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Analyzing the Stability of Washita Riverbanks near a Bridge

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Abstract:

A major source of sediment in streams and rivers is due to streambank failure and erosion. Erosion of streambanks represents up to 80% of total sediment yield in some river watersheds. The Bank Stability and Toe Erosion Model (BSTEM) was developed in order to predict streambank failure and erosion due to both fluvial erosion and geotechnical failure. The objective of this research is to establish and compare the stability of banks and soil erosion for Washita River for a cross-section profile in two different years 1968 and 1992 near a bridge using BSTEM. The BSTEM was developed for three different scenarios: water table is equal to applied stream level (GW=WL), water table is equal to previous reading of stream level (GW=PWL), and water table is equal to two days lag of stream level (GW=2WL). The BSTEM was utilized data from 2009 flow hydrograph. Field data measured by Oklahoma Department of Transportation were performed in this study for both years. The results show that most of bank failures occur in recession limb of hydrograph but not always. This study showed that bank stability is not effective by water table and stream flow only but also was effective by bank geometry and soil properties. The study provides valuable information about erosion on this bridge that may be used to rehabilitate the bridges.

Key words: BSTEM, Streambanks Stability, Washita River, Streambanks Erosion

Introduction

Watershed degradation is a global problem in the world. Soil erosion by water is one of the significant problems causing the degradation. Both human activities and natural events can disturb the stability of rivers. Fluvial processes in an alluvial river can cause huge erosion for riverbanks. Erosion of streambanks represents about 80 % of the total sediment yield in river watershed. Cross section profile of rivers could be shifted from time to time depending on many factors. Some of these changes could be found or occur near the bridges which were constructed on these streams. Oklahoma is one of the states in the USA that is suffering from soil erosion in many major rivers such as Washita River. Therefore, studying the stability of streambanks near these structures is very significant to identify the state of these bridges.

Numerous studies and methods have been conducted to analyse and determine the stability of streambanks. Collin (1846) found in field observations that clay slopes can fail as circled pattern by effective of shear strength. His work did not receive attention until 1940. Curved failure surfaces were again reported in Sweden (Petterson, 1956). Petterson (1956) developed a method for cylindrical surfaces and divided the mass of the sliding slope into a number of vertical slices. Further studies have used circular and non circular sliding surfaces analyses (Bishop, 1955; Janbu et. al., 1956). Skempton (1964) presented a technique to determine the slope stability using the simplest form of a sliding surface. This surface plane is parallel to the ground surface. Morgenstern and Price (1965) assumed that the angle of the center of circle values varied systematically across the slide mass and depended on a scaling factor which was evaluated to determine factor of safety. Fredlund and Krahn (1977) developed a general procedure to determine slope stability for non-circular surfaces by selecting a centre of moment.

All above techniques required hard work and time to accomplish the bank stability calculations. The National Sedimentation Laboratory of USDA-ARS has developed a Bank Stability and Toe Erosion Model (BSTEM) to determine bank stability with an easier and faster technique (Simon et. al., 2000). This model can be embedded into Microsoft Excel Software and use macros to perform complicated calculations which are very difficult to do by hand. This bank stability model combines three limit equilibrium method models that determine the factor of safety (Fs) for multi-layer streambanks.

Recent studies show that toe erosion by stream flow undercutting the bank, bank sloughing by removal of matric suction, and fluvial erodibility and geotechnical parameters are significant factors on streambanks erosion and failure and should incorporated in BSTEM (Crosta and di Prisco, 1999; Simon and Collison, 2002; Midgley et al., 2012; Al-Madhhachi et al., 2014; Daly et al., 2015). Midgley et al. (2012) investigated the long-term composite streambank retreat during a hydraulically active period on a rapidly migrating stream and evaluated BSTEM's skill to calculate the measured streambank retreat. They found that 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. Their 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.

Daly et al. (2015) developed and applied simplified procedures for estimating root cohesion based on top and bottom ground biomass evaluations and applied BSTEM to a series of 10 composite streambanks distributed along the Barren Fork Creek in eastern Oklahoma. Daly et al. (2015) found that BSTEM modeling also provided an advantageous calculation tool for evaluating retreat rates compared to in situ bank retreat measurements due to the magnitude and episodic nature of streambank erosion and failures. However, very limited researches to no one that considered applying BSTEM on streambank near the bridges with different groundwater levels.

The objective of this paper was to determine and compared the stability of banks and soil erosion for Washita River for cross-section profile in different years 1968 and 1992 at bridge number b17351 using BSTEM. Different scenarios were applied for water table conditions.

Methods and Materials

Study Area and Data Collection

Washita River is a left bank tributary of the Red River which originates in northwestern Texas and flows east across the Oklahoma boundary (Tyagi and Moti, 2007). Washita River enters Oklahoma in Roger Mills County. It has a drainage area of 8018 square miles and is 626 miles in length (Figure 1). In Oklahoma, Washita River flows through twelve counties: Rogers Mills, Custer, Washita, Kiowa, Caddo, Grady, Garvin, Murray, Carter, Johnston, Marshall, and Bryan. This river has properties of meandering, medium hard shale, fine and coarse sand mix, and a sandy soil channel. The channel slope averages about 3.3 feet/mile and river bank height ranges between 5 to 18 m (Tyagi and Moti, 2007).

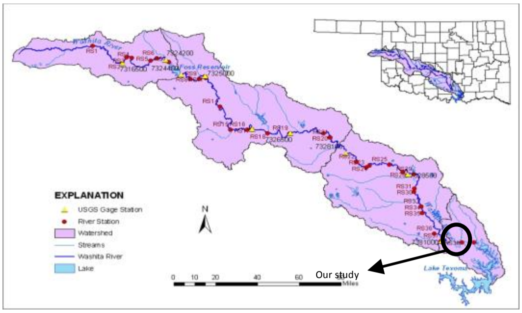


Figure 1. Location of study points and USGS gage stations along the Washita River (Tyagi and Moti, 2007).

About nine USGS stations are located along the Washita River with 39 river stations (RS). Our study was on station RS 38 at bridge b17351 in Johnston County (Figure 1). The bridge b12645 located between (34° 13' 18") N and (96° 48' 06") W on highway SH1 and this bridge was built in 1968. The description of the USGS gage for our study at Dickson Station which is the nearest point to this bridge is shown in Table 1. Because there was not enough information about flow data for these years (1968 and 1992), 2009 data of flow hydrograph were performed. Table 2 shows the gage height flow for Washita River at Dickson Station (Data were taken from USGS Website). Washita River has a slope of 1.38 feet/mile between RS37 and RS38 and this slope is used in this analysis. Field data measured over a long period of time by Oklahoma Department of Transportation (ODOT) were performed in this study. Cross-section profile geometries of Washita River on bridge b17351 were plotted for two different years (1968 and 1992) from data provided by ODOT and these geometries are shown in Figure 2.

Table 1. Description of USGS gage station at Dickson Station (Tyagi and Moti, 2007).

Data Locations and descriptions	Data Available
USGS 07331000 Washita River near Dickson, OK Carter County, Oklahoma Hydrologic Unit Code 11130303 Latitude 34°14'00", Longitude 96°58'32" NAD27 Drainage area 7,202 square miles Contributing drainage area 7,202 square miles Gage datum 650.57 feet above sea level NGVD29	1928-2007

Table 2. Gage height and discharge for 2009 flow hydrograph, Washita River at Dickson (USGS 07331000, USGS Website).

Date / Time	Gage height, m	Water depth, m	Discharge, m^3/s
06/01/2009 02:00	3.56	3.56	53.52
06/01/2009 11:00	3.57	3.57	54.37
06/01/2009 14:00	3.57	3.57	54.93
06/01/2009 21:00	3.58	3.58	55.22
06/02/2009 23:00	3.48	3.48	45.87
06/03/2009 02:00	3.47	3.48	45.02

06/03/2009 11:00	3.89	3.89	94.58
06/03/2009 14:00	4.74	4.74	240.41
06/03/2009 21:00	5.84	5.84	523.86
06/04/2009 17:00	4.85	4.85	262.50
06/05/2009 17:00	4.26	4.26	151.21
06/06/2009 17:00	4.05	4.05	117.23
06/07/2009 17:00	3.92	3.92	99.11
06/08/2009 17:00	3.87	3.87	92.31

Methodology

The BSTEM model combines three techniques: horizontal layers (Simon et. al., 2000), vertical slices with tension crack (Morgenstern and Price, 1965), and cantilever failures (Thorne and Tovey, 1981) to determine the factor of safety (Fs) for five layers of streambanks. This model considers the effect of pore-water pressure (both negative and positive), confining pressure due to streamflow, soil properties, and vegetation, and these data could be utilized as input data. The bank is considered Stable if Fs > 1.3, Unstable if Fs < 1, and Conditionally Stable if Fs is between 1 and 1.3. The model was also performed to determine the bank toe erosion due to hydraulic flow and boundary shear stress such as critical shear stress and erodibility coefficient. The BSTEM model inspects the normal and shear forces active in slices of the failure blocks.

In general, F_s is determined as the ratio between the resisting forces and the driving forces along a potential failure plane. The resisting forces of unsaturated condition can be defined by modified Mohr-Coulomb equation:

$$\tau_r = \acute{c} + \sigma \tan(\theta) + \varphi \tan(\alpha) \tag{1}$$

where τ_r is the shear strength of the soil (kPa), $\acute{c}$ is the effective cohesion (kPa), σ is the normal stress (kPa), θ is the effective internal angle of friction in degrees (Fredlund and Rahardjo, 1993), φ is the matric suction (kPa), and α is an angle that describes the relationship between shear strength and matric suction (degrees) and assumes to be between 10 and 20 degrees according to Fredlund and Rahardjo (1993). Soil weight is representing the driving force and expressed as:

$$W_d = W \sin(\beta) \tag{2}$$

where W_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). The failure plane with the lowest F_s was performing by combining various failure plane angle and shear emergence elevation (on the bank face).

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) and it is expressed as:

$$E_r = k_d(\tau_o - \tau_c) \tag{3}$$

where E_r is the erosion rate (m/s), k_d is the erodibility coefficient (m^3/ N.s), τ_o is the average shear stress (kPa), τ_c is the soil's critical shear stress (kPa). The k_d and τ_c parameters are functions of numerous soil properties. 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.

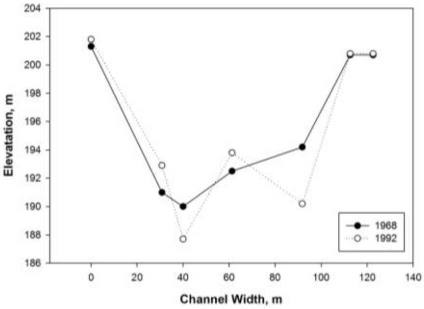


Figure 2. Cross-section Profile at bridge b17351 on SH 1, Washita River

BSTEM model was performed to calculate the bank stability and hydraulic erosion for right banks (erosion occurs on right bank of Washita River at RS 38) of cross-section profiles which are shown in Figure 2. In this study, the input geometry represents the right banks of cross-section profile for each year separately (1968 and 1992) (see Figure 2). Table 2 shows the flow depths and discharge from June 1, 2009 until June 8, 2009 (Data were taken from USGS Website). The shaded values represented the maximum water depth which occurs at peak discharge. The BSTEM model was run from 06/03/2009 at 02:00 A.M. to 06/08/2009 at 17:00 P.M. for different duration times of the flow.

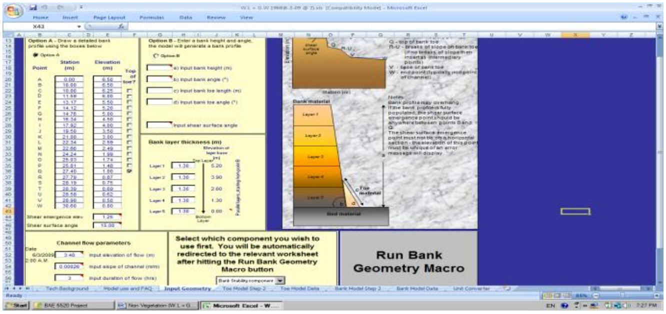
Three different scenarios of ground water level were applied in the BSTEM model: ground water table is equal to applied stream level (GW=WL), ground water table is equal to previous reading of stream level (GW=PWL), and ground water table is equal to two days lag of stream level (GW=2WL). The data for both groundwater and water level were taken from Table 2. The procedure to run the model for first scenario (GW=WL) in year 1968 (as an example) using BSTEM model in Microsoft Excel Solver is given in the following steps.

The geometry profile was entered (data was performed from Figure 2 for right banks) and option (A) was chosen. The “Top of Toe” box was checked next to a point with an elevation on 1 m as shown in Figure (3a). The bank soil layers were divided into five equal intervals thickness (1.3 m). The flow hydrograph starts with date (06/03/2009 at 02:00 A.M.) and elevation of flow 3.48 m, channel slope 0.00026, and duration time 3 hours were incorporated (Table 2). On the “Toe Model Step 2 Tap”, Fine sand (0.125 mm) for first four layers and moderate cohesive for fifth layer (fine sand to soft clay soil) were selected and there was no bank protection or toe protection.

On “Bank Model Step 2 Tap”, the rounded sand for first four layers and soft clay for last layer were selected because

Washita River was fine sandy to soft clay stratum (Tyagi and Moti, 2007). For first scenario, water table was equal to stream level (3.48 m for this example). Then, on "Input Geometry Tab", the model was run for both "Toe Erosion Component" and "Bank Stability Component". Default values of k_d and τ_c parameters of each layer were selected to estimate the toe erosion of the banks. Suitable "shear emergence elevation" and "shear surface angle" values were selected until getting the required factor of safety. "Export Coordinates back into model" button would update the soil profile in input geometry tab when failure or soil erosion occurred (Figure 3b). Finally, the date and time, stream stage, duration time, and water table were updated for next run. The above steps were performed for different scenarios and for both years.

(a) Input geometry profile



Option A - Draw a detailed bank profile using the boxes below

● Option A

Point	Station (m)	Elevation (m)
A	0.00	6.50
B	10.00	6.50
C	10.80	6.25
D	11.59	6.00
E	13.17	5.50
F	14.12	5.20
G	14.76	5.00
H	16.34	4.50
I	17.92	4.00
J	19.50	3.50
K	21.08	3.00
L	22.34	2.59
M	22.66	2.49
N	24.24	1.99
O	25.03	1.74
P	25.81	1.49
Q	27.40	1.00
R	27.79	0.87
S	28.19	0.75
T	28.39	0.69
U	28.58	0.62
V	28.98	0.50
W	30.60	0.00

Shear emergence elev 1.28

Shear surface angle 15.00

Option B - Enter a bank height and angle, the model will generate a bank profile

○ Option B

a) Input bank height (m)

b) Input bank angle (°)

c) Input bank toe length (m)

d) Input bank toe angle (°)

Input shear surface angle

Bank layer thickness (m)

	Thickness	Elevation of layer base (m)
Layer 1	1.30	5.20
Layer 2	1.30	3.90
Layer 3	1.30	2.60
Layer 4	1.30	1.30
Layer 5	1.30	0.00

Q - top of bank toe
R-U - breaks of slope on bank toe (if no breaks of slope then insert as intermediary points)
V - base of bank toe
W - end point (typically mid point of channel)

Notes:
Bank profile may overhang. If the bank profile is fully populated, the shear surface emergence point should be anywhere between points B and Q.
The shear surface emergence point must not be on a horizontal section - the elevation of this point must be unique or an error message will display

Channel flow parameters

Date 6/3/2009 2:00 A.M.

3.40 Input elevation of flow (m)

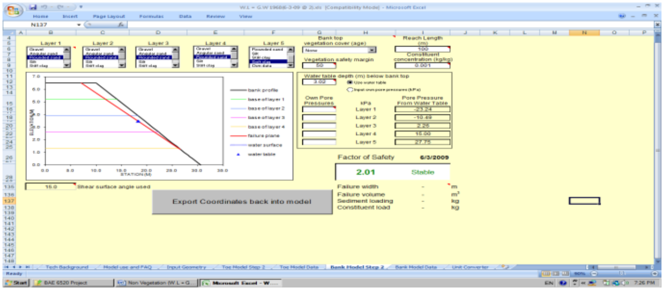
0.00026 Input slope of channel (m/m)

3 Input duration of flow (hrs)

Select which component you wish to use first. You will be automatically redirected to the relevant worksheet after hitting the Run Bank Geometry Macro button

Bank Stability component

(b) Factor of safety



Bank top vegetation cover (age): None

Reach Length (m): 100

Vegetation safety margin: 50

Constituent concentration (kg/kg): 0.001

Water table depth (m) below bank top: 3.02

● Use water table

○ Input own pore pressures (kPa)

Own Pore Pressures	kPa	Pore Pressure From Water Table
	Layer 1	-23.24
	Layer 2	-10.49
	Layer 3	2.25
	Layer 4	15.00
	Layer 5	27.75

Factor of Safety 6/3/2009

2.01 Stable

15.0 Shear surface angle used

Failure width	-	m
Failure volume	-	m^3
Sediment loading	-	kg
Constituent load	-	kg

Figure 3. BSTEM model was performed for right bank of Washita River at RS 38 in 1968 on (a) Input geometry profile, and (b) Factor of safety (Fs).

Results and Discussion

More than 54 runs for both 1968 and 1992 were performed using the BSTEM model from date 06/03/2009 at 02:00 A.M. to 06/08/2009 at 17:00 P.M. for three different groundwater scenarios. In each run, the factor of safety (Fs) and hydraulic erosion were calculated. The first scenario represents that ground water table is equal to applied stream level (GW=WL). The second scenario represents that ground water table is equal to pervious reading of stream level (GW=PWL). The third scenario represents that ground water table is equal to stream level of two days lag (GW=2WL).

Table 3 shows that the values of hydraulic erosion for three different scenarios of ground water table condition in 1968 and 1992. As expected, soil erosion was increased when stream level was increased. It was noted from this table that the erosion values in 1968 are more than from those in 1992 for all three scenarios even though the data of hydrograph flow are the same because banks slope, banks material, layer thickness (1.3 m in 1968 and 2.1 m in 1992), and toe height (1m in 1968 and 2 m in 1992) were different for both years.

Table 3. Fluvial erosion (in m^3) calculated using BSTEM model for three different scenarios of groundwater in 1968 and 1992, Washita River.

Date	Water depth, m	1968			1992		
		GW = WL	GW=PWL	GW=2WL	GW = WL	GW=PWL	GW=2WL
6-3-09 @ 02:00	3.48	0.07	0.07	0.07	0.01	0.01	0.01
6-3-09 @ 11:00	3.89	0.3	0.3	0.3	0.03	0.03	0.03
6-3-09 @ 14:00	4.75	0.19	0.19	0.19	0.04	0.04	0.04
6-3-09 @ 21:00	5.85	0.77	0.77	0.77	0.25	0.25	0.25
6-4-09 @ 17:00	4.85	1.15	1.15	1.15	0.45	0.33	0.32
6-5-09 @ 17:00	4.26	0.92	0.92	0.92	0.33	0.27	0.22
6-6-09 @ 17:00	4.05	0.86	0.86	0.96	0.29	0.21	0.19
6-7-09 @ 17:00	3.93	0.63	0.63	0.81	0.28	0.18	0.18
6-8-09 @ 17:00	3.87	0.46	0.79	0.77	0.23	0.18	0.18

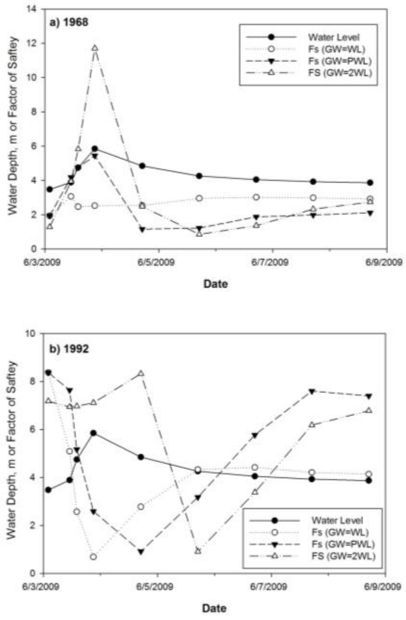


Figure 4. Factor of safety (Fs) for Washita River bank of three different scenarios of groundwater levels for (a) 1968, and (b) 1992

Figure 4a shows the factor of safety (Fs) for three different scenarios of groundwater in 1968. It was noted from that Washita Riverbank was unstable at date 6/5/09 for third scenario (GW=2WL) when ground water level stays high and stream level decrease. While maximum Fs occurred at high stream level because confining pressure holds the bank from failure. The bank was conditional stable in two cases of second scenario (GW=PWL). While bank was remain stable for all runs for first scenario (GW=WL). Similarly, Figure 4b shows the factor of safety for three different scenarios of groundwater in 1992. It was interested that Washita Riverbank was unstable for all three scenarios at dates 6/3 at 21:00, 6/4 at 17:00, and 6/5 at 17:00, respectively. That was due to bank failure did not always occur at recession limb of flow hydrograph (see first scenario, GW=WL).

Furthermore, Figures 5 show the comparison for factor of safety between 1968 and 1992 for three different scenarios of groundwater condition. In Figure 5a, the first scenario (GW=WL) was applied. It is clear from this figure that bank failure occurs in high stream level in 1992. Bank height and slope play important role to cause this failure (not only the effective of groundwater). In Figure 5b, the second scenario (GW=PWL) is applied. The figure shows that bank was failure in recession limb of flow hydrograph in 1992 while it was staying stable in 1968. Finally, Figure 5c shows the application of third scenario (GW=2WL) in years 1968 and 1992. It was observed that bank failure occurs for both years at recession limb of flow hydrograph due to high water table while decrease in stream level.

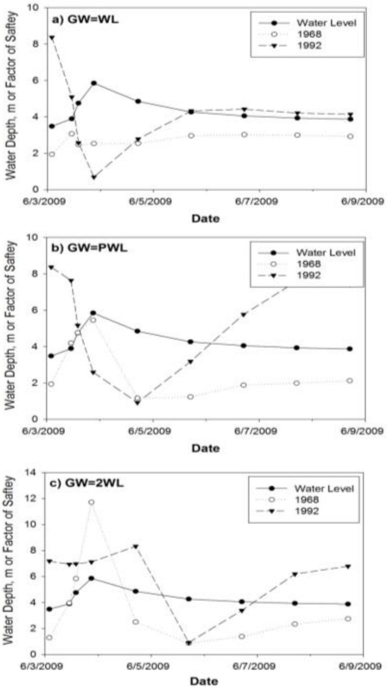


Figure 5. Comparison of factor of safety (Fs) between 1968 and 1992 for (a) Ground water is equal to water level (GW=WL), (b) Ground water is equal to previous reading of water level (GW=PWL), and (c) Ground water is equal to 2 days lag of water Level (GW=2WL).

Summary and Conclusions

Washita River is one of the major rivers in Oklahoma that is suffering from soil erosion. This study shows the analysing of Washita Riverbank stability at bridge b17351 using BSTEM model in years 1968 and 1992 for three different scenarios: water table is equal to applied stream level (GW=WL), water table is equal to previous reading of stream level (GW=PWL), and water table is equal to two days lag of stream level (GW=2WL). The BSTEM was utilized data from 2009 flow hydrograph. Field data measured by Oklahoma Department of Transportation (ODOT) were used in this study for both years. The results shows that the erosion values in 1968 were more than from those in 1992 for all three scenarios due to the different in bank geometry slope and toe height for both years. On the other hand, Banks stability was different for each scenario. Most of bank failures occur in recession limb of hydrograph but not always. This is show that bank stability was not effective by water table and stream flow only but also was effective by bank geometry and soil properties. This study provides valuable information about erosion on this bridge that may be used to rehabilitate the bridges.

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