ERODIBILITY OF SEDIMENT AT BRIDGE FOUNDATIONS IN GEORGIA

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Abstract One of the most important variables required in prediction of clear-water contraction scour at bridge foundations is the critical shear stress of the sediment at the level of the bridge foundation. While critical shear stresses are relatively well known for sands and gravels, the contribution of clays in fine-grained sediments results in difficulties with respect to characterization of erosion resistance. As a result, a number of different techniques have been developed for determining the critical shear stress at which sediment motion begins. The objective of this study is to characterize the critical shear stress of representative sediments throughout Georgia in order to improve estimates of bridge contraction scour by measuring critical shear stress in a flume and with a controlled-stress rheometer. Values of the Shields parameter are determined and related to fines fraction and the dimensionless particle number.

INTRODUCTION

The critical shear stress for initiation of sediment motion is an essential parameter for estimating clear-water contraction scour depths at bridge foundations (Richardson and Davis 2001); yet it remains one of the most elusive parameters to measure in fine-grained sediments. The structure or fabric of the fine-grained matrix and its concomitant resistance to erosion are dependent on many factors including porewater chemistry, clay mineralogy, organic matter, water content and depth of deposit. Using the same flume as reported in this study, Ravisangar et al. (2005) showed that relationships between critical shear stress and bulk density of settled kaolinite sediment depend on its fabric as described by edge-edge, edge-face, and face-face particle associations, which in turn are formed in response to particular values of ionic strength, pH and natural organic matter concentrations in the porewater.

In contrast to studies on pure kaolinite, natural sediments at many bridge foundations in Georgia are usually mixed sediments with various proportions of silt, clay and sand sizes. Relatively little research has been conducted on the erodibility of mixed sediments. Panagiotopoulos, Voulgaris, and Collins (1997) conducted erosion experiments on artificially mixed sediments in which varying amounts of fine-grained sediment (estuary mud) were added to fine sand. Their results showed that resistance to erodibility increased significantly when the mud content exceeded 30% (clay mineral content > 11-15%) because the clay minerals filled the spaces between the sand particles and controlled the erosion process. Briaud et al. (2001) measured the erodibility of several natural soils in Texas and concluded that there was no correlation between critical shear stress for erosion and geotechnical properties such as shear strength and plasticity index. This result is in agreement with the conclusion of Zreik et al. (1998) that critical shear stress depends on the microstructure of fine-grained sediments rather than on bulk shear strength.

Although a regional approach to estimation of critical shear stress was attempted initially, in which Shelby tube cores taken throughout Georgia were tested in an erosion flume, the degree of

variability in the values of critical shear stress even within the same sediment core made that objective rather difficult except in qualitative terms. Part of the reason for the high variability in Piedmont surficial residual soils in Georgia, for example, is the complexity of the source igneous and metamorphic rock and the variability in the weathering processes (Lutenegger, Cerato, and Harrington, 2003). In the Georgia Coastal Plain, as another example, existence of sediments from erosion of the weathered Piedmont crystalline rocks as well as marine sediments derived from fluctuating sea levels during the Pleistocene produced mixed sand and clay sediments.

The results of the initial flume studies (Sturm et al. 2004, Navarro 2004)) included a relationship for critical shear stress in a Shields diagram with fines fraction as a third parameter. In the present study (Sturm et al. 2008, Hobson 2008), additional bridge sites were sampled to confirm the previous results, and a second test method was added. This method used the yield stress of the fine fraction of some of the samples, which was measured by a controlled stress rheometer, as a surrogate for the sediment fabric. These methods are described and discussed in the following sections of the paper, but the research is ongoing with more carefully controlled laboratory soil size distributions.

EXPERIMENTAL METHODS

Shelby tube core samples were collected by the Georgia Department of Transportation (GDOT) from a total of fifteen bridge sites distributed among the physiographic regions of Georgia as shown in Figure 1. The samples were taken at various depths corresponding to the bridge foundation depth but in general were 3 to 10 m deep. These samples were tested in the Georgia Tech erosion flume to determine critical shear stress. In addition, several other soil properties were determined for each soil sample including liquid limit, plastic limit, particle size distribution, organic content, specific gravity, and bulk density. For those samples consisting of a significant fraction of fine-grained particles, the fine fraction was separated and tested for yield stress in a controlled-stress rheometer.

Erosion Flume The open-channel flow flume used for erosion testing of the Shelby tube samples is shown in Figure 2. The Shelby tube sample is placed below the bed of the flume, and the soil is extruded into the flume by a piston into a uniform flow. The flume has been calibrated so that a known shear stress, which was determined from measurements of velocity profiles by a laser Doppler anemometer and fitting of the log law, can be applied to the sample by adjusting the flow rate, flume slope, and flow depth. For a given shear stress, the sample is gradually extruded while it erodes so that the erosion surface remains level with the flume bed. A cable-pull potentiometer is used to measure the piston position as a function of time from which an erosion rate can be determined after the dry density of the sample is measured. Several pairs of shear stress and erosion rate data points are collected in this way for increasing shear stresses. From the plot of erosion rate vs. shear stress, the data are fitted by a straight line that is extended to zero erosion rate. The shear stress intercept is then the critical shear stress for the sample. Additional details of the experimental procedure are given by Navarro (2004) and Hobson (2008).

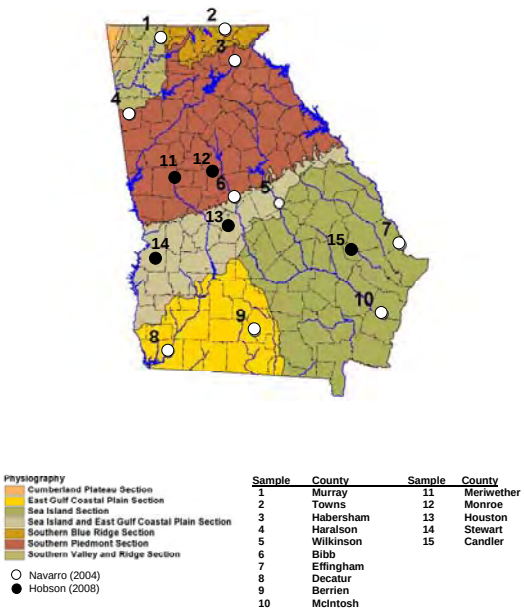

Figure 1 Shelby tube core sample locations.

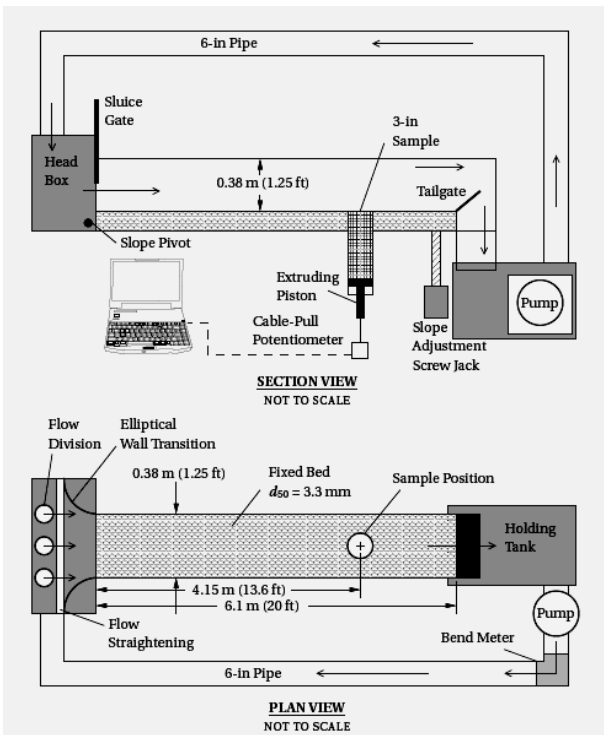

Figure 2 Erosion testing flume.

Rheometer The yield stress experiments were performed with a Haake RheoStress RS65 stress controlled rheometer. The rheometer measures the viscosity and/or yield stress of a fluid as a result of applying an increasing shear stress with time. The instrument consists of a cup and a

concentric cylinder that is submerged and then rotated in the fluid. The test is used as a means of estimating the strength of the interparticle forces of the fine fraction of the sediment sample. The fine sediment samples were mixed with varying amounts of water and allowed to settle for 24 hours in the rheometer cup before testing.

In a previous study of estuary mud, Hoepner (2000) programmed the rheometer to logarithmically increase the shear stress from 0.04 Pa to 12 Pa over a period of 300 seconds. The same logarithmic rate was used in this study. The upper yield stress, τ_{y2} , as defined by Otsubo and Muraoka (1988), is determined by fitting straight lines to the initial steep and final flatter parts of the stress vs. *strain-rate* flow curves. This procedure is illustrated in Figure 3. A lower yield stress was estimated based on the stress-strain curve, but it is not discussed herein for purposes of brevity.

Yield stresses of the reconstituted and settled fine sediment samples were determined as a function of prepared water content. Then, characteristic values of the yield stress were estimated for each Shelby tube sample depth from a best fit of the data at a *common water content, w=* 150%, to provide a relative index for comparison. In several cases, insufficient fine sediment was present to conduct rheometer tests.

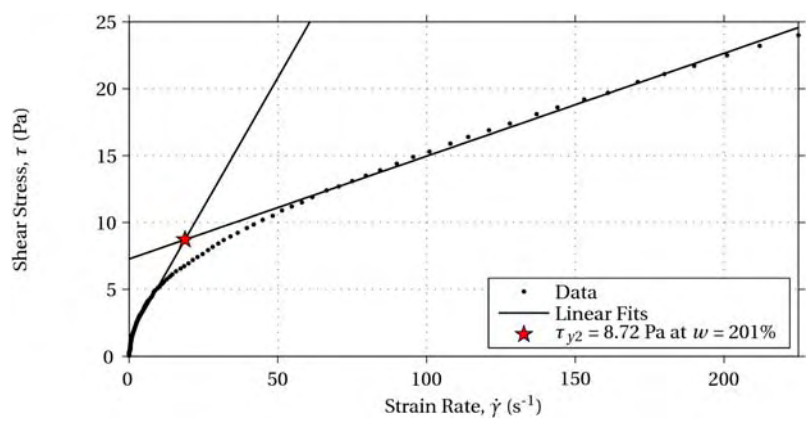

Figure 3 Determining the upper yield stress from a strain rate-stress flow curve.

RESULTS

The measured critical shear stresses varied from 1 to 21 Pa which was the maximum that could be obtained with the flume. A few samples exhibited a critical shear stress that exceeded the maximum. The sediment properties varied over the ranges shown in Table 1. The upper values for water content and Atterberg limits correspond to an organic clay found on the Atlantic coast which could not be eroded in the flume.

Table 1 Sediment sample properties.

Specific gravity	Organic matter, %	Water content, %	Liquid Limit, %	Plasticity index, %	d_{50}, mm	Fine fraction
2.45–2.84	0.3–10	16–120	28–130	5–70	0.002–1.0	0.03–0.7

Navarro (2004) conducted a stepwise multiple linear regression for critical shear stress as a function of sediment properties and found that *Fines fraction* (silt + clay), organic matter and median grain size (d_{50}) were the three best independent variables providing an explanation of about 70% of the variance. With the adddition of the data measured by Hobson(2008), the results were essentially the same.

Nonlinear regression was performed on the Shields parameter τ_{*c} as a function of *Fines fraction* and a dimensionless diameter d_* formed from a combination of the Shields parameter and particle Reynolds number. The data are plotted, and the variables are defined, in Figure 4. If the two data sets are combined, the best-fit regression relationship is nearly the same as for the first data set and is given by

$$\tau_{*c} = 0.644 \times 10^{2.48 Fines} d_*^{-0.409} \tag{1}$$

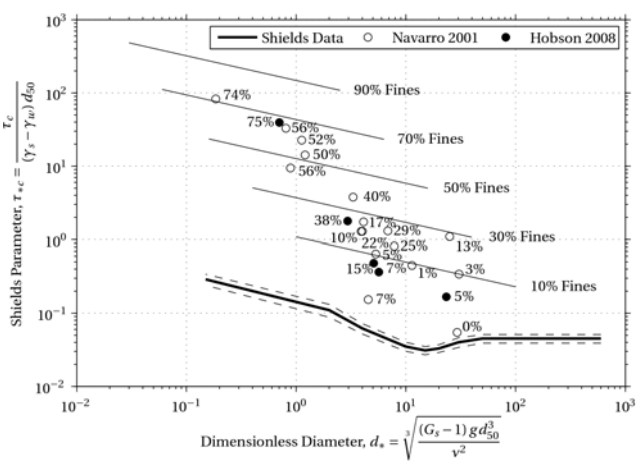

Figure 4 Modified Shields diagram for combined data set.

where γ_s = specific weight of the sediment; γ_w = specific weight of water; d_{50} = median particle sediment size; G_s = specific gravity of sediment; g = gravitational acceleration; ν = kinematic viscosity of water; and *Fines* = decimal fraction by weight of silt plus clay in the particle size distribution. The coefficient of determination of Equation 1 is 0.90. Error intervals for the limits of 0.5 to 2.0 times the predicted value of Shields parameter enclose 86% of the data. Note that the best-fit curves for τ_{*c} as a function of d_* and *Fines* in Figure 4 are nearly parallel to the laminar flow/smooth turbulent flow portion of the Shields curve ($d_* < 2$). From Equation 1, the best-fit slope is –0.41, which is very close to the accepted value of –0.39 for the laminar/smooth turbulent portion of the Shields curve (Sturm 2009).

Upper and lower yield stresses were nondimensionalized in the same manner as for the Shields parameter using the median particle size of the entire size distribution. When regressed against the dimensionless particle size, d_*, also defined in terms of the median particle size for the full size distribution, the result for the upper dimensionless yield stress as shown in Figure 5 is

$$\tau_{*y2} = 5.30 \times 10^6 \, d_*^{-2.78} \qquad R^2 = 0.97 \tag{2}$$

in which τ_{*y2} = dimensionless upper yield stress. The upper yield stress provides a better fit of the data than the lower value also shown in Figure 5. Unfortunately, insufficient data were available to relate the yield stress directly to the critical shear stress, but the fact that both can be related to d_* suggests that they are related to each other through Equations 1 and 2. The result is a relationship in which the upper yield stress reflects the influence of the clay minerals in the fines on the critical value of the Shields parameter. This suggests that the yield stress of fine grained sediments can be measured from rheometer tests of highly nonerodible samples for which critical shear stress cannot be measured in the flume and then used to to estimate the Shields parameter. What is needed to obtain a direct experimental confirmation of such a relationship is a set of samples for which both yield stress from the rheometer and critical shear stress from the flume can be measured and compared.

CONCLUSION

Erosion testing of Shelby tube samples from fifteen bridge sites has resulted in a relationship for critical shear stress which is an important parameter used in estimating bridge contraction scour. The recommended relationship for the critical Shields shear stress parameter depends on a dimensionless diameter and the fraction of fine sediments by weight (silt + clay) in the sediment.

Rheometer testing of the fine fraction of the Shelby tube samples has produced a proposed relationship for the upper yield stress that reveals a connection with the critical shear stress obtained from erosion testing in the flume. The critical value of the Shields parameter is shown to depend on the fines fraction in the soil and on the upper yield stress from the rheometer, which indicates the influence of the mineralogy of the fine size fraction of the sediment. Further experiments are needed to solidify this relationship which is especially important because of the common occurrence of mixed-layer sediments with a significant fine size fraction in Georgia.

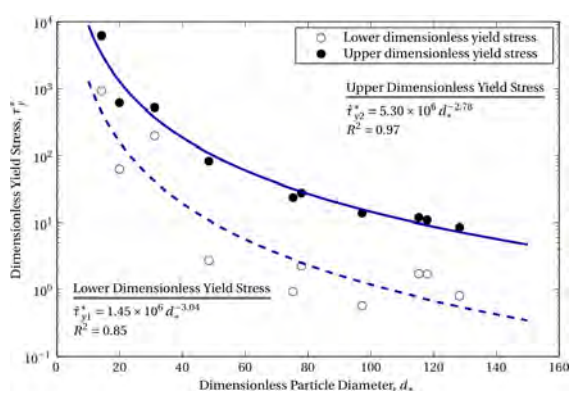

Figure 5 Critical Shields yield stress parameter for upper and lower yield stress as a function of d_*.

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