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EVALUATION OF SCOUR POTENTIAL OF COHESIVE SOILS

FINAL REPORT
PROJECT 930-644

By
Jack Mobley
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Highway Research Center
Auburn University, Alabama

Sponsored by
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INTRODUCTION

Prediction of scour at bridge river crossings is an evolving process. Hydraulic models to estimate water velocity and, therefore, the shear stresses that erode soil are reasonably well developed. The weak link remains methods for estimating soil erodability. Procedures in use today for highway bridges, such as HEC-18 and HEC-20 (FHWA engineering circulars), contain erodability models for non-cohesive soils. In these models a soils erodability is directly related to the soil grain size, i.e., larger soil particles require higher velocities for removal and transport. This basic erosion model is inappropriate for cohesive soils since their erosion resistance will generally increase with decreasing grain size and, therefore, increasing plasticity. The term generally is used because the influence of particle mineralogy (which would differentiate clay particles from less active silt particles) and density are also factors that affect soil erodability.

Briaud et al. (1999, 2001a, 2001b, 2004) developed a model (erosion function) for characterizing the erodability of soil. This model, shown in Figure 1, is a plot of soil erosion rate ($\dot{z}$ in units of mm per hour) versus shear stress at the soil/water interface (τ in units of N per m^2). Key components of the erosion function are (1) the critical shear stress (τ_c) below which the soil will not erode; (2) the initial soil erosion rate (Si) defined as the slope of the erosion rate-shear stress curve at the critical shear stress; and (3) the post critical shear stress erosion rate relationship. This relationship is shown in Figure 1 as a curve where the erosion rate decreases with increasing shear stress, but a range of curve shapes is possible as will be shown later.

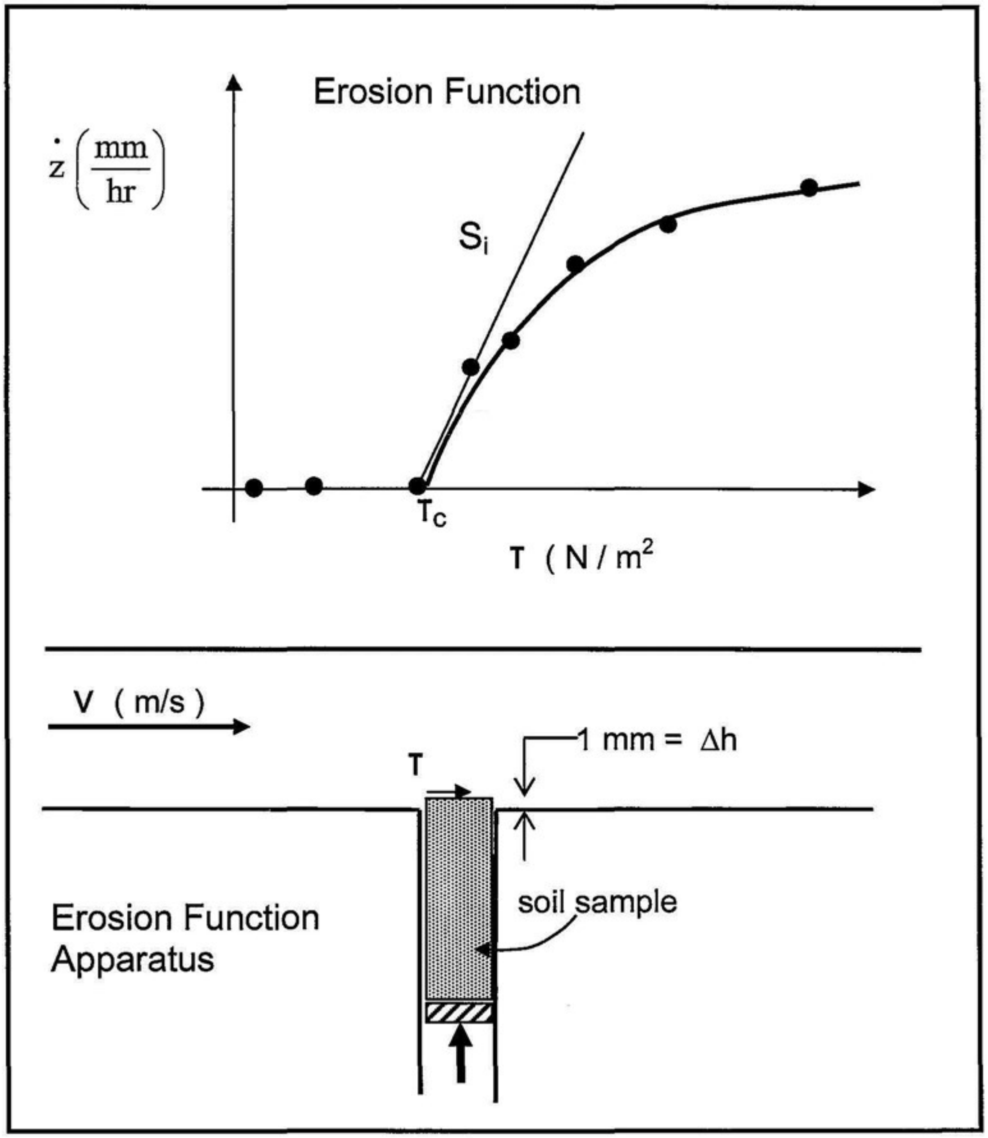


Figure 1: Erosion Function and Erosion Function Apparatus Operation

Briaud et al. also developed an apparatus for measuring erosion of cohesive soils to quantify erosion functions. The operation of their erosion function apparatus (EFA) is shown schematically in Figure 1 with a photograph of the apparatus shown in Figure 2. A 1 mm thick portion of soil (typically from a Shelby tube) is pushed into a stream of water and the time required for erosion noted to establish an erosion rate ($\dot{z}$(mm/hr)). Shear stress is computed from water velocity to establish one point on the erosion function and the process repeated to develop a complete relationship as shown in Figure 1.

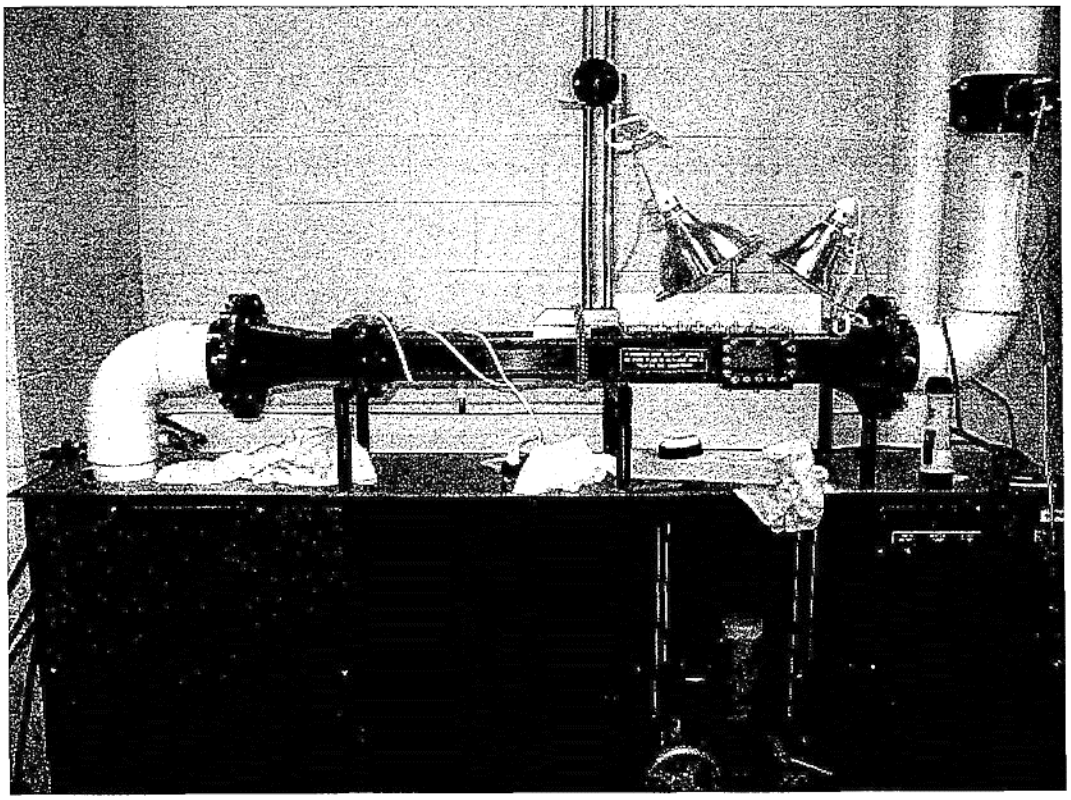


Figure 2: The Auburn University EFA

Briaud et al. combined hydraulic models with erosion functions, in a method labeled SRICOS (Scour Rate in Cohesive Soils) to predict rates of scour at bridge sites. Earlier research at Auburn University (AU) for the Alabama Department of Transportation (Curry et al. (2003), Güven et. al (2002)) extended this work for Alabama soils and bridges.

As part of this early research at AU a number of soils from Alabama bridge sites was tested in the EFA to develop erosion functions (Crim (2003), Crim et al. (2003b)). Crim found that with some creativity the EFA could be used to develop erosion functions. Crim also confirmed correlations between critical shear stress and soil plasticity index and compaction reported by Briaud et al. (2001a).

What led to the research reported herein was the question of whether the EFA might be used to study the erodability of earth materials that might be loosely described as hard cohesive soils or soft rock. Typical of these type materials in Alabama would be highly over consolidated clays, shales, marls, chalks and limerock. The key question with these type materials is whether or not their critical shear stress might be larger than the shear stress produced by some maximum velocity expected during flooding. If the answer is yes, then scour would not be an issue. In Alabama this maximum expected flood velocity might be around 3 – 3.5 m/sec (10 – 12 ft/sec).

It was the intent of this research project to obtain samples of typical hard soils/soft rock for testing in the EFA to study their erodability. For some this could mean developing erosion functions but for highly erosion resistant materials could mean establishing that the critical shear stress is larger than the shear stress produced by maximum expected flood velocity.

The hard soils/soft rocks of interest cannot be sampled with Shelby tubes but must be sampled by coring. This type sample required a modification of the EFA which is designed to accept soil samples directly from Shelby tubes. As shown in Figure 1, soil is pushed from the Shelby tube into the stream of flowing water. To accommodate the smaller diameter of cores the EFA was modified as shown in Figure 3. A thick walled cylinder (outer diameter of a Shelby tube) was fabricated to fit into the EFA. The inside diameter of the cylinder was sized for cores (D = 4.45 cm or D = 4.75 cm). The EFA mechanism for pushing the soil into the flowing water was also modified for these smaller diameter samples. These modifications allowed the same basic testing procedures as used with samples of softer soils provided in Shelby tubes.

Samples of three Alabama soils were provided for testing; (1) a stiff clay from a culvert replacement project in Talladega County; (2) a hard silt from a bridge crossing of the Sucarnoochee river in Sumter County and (3) a Mooreville chalk from a bridge crossing of Bogue Chitto Creek in Dallas County. In addition a model soil comprised of a clean sand and Bentonite was tested to demonstrate how erosion functions are affected by clay content and compaction.

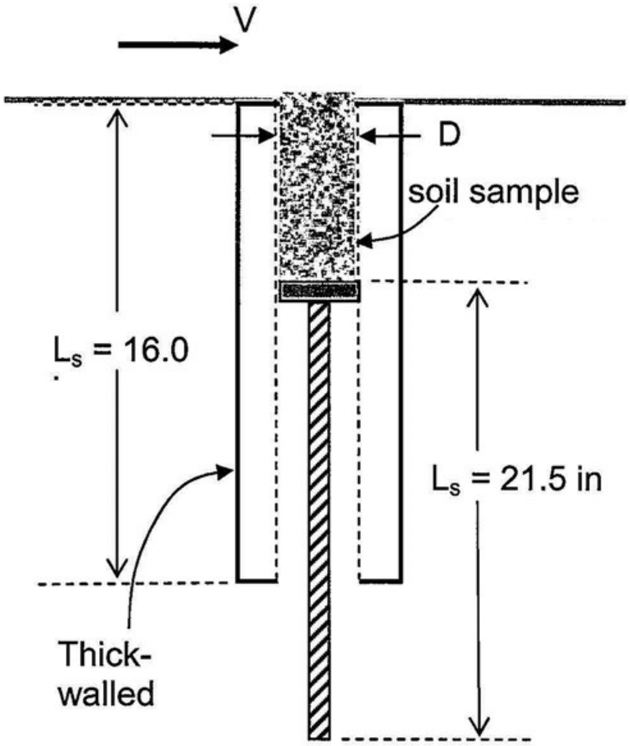


Figure 3: Core Injection Cylinder (CIC) Geometry

TEST RESULTS

Talladega County Stiff Clay

Shelby tube samples were provided from borings for a culvert replacement project in Talladega County. Borings were mostly to a depth of around 4.5 meters. The boring logs described the soil encountered as stiff or very stiff clay with occasional chert pebbles. The "N values" for the soil ranged from 15 to 20. Limestone/dolomite was encountered in several borings at around 4.5 meters depth. Based on index properties in Table 4 the soil would be classified as SC.

Table 1: Talladega Soil Sample Properties

Sample Identification Number	Water Content %	Liquid Limit %	Plastic Limit %	Plasticity Index LL - PL	Dry Density g/cm^3	% < No. 200 Sieve
78296	26.4	27.0	21.1	5.9	1.635	15.2
78301	13.7	22.7	17.0	5.7	1.817	14.2
78311	18.8	28.4	22.2	6.2	1.658	14.9
78316	12.7	24.5	18.0	6.5	1.92	N/A

Several methods were tried to measure erosion. However, there was a common erosion pattern for every tested sample. Silty, clayey emission occurred around the sample edges, and erosion began to occur on the upstream surface as shown in Figure 4. Occasionally large spalls would suddenly occur on the sample surface.

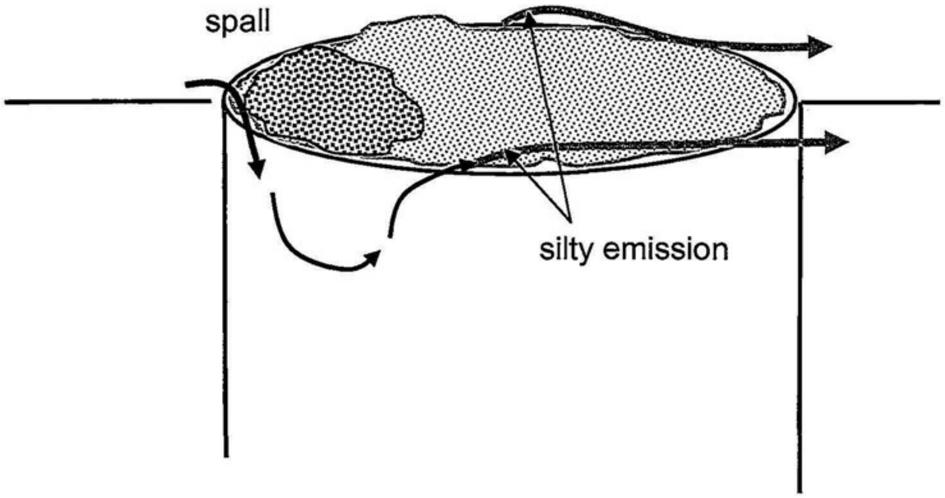


Figure 4: Flow Path for Silty Emission from Lateral Boundaries

Samples 78296 and 78301 were tested and the soil eroded measured using conventional EFA procedures. There was no difficulty in preparing a smooth, flat surface to be exposed to uniform shear stress. Soil was projected into a given velocity for erosion in 1 mm increments. After the test, the average velocity was determined, and the erosion rate was interpreted as the total eroded height divided by the test duration. This procedure was repeated at different velocities to generate an erosion function displaying shear stress (N/m^2) versus erosion rate (mm/hr). Results for sample 78296 are shown in Figure 5 and Table 2, and for sample 78301 in Figure 6 and Table 3. The relationship between τ (shear stress) and V (average velocity in the test section) is $\tau = \frac{f\rho V^2}{8}$ where ρ = 1000kg/m^3 and f = the friction factor. Although the friction factor is variable, see Crim (2000a and 2000b), f = 0.01 was applied in all calculations in this report. For the range of Reynolds numbers and the uncertainty of the relative roughness in these experiments f = 0.01 was a reasonable average value for the friction factor.

Table 2: Talladega Sample 78296 EFA Test Results

Velocity, m/s	Shear Stress, N/m^2	Eroded Depth, mm	Test Duration, minutes	Erosion Rate, mm/hr
0.491	0.301	0	60	0
0.786	0.772	3	60	3
1.334	2.224	22	60	22
1.557	3.030	18	60	18
1.995	4.975	25	15	100

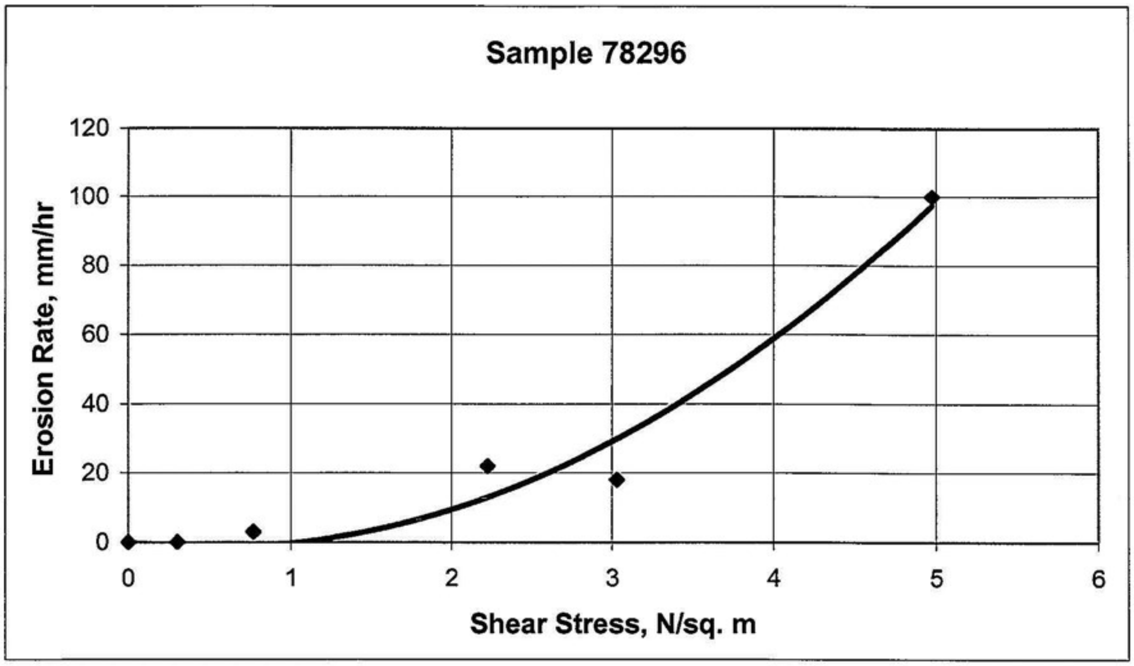


Figure 5: Talladega Sample 78296 EFA Test Results

Table 3: Talladega Sample 789301 EFA Test Results

Velocity, m/s	Shear Stress, N/m^2	Eroded Depth, mm	Test Duration, minutes	Erosion Rate, mm/hr
0.198	0.049	0	60	0
0.507	0.321	5	60	5
0.730	0.666	6	60	6
1.170	1.710	21	60	21
1.468	2.694	20	10	120

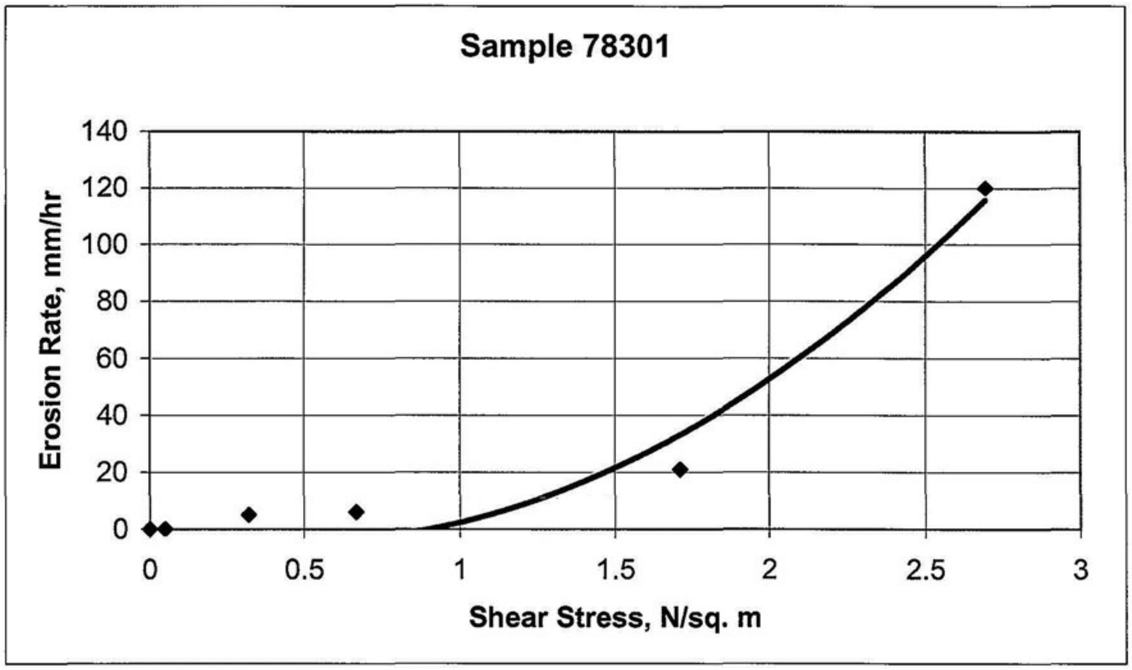


Figure 6: Talladega Sample 78301 EFA Test Results

Both samples appear to have a non-linear relationship between shear stress and erosion rates. They show erosion increasing at a growing rate with respect to shear stress. The critical shear stress for both samples appears to be about 1 N/m^2, but for larger shear stresses, sample 78301 was much more erosion resistant than sample 78296. For example, the erosion rates at a shear stress of 2.5 N/m^2 (velocity of 1.4 m/sec) was 100mm/hr for sample 78301 and 20 mm/hr for sample 78296. These erosion rates are consistent with the higher density and lower water content for sample 78301 in Table 1.

The soil eroded for samples 78305 and 78311 was measured using a modified method. The testing difference was that the soil was trimmed flush with the bottom of the EFA flume rather than projecting 1 mm into the flow. In addition a method different from visual observation was attempted to estimate the amount of erosion. There was much difficulty in preparing a smooth, flat surface, so water was dropped into any initial surface voids and collected with a dry paper towel. The masses of the dry and wet paper towel were recorded, and the difference corresponds to the mass of water filling the voids. Using the density of water (1 g/cm^3), the volume of the voids could be calculated. An EFA test was performed and the procedure was repeated to measure any new voids caused by erosion. The difference between void volume before and after an EFA test corresponds to the mass of soil eroded. Hence, erosion rates can be calculated and converted to mm/hr.

Results for samples 78305 and 78311 are displayed in Tables 4 and 5. It should be noted that a new sample surface was not prepared for each test at the same velocity and shear stress. For example, the sample surface at the end of a 10 minute test was the same as at the beginning of a 30 minute test.

Table 4: Sample 78305 EFA Test Results

Test Duration, minutes	Surface void volume increase, mm^3	Erosion Rate, mm^3/hr	Erosion Rate, mm/hr
10	498	2988	0.73
30	461	922	0.23
60	1004	1004	0.25

Sample 78305, V = 0.70 m/s, τ = 0.61 N/m^2

Test Duration, minutes	Surface void volume increase, mm^3	Erosion Rate, mm^3/hr	Erosion Rate, mm/hr
10	209	1254	0.31
30	403	806	0.20
60	587	587	0.15

Sample 78305, V = 1.20 m/s, τ = 1.8 N/m^2

Test Duration, minutes	Surface void volume increase, mm^3	Erosion Rate, mm^3/hr	Erosion Rate, mm/hr
10	4454	26724	6.56
30	1407	2814	0.69
60	134	134	0.03

Sample 78305, V = 1.90 m/s, τ = 4.5 N/m^2

Table 5: Sample 78311 EFA Test Results

Test Duration, minutes	Surface void volume increase, mm^3	Erosion Rate, mm^3/hr	Erosion Rate, mm/hr
10	4380	26280	6.45
30	514	1028	0.25
60	1381	1381	0.34

Sample 78311, V = 0.80 m/s, τ = 0.64 N/m^2

Test Duration, minutes	Surface void volume increase, mm^3	Erosion Rate, mm^3/hr	Erosion Rate, mm/hr
10	4368	26208	6.44
30	3473	6946	1.71
60	6137	6137	1.51

Sample 78311, V = 1.60 m/s, τ = 3.2 N/m^2

These tests showed an overall decrease in erosion rate with respect to time. For example, sample 78305 at V = 1.90 m/s produced an erosion rate of 6.56 mm/hr during the first 10 minute test, but it only a 0.03 mm/hr rate during the last 60 minute test. This illustrates the influence of surface preparation on erosion rate, with equilibrium (zero erosion) eventually being achieved. Sample 78311 eroded in the same manner, but still had an erosion rate of 1.51 mm/hr with V = 1.60 m/s after the 60 minutes test duration.

Two conventional EFA tests were performed on Talladega sample 78316. These two tests are referred to as 316A and 316B, which were performed on the top 20 cm segment of the sample. There was much difficulty in surface preparation for test 316A, and this resulted in disturbance and surface irregularities which made it difficult to interpret exact erosion rates. From observation, about half of the original volume above the flume bed eroded during an 87 minute test at an average velocity of 1.30 m/s.

Test 316B was conducted for approximately 4.60 hours. Velocity was set to 0.65 m/s for the first 3.17 hours and 0.90 m/s for the final 1.43 hours. At 2.25 hours, a large spall suddenly flew out of the upstream 1/3 end, as shown in Figure 7. Along with the silty emission from the edges, this void grew larger at V = 0.90 m/s for the final 1.43 hours. After testing, this sample was ejected 5 cm above the Shelby tube surface for examination (Figure 8). Around a pocket of small pebbles, erosion was obvious at the leading edge of the sample. In contrast, the downstream 2/3 of the sample surface showed very little erosion.

These tests illustrate the difficulties encountered when testing real soils. Surface preparation and discontinuities (such as the small chert pebbles) can cause erratic sample erosion. For comparison, reasonably consistent erosion functions developed for homogeneous prepared samples of model soils will be presented later.

Test 316B, Test Start

Δt = 2.25 Hours, V = 0.65 m/s

Δt = 4 Hours, v = 0.90 m/s

Figure 7: Talladega EFA Test 316B

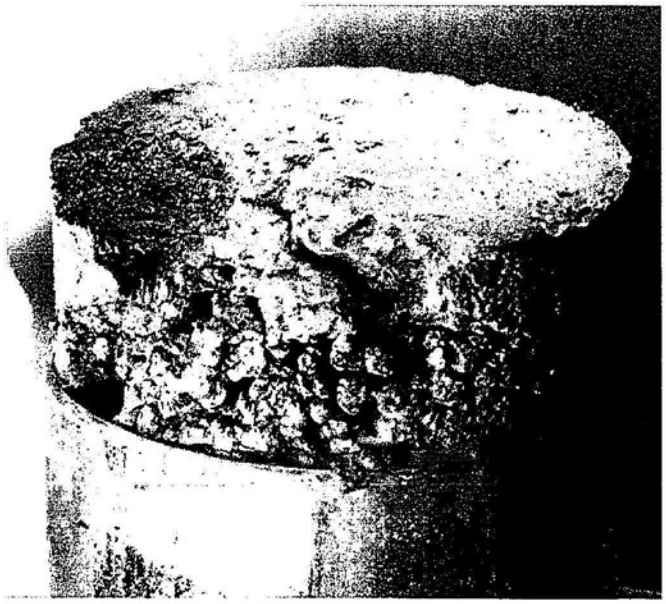


Figure 8: Talladega EFA Test 316B, Test End

<u>Sumter County Hard Silt</u>

Core samples were provided from a boring in the vicinity of the west abutment of the US 80 Bridge over the Sucarnoochee River in Sumter County. The hard (N = 40–50) silt (MH, A-7-5) is a thick layer with top elevation of about 75 ft that is overlain by about 30 ft of softer and looser alluvial clay, silt and sand. The hard silt has a liquid limit of around 70, a moisture content of around 45% and around 98% passing the #200 sieve. The cores and soil properties were provided by Southern Earth Sciences, Inc. of Mobile, AL.

Because of the layered structure of the silt (Figure 9) it was not possible to trim the cores to prepare a surface for testing without causing some disturbance. Figure 10 illustrates the difficulties encountered in preparing a uniform surface. In addition the layered structure of the hard silt resulted in very erratic sample erosion. Most of the soil was removed in large chunks rather than at a steady uniform rate. After some soil loss at a given water velocity no additional loss would occur until the velocity was increased.

Figure 9: Sumter County Sample Structure and Horizontal Layering

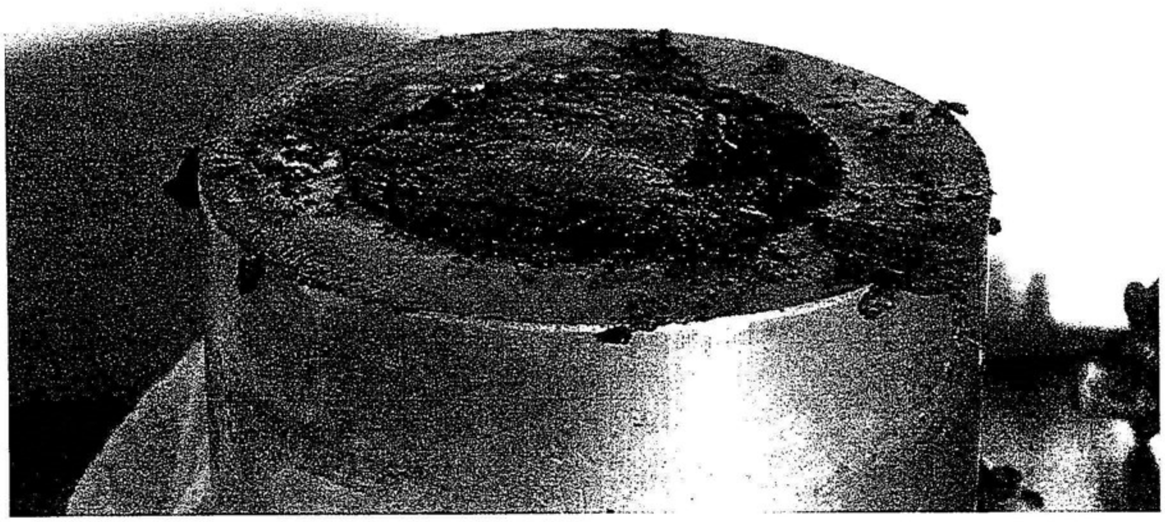


Figure 10: Sumter County Surface Preparation Difficulties

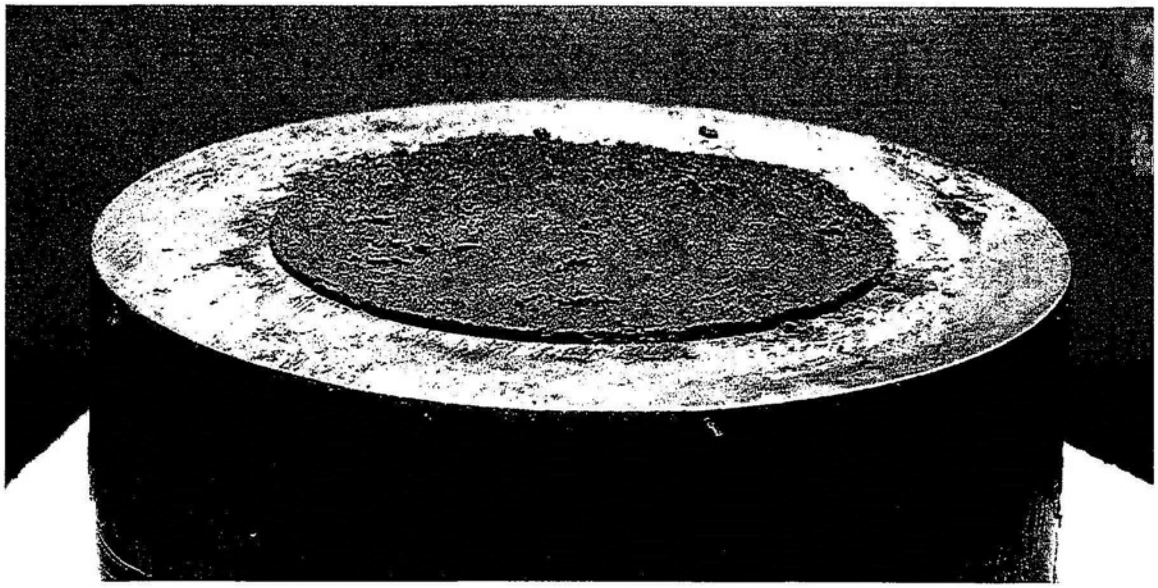
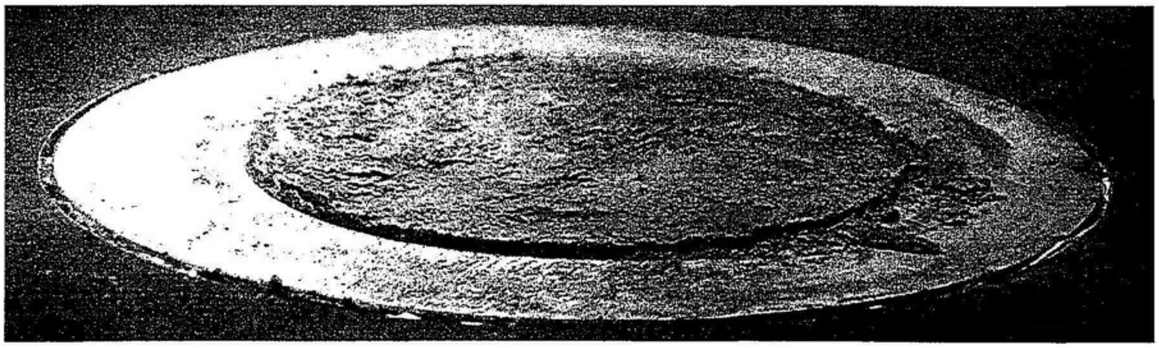


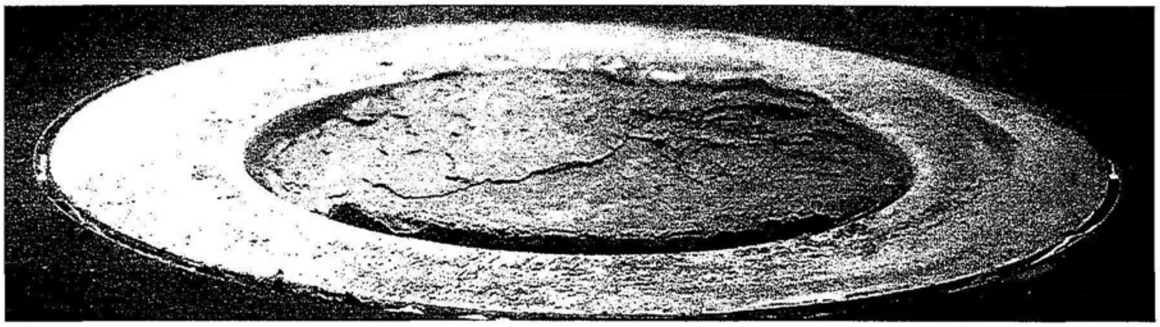
Figure 11: Sucarnoochee07 Prepared Surface at 1 mm Protrusion

This type of erosion development is illustrated in Figures 11 and 12. Figure 11 shows the as prepared sample surface. As shown in Figure 12, some initial erosion occurred at a velocity of 0.32 m/s but equilibrium was soon achieved (Time = 24 minutes). More erosion occurred when the velocity was increased to 0.74 m/sec, but the surface stabilized and remained so for some time (Time = 2 hours, 10 minutes). The entire 1 mm of sample was not eroded until the velocity was increased to 0.99 m/s (Time = 2 hours, 14 minutes).

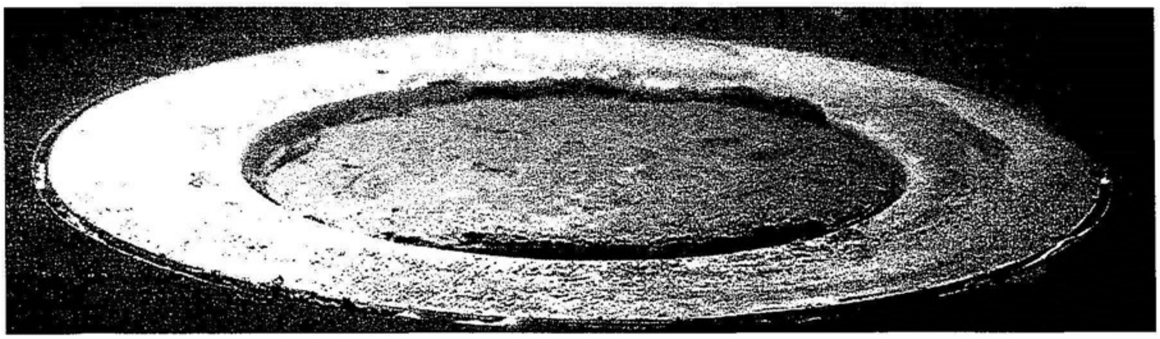
This type behavior made interpretation difficult. However, seven samples were tested and based on some creative interpretation it is estimated that the critical shear stress for the hard silt is between 0.2 and 1.2 N/m^2 which corresponds to velocities from 0.3 to 0.7 m/s. This would mean the hard silt at the Sucarnoochee River crossing would be susceptible to scour at velocities less than the maximum of 3 – 3.5 m/s which might be expected for Alabama Rivers.



Time = 24 minutes, V = 0.32 m/s



Time = 2 hours 10 minutes, V = 0.74 m/s



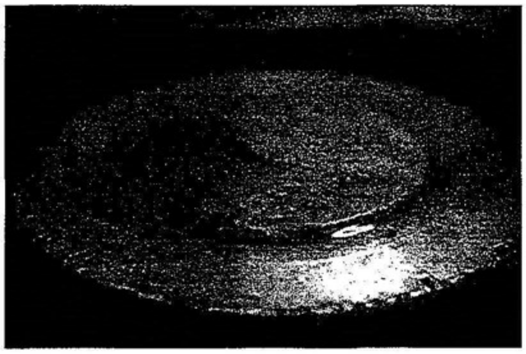
Time = 2 hours 14 minutes, V = 0.99 m/s

Figure 12: Sucarnoochee07 EFA Testing

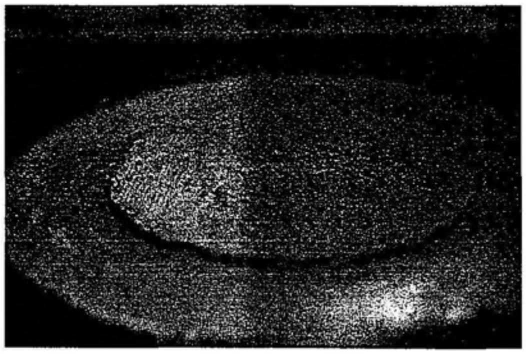
Dallas County Mooreville Chalk

Cores of Mooreville chalk were provided from borings for a bridge replacement project over Bogue Chitto Creek in Dallas County. The top of the thick chalk layers is at about elevation 120 ft and is overlain by about 25 ft of alluvial deposits.

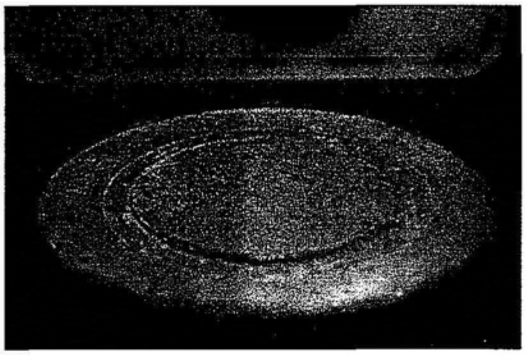
Conventional EFA testing was performed on three Mooreville chalk core samples. Surface preparation was not an issue. The flow control valve on the EFA was set to produce the highest possible EFA velocity (approximately 6 m/s), where it remained for entire test durations. The tests yielded minimal erosion as shown in Figure 13. Chalk core 78935 was tested for roughly two hours. About 1/3 of the surface above the flume bed suddenly separated and eroded after an hour of testing but there was no evidence of any additional erosion. Sample 78936 did not show any signs of erosion for two hours. A small amount of erosion occurred for sample 78956 during the first hour of testing, but no erosion occurred during the second hour. Based on these tests, it is reasonable to conclude that the Mooreville chalk tested would not scour if subjected the highest velocities that might be expected for Alabama Rivers, i.e., the critical shear stress for Mooreville chalk is greater than 15.3 N/m^2
($V = 3.5$ m/s).



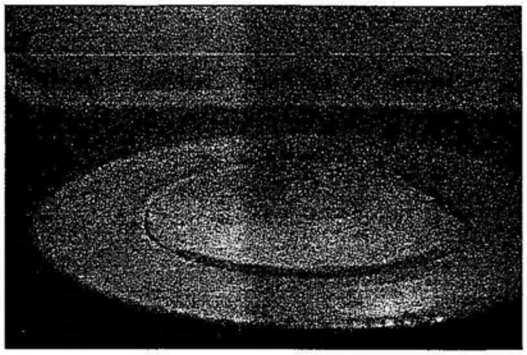
78935, Δt = 1 Hour



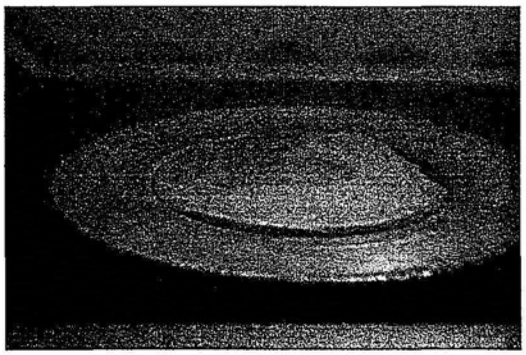
78936, Test End, Δt = 2 Hours



78956, Δt = 0



78956, Δt = 1 Hour



78956, Δt = 2 Hour

Figure 13: EFA Testing on Dallas County Samples

Model Soils

The limited number of natural soils provided did not allow a study of the effect of cohesion on erosion resistance. Model soils were prepared with varying clay contents, water contents and compaction level to study their effects. Reasonably consistent erosion function were developed for these model soils by testing in the EFA. The erosion functions demonstrate the expected increased erosion resistance with increased cohesion (increased clay content and compaction). The ability to generate erosion functions for these uniform soils highlights difficulties caused by sample preparation and discontinuities when testing natural soils.

The model soils were comprised of a uniform sand (SP with uniformity coefficient of 2.06 and gradation shown in Figure 14) and bentonite. The moisture content was controlled and samples compacted in the core injection cylinder. Samples were compacted to two densities: 1.7 g/cm^3 and 1.9 g/cm^3. At a density of 1.7 g/cm^3, soil samples contained the following bentonite contents (by mass): 5%, 8.5%, 20.8%, and 25%. Samples compacted to a density of 1.9 g/cm^3 contained bentonite contents of 3.5%, 5%, 8.5%, 12.5%, 15.0%, 20.8%, and 25.0%.

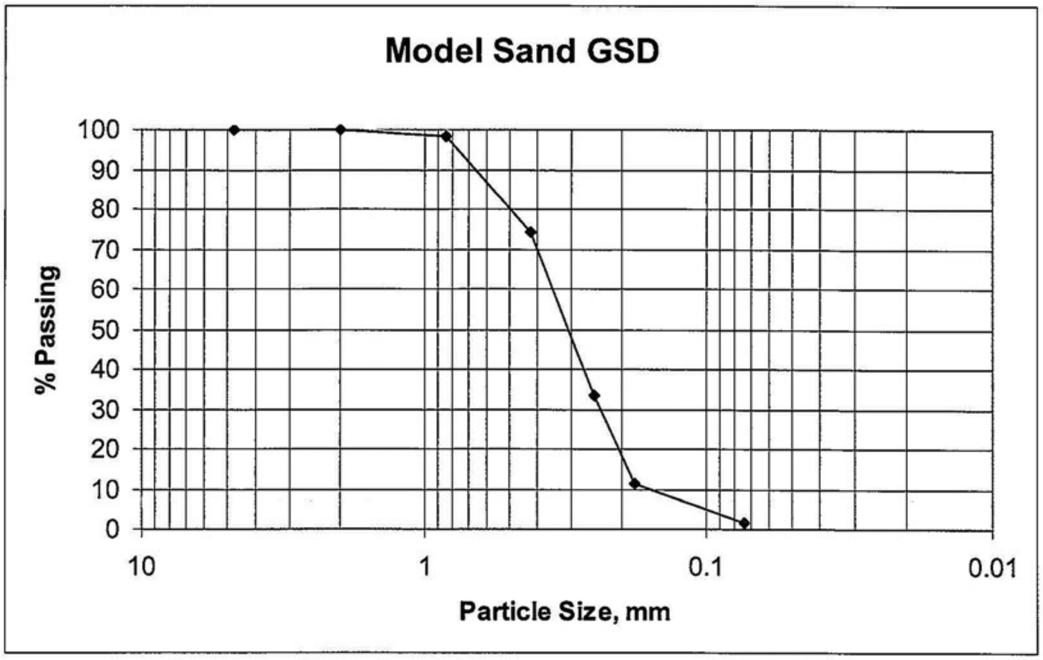


Figure 14: Model Sand Grain Size Distribution

Erosion functions for the model soils are shown in Figures 15 and 16. The model soils erode as expected for cohesive soils at Bentonite contents of 8.5% and above. At these Bentonite contents, there are reasonably well defined critical shear stresses and reasonably well established erosion rate curves for larger shear stresses. Erosion develops uniformly with time which permits computation of erosion rates for test velocities (shear stresses).

Samples containing less than 8.5% Bentonite had erosion that increased greatly with time; scour holes developed on the surfaces which grew larger and rapidly accelerated erosion. This made the interpretation of erosion into numerical values difficult, since theoretically the erosion rate is always increasing. Nevertheless, these values were interpreted as best as possible from observation and included in Figures 15 and 16.

The critical shear stresses for Bentonite contents of 8.5% and greater increase rather consistently as Bentonite content increases. However, the erosion rate curves for larger shear stresses are somewhat erratic with some overlaps and inconsistencies.

Figures 17 and 18 illustrate the significance of density on erosion rates. For soil that contained 25% clay and tested at 6.0 m/s (τ = 45 N/m^2), the measured erosion rate for the 1.70 g/cm^3 soil was 84 mm/hr, while the 1.90 g/cm^3 soil eroded at a rate of only 34 mm/hr. An increase of 0.2 g/cm^3 resulted in a 60% decrease in erosion rate. For soil composed of 20% clay, the higher density resulted in a reduction of about half the erosion rate.

Figure 19 indicates there is a reasonably linear relationship between τ_c and clay content for both densities. As expected, higher density yields higher values of τ_c for a given clay content. It should be noted that if data points for 5% bentonite are excluded, the slopes of both trends are close (Figure 20). The basis for this exclusion is that model soils with 5% bentonite eroded more like cohesionless soil.

Table 6 shows how the plasticity index (PI) of the model soils increases with increasing Bentonite content. This relationship and the relationships discussed above between τ_c, density and Bentonite content reinforce the notion that more cohesive soils are more erosion resistant.

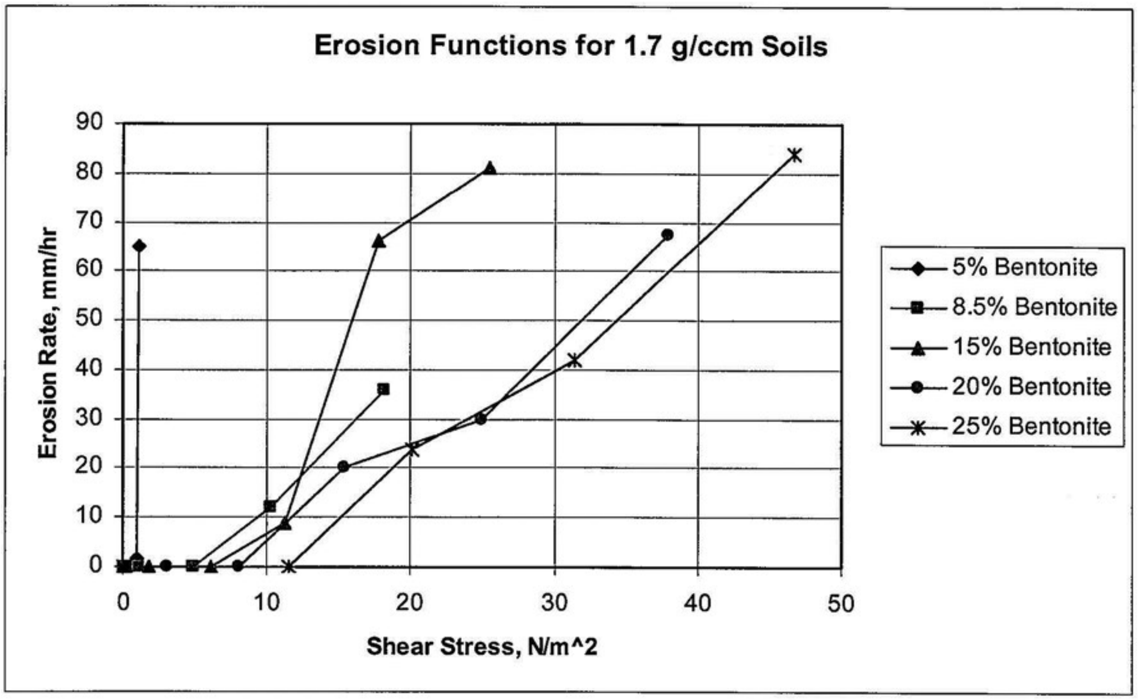


Figure 15: Erosion Functions for Model Soils Compacted to 1.7 g/cm^3

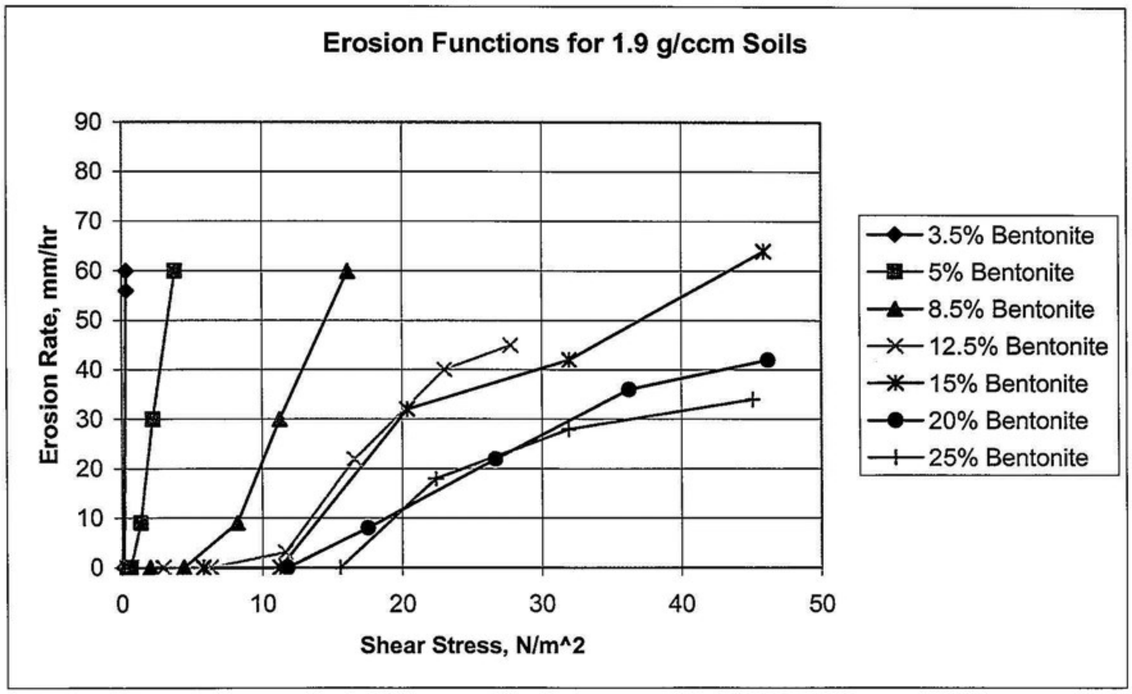


Figure 16: Erosion Functions for Model Soils Compacted to 1.9 g/cm^3

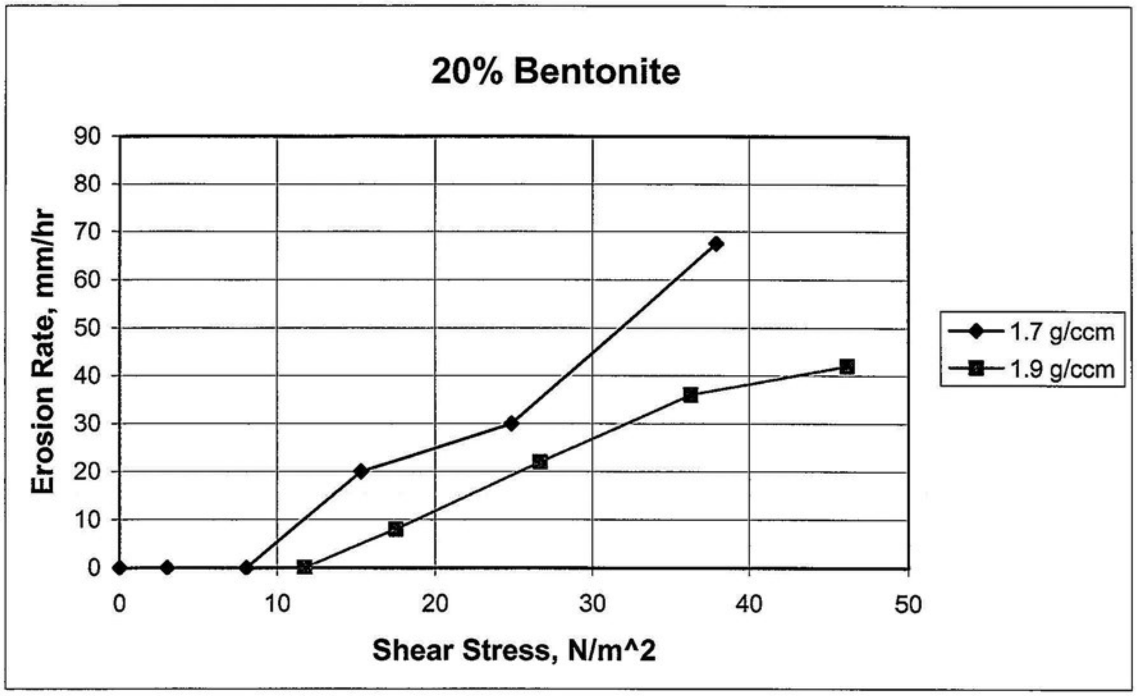


Figure 17: Comparison of Erosion Function Densities at 20% Bentonite

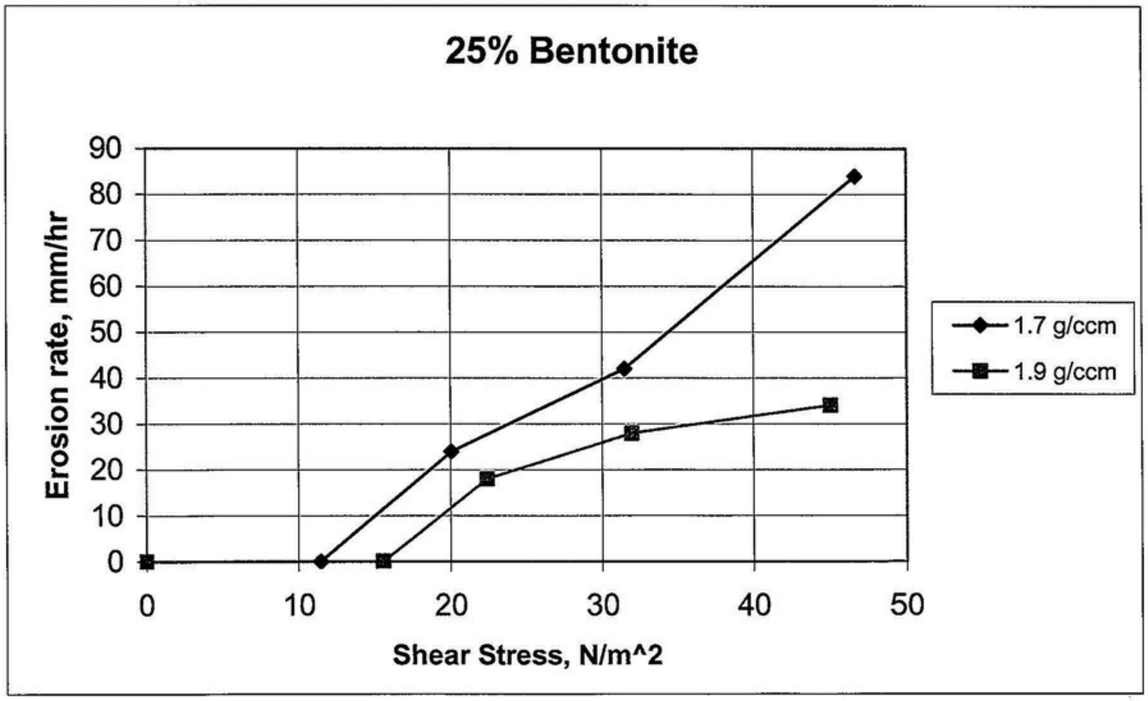


Figure 18: Comparison of Erosion Function Densities at 25% Bentonite

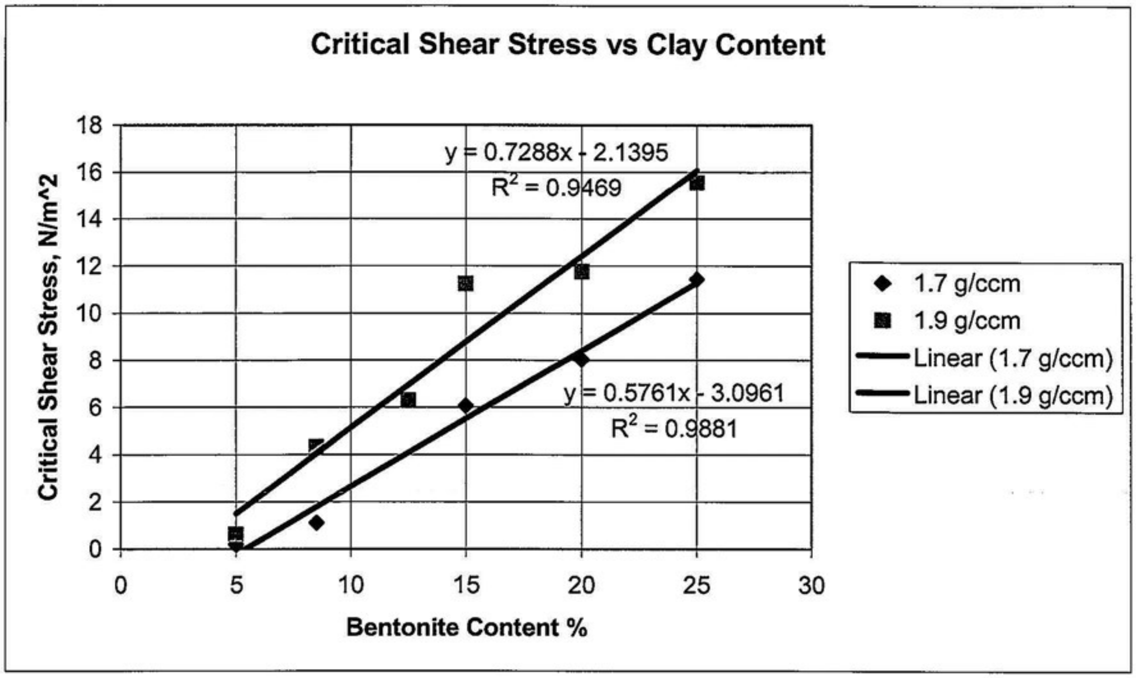


Figure 19: Correlations between Critical Shear Stress and Bentonite %

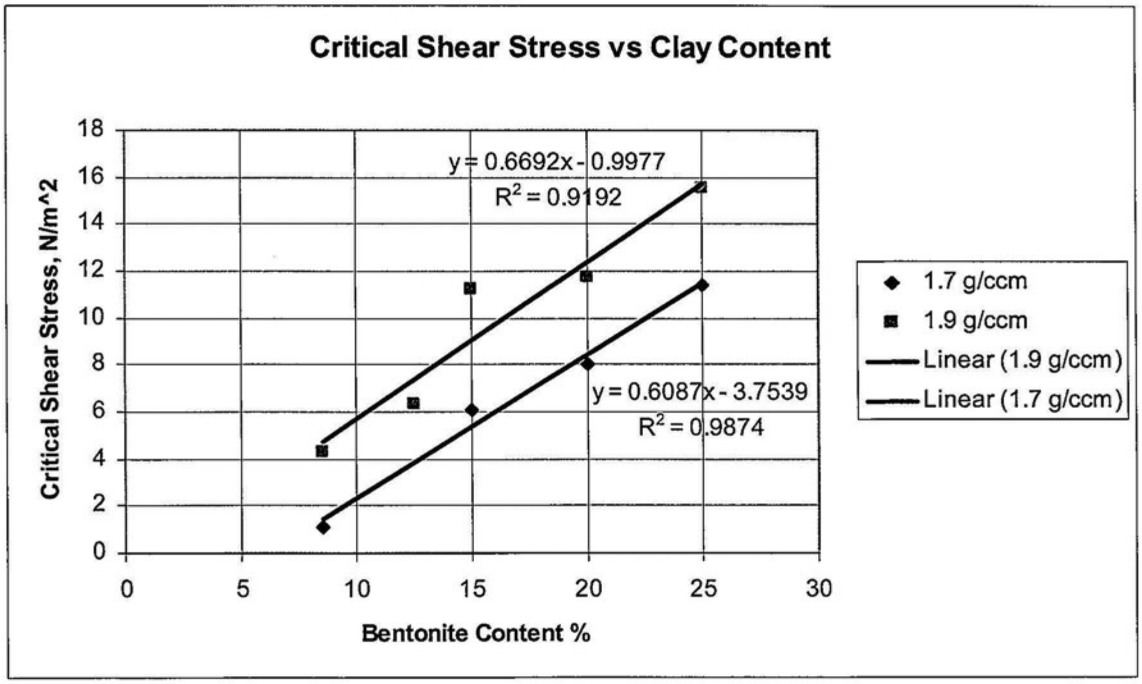


Figure 20: Modified Correlations between Critical Shear Stress and Bentonite %

Table 6: Model Soil Atterburg Limits

Clay Content	Plastic Limit	Liquid Limit	Plasticity Index
8.5% Bentonite	35.3	44.9	9.8
12.5% Bentonite	43.0	55.0	12.0
15% Bentonite	58.9	32.0	26.9
20% Bentonite	42.7	76.6	33.9
25% Bentonite	35.1	90.6	55.5

SUMMARY AND CONCLUSIONS

The erosion functions developed for the model soils demonstrated the expected influence of soil cohesion on erosion resistance, i.e., larger cohesion gives greater erosion resistance. Sample preparation and discontinuities in natural soils can result in erratic erosion development that makes development of consistent erosion functions difficult.

The behavior of the Talladega County stiff clay (SC) was quite erratic. However, approximate erosion functions were developed for two samples that showed increasing erosion rates with increasing shear stress greater than a critical shear stress of about 1 N/m^2.

The layered structure of the Sumter County hard silt made sample surface preparation difficulty and resulted in erratic erosion development. The critical shear stress for the hard silt is estimated to be between 0.2 and 1.2 N/m^2 (velocity 0.3 to 0.7 m/sec).

The Mooreville chalk from Dallas County did not erode when subjected to a shear stress of 45.0 N/m^2 (V = 6 m/sec).

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