PREDICTING THE DEPTH OF EROSION IN RESERVOIRS FOLLOWING DAM REMOVAL USING BANK STABILITY ANALYSIS

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ABSTRACT

Dam removal has emerged in the U.S. as a critical concern for river management. Of particular interest is predicting the quantity of sediment that will be eroded from a reservoir following dam removal, which necessitates predicting the geometry a channel will approach as it forms in the reservoir. The geometry and sediment characteristics of the Koshkonong River were measured as it adjusted to the removal of the Rockdale Dam. Bank stability modeling was used as a tool for predicting the maximum depth of the evolving channel and general agreement was found between depths predicted with the model and those observed up to one year following dam removal. Model sensitivity analysis showed strong control of bank heights by groundwater levels in the reservoir sediment, as well as some control by vegetation established on the sediment surface. Long-term monitoring is needed to assess the accuracy of the model, but preliminary agreement is encouraging for applying this model and similar models to future dam removals.

Key Words: Dam removal, Bank stability model, Channel evolution, Reservoir sediment

1 INTRODUCTION

1. 1 Dam Removal

The aging of the more than 75,000 dams in the U.S., coupled with the increasing awareness of their environmental costs, has made dam decommissioning and removal a topic of current interest to the scientific community, management agencies, and the general public. It is estimated that 85% of the dams in the U.S. will be near the end of their operational lives by the year 2020 (FEMA, 1999), necessitating thorough consideration of dam removal or repair for an increasingly large number of structures. The debate over dam removal is occurring within a vacuum of science surrounding the physical and biological impacts of dam removal, and while emerging studies are beginning to document these impacts, they are limited to the removal of small dams (Stanley et al., 2002). Because of paucity of studies, engineers and managers are relying on geomorphic analogies for predicting the impacts of dam removal (Doyle et al., 2003). The applicability of these analogies across a range of geomorphic conditions is questionable (Pizzuto, 2002), and careful testing within constrained conditions is needed.

Our work focuses on the geomorphic and ecological impacts (Stanley et al., 2002; Stanley and Doyle, 2002) of dam removal in low gradient, fine-sediment (i.e., sand and silt) channels of the Midwestern US. Preliminary observations at several sites led the authors to hypothesize a conceptual channel evolution model for predicting geomorphic responses to dam removal in these types of channels (Doyle et al., 2002, 2003). The objective of this paper is to apply an existing bank stability model to predict the depth of erosion in a reservoir following the removal of a dam, thus quantifying a specific component of earlier conceptual work by the authors.

1.2 Channel Evolution and Bank Stability

The geomorphic forms and processes that occur within a reservoir following dam removal in a fine-grained system generally follow a conceptual channel evolution model (Fig. 1; Doyle et al., 2003).

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Previous modeling of channel changes following dam removal has focused exclusively on bed elevation changes (Williams, 1977). However, the adjustment of channel width can be an important mechanism of channel response for disturbed channels, perhaps more significant than bed adjustments in certain environmental conditions and certainly a significant source of sediment for downstream reaches (Simon, 1992; Simon and Darby, 1997).

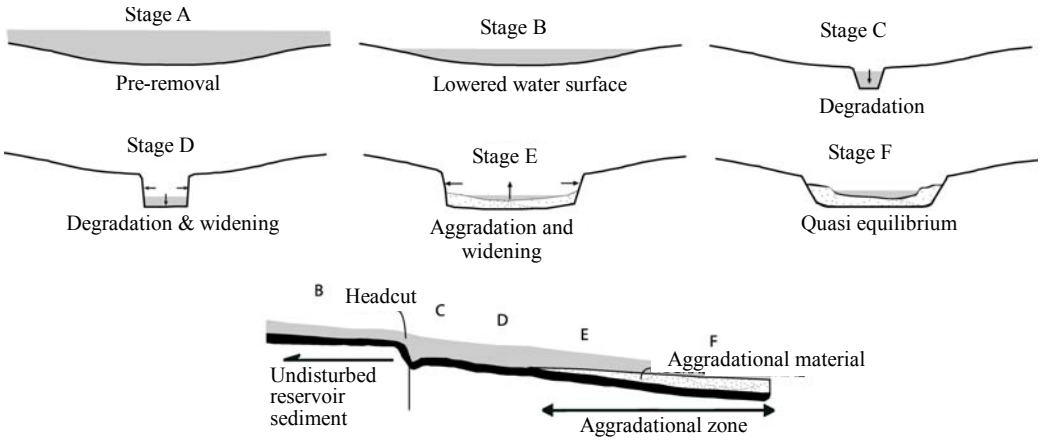

Fig. 1 Channel evolution model applied to channel development in a reservoir following dam removal (from Doyle et al., 2003). Upper portion of Fig. describes changes occurring at a given cross section through time. The lower portion of the Fig. describes changes along the channel profile at a single point in time

Existing bank stability models (review by Simon et al., 1999) allow stepping beyond the proposed conceptual model and moving towards constraining the forms and processes associated with channel response to dam removal. In particular, bank stability models allow approximating the depth to which a channel will incise before the channel begins to widen, and the effect of groundwater lowering and vegetation establishment on long-term sediment stability.

Stream bank erosion in channels with cohesive banks is primarily a geotechnical phenomenon rather than a hydraulic one because fluvial erosion of bank materials is negligible in comparison to the quantity of material eroded via mass-wasting. Bank failures are generally either rotational or planar, and while rotational failures are present along many channels, planar failures occur earlier in the adjustment sequence than do rotational failures, and, thus, represent an initial critical bank condition (Simon et al., 1999). Further, bank failures have been reported to occur most frequently during the recessional period of a hydrograph, when banks are saturated and less stable (Simon et al., 1999).

Saturated bank conditions following a storm event are analogous to reservoir sediment conditions immediately following dam removal. As reservoir sediment dewaters, the banks become more like normal streambanks during dry conditions, and in turn, stability should increase. Thus, modeling planar bank failure during saturated conditions should provide a worst-case scenario for the stability of reservoir sediment during channel evolution following a dam removal. Further, the effect of reduced saturation conditions can give an indication of how gradual dewatering of reservoir sediment via staged drawdown can impact reservoir sediment stability.

2 STUDY SITE

The Koshkonong River at the Rockdale Dam is a mixed sand and gravel-bed channel draining approximately 360 km^2 in the low-relief, glaciated region of south-central Wisconsin. The Rockdale Dam was 3.3 m high and created an impoundment of approximately 42 ha in August 2000. The reservoir was filled primarily with fine sediment several meters thick at the downstream end, and sand and fine gravel at the upstream end of the reservoir in the form of a prograding delta. The dam was breached to grade on September 12, 2000 with the remainder of the structure (i.e., lateral portion) removed during late June 2001. No attempts were made to stabilize the impoundment sediment through August 2001. More detailed site descriptions and descriptions of the dam removal are available in Doyle et al. (2003).

3 METHODS

3.1 Bank Stability Modeling

To quantify bank stability, the Agricultural Research Service's Channel Bank Stability Model (Collison and Simon, 2001; Simon and Collison, 2002) was used because it incorporates the effects of vegetation and sediment saturation on bank stability, has been used in a variety of geomorphic settings, and is available for public use. Streambank stability is governed by the gravitational forces acting on the bank at any time, and the resistance (shear strength) of the bank material. Driving forces are the weight of the bank material (which is greatest when the bank is saturated and least when the bank is unsaturated) and any positive pore-water pressure. In contrast, several forces resist bank failure. Bank resistance is first a function of the shear strength of the bank material, which is governed by the size of the bank failure and bank material properties. Matric suction, or negative pore pressure, also works to stabilize banks and can increase the shear strength of the bank material by up to 20% (Simon et al., 1999). Finally, high, in-channel water levels provide a hydrostatic force which works to hold up the streambank. These relevant components have been combined in an algorithm that represents the ongoing refinement of bank stability analysis (Simon et al., 1999; Simon and Collison, 2002):

$$F_S = \frac{\sum c_i' L_i + \left(S_i \tan \phi_i^b\right) + \left[W_i \cos \beta - U_i + P_i \cos(\alpha - \beta)\right] \tan \phi_i'}{\sum W_i \sin \beta - P_i \sin(\alpha - \beta)} \quad (1)$$

where F_S = factor of safety of the streambank, c_i' = effective cohesion of the i^{th} layer, L_i = length of the failure plane incorporated within the i^{th} layer, S_i = force produced by matric suction on the unsaturated part of the failure surface within the i^{th} layer, W_i = weight of the i^{th} layer, U_i = hydrostatic-uplift force on the saturated portion of the failure surface within the i^{th} layer, P_i = the hydrostatic-confining force due to external water level acting on the i^{th} layer, α = failure-plane angle (degrees from horizontal), β = bank angle (degrees from horizontal), φ_i' = the soil friction angle in the i^{th} layer, and φ_i^b = a parameter describing the rate of increase in soil strength with increasing matric suction in the i^{th} layer. This model uses the Mohr-Coulomb failure criterion for the saturated portion of the bank and the Fredlund and Rahardjo (1993) criterion for the unsaturated portion. The model is a summation over the entire bank in order to incorporate layered soils, changes in soil unit weight based on moisture content, and external confining pressure from streamflow. In addition to the above model, Simon and Collison (2002) estimated the increase in soil strength as a function of tensile strength and root distortion during shear, and Collison and Simon (2001) incorporated this effect into the Agricultural Research Service's Channel Bank Stability Model.

The Collison and Simon model can be used to calculate a factor of safety for different bank configurations (e.g., various bank heights and angles) given bank material types as well as saturation and vegetation conditions. A factor of safety equal to one represents critical bank conditions (i.e. critical bank height), because the banks are at the point of incipient failure, and, thus, represents the maximum depth of channel erosion. Using a given material stratigraphy, the stability of various channel bank configurations can be quantified in graphical form as given in Fig. 2. On these plots, any configuration below the critical lines would be considered stable. As the bank geometry nears the critical line, bank failure becomes more likely. In this case, these lines represent the maximum depth to which a channel will incise into reservoir sediment following dam removal before widening ensues, and most-likely the maximum depth of erosion as subsequent adjustment will predominantly be lateral.

3.2 Data Collection and Analysis

A series of cross sections were surveyed within the reservoir, upstream of the reservoir, and downstream of the dam sporadically from June 2000 through August 2001, providing pre- and post-removal geomorphic data (Doyle et al., 2003). Sediment cores were collected from the reservoir using a 13 cm diameter core and bucket auger. Descriptions of core material were recorded in the field, noting the size of material, and color of sediment as well as the presence of organic debris. Sub-samples of the core samples were retained for laboratory particle size analysis.

Because actual measurements of the geotechnical properties of the reservoir sediment were not available, previously published values (Table 1) were applied to the bank stability model. In the absence

of data on actual shear surface angles, the shear surface angle was assumed to be the average of the soil friction angle and the bank angle (Collison and Simon, 2001). That is

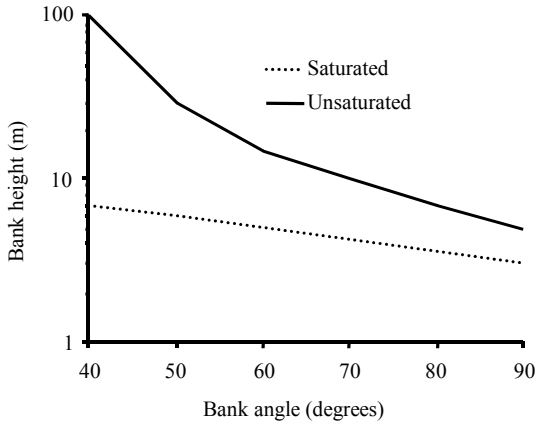

Fig. 2 Bank stability chart adapted from Simon et al. (1999). Bank geometries that plot above the lines are unstable and those below the lines are stable

Table 1 Bank material properties used for stability modeling (from Collison and Simon, 2001)

Sediment type	Friction angle φ' (degrees)	Cohesion c' (kPa)	Saturated unit weight W (kN/m^3)	φ^b (degrees)
Gravel	36	0	20	5
Sand	36	0	18	15
Silt	25	5	18	15
Soft clay	30	10	16	15

$$\beta = \frac{\varphi' + \alpha}{2} \tag{2}$$

Critical bank heights and angles were then estimated for variable bank saturation conditions (Thorne, 1999) at cross sections where bed degradation and mass-wasting was evident, and these values were used to estimate the potential for continued degradation or channel widening. Finally, a 5-yr old black willow vegetation cover was used to model the potential increased bank stability due to vegetation. Of all the vegetation in the ARS model with data available, black willow represented the species that created the least impact on bank stability. Thus, modeling using black willow provided a conservative estimate of vegetation influence on bank stability.

4 RESULTS

Within the Koshkonong River reservoir, the accumulated fine sediment was approximately 2 m in thickness from the dam to approximately 700 m upstream of the dam, and approximately 1 m thick from there to the prograding delta (approximately at 1,500 m upstream of the dam). In the downstream 1,000 m of the reservoir, the sediment was highly consolidated. There was a distinct difference between the fine surface sediment (36% sand, 45% silt, 19% clay; based on hydrometer analysis), and the underlying coarser sediment (gravel with $d_{50} > 3$ mm) (Table 2). This underlying gravel layer was interpreted as the pre-dam channel substrate.

Removal of the Rockdale dam instigated upstream progressing channel incision via headcut migration, which through time formed a distinct channel via bed degradation and associated mass-wasting of the channel banks. A detailed description of the hydraulic and sediment transport conditions following dam removal is given in Doyle et al. (2003). Mass wasting was accomplished through planar failures rather than rotational slump failures. Incision was limited to the lower 400 m of the reservoir, as the headcut did not migrate beyond this point.

Table 2 Rockdale Reservoir on the Koshkonong River stratigraphic conditions

Cross section[a]	Bank	Top of sediment unit[b] (m)	Bottom of sediment unit[b] (m)	Sediment description
40	Left	0	2.65	Silt
40	Left	2.65	-	Gravel
40	Right	0	2.05	Silt
40	Right	2.05	2.45	Soft clay
40	Right	2.45	-	Gravel
150	Left	0	0.5	Silt
150	Left	0.5	1.5	Sand
150	Left	1.5	-	Gravel
150	Right	0	1.9	Silt
150	Right	1.9	2.2	Sand
150	Right	2.2	-	Gravel
400	Left	0	2.4	Silt
400	Left	2.4	-	Gravel
400	Right	0	2.05	Silt
400	Right	2.05	2.5	Sand
400	Right	2.5	-	Gravel

[a] distance upstream of dam in meters
[b] depth relative to top of reservoir sediment surface

Bank stability modeling showed that section 40 (i.e. 40 m upstream of the dam) was near the threshold of stability in May 2001, but that aggradation worked to stabilize channel banks by August 2001 (Fig. 3). These modeling results agreed with the observations of unstable and slumping banks at this section during the spring of 2001, but lack of widening in August of 2001. At section 150, the left channel bank was unstable and the right bank was stable according to stability modeling using saturated conditions (Fig. 3), and the observations of slumping banks through August 2001 supported these general predictions. Finally, banks at section 400 were well under the critical bank height based on modeling, although the bed at this section was only beginning to incise (Fig. 3).

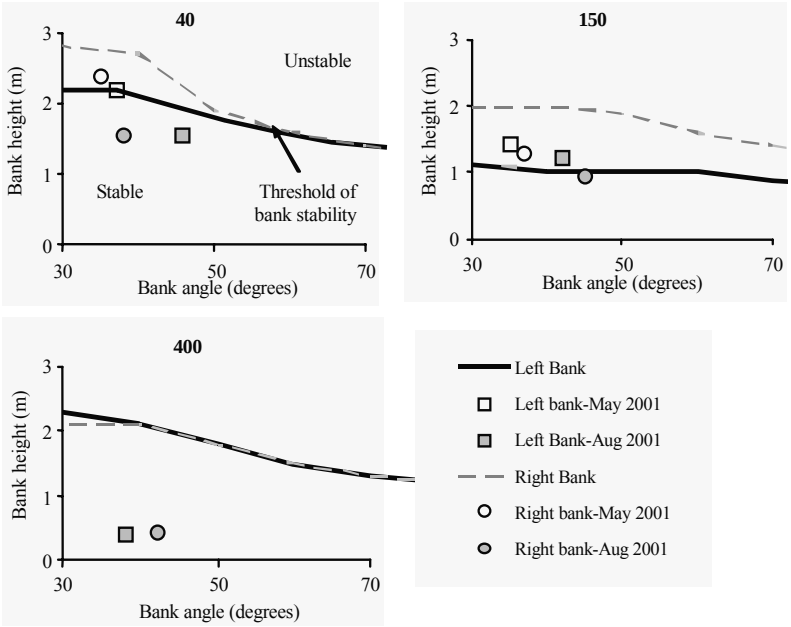

Fig. 3 Bank stability diagrams for channel banks on the incising Koshkonong River within the Rockdale reservoir following dam removal. Bank geometries which plot below the threshold lines are stable and those above the line are unstable. Threshold lines were computed assuming saturated banks. Numbers above plots are site locations in meters upstream from the removed dam

Bank stability modeling also showed the effect of the ground water table elevation and vegetation on overall bank stability. For example, while the left bank at section 150 was unstable at saturated conditions in May 2001, this bank was stable if the water table was 1 meter below the sediment surface (Fig. 4), as was the case in May and August of 2001 during low-flow conditions. In addition, modeling showed that bank stability is increased further if vegetation is established on the channel banks (Fig. 4), as was beginning to occur by August 2001. Thus, reservoir dewatering and vegetation establishment can combine to nearly double stable bank heights (Fig. 4).

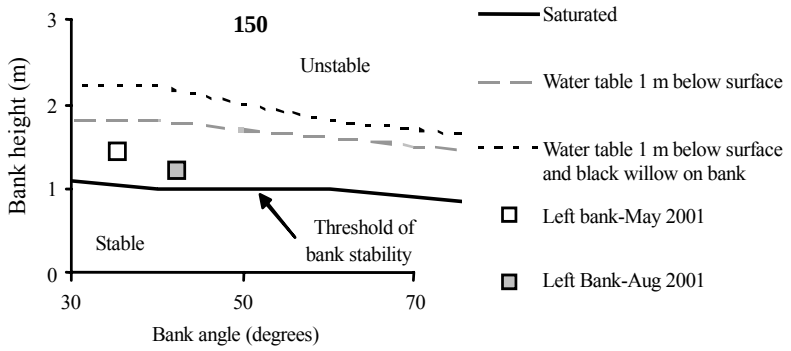

Fig. 4 Bank stability diagram with variable bank conditions for cross section 150 m upstream of the dam site on the Koshkonong River following dam removal

5 DISCUSSION AND CONCLUSIONS

The bank stability analysis, performed using data easily collected at a dam removal site and soil parameters presented in the literature, provided reasonable estimates of stable bank heights observed in the field. However, given the limited temporal and spatial scale of the study, and the fact that the model was uncalibrated, long-term accuracy cannot be addressed. A surprise of the analysis is the relative instability of the channel banks at low angles for planar failures. At such low slopes (less than 50 degrees), banks are generally stable with respect to planar failures, and rotational failures are much more likely. However, rotational failures were not observed at this site, although they were observed at another dam removal study site (Doyle et al., 2003).

The utility of the analysis used here, or similar modeling approaches, is potentially quite great. The critical bank height suggested by the model should be an approximation of the maximum depth to which a channel will incise following a dam removal. Once the critical height of the reservoir sediment is reached, any subsequent incision will induce widening. This widening will in turn reduce the energy exerted by the flow (Simon, 1992), and, thus, reduce subsequent incision. While the static nature of the bank stability analysis does not permit long-term dynamic simulation of channel changes following a dam removal like would be possible using other methods (Williams, 1977), it does allow constraining at least one of the dimensions of channel development.

The bank stability analysis also indicates the important role of sediment saturation on channel development. The analysis showed that channel depths could vary by a factor of two in some cases, depending on the degree of saturation. Thus, staging a dam removal over a period of months could potentially greatly increase the depth and decrease the width of an incising channel. This effect may be significant over short periods of time, although channel geometry over longer timescales is likely to be independent of the method in which the dam is removed. This analysis also elucidates the role of floods following dam removal. Small flows immediately following dam removal when reservoir sediment is saturated have the ability to drastically alter channel morphology. In contrast, a large flood which occurs after the sediment has dewatered and stabilized will be much less effective because of the greatly increased bank stability.

Finally, the effect of vegetation also was shown by the modeling. The effect of vegetation in the modeling was modest, although the conservative results suggest that other types of vegetation may impact

stable channel widths and depths by a greater degree. Further, there is likely to be strong seasonal impact of vegetation on bank stability depending on the growth conditions of the bank vegetation throughout the year.

While vegetation was shown to impact bank stability, bank sediment saturation had a greater effect on bank stability in that small changes in saturation had large changes in stable bank heights. Further, vegetation will most likely take at least several months to years to become established on reservoir sediment, during which time large-scale changes will be occurring primarily controlled by groundwater changes. Thus, vegetation is expected to be less of a factor in controlling initial channel form development when compared to groundwater changes.

Long-term channel changes following dam removal remain, for the most part, unknown. Bank stability analysis was used to estimate the depth of channel incision until banks began to fail. The model agreed fairly well with observations from a field site over the course of a year following dam removal. Long-term monitoring is needed to estimate the viability of this method for broader applications, and for calibrating the model at specific sites. Further, data from dam removals in other settings are needed to test the robustness of the procedure.

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