River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds) - © 2010 Bundesanstalt für Wasserbau ISBN 978-3-939230-00-7

Effects of spatial variability on the estimation of erosion rates for cohesive riverbanks

Soonkie Nam, John Petrie & Panayiotis Diplas
Virginia Polytechnic Institute and State University, Blacksburg, VA, USA
Marte S. Gutierrez
Colorado School of Mines, Golden, CO, USA

ABSTRACT: Human activities, such as dam construction, can cause excessive erosion of a riverbank due to alteration of the natural flow regime. This erosion can lead to degradation in water quality and aquatic habitat as well as loss of land and damage to riparian structures. Accurate estimation of erosion rates for cohesive riverbanks is a difficult task owing to the complex nature of cohesive soils and their interaction with the river flow. Past work has attempted to correlate physical and chemical soil properties with erosion rates, however the wide range of soil properties has made it difficult to produce a general model for cohesive soil erosion. The erodibility of riverbank soil on the lower Roanoke River, North Carolina USA, was estimated in situ employing the jet erosion test (JET) apparatus. The JET applies a water jet of uniform velocity directly to the soil and measures the resulting scour depth evolution over time. The measured data are then used to determine two empirical parameters, the erodibility coefficient and critical shear stress. Several JETs were performed on different soil layers at sites with bank materials composed primarily of silts and clays. The physical properties of each soil layer were determined through laboratory analysis. Using boundary shear stress calculations from a simple analytical model, erosion rates are calculated assuming a linear excess shear stress model, and the effects of the spatial variability of soil properties on calculated erosion are investigated. While previous research has shown that the JET produces consistent results under controlled environments, results here demonstrate the importance of considering spatial variability of soil types when estimating erosion rates.

Keywords: Jet erosion test, Erodibility, Critical shear stress, River bank erosion

1 INTRODUCTION

Various types of human activities can cause excessive erosion of a riverbank due to alteration of the natural flow regime. Some problems due to erosion include loss of land, damage to riparian structures, transport of pollutants, and degradation in water quality and aquatic habitat. As listed, erosion causes not only financial losses but also environmental problems. Therefore, active controls are beneficial in an effort to reduce erosion.

To quantify the effects of erosion, proper estimation of erosion induced by the activities and controls of human-induced activities are required. However, estimation of soil erodibility and flow characteristics in a river contain great uncertainty and variability due to the complex nature of soils and their interactions with the river flow.

Riverbank soils can be simply classified as non-cohesive or cohesive. Non-cohesive soils, including sand and gravel, are typically granular and coarser than cohesive soils causing the properties of individual soil particles to dominate the characteristics of the soils. On the contrary, cohesive soils, such as silt and clay, are finer and the soil minerals, structure, chemicals and interacting forces are typically more important to the overall soil characteristics than the physical properties of soil particles.

Erodibility of non-cohesive soils is determined by gravitational forces and soil parameters such as particle size, shape, and unit weight of soil (Graf, 1971), whereas that of cohesive soils is much more difficult to estimate. As summarized by Grissinger (1982), correlations of erosion rates with combinations of plasticity, percentage of clay particles, soil mineralogy, cation exchange capacity (CEC), and many other physical and chemical soil properties have been investigated, but the wide range of soil properties and complexity of interactions of different parameters have made it difficult to develop a general model for cohesive soil erosion.

This study investigates the variability of erodibility parameters of cohesive soils and their influences on erosion rate calculations for the riverbanks of the lower Roanoke River near Roanoke Rapids, North Carolina, USA, estimated by the in situ submerged jet erosion test.

1.1 *Estimation of erosion rate*

Due to the complexity of cohesive soil erosion, empirical methods have been widely employed and accepted for cohesive soils for several decades. The linear excess shear stress equation is often used to estimate erosion and is commonly presented with three parameters: the erodibility coefficient (k_d) and applied and critical shear stresses (τ_o and τ_c), which imply the rate of erosion when a given hydraulic shear stress is applied and the ease of initiating erosion, respectively (Hanson and Cook, 2004; Wan and Fell, 2004).

$$\varepsilon = k_d\left(\tau_o - \tau_c\right)^a \qquad \text{for} \quad \tau_o > \tau_c$$

$$\varepsilon = 0 \qquad \text{for} \quad \tau_o \le \tau_c \qquad (1)$$

where, ε = erosion rate (m/s), k_d = erodibility coefficient (m^3/N·s), τ_o = applied shear stress by flow (Pa), τ_c = critical shear stress of soil, and *a* is a constant commonly assumed to 1.

The applied shear stress (τ_o) is related to the flow conditions, whereas the other two parameters, erodibility coefficient (k_d) and critical shear stress (τ_c), are soil characteristics that typically are determined by experiments. Erosion is considered to occur when the applied shear stress is greater than the critical shear stress of the soil ($\tau_o > \tau_c$), and the total erosion is proportional to the erosion rate and time interval over which erosion occurs.

1.2 *Jet erosion test*

There are several available methods to measure soil erodibility such as flume tests, jet erosion tests, rotating cylinder tests, soil dispersion tests, hole or crack tests, and the erosion function apparatus (Wan and Fell, 2004). In this study, a submerged jet test device was used on riverbanks in the field.

The submerged jet test device was proposed by Hanson (1990a; 1990b; 1991) as an in-situ test technique to determine the erodibility coefficient and critical shear stress of soils (Figure 1). This test evaluates the erodibility of cohesive soils by measuring the depth scoured by a water jet over time. A jet of water is discharged directly to the soil and the depth of the hole produced and duration are measured. Theoretically, the maximum scour depth at equilibrium is required to estimate the erosion parameters. However, it may take hours or even days to reach equilibrium. Hanson & Cook (1997) determined the two empirical erodibility parameters (k_d and τ_c) by adapting analytical procedures to estimate scour depth and critical shear stress at equilibrium proposed by Stein et al. (1993) and Stein & Nett (1997). The theory, principles and procedures of the test are described in detail in Hanson & Cook (2004) and Annandale (2006). The jet test device has been applied in several studies due to advantages such that it is simple, relatively inexpensive, can be performed in the field even on steep slopes, and the erosion parameters are easily calculated using a spreadsheet developed by Hanson and Cook (1997) (Clark and Wynn, 2007; Wahl et al., 2008; Walowsky Jr. et al., 2008; Wynn and Mostaghimi, 2006).

Figure 1. Jet erosion test device

A few studies confirmed the accuracy and consistency of the jet test results under controlled environment (Hanson and Cook, 1997; Hanson and Cook, 2004; Wahl et al., 2008) while others have reported a wide range of results in nature (Hanson and Simon, 2001; Shugar et al., 2007; Simon and Thomas, 2002; Thoman and Niezgoda, 2008; Wynn and Mostaghimi, 2006). However, in practice, most studies with the jet test used it as a single experimental method to obtain the erodibility parameters due to limitations such as the availability of other tests and field conditions. In addition, the results are typically limited to a small number of tests.

1.3 *Applied shear stress by flow*

The applied shear stress by flow also needs to be determined in addition to the soil-related parameters for erosion rate calculations. Several analytical and numerical methods are available for 2D and 3D, and straight and curved channels. The current study employed a simple analytical equation to estimate the distribution of boundary shear stress. While more advanced techniques exist (e.g. Kean et al., 2009, Shiono & Knight, 1991) the simplified technique presented here allows the general trends to be identified even if the magnitudes are not precise.

Boundary shear stress on trapezoidal channels

A simple equation for the boundary shear stress in trapezoidal channel is adapted to estimate maximum shear stress on the slope.

$$\tau_o = \gamma RS \qquad (2)$$

where, τ_o = average shear stress on the boundary (Pa), γ = unit weight of water (N/m^3), R = hydraulic radius (m), and S = channel slope (m/m).

Equation (2) is based on the assumption of one dimensional flow and that the boundary shear stress is averaged over the wetted perimeter, whereas the actual shear stress distribution on a riverbank is not uniform due to the channel slope and curvature.

$$\tau_{0\ max} = 1.1 \cdot \gamma RS \qquad (3)$$

Thus, Equation (2) is updated to Equation (3) for the maximum boundary shear stress on the slope ($\tau_{o\ max}$) which is estimated using the figures suggested by Anderson (1970) (Chang, 2002).

2 LABORATORY AND IN SITU EXPERIMENTS

2.1 *Soil properties*

Soil properties were determined from laboratory tests using disturbed soil samples obtained randomly from the sites, and the sampling locations were recorded to correlate with jet tests locations. Grain size distributions and Atterberg tests results of the soils are shown in Figure 2 and Figure 3, respectively.

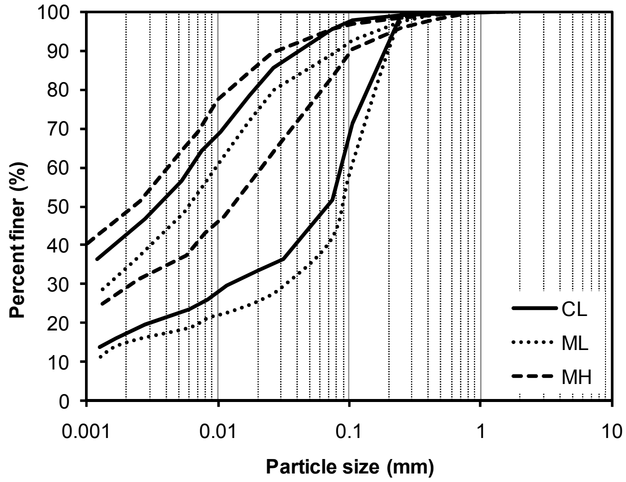

Figure 2. Grain size distribution curves

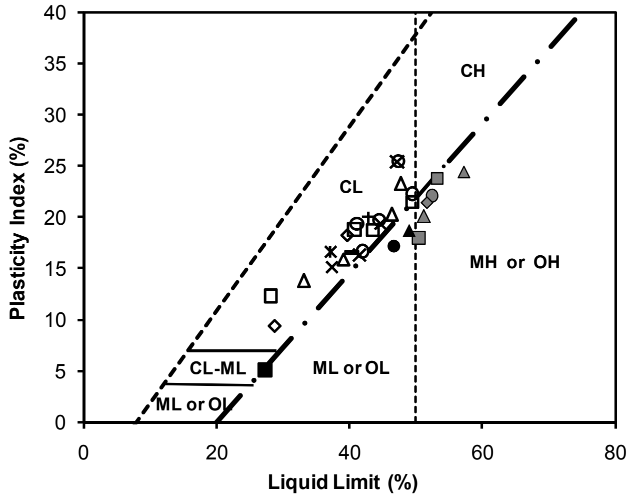

Figure 3. Atterberg test and soil classification

As shown in Figure 3, the soils are classified as low and high plasticity silts (ML and MH) and low plasticity clay (CL) by the unified soil classification system (USCS). The overall results are summarized in Table 1 with soil types.

Table 1. Soil properties

USCS	Sand %	Silt %	Clay %	LL	PI	No. of Sample
CL	16.6	50.2	33.2	41.8	18.6	26
	10.9	8.1	7.3	5.8	3.9	
ML	25.8	47.9	26.3	41.0	13.8	10 (3)*
	18.4	10.9	9.5	11.9	7.2	
MH	9.2	44.7	46.2	52.7	21.6	7
	3.3	2.9	2.8	2.4	2.4	

* 10 samples for grain size distribution and 3 samples for Atterberg tests.
**Upper rows present average value, lower rows present standard deviation.
***LL=Liquid Limit, PI=Plasticity Index

2.2 *Jet erosion test*

Eleven in situ jet tests were performed on the riverbank at different locations in different soils: 5 from CL, 2 from ML, and 4 from MH. The test locations were randomly selected within the soil layers where the properties were known. The detailed procedures for the jet erosion tests are available in Hanson & Cook (2004).

3 RESULTS

3.1 *Erodibility parameters for soils*

The results of the jet tests are shown in Figure 4 and Table 2. A wide range of both erodibility coefficients (k_d) and critical shear stress (τ_c) was observed with no clear relationship between the two parameters. Large standard deviations of each parameter indicate the spatial variability of the parameters within the same soil type.

Based on the same erosion criteria used by Hanson and Simon (2001) as shown with the dotted lines in Figure 4, the soils can be classified as moderately resistant to very erodible soils.

Table 2. Jet test results

USCS	Erodibility coefficient (k_d, m^3/N·s)	Critical shear stress (τ_c, Pa)	No. of Sample
CL	2.0×10^{-6}	3.8	5
	2.4×10^{-6}	2.7	
ML	1.2×10^{-6}	5.2	2
	1.5×10^{-6}	5.7	
MH	1.0×10^{-6}	9.6	4
	1.1×10^{-6}	6.3	

*Upper rows present average value, lower rows present standard deviation.

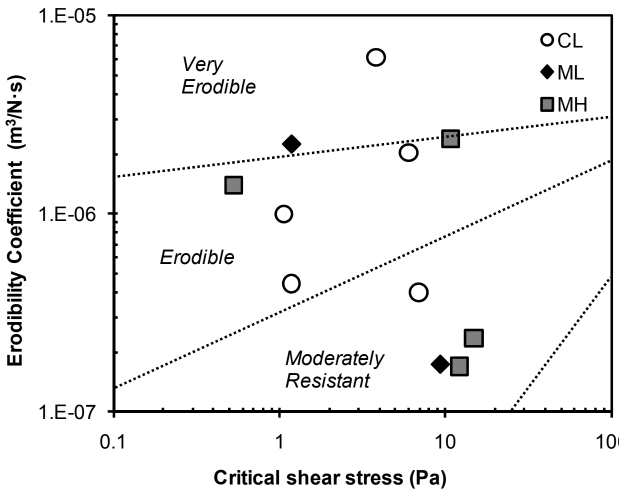

Figure 4. Jet test results from the lower Roanoke River with the classifications of Hanson & Simon (2001).

Although Hanson and Simon (2001) observed a relatively linear relationship between the two parameters after performing 63 jet tests; increasing critical shears stress corresponds to decreasing erodibility coefficient in log-log scale, they also observed very erodible to very resistant soils with a wide variation spanning four orders and six orders of magnitude for k_d and τ_c, respectively. Similar relationships and wide variations were also observed by Shugar et al. (2007) and Thoman and Niezgoda (2008).

3.2 *Estimation of applied shear stress*

The boundary shear stress on the bank slope by flow is estimated using a simple analytical method.

As a hydropower dam is located about 77 river kilometers upstream from the field, it is assumed that a constant discharge with bankfull flow, which is 566 m^3/s discharge from the dam, could be one of critical conditions for erosion in the field. Thus, the applied shear stress at this condition is calculated to estimate the maximum erosion on the riverbank.

In the analytical method, the maximum shear stress is assumed to develop at 2/3 of the flow depth and decreases to zero linearly to the top and bottom of the bank. Bed load movement in the river channel is not considered in this study.

As shown in Figure 5, the maximum shear stresses are estimated as 4.1 Pa at 566 m^3/s discharge condition.

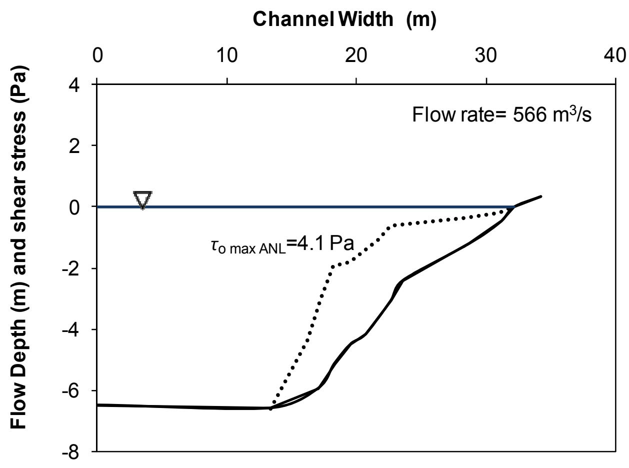

Figure 5. Assumed shear stress distributions by analytical method

3.3 *Variability of erosion rate*

As the erosion rates are determined by three different parameters (k_d, τ_c, and τ_o), soils may have higher predicted erosion rates although one or two of the parameters are lower. This is due to the fact that the erosion rate is determined as a product of erodibility term and shear stress term as shown in Equation (1).

Table 3. Variations of each parameter

Soil Type	$\frac{k_{d\ max}}{k_{d\ min}}$	$\frac{\tau_{c\ max}}{\tau_{c\ min}}$	$\frac{(k_d \times \tau_c)_{max}}{(k_d \times \tau_c)_{min}}$
CL	6.5	15.3	45
ML	7.8	12.9	1.7
MH	27.9	14	35

Table 3 shows the ratios of maximum and minimum values of each parameter for soils. The ratios indicate how the parameters vary within each soil, and how they change after multiplication.

In Table 4, the erosion rates with all combinations of the required parameters under 566m^3/s flow condition are compared. Each column in Table 4 includes a series of data under the same applied shear stress. Each calculated erosion rate in the same column has a different erodibility coefficient and critical shear stress but the same applied shear stress. The results in each row are calculated with same erodibility parameters but different applied shear stresses.

Table 4. Erosion rates with different applied shear stresses

Soil Type	Erosion rate (ε, m/day)					
	Case No	1	2	3	4	5
	τ_o	1	2	4.1	8	10
CL	k_d=0.40 τ_c=6.90	0.000	0.000	0.000	0.038	0.107
	k_d=0.44 τ_c =1.18	0.000	0.032	0.112	0.261	0.338
	k_d=6.13 τ_c =3.82	0.000	0.000	0.147	2.211	3.270
	k_d=1.00 τ_c =1.07	0.000	0.080	0.261	0.597	0.769
	k_d=2.03 τ_c =6.02	0.000	0.000	0.000	0.350	0.701
ML	k_d=0.17 τ_c =9.26	0.000	0.000	0.000	0.000	0.011
	k_d=2.23 τ_c =1.19	0.000	0.156	0.560	1.311	1.695
MH	k_d=0.17 τ_c =12.13	0.000	0.000	0.000	0.000	0.000
	k_d=0.24 τ_c =14.81	0.000	0.000	0.000	0.000	0.000
	k_d=1.39 τ_c =0.53	0.056	0.176	0.427	0.894	1.134
	k_d=2.39 τ_c =10.79	0.000	0.000	0.000	0.000	0.000

Case 3 is for the field conditions that the applied shear stress was obtained from calculations. In the other cases, the applied shear stress was increased from 1 to 10, which represent flow conditions other than the bankful discharge.

In Case 3, no erosion was predicted for 6 out of the 11 samples due to the large measured critical shear stress. The other 5 samples (three CL, one ML and one MH soil) were found to be eroded, with predicted erosion rates of 0.26m/day, 0.56m/day, and 0.43 m/day, for CL, ML and MH soils, respectively. It also shows that erosion rates range from 2.3 times (when τ_o=4.1) to 58 times (when τ_o=8) in the clayey soils without considering no erosion cases.

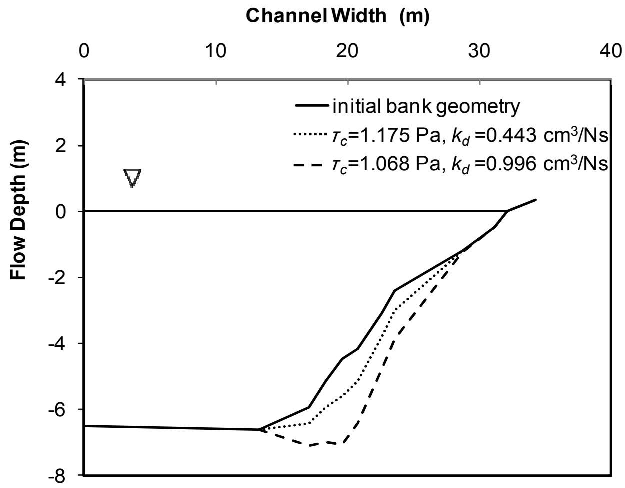

Figure 6 Eroded bank geometry after 10 days

Figure 6 shows an example of the erosion predicted from two different jet test results for the same soil when the applied shear stress was assumed as 4.1 Pa and the flow continued for 10 days. With different values of the erodibility parameters, the total erosion ranges from zero to 2.57m for 10 days.

4 CONCLUSION AND DISCUSSION

Erosion rates are calculated using a linear excess shear stress equation with erodibility parameters (k_d and τ_c) determined by jet erosion tests, and the applied shear stress obtained from analytical method.

The values of the erodibility parameters obtained from the jet erosion tests varied considerably exhibiting wide ranges for the same soil. The standard deviations of the erodibility parameters in the same soil were larger than the averages, and, thus, larger differences in the calculated erosion rate were observed. Due to the fact that the erosion rate is determined by the product of erodibility coefficient and shear stress differences, the calculated erosion rates are not proportional to the parameters. The lowest erosion rate was determined to be zero for all three soil types, and the largest erosion rates were 0.27, 0.56, and 0.43 m/day for CL, ML and MH soils, respectively.

Assuming that the jet erosion tests were performed at a place representing that soil layer and the other variables are obtained from reliable sources, the erosion rate of clayey soils would be one of the values in the Case 3-CL, which are, zero, 0.112, 0.147, and 0.261 m/day. For overall period that the dam discharge is over 566 m^3/sec, the predicted annual erosions from the 4 different erosion rates will be significantly different.

The estimated erosions in practical cases may involve similar or worse uncertainty in the results due to the fact that the typical number of tests performed in the field for practical cases is also similar or even smaller (Wahl, 2008; Walowsky Jr. et al., 2008).

Thus, the variability of the tests results should be reviewed before making erosion estimation using additional information such as statistical analysis with more test results, other references for the erodibility of the similar type of soils, or other empirical correlations using the other frequently available soil properties.

ACKNOWLEDGEMENTS

The support of Dominion, U.S. Army Corps of Engineers and the Edna Bailey Sussman Fund is gratefully acknowledged. The authors also would like to thank David Liu for assisting with field work.

REFERENCES

Anderson, A.G., Davenport, J.T. and Paintal, A.S., 1970. Tentative design procedure for riprap-lined channels. National Cooperative Highway Research Program Report 108. Highway Research Board.

Annandale, G.W., 2006. Scour technology : mechanics and engineering practice. McGraw-Hill, New York.

Chang, H.H., 2002. Fluvial Processes in River Engineering. Krieger Publishing Co., Malabar, FL.

Clark, L.A. and Wynn, T.M., 2007. Methods for determining streambank critical shear stress and soil erodibility: Implications for erosion rate predictions. Transactions of the ASABE, 50(1): 95-106.

Graf, W.H., 1971. Hydraulics of Sediment Transport. McGraw Hill, New York.

Grissinger, E.H., 1982. Bank erosion of cohesive materials. In: R.D. Hey, J.C. Bathurst and C.R. Thorne (Editors), Gravel-bed Rivers. John Wiley & Sons, New York, pp. 273-287.

Hanson, G.J., 1990a. Surface erodibility of earthen channels at high stresses. Part I-Open channel testing. Transactions of the ASAE, 33(1): 127-131.

Hanson, G.J., 1990b. Surface erodibility of earthen channels at high stresses. Part II-Developing an in situ testing device. Transactions of the ASAE, 33(1): 132-137.

Hanson, G.J., 1991. Development of a jet index to characterize erosion resistance of soils in earthen spillways. Transactions of the ASAE, 34(5): 2015-2020.

Hanson, G.J. and Cook, K.R., 1997. Development of excess shear stress parameters for circular jet testing, 1997 ASAE Annual International Meeting. ASAE, Minneapolis, MN, USA, pp. 97-2227.

Hanson, G.J. and Cook, K.R., 2004. Apparatus, test procedures, and analytical methods to measure soil erodibility in situ. Applied Engineering in Agriculture, 20(4): 455-462.

Hanson, G.J. and Simon, A., 2001. Erodibility of cohesive streambeds in the loess area of the midwestern USA. Hydrological Processes, 15(1): 23-38.

Kean, J.W., Kuhnle, R.A., Smith, J.D., Alonso, C.V. and Langendoen, E.J., 2009. Test of a method to calculate near-bank velocity and boundary shear stress. Journal of Hydraulic Engineering, 135(7): 588-601.

Shiono, K. and Knight, D.W., 1991. Turbulent open-channel flows with variable depth across the channel. Journal of Fluid Mechanics, 222: 617-646.

Shugar, D., Kostaschuk, R., Ashmore, P., Desloges, J. and Burge, L., 2007. In situ jet-testing of the erosional resistance of cohesive streambeds. Canadian Journal of Civil Engineering, 34(9): 1192-1195.

Simon, A. and Thomas, R.E., 2002. Processes and forms of an unstable alluvial system with resistant, cohesive streambeds. Earth Surface Processes and Landforms, 27(7): 699-718.

Stein, O.R., Alonso, C.V. and Julien, P.Y., 1993. Mechanics of jet scour downstream of a headcut. Journal of Hydraulic Research, 31(6): 723-738.

Stein, O.R. and Nett, D.D., 1997. Impinging jet calibration of excess shear sediment detachment parameters. Transactions of the ASAE, 40(6): 1573-1580.

Thoman, R.W. and Niezgoda, S.L., 2008. Determining erodibility, critical shear stress, and allowable discharge estimates for cohesive channels: Case study in the Powder River Basin of Wyoming. Journal of Hydraulic Engineering, 134(12): 1677-1687.

Wahl, T.L., 2008. Stability analysis of proposed unlined spillway channel for upper San Joaquin River Basin RM 274 embankment dam alternative. HL-2008-06, Bureau of Reclamation.

Wahl, T.L., Regazzoni, P.-L. and Erdogan, Z., 2008. Determining erosion indices of cohesive soils with the hole erosion test and jet erosion test. DSO-08-05, Bureau of Reclamation.

Walowsky Jr., D., Wright, P. and Henry, C., 2008. Jet test to evaluate the head cutting of glacial till in auxiliary spillways in New York state, 2008 ASABE Annual International Meeting, Providence, RI, pp. 08-5132.

Wan, C.F. and Fell, R., 2004. Investigation of rate of erosion of soils in embankment dams. Journal of Geotechnical and Geoenvironmental Engineering, 130(4): 373-380.

Wynn, T. and Mostaghimi, S., 2006. The effects of vegetation and soil type on streambank erosion, Southwestern Virginia, USA. Journal of the American Water Resources Association, 42(1): 69-82.