Incorporating Bank-Toe Erosion by Hydraulic Shear into a Bank-Stability Model: Missouri River, Eastern Montana

Andrew Simon, Eddy J. Langendoen, Robert Thomas

Abstract

Bank-stability concerns along the Missouri River, eastern Montana are heightened by a simulated change in flow releases from Fort Peck Dam to improve habitat conditions for Pallid Sturgeon. The effects of the simulated flow releases on streambank pore-pressures and bank-toe erosion needs to be evaluated to properly model bank-stability. The Bank-Stability Model used incorporates pore-water pressure distributions, layering, confining pressures, reinforcement effects of riparian vegetation and complex bank geometries to solve for the factor of safety. To increase the applicability and accuracy of the model for use in predicting critical conditions, the hydraulic effects of bank-toe erosion have been added.

According to the simulated flow-release plan, flows of 216 m^3/s are increased by 38.3 $m^3/s/day$ for 12 days to 675 m^3/s, held for 60 days and decreased for 12 days back to 216 m^3/s. Results show the important contribution of bank-toe erodibility in controlling mass failure. Banks at River Miles 1624, 1676 and 1716 attain $F_s < 1.0$ indicating imminent failure. These sites contain less resistant sandy-silt material at the bank toe, and experienced simulated undercutting up to 3m. More resistant cohesive, clay bank toes at River Miles 1589 and 1762 were undercut only 0.2 m and remained stable.

Keywords: bank-stability, toe erosion, dams

Simon is a Research Geologist and Langendoen is a Research Hydraulic Engineer, both at the USDA-ARS, National Sedimentation Laboratory, Oxford, MS 38655. E-mail: asimon@ars.usda.gov. Thomas is a doctoral student in the Department of Geography, University of Leeds, UK.

Introduction

Fort Peck Dam was constructed on the Upper Missouri River between 1933 and 1940. Closure in 1937 radically modified the downstream regime. Ecologic and geomorphic function of the Missouri River, with the natural cycle of intermittent, short duration, high flows during spring were replaced by a system of controlled, long duration, moderately high flows during the winter. This regime, combined with the sediment-depleted nature of the discharge, led to downstream incision. Work by Simon et al. (1999a) showed that bank instability along the Missouri River is promoted by a combination of channel incision, fluvial undercutting and increases in pore-water pressure in the bank due to the modified flow regime. During long-duration flow releases, water infiltrates into the riverbank eliminating matric suction that enhances soil strength and promoting positive pore-water pressures. Infiltration is enhanced compared with natural events since high stages are maintained for a longer duration. When flow is lowered in regulated rivers this has traditionally occurred at a rapid rate, resulting in a loss of confining pressure that is often more rapid than the dissipation of pore-water pressure from drainage. Such drawdown conditions often result in bank instability and mass failures, with associated problems including loss of farmland and damage to water-supply inlets.

Methods

The objective of this study was to determine the potential impact of a synthetic spring release from Fort Peck Dam, MT on bank erosion of five downstream sites in eastern Montana. The study reach extends from River Mile 1762, below Fort Peck Dam, downstream to River Mile 1589. Five sites were chosen: River Mile 1762 (Milk River), River Mile 1716 (Pipal), River Mile 1676 (Woods Peninsula), River Mile 1624 (Tveit-

Johnson), and River Mile 1589 (Nohly). These sites represent a range of typical conditions along the Missouri River in eastern Montana.

For the purpose of this study we assumed a hypothetical spring release every three years on the Missouri River downstream of Fort Peck Dam, to trigger migration and spawning by Pallid Sturgeon (*Scaphirhynchus albus*). The simulated regime involved raising discharge from a base flow level, taken to be 216 m^3/sec (8000 ft^3/sec) to a maximum level of 675 m^3/sec (25000 ft^3/sec) in stages over 12 days, maintaining flow for between 6 and 36 days (depending on water temperature) and then returning flow to the original base level over 12 days. These two extremes were taken as the 'best-' (6 days) and 'worst-' (36 days) case scenarios from a bank stability perspective, and an interim scenario with a peak of 18 days was also tested.

A two dimensional hydrology model, GeoSlope SEEP/W^{TM} (GeoSlope International Ltd 1998) was used to evaluate the effect of the simulated flow regime on streambank pore-water pressures. These pore-water pressures were combined with geotechnical field data to perform bank stability assessment using a bank-stability model (Simon et al. 2000). The Bank Stability and Toe-Erosion Model was used to investigate the effects of high flows on bank-toe scour, and resulting bank geometry. The eroded bank profiles were then re-analyzed in the Bank-Stability Model to differentiate changes in bank stability due to hydrologic effects and those due to erosion.

Pore-water pressure modeling

The SEEP/W^{TM} software package was employed to model pore-water pressures created under the imposed hydrologic conditions. SEEP/W is a two-dimensional finite element hydrology model that simulates the movement of water and the resulting pore-water pressures for both saturated and unsaturated conditions using Richard's equation.

A finite-element mesh was created for each site based on profiles measured in the field (Simon et al. 1999a) to provide a framework to model pore-water pressures created under the simulated flow regime. Saturated hydraulic conductivity (Table 1) required for the SEEP/W modeling was measured in the field during the summer of 2001. Initial soil moisture conditions were simulated running a steady state analysis on each mesh with average spring groundwater level and slight surface evaporation, to create a realistic soil moisture distribution prior to imposition of the flow release. Local stage vs. time functions were developed from rating curves and used as boundary conditions for the transient analysis, simulating flow as a series of time-dependent heads on nodes along the bank toe and face.

Bank-stability analysis

The Bank-Stability Model calculates the ratio [Factor of Safety (F_s)] between the forces that drive and resist mass-bank failure. The model accounts for the geotechnical properties of the bank material including soil shear strength (cohesion, angle of internal friction, and unit weight), positive and negative pore-water

Table 1. Geotechnical and hydrologic parameters input to SEEP/W, Bank Stability Model and Bank and Toe Erosion Model.

Site Name	River Mile	USCS	Friction angle, ϕ' (degrees)	Cohesion, c' (kPa)	Saturated unit weight (kN/m^3)	ϕ^b (degrees)	Saturated conductivity (ms^{-1})	Critical shear stress (Pa)	Erodibility coefficient (k) (cm^3/N-s)
Nohly	1589	ML	30.1	13.2	21.4	17	3.2e^{-7}	3.94	0.5
		CH-CL	29.1	7.34	22.2	17	9.9e^{-7}	10	0.32
Tveit-Johnson	1624	CL	26.9	9.4	20.6	17	3.5e^{-7}	7.06	0.38
		CL	5.5	31.5	20.8	17	3.5e^{-7}	7.06	0.38
		SM	32.9	1.85	23.0	17	5.0e^{-6}	1.34	0.86
Woods Peninsula	1676	SM	26.9	0.36	21.4	17	2.0e^{-6}	1.34	0.86
		CL	0	78.9	21.6	17	2.0e^{-6}	7.06	0.38
		SP	35.0	0	21.6	17	1.3e^{-6}	0.31	1.8
Pipal	1716	SM	37.7	0	21.0	17	8.5e^{-6}	1.34	0.86
		CL-CH	13.4	22.3	21.4	17	2.3e^{-8}	10	0.32
		SM	37.9	0	20.9	17	8.5e^{-6}	1.34	0.86
Milk River	1762	CH	9.9	27.7	20.2	17	4.3e^{-6}	13.4	0.27

pressure and confining pressure exerted by flow (Simon and Curini 1998, Simon et al. 1999b). The model assumes a wedge-type failure mechanism.

In the part of the streambank above the "normal" level of the groundwater table, bank materials are unsaturated, pores are filled with water and with air, and pore-water pressure is negative. The difference ($\mu_a - \mu_w$) between the air pressure (μ_a) and the water pressure in the pores (μ_w) represents matric-suction (ψ). The increase in shear strength due to an increase in matric suction is described by the angle ϕ^b. Incorporating this effect into the standard Mohr-Coulomb equation produces (Fredlund et al. 1978):

$$S_r = c' + (\sigma - \mu_a) \tan \phi' + (\mu_a - \mu_w) \tan \phi^b \qquad (1)$$

where S_r = shear stress at failure, ($\sigma - \mu_a$) = net normal stress on the failure plane at failure. The value of ϕ^b is generally between 10º and 20º, and increases with the degree of saturation.

It attains a maximum value of ϕ' under saturated conditions (Fredlund and Rahardjo 1993). The effects of matric suction on shear strength is reflected in the apparent or total cohesion (c_a) term although this does not signify that matric suction is a true form of cohesion (Fredlund and Rahardjo 1993):

$$c_a = c' + (\mu_a - \mu_w) \tan \phi^b = c' + \psi \tan \phi^b \qquad (2)$$

Negative pore-water pressures (positive matric suction; ψ) in the unsaturated zone provide an apparent cohesion over and above the effective cohesion, and thus, greater shearing resistance.

The factor of safety algorithm used by the bank stability model represents the continued refinement of bank-failure analyses by incorporating additional forces and soil variability to equations 1 and 2 (Osman and Thorne 1988, Simon et al. 1991, Simon and Curini 1998, Casagli et al. 1999, Rinaldi and Casagli 1999).

Geotechnical data (Table 1) and bank geometry used in the bank-stability analysis were taken from Simon et al. (1999a) and from field investigations. Pore-water pressures were taken from the seepage modeling, and river stage at a given time (used to calculate confining pressure) was determined from the synthesized discharge hydrographs. The effects of bank-toe erosion on stability were investigated by re-running the model using iterated bank profiles generated by the Bank and Toe-Erosion Model.

Bank and toe-erosion modeling

During the summer of 2001 critical shear stress and erodibility of cohesive materials were measured on a variety of bank and bank toe materials along the Missouri River using a non-vertical submerged jet-test device (Hanson 1990, Hanson 1991). The device applies an impinging, submerged jet on the bank materials and measures the applied shear stress and erosion rate. The relation between the two is used to calculate the critical shear stress (at zero applied stress) and erodibility coefficient (*k*; the slope of the erosion rate vs. applied stress curve).

The Bank Stability and Toe-Erosion Model predicts the change in channel geometry that will result from exposure of bank and toe materials to flows of a given stage and duration. It calculates erosion of cohesives using an excess shear-stress approach from the model of Partheniades (1965):

$$\varepsilon = k\,(\tau_o - \tau_c)^a \qquad (3)$$

where ε = the erosion rate, in ms^{-1}; k is an erodibility coefficient, in m^3/Ns^{-1}; $\tau_o - \tau_c$ is the excess shear stress, in Pa; τ_o is the average bed shear stress, in Pa; τ_c is the critical shear stress, in Pa; and a = an exponent (often assumed = 1.0). The measure of material resistance to hydraulic stresses is a function of both τ_c and k. Results of almost 200 tests at stream sites from Arizona, California, Iowa, Mississippi, Missouri, Montana, Nebraska, Nevada and Tennessee indicate that k can be estimated as a function of τ_c (Hanson and Simon 2001):

$$k = 0.1\,\tau_c^{-0.5} \qquad (4)$$

Resistance of non-cohesive materials is a function of surface roughness and particle size (weight), and is expressed in terms of the Shields criteria.

Average boundary shear stress

Average boundary shear stress (τ_o) was calculated from the hydrograph via the rating curve, and from channel slope, using the method outlined in Langendoen et al. (2001).

The channel geometry parameters input into the Bank Stability and Toe-Erosion Model (bank heights, average bank angle and bank-toe length) were calculated from bank profiles. Channel slopes were calculated from thalweg elevations obtained from

Simon et al. (1999a). The model was run using the simulated flow conditions as a driving input. The predicted bank profile was calculated on a daily basis and imported into the Bank Stability Model so that the stability of both the initial and the predicted bank profile could be assessed.

Boundary and critical shear stress used

Critical shear stresses for the bank materials measured are shown in Table 1, with values ranging from 0.3 to 13.4 Pa. The most resistant materials were clay layers (τ_c = 7.1 – 10.0 Pa) while the least resistant were sand layers (τ_c = 0.3 Pa). For any given flow, boundary shear stress at the five sites varies due to local channel gradient and channel geometry with narrow channels confining flow, resulting in higher shear stresses. Peak, local boundary shear stress at the break of slope between the bank and the toe for the five sites is as follows (from downstream to upstream); Nohly: 3.9 Pa, Tveit-Johnson: 4.9 Pa, Woods Peninsula: 2.0 Pa, Pipal: 3.2 Pa, Milk River: 4.5 Pa.

Bank Stability and Erosion Results

Results from the stability analyses are expressed in terms of a Factor of Safety (F_s). A value of 1.0 indicates the critical case and imminent failure; values above one are theoretically viewed as stable. However, the uncertainty and variability of soil properties and failure geometries results are such that we consider values between 1.0 and 1.3 *conditionally stable*.

River mile 1624 (Tveit-Johnson)

The streambank is 9.6 m high and composed of a basal layer of sandy silt approximately 4.5 m thick with an upper layer of clay. Initial results show the streambank to be stable (F_s = 1.69) during baseflow conditions, and that negative pore-water pressure in the streambank decreased during the initial 12-day rise in stage. Stability increased very slightly with the rise in flow due to confining pressure (F_s = 1.71). During drawdown the streambank drained rapidly, and experienced a slight decline in stability as confining pressure was released (Regime 1: F_s = 1.54, Regime 2: F_s = 1.46, Regime 3: F_s = 1.40) after drawdown assuming no bank-toe erosion. The results for Regime 1 showed that F_s had not started to recover at the end of the flow release so this simulation was extended to ensure that F_s never reached critical levels. The value after 70 days was 1.49, and after 140 days 1.48 where after it recovered slowly.

Although the non-eroded bank was quite stable, results indicate that streambank failure is possible when bank-toe erosion is accounted for. Flow at this site is somewhat confined, generating relatively high boundary shear stresses. Critical shear stress for the bank base material is 1.3 Pa, compared with a local boundary shear stress of 4.9 Pa during peak flow. End-of-simulation stability values accounting for erosion were as follows; Regime 1: F_s = 1.31, Regime 2: F_s = 1.13 and Regime 3: F_s = 0.98. As with the non-eroded simulation, under Regime 1 the F_s value had not recovered at the end of the initial period and an extended simulation was performed, resulting in a minimum value of 1.28 after 70 days. Bank-toe erosion produced increasingly large failures with each successive flow regime.

Results highlight the vulnerability of this site to bank-toe erosion. Even the shortest regime results in approximately 1.5 m of bank-toe erosion, with approximately 2 m of erosion under the worst-case flow release.

River mile 1589 (Nohly)

The streambank is 6.5 m high and is composed of a basal layer of clay approximately 2.5 m thick with an upper layer of silt. Initial results show the streambank to be stable (F_s = 1.45) during baseflow conditions. Negative pore-water pressure in the streambank decreased during the initial 12-day rise in flow and continued to decline during the period of maintained high flow. Stability increased (F_s = 1.58) during the initial 12-day rise in flow as confining pressure increased F_s more rapidly than rising pore-water pressures could decrease it. F_s decreased during the maintained high flow as pore-water pressure continued to increase due to water infiltration from the channel into the bank. During drawdown stability declined but the streambank remained stable under the two shorter regimes (Regime 1: F_s = 1.34, Regime: 2 F_s = 1.31) and conditionally stable under the longest regime (Regime 3: F_s = 1.25) as confining pressure was removed faster than drainage allowed the pore-water pressures to equilibrate.

Critical shear stresses for the materials at this site (10 Pa at the bank toe) exceeded the boundary shear stresses (3.9 Pa at the base), resulting in no erosion during the flow release. The results suggest that the simulated flow regime incorporates sufficiently slow changes in stage to maintain bank stability by allowing pore-water pressure to equilibrate.

River mile 1676 (Woods Peninsula)

The streambank is 6.4 m high and is composed of a 2.4 m thick basal layer of sand, a middle 0.6m thick layer of clay and an upper 3.4m thick layer of sandy silt. Initial results show the streambank to be barely stable (F_s = 1.06) during baseflow conditions.

Negative pore-water pressure was reduced during the initial 12-day rise in flow, with a lag effect due to the low permeability of the bank materials. Stability remained constant (F_s = 1.06 after 12 days) as the resisting force of confining pressure matched the driving force caused by the loss of negative pore-water pressure. Negative pore-water pressure continued to fall during the period of maintained high flow, and F_s fell accordingly. The bank became unstable under all three regimes, with minimum values of F_s = 0.61, 0.59 and 0.57 respectively for the three flow scenarios.

Although the bank toe material at this site has a low critical shear stress (0.3 Pa) the applied boundary shear stresses are also quite low (peak stress at bank toe of 2.0 Pa) due to the wide channel and low gradient. The relatively small amount of bank toe erosion that occurred was not sufficient to displace the optimum location for the failure surface significantly, and the minimum stability values are almost unchanged for the eroded banks. The results suggest that this site is already very vulnerable to instability, and that the simulated flow regime is likely to trigger streambank failure due to detrimental hydrologic effects.

River mile 1716 (Pipal)

The streambank is 6.7 m high and is composed of a 2.8 m thick basal layer of sandy silt, a middle 0.9m thick layer of brown clay and an upper 3 m-thick layer of sandy silt. Initial results show the streambank to be conditionally stable (F_s = 1.28) during baseflow conditions. Negative pore-water pressure decreased rapidly during the initial 12-day rise in stage. Stability declined sharply as the resisting confining pressure was less than the driving force caused by the loss of negative pore-water pressure. Negative pore-water pressure continued to decline during the maintained high flow as water continued to infiltrate the streambank. Under all three regimes the bank failed before drawdown began, with minimum values of F_s = 0.94, 0.91 and 0.8 reassuming no bank erosion. A small amount of toe erosion was predicted by the model, reducing bank stability to F_s = 0.88, 0.81 and 0.75 under the three regimes. Failure was due to a combination of loss of matric suction and bank-toe erosion. Both bank saturation and bank undercutting are critical issues at this site.

River mile 1762 (Milk River)

The streambank is 6.7 m high and is composed of homogenous dark brown silty clay. Initial results show the streambank to be extremely stable (F_s = 3.71) during baseflow conditions. A high level of stability is maintained throughout the simulated flow regime due to the relatively low bank angle compared to other sites, and the cohesive nature of the bank material. Negative pore-water pressure declined rapidly during the initial 12-day rise in flow level. Stability over this period increased slightly (F_s = 3.80) suggesting that the confining pressure of the flow was able to offset the rapid loss of suction caused by the infiltration of water into the streambank. Pore-water pressure remained fairly constant during the maintained high flow indicating rapid equilibration between channel and banks during this period and resulting in a fairly constant factor of safety. During the 12-day drawdown period the streambank remained very stable although F_s declined (F_s = 3.32, 3.31 and 3.31 under the three regimes) as confining pressure was removed faster than drainage allowed the pore-water pressure to equilibrate. Due to the high critical shear stress of the bank material (13.4 Pa compared with a peak local boundary shear stress of 4.5 Pa) no bank or toe erosion occurred. The combination of non-vertical banks, high cohesion and high critical shear stress resulted in a very stable bank.

Discussion and Conclusions

A combination of hydrology, erosion and bank stability modeling has been used to predict the impact of flood release on five riverbanks typical of conditions along the Missouri River in eastern Montana. The simulations and field data collection undertaken show a range of responses illustrative of different processes controlling bank-stability. Two sites (Milk River and Nohly) appear to be relatively stable and are unaffected by the simulated flood release. One site (Tveit-Johnson) resists the hydrologic (infiltration) effects of the flood, but is sensitive to basal undercutting of the banks. This site would require bank-toe protection to maintain stability. Woods Peninsula is close to the failure threshold under ambient spring conditions, and infiltration-induced failures are likely to be triggered by any increase in stage. The Pipal site is conditionally stable under ambient spring conditions, and is vulnerable both to infiltration and bank erosion.

Results indicate that the slow drawdown incorporated in the simulated flow regime permits pore-water pressure to dissipate sufficiently, and is not a factor in potential instability. In a wider context the work shows how site vulnerability, and potential remedies, can be identified relatively quickly using a combination of a comparatively sophisticated, seepage model coupled to two simple and widely accessible bank erosion and stability models. It also highlights the need to account for the three processes simulated here; comparison of the Factor of Safety data reveals the extent to which it is combinations of infiltration, hydraulic erosion and geotechnical failure that lead to bank failure. Simpler modeling approaches run the risk of overestimating bank stability.

Acknowledgments

The authors would like to thank Andy Collison and Tony Layzell for their assistance with the development of the Bank Stability Model interface.

References

Casagli, N.N., M. Rinaldi, A. Gargini, and A. Curini. 1999. Monitoring of pore-water pressure and stability of streambanks: Results from an experimental site on the Sieve River, Italy. Earth Surface Processes and Landforms 24:1095-1114.

Fredlund, D.G., N.R. Morgenstern, and R.A. Widger. 1978. The shear strength of unsaturated soils. Canadian Geotechnical Journal 15:313-321.

Fredlund, D.G., and H. Rahardjo. 1993. Soil Mechanics of Unsaturated Soils. John Wiley & Sons, New York.

GeoSlope International Ltd. 1998. SEEP/W Users Guide Version 4, GeoSlope International, Calgary, Canada.

Hanson, G.J. 1990. Surface erodibility of earthen channels at high stresses. Part II - Developing an in-situ testing device. Transactions of the American Society of Agricultural Engineers 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 American Society of Agricultural Engineers 36(5).

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

Langendoen, E., R. Thomas, and A. Simon. 2001. Modelling bank and near-bank processes using the CONCEPTS model. In Proceedings of the BGRG Conference, Nottingham, UK.

Partheniades, E. 1965. Erosion and deposition of cohesive soils. Journal of Hydraulics Division of the American Society of Agricultural Engineers 91:105-139.

Osman, A.M., and C. R. Thorne. 1988. Riverbank stability analysis. I: Theory. Journal of Hydraulic Engineering 114(2):134-150.

Rinaldi, M., and N. Casagli. 1999. Monitoring of streambanks in partially saturated soils and effects of negative pore-water pressures: The Sieve River (Italy). Geomorphology 26:253-277.

Simon, A., and A. Curini. 1998. Pore pressure and bank stability: The influence of matric suction. In S. Abt, ed., Hydraulic Engineering ’98, American Society of Agricultural Engineers.

Simon, A., W. J. Wolfe, and A. Molinas. 1991. Mass wasting algorithms in an alluvial channel model. In Proceedings of the Fifth Federal Interagency Sedimentation Conference, Las Vegas, NV, pp. 2(8)22-29.

Simon, A., F.D. Shields, R. Ettema, C. Alonso, M.M. Garsjo, A. Curini, and L. Steffen. 1999a. Channel erosion on the Missouri River, Montana, between Fort Peck Dam and the North Dakota border. USDA-ARS, National Sedimentation Laboratory Research Report, Oxford, MS.

Simon, A., A. Curini, S.E. Darby, and E.J. Langendoen. 1999b. Streambank Mechanics and the Role of Bank and Near-Bank Processes in Incised Channels. In S.E. Darby, and A. Simon, eds., Incised River Channels: Processes, Forms, Engineering, and Management, pp. 123-152. John Wiley & Sons, London.

Simon, A., A. Curini, S.E. Darby, and E. Langendoen. 2000. Bank and near-bank processes in and incised channel. Geomorphology 35:193-217.