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Erosion Function Apparatus Overview and Discussion of Influence Factors on Cohesive Soil Erosion Rate in EFA Test

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Abstract: The EFA (Erosion Function Apparatus) is a new device used to measure the erodibility function of soils and soft rocks. Samples are taken from the bridge site in a thin wall steel tube which is then fitted through a tight opening at the bottom of a pipe with a rectangular cross section. Water flows over the soil or soft rock sample. The erosion rate of the soil or soft rock is recorded and the hydraulic shear stress applied at the interface is calculated by using Moody Chart. The advantages and limitations of the EFA are discussed in this paper. The results of tests using water with different pH and salinity show that both factors influence the erodibility function. An attempt is made to find a correlation between the critical shear stress, and the initial slope of the erodibility function on one hand and the water content, the undrained shear strength, the plasticity index and the percentage passing the #200 sieve on the other. This attempt is unsuccessful.

INTRODUCTION

Bridge scour is an important factor which can cause the failure of a bridge. One thousand bridges have collapsed between 1961 and 1991 in the United States and 60% of the failures are due to the scour (Shirole and Holt, 1991). Only 2% of the bridge failures in that database were due to earthquakes. A new method called SRICOS (Scour Rate in Cohesive Soil) was published (Briaud et al., 1999). This method was proposed to predict the scour depth versus time around a bridge pier. One essential part of SRICOS method is to test the soil samples collected at the site in the EFA (Erosion Function Apparatus) to obtain the scour rate versus hydraulic shear stress applied curve or erodibility function (Briaud et al, 1999). The EFA test gives

- The erosion rate versus shear stress curve
- The critical shear stress at which erosion starts

These two results are used in the SRICOS method to predict bridge scour.

This paper presents the EFA, the EFA test and gives some EFA test results including some tests to quantify the influence of the pH and salinity of the water eroding the cohesive soil.

EFA (EROSION FUNCTION APPARATUS) OVERVIEW

The EFA was designed, developed, patented, and licensed at Texas A&M University starting in 1991 (Briaud et al., 1999). Humboldt is now manufacturing the device which is in its third generation of evolution.

Basic Principle

The EFA is used to measure the erosion rate of different types of soils and soft rocks, ranging from clay to gravel, and from soft soils to soft rocks. The conceptual

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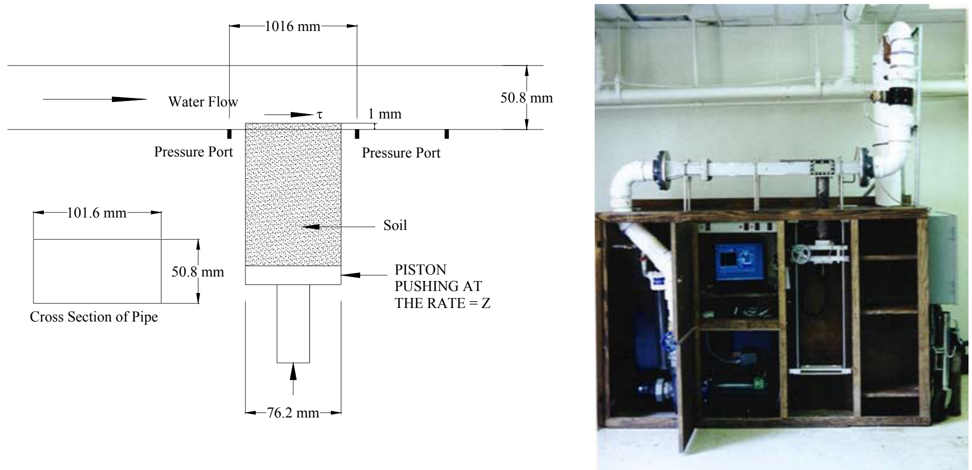


(a) **(b)**

Figure 1: (a) Conceptual Diagram; (b) Photograph of EFA

diagram and photograph of the EFA are shown in Figure 1. The soil sample is taken from the bridge site by pushing an ASTM standard Shelby tube with a 76.2 mm outside diameter (ASTM 1999a). If the tested material is a soft rock, a core sample can be obtained and placed in the Shelby tube. The Shelby tube will be put into the rectangular cross section pipe through a circular opening in the bottom of the pipe. The dimension of the rectangular cross section of the pipe is 101.6 × 50.8 mm. The length of the horizontal pipe is approximately 1.2 m. The water is driven through the pipe by a pump. A valve is used to adjust and regulate the flow velocity and a flow meter is installed to measure the flow rate. The end of the Shelby tube is kept flush with the bottom of the rectangular pipe. A piston pushes the soil sample until it protrudes 1mm into the rectangular pipe. This 1mm protrusion of the soil sample will be eroded with time.

General Procedure of EFA Test

The general procedure of the EFA test is as follows: (Briaud et al., 2001)

1. Place the sample in the EFA, fill the pipe with water, and wait one hour.
2. Set the initial water velocity, say 0.2 m/s.
3. Push 1mm of soil sample out of the steel tube into the test section
4. Pushing the soil sample when necessary during the erosion process to maintain a soil or soft rock protrusion between 0 mm and 1 mm into the flow until a 50 mm length of soil is eroded or 1 hour has been reached, whichever comes first. The scour rate corresponding to that velocity is calculated as the total soil push divided by the time required for the erosion process.
5. Stop the pump, take out the Shelby tube, trim the surface to be flush with the bottom of the rectangular pipe and then repeat Step 2 to 4 with another water velocity.
6. Once 6 to 8 velocities have been tested, the scour rate vs. velocity curve is

obtained, and is converted into the scour rate vs. shear stress curve or erodibility function.

EFA Test Results

The test result consists of the erosion rate $\dot{z}$ versus shear stress τ curve (Figure 2) also called erodibility function. For each flow velocity, the erosion rate (mm/hr) is simply obtained by dividing the length of sample eroded by the time required to do so. After several attempts at measuring the shear stress τ in the apparatus it was found that the best way to obtain τ was by using the Moody Chart (Moody, 1944) for pipe flows.

$$\tau = \frac{1}{8} f \rho \upsilon^2$$

Where τ is the shear stress on the wall of the pipe, f is the friction factor obtained from Moody Chart (Figure 3), ρ is the mass density of water (1000 kg/m3) and υ is the mean flow velocity in the pipe. The details of the calculations can be found in Briaud et al. (2001).

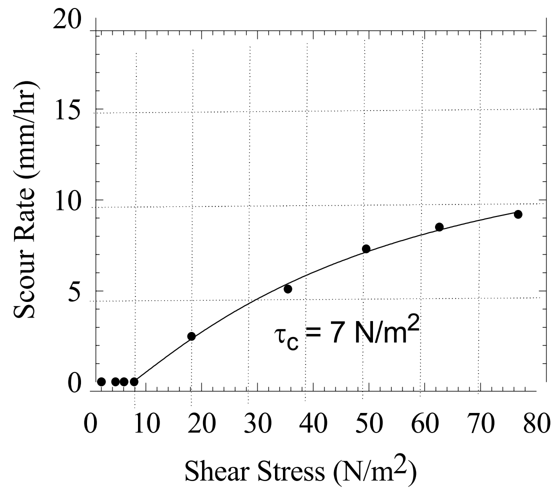


Figure 2: Typical EFA Test Result

Advantages of the EFA

1. Minimum sample disturbance.
2. Direct site specific measurement of the erosion rate vs. shear stress curve (erodibility founction) including the critical shear stress for the soil or soft rock.
3. Test results incorporated in a scour prediction method (SRICOS) which may save foundation depth.

Drawbacks of the EFA

1. Requires samples from the site.
2. Test takes about one hour per velocity.
3. Size of particles that can be tested limited by size of sample.

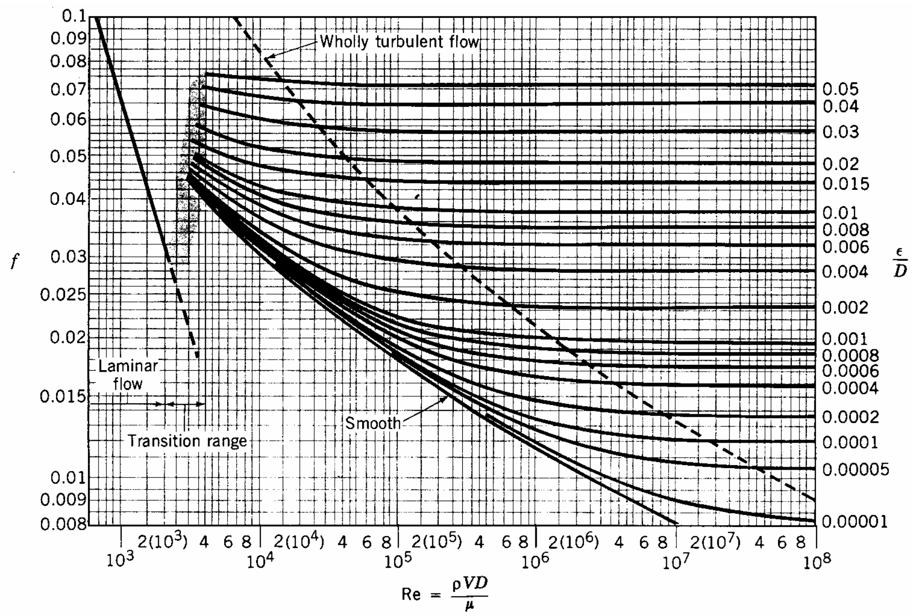


Figure 3: Moody Chart [Reprinted with Permission from Munson et al. (1990)]

INFLUENCE OF WATER pH ON ERODIBILITY FUNCTION

The erosion of cohesive soils is a very complicated process. Gravitation and friction laws control the scour process of cohesionless soils while physicochemical laws control the scour process in cohesive soil. The scour process is a soil-water interaction, which involves a large number of factors. The erodibility of a cohesive soil is characterized by the erodibility function, which is the $\dot{z}$ versus τ curve. It requires a number of curve-fitting parameters to describe the nonlinear relationship between $\dot{z}$ and τ (Briaud et al., 2001). One of the curve-fitting parameters is the critical shear stress τ_c, the shear stress at which erosion begins. For sands, HEC-18 gives some equations to calculate the critical shear stress by using the size of the grains represented by D_{50}. For clay, it is difficult to use a formula to get the τ_c value directly because of the large number of factors influencing it. Briaud et al. (1999) summarized the influence factors for τ_c: soil water content, soil unit weight, soil plasticity, soil shear strength, soil void ratio, soil swell, soil mean grain size, soil percentage passing the No. 200 sieve, soil clay mineral, soil dispersion ratio, soil cation exchange capacity, soil sodium absorption ratio, soil pH, soil temperature and water chemical composition. In order to evaluate the influence of this last factor on the erodibility function of a cohesive soil, two major water chemistry factors (water pH and salinity) were selected and a series of tests were run in the EFA for this purpose.

<u>Introduction</u>

The purpose of the pH tests was to study the possible influence of the pH on the erodibility of clays. The clay tested was a porcelain clay. Many researchers have studied the influence of the water pH value or the soil pH value on the erodibility of a cohesive soil. Alizadeh (1970) found that the pH value in the eroding water and the pH value in the soil influences significantly the erodibility of a cohesive soil. Arulanandan et al. (1980) also mention that the pH value of the eroding fluid and the soil pH value were critical factors for the erodibility of a cohesive soil. Sherard et al. (1976) found that the erodibility of a Ca-Montmorillonite in an embankment, which was severely damaged by rainfall, could be reduced by using sodium salt, such as Na_2CO_3. Shaikh et al. (1988) used a series of flume tests with three different types of clay. Their results showed that the soil pore water chemistry is the most important parameter affecting the erodibility of unsaturated compacted clays. The pore water chemistry was characterized by the SAR (Sodium Absorption Ratio) and the TDS (Total Dissolved Salts). The SAR is the ratio of the dissolved sodium ions to other main basic cations, such as Ca and Mg in the pore water; and the TDS is the total dissolved salt, or total dissolved solids concentration. The erosion rate of the Ca-Montmorillonte with a TDS=7.8 and an SAR=0.4 was 300 times greater than that of the Na-Montmorillonite with a TDS=20.5 and an SAR=19.8.

Experimental Parameters

The soil used was the Armadillo Porcelain Clay. The predominant component of this commercial clay is Kaolinite. The chemical formula for Kaolinite is $Si_2Al_2O_5\,(OH)_4$. The layers of Kaolinite are composed of one silica tetrahedral sheet and one alumina octahedral sheet (gibbsite). Kaolinite is the most prominent member of this group, which also includes halloysite, nacrite and dickite. Tap water was used as the eroding water. The chemical material used to bring the pH value down was sodium bisulfate ($NaHSO_3$). It is the main component of the product named pH minus, which contains 94.5% of $NaHSO_3$ and 5.5% of other ingredients. The chemical material used to raise the pH value is soda ash or sodium carbonate (Na_2CO_3). It is the main component of the product called pH plus. It contains 99.6% of Na_2CO_3 and 0.4 % of the inter ingredients. Before the tests started, the water tank was filled with tap water. Then the pH plus or pH minus products were gradually added into the tank. A pH probe (OAKTON pH Tester 3) was used to measure the pH value when the chemical material was absolutely dissolved into the water. Once the desired pH value was reached, the EFA tests were started immediately. During the tests, there was neither fresh water filled in nor water pumped out. The following table shows some chemical properties of the eroding water.

Properties	Tap water	Acid Condition	Alkalinity Condition
Molar Concentration (M/L)	N/A	0.0077	0.463
pH Value	8.39	5	10.79
TDS (mg/L)	536	1210	>19900
SAR (ppm)	500	1200	44300
Conductivity (millisiements)	1.1	2.4	65.40

General Procedures for pH Tests in the EFA

1. Push a standard Shelby tube (ASTM) with a perpendicular direction into a porcelain clay block to get the soil sample. Then label the tube properly.
2. Fill the water tank and gradually add pH minus or pH plus into water. Make sure that the desired pH value of water has been reached before the test start.

3. Start the pump and achieve an initial low water velocity in the flume. The water flows over the sample at the chosen velocity and 1mm of soil sample is pushed into the flow.
4. Keep pushing the soil sample in Shelby tube to maintain the protrusion of soil sample between 0mm and 1mm in the flow until a 50mm height of soil has been eroded or 1 hour is reached, whichever comes first. The scour rate can be calculated as the total soil push divided by the time it takes to erode it.
5. Stop the pump, take out the tube and trim the clay surface to be flush with the edge of the Shelby tube. Then repeat Step 2 to Step 4 with a higher flow velocity.
6. Once 6 to 8 velocities have been performed, the scour rate vs. velocity curve is obtained. Then the scour rate vs. shear stress curve can be calculated by using Moody Chart.

<u>Test Results</u>:
The results of the pH tests are shown on figure 4. They indicate that whenever the pH value was away from neutral, the scour rate of the porcelain clay decreased and the critical shear stress τc increased. The initial slope Si of the scour rate vs. shear stress curve did not change much when the pH value changed. The surface charges of some soil are dependent on the soil properties (Brady, 1990). Porcelain clay belongs to this type of soil. As the pH value increases, the cation concentration changes and affects the resistance to erosion.

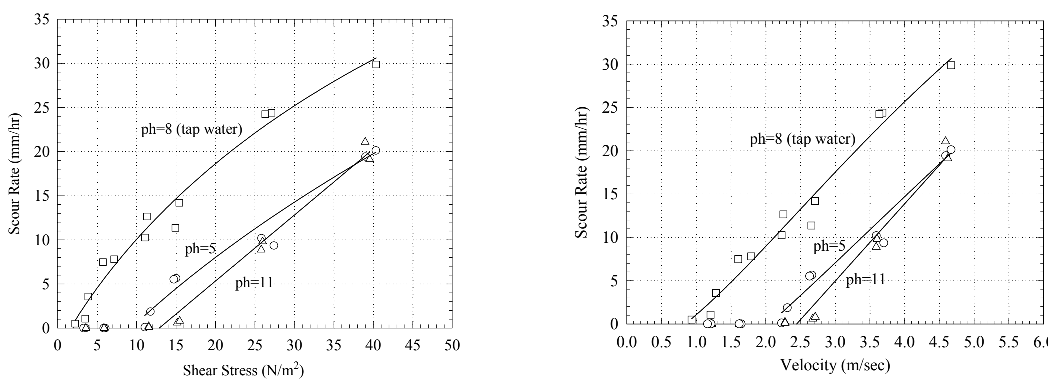


Figure 4: Relationship between Erosion Rate and Shear Stress & Velocity for different pH Values

INFLUENCE OF WATER SALINITY ON ERODIBILITY FUNCTION

<u>Introduction</u>
In delta areas, where the river flows into the sea or bridges cross an inlet, the salt concentration in the water under the bridge can range from 0 to 35,000 ppm (part per million). EFA tests using water at the right salinity can simulate the real condition.

Sherard et al. (1972) carried out extensive research work on piping in earth dams of dispersive clay in Australia. It was found that two major factors would influence the erosion rate of dispersive clays: SAR and TDS. Sherard reported that smaller TDS concentrations in the eroding water lead to higher erosion rates in clay soils. Arulanandan (1975) performed a series of erosion tests in Yolo Loam using a rotating cylinder apparatus with different concentrations of NaCl in the eroding water: distilled water, 0.001N NaCl and 0.005N NaCl. Figure 5 shows the results of the tests and indicates that the critical shear stress increases with the salt concentration and so does the erosion rate.

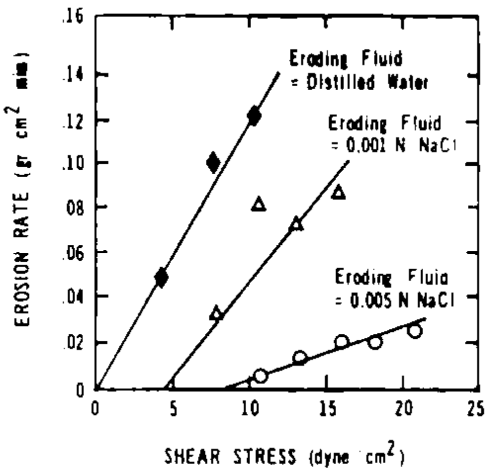


Figure 5: Relationship Between Erosion Rate and Shear Stress for Different Concentration of Eroding Fluid (After K. Arulanandan)

Liou (1970), Sherard et al. (1972, 1976) and Sargunan et al. (1973) also studied the effect of the chemical composition of the pore water on the soil erosion rate. They concluded that the presence of cations in the pore water tends to make the soil more scour resistant because they reduce the repulsive electric force between clay particles.

Experimental Parameters:

The porcelain clay used for the pH tests was also used for the salinity tests in the EFA. Tap water was used as the eroding water and mixed with salt to reach the following concentrations: 500ppm salinity (tap water), 17500ppm salinity (50% seawater), 35000ppm salinity (100% seawater). The salt used in the salinity tests was table salt, 99% of which was NaCl. Before the test, table salt was gradually added into the water with mechanical agitation. A salinity probe (ORION Model 115) was used to measure and monitor the change in salt concentration. As in the pH tests, there was neither salt nor water added or withdrawn during the EFA test. The following table shows the selected chemical properties of eroding water for the salinity test.

Properties	Tap water	50% seawater	100% seawater
Salinity (ppm)	500	17500	35000
TDS (mg/l)	536	15900	>19900
PH Values	8.39	8.12	7.96
Conductivity (millisiements)	1.15	28.3	52.9

General Procedure for Salinity Tests in the EFA:
The procedure for the salinity tests was similar to the procedure for the pH tests. Please refer to the corresponding section in the pH test and just replace table salt with pH plus or pH minus at the appropriate places.

Experimental Results

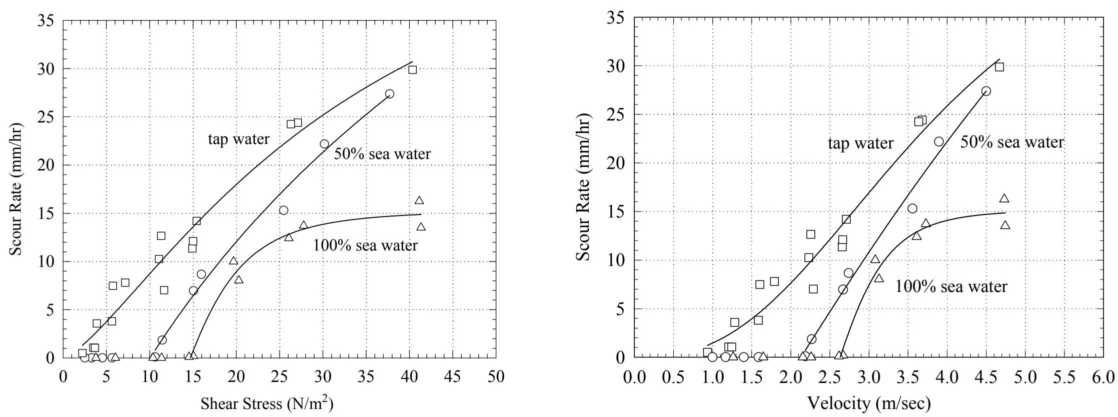
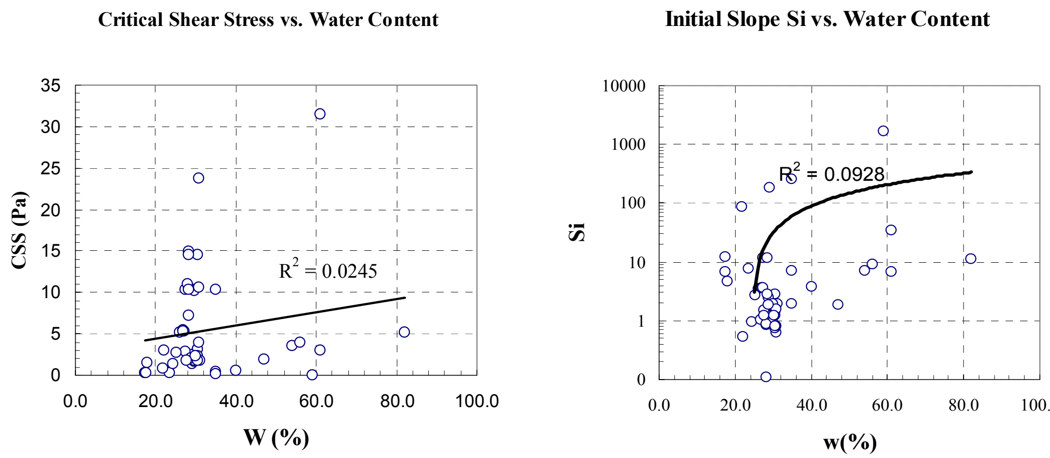


Figure 5: Relationship Between Erosion Rate and Shear Stress & Velocity for Different Concentration of Salinity of Eroding Fluid

Data Analysis:
The results of the salinity tests are similar to the tests by Arulanandan (1975). They show that the scour rate decreases with increasing salinity, while the critical shear stress increases with increasing salinity. The influence of salinity on the scour rate and the critical shear stress seems to be significant. Some differences with Arulanandan's work were also found. First, the initial slope of the scour rate vs. shear stress curve in Arulanandan's tests decreased with increasing salinity, while it was the opposite in the EFA salinity tests. Second, at high salinity concentration in EFA tests, the scour rate vs. shear stress curves lost linearity and converged to a maximum value. While the curves from Arulanandan's tests were linear. A possible explanation is that the shear stress level in Arulanandan's tests is quite low compared to the EFA tests. The maximum shear stress for Arulanandan's tests is about 2 N/m^2; compared to 40 N/m^2.in the EFA tests.

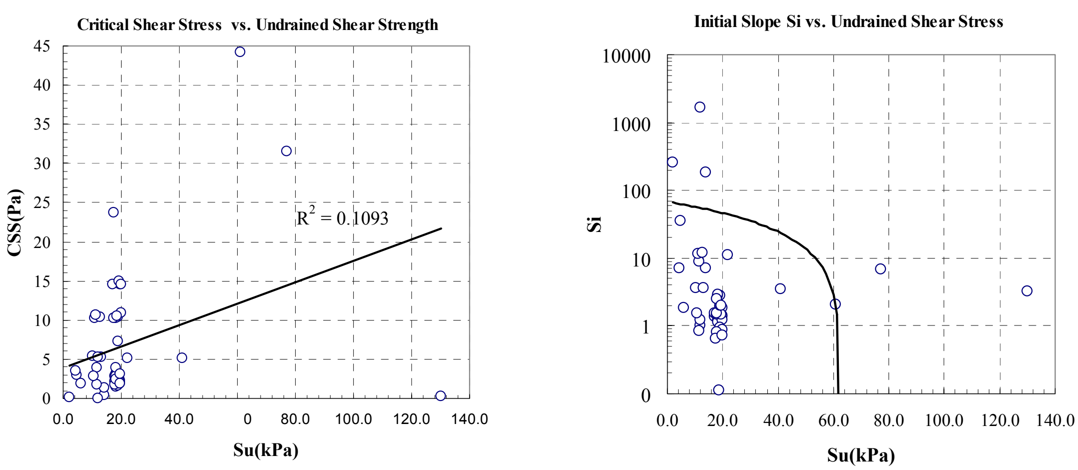
INFLUENCE OF SOIL PROPERTIES ON ERODIBILITY FUNCTION

More than 100 EFA tests have been performed at Texas A&M University on different soils. Based on the data accumulated, a scour database has been organized. Using this database, the potential relationship between on one hand the critical shear stress and the initial slope of scour rate vs. shear stress curve and on the other hand the water content (w%), the undrained shear strength (Su), the plastic index (PI), and the percentage passing sieve no. 200. The following figures show the results.



(a) **(b)**

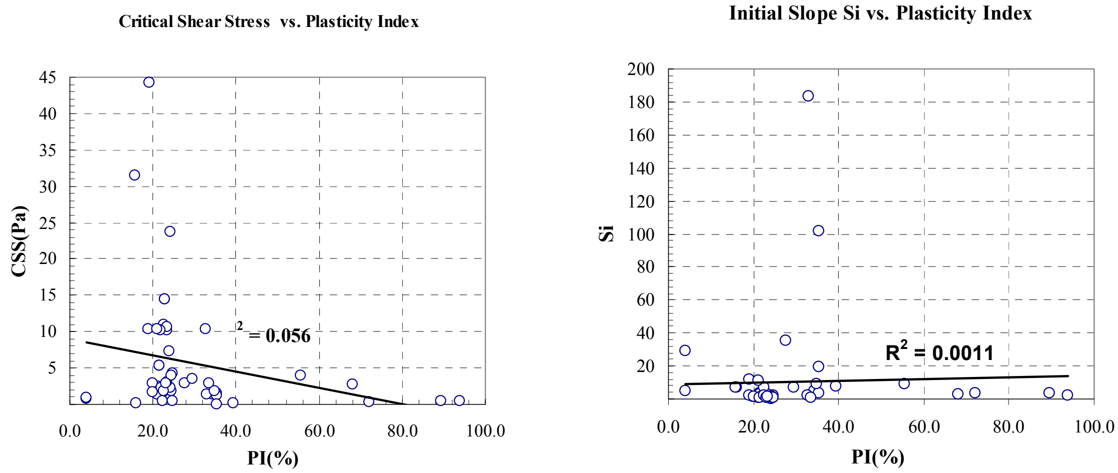
Figure 7: (a) Relationship Between Critical Shear Stress vs. Water Content; (b) Relationship Between Initial Slope Si vs. Water Content



(a) **(b)**

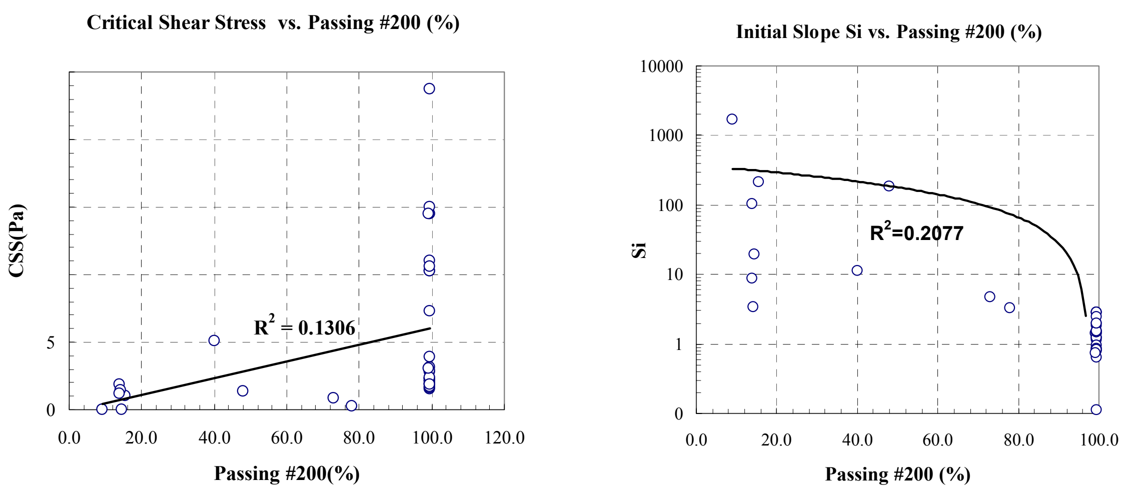
Figure 8: (a) Relationship Between Critical Shear Stress vs. Undrained Shear Strength; (b) Relationship Between Initial Slope Si vs. Undrained Shear Strength

Each figure also indicates the R^2 value obtained from various regressions. It is clear that no satisfactory relationship could be found. The fact that no relationship could be found between the critical shear stress or the initial slope of the erodibility function on one hand and common soil properties on the other seems to be at odds with the accepted idea that different cohesive soils erode at different rates. Indeed if different clays erode at different rates then the erodibility function and therefore its parameters should be



(a) (b)

Figure 9: (a) Relationship Between Critical Shear Stress vs. Plasticity Index; (b) Relationship Between Initial Slope Si vs. Plasticity Index



(a) (b)

Figure 10: (a) Relationship Between Critical Shear Stress vs. Percentage Passing #200 Sieve; (b) Relationship Between Initial Slope Si vs. Percentage Passing #200 Sieve

functions of the soils properties. The likely explanation is that there is a relationship between erodibility and soils properties but that this relationship is quite complicated, involves advanced soil properties, and has not be found within the budget and time of the research projects undertaken by various researchers. Instead, it was found much easier to develop an apparatus which could measure the erodibility function on any sample of cohesive soil from a site. This apparatus is the erosion function apparatus or EFA.

CONCLUSIONS

The EFA has proven to be a simple and reliable device to study the erosion function of different soils and soft rocks. In this paper, the influence of the pH and salinity of the water were investigated and a database of EFA test results was used to try to develop a correlation between the erodibility function and various soil properties.

1. **pH tests:** the pH value of the eroding water affects the erosion process. The erosion rate was largest and the critical shear stress lowest when the water was neutral (pH = 7). The erosion rate decreased and the critical shear stress increased when the pH became acidic and when the pH became alkaline. It is suggested that the total dissolved salts content is the factor which influences the erodibility of the soil through the pH. If tap water is used as the eroding water (pH ~ 7), it will be more conservative compared to using water with a low pH or a high pH value.
2. **Salinity tests:** the salinity of the eroding water affects the erosion process. The erosion rate decreases and the critical shear stress increases when the salt content increases. The cations in the eroding water tend to neutralize the surface electronegativity of clay particles thereby making the clay more erosion resistant. If tap water is used as the eroding water, it will be more conservative compared to using water with a higher salt content.
3. **Correlations to soil properties:** a database of about 100 EFA tests was organized. For each soil tested, the following soil properties were measured: water content, undrained shear strength, plasticity index, percent passing sieve number 200. All attempted correlations lead to very poor R^2 values; therefore the conclusion is that there is no simple correlation between erodibility parameters and the chosen soil properties. On the other hand it is well accepted that different soils erode at different rates. The apparent contradiction between the last two statements suggests that a relationship exists but that it is complex and involves many soil properties. If this is the case then, rather than measuring all those soil properties, it is much easier to measure the erodibility function directly with the EFA for example.

ACKNOWLEDGMENTS

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