Iran. J. Agric. Res. Vol. 4, No. 2, 1976

A METHOD FOR MEASURING THE CRITICAL SHEAR STRESS OF COHESIVE SOILS[1]

A. Alizadeh and K. Arulanandan[2]

ABSTRACT

A rotating cylinder apparatus was used to study the erodibility of cohesive soils. Hydraulic erodibility has been defined in terms of critical shear stress. Critical shear stress was obtained by measuring erosion rate as a function of shear stress. The results show that a definite relationship exists between shear stress and erosion rate. The shear stress required to produce zero erosion rate (critical shear stress) was obtained by extrapolation of shear stress versus erosion rate. Based on several of the cohesive soils used in this study, the apparatus tested is a valuable tool for studying erosion.

INTRODUCTION

The phenomenon of erosion occurs when fluid flow-induced shearing stress on the surface reaches value great enough to cause particle removal from the surface. The

---

[1] Contribution from the Department of Civil Engineering, University of California, Davis, Ca., U.S.A.

[2] Formerly Graduate Student (now Assistant Professor, Department of Agricultural Science and Crop Production, School of Agriculture, Ferdowsi University, Mashhad, Iran) and Professor of Soil Mechanics, Department of Civil Engineering, University of California, Davis, Ca., U.S.A., respectively.

magnitude of these shearing forces largely depends upon the turbulent shear of the flow and the nature of the exposed surface. For any particular bed, the flow condition may reach a critical point where the surface is unable to resist the hydrodynamic forces and thus the particles start to move.

For a long time, the condition of flow in which soil particles start to erode has been described in terms of critical flow velocity (6). The use of average critical velocity has been criticized by many investigators. The most important unanswered question is the relationship between average flow velocity and the bottom velocities which basically cause erosion. For this reason, most of the hydraulic engineers agree to use a more satisfactory parameter, the bed shear stress.

It seems more reasonable to consider bed shear stress as a flow parameter than average flow velocity because bed shear stress might be the result of flow-induced driving forces acting on all soil particles within the unit area of the bed. For non-cohesive soils, the higher the shear stress, the greater the chance a given size of particle of soil will be eroded. The critical shear stress (τ_c) is defined as the bed shear stress induced by water flow which would cause particle removal. However, various workers have used different criteria for defining critical shear stress. In his studies of erosion, Dunn (2) defined critical shear stress as a state of shear stress in which the eroding fluid becomes cloudy, while Smerdon and Beasley (7) have defined it as that shear stress in which the bed materials are in general motion. Thus, although the laboratory results show that there is a well-defined correlation between soil parameters and critical shear stress (4), the results obtained by various investigators are different. In connection with these problems, the critical shear stress has been defined as the value of shear stress for zero sediment discharge obtained by extrapolating a line of observed sediment discharge versus shear stress (1). Since this value is independent of some qualitative criteria, a similar concept to this has also been adapted for this investigation.

The purpose of this study was to test a rotating shear apparatus and determine the critical shear stress which indicates erosion in cohesive soils.

MATERIALS AND METHODS

Apparatus: The testing apparatus used for erosion studies operates on a principle similar to some viscosimeters. The apparatus used in this investigation was basically the same as that of Moore and Masch (4) and of Espey (3), except for some modifications. Two concentric cylinders are separated by an annular space filled with water. Figure 1 shows the cross section of the apparatus.

As the outer cylinder is rotated with the inner cylinder (soil sample) held stationary, rotation is imparted to the fluid. The movement of the fluid, in turn, transmits a shear to the surface of the inner cylinder (soil). This shear and the resulting torque on the inner cylinder can be obtained by the following equations (8):

$$\omega = \frac{u}{2\pi\mu h}\left[\frac{1}{(R_1)^2} - \frac{1}{(R_2)^2}\right] \qquad [1]$$

$$\omega = \frac{\tau}{\mu}\left[1 - \frac{(R_1)^2}{(R_2)^2}\right] \qquad [2]$$

where ω = angular velocity T^{-1}

$u = 2\pi(R_1)^2 ht$ = torque on the inner cylinder FL

h = height of the inner cylinder L

μ = dynamic viscosity FTL^{-2}

R_1 = radius of inner cylinder L

R_2 = radius of inner face of the outer cylinder L

τ = boundary shear FL^{-2}

For equation [2] to be applicable, the flow in the annular space between the outer rotating cylinder and the fixed cylindrical soil sample must be that of stable Couette flow. Generally, the flow in the annulus between the rotating cylinders tends to be quite stable because of the effect of internal forces. Fluid particles near the outer rotating boundary are kept from moving radially inward by large centrifugal forces, whereas those particles near the inner boundary do not move outward because of smaller centrifugal forces. Because of stabilizing internal forces resulting from velocity distribution in the annular space, the turbulence at the soil surface is very low, and the fluctuation of the instantaneous shear stress on the surface of the soil is very small (5). The apparatus has upper and lower end pieces which are positioned above and below the ends of the soil sample (Fig. 1). Since the narrow gap between the soil sample and the end pieces prevents or at least reduces the movement of the fluid occupying this space, the end result is a reduction of shear on the ends of the soil sample. In this study, it was assumed that there was not shear on the ends of the soil sample and that the entire torque registered by the apparatus was due to the shearing force acting on the cylindrical outer surface of the soil sample.

Calibration of the apparatus. Calibration was accomplished by applying known loads tangent to the periphery of a dummy soil sample by means of a pulley, string and weights. For each speed of the outer cylinder, the shear on the soil sample was measured by putting weights in the scale pans until the torque indicator just moved in the opposite direction. Dividing the known load by the exposed surface area of the soil sample gave the average shear on the soil sample corresponding to the point deflection produced by the load. For a soil sample 8.03 cm long and 7.50 cm diameter, positioned inside the cylinder (10.00 cm inside diameter), a calibration curve was obtained which is shown in Fig. 2. As can be seen from Fig. 2, the calibration curve differs from the theoretical straight line. This may be due to unavoidable friction losses. It can also be seen that stable Couette-type flow occurs only up to about 410 rpm.

Sample preparation. Samples of soil were mixed with water to form soil slurry. This mixture was then placed into a three-inch diameter consolidation mold. Consolidating the mixture in the mold beginning with a slurry ensured no pockets of entrap-

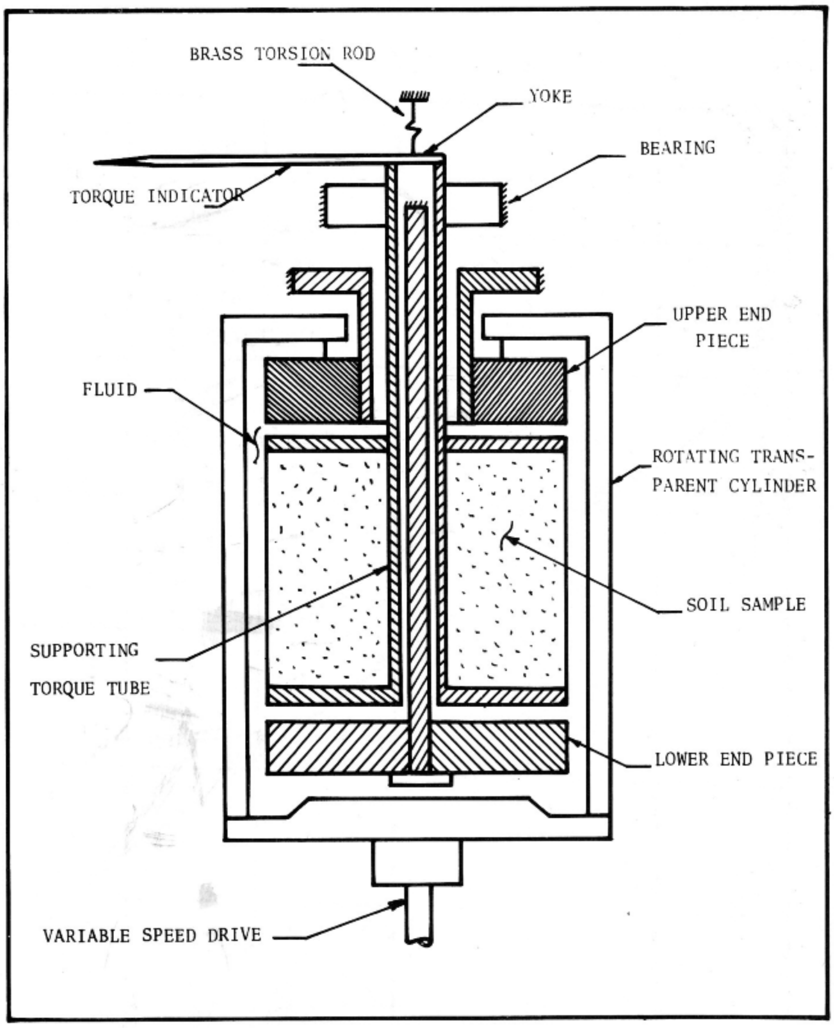


FIG.1 (1) CROSS SECTION OF APPARATUS

(after Masch et al,1965)

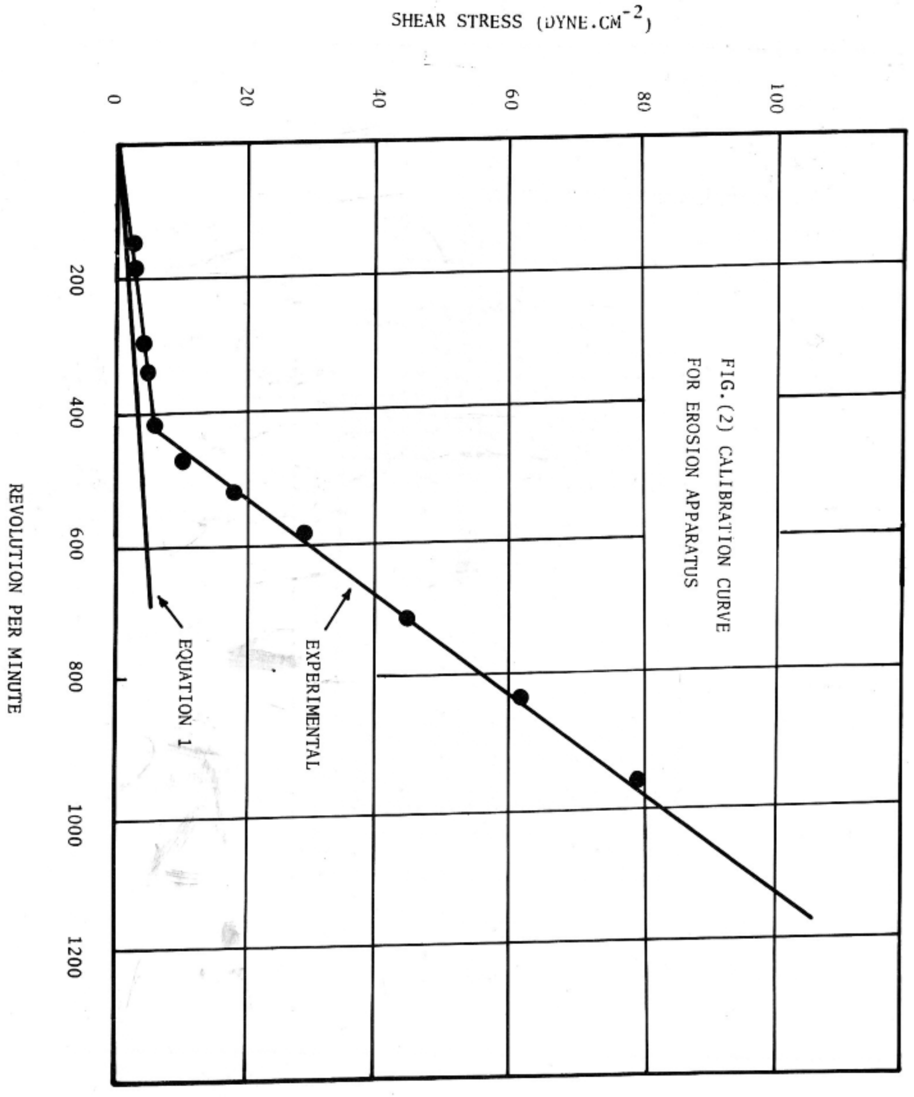


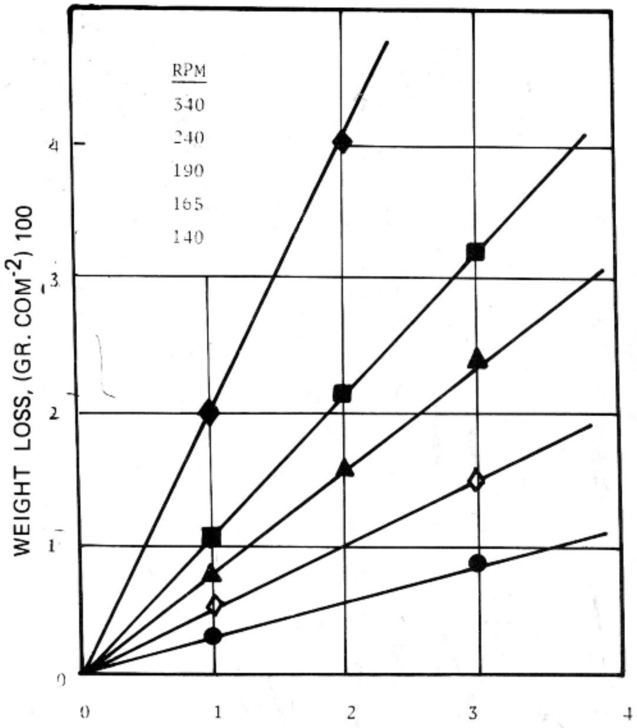
FIG.(2) CALIBRATION CURVE FOR EROSION APPARATUS ped air. As the soil was placed in the mold, it was stirred with a thin rod in order to bring any air voids to the surface. The mold had porous stones at both ends to facilitate outflow of water during consolidation.

After the consolidation had been completed, the soil sample was ejected from the mold and trimmed to the required height. Portions of the trimings were used for water content determination.

Erosion testing procedure. The 8.0 cm long specimen, supported by a mandrel, was concentrically placed into the erosion device. Prior to insertion, its height and weight were determined. The annular space between the sample and outer cylinder (1.25 cm) was filled with distilled water. The sample was then loaded to a preselected value of shear by allowing the outer cylinder to rotate at a specific speed. At this shear stress soil was eroded for one minute. The water was then drained and the wet sample was removed and weighed. The sample was returned to the device and allowed to scour for another minute, and its weight loss was again determined. This procedure was repeated for other speeds.

RESULTS AND DISCUSSION

Since the dimension and water content of the sample are known, the dry weight loss per unit area of soil sample could be calculated. The soil used was a Yolo loam with a pH of 8.2 and cation exchange capacity of 19.8 meq/100g. It contained 9.7, 10.6, 6.2 and 0.3 meq/100g of exchangeable Ca, Mg, Na and K, respectively. The dry weight loss per unit area for this soil sample is plotted versus time of erosion as shown in Fig. 3. If the slopes of the lines in Fig. 3 are plotted against the corresponding shear stress, a straight line which intercepts the abcissa will be obtained (Fig. 4). It is seen that the relationship between the erosion rate and the induced shear is linear over a considerable range of shear stress. This linearity was observed in most of the tests which were run in this investigation.



FIG(3)PLOT OF WEIGHT LOSS PER UNIT AREA VERSUS TIME FOR YOLO LOAM.

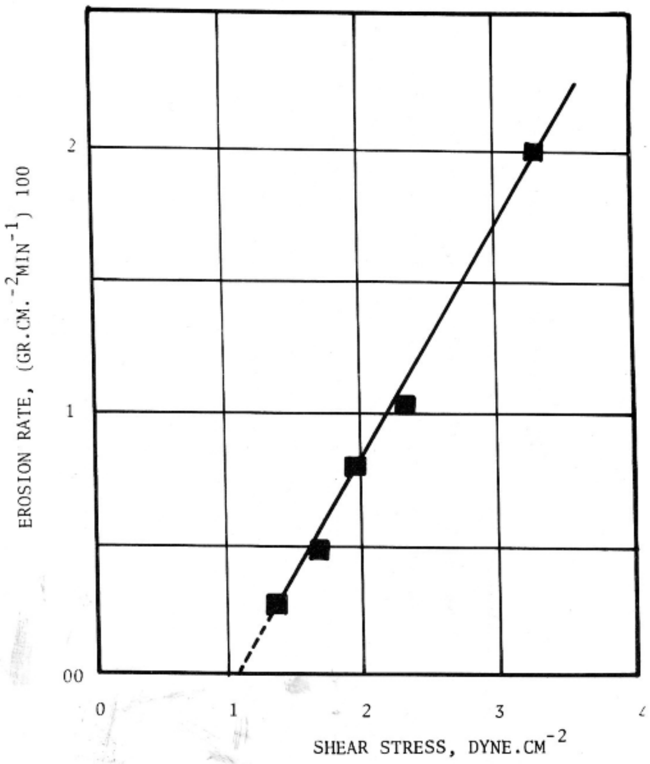


FIG.(4) PLOT OF SHEAR STRESS VERSUS EROSTON RATE FOR YOLO LOAM.

The intercept point on the induced shear axis in Fig. 4 corresponds to zero erosion rate. This point indicates the critical shear stress required to initiate erosion. The slope also indicates the change in erosion rate per unit of induced shear stress above the critical value.

Since erosion rate and the critical shear stress are the two most important erodibility indices, the following conclusions appear to be justified.

1. Test procedure and the method of measuring hydraulic critical shear stress is simple.
2. Preparation of soil samples is not difficult. Since the reproducibility of the results were proved in this investigation, having identical samples, this method is feasible to study the effect of various factors on the erodibility of cohesive soils.

LITERATURE CITED

1. Arulanandan, K., A. Sargunam, P.I. Loganathan and R.B. Krone. 1973. Application of chemical and electrical parameters to prediction of erodibility. U.S. Highway Research Board, Washington D.C., Special Report 135: 42-51.

2. Dunn, I.S. 1959. Tractive resistance of cohesive channels. J. Soil Mech. Found. Div., Proc. Amer. Soc. Civil Eng. No. SM3: 1-24.

3. Espey, W.H. 1963. A new test to measure the scour of cohesive soils. M.S. Thesis, University of Texas, Austin, Texas.

4. Moore, W.L. and F.D. Masch, 1962. Experiments on the scour resistance of cohesive sediments. J. Geophys. Res. 67: 1437-1449.
5. Masch, F.D., W.H. Espey and W.L. Moore. 1965. Measurement of the shear resistance of cohesive sediments. Proc. Federal-Agency Sedim. Conf. ARS, Washington D.C., Pub. No. 970: 151-155.

6. Partheniades, E. and R.E. Passwell. 1970. Erodibility of channels with cohesive boundary. J. Hyd. Div., Proc. Amer. Soc. Civil Eng. No. HY3: 755-771.
7. Smerdon, E.T. and R.P. Beasily. 1959. The tractive force theory applied to stability of open channels in cohesive soils. Res. Bull. 715, College of Agriculture, Agric. Exp. Sta.,Columbia, Missouri.
8. Taylor, G.I. 1963. Fluid friction between rotating cylinders. Proc. Royal Soc. London, Series A, 157: 546-564.