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RESEARCH ARTICLE

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Failure modes in cedar tree revetments: Observations on rivers and streams in eastern Kansas, USA

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Abstract

A cedar tree revetment is a bioengineering technique intended to stabilize eroding stream banks using longitudinally placed cedar trees. This technique, which has been implemented on many rivers and streams across the United States, has been proposed as a less expensive, ecologically compatible bank stabilization method. The limited documentation of these types of bioengineering techniques indicates high failure rates. River engineers need to understand the potential failure modes of cedar tree revetments, so they can take appropriate countermeasures when applying this technique. This article documents four common failure modes observed during post-project site assessments on 12 streams in eastern Kansas, USA that took place in 2019 and 2020. These modes are (1) bed degradation with structure perching, (2) failure in flexion, (3) loose cables, and (4) lack of sediment infilling. Computed factors of safety for top of bank discharge range from 0.3 to 6.0 in flexion (bending stress vs. strength) and range from 1.7 to 40.1 for anchor forces vs. anchor strength. These factors of safety suggest that failure in flexion is an important failure mechanism that should be considered and mitigated during design of cedar tree revetments. Moreover, failure rate varies directly with project age. The authors hypothesize that progressive processes such as breaking of bankside branches may cause loose cables and cyclical loading and wetting/drying may lower the bending strength of the trees over time. Avoiding degrading streams, additional anchoring, and trimming the bank-side branches of the cedar trees are suggested as means to reduce these types of failures.

KEYWORDS
bank stabilization, cedar tree revetments, geomorphology, river engineering, river restoration

1 | INTRODUCTION

Tree revetments are a common method of bank protection and have been used in the United States since at least the 1930s (Roseboom et al., 1992). In the Midwestern United States, they are typically constructed from eastern red cedar (*Juniperus virginiana*), although other species of deciduous and coniferous trees have also been used. The trees are usually placed longitudinally along the toe of the bank, either in one or two rows, and are attached to the bank or bed using earth anchors. While restoration practice in many regions of the United States favors biodegradable rope or twine, practitioners in the Midwestern United States almost exclusively use metal cable. Figure 1 illustrates a typical tree revetment configuration.

While hard armoring with rip rap has been shown in most cases to be superior for the primary objective of bank stabilization (Bigham, 2020), cedar tree revetments have several secondary advantages over projects constructed from rock. One such advantage is their lower cost. Trees used to construct the revetment can often be obtained near the site at no cost except for the labor to cut and transport them. Also, construction does not require heavy equipment with its

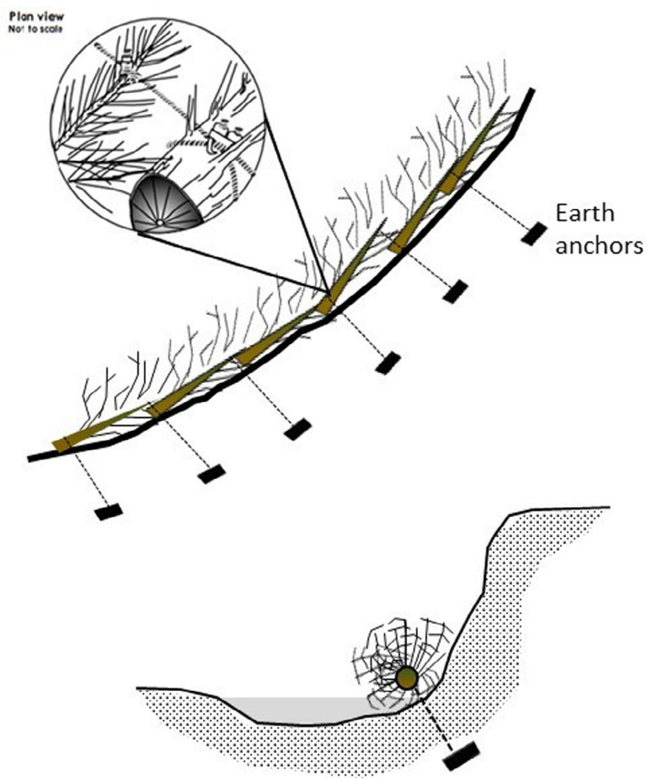

FIGURE 1 Illustration of a typical cedar tree revetment (Modified from NRCS, 1996) [Color figure can be viewed at wileyonlinelibrary.com]

attendant costs, access issues, and environmental constraints. Cedar tree revetments can be installed by landowners, volunteers, or others without much technical skill. Dave and Mittelstet (2017) report a proposed cost of $72 per meter for cedar tree revetments in Nebraska, while Nassar (2019) reported a cost of $52 per meter in eastern Kansas. Both estimates are less expensive than the cost for rock toe of $179 per linear meter estimated by Dave and Mittelstet (2017).

Another benefit of cedar tree revetment is that they provide woody habitat and cover for aquatic organisms (Gough, 1991). However, this may not be a significant benefit if the stream already has an abundance of woody debris. Gough (1991) reported a narrowing and deepening in bends that were stabilized with cedar revetments; creating greater diversity in depth and velocity. McClure (1991) reported that hiding cover for trout increased 195% for six reaches of a Montana stream after tree revetment installation, compared to a 36% decrease for riprapped reaches.

2 | SITE BACKGROUND

A literature review and personal inquiry with bank stabilization practitioners in Kansas identified 12 cedar tree revetment projects in Eastern Kansas that were at least 3 years old (see Figure 2). All projects used eastern red cedar (*Juniperus vinginiana*), oriented with the tips facing downstream, as in Figure 1. The most upstream tree was attached with a metal cable looped around the base and attached to the bank with a duckbill anchor. A location near the tip of the tree was cabled and attached to the base of the next tree.

The majority of the revetments were installed by undergraduate and graduate students at Kansas State University under the direction of Dr. Charles Barden (Barden & Nassar, 2018). Some were installed by Philip Balch of Wildhorse Riverworks. In February and September of 2020, after reviewing available documentation which consisted primarily of pre- and post-project photographs, the authors, accompanied by Dr. Barden, visited and visually inspected these 12 sites. At many locations entire trees were missing, leaving a gap of exposed bank, while adjacent trees were intact and appeared to be providing some stabilization. Damage on the remaining revetments provide clues from which failure mechanisms can be inferred.

Table 1 provides the year of construction, coordinates, and % failure for each site. The percent failure indicates the absence of the cedar tree or significant displacement such that it is no longer protecting the bank toe where originally placed, not a failure of the bank. These are provided as ranges and represent a visually based field estimation, not a measurement.

Table 2 provides geomorphic information for each site, derived from LIDAR using the FluvialGeomorph (FG) tool (Haring & Biedenharn, 2021; Haring & Dougherty, 2021). The width corresponds to the width of the channel at the geomorphic bankfull stage as defined by Leopold (1994). The W/D ratio is calculated by W^2/A where A = the cross-sectional area up to the geomorphic bankfull stage, W = the bankfull width, and D = the mean depth. These metrics are approximate because the LIDAR does not penetrate the water, and the depth of water on the days of the LIDAR flights is unknown.

2.1 | Hydrology

Barden and Nassar (2018) report successful toe stabilization and sediment trapping by the revetments at four of the sites (Little Solider Creek, Little Grasshopper Creek, Plum Creek, and Wolfley Creek), as of 2017, which suggests that the failures documented in this article resulted from more recent hydrologic events. Very likely the failures resulted from sustained high discharges during 2019 when annual precipitation was 125–200% of normal (NOAA 2020). All but one project (Solider Creek) were installed on ungaged streams. Gages on streams in the area indicate peak discharges in 2019 between a 2 and 10-year event at most gages and between a 20-year to 50-year event at the two most southern gages (Table 3).

While the exact discharges experienced in the ungaged project streams is unknown, field observations and the discharges at nearby gaged streams indicate that the stages likely ranged between the geomorphic bankfull stage and the top of bank.

3 | METHODS

Failure modes were assessed using three methodologies: (1) Field observation, (2) Comparison of vertical and horizontal forces

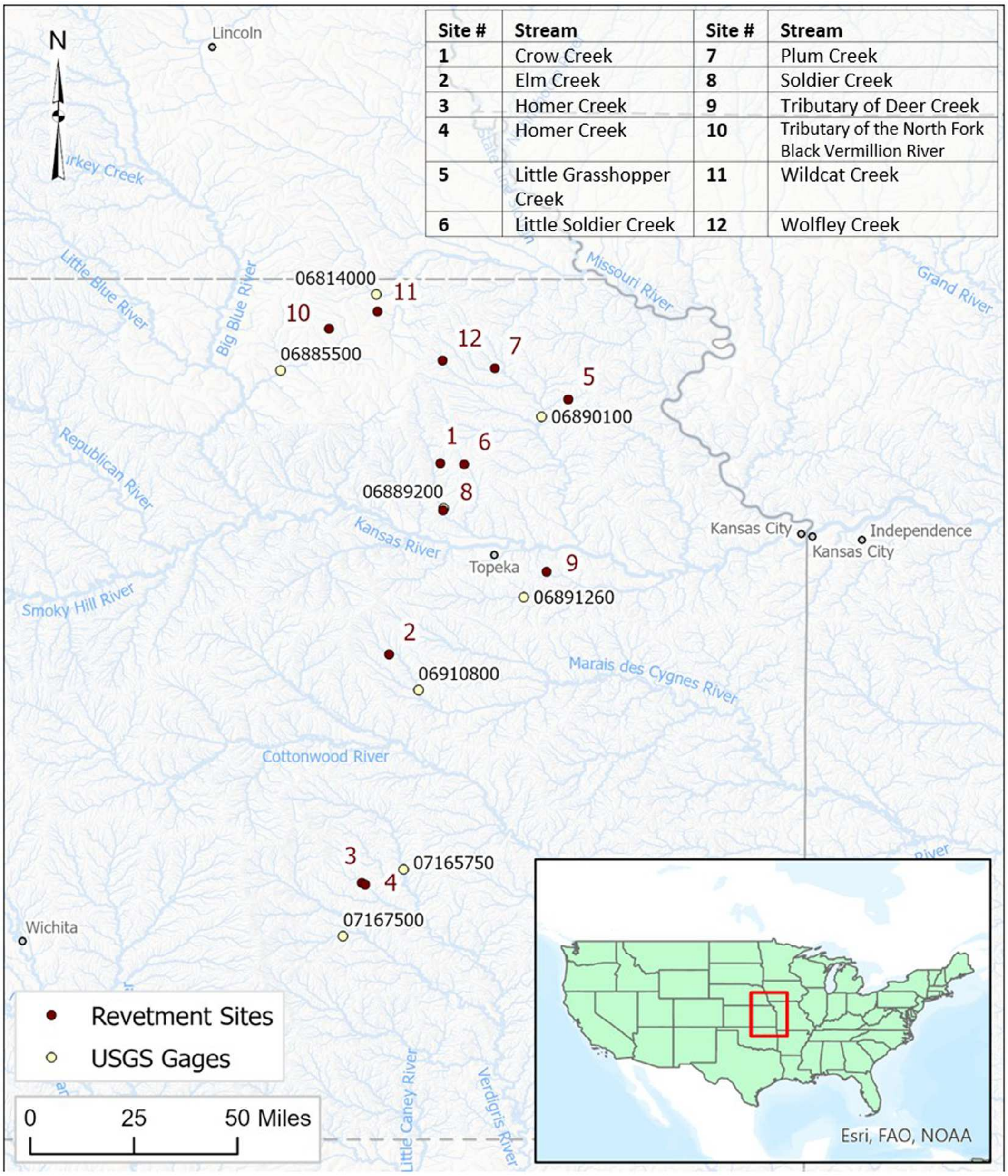

FIGURE 2 Locations of inspected cedar tree revetment sites in Eastern Kansas. Gages correspond to nearby gaged streams, as explained in later paragraphs [Color figure can be viewed at wileyonlinelibrary.com]

vs. anchor forces, and (3) Comparison of bending stress vs. bending strength.

3.1 | Anchor force analysis

The factor of safety is computed as the maximum anchor force divided by the applied force.

The applied forces were computed using the following equations:

$$F_A = \sqrt{F_V^2 + F_H^2},$$

where F_A = the total required anchor force; F_V = the sum of vertical forces, $= F_B + F_L$; F_B = the net buoyance force $= (\gamma_w - \gamma_{tree})V$; $\gamma_w =$ specific weight of water, 9810 N/m^3; γ_{tree} = specific weight of cedar tree, 5152 N/m^3 (Rafferty, 2016); V = tree volume (approximated as a truncated cone) $= \frac{1}{3}\pi L\left(r_{butt}^2 + r_{butt} r_{tip} + r_{tip}^2\right)$; L = the length of the tree, estimated to be 1.98 m; r_{butt} = the radius of the butt end of the trunk, estimated to be 16.5 cm; r_{tip} = the radius of the tip of the trunk, estimated to be 3.4 cm; F_L = the lift force $= \frac{C_L A \gamma_w u^2}{2g}$; C_L = lift coefficient = 0.45 (Rafferty, 2016); A = area perpendicular to flow, in this case the cross sectional area of the butt end of the tree, including branches, m^2; u = outer bend velocity $= u_{ave}(1.74 - 0.52 log(Rc/W))$; g = the gravitational acceleration constant; F_H = applied horizontal force $= \frac{C_D A \gamma_w u^2}{2g}$; C_D = drag coefficient = 0.8 (Rafferty, 2016).

TABLE 1 Summary of inspected cedar revetment sites

Site #	Stream	Year built	Latitude	Longitude	Rows	Drainage area (sq-km)	% failure
1	Crow Creek	1999	39.359	−95.8849	1	24.0	50–75
2	Elm Creek	1995	38.6921	−96.0635	2	115.9	>75
3	Homer Creek	2014	37.8944	−96.158	1	104.5	<25
4	Homer Creek	2015	37.8888	−96.1471	1	105.4	25–50
5	Little Grasshopper Creek	2017	39.5821	−95.4392	1	58.0	25–50
6	Little Soldier Creek	2000	39.3552	−95.8022	1	25.4	50–75
7	Plum Creek	2010	39.6899	−95.6944	1	46.6	50–75
8	Soldier Creek	1995	39.1944	−95.8757	2	417.1	100
9	Tributary of deer creek	2017	38.9801	−95.516	1	2.7	<25
10	Tributary of the north fork black Vermillion River	2007	39.8276	−96.2738	1	14.9	>75
11	Wildcat Creek	1995	39.888	−96.1035	2	57.8	100
12	Wolfley Creek	2017	39.7168	−95.8771	1	21.6	25–50

TABLE 2 FGLIDAR-derived geomorphic metrics for inspected cedar revetment sites

Site #	Stream	LIDAR year	Bank height, m	Radius of curvature (Rc), m	*W*, m	Rc/W	*W*/D	LiDAR water surface slope, m/m
1	Crow Creek	2012	3.3	57.6	11.8	4.9	7.7	0.0031
2	Elm Creek	2010–11	4.5	52.2	22.4	2.3	3.1	0.0003
3	Homer Creek (ds)	2012	3.2	59.5	24.5	2.5	4.4	0.0022
4	Homer Creek (us)	2012	4.5	64.9	22.3	2.9	3.3	0.0014
5	Little Grasshopper Creek	2010	4.1	22.9	12.0	1.9	4.0	0.0016
6	Little Soldier Creek	2012	3.1	32.4	18.9	1.7	4.2	0.0016
7	Plum Creek	2012	4.5	68.6	17.3	4.0	2.9	0.0025
8	Soldier Creek	2006	6.4	58.0	23.3	2.5	2.5	0.0049
9	Tributary of deer creek	2014–15	1.5	23.8	12.9	1.9	5.8	0.0070
10	Tributary of the north fork black Vermillion River	2006	3.6	44.6	20.2	2.2	7.1	0.0026
11	Wildcat Creek	2012	4.8	36.9	17.9	2.1	2.2	0.0012
12	Wolfley Creek	2012	3.4	31.3	13.3	2.4	3.1	0.0022

TABLE 3 2019 peak discharges and recurrence interval for nearby stream gages

USGS gage #	Stream	Drainage area (sq km)	2019 peak discharge (m^3/s)	2019 recurrence interval	2 year discharge (m^3/s)	Days 2 year discharge exceeded 2019
06814000	Turkey Cr	715	294	2 to 5 year	175	6
06885500	Black Vermillion R	1062	484	5 to 10 year	221	7
06889200	Soldier Cr	386	309	5 to 10 year	129	4
06890100	Delaware R	1116	479	2 to 5 year	353	6
06891260	Wakarusa R	425	326	10 year	139	8
07165750	Verdigris R	756	439	20 to 50 year	198	9
07167500	Otter C	334	1263	20 to 50 year	254	5
06910800	Marais des Cygnes R	458	236	2 to 5 year	193	2

For the computation of volume, a one-tree segment of the revetment was idealized as a tapering pole with the dimensions shown in Figure 3. The volume for the cedar tree trunk with the dimensions shown in Figure 3 is 0.023 m^3, not including branches. For purposes

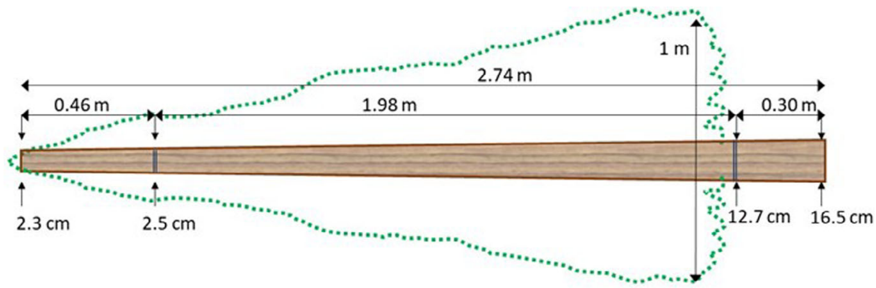

FIGURE 3 Dimensions of cedar tree trunk used in force balance calculations [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 4 FG LiDAR-derived parameters used in the hydraulic analysis

Site #	Stream	Est. manning n	LiDAR water surface slope, m/m	*P*, m	XS area, m^2
1	Crow Creek	0.045	0.0031	30.3	50
2	Elm Creek	0.037	0.0003	38.6	92
3	Homer Creek (ds)	0.037	0.0022	50.0	98
4	Homer Creek (us)	0.037	0.0014	32.6	67
5	Little Grasshopper Creek	0.03	0.0016	26.0	54
6	Little Soldier Creek	0.035	0.0016	28.4	55
7	Plum Creek	0.035	0.0025	26.1	63
8	Soldier Creek	0.03	0.0049	27.0	68
9	Tributary of deer creek	0.03	0.007	17.2	18
10	Tributary of the north fork black Vermillion River	0.052	0.0026	33.1	79
11	Wildcat Creek	0.03	0.0012	25.2	75
12	Wolfley Creek	0.03	0.0022	21.8	50

of computing drag and lift, the branches were included, yielding a cross sectional area of 0.79 m^2.

A major uncertainty in the computation of applied forces is the lack of velocity data (or stage data from which velocity can be computed) at all sites except Soldier Creek. At Soldier Creek, the peak discharge was 309 m^3/s (see Table 3), which roughly corresponds to a major terrace. At the remaining sites, a high terrace was selected and the area, wetted perimeter, and slope was estimated using LIDAR. The average velocity, u_{ave}, was computed using Manning's Equation with roughness values estimated using the U.S. Geological Survey photographic method documented in Barnes (1967). Table 4 lists the inputs to the hydraulic analysis.

The maximum anchor force for properly set DB88 anchors in normal soil is 13.3 kN (Rafferty, 2016).

3.2 | Bending stress analysis

Based on the observed failure mode of trees snapping in the middle (discussed in the results section), a bending stress analysis was also performed. The revetment was idealized as a uniformly loaded, tapering pole, and the maximum bending stress was computed using the equations presented in McCutcheon (1983):

Section Modulus: $S_A = \frac{\pi}{32} d_{tip}^3$

Diameter Ratio: $r = d_{butt}/d_{tip}$

Normalized Distance at Location of Max Stress: $\varepsilon = \frac{r-\sqrt{r^2-r+1}}{r-1}$

Maximum Bending Stress:

$$f = \frac{wL^2}{8S_A} \times \frac{4\varepsilon(1-\varepsilon)}{(1+(r-1)\varepsilon)^3}$$

where w = the uniform load (approximated. as F_V/L); L = the distance between anchor points (1.98 m from Figure 3); d_{tip} = the diameter at the tip anchor location (0.025 m from Figure 3); d_{butt} = the diameter at the butt anchor location (0.127 m from Figure 3).

The bending strength of eastern red cedar is 67,000 kN/m^2 at 12% moisture content (Markwardt, 1930). For this analysis, the moisture content is assumed to be 20%, which reduces the bending strength by 25% to 50,250 kN/m^2 (Gerhards, 1980).

4 | RESULTS

4.1 | Observed damage/failure modes

The following section documents common failure mechanisms inferred from damaged and failed revetments observed during the 2020 site visits. These are not a comprehensive list of all potential failures for these types of projects, just those observed at the 12 Kansas sites visited.

4.1.1 | Failure mode 1: Bed degradation with structure perching

Multiple sites showed evidence of recent bed degradation, the lowering of local base level due to channel incision processes. These channel geomorphic processes have been qualitatively described in Channel Evolution Models (Cluer & Thorne, 2013; Hawley, Bledsoe, Stein, & Haines, 2011; Schumm, Harvey, & Watson, 1984; Simon & Hupp, 1986) that predict channel widening and deepening conditions in degrading channels. At the Wolfly Creek project (Site 12), the bed degraded, which stranded the revetment above the new, unprotected toe. Figure 4 shows the installation of a single row of cedar trees lining the toe of Wolfley Creek. In Figure 5, the single row of cedar trees is visibly perched above the base flow water surface. Multiple knickpoints ranging from 150 to 300 m upstream provided further indication of recent degradation. Based on installation notes (pers. commun., Charles Barden, 2020) and channel changes upstream viewed during the site visit, the channel lowered 0.3 to 0.6 m in elevation since construction of the revetment.

Typically, localized scour at the revetment toe could exacerbate slope instability (NRCS, 2007). In Wolfley Creek and the other Kansas streams visited, glacially deposited, resistive clay materials within the toe of the bank and bed likely slow the scour, degradation, and widening processes and provide some level of toe protection behind and below the existing revetment.

FIGURE 4 Construction of the cedar tree revetment on Wolfley Creek April 2017 (Nassar, 2019) [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 Channel bed degradation on Wolfley Creek Cedar tree revetment April 2017 (Nassar, 2019). Red lines indicate channel degradation. Blue line indicates flow direction [Color figure can be viewed at wileyonlinelibrary.com]

At Wolfley Creek, widespread revetment failure had not occurred as of the visit. At other sites where a resistant toe was absent, this level of degradation could lead to toe undercutting and slope failure.

4.1.2 | Failure mode 2: Failure due to flexion

At several sites, the cedar tree trunks snapped somewhere between the anchors. Both sides of the snapped trunk were still attached at one end with cables that were anchored to the bank. This allowed the unattached side of each segment to float freely and oscillate in the current. Figure 6 illustrates this process. In Figure 6, the "lift forces" include both buoyancy and hydraulic lift. The exact mechanisms leading one tree to fail and another to remain intake are unclear; in places only a single tree was missing in a line with no obvious differentiating factors. Tree diameters, anchoring locations, and local hydraulic forces all vary to some degree and contribute to failure of a single tree.

Figures 7 and 8 show the top half of snapped cedar trunks that have displaced or rotated downstream, resulting in a bare, unprotected bank. These failures could be identified because both halves of the trunks were still present.

4.1.3 | Failure mode 3: Loose cables and tree floating

The trees were initially installed tight against the bank toe (for a single row revetment) or against the lower bank face (for the second of a two-row revetment). However, on inspection, many revetments had significant lengths of cable extending from the bank to the trunk of the tree. The anchor force analysis (presented below) does not suggest that excessive forces caused the cables to pull out. Erosion at the anchor site, deterioration of branches on the bank side of the trunk, or improper installation are likely causes. The longer cable allowed the trees to float up during high discharges (Figure 9), which left the toe unprotected. Moreover, longer cables allow the revetment to oscillate in high discharges, which would further encourage pull out, break branches, cause repeated impacts against the bank, and shake loose trapped sediments.

4.1.4 | Failure model 4: Lack of sediment filling

Cedar tree revetments provide energy dissipation at the toe of the eroding bank which reduces near bank velocities (Klein, 2019) and encourages deposition (Sheeter & Claire, 1989). Fine fern and scale-like leaves provide a dense matrix to effectively catch sediment during higher discharges events. Sediment filling also occurs as the revetment catches failed material from the mid and upper bank (Figure 10).

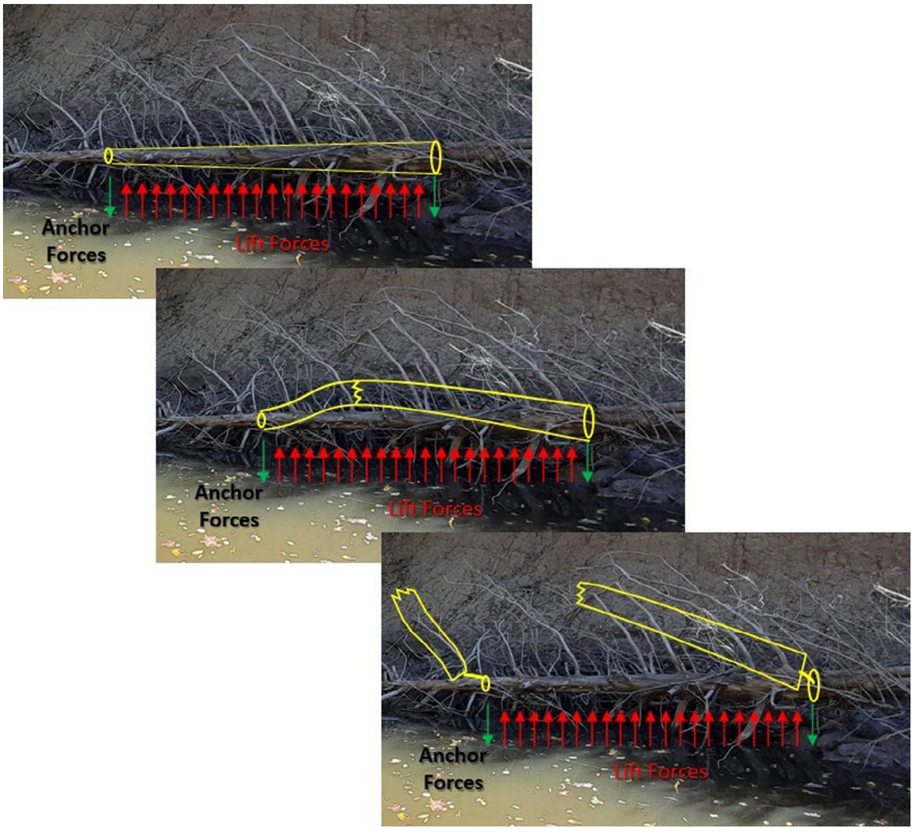

FIGURE 6 Progression of revetment failure in flexion. Force is idealized as uniform [Color figure can be viewed at wileyonlinelibrary.com]

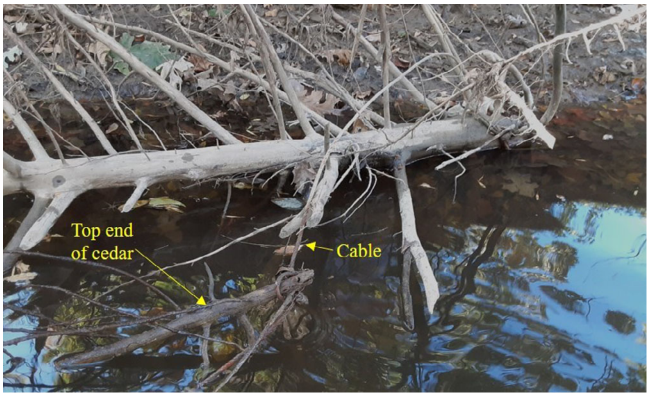

FIGURE 7 Revetment that failed due to flexion. Project #1 on Homer Creek, KS [Color figure can be viewed at wileyonlinelibrary.com]

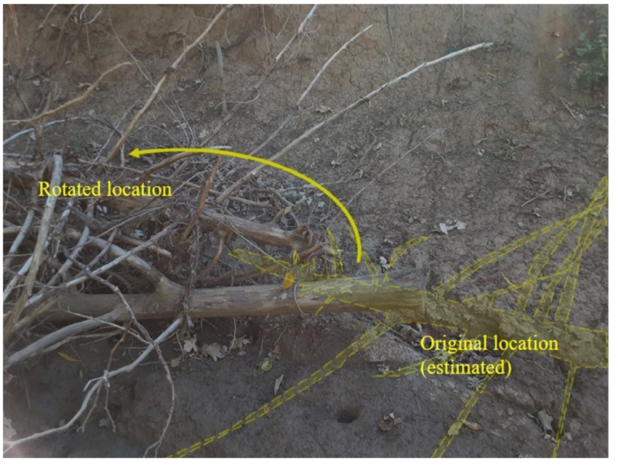

FIGURE 8 Revetment that failed due to flexion. The top end rotated and lodged on top of the next revetment downstream. Project #2 on Homer Creek, KS [Color figure can be viewed at wileyonlinelibrary.com]

Sediment filling plays a key role in the effectiveness and longevity of the revetment. Sediment provides alluvial materials for bank vegetation to re-establish and colonize the newly developed berms. Establishment of vegetation allows for additional dissipation of flow energy and further deposition of sediment. If stable vegetation is not re-established at the toe of the slope, then the mid and upper banks have a greater chance to further de-stabilize. The added sediment also provides ballast weight on the cedar trees which reduces bending forces and net vertical forces.

However, at many sites visited, the revetments were not filled with sediment (Figure 11). As discussed above, loose cables could allow oscillation and movement during high discharges, which would cause the cedars to "shake loose" the sediment. Without sufficient catching and infilling of sediment around the revetments, there is a higher probability of failure.

4.2 | Anchor force analysis

The required anchor forces for discharge computed at the top of bank are presented in Table 5. This represents the maximum force that

FIGURE 9 Loose cable allowed the revetment to float up during high discharges. Plumb Creek, KS [Color figure can be viewed at wileyonlinelibrary.com]

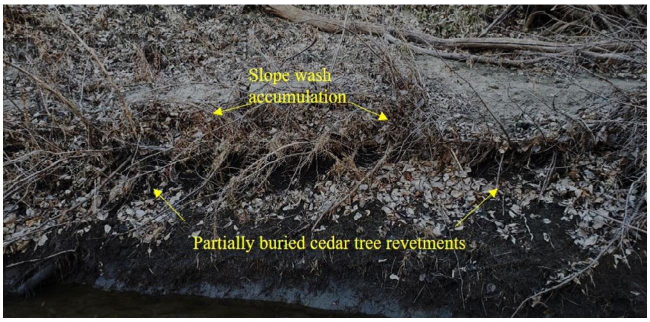

FIGURE 10 Slope wash accumulation forming a bench or berm above cedar tree revetments on Wolfley Creek, KS [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 11 Cedar tree revetments have not captured sediment. One revetment is missing. Homer Creek, KS [Color figure can be viewed at wileyonlinelibrary.com]

could be expected to occur, which likely exceeded the 2019 flood levels at most locations. The anchor force required to offset horizontal and vertical forces was well below the 13,000 N that a single, properly installed anchor should supply in "normal soil". Considering two anchors, the factor of safety (FS-F) ranges from 1.7 to 40.1. All twelve sites have factors of safety in excess of the 1.5 recommended by Rafferty (2016), suggesting that properly installed anchors should have been more than sufficient to resist buoyancy, lift, and drag forces in their as-built condition. Due to uncertainty in hydrologic conditions and uncertainty in the drag and lift coefficients, this analysis should be viewed as highly approximate.

4.3 | Bending stress analysis

The results of the bending stress analysis, presented in Table 6, indicate that the bending stress factor of safety (FS-B) ranged from 0.3 to 6.0. The literature does not include a suggested factor of safety for bending; typical log diameters for other large wood projects are much larger than those of cedar tree revetments, causing bending to not be a critical failure mode. Six out of 12 of these cedar tree revetment projects have factors of safety in bending at or <1.0, suggesting that failure in bending could have occurred immediately post-construction, had a hydrologic event sufficient to fill the channel to the top of bank occurred. Field evidence supports this failure mode, as several revetment trees had snapped in the middle while remaining anchored on both sides. At Homer Creek, however, this occurred even though the factor of safety ranged from 1.4 to 2.1. This could have been caused by additional forces such as debris impacts, soil slumping or by decreased strength due to a combination of wood fatigue from repetitive bending (FPL, 1999) and repeated cycles of wetting and drying over many years.

Correlation analysis indicated that the percent failure correlates strongest with the age of the project and second with the bank height. Figure 12 presents a linear best-fit equation between project age and observed failure percentage. This indicates that progressive weakening from repeated bending, oscillations due to loose cables, channel degradation, flanking, and other processes that occur over time may be significant failure mechanisms.

The bank height was also weakly correlated with the age of the project (the bank height is smaller at newer projects), but including both parameters in a multivariate regression yielded a slightly stronger prediction. The first parameter (age) has a p-value of 0.0024. The second parameter (bank height) has a p-value of 0.07. Figure 13 shows the agreement of the multivariate equation with the observed values.

5 | DISCUSSION

Neither the anchor force nor the bending factors of safety were strongly correlated with the observed failure rates. This is most likely because the anchor forces and bending strength were assumed equal across locations and constant across time in their "as-built" condition, as well as due to uncertainty in the hydrologic events that occurred at each site. Moreover, the factors of safety do not include the effects of time, which as indicated in Figure 12, are significant. The strong correlation between age and failure rate suggests that decreasing

TABLE 5 Anchor force analysis

Site #	Q (m^3/s)	u_{ave} (m/s)	u_{max} (m/s)	F_B (N)	F_L (N)	F_V (N)	F_H (N)	F_A (N)	FS-F
1	87	1.7	2.4	107	1017	1125	1809	2130	12.5
2	77	0.8	1.3	107	296	404	527	664	40.1
3	196	2.0	3.1	107	1651	1758	2935	3421	7.8
4	109	1.6	2.4	107	1062	1169	1887	2220	12.0
5	119	2.2	3.5	107	2139	2246	3802	4416	6.0
6	97	1.8	2.9	107	1462	1569	2599	3036	8.8
7	164	2.6	3.7	107	2399	2506	4264	4946	5.4
8	295	4.3	6.6	107	7788	7895	13,846	15,939	1.7
9	50	2.8	4.5	107	3639	3746	6469	7475	3.6
10	138	1.7	2.7	107	1318	1425	2344	2743	9.7
11	178	2.4	3.7	107	2486	2593	4419	5124	5.2
12	138	2.7	4.2	107	3136	3243	5576	6450	4.1

TABLE 6 Bending stress analysis–discharge at the top of bank

Site	F_v (N)	L (m)	w (N/m)	d_B (m)	d_A (m)	r	S_A (m^3)	ξ	f (kN/m^2)	FS-B
1	1125	1.98	567.97	0.127	0.025	5.08	1.53E-06	0.1027	23,407	2.1
2	404	1.98	203.80	0.127	0.025	5.08	1.53E-06	0.1027	8399	6.0
3	1758	1.98	887.88	0.127	0.025	5.08	1.53E-06	0.1027	36,591	1.4
4	1169	1.98	590.31	0.127	0.025	5.08	1.53E-06	0.1027	24,328	2.1
5	2246	1.98	1134.22	0.127	0.025	5.08	1.53E-06	0.1027	46,744	1.1
6	1569	1.98	792.39	0.127	0.025	5.08	1.53E-06	0.1027	32,656	1.5
7	2506	1.98	1265.54	0.127	0.025	5.08	1.53E-06	0.1027	52,156	1.0
8	7895	1.98	3987.53	0.127	0.025	5.08	1.53E-06	0.1027	164,335	0.3
9	3746	1.98	1891.80	0.127	0.025	5.08	1.53E-06	0.1027	77,965	0.6
10	1425	1.98	719.91	0.127	0.025	5.08	1.53E-06	0.1027	29,669	1.7
11	2593	1.98	1309.55	0.127	0.025	5.08	1.53E-06	0.1027	53,970	0.9
12	3243	1.98	1638.11	0.127	0.025	5.08	1.53E-06	0.1027	67,510	0.7

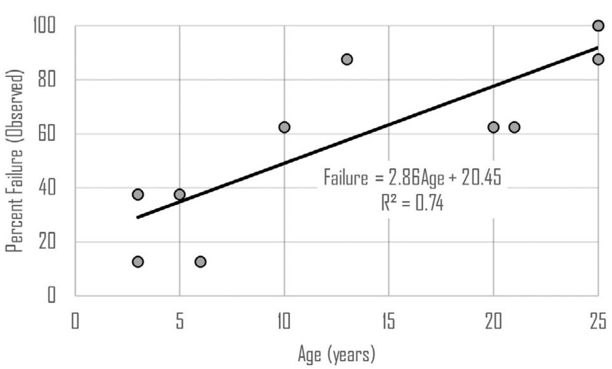

FIGURE 12 Failure rate as a function of project age

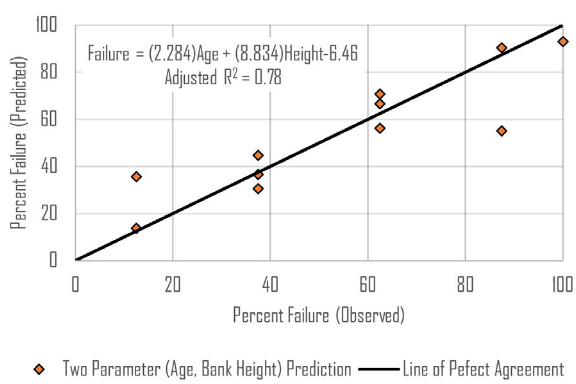

FIGURE 13 Failure rate as a function of age and bank height [Color figure can be viewed at wileyonlinelibrary.com]

anchor strength (due to cable loosening or degradation-induced slumping) and decreases to bending strength (due to repetitive loading and wetting-drying cycles) should be explicitly included in the design process.

Work beyond the scope of this article, including quantitative laboratory experiments, physical modeling, and/or field testing, would be necessary to provide quantitative design guidance for reductions in failure rates. The following paragraphs suggest solutions based on field observations, engineering judgement, the bending stress equation, and practices observed in other regions, which can be valuable

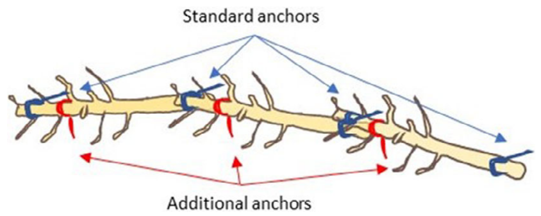

FIGURE 14 Concept for a third anchor oriented downward [Color figure can be viewed at wileyonlinelibrary.com]

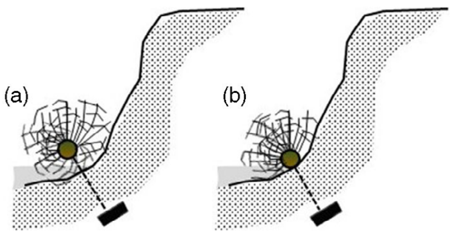

FIGURE 15 (a) Configuration of visited revetments. Branches between the trunk and the bank may break off over time. (b) Suggested configuration. Bank-side branches removed and trunk installed in contact with soil [Color figure can be viewed at wileyonlinelibrary.com]

considerations while the quantitative guidance is lacking. These suggestions are not comprehensive for reducing every type of failure—but in the authors' opinion they likely decrease failures by the modes specified in this document.

The risk of revetment perching due to channel degradation can be avoided by installation of grade control, anchoring trees to boulders that could launch as the stream degrades, installing the trees above a stabilized toe that has sufficient volume to launch as the bed degrades, or through a myriad of other river engineering techniques (FISRWG, 1998; Newbury & Gaboury, 1993a; Newbury & Gaboury, 1993b; NRCS, 2007). These options would require additional construction equipment, rock material, and permitting that would increase the costs significantly compared to cedar tree revetments alone. For low-cost stabilization using only cedar tree revetments, degrading streams should be avoided entirely.

Bending stress can be reduced significantly by adding a third anchor between the typical two anchors at the location of maximum moment (Figure 14). This echoes other authors' suggestions that additional anchoring could reduce failures in woody debris structures (D'Aoust & Millar, 2000; Miller & Craig Kochel, 2013; Shields Jr., Knight, Morin, & Blank, 2003). The results in Table 6 indicate that with only two anchors, bending stress may induce failure even in the as-built condition should a sufficiently large hydrologic event occur. Using the equations presented in the Methods section and the dimensions shown in Figure 3, the bending stress is minimized to 17% of the original stress by adding a third anchor 23% of the way from the existing tip anchor to butt anchor, which is the location of maximum moment. Moreover, a third anchor placed at the location of the maximum moment would significantly reduce the magnitude of cyclical bending of the tree, which might decrease weakening over time and lead to increased longevity. Differing dimensions of any given tree will dictate a slightly different optimum placement location for the third anchor, but the anchor should be closer to tip rather than in the middle. To reduce floating should some erosion occur behind the revetment, the additional "middle" anchor should be anchored to the bank or bed below the revetment rather than level with the existing anchors.

Finally, the branches on the bank side of the revetment could be trimmed to allow the trunk of the cedar to be flush with the bank (Figure 15)—a technique practiced with success by the Anoka Conservation District in Minnesota, USA (Pers. Commun., Mollie Annen, 2021) but not widely utilized elsewhere. This would eliminate loose cable due to the deterioration of the bank side branches and allow tighter anchoring to the bank, which would decrease the impacts of trees floating and oscillating and could lead to greater sediment retention.

6 | CONCLUSION

Cedar tree revetments represent an attractive stabilization option due their low cost and potential ecological value; however, they are prone to failure during high discharges and after many years. An approximation of forces and bending stress at 12 cedar tree revetment projects in Kansas, USA indicated sufficient factors of safety in the as-built condition for anchor forces, but insufficient factors of safety at 6/12 sites for bending stress. Field observations following moderate flooding indicated numerous failures and evidenced four prevalent failure modes: (1) Degradation with structure perching, (2) Failure in flexion, (3) Loose cables, and (4) Lack of sediment in-filling. The rate of failure is highly correlated with project age and moderately correlated with bank height. Unmeasured progressive processes such as wetting and drying, cyclic loading and unloading, and oscillation due to loose cables, likely play an important role in the failures. Equations to predict failure rate were presented, but these may not be valid in other regions. Initial suggestions for reducing failures include avoiding degrading streams, installing a third anchor oriented downward, and trimming the bank-side branches of the cedar tree to allow tighter installation to the bank. Additional testing and quantification are needed, particularly to quantify the long-term effects of cyclical loading and wetting and drying on bending strength.

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DATA AVAILABILITY STATEMENT

Data that support the findings of this study are available from the corresponding author upon reasonable request.

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