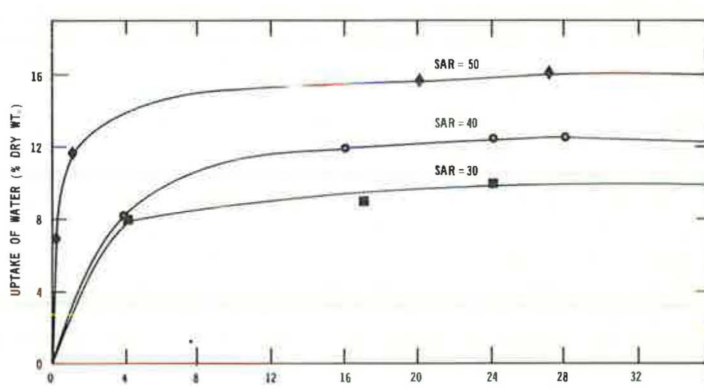


Figure 10. Water uptake of saturated Yolo loam at three different SAR and at a salt concentration of 0.05 N.



however, be tested in the rotating cylinder, whereas both saturated and compacted samples can be tested in the flume. The different testing methods appear to give different erosion rates under the same shear stress. Further studies are necessary to explain this behavior.

2. Samples of saturated soils prepared at low SAR exhibit critical shear stresses that are independent of water content, whereas in compacted soils the critical shear stress is highly dependent on the water content. The higher the water content, the lower the swell is and hence the higher the shear stresses required to initiate erosion. The mechanism of initiation of erosion in saturated soils is controlled both by structure and the osmotic pressure gradient developed due to the difference in concentration of the pore and eroding fluids (3). Structure and osmotic pressure gradient control the swelling of clays. The larger the swelling, the lower is the critical shear stress. For the samples of saturated clays prepared at low SAR, the osmotic pressure gradient and particle orientation are not significantly changed during consolidation, and hence the swelling is not significantly affected. Thus the critical shear stress is seen to be independent of water content for the low SAR samples. Increasing the SAR of a soil at a given concentration does change the osmotic swell behavior (Fig. 10), and hence the critical shear stresses (Fig. 3). The critical shear stress in both compacted and saturated soil is controlled by the swell behavior of the soil. In compacted soils the osmotic pressure concept can satisfactorily explain a good portion of the swelling (19) Structure also affects the swelling of compacted clays (16). In saturated soil the swelling behavior is dictated by the structure and osmotic pressure gradient created by the differences in concentrations of the pore and eroding fluids. It is to be noted that different methods of compaction will induce different structures and hence different amounts of swell (16), and thus should produce different critical shear stresses.

3. Flaking is instantaneous for samples compacted on the dry side of the line of optimum, and thus the shear stress required to initiate erosion is zero. The flaking rate is slower for a dispersed soil than a flocculated one. Slaking rate is shown to be controlled by the permeability of the system, because a montmorillonitic clay with a lower permeability exhibits a larger flaking time than a kaolinite clay with a larger permeability.

ACKNOWLEDGMENTS

Support for this research project by the Davis Faculty Research Grant and the National Science Foundation is gratefully acknowledged. Special thanks are due to Ranjan Ariathurai for assistance in the development of the flume apparatus and the interest taken in this study. Part of the flume tests were carried out by Kiruppa Ariathurai, to whom the authors are grateful.

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