EVALUATION OF AN IN SITU MEASUREMENT TECHNIQUE FOR STREAMBANK CRITICAL SHEAR STRESS AND SOIL ERODIBILITY

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Abstract The multiangle submerged jet test device (JTD) represents a relatively simple *in situ* method of measuring critical shear stress (τ_c) and soil erodibility (k_d). Previous research has shown k_d and τ_c can vary by up to three and five orders of magnitude, respectively, at a single site; therefore, it is essential to determine if the large range in measurements is due to natural variability in soil properties or errors due to the test method and JTD. The goal of this study was to evaluate the precision and accuracy of the JTD in measuring τ_c and k_d. To determine the precision, a total of 20 jet tests were conducted on remolded clay loam and clay soil samples (10 tests per soil type). For each soil type, the pairs of τ_c and k_d data were analyzed to determine the test standard deviation. The k_d and τ_c values for clay loam ranged from 1.68 to 2.81 cm^3/N-s (μ = 2.30 cm^3/N-s; σ = 0.35 cm^3/N-s) and 0.28 to 0.79 Pa (μ = 0.48 Pa; σ = 0.16 Pa), respectively. The k_d and τ_c values for clay ranged from 1.36 to 2.69 cm^3/N-s (μ = 2.11 cm^3/N-s; σ = 0.41 cm^3/N-s) and 0.30 to 2.72 Pa (μ = 1.25 Pa; σ = 0.74 Pa), respectively. The small variation of k_d and τ_c suggests the multiangle submerged jet test device is precise, and tests can be repeated on similar soils; indicating the wide range of erosion parameter values measured in the field is a result of natural sources of variability, such as subaerial processes and variations in soil moisture, bulk density, and composition. To evaluate the accuracy, k_d and τ_c results from the JTD will be compared with measurements from traditional flume tests using the same two soil types. The flume testing is ongoing and will be completed by April 2010.

INTRODUCTION

The physical, chemical, and biological damage of sediment pollution in streams costs approximately $16 billion annually in North America (Pons, 2003). The major source of sediment is non-point source (NPS) pollution, including erosion and runoff from urban and agriculture lands (USEPA, 2002). However, excessive erosion and the associated sediment load from channel erosion have historically been overlooked. In some watersheds, channel degradation can contribute as much as 85% of the total stream sediment load (Simon et al., 2000). Quantification of the stream sediment load is required for the development of sediment Total Maximum Daily Loads (TMDLs) and sound watershed management strategies, as required by the U.S. Clean Water Act. Streambank retreat not only contributes to stream sediment load, but also impacts floodplain residents, riparian ecosystems, and riparian and floodplain structures (Lawler et al., 1997; ASCE, 1998).

To prevent fluvial entrainment, the applied fluvial shear stress on the bank must stay below erosive levels. The critical condition for erosion is typically quantified by the soil critical shear stress, which is defined as the hydraulic force required to initiate the detachment of sediment particles or aggregates (τ_c). Erosion rates are considered zero when the applied shear stresses are below the critical shear stress (Osman and Thorne, 1988; Nearing et al., 1989; Hanson, 1989, 1990a, 1990b; Ravens and Gschwend, 1999). Some researchers have questioned the validity of the critical shear stress concept (Lavelle and Mofjeld, 1987). Despite criticisms, determining τ_c and accurately estimating erosion rates are important for understanding and managing streambank retreat (Owoputi and Stolte, 1995).

Since channel boundaries can include cohesive soils, standard sediment transport theory for non-cohesive soils is not applicable. The excess shear stress equation (Equation 1) is frequently used to estimate the erosion rate (ε) of cohesive soils (Hanson, 1989, 1990a, 1990b; Hanson and Cook, 1997; Allen et al., 1999; Wan and Fell, 2004; Julian and Torres, 2006):

$$\varepsilon = k_d(\tau_a - \tau_c)^a \tag{1}$$

where, k_d is soil erodibility coefficient (m^3/N-s); τ_a is the applied hydraulic shear stress on the soil (N/m^2); τ_c is the soil critical shear stress (N/m^2); and, a is an exponent typically assumed equal to one. Two assumptions limit the excess shear stress equation: 1) soil erodibility remains constant throughout the soil mass; and, 2) erosion rate and shear stress are linearly related once the critical shear stress is exceeded (Osman and Thorne, 1988; Moody et al., 2005). Two of the parameters in the excess shear stress equation (τ_c and k_d) are considered soil properties, and are needed to estimate erosion rates. The soil erodibility coefficient (k_d) quantitatively describes the ease of particle detachment from soil. This coefficient incorporates both processes of particle motion initiation (soil-property

dependent) and sediment transport (fluid-property dependent) (Moody et al., 2005). Reliable parameter prediction is needed for planning effective erosion control programs, TMDL development and implementation, and watershed management (Harder et al., 1976).

In addition to the underlying assumptions, application of the excess shear stress equation (Equation 1) is limited by the difficulty of determining τ_c and k_d. These parameters can be estimated empirically from soil or flow properties, which recent research has shown significantly underestimates the parameters (Clark and Wynn, 2007), or determined experimentally in the laboratory or in the field. In some cases, critical shear stress is assumed zero (Hanson, 1990a, 1990b; Foster et al., 1977). Typically, critical shear stress is determined by visual observation during experiments, which requires descriptive criteria for the point of erosion initiation. This defined initiation point of sediment movement is subjective and difficult to determine, resulting in multiple definitions (Dunn, 1959; Smerdon and Beasley, 1961; Kamphuis and Hall, 1983; Graf, 1984; Owoputi and Stolte, 1995). Quantitative methods for determining critical shear stress are recommended to remove the subjectivity of visual initiation determination. A common graphing technique to estimate τ_c and k_d is based on the excess shear stress equation , where the parameters are estimated from a linear fit of the hydraulic boundary shear stress and erosion rate (Hanson, 1989; Hanson and Cook, 1997).

The soil parameters are also difficult to determine by traditional flume studies; many biological, physical, and chemical factors that impact cohesive soil erosion are difficult to replicate in the laboratory (Kamphuis and Hall, 1983; Osman and Thorne, 1988; Aberle et al., 2003; Debnath et al., 2007). Moisture content, flow properties, bank material composition, climate, subsurface conditions, clay content, soil structure, vegetation, soil chemistry, and eroding and pore fluid chemistry are some of the factors that affect cohesive erosion (Harder et al., 1976; Arulanandan et al., 1980; Grissinger, 1982; Kamphuis and Hall, 1983; Thorne and Osman, 1988; Lawler et al., 1997; Knighton, 1998). *In situ* tests are needed to incorporate natural field conditions and the influence of soil structure and variability on streambank erosion. The goal of this study was to evaluate the precision and accuracy of a portable multiangle submerged jet test device (JTD), which was designed with this purpose in mind.

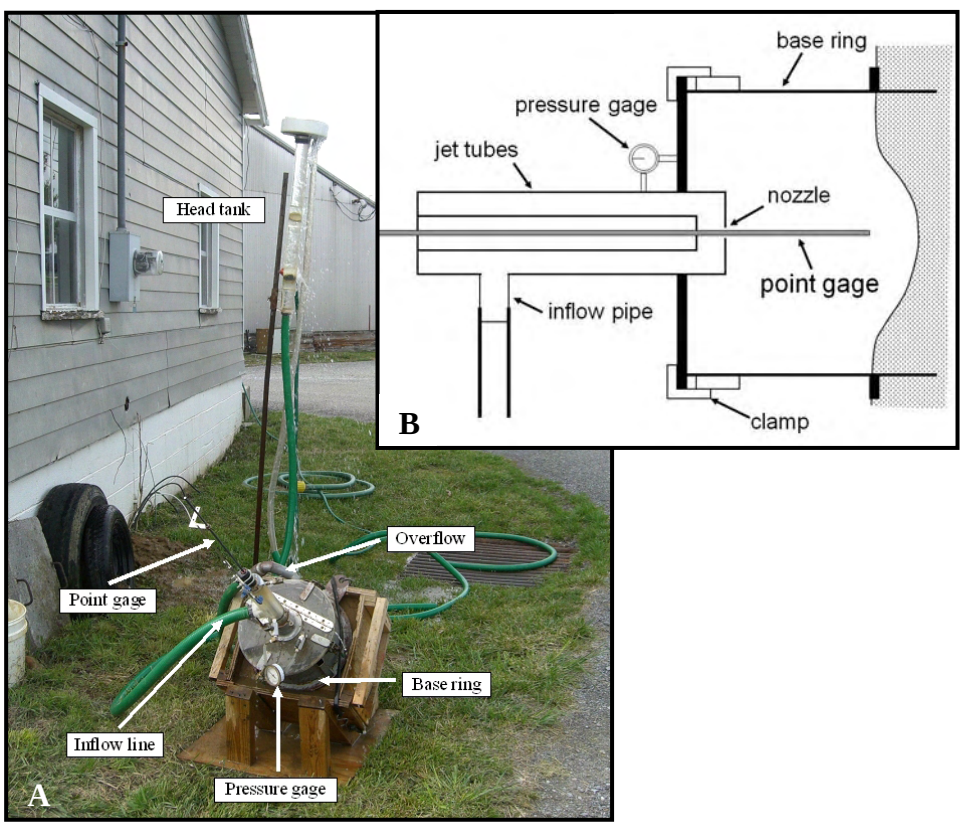

Figure 1 The multiangle submerged jet test device: A) testing setup; and B) schematic.

The multiangle submerged jet test device (Figure 1) represents a relatively simple, inexpensive *in situ* method of measuring k_d and τ_c (Hanson, 1990a; ASTM, 2007). Submerged jets have been utilized since the late 1950's for studying cohesive erosion in both laboratory and field studies (Dunn, 1959; Moore and Masch, 1962; Hollick, 1976; Hanson, 1990a; Hanson, 1991; Hanson and Robinson, 1993; Allen et al., 1997; Allen et al., 1999; Hanson and Simon, 2001; Mazurek et al., 2001; Wynn and Mostaghimi, 2006; Wynn et al., 2008). Previous research has shown k_d and τ_c can vary by up to three and five orders of magnitude, respectively, at a single site (Wynn and Mostaghimi, 2006; Wynn et al., 2008). There are no data available on the precision and accuracy of the test method, so it is impossible to determine if the wide range in values are the result of natural variability in soil properties or test error. Quantifying the accuracy and precision of the JTD is critical in developing this tool to measure soil erodibility and critical shear stress for estimating streambank erosion, and is important for research advances in the areas of water quality management and modeling, fluvial geomorphology, and stream restoration

METHODS

To evaluate the precision of the JTD without the variability due to soil structure, moisture content, and climate processes, ten jet tests per soil type were conducted on uniform remolded clay loam and clay samples. The resulting pairs of k_d and τ_c were analyzed to determine the test standard deviation. To evaluate the jet test accuracy, soil τ_c and k_d measurements from jet tests will be statistically compared with measurements from traditional flume tests. Four flume erosion tests, each at a different applied shear stress, will be conducted for each soil type to estimate k_d and τ_c. The flume tests are ongoing and will be completed by April 2010.

Soil Preparation: The two remolded soils used during the erosion tests were classified as USDA textures clay loam and clay. The clay loam was a Groseclose silt loam (fine, mixed, semiactive, mesic Typic Hapludults), while the testing soil "clay" was a mixture of the clay loam with locally excavated red clay subsoil.

The clay loam (29% sand, 40% silt, 31% clay; Plasticity Index = 9) preparation consisted of sieving soil through a 0.64-cm opening mesh screen to remove any vegetation and gravel, and to break apart large soil masses. The soil was air dried to an average gravimetric moisture content of 0.12 and thoroughly mixed to ensure a homogeneous sample.

The clay soil (18% sand, 32% silt, 50% clay; Plasticity Index = 24) was a mixture of 50 percent clay loam (sieved as described above) and 50 percent clay (by weight) that was excavated at a local construction site. Dry clay aggregates were manually ground in a sausage grinder; the soil was then sieved through a series 12 sieve with 1.651 mm openings. The small amount of gravel in the soil was removed before grinding or by the sieve. The retained clay portion in the sieve was crushed with a wooden roller and re-sieved. Before mixing, the sieved clay and clay loam were air-dried to a gravimetric moisture content of 0.09 and 0.08, respectively.

Using a small cement mixer (BigCat Mixer Type B, Monarch Industries), 4.5 kg of both clay loam and sieved clay were mixed together for several minutes to attain a homogenous mixture. This procedure was repeated twice for a single 27.2 kg mixture (13.6 kg of each soil). The testing clay mixture (hereafter called "clay") was moistened by sprinkling tap water with a watering can onto the soil, and raking the soil and water evenly together. The clay was sieved through a 0.64-cm opening screen to break apart the any large aggregates and air dried to an average gravimetric moisture content of 0.16.

Submerged Jet Testing Testing Methods: The clay loam and clay soil were compacted into 38-cm square wooden boxes at a bulk density of 1.5 g/cm^3. Each remolded soil consisted of 54.4 kg, compacted evenly in 4.5-kg lifts to at least 6.9 MPa using a hydraulic press (Dayton model 4Z194A; 0 to 17.2 MPa; Dayton Electric Manufacturing Company). After compacting 27.2 kg, a soil sample was collected from the remaining soil to be compacted to determine gravimetric moisture content. The collected soil sample was weighed and then dried at minimum of 105°C for at least of 24 hours. After drying, the sample cooled for at least 15 min. in a desiccator before weighing again (USDA, 1996). Compacted soil was wetted and drained (top to bottom) with the eroding fluid (Blacksburg, VA public water supply) overnight for at least 16 hrs before jet testing. Each box was compacted, saturated, drained, and tested within the same time period (over a period of two days) to reduce variability among the tests due to soil consolidation.

The soil-filled boxes were set at a 45° testing angle with a wooden platform (Figure 2). After inserting and securing the JTD base ring to the wooden platform, bentonite was molded along the inside ring edge to seal the test area. Jet

testing was conducted with a preliminary head setting of 202 cm for clay loam and 203 cm for clay tests, city water via hose connection filled the head tank and flowed through the nozzle to fill the JTD base ring. The jet testing followed the procedures outlined in Hanson and Cook (2004).

Figure 2 The multiangle submerged jet test device during testing of a remolded clay loam sample in wooden box: A) side view of jet test device during testing; and, B) scour result from jet testing.

Each of the ten jet tests ran for 45 min. with scour depth measurements taken every 5 min. (nine scour measurements per test). During each measurement, the point gage was inserted through the nozzle, stopping the jet (and time), and lowered to eroded soil surface. Pressure differentials were measured during the 5-min. testing intervals while the jet was running. Temperature and conductivity of the water inside the JTD ring were recorded during the first scour measurement at 5 min. and a second conductivity measurement was taken during the last scour measurement at 45 min. Water temperature was measured with a Fisher Scientific Traceable digital handheld thermometer (-50°C to +300°C; +/- 1°C between -20°C and +100°C; Fisher Scientific, Pittsburgh, PA, USA) and conductivity was measured with a Horiba compact Twin Cond conductivity meter B-173 (0 μS/cm to 19.9 mS/cm; +/- 2% full scale +/- 1 digit; Horiba, Ltd., Kyoto, Japan). At test completion, at least two samples were taken with 5.0-cm diameter metal sampling rings to measure bulk density and moisture content. One sample was taken inside the JTD ring next to the scour hole, and one from an upper corner outside the JTD ring. The collected samples were weighed and then dried to a constant weight at a minimum of 105°C. After drying, the bulk density samples cooled in a desiccator before weighing again (USDA, 1996).

Data Analysis Test data were entered into a spreadsheet routine, developed by Hanson and Cook (2004), to estimate τ_c and k_d. Critical shear stress was calculated from the equilibrium scour depth, which was determined by fitting the scour depth versus time data to a logarithmic hyperbolic function, following procedures of Blasidell et al. (1981) (Hanson and Cook, 1997, 2004). The soil erodibility coefficient was determined using a least-squares regression based on measured scour depth, time, calculated τ_c, and a dimensionless time function (Hanson and Cook, 2004). The ten pairs of τ_c and k_d data were analyzed to determine the test standard deviation for each of the two soil types. Additionally, one-sample t-tests were done to statistically compare the ten cumulative means formed by the addition of each separate test to the overall mean of all ten tests to provide guidance on the minimum number of tests required to confidently determine τ_c and k_d. Assuming the population mean is equal to the overall mean of ten tests, the null hypothesis was defined as the cumulative mean after a specific number of tests was equal to the overall mean of ten tests (i.e. mean after first 3 tests was equal to overall mean of ten tests).

Flume Testing To evaluate the jet test accuracy, soil τ_c and k_d measurements from jet tests will be compared with measurements from traditional flume tests. Remolded soil samples will be prepared using similar conditions as for the jet tests. Each remolded sample will be prepared by compacting 1.70 kg of soil into a metal box (15 cm x 15 cm x 5 cm) in two 0.85-kg lifts to at least 3.5 MPa with a hydraulic press. The remolded soil will be wetted and drained overnight, similar to the samples for the jet tests. The soil box will be sealed in the bed of a recirculating hydraulic flume (6-m long; 1-m wide; 0.4-m deep; Engineering Laboratory Design, Inc.; Lake City, Minnesota, USA) (Figure 3), and the soil surface will be maintained flush with the flume bed by an air bellow underneath the sample during testing. The erosion rate during each 45-min. test will be estimated for four different applied shear stresses from the

dry mass weight of soil lost during the test, and τ_c and k_d will be estimated for each soil type by plotting the erosion rate versus the applied shear stress for the four tests. Finally, the parameter values from the jet test and the flume runs will be compared statistically to assess the accuracy of the JTD.

Figure 3 The recirculating hydraulic research flume setup.

RESULTS AND DISCUSSION

Multiangle Submerged Jet Test Device Precision For the jet tests, the k_d and τ_c values for clay loam ranged from 1.68 to 2.81 cm^3/N-s (μ = 2.30 cm^3/N-s; σ = 0.35 cm^3/N-s) and 0.28 to 0.78 Pa (μ = 0.48 Pa; σ = 0.16 Pa), respectively (Table 1). The k_d and τ_c values for clay ranged from 1.36 to 2.69 cm^3/N-s (μ = 2.11 cm^3/N-s; σ = 0.41 cm^3/N-s) and 0.30 to 2.72 Pa (μ = 1.25 Pa; σ = 0.74 Pa), respectively (Table 2). An inverse relationship between τ_c and k_d was observed, similar to the results of Arulanandan et al. (1980), Hanson and Cook (1997, 2001).

The vast difference in k_d and τ_c variability between field and the laboratory jet test data can be observed in Figure 4. Wynn et al. (2008) jet tested streambanks along Stroubles Creek, near Blacksburg, Virginia, USA, and the resulting k_d and τ_c measurements ranged from 0.01 to 8.59 cm^3/N-s (μ = 0.71 cm^3/N-s; σ = 1.14 cm^3/N-s) and 0.00 to 43.32 Pa (μ = 10.55 Pa; σ = 11.14 Pa), respectively. Jet tests along the East Fork of the Little River, near Pilot, Virginia measured k_d values between 1.17 and 8.36 cm^3/N-s (μ = 3.96 cm^3/N-s; σ = 2.09 cm^3/N-s) and τ_c values between 0.01 and 12.23 Pa (μ = 1.57 Pa; σ = 2.71 Pa) (Wynn and Mostaghimi, 2006). The standard deviation of critical shear stress for the remolded samples was low, but τ_c from field data had a range of five orders of magnitude at both field sites with similar soils to this study (Wynn et al., 2008; Wynn and Mostaghimi, 2006).

The small variation of the two soil parameters for the remolded clay loam and clay, compared to the large range of values observed in the field at a single site, suggests the multiangle submerged jet test is precise and jet tests can be repeated with similar soil conditions. These results also indicate there are other significant factors influencing cohesive soil erodibility and critical shear stress. The large variability of τ_c values measured in the field, compared with results from this study, suggest that changes in streambank surface soils due to subaerial processes play a significant role in determining the minimum shear stress required to initiate sediment movement for cohesive soils. All the remolded samples used in this study had the same surface condition, a smooth, flat soil surface with no vegetation, or surface weathering.

Table 1 Jet test conditions and results for remolded clay loam samples with the multiangle submerged jet test device.

Jet Test Clay Loam Run	Compaction θ_d[a]	Initial Testing θ_d	ρ_b[b] (g/cm^3)	τ_c[c] (Pa)	k_d[d] (cm^3/N-s)	Water Temp (°C)	Water Conductivity[e] (µS/cm)
1	0.11	0.22	1.52	0.57	1.68	15.2	143
2	0.13	0.21	1.51	0.40	2.13	19.4	154
3	0.11	0.23	1.54	0.78	2.31	20.0	160
4	0.12	0.25	1.54	0.55	2.42	20.5	160
5	0.12	0.22	1.52	0.48	1.99	21.3	154
6	0.13	0.23	1.53	0.33	2.69	21.0	156
7	0.12	0.23	1.52	0.42	2.59	21.3	153
8	0.13	0.22	1.56	0.35	2.31	21.6	172
9	0.12	0.22	1.53	0.28	2.81	21.2	157
10	0.14	0.23	1.54	0.63	2.03	23.2	171
Mean	*0.12*	*0.23*	*1.53*	*0.48*	*2.30*	*20.5*	*158*
Std Deviation	*0.01*	*0.01*	*0.01*	*0.16*	*0.35*	*2.1*	*8*

[a] Gravimetric soil moisture content; [b] Bulk density; [c] Critical shear stress; [d] Soil erodibility; [e] Average of test start and end measurements

Table 2 Jet test conditions and results for remolded clay samples with the multiangle submerged jet test device.

Jet Test Clay Run	Compaction θ_d[a]	Initial Testing θ_d[b]	ρ_b[c] (g/cm^3)	τ_c[d] (Pa)	k_d[e] (cm^3/N-s)	Water Temp[f] (°C)	Water Conductivity[g] (µS/cm)
1	0.16	0.26	1.43	0.57	2.69	9.1	154
2	0.17	0.25	1.48	1.13	1.78	13.1	170
3	0.16	0.26	1.45	1.19	1.86	13.6	164
4	0.16	0.27	1.46	0.30	2.23	16.8	153
5	0.17	0.27	1.47	0.88	1.79	16.9	164
6	0.16	0.27	1.46	1.06	2.13	17.9	150
7	0.16	0.26	1.45	1.32	2.29	18.7	163
8	0.16	0.26	1.53	2.72	1.36	21.2	171
9	0.15	0.26	1.44	1.05	2.43	21.2	183
10	0.15	0.27	1.44	2.30	2.53	21.5	171
Mean	*0.16*	*0.26*	*1.46*	*1.25*	*2.11*	*17.0*	*164*
Std Deviation	*0.01*	*0.01*	*0.03*	*0.74*	*0.41*	*4.1*	*10*

[a] Gravimetric soil moisture content; [b] Average of two or three measurements (except Runs 3 and 5 with only one measurement); [c] Bulk density, average of two measurements (except Runs 4 and 6 with only one measurement); [d] Critical shear stress; [e] Soil erodibility; [f] Average of pre-test and post-test; [g] Average of four measurements (pre-test, post-test, start, and end)

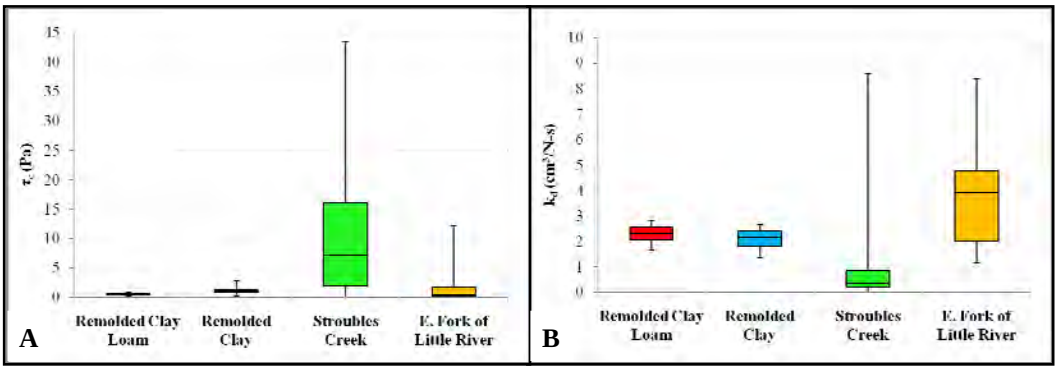

Figure 4 Boxplots of A) critical shear stress (τ_c); and, B) soil erodibility (k_d) measurements with the multiangle submerged jet test device for remolded clay loam and clay soils, Stroubles Creek streambanks near Blacksburg, VA (Wynn et al., 2008) and East Fork of the Little River streambanks near Pilot, VA (Wynn and Mostaghimi, 2006).

The remolded samples for each soil type were prepared to ensure there was minimal variability due to soil structure, moisture content, bulk density, and subaerial processes, which are known factors to impact cohesive soil erosion. The clay loam was compacted with a gravimetric soil moisture content of 0.1 (μ = 0.12; σ = 0.01) to a bulk density of 1.5 g/cm^3 (μ = 1.53 g/cm^3; σ = 0.01 g/cm^3), and jet tested with a soil moisture content of 0.2 (μ = 0.23; σ = 0.01) (Table 1). Similarly, the remolded clay was compacted and tested with a slightly higher gravimetric soil moisture content than the clay loam at 0.2 (μ = 0.16; σ = 0.01) and 0.3 (μ = 0.26; σ = 0.01), respectively, and compacted to a bulk density of 1.5 g/cm^3 (μ = 1.46 g/cm^3; σ = 0.03 g/cm^3) (Table 2). Hanson and Robinson (1993) found bulk density and moisture content at the time of compaction had major influences on the erodibility of cohesive soils. During that study, soil erodibility decreased when either bulk density (constant compaction moisture) or compaction moisture (constant bulk density) increased. The soil samples were prepared with similar compacting moisture contents and bulk densities, and tested at consistent moisture contents to decrease the influences on erosion.

Water temperature and conductivity remained relatively constant throughout all the tests. Consistent temperature and conductivity between tests was important because eroding fluid chemistry influences cohesive soil erosion (Kamphuis and Hall, 1983; Lawler et al., 1997; Harder, 1976; Arulanandan et al., 1980). The wide range of measured values for k_d and τ_c in natural stream tests confirms the importance of other factors in cohesive soil erosion, including soil moisture content, bulk density and structure, vegetation, and, subaerial processes (Allen et al., 1999; Hanson and Simon, 2001; Wynn and Mostaghimi, 2006; Wynn et al., 2008).

The cumulative scour depth ranged from 5.6 to 7.3 cm and from 4.3 to 7.1 cm, respectively, for remolded clay loam and clay soils. All ten tests for each soil type eroded in similar manner, as seen by the similar shapes of the scour curves in Figure 5. The initial high erosion rate decreased after the first five min. and then slowly decreased throughout the test. The scour curves of the clay soil usually leveled out more than the clay loam soil during the 45-minute jet tests. The erosion during the first 5-min. of the tests usually influenced the scour depth throughout the remaining duration of the test.

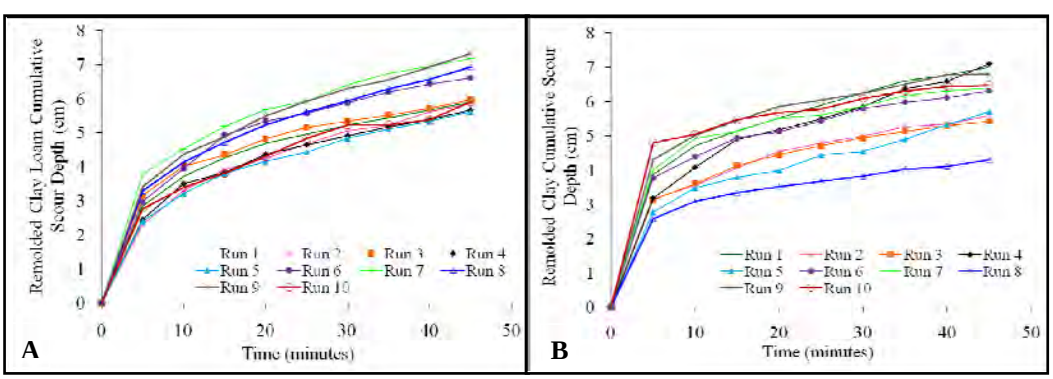

Figure 5 Cumulative scour depth for ten tests on A) clay loam; and, B) clay samples using the jet test device.

The high erosion rate at the start of the test is typically attributed to weakening of the soil surface due to soil wet/dry or freeze/thaw cycling. However, prior to the jet tests, the samples were protected from surface weathering, so this initial high erosion rate was likely a characteristic of the jet test, and not the result of subaerial processes. The initial high erosion rate was instead likely the result of decreases in the applied shear stress as the scour hole deepened and the distance to the soil surface increased. Additionally, the scour rates for both soils remained relatively constant throughout each test, as compared to the more variable rates observed during field studies (Wynn and Mostaghimi, 2006; Wynn et al., 2008) (Figure 6). Cumulative scour depth curves from jet tests on natural cohesive streambanks tend to be a series of steps, where the scour rates level off, and then quickly increase. Aggregate erosion, vegetation, animal burrows, and other factors contribute to the fluctuations of scour rates during jet tests. As stated earlier, the clay loam and clay soils were sieved and thoroughly mixed, thus minimizing the presence of large aggregates, gravel, or roots. Thus, the difference between these scour rates and those observed for cohesive soils in the field lends support to the belief that cohesive soils erode as aggregates, rather than as individual particles.

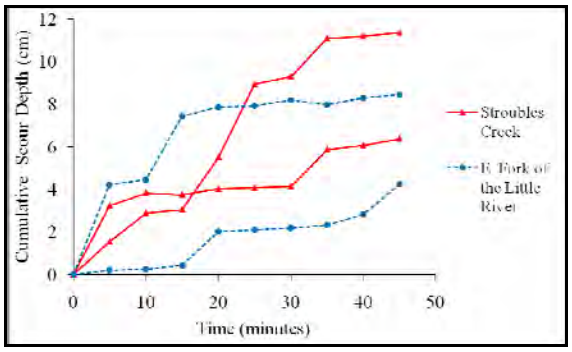

Figure 6 Cumulative scour depth for jet tests on streambanks of Stroubles Creek, near Blacksburg, VA (Wynn et al., 2008) and East Fork of the Little River, near Pilot, VA (Wynn and Mostaghimi, 2006).

Typically in the field, three jet tests are conducted to obtain average values of the erosion parameters (Hanson and Cook, 2004). Results from the laboratory tests suggest three tests may not be sufficient for estimating an average k_d and τ_c. Erodibility variance leveled out with nine tests for both clay loam and clay soils (Figure 7). Critical shear stress variance leveled with five tests for clay loam, and for clay, it started to level with seven tests and then peaked with run eight. The critical shear stress measured for clay run eight was the highest out of the ten jet tests. Compared with the rest of the nine clay tests, the compaction and testing moisture content of run eight were similar, but the bulk density of the soil tested was 0.05 g/cm^3 greater than the highest bulk density tested in the previous tests. This slight difference in bulk density impacted how the clay eroded, as seen in Figure 5, where run eight had the lowest scour depth. This sensitivity to small changes in initial conditions seen in the erosion of carefully prepared remolded soils implies that the differences in soil conditions of the same streambank could have an even larger influence on erosion parameter measurements in the field.

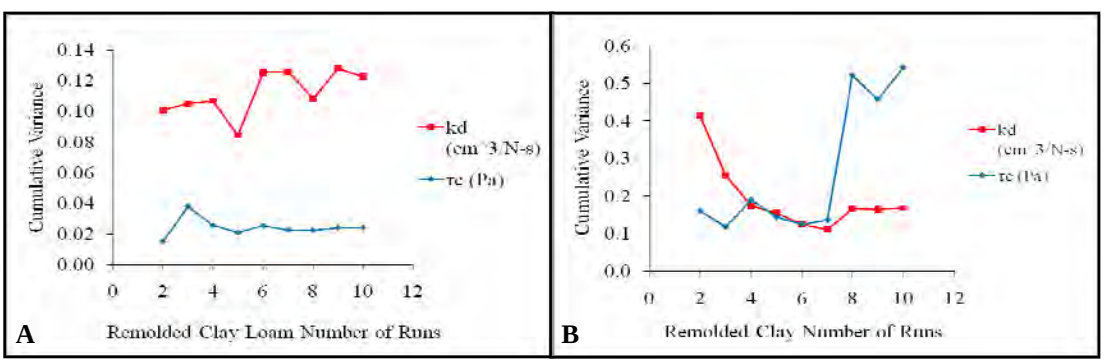

Figure 7 Variance change with additional runs for A) clay loam; and, B) clay.

Multiangle Submerged Jet Test Device Accuracy The results for the accuracy of the multiangle submerged jet test device are pending the conclusion of the flume tests.

CONCLUSION

Results from this study indicate the multiangle submerged jet test device has a precision of +/- 0.35 cm^3/N-s and +/- 0.16 Pa for clay loam k_d and τ_c, respectively, and a precision of +/- 0.41 cm^3/N-s and +/- 0.74 Pa for clay k_d and τ_c, respectively. This suggests the variability of critical shear stress and soil erodibility measured with the jet test device may be influenced by soil type. Compared with k_d and τ_c results from previous field jet testing (Hanson and Simon, 2001; Wynn and Mostaghimi, 2006; Wynn et al., 2008), the variation among the two erosion parameters for remolded soil was small. Both Wynn and Mostaghimi (2006) and Wynn et al. (2008) had a critical shear stress range of five orders of magnitude, and both study sites had similar soil to the remolded clay loam. Tests on the uniform soils provided a contrast to field tests, indicating subaerial processes, soil structure, and other factors play a significant role in the erodibility and critical shear stress of cohesive soils. The small variation of the two soil parameters, compared to the large range of values observed in the field at a single site, suggests the multiangle submerged jet test device is precise, and tests can be repeated with similar soil conditions. Evaluation of the accuracy for the device is pending completion of laboratory flume tests.

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