Use of Rotational Erosion Device on Cohesive Soils

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Water erosion of cohesive soils is a complex phenomenon that includes different processes. A classification of erosion processes is proposed and examples are given in relation to highway construction. In the case of the scour resistance of solid clays, available prediction methods propose relationships between physical or mechanical parameters and the critical hydraulic shear stress (τc) that defines a boundary between erosion and no erosion, whereas erosion rates usually are not estimated. These methods have been questioned because it appears that the physicochemical parameters of both the clay and the eroding water control the erosion process. Subsequent research on these parameters has yet to yield reliable predictions based on indirect measurements. Consequently, it is deemed necessary to test the clay and eroding water for each case. In order to study the erodibility of solid cohesive soils, a rotational erosion device has been improved. Either intact or remolded samples can be tested, physicochemical parameters can be controlled, and the hydraulic shear stress (τ) and the erosion rate ($\dot{e}$) can be adequately determined. A relatively complete and accurate graph of $\dot{e}$ versus τ, including $\dot{e}$-values for τ-values lower than critical, can be established. The influence of water quality or of any stabilizing treatment of the cohesive soil may be quantitatively analyzed.

The erosion of cohesive soils may be an economically important problem that must be controlled in natural rivers and excavated irrigation and drainage channels, on natural and man-made slopes, and under highway pavements.

A solid cohesive soil may be eroded by the different processes shown schematically in Figure 1. They may be classified according to three criteria:

- Duration: occasional (O) or permanent (P),
- Type: steady (S) or unsteady (U), and
- Location: external (E) or internal (I).

Examples of erosion processes are given in Table 1. These processes produce sediments that are transported, sorted, and deposited and as such give rise to another problem, namely, the erosion of aqueous unconsolidated cohesive sediments.

Problems related to rain and wind erosion frequently occur in highway construction and have been covered in two TRB publications *(1, 2)*. This paper deals only with quantitative measurements of the scour resistance (external process) of cohesive soils, using a modified rotational erosion device that simulates an external erosion process.

A few researchers have attempted to use external erosion test results for predicting internal erosion *(3)* or, alternatively, pinhole test results for predicting external erosion (*4*,pp.23–34). However, it is known that for certain clays, field observations of internal erosion do not substantiate the clay behavior during pinhole tests (*5*,pp.74–93). Furthermore, it is believed that the internal and external erosion processes cannot be realistically compared (*6*,pp.3–12;*7*, *8*), even if they are influenced by many common factors.

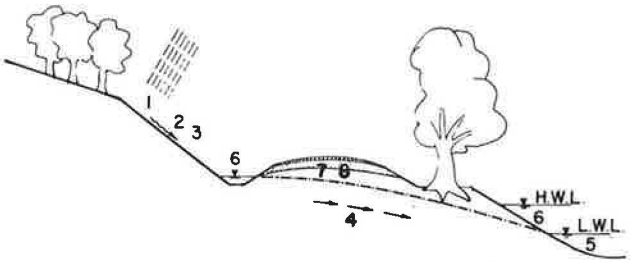

FIGURE 1 Different erosion processes involving cohesive soils (see Table 1).

BACKGROUND

For granular soils the water erosion processes are fairly well understood: they depend mainly on particle size, particle shape,

TABLE 1 EXAMPLES OF EROSION PROCESSES AND CLASSIFICATION ACCORDING TO DURATION, TYPE, AND LOCATION

Erosion Mode[a]	No., Figure 1	Example
OSE	1(2, 3)	Occasional steady rain erosion; splash, rill, and inter-rill erosions
	6	Occasional scour erosion of river above low-water line
OSI	4	Occasional internal erosion within clay foundation of road
OUE	1(2, 3)	Occasional nonsteady rain erosion
	6	Occasional scour erosion of clayey river soil caused by wave action or transported ice or debris influenced by frost action
OUI	7	Occasional dynamic erosion of clay due to traffic; end result, subbase contamination
PSE	5	Scour erosion in regulated canal
PSI	4	Internal erosion within clayey core of dam
PUE	5	Scour erosion of river under low-water line
PUI	8	Internal erosion of clay due to vibrating machine

[a]Duration: occasional (O) or permanent (P); type: steady (S) or unsteady (U); and location: external (E) or internal (I).

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gradation, relative density, and the type and the amount of sediment present in the eroding fluid *(9)*. Much less is known for cohesive soils: erosion appears to be controlled by physicochemical factors. In sucessive state-of-the-art reports *(10–13*,pp.52–74) it has been concluded that the need to define the fundamental erosion processes of cohesive soils and to develop criteria and guidelines applicable to field problems is great.

Research on the erodibility of cohesive soils has been carried out by hydrotechnical and agricultural engineers and by soil scientists, who have oriented it to their needs. Hydraulic engineers use the hydraulic or tractive force defined as the shear stress induced on the soil surface by flowing water. They have defined a critical shear stress (τc) above which scour of a solid cohesive soil begins. To design a hydraulically stable channel, either a critical tractive stress or the corresponding safe water velocity (at a given depth and location) is selected to avoid undesirable erosion. Hydraulic engineers have proposed predicting τc from physical or mechanical properties.

Agricultural engineers are concerned with erosion control in permanent or temporary irrigation channels and with land erosion from rainfall in relation to damage to agricultural productivity. They take into account the influence of soil type, vegetation, and duration of rain or irrigation.

Research by soil scientists is often limited to regional aspects, and the mineralogical and chemical properties of the soil are systematically underlined.

From the available results, it appears that the erosion of cohesive soils is an interdisciplinary field and that the fundamental erosive actions are not fully understood. The electrochemical bonds between fine particles of cohesive soils have a marked influence on their erodibility. These bonds depend on many parameters, which in turn are influenced by the physicochemistry of the eroding fluid. All these factors play a great part in the complexity and the interdisciplinary character of the problem.

The external erosion of cohesive soils has been investigated with the following experimental techniques:

1. Submerged water jets perpendicular to a clay surface,
2. Open flume tests,
3. Channel tests, and
4. Rotating cylinder tests.

Techniques 1, 2, and 3 have yielded different design methods related to the physical or the mechanical properties of soils. However, their capabilities are limited: usually erosion is visually appreciated without any quantitative measurements. Furthermore, as mentioned by Berghager and Ladd *(14)*, most investigators do not adequately control the geotechnical properties of the clays.

For a better accounting of physicochemical factors, it was deemed necessary to devise new testing techniques that allow these factors to be controlled. The rotational erosion device was developed initially by Moore and Masch *(15)* at the University of Texas at Austin and has been modified by others. In the early 1960s, Epsey *(16)* and Masch et al. *(17*,pp.151–155) operated it with a mixture of water and glycerine and more recently a research team [Arulanandan et al. *(18, 19)*] at the University of California Davis Campus carried out extensive research with this technique. The research focused on remolded and reconsolidated samples of artificial clay mixes. It was shown that the critical shear stress depends on the combination of clay and eroding water and on the influence of physicochemical parameters such as the sodium absorption ratio and the concentration of pore-fluid ions. Predictive charts have been developed for certain remolded artificial soils *(20)*. No such data are available for undisturbed natural clays.

The principle of the rotational erosion device is to use an annular water flow around a stationary soil sample (Figure 2). When the outer plexiglass cylinder is rotated (at regulated speeds up to 2,500 rpm), rotation is imparted to the fluid, which in turn transmits a shear to the surface of the soil cylindrical sample. An erodibility test includes successive stages of constant revolutions per minute. For each stage, the erosion rate ($\dot{e}$) is defined as the sample loss (dry weight) per unit surface and per unit time. The shear stress acting on the soil cylinder is derived from the torque required to hold it stationary.

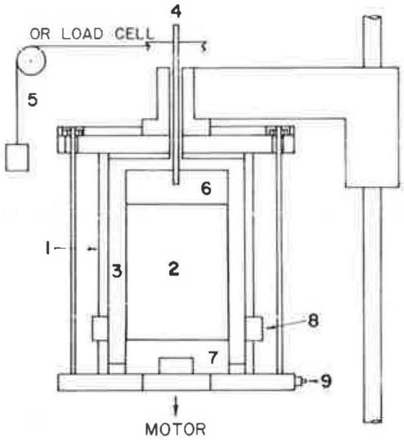

FIGURE 2 Rotational erosion device: *(1)* rotating external cylinder, *(2)* soil sample, *(3)* eroding water in annular space, *(4)* guiding shaft for installation, *(5)* torque measurement system, *(6)* head, *(7)* base, *(8)* access for cleaning, *(9)* gravity drainage.

Recent changes in the technical design and the test procedure for the rotational erosion device are discussed.

CHANGES IN TECHNICAL DESIGN

Intact or Remolded Samples

Previously only remolded cohesive soils or mixes could be tested in the rotational erosion device. In the Davis studies, a paste was prepared with distilled water, and a salt solution was then added to obtain a slurry. The salt solution consisted of predetermined amounts of Ca, Mg, K, and Na that matched as nearly as possible the chemical composition of the fluid extracted from the soil paste. The sample was then reconsolidated around a metallic shaft to which lower and upper plates were connected for support and trimming of the sample. The protruding portion of the shaft was used to suspend the soil sample, which was positioned and guided only at one end.

For studies related to natural rivers or excavated channels, it is better to use intact samples. Thus, the apparatus was modified to accept either intact or remolded reconsolidated samples. The soil sample was mounted between two metallic short cylinders (base and head) of the same diameter, both guided in rotation by ball bearings (Figure 2). The shaft through the sample was eliminated. The base rotated freely relative to the bottom of the outer transparent cylinder. The torque transmitted by the eroding fluid to the soil cylinder was measured by means of an upper shaft connected to the head. Cell and sample rotations were completely independent.

The present device now allows for the study of either intact or remolded samples with an improved rotation guidance, a better alignment, a lower inherent friction, and a damped influence of end supports on the annular flow regime.

Measurement of Torque

Previously a known torque was applied to a dummy sample by means of a pulley-and-weight system, and the revolutions per minute (rpm) required to initiate the sample rotation were noted. The resulting calibration curve of the applied shear stress versus the rotation speed of the outer cylinder was used for real tests in which the clay samples were held stationary by a torsion wire. Thus, it was assumed that the clay sample was submitted to the same shear stress as that measured with the dummy sample for a given speed.

The preceding assumption was verified with the present device. Various torsion wires were tested and calibrated. None permitted a satisfactory determination of the shear stress acting on the clay surface.

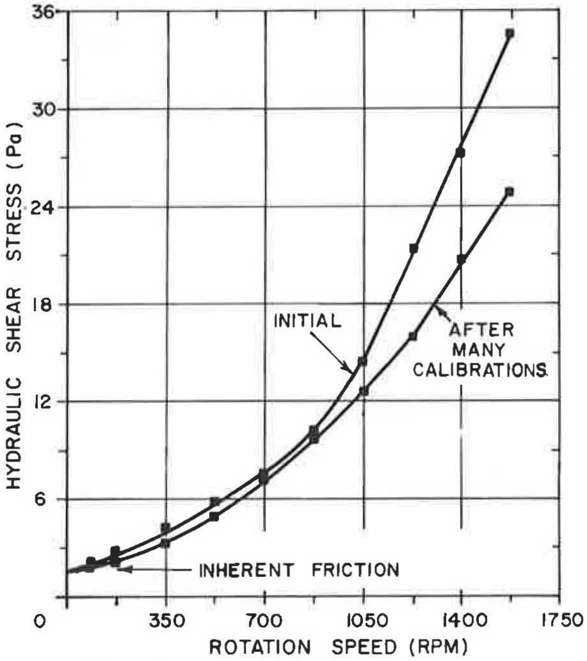

FIGURE 3 Variation of hydraulic shear stress at surface of sample of bituminous concrete versus rotation speed and number of calibrations.

The torque was then directly measured by using a pulley-and-weight system with masses ranging from 0 to 40 g at ±0.1 g. The initial tests on clays revealed that during multistage cycles of increasing and then decreasing rotation speeds, the shear stress may vary for the same rpm level. Because this phenomenon was not mentioned in the literature, different factors were considered, in particular, that of the accuracy of the measurements.

It was concluded that the shear stress acting on the soil surface depends on its roughness, in contradiction to Schlichting's equation *(21)* as presented by Arulanandan et al. *(18)*, and that this roughness is variable throughout a test because it depends on the erosive action. This conclusion became obvious after several calibrations of τ versus rotation speed had been attempted with the same sample of bituminous concrete, the surface of which became smoother as the number of calibrations increased (Figure 3).

Consequently the mean flow-induced shear stress can now be directly and continuously determined. During a stage at constant speed, the torque required to maintain the sample stationary may vary; normally it increases when particles detach and decreases when the eroded zones smooth and heal.

Measurement of Eroded Mass

Previously, before a multistage test, the sample was immersed in the eroding fluid for a period of 2 to 3 hr. At the beginning of each test stage (constant rpm), the sample with its internal shaft was immersed for 2 to 4 min to estimate the water uptake or expulsion. At the end of each 2-min stage, the sample was taken out and weighed. The difference in weight before and after each test stage, corrected for water uptake or expulsion, was considered to be the amount of eroded material. For shear stress values lower than critical, negative erosion rates were frequently calculated in the range 0 to –30 g/(m^2 · min) and down to –60 g/(m^2 · min).

This method was deemed questionable for two reasons: *(a)* the dripping sample was wiped and rapidly weighed, resulting in an approximate moist weight; thus, the small difference between two successive readings was quite inaccurate; and *(b)* repetitive manipulations disturbed the sample.

A new measuring technique was developed so that the clay sample need never be removed from the apparatus during the test. The eroding fluid was drained at the end of each test stage. The cell was then cleaned by means of a water aspiration system and rinsed with fresh eroding fluid. The amount of oven-dried eroded material was then weighed. These modifications allowed for a more accurate determination of both the shear stress and the erosion rate. In previous studies, the intercept on the τ-axis, corresponding to a zero erosion rate, was defined as the critical shear stress necessary to initiate important external erosion. With this device, the critical shear stress is defined as the point where the slope of the curve ($\dot{e}$, τ) changes abruptly.

Inherent Friction of Device

A good determination of the torque requires that the sample never be manipulated during the test: the only quantity attainable is the sum of the variable torque applied to the sample and that due to the inherent friction of the rotational device. The former depends on the roughness of the soil surface and on the rotation speed, whereas the latter is a mechanical rolling friction depending on the relative adjustment of the many coaxially rotating parts of the apparatus. If the cell is dismantled for sample removal at the end of each test stage, the resulting mechanical readjustments affect the inherent friction, which thus takes on as many different values as stages. However, if the sample is not manipulated, the inherent friction may be deemed constant throughout the test, and it is obtained by extrapolating the curve of τ versus rpm back toward the ordinate.

The inherent friction torque was much reduced through mechanical improvements of the rotational device and ranged from 0.05 to 0.30 N · cm. Maintaining such low values requires that some of the 10 coaxial ball bearings be replaced frequently because of abrasion by eroded sand and silt particles.

Protection of Sample Edges

In flume tests preferential erosion occurs at the contact interfaces of clay plates. Similarly, in the rotational erosion device preferential erosion frequently starts at the sample and head or base interfaces. To avoid this phenomenon, cylindrical steel foils are used to protect the contact interfaces.

SAMPLE PREPARATION

The natural clay samples must be cut from intact blocks using a template and a steel wire. The cohesive soils and the artificial mixes can be reconstituted and reconsolidated in a triaxial cell after physicochemical or mechanical treatment. In both cases, the rotational shear device allows for in situ conditions to be adequately respected.

The preparation method has a marked influence on erodibility test results. For example, the cutting of an intact sample with a thin-wall tube is not recommended: the sample surface is scaled because of surface remolding. In the case of remolded samples reconsolidated in an odometric cell, it is likely that the same surface problem would appear.

It was noted that triaxially prepared samples have a smoother and less erodible surface than samples cut from the same clay for shear stress values lower than critical. A schematic representation of this phenomenon is given in Figure 4: Curve A is for the cut intact samples, whereas Curve B is for the triaxially prepared samples of the same clay, remolded and reconsolidated at the same consolidation pressure. Generally, lower shear stresses develop at the same rotation speed on triaxially prepared samples (B): they rarely suffer from small aggregate loss before the shear stress threshold contrary to cut-sample behavior (A). This explains why Curve A is above Curve B before the critical shear stress is attained. It was also noted that the mean τc-value for the triaxially prepared samples (B) was higher than that for the cut intact samples (A). This fact may be related to the lower water content for B samples than for A samples, even if the consolidation pressure is the same. It may also be related to the horizontal consolidation pressure, which is lower for intact clays (A) than for remolded isotropically consolidated samples (B).

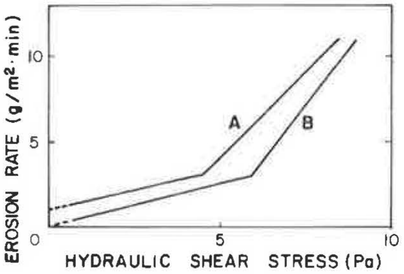

FIGURE 4 Schematized influence of sample preparation method: *(a)* intact clay samples and *(b)* triaxially prepared samples (same consolidation).

TEST PROCEDURES

A soil cylinder (75 mm in diameter and 89 mm high) is mounted coaxially on a pivoting base inside a transparent cylinder (102 mm in internal diameter) that can be rotated at a regulated speed up to 1,750 rpm. The annular space is filled with the water to be tested for its erosive properties. Rotation is imparted to the fluid by the rotating external cylinder, thereby transmitting a shear to the surface of the soil sample, which is held stationary by a pulley-and-weight system. Each test is composed of several stages at constant rotation speed, which in some respects is similar to the odometric testing procedure. A constant speed is held for 10 to 30 min and the torque is continuously recorded with a precision of 0.1 Pa for the τ-values. At the end of each stage, the fluid is drained and the cell cleaned with fresh fluid. All eroded particles thus

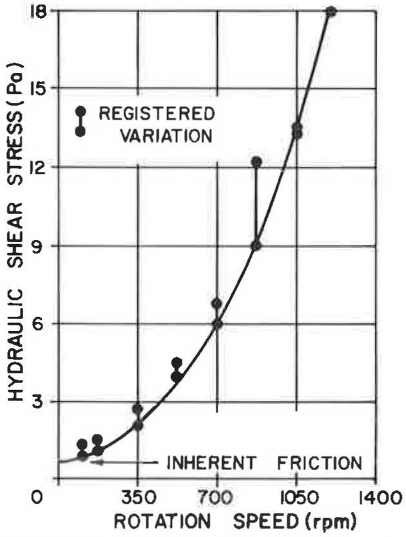

FIGURE 5 Variation of hydraulic shear stress acting on soil sample and minimum registered friction versus rotation speed.

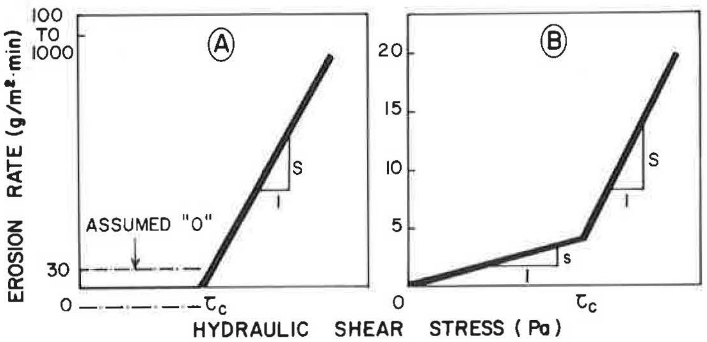

FIGURE 6 Typical results of erosion rate versus hydraulic shear stress: *(a)* earlier device (remolded samples only) and *(b)* device described in this paper (intact or remolded samples).

recovered are oven dried and then weighed at ±0.01 g. Once installed, the soil sample is never manipulated.

A test report includes a table of all measurements, a graph of the torque versus the speed (Figure 5) and a graph of the erosion rate $\dot{e}$ versus the contact shear stress τ.

For a good evaluation of the erodibility of a cohesive soil by a given eroding water, 6 to 10 samples are necessary. All test results are gathered to statistically determine *(a)* the τc-threshold above which the erosion rate $\dot{e}$ increases considerably and *(b)* the graph of the mean erosion rate [g/(m^2 · min)] versus the shear stress (Figure 6*b*). For natural clays, the usual range noted for $\dot{e}$ was 0 to 30 g/(m^2 · min) as compared with 0 to 1000 g/(m^2 · min) obtained by Arulanandan et al. *(18)* for artificial clayey mixes.

The influence of any treatment of the cohesive soil on its erodibility may be studied and the performance quantitatively evaluated in terms of the percentage of stabilizing agent (lime, cement, etc.). Similarly the influence of the water physicochemistry (pH, dissolved salts, cations, etc.) may be quantitatively analyzed.

APPLICATIONS

The rotational erosion device can be used for external erosion processes related to natural river diversions and excavated channels. It can also be used for erosion processes related to pumping by rigid pavements, a major contributor to their failure. If slab deflections occur, fines can be removed through pore-water pressure buildup in the subbase, or through water movements inducing surface erosion of subbase and shoulder materials. In recent research, Van Wijk *(22)* selected three testing procedures to investigate and characterize the erosion of rigid pavement subbase and shoulder materials: a brush test, a jetting test, and a rotational erosion technique with a device developed along the same lines as those used for the apparatus presented in this paper, after previous consultation with the author. The rotational erosion device gave the most useful results for cohesive and stabilized materials, according to Van Wijk *(22)*.

In the case of flexible pavements, pore-water pressure can build up in fine subgrade soils and some of the fines are removed and pumped out. This adversely contaminates the subbase aggregates: they are mechanically weakened, their permeability decreases, and their frost susceptibility increases. The performance of different geotextiles as separators has been investigated by Snaith and Bell *(23)*, Bell et al. *(24*,pp.429–434), Loubinoux et al. *(25*,pp.43–48), Salter *(26)*, Hoare *(27*,pp.423–428), Friedli and Anderson *(29*,pp.473–478), and Brochier *(30)*. According to the available results, it appears that no filter method will completely prevent fines contamination by pumping. Consequently, the erodibility of cohesive soils is still an important parameter to be evaluated for flexible pavements. This erosion is internal and of the OUI type: a reduced-scale-model method respecting physicochemical conditions is deemed more adequate than the rotational erosion device for simulating this erosion process.

CONCLUSIONS

The rotational erosion device is used for quantitative measurements of the scour resistance of cohesive soils. It has been modified to accept either intact or remolded cohesive soils, with an improved rotation guidance, a better alignment, a lower internal friction, and a reduction of the influence of end conditions of the fluid annular flow. The procedure to measure the eroded mass of soil has been modified. The major advantages of these modifications are that both the shear stress and the erosion rate can be determined more accurately and intact samples can be tested. Typical test results obtained with the improved devices are shown in Figure 6*b* and may be compared with those typically given by the previous apparatus (Figure 6*a*). This modified rotating-cylinder technique better meets the conditions required for a fundamental study of scour resistance of solid cohesive soils.

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