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Evaluation of the bank stability and toe erosion model (BSTEM) for predicting lateral retreat on composite streambanks

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ABSTRACT

Streambank erosion is known to be a major source of sediment in streams and rivers. The Bank Stability and Toe Erosion Model (BSTEM) was developed in order to predict streambank retreat due to both fluvial erosion and geotechnical failure. However, few, if any, model evaluations using long-term streambank retreat data have been performed. The objectives of this research were to (1) monitor long-term composite streambank retreat during a hydraulically active period on a rapidly migrating stream, (2) evaluate BSTEM's ability to predict the measured streambank retreat, and (3) assess the importance of accurate geotechnical, fluvial erosion, and near-bank pore-water pressure properties. The Barren Fork Creek in northeastern Oklahoma laterally eroded 7.8 to 20.9 m along a 100-m length of stream between April and October 2009 based on regular bank location surveys. The most significant lateral retreat occurred in mid- to late-May and September due to a series of storm events, and not necessarily the most extreme events observed during the monitoring period. BSTEM (version 5.2) was not originally programmed to run multiple hydrographs iteratively, so a subroutine was written that automatically input the temporal sequence of stream stage and to lag the water table in the near-bank ground water depending on user settings. Eight BSTEM simulations of the Barren Fork Creek streambank were performed using combinations of the following input data: with and without a water table lag; default BSTEM geotechnical parameters (moderate silt loam) versus laboratory measured geotechnical parameters based on direct shear tests on saturated soil samples; and default BSTEM fluvial erosion parameters versus field measured fluvial erosion parameters from submerged jet tests. Using default BSTEM input values underestimated the actual erosion that occurred. Lagging the water table predicted more geotechnical failures resulting in greater streambank retreat. Using measured fluvial and geotechnical parameters and a water table lag also under predicted retreat (approximately 3.3 m), but did predict the appropriate timing of streambank collapses. The under prediction of retreat was hypothesized to be due to over predicting the critical shear stress of the non-cohesive gravel, under predicting the erodibility of the non-cohesive gravel, and/or under predicting the imposed shear stress acting on the streambank. Current research improving our understanding of shear stress distributions, streambank pore-water pressure dynamics, and methods for estimating excess shear stress parameters for noncohesive soils will be critical for improving BSTEM and other streambank stability models.

1. Introduction

Excessive sediment is one of the most common surface water pollutants. It diminishes water quality and destroys aquatic habitat. Streambank erosion is known to contribute a majority of the total sediment load to streams and rivers in some watersheds (Simon and Darby, 1999; Sekely et al., 2002; Evans et al., 2006; Wilson et al., 2008). In fact, sediment loads and streambank stability have been major concerns for decades and abundant money has been spent on stream bank stabilization (Lavendel, 2002; Bernhardt et al., 2005). This is an expensive practice but important for slowing bank retreat accelerated by land use change and reducing downstream sediment concentrations.

Several mechanisms can lead to streambank failure and sediment loading to streams including toe erosion by stream flow undercutting the bank and bank sloughing by removal of matric suction (i.e., generation of positive pore-water pressure) due to precipitation infiltration or streambank storage (Crosta and di Prisco, 1999; Simon and Collison, 2002). Streambank stability models are commonly utilized to investigate the primary mechanisms of bank instability and propose strategies for stabilizing streambanks. One of the most commonly used and most advanced streambank stability models is the Bank Stability and Toe Erosion Model (BSTEM), developed by the National Sedimentation Laboratory in Oxford, Mississippi, USA (Simon et al., 2000). BSTEM has been continually modified and improved by the authors since its creation. The most current public model is BSTEM

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version 5.2 and consists of two different components: a bank stability module and a toe erosion module.

To model bank stability, BSTEM calculates a factor of safety (*FoS*) using three different limit equilibrium-method models: horizontal layers, vertical slices, and cantilever shear failure. Across horizontal layers, the model accounts for up to five user-input soil layers with unique geotechnical properties. Along vertical slices, the model examines the normal and shear forces active in slices of the failure blocks (portions of the bank above the failure surface). In general, *FoS* is calculated as the ratio between the resisting forces and the driving forces along a potential failure plane. The resisting forces can be defined by the Mohr-Coulomb equation:

$$s_r = c' + (\sigma - \mu_w)\tan(\varphi') \tag{1}$$

where s_r is the shear strength of the soil (kPa), c' is the effective cohesion (kPa), σ is the normal stress (kPa), μ_w is the pore-water pressure (kPa), and ϕ' is the effective internal angle of friction in degrees (Fredlund and Rahardjo, 1993). With unsaturated conditions, soil shear strength is increased by matric suction (Darby and Thorne, 1996; Crosta and di Prisco, 1999; Darby et al., 2007). In this case the shear strength can be represented by the modified Mohr-Coulomb equation:

$$s_r = c' + \sigma\tan(\varphi') + \psi\tan\left(\varphi^b\right) \tag{2}$$

where ψ is the matric suction (kPa) and ϕ^b is an angle that describes the relationship between shear strength and matric suction (degrees). Fredlund and Rahardjo (1993) assume ϕ^b to be between 10 and 20 degrees and that ϕ^b approaches ϕ' at saturation. Soil weight is the dominating driving force defined by

$$s_d = W\sin(\beta) \tag{3}$$

where s_d is the driving stress (kPa), W is the weight of the wet soil block per unit area of failure plane (kN m^{-2}), and β is the angle of the failure plane in degrees (Simon et al., 2000). Various combinations of failure plane angle and shear emergence elevation (on the bank face) must be considered in order to determine the failure plane with the lowest *FoS* value, which is the plane on which failure is assumed to occur when FoS approaches unity. Recent versions of BSTEM include a subroutine that uses an iterative procedure to automatically determine this information. In summary, the following soil properties influence bank stability and must be estimated or measured: effective internal angle of friction (ϕ'), effective cohesion (c'), unit weight (W), pore-water pressure (μ_w) or matric suction (ψ), and the angle ϕ^b.

The toe erosion component of BSTEM estimates bank undercutting as a result of fluvial erosion (Simon et al., 2000). The model predicts erosion based on an excess shear stress equation originally proposed by Partheniades (1965). Erosion rate, ε (m s^{-1}), is calculated as

$$\varepsilon = \kappa(\tau_o - \tau_c)^a \tag{4}$$

where κ is the erodibility coefficient ($m^3\,N^{-1}\,s^{-1}$), τ_o is the average shear stress (kPa), τ_c is the soil's critical shear stress (kPa), and a is an exponent usually assumed to be unity. The κ and τ_c parameters are functions of numerous soil properties. For non-cohesive soils, τ_c is typically estimated based on the median particle diameter of the soil (Garcia, 2008). Rinaldi et al. (2008) noted the difficulty in estimating κ and that no direct methods exist for estimating this parameter. The two parameters are difficult to approximate for cohesive soils but can be estimated using various methods. One of these methods was developed by Hanson (1990) using an in situ jet-test device.

The average shear stress (kPa) in BSTEM is calculated using the following equation assuming steady, uniform streamflow (Simon et al., 2000):

$$\tau_o = \gamma_w RS \tag{5}$$

where γ_w is the unit weight of water (9.81 kN m^{-3}), R is the hydraulic radius (m), and S is the channel slope (m m^{-1}). BSTEM divides the bank profile into 23 separate nodes. For each of these nodes, BSTEM calculates τ_o depending on the segment of flow affecting each node. This method creates a distribution of boundary shear stresses and not just one average shear stress applied over the entire bank. This is still a simplification of the actual shear stress distribution which can be affected by secondary flow and three-dimensional effects in the near-bank zone (Pizzuto, 2008). Papanicolaou et al. (2007) suggested that due to secondary currents the bottom half of the streambank may experience stress distributions two to three times higher than the shear stress calculated by first order approximations. In BSTEM, the boundary shear stress is corrected for the effects of curvature using the “no-lag kinematic model” (Crosato, 2007):

$$\tau_o = \frac{\gamma_w n^2 (u + U)^2}{R^{1/3}} \tag{6}$$

where n is Manning's roughness coefficient, u is the reach-averaged water velocity (m s^{-1}), and U is the increase in the near-bank velocity due to superelevation (m s^{-1}).

BSTEM is composed of multiple tabs for inputting geometric, soil, and hydraulic properties and outputting model results. The “Input Geometry” tab contains fields to input the bank profile, soil layer thickness, and channel and flow parameters. Up to five distinct soil layers can be defined with up to 23 points to define the bank profile. Soil properties for each soil layer indicated on the “Input Geometry” tab are input in the “Bank Material” tab. Users can select default soil parameter values for a given soil type or input user defined values. This tab also contains calculations for estimating τ_c based on particle diameter and estimating κ based on τ_c (Hanson and Simon, 2001). The “Bank Model Output” tab requires the user to input a near bank water table depth or pore-water pressures at several depths. The bank stability model is initiated from this tab and displays the results including the FoS, bank geometry, and failure plane emergence elevation and angle. If an *FoS* value of less than 1.0 is calculated, the program will display the new failed geometry. This new geometry can be exported back into the “Input Geometry” tab for further analysis. The “Toe Erosion Output” tab allows users to initiate the toe erosion module for a specified flow duration. Results displayed include calculated shear stress, new bank profile, and the amount of erosion. Again, this new bank profile can be exported back to the “Input Geometry” tab for further analysis.

BSTEM has been frequently used to simulate bank stability and lateral retreat for estimating stream sediment loading (Simon et al., 2009), stream rehabilitation projects (Lindow et al., 2009), and research on streambank erosion and failure mechanisms (Wilson et al., 2007; Cancienne et al., 2008). However, few, if any, independent evaluations of BSTEM with long-term streambank erosion and failure data have been conducted. Such a data set will also help answer questions relative to which streambank parameters are most critical for deriving appropriate estimates of lateral streambank retreat on composite streambanks. The importance of near-bank groundwater on streambank erosion and failure has been emphasized (Simon et al., 2000; Rinaldi et al., 2008; Fox and Wilson, 2010), but little practical guidance has been provided on how to consider this mechanism of instability.

Therefore, the objectives of this research were to (1) monitor long-term composite streambank retreat during a hydraulically active period on a rapidly migrating stream, (2) evaluate BSTEM's ability to predict the measured streambank retreat, and (3) assess the importance of accurate geotechnical, fluvial erosion, and near-bank pore-water pressure properties. Note that calibration and validation of the model was not the goal of this research (i.e., there are several parameters that can be adjusted in the model to match the observed