DRAFT- Lessons Learned from Bank Stabilization Failures

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Abstract

The ancient philosopher Chanakya said, "Learn from the mistakes of others. You can't live long enough to make them all yourselves." In that spirit, this extended abstract is about bank stabilization that failed, meaning the bank eroded anyway, the project required a significant modification or repair, or the project caused some unforeseen impact that required a modification or repair. These failures come from post-project assessments of bendway weirs, rock vanes, rock revetments, cedar tree revetments, gravel rolls, and other standard and unique bank stabilization attempts across the Midwestern United States. In addition to our own experience, we have asked other bank stabilization practitioners for their top failure modes.

Introduction

Riverbank stabilization is one of the most common river engineer interventions in the world. In the Midwestern United States, state departments of transportation, utility companies, owners of bankside infrastructure, farmers, watershed protection groups, and others have stabilized banks using combination of methods. These include Whole Bank Riprap Revetments (WBRR), Longitudinal Peaked/Fill Stone Toe Protection (LPFSTP), toe protection with baffle dikes, bendway weirs, vanes, dikes, cedar tree revetments, gravel rolls, toe wood, bank shaping with plantings, and other methods.

We have seen failures in every type of bank protection. Some of these failures have been formally documented; most have not. What follows is an informal discussion of the most common failures we, the authors have observed. We also sent an email query to a few experts with decades of bank stabilization experience asking about the most common failure modes they have observed. Portions of their responses are quoted.

Purpose of Bank Stabilization

Each bank stabilization practice provides a unique set of goals for stabilization and ecological benefits that can vary widely (Franz et el., 2022a). For example, WBRR provide different stabilization components and benefits verse LPFSTP with vegetative components in the mid and upper bank. The WBRR is typically used for projects where any bank erosion is unacceptable, such as to protect levees, bridge approaches, roadways, and other infrastructure. The LPFSTP is typically used in areas that have more flexibility in stabilizing the mid and upper banks with vegetation that takes more time to fully develop. The addition of vegetation provides more ecological (biologic materials and habitat), hydraulic (reduction in velocities-sediment fine deposits) and aesthetic (reduction in visible hard stabilization methods) benefits than the standard WBRR (Haring et al., 2021). If WBRR projects are not maintained, vegetation often develops within the revetment adding to the benefits described (Figure 1, left). However, in some regions invasive species may become dominant such as kudzo, providing little or no ecological or stabilization benefits (Figure 1, right).

Figure 1. (Left) A whole rank riprap revetment in process of vegetative colonization. Wolf Creek, Missouri. (Right) A whole bank riprap revetment colonized by invasive kudzo. Clear Creek, Mississippi.

The river stabilization practitioner needs to develop an appropriate understanding of the project goals and objectives so that the stabilization/restoration plans can be implemented, and potential failure modes considered.

Common Bank Stabilization Failure Modes

Haring et al. (2023 in-review) and USACE (2022) list the following contributors to failure:

- Unidentified or misinterpreted physical stream processes such as channel degradation or aggradation
- Local scour issues with existing infrastructure or transitions in materials at revetment locations
- Under predicting channel planform scour within the stabilization reach leading to excessive launching of restoration materials
- Restoration materials do not last long enough to stabilize local erosion or are not resilient enough to handle flow abrasion
- Not starting and stopping the stabilization project at a stable beginning and ending point
- Project is flanked because the stabilization project did not consider high flow channels, changes to upstream and downstream channel alignments, etc.
- Overland flow or excessive local drainage causing erosion from the backside of the project
- Geotechnical issues associated with bank stability without appropriate mitigation
- Project not installed properly-contractor has little riverine-construction experience and little direction from construction representative and designer

- Needed irrigation or other specific project components are not completed as designed
- Sponsor goals and objectives do not match with the project constructed
- Ecological and environmental benefits do not develop as designed
- Project monitoring is not being completed to identify deficiencies
- Adaptive Management or Operations and Maintenance Plan is not followed to correct deficiencies

These contributors to bank stabilization failure group into four categories:

1) **Site Specific and Watershed Characterization Failure:** Incorrect geomorphic, hydraulic, hydrologic and ecological site characterization can lead to failure modes that compromise the success of a project. Geomorphic and hydraulic characterization are important for determining critical thresholds and metrics associated with stable channel design. If this information is not collected appropriately then the project will likely fail. Inappropriate hydrologic data analysis or not planning for future watershed changes could increase or decrease project failure rates depending on how significant the changes are. Ecological failure is affected by not providing the benefits that from the project's original goals and objectives. These should have a mechanism for adjustment based on a robust adaptive management plan (Franz et el., 2022a).
2) **Design Failure:** Bank stabilization design failures characteristically develop from two main issues, misinterpretation of physical channel processes and applying an inappropriate practice. Physical channel and watershed processes need to be studied and understood prior to establishing the appropriate bank stabilization practice(s). For example, installing bank stabilization (riprap, vegetation or a combination) practices in a degrading stream channel will most often lead to project failure unless channel bed stabilization is also included.
3) **Project Material Failure:** Whether it be riprap or vegetation, the appropriate materials need to be acquired to successfully implement a bank stabilization project (Haring et al., 2023 in review). Riprap must be sized appropriately to resist hydraulic forces and avoid movement (USACE 1994). This may cause excessive loss of toe protection-launching more riprap than what was originally calculated or scouring material from mid and upper bank sites on WBRR sites. Substituting vegetation in instances where velocities are too high to withstand erosion will also cause erosion of the revetment. There have been other cases where use of non-approved riprap or concrete have caused project failure due to weathering of riprap and increased scour around slabby concrete revetment sites.
4) **Ecological Failure:** Revisiting the goals and objectives of the project is important in determining whether ecological goals have been met with the project. A robust monitoring plan is essential to make sure the project is meeting the originally established ecological success criteria. In post-project ecological assessments, if the criteria is not being met then an adaptive management plan can be used to adjust the project to successfully meet the original goals and objectives. It is the authors experience that monitoring and adaptive management plans are typically not or only partially implemented because of schedule, expertise and cost. Most bank stabilization projects could benefit greatly for a requirement to follow both plans.

Redirective (Indirect) Project Flanking

Redirective or indirect stabilization are a group of practices that use structures projecting out from the bank to catch and redirect the main channel thalweg. This realigns the main channel velocities away from the bank and directs more erosive flows toward the inside of the channel. These types of structures can be implemented in straight channels (bendway) or in more tight radius curves (barbs). Many types of redirective structures exist, including hard points, dikes, weirs, veins, barbs, etc. (USACE 1999). Redirective structures can be made with loose riprap, wood, gabion baskets, sand-filled geotextiles, and other materials.

We have observed failure by flanking with virtually every type of redirective stabilization technique. This is especially problematic in redirective techniques such as bendway weirs, barbs, or vanes, as these structures can actually accelerate erosion rate at the structure/bank interface. The rock vanes built on the Republican River upstream from Milford Lake offers a clear example. Within the first 6 years, the most downstream 6 out of 10 total vanes had been flanked. Other the next 2 years, the river flanked the remaining four structures.

Figure 2. Flanking of rock vanes on the Republican River, KS failed multiple structures within 6 years and all the structures within 8 years. Flow is from top to bottom. From Williams and Shelley (2020).

Bank stabilization expert Phil Balch (Wildhorse Riverworks) adds the following insight:

> "There is a tendency on some sites for bank scalloping between weirs. After the 2017 floods on the Big Blue River, I noticed the scalloping on sites where I did not use longitudinal peaked stone toe protection (LPSTP) throughout the entire project. Sites with the LPSTP did not have any scalloping. Since then, I always use some form of continuous toe protection."

Flanking of Longitudinal Toe Protection

Rivers can flank longitudinal toe protection when the protection does not cover a sufficient vertical percentage of the bank. In other words, at high flows sufficient shear stress exists to cause erosion of the bank face above the hard protection.

Channel planform changes can induce flanking on the upstream and downstream ends of a project. River engineering expert David Biedenharn (US Army Corps of Engineers) states:

> "Downstream flanking is the most frequently encountered since streams often tend to migrate down-valley (and sometimes this only causes a local problem), but when

upstream flanking occurs, there may be a more likelihood of total failure of the structure."

Flanking can also occur where the point bar opposite of the eroding bank is composed of non-erodible materials. Phil Balch (Wildhorse Riverworks) adds:

> "I have seen this years ago on Missouri Department of Conservation project south of Jefferson City, MO. They built bendway weirs (more like jetties, they were probably 6 feet tall) to a well vegetated mid bar. I'm sure they thought the stream would remove the bar, but it didn't and ended up flanking the weirs."

Flanking can be minimized by extending the protection to stable positions upstream and downstream, and keying in structures to the bank.

Localized Scour Around Structures

Both rock and large woody debris protection methods induce localized scour. Scour at the tips of dikes and bendway weirs is common. In the case of longitudinal bank protection built with loose riprap, the rock will launch and fill the scour hole. Failure of the stabilization occurs if there is not enough rock remaining to protect the bank toe after the rock has launched to fill the scour.

Non-launchable protection can fail even more catastrophically. The Missouri Department of Conservation, installed an experimental "gravel roll" in conjunction with bank sloping and vegetation plantings on Mill Creek in the Missouri Ozarks. The gravel roll was built by placing erosion control fabric at the toe of the streambank, backfilling with gravel, rolling over the fabric, and sewing it together. The gravel roll was intended to stabilize the toe while the bank sloping and plantings provided long-term stability. Instead, the gravel roll failed during the first out of bank event, which occurred that same year. Persinger et al. (2007) report the failure occurred because the gravel roll did not launch and adjust to scour the way riprap does. Rather, it acted as a single long tube. Moreover, the gravel roll did not protect a sufficient vertical percentage of the riverbank, which allowed mid and upper bank erosion and flanking.

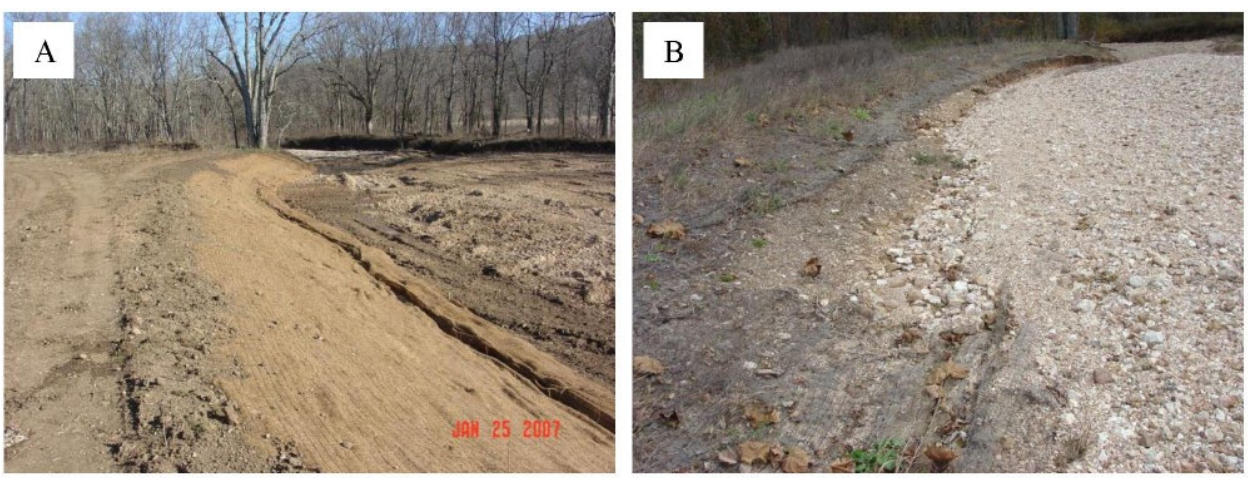

Figure 3. (A) A newly gravel roll installed at the toe of the bank of Mill Creek, MO on January 2007. (B) Same site, post failure, November 2007. From Persinger et al. (2007).

To compensate, some many practitioners will either trench in their structures or else make them extra wide and long to account for the launching. Wood structures can be built on a launchable rock toe.

Systemic Degradation

Rock launching can also occur due to system-wide degradation and headcutting. Bed degradation reduces the height and thickness of the rock revetment, increases the bank height and associated geotechnical driving forces, and increases channel velocities during high flows.

Inappropriately Sized Material

Rock sizing should be the least problematic of all aspects of bank stabilization; engineers have equations and well-established procedures for sizing rock. Notwithstanding, we have observed many stabilization projects that fail because the rock is simply too small. This can occur when rock size is selected without utilizing or at least checking the size against equations based on local hydraulic forces, i.e. a “standard gradation” was used under conditions that generated greater than “standard” hydraulic forces.

Rock fragmentation and disintegration can also lead to smaller rock sizes that fail prematurely (Figure 4). Rock blasting can induce microfractures that speed disintegration.

Figure 4. Rock weathering and disintegration in a structure on the Republican River, KS.

Insufficient rock size can also occur due to construction error. On the Missouri HWY 617 project, a single moderate flow event caused bendway weirs to lose a significant percentage of their length one month after construction (Figure 5). On investigation, we found that the rocks had sorted during construction, such that all the large rocks were in a few weirs and all the small rocks in other weirs. To compound the issue, the point bar opposite of the weirs contained layers of bedrock. Unsurprisingly, the weirs with the smaller rocks were washing away.

Figure 5. Rock was too small in this bendway weir near Missouri HWY 617. Rock is washing away from a single, moderate flow event. January 2012.

This site was repaired by encapsulating the weirs with larger, well-graded rock. At last inspection the project was functioning properly.

Cedar Tree Revetment Failure Modes

Cedar tree revetments involve anchoring cut cedar trees longitudinally along the toe of an eroding bank. Failure rates for cedar tree revetments are relatively high; at sites we visited in Kansas failure rates were 35% for 5-year-old projects, rising to 92% for 25-year-old projects Shelley et al. (2022). The most common failure modes were trees snapping in the middle, undermining due to degradation, and loose cables allowing flanking and excessive movement. The presentation will provide several examples.

On Riceford Creek in Minnesota, high flows eroded the bank above and then behind the cedar tree toe revetment (Figure 6). Erosion proceeded far enough to unbury the anchors. The next high flow event is likely to dislodge these trees completely.

Figure 6. Flanking of a cedar tree revetment on Riceford Creek, MN has eroded so far that the anchor is no longer buried and water flows behind the tree.

Vegetative Project Flanking-Plantings

Vegetation is crucial to the long-term success at many stabilization sites. Vegetation provides roughness that slows velocities and roots that provide surface armoring and geotechnical strength. However, engineering requirements and construction quality control are often lax on plant handling and installation, leading to low success rate for vegetation. Says Balch:

> The biggest thing that I've seen on bare root plantings is over pruning the roots and not keeping them wet until planted.
>
> The biggest failures that I have observed in live cuttings is the harvesting, handling, transportation, and installation. Cuttings are often harvested and left lying in the open sunlight without being covered or kept moist. Once they dry out, the survival rate drops dramatically. The other problem with live cutting installation is not having a good soil contact with the cuttings. On one project in Wichita, the contractor was creating a 2-inch diameter hole for a 3/4 inch cutting. The other mistake I have done and seen others do, is leaving too much of the cutting exposed above ground. For the best survival, three fourths of the cutting should be in the ground.

Conclusion

Bank stabilization has been practiced successfully across the United States using a variety of methods. However, failures are also relatively common. This presentation highlights some common reasons these projects fail. By considering and protecting against these failure modes, engineers can design more successful projects.

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