United States Department of Agriculture

NRCS

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SUBJECT: ENGINEERING TECHNICAL NOTE NO. 23, DESIGN OF STREAM BARBS (Version 2.0)

Purpose: To distribute updated Oregon Technical Note No. 23, "Design of Stream Barbs".

Effective Date: Upon receipt.

Explanation: The NRCS Oregon has designed and constructed river and stream barbs for streambank protection and habitat improvement based on our existing standards in conjunction with sources of information which may vary from designer to designer. This technical note provides a consistent source of information which should be used as a general guide for the design of stream barbs. The use of this guide will provide a consistent methodology for the understanding of reach scale river hydraulics and geometric design criteria. The designer should understand that each stream and project site is unique and adaptations to these guidelines may be necessary. Note that barbs as defined within this technical note differ from previous structures including: bank barbs (Reichmuth, 1993), low rock sills (Saele, 1994), boulder vanes (Rosgen, 1998) or bendway weirs (Davinroy & Redington, 1996, Derrick, 1996, and COE, 1993).

This Technical Note is available online at:

http://www.or.nrcs.usda.gov/technical/eng-notes.html

Also available online is the updated Table of Contents. It may be found at:

ftp://ftp-fc.sc.egov.usda.gov/OR/Technical_Notes/Engineering/Engineering_Table_of_Contents.pdf

Filing Instructions: Replace the Table of Contents and Engineering Technical Note 23 with the updated version, in the Engineering section of your Technical Note binder.

David R. Dishman, P.E.
Leader - Implementation

DIST:
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Engineers and Technicians
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TECHNICAL NOTE 23

U.S. DEPARTMENT OF AGRICULTURE NATURAL RESOURCES CONSERVATION SERVICE
PORTLAND, OREGON April 2005

Design of Stream Barbs

Version 2.0

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BACKGROUND

Stream barbs have been used by the Natural Resources Conservation Service (NRCS) in Oregon for river and stream bank protection since the late 1980s. Although stream barbs have been extensively used, limited documentation exists of long-term performance and specific design criteria. Oregon NRCS previously provided design guidance, which resulted in Version 1.3 of this Technical Note. Since the release of that document, significant efforts have been made to document field performance of new projects and review literature on barbs and meander bend mechanics. This Technical Note represents the culmination of field monitoring performance data and contemporary research for river and stream barb applications.

DESCRIPTION

Barbs are used for streambank stabilization, erosion mitigation and fisheries habitat improvement in meandering, alluvial river systems. Barbs are constructed from a variety of materials that constitute a series of upstream-directed structures (facing flow) located on the outside of a meander bend.

Barbs transfer erosive velocity away from the stream bank through interruption of helicoidal currents and cross-stream flow that develop within the meander bend. This redistribution of hydraulic forces controls the location of the thalweg (location of maximum bed shear) to a position away from the project bank. Barb systems that function correctly meet stream bank stability and habitat goals without transferring excess energy out of the project reach. Most importantly, barbs are able to meet multiple project objectives without causing unanticipated impacts downstream.

Geomorphic Setting

Barbs are effective for controlling tractive stress induced erosion on the outside of meander bends in lower gradient alluvial river systems. These rivers are generally lowland meandering systems with cobble or gravel beds positioned within valley bottoms adjacent to broad floodplains. Appropriate channel morphology for barb applications are generally C3 and C4 stream types (Rosgen, 1994) that consist of the following parameters: width to depth ratio greater than 12, channel slope less than 2%, sinuosity greater than 1.2, and cobble or gravel streambed substrate.

The use of barbs is not necessarily constrained by these values or channel types, but this criteria should be used as a general guideline for identifying appropriate river systems. The width to depth ratio exerts an important influence on the pattern of flow in meander bends (Knighton, 1998). Barbs are not recommended for narrow, deep channels (w/d <10), where bars are less likely to form and near bed flows move inward reducing near bank stress. When the ratio is relatively large (w/d >10), point bar development is more extensive, potentially leading to meander migration, bank erosion and the suitability of barbs as a stabilization option.

Vertical stability of the project reach should be evaluated using standard fluvial geomorphic protocols to identify active aggradation or channel incision. If the channel is experiencing active deposition and aggradation of the streambed, barbs may be used to reduce the width-depth ratio and increase sediment transport competence. Note that aggrading streams often experience significant plan-form instability and may result in a braided (D stream type) channel. Entrenched or incised channels will require a different treatment alternative, such as full-span rock weirs, as barbs will only mitigate lateral erosion.

The use of barbs is also evaluated within the proper context of the larger geomorphic setting. To improve the likelihood of barb performance and success, barbs should be located near the outside of the historical meander migration corridor. This reduces the risk of unforeseen large-scale river changes and potential flanking of the structures. The migration corridor will often correspond to the meander belt width in C stream types as illustrated in Figure 1.

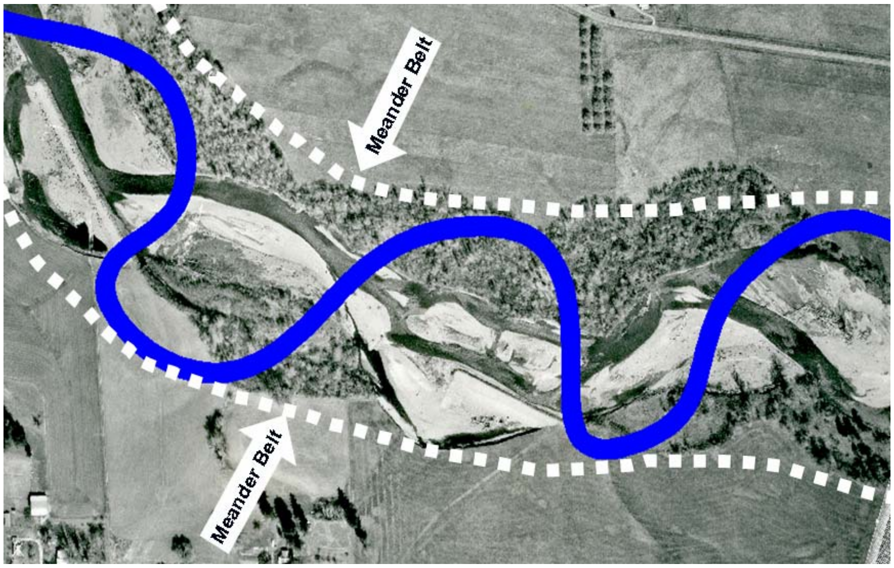

Figure 1. Historic meander migration limits.

Hydrology

Meander geometry and channel characteristics are not related to a single dominant discharge (e.g., 100-year flood) but to a range of flows, whose sediment transport competence varies with the channel's boundary materials. A surrogate for this range of flows is the channel forming flow (CFF) or dominant discharge that is defined as a frequent, moderate magnitude discharge that transports the greatest amount of sediment over a long period of time and maintains the average morphologic characteristics of the channel. Bankfull discharge is often used synonymously for CFF and refers to the discharge where water begins to flow out of bank (in non-incised channels) and onto the floodplain. The bankfull stage generally coincides with the regulatory interpretation of "ordinary high water."

Meander Hydraulics

The magnitude of hydraulic forces are affected by the degree of curvature of the meander bend and the channel width. Knighton (1998) identifies a consistent relationship between meander parameters and channel width (w) where the latter operates as a scale variable of the channel system. The term "tortuosity" is introduced as an index of meander geometries effect on these forces and is defined as the radius of meander curvature (Rc) divided by the channel top width (Rc/w). The channel radius is measured through the meander bend along the thalweg and the width is taken as the water surface top width at bankfull stage in the uniform riffle section upstream of the meander. Tortuosity generally varies throughout the bend since natural meanders often exhibit compound bends rather than continuous curves as shown in Figure 2.

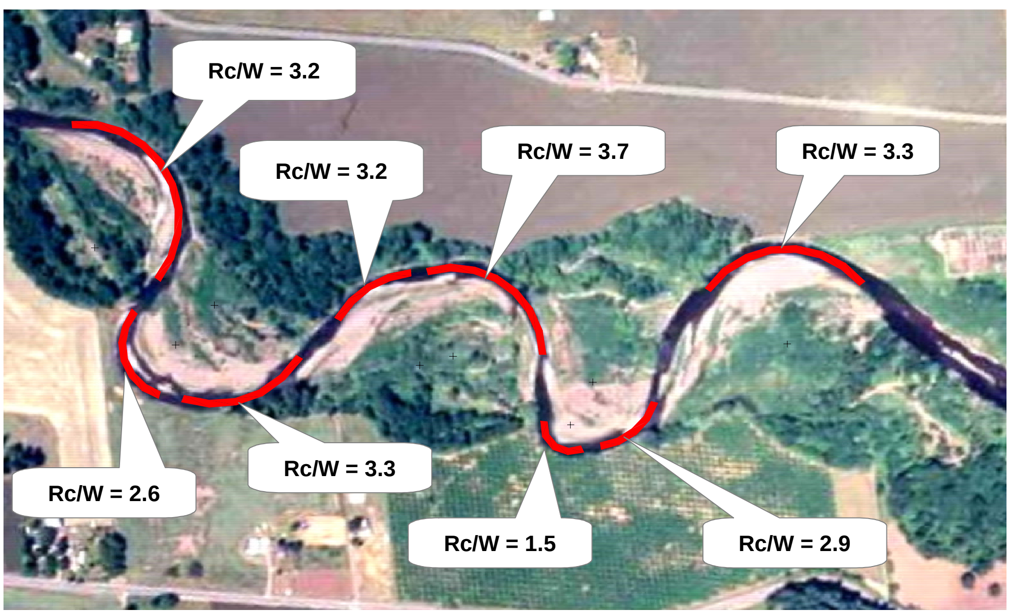

Figure 2. Examples of variable tortuosity through a river segment.

Chang (1988) identified the median value for tortuosity to be 3, which correlates well with the median value of 2.7 determined from measurements performed by Leopold et. al., (1964). Leopold also noted that the radius is often about 2.3 times the channel width. Chang states that because this ratio results from using conditions of minimum stream power, it represents the maximum curvature for which a river does the least work in turning. Additional research by Williams (1986) identified 42% of tortuosity ratios ranging between two and three with a corresponding mean of 2.43 for his data set. Henderson (1966) suggests that "values of the Rc/w (tortuosity) ratio are found to be as small as 1.5 and as large as 10; but the median value occurs in the range 2 to 3, and it is within that range that the river engineer should look when planning to simulate natural meanders in river training works".

Barbs are designed to influence meander bend hydraulic forces caused by water flowing against an irregular channel boundary. The primary hydraulic flow components accounted for in design are (1) longitudinal velocity, (2) helicoidal flow, and (3) cross-stream flow. Longitudinal velocity is the velocity vector component that parallels the channel boundary in the stream-wise direction and is relatively simple to understand. The more complex helicoidal flow and cross-stream flow are described in more detail below.

1. **Helicoidal Flow** - The transverse spiraling current directed towards the outer bank near the water surface and towards the inner bank (point bar) near the streambed to give a helicoidal circulation around the primary longitudinal downstream velocity component.
2. **Cross-stream Flow** - The maximum velocity and current that occurs as the thalweg swings from one bank to the other across the channel centerline (Chang, 1988).

Helicoidal Flow

Centrifugal acceleration acts outwardly on water as it flows through a meander bend and leads to a differential water surface elevation (superelevation). This results in a downward acting pressure gradient that is magnified by the degree of curvature and tortuosity of the meander. The combination of this superelevation induced pressure gradient and the main downstream velocity component are major factors affecting the spiraling circulation referred to as helicoidal flow.

Helicoidal flow revolves around the primary stream-wise component of discharge (and velocity) with rotational flow behavior as shown in Figure 3. The section views within this figure illustrate the velocity vector orientations relative to change in morphologic form through the stream reach.

The pool sections below illustrate the fully developed helicoidal flow that results in significant near-bank shear stress, the primary force affecting stream bank erosion.

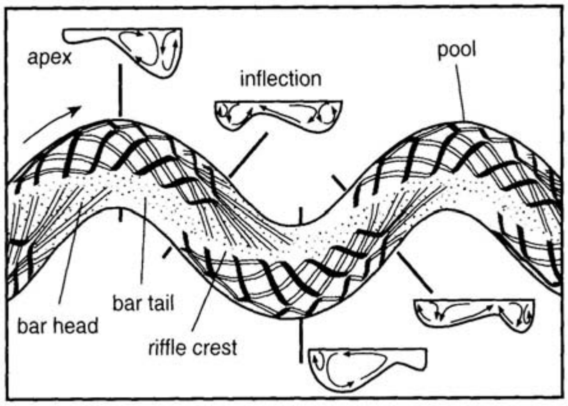

Figure 3. Helicoidal flow through a series of meander bends (*Knighton, 1998).*

The strength of the helicoidal flow and the potential for bank erosion increases as the tortuosity ratio lowers. Field data and project monitoring have identified helicoidal flow as the primary design consideration in meanders with tortuosity ratios greater than three. For tortuosity ratios less than three, helicoidal flow is a primary factor as is cross-stream flow which is described below.

Cross-Stream Flow

When tortuosity ratios are three or less, the primary component of longitudinal velocity impacts the outer stream bank at a very abrupt angle. The resulting momentum transfer of the fluid mass directly into the streambank and the work the bank performs in turning the flow may result in significant bank erosion. The impact of fluid mass into the streambank within tight meander bends is termed cross-stream flow and results from the angular difference between the discharge centerline (thalweg) and channel centerline and occurs as the primary longitudinal velocity shifts from one bank to the other (Figure 4).

Tortuosity >3 **Tortuosity <3**

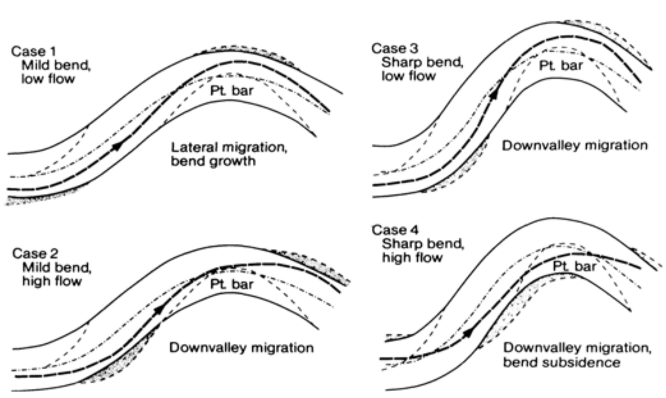

Figure 4. Cross-stream flow as a function of tortuosity (*Chang, 1988).*

Bathurst et. al. (1979) found that at intermediate discharges helicoidal flow is relatively strong, but at high discharges (greater than bankfull) the effects of the primary (cross-stream) flow becomes dominant as the main flow follows a straighter path. Thorne (personal communication 2005) suggests that the most pronounced effects of cross-stream flow occur between an intermediate flow and flood discharge. It is critical that the design engineer account for the effects of cross-stream flow in addition to the amplified magnitude of helicoidal flow in meanders with tortuosity less than three. For design, this requires tighter barb spacing through the meander bend, tighter barb angles relative to the bank-line and potentially large-scale roughness elements (such as large wood) placed between the barbs.

The magnitude of hydraulic forces depends on the tortuosity of the meander bend and is summarized in the following table:

HYDRAULIC FORCE	RELATIONSHIP TO TORTUOSITY
Helicoidal Flow	Principle force considered with Rc/w > 3 Magnitude increases as Tortuosity decreases
Cross-stream Flow	Critical consideration for Rc/w < 3 Magnitude increases as Tortuosity decreases

Hydraulic Effects on Meander Bend Erosion

Hydraulic forces are highest near the outside bank with maximum shear generally occurring near the bend exit. This often results in the highest rates of erosion concentrated against the outer bank, downstream of the bend apex. Across the channel along the opposite bank, point-bar building occurs with sediment and bed material supplied by both primary longitudinal and helicoidal currents, a process that results in a downvalley tendency to meander migration.

Chow (1959) noted that the downstream portion of the meander bend should be the first area considered in bank protection and Klingeman et. al., (1984) found that, in general, the place where bank erosion is most frequent and where streambank protective measures most commonly fail is just downstream from the axis of the bend. These observations agree with Leopold's (1964) discussion of the zone of maximum boundary shear stress close to the outer bank beyond the bend apex in the lower third of the meander.

Barb Hydraulics

Barbs influence near bank velocity and shear stress distribution through disruption of helicoidal currents and partial interception of cross-stream flow. Control of these hydraulic forces results in the redistribution of energy from the near-bank region to the center of the channel. Flow across the barb occurs somewhat normal to the longitudinal axis of each structure and intersects the contraction-accelerated discharge at each barb end. The convergence of these flow components results in energy dissipation through turbulent flow mixing and forces the resultant vector flow direction away from the protected bank as shown in Figure 5.

Figure 5. Turbulent zone at intersection of cross-structure flow and contraction accelerated flow at 75% bankfull discharge.

Effective barb design results in a structure induced zone of subcritical flow upstream and along the protected stream bank. Head (potential energy) increases in the zone upstream of the barb through the backwater effect described by Chow (1959). This is an important design concept in that each structure effectively backwaters a zone upstream to the next barb location. The upstream progression of subcritical reaches in the near-bank region controls erosion and ultimately leads to deposition of sediments along the protected bank-line as illustrated in Figures 6 and 7.

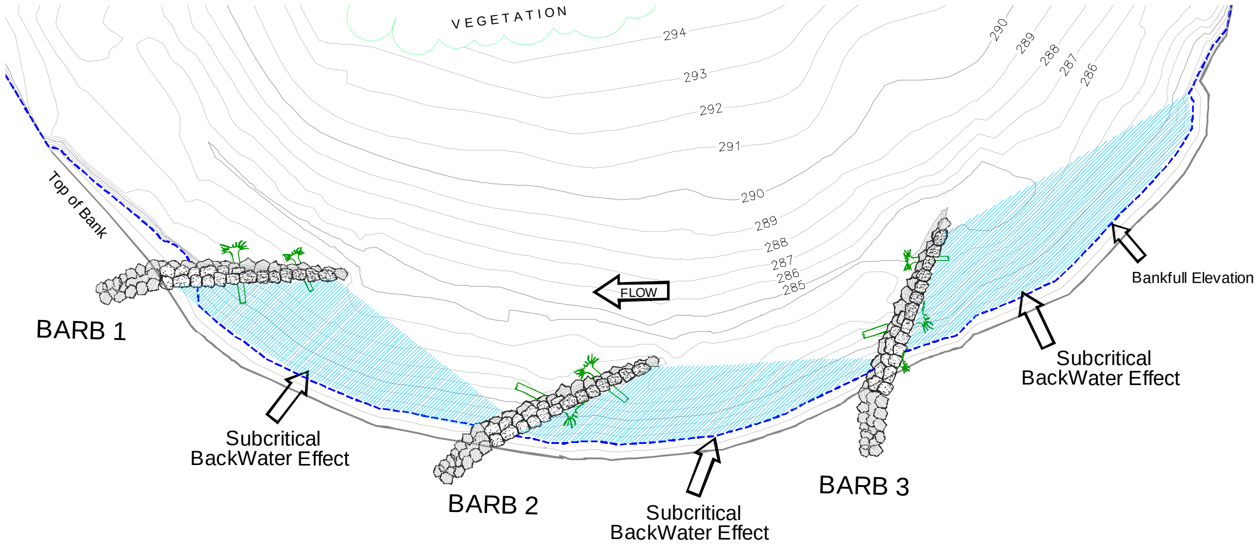

Figure 6. Upstream progression of subcritical backwater reaches.

The sloping weir crest of each barb results in a stage-progressive hydraulic effect along the longitudinal axis of the structure. Critical depth occurs immediately upstream of the barb weir crest and a supercritical flow transition occurs across the structure. This results in a hydraulic jump that is influenced by the downstream tailwater elevation (Case III Condition, Chow, 1959). The hydraulic jump provides energy dissipation through the transition of potential energy (increased upstream head) to kinetic energy (supercritical velocity) across each structure for increasing stages and discharge.

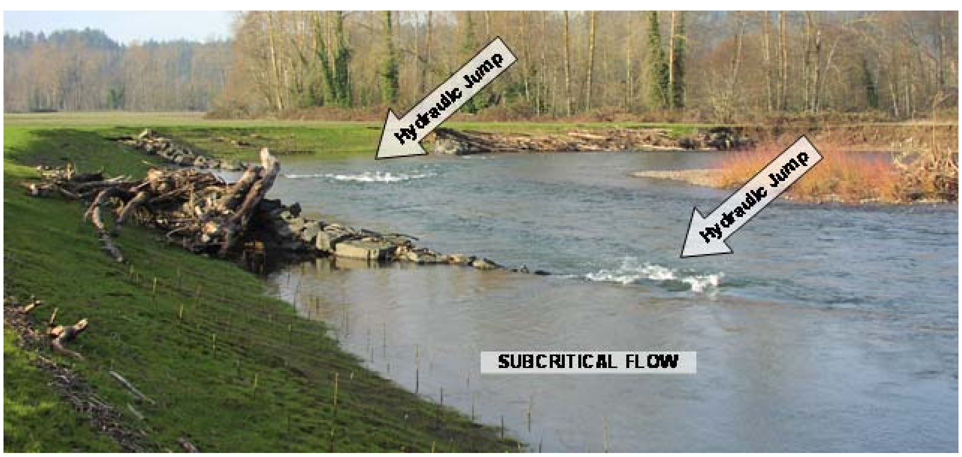

Figure 7. Hydraulic effects across and upstream of stream barbs at intermediate discharge.

Flow leaving the meander bend is an important factor in locating the first structure. The first barb is placed to transition flow leaving the meander into the downstream receiving riffle. Velocity distributions within riffle sections are generally uniform with the highest velocity located near the channel centerline. Positioning of the first barb maintains this natural velocity distribution and prevents adverse affects on downstream streambanks.

Bed Scour and Sediment Transport

Barb induced energy re-distribution away from the outer bank towards the center of the channel results in scour near the ends of the barbs and realignment of the thalweg. Based on field observations and laboratory results, Johnson, et. al., (2001), Matsuura and Townsend, (2004), Klingeman et. al., (1984), Kuhnle et. al., (2001) the greatest scour depths occur at the barb end and immediately downstream of the structure. This scour results from contraction flow acceleration by a local reduction of the width-depth ratio, a structure induced hydraulic jump and turbulence generated from flow mixing. The process aligns the channel thalweg away from the stream bank to a position near the outer quarter to end of the barb as shown in Figure 8. The result is a barb design that re-distributes available energy within the project reach and does not transfer it downstream. The increased velocities mobilize bed material that transfers immediately downstream of the barb and/or to the receiving riffle. The resulting scour hole reduces the channel width to depth ratio and increases pool habitat.

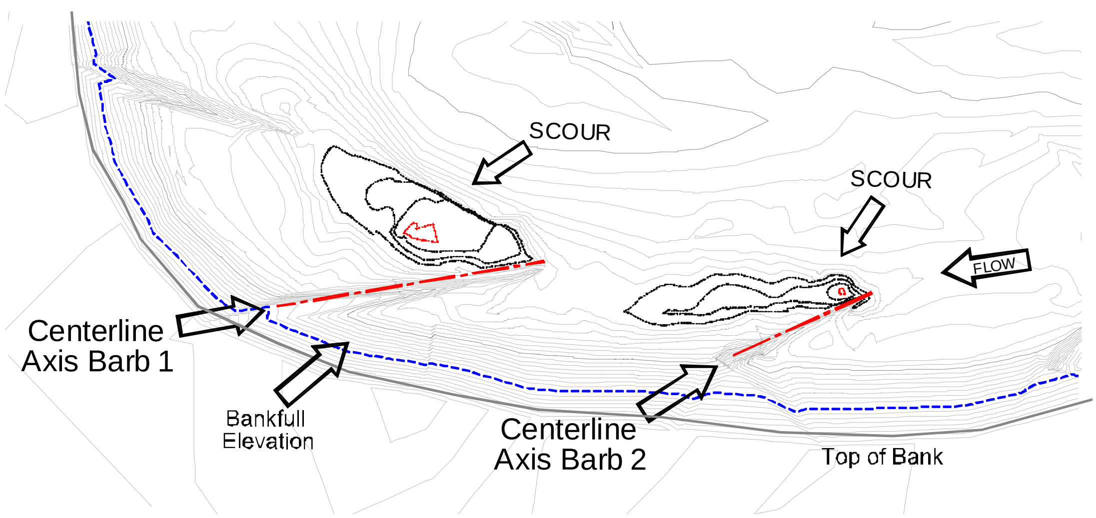

Figure 8. Scour effects at the end of barbs (half-foot contour interval).

A reduction in near bank velocity gradients through the subcritical backwater effect promotes sediment deposition upstream of the barb structures. The quiescent flow condition allows bedload and fine sediments to fall out of suspension resulting in deposition in the near-bank region. Many successful barb projects have been implemented, providing hydraulic control as designed, then transitioning over time to increased roughness through the propagation of riparian vegetation on the fine sediments that accumulate upstream of the structures. In time several projects have become nearly indistinguishable through this process as the design hydraulic influence of the structures is reduced to large-scale roughness effects of the propagated vegetation species.

Habitat Effects

Erosion and sediment input is a natural process necessary to supply gravels and add complexity to streams. However, meanders that are "overextended" with unstable width to depth ratios can have a detrimental effect on habitat by creating shallow water depths, increased ambient turbidity and increased water temperatures. Streambank stabilization in the agricultural setting typically involves an eroding bank that has little or no riparian buffer due to farming practices. As a result, erosion advances at an accelerated rate with little resistance from natural vegetation.

Barbs are an effective measure for stabilization of eroding banks that create unnatural sediment supplies and high levels of ambient turbidity. Complexity in habitat is important for aquatic species because it provides cover, shelter, food resources, and increases species interaction. Barbs provide habitat diversity and create holding (refugia) locations for aquatic species during high and low flows. Velocity shelter areas are generated during high flows and the scour pools below the end of each structure provide low flow habitat. Control of near-bank velocities allows bioengineering methods, including planting with native plants and trees, to be installed and provide wildlife and aquatic habitat enhancements such as food and cover. Barbs that incorporate large wood add additional complexity and aquatic habitat benefits by providing in-stream cover for fish and food for aquatic invertebrates. Monitoring of projects throughout the Pacific Northwest has found that there are higher fish densities at projects incorporating large wood than without large wood (Peters, 2003).

Figure 9. Large wood placement within barb section.

DESIGN RECOMMENDATIONS

This section contains recommendations and guidelines to assist with the design of barbs for bank stabilization and habitat enhancement and is based on historic performance monitoring of installed projects as well as published research. These guidelines are not a substitute for engineering judgment where site-specific conditions may require deviations. It is also assumed that a detailed geomorphic and historic channel analysis have been done to warrant the use of barbs as a streambank stabilization alternative.

Site Information

Preliminary information and data that will be collected includes historical and current aerial photography, soils information, survey benchmark coordinates, stream gage data and endangered species information. The design engineer will stratify the erosion mechanism as either a tractive stress or geotechnical slope failure with the latter case requiring a bank stabilization treatment other than barbs. A topographic survey is performed of the project reach extending from the upstream riffle, through the project meander, to the downstream riffle. The survey should include all grade breaks and geomorphic features within bankfull stage such as bank lines, thalweg, point bar geometry and vegetation lines. In addition, the survey should capture floodplain features to enable accurate modeling in HEC-RAS.

Hydraulic Analysis

A hydraulic analysis is performed to identify bankfull water surface elevations and profiles within the project reach. This analysis is based on cross-sections taken from reach topographic surveys and imported into HEC-RAS. Discharge is obtained from USGS regional regression equations or statistical analysis of stream gage annual peaks (preferably from the river under consideration or a regional evaluation can be performed). Bankfull stage is obtained by modeling the one to two year peak discharge water surface profiles and correlating them to significant morphologic features. Bankfull field indicators include debris drift lines, bank scour lines, breaks in vegetation and the top of the point bar at the inside of the meander bend.

Once bankfull discharge is determined and the HEC-RAS model calibrates with field indicators, additional discharges (up to the 100-year event) are analyzed to determine stage-velocity relationships. Velocity will generally increase up to bankfull stage at which point overbank flooding across the point bar occurs. At bankfull stage, a large increase in wetted perimeter occurs for a small increase in area which results in a reduction of the hydraulic radius.

Figure 10 defines the geometric variables associated with stream barbs. The following sections contain specific guidance on barb design including desired thalweg location, barb position, horizontal angle, barb length and spacing. Several iterations should be performed to gain familiarity with the geometric constraints and potential alternatives as there are several possible successful solutions. Developed alternatives should be taken to the project site and evaluated for "fit" with further design iterations performed as necessary.

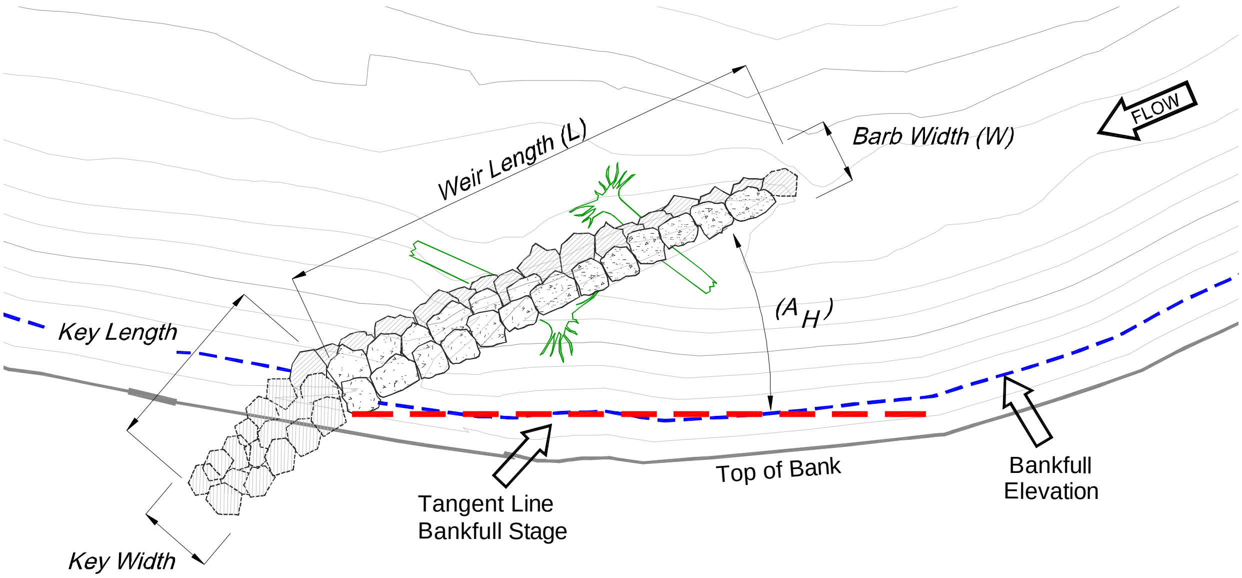

Figure 10. Barb definition diagram.

Location & Spacing

Barbs are generally located as a series of two or more structures on the outside bank of meander bends. The barb array begins with placement of the first structure at the downstream end of the project site with spacing of subsequent structures proceeding upstream to the beginning of erosion or project terminus. The following steps aid in locating the first barb:

1. Place the first barb in the downstream quarter of the meander bend or near the downstream end of erosion and streambank instability.

2. The hydraulic influence of the first barb should transition flow into the downstream channel and receiving riffle. To aid in locating this barb, establish a line of projection through the centerline axis of the downstream riffle and extend upstream to the point of intersection with the project meander as illustrated in Figure 11. The first barb (keyed at a position in the bank near the end of erosion) should intersect this riffle centerline projection near the middle to end of barb.

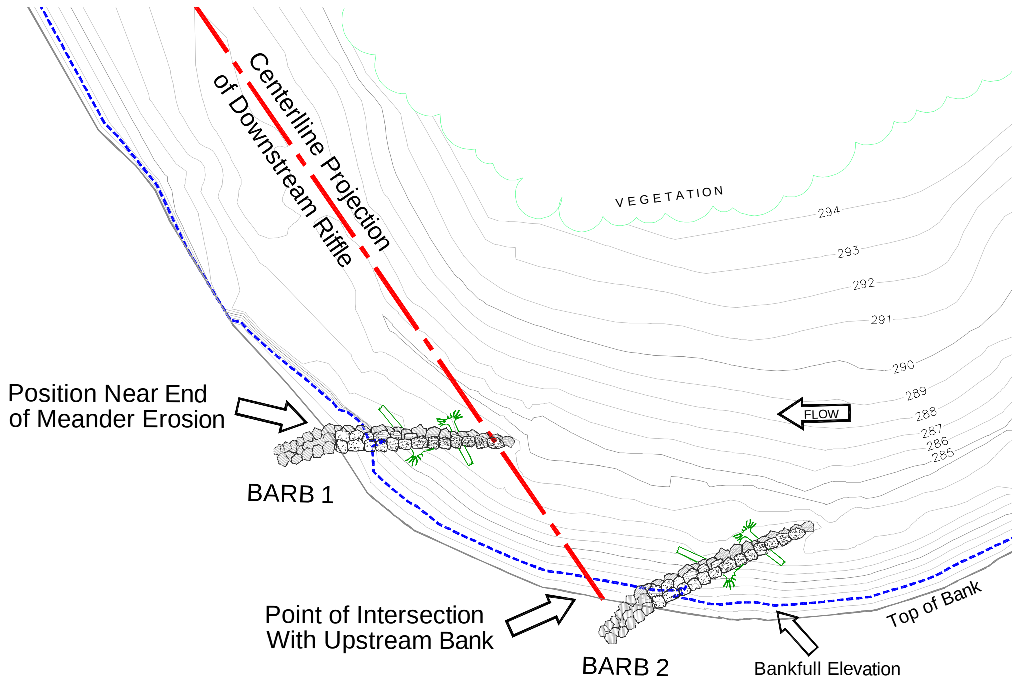

Figure 11. Location of Barb 1.

3. The position of the first barb is also dependent on the horizontal angle (**A_H**) of the barb as referenced to the tangent line of the bank and weir length (**L**). It is critical that **A_H** not exceed 25° for tortuosity ratios less than three due to the potential for splitting of cross-stream flow, a condition that results in a strong upstream back-eddy that may erode the bank. Positioning recommendations described in Step 1 may require adjustment to maintain the recommended angle and intercept of the downstream riffle line of projection.

4. Spacing is dependent on meander tortuosity, weir length (**L**) and horizontal angle (**A_H**). Once the first barb is located, draw a tangent line (with the upstream bank) at the bankfull elevation. Translate this line out to the end of the barb and extend it upstream to a point of intersection with the upstream bank. The point of intersection of this line with the bankfull elevation is an approximate location where Barb 2 should key into the bank. This represents the maximum spacing and should generally be used for tortuosity greater than three. Tighter spacing is advised when tortuosity is less than three with spacing performed by the same process as above, except for translation of the bank tangent line to the mid point of the barb rather than the end. Repeat this process working upstream as illustrated in Figure 12.

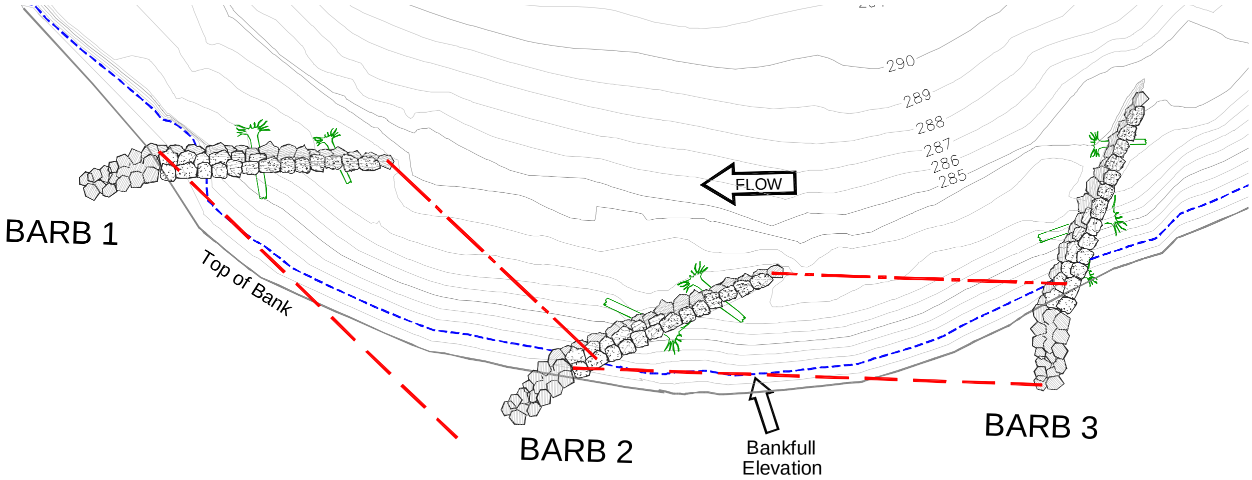

Figure 12. Example of barb spacing methodology.

Earlier design guidance recommended vector analysis for barb spacing. While this method correctly identifies the direction of cross-structure flow, it is not appropriate for barb spacing (particularly for tortuosity < 3). The method results in barbs with either excessive spacing or a large horizontal angle that potentially captures too much cross-stream flow, a condition that creates back-eddies and erosion upstream of each structure.

Length

Aerial photo analysis, survey information, and field investigations are used to identify ranges of stable tortuosity ratios and target radii of curvature for the project reach. A curve is placed through the meander bend representing the proposed thalweg location. Each barb extends from the bank-line to the proposed thalweg curve at the design horizontal angle ($\mathbf{A_H}$). This process generally involves some iteration with the understanding that an increase in meander radius increases the tortuosity ratio and decreases the magnitude of helicoidal and cross-stream flow. Barb layout often results in a range of lengths that should not exceed 1/3 the cross-section top width at bankfull stage. The key extends into the bank from 1/4 to 1/3 of the barb length to protect the structure from flanking, a common mode of failure. Lower tortuosity ratios (<3) may require longer key lengths for additional protection, depending on soil types.

Horizontal Angle (A_H)

$\mathbf{A_H}$ is the angle between the tangent line placed along the upstream bank (at bankfull stage) and the centerline of the longitudinal axis of the barb (Figure 10). Recommendations for this angle have varied throughout the development of barbs from 30° to 60°; however, field observations of failed structures and performance monitoring of successful projects warrants a reduction of horizontal angle recommendations. Based on field monitoring of successful sites and published research the optimal angle for stream barbs is between 20º to 30º. When tortuosity is less than three, it is critical $\mathbf{A_H}$ not exceed 25º or the barb can capture to high a proportion of the cross-stream flow, a condition that results in a strong back-eddies upstream of the structure.

Width

The barb weir crest must fully develop critical flow near the leading edge of the structure for energy dissipation through a hydraulic jump. Therefore, the barb should approximate a broad-crested weir where the exposed weir top width (not including the footer) varies between one to three times the d_{100}. This is important considering likely impacts from large wood, ice and other material against the structure.

The barb width (**W**) is typically narrow at the end (width = d_{100}) and progressively widens to the structures intersection with the bank. The key maintains this width into the bank as shown in Figure 10. The total section width is somewhat wider considering the material available and the width of the footer combined with the weir. This combined width will be a function of the streamwise imbrication of the structure where the footer provides foundation support for the weir rock and is set to provide resistance to overturning and downstream translation. Regulatory agencies typically require integration of large wood within barbs. The weir width may need adjustment to provide adequate ballast for the recommended buoyancy safety factor of 1.5. for the large wood.

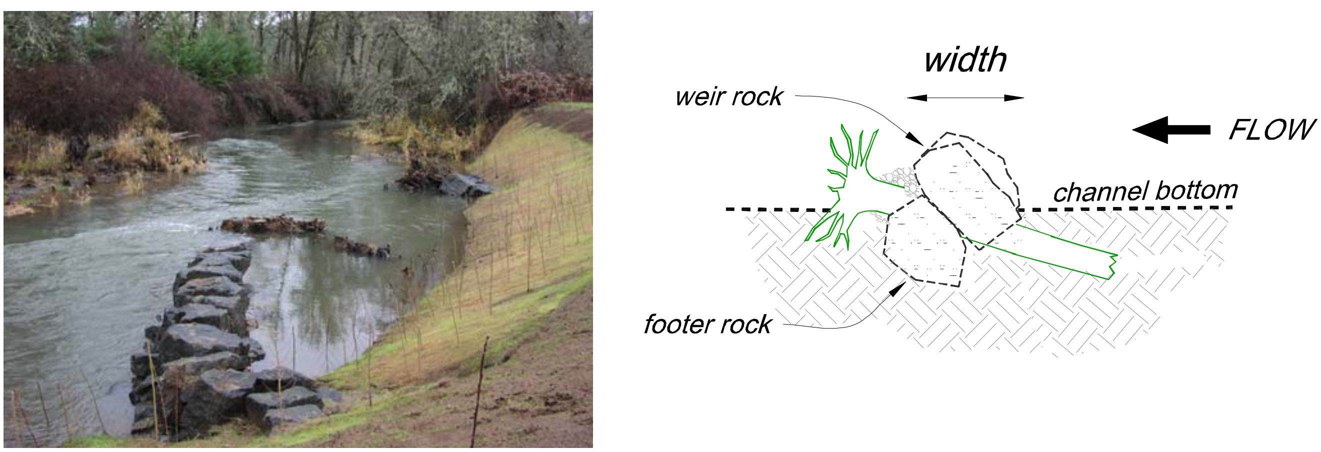

Figure 13. Section views illustrating barb width.

Barb Slope & Height

The bankfull stage obtained from the reach hydraulic analysis is used to set the structure height for each barb through the project reach. The top of the barb is set at bankfull stage and the key extends into the bank at this elevation as illustrated in Figure 14. The end of each structure is set at the proposed thalweg location established by the spacing criteria. At a minimum, a d_{100} rock is set into the streambed at the barb tip. This is where the largest scour will occur, therefore, if the d_{100} does not extend below the calculated scour depth or 2.5 times the exposed height of the rock above the streambed (whichever is greater), footer rocks will be required. Calculated scour depths should be field verified by observing scour around nearby logs, bridge abutments, and similar hydraulic elements.

Weir slope is calculated by the difference in elevation from the barb end and the bankfull elevation divided by the weir length (Figure 14). The constant slope range that exerts the maximum energy dissipation and progressive hydraulic effect is between 5% to 8% or 1 foot vertical to 15 feet horizontal. As stage and velocity increase, the sloping crest controls the hydraulic jump and the subcritical zone upstream of the structure.

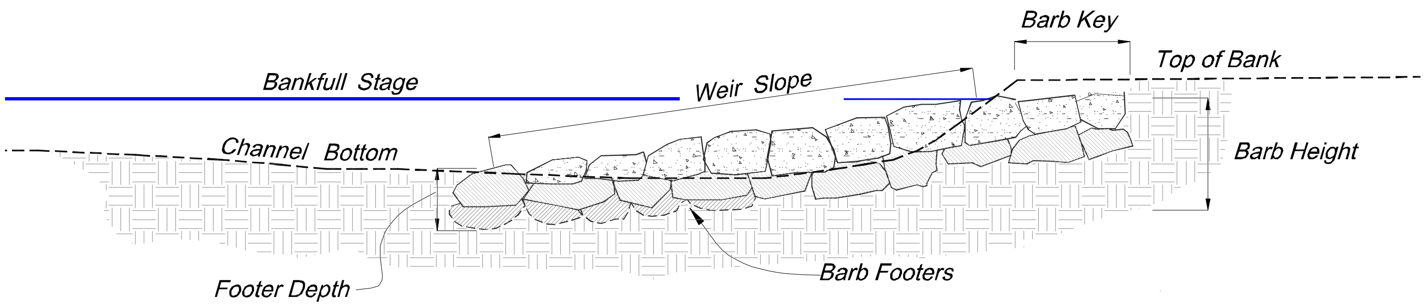

Figure 14. Barb profile looking downstream.

Barb Rock Sizing

Barbs are usually constructed in one of two ways depending on availability of rock, site access, localized construction practices, and machinery. One method is to construct the barb section using successively rising graded layers of rocks that are built on top of each other with the d_{100} usually less than 24 inches as illustrated in Figure 15. References for determining the gradation of rock using this method are found in NRCS Minnesota Technical Release 3, “Loose Riprap Protection” or The Corp of Engineers, EM 1110-2-1601, “Hydraulic Design of Flood Control Channels”.

The other method utilizes relatively large rock (usually greater than 36 inches) elements to construct the barb and gaps are filled with small rock as necessary to make the structure impervious as illustrated in Figure 15. Large rock is generally preferred for ease of construction and resistance to displacement. Imbrication of the weir elements should be in the downstream direction against the footer to resist downstream translation. Material should be sound, dense, and free from cracks, seams or other defects that could increase susceptibility to deterioration or fracture. The incorporation of large wood will require that ballast considerations be accounted for in the rock sizing computations.

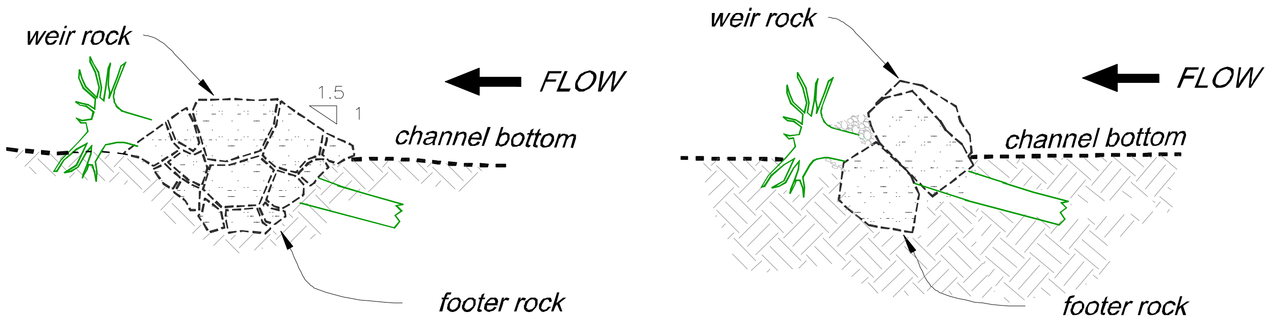

Figure 15. Barb section view using graded material (left) and large elements (right).

Several methods have been used for design of barb rock elements including the Far West States-Lane method; however, it is recommended that a physics based threshold stability analysis be utilized for determining the minimum size of the weir and footer rock. The project reach HEC-RAS model is used to identify the maximum anticipated velocities which are used in solution of the following equations. Figure 16 is a free-body diagram (FBD) of a boulder resting on the streambed. The FBD is of an isolated rock that does not account for streambed slope, as the sine component of the body force is insignificant. This analysis represents a conservative scenario as lateral anchoring and shielding of surrounding boulders provide for an additional factor of safety. A threshold stability analysis is carried out for two modes of failure: (1) sliding and (2) overturning or moment stability of the boulder element.

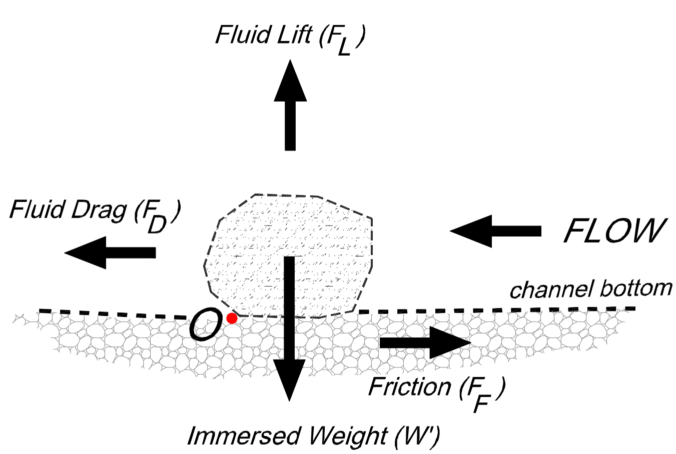

Figure 16. Free body diagram of immersed rock.

1. Sliding Analysis:

   Sum of the forces in the x-direction yields the following equations:

$$\sum F_x = 0 = F_D - F_F$$ **Equation 1**

where

$$F_D = C_D \cdot A \cdot \rho_w \cdot \frac{v^2}{2}$$ **Equation 2**

and

$$F_F = (W' - F_L) \cdot f = [(V_{boulder} \cdot \rho_w \cdot g \cdot (S_b - 1)) - 0.85 \cdot F_D] \cdot f$$ **Equation 3**

C_D = 0.3 to 0.5 although can be as high as 2.0 for partially submerged rocks
A = Projection of exposed rock area to hydraulic force(ft^2)
v = Maximum instantaneous stream velocity (fps)
g = 32.2 ft / s^2
S_b = Specific gravity of boulder (typically 2.65)
f = Friction factor[1]
V = Boulder Volume ft^3
F_L = 0.85* F_D based on work by Chepil, 1958.

[1] *The friction factor is taken as the tangent of the friction angle of the boulder on the streambed. Based on graphs in the Bureau of Reclamation's Earth Manual (1999), this factor is generally greater than 0.80 for rocks greater than 3 inches and is often predicted by taking the tangent of the angle of repose for the material in question.*

2. Moment Stability Analysis:

   Assume the resultant fluid force acts through the centroid of the boulder and sum the moments about point "O" to eliminate the friction force:

$$\sum M_O = 0 = (W' - F_D - F_L) \cdot \frac{D}{2}$$ **Equation 4**

These equations are easily solved using a spreadsheet to determine stable rock sizes for a given maximum velocity. The design engineer should employ this method with reference to site specific circumstances and evaluate the sensitivity of the various coefficients to ensure adequate factors of safety are achieved with the design. At a minimum, a factor of safety of 1.5 should be used for resisting translation and rotation of the element.

An additional method is proposed by Julien (2004) which suggests a simplified analysis for incipient motion considering fully turbulent flow over a rough horizontal surface with the boulder fully immersed. This method is used as an additional check against results obtained using the preceding procedure.

$$d_s = \frac{21 \cdot y \cdot S_f}{S_b - 1}$$ **Equation 5**

where

d_s = minimum boulder diameter (ft)
y = flow depth at bankfull (ft)
S_f = friction slope (ft/ft)
S_b = specific gravity of boulder (2.65 typically)

Scour

Barb generated hydraulic forces transferred to the streambed generate a downstream scour hole that results in energy expenditure within the immediate project reach. The estimation of scour depth controls the placement of barb footer rocks below the streambed to prevent structure failure due to undermining. Scour equations are typically based on empirical laboratory experiments; hence, it is recommended the results of the presented equation be field substantiated by observing scour around nearby logs, bridge abutments, and similar hydraulic elements. The Bureau of Reclamation's Design of Small Dams identifies the Veronese equation to determine ultimate scour depth that will stabilize irrespective of material size.

$$d_s = 1.32 \cdot H_t^{0.225} \cdot q^{0.54}$$ **Equation 6**

d_s = maximum depth of scour below the tailwater elevation (ft)
H_t = Hydraulic head differential between headwater and tailwater (ft)
q = unit discharge per length of weir (cfs/ft)

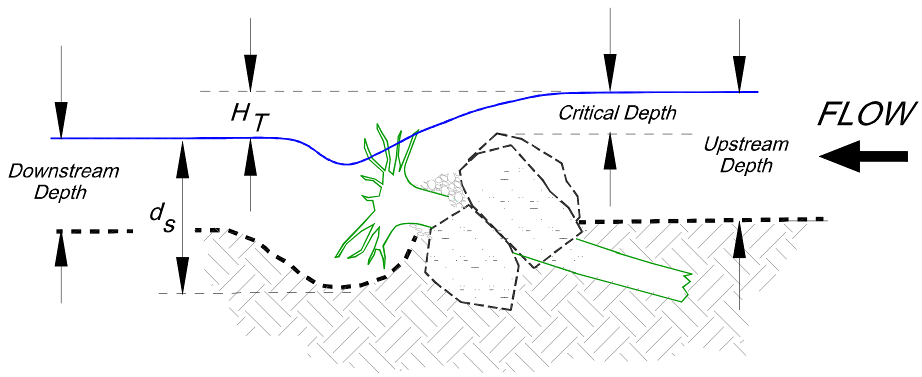

Figure 17. Bed scour immediately downstream of barb.

The equation typically yields conservative results which become more appropriate as the tortuosity decreases and the meander hydraulic forces increase. As a rule, the footer rock should be placed a minimum of the d_{100} into the streambed or 2.5 times the exposed height of the rock, whichever is greater.

Common Failure Modes

Barbs have been installed throughout the United States with limited or no guidance. As a result, several failures have occurred that could have been avoided. Based on field observations, the following table summarizes these common modes of failure.

Failure Mechanism	Typical Cause of Failure
Flanking of Barb	Horizontal Angle too large, key length too short, spacing between barbs too large.
Structure Undermined Downstream	Footer rock depth too shallow.
Erosion Between Barbs	Barb spacing too great, horizontal angle too large, capture of-stream flow causing back-eddy.
Rock Displacement	Poor construction techniques resulting in weir rocks that are not locked in together.

Bank Shaping

Vertical banks on the outside of meander bends are inherently unstable and susceptible to undercutting and geotechnical failure. Once in an unstable position, the bank may continue to erode due to toe scour, mass block failure, and rapid drawdown/saturation. Barbs reduce toe scour and velocity induced erosion; however, barbs do not address bank failure due to soil instability and drawdown/saturation. Barb projects should incorporate bank shaping and vegetative practices to address these additional failure mechanisms.

Bank shaping begins at the toe of the vertical bank and extends away from the stream at the optimal slope of 3 horizontal units to 1 vertical (3H:1V) or flatter. This provides a stable slope and an adequate surface for vegetative planting and maintenance. Steeper slopes, such as 2H:1V, can be used but are difficult to access for planting vegetation and placing erosion control blankets.

Erosion control blankets should be installed on banks immediately after shaping and prior to high flows. Erosion blankets typically consist of decomposable materials such as coir (coconut husks) or straw.   Due to the large number of manufacturer's of erosion blankets, a performance specification should be used to specify the blanket that includes maximum shear stress and permissible velocities as well as longevity of material. When installing erosion control blankets, ensure adequate anchorage of the blanket ends into the streambank.

Vegetative Planting

Barbs reduce near-bank shear stress and velocity by redistribution of hydraulic energy away from the bank. The use of barbs for streambank stabilization should include bioengineering and vegetative practices. Vegetation provides additional roughness to dissipate energy along the streambank and enhances wildlife habitat and water quality. Willows are the most common vegetation used to enhance streambank stabilization projects. There are several ways to plant willows; however, the most effective is by installing willow clumps with a trackhoe. This is achieved by digging up entire willow plants with roots intact and planting in prepared holes along the streambank. There are several advantages to this technique including increased plant survival rate, quicker establishment of roughness, and greater energy dissipation in the near-bank region. A complete explanation of the procedures and techniques is available in NRCS Technical Note 42 (Plant Materials).

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