ANCHORING AND PLACEMENT OF LARGE WOOD APPENDIX

1 INTRODUCTION

This appendix describes methods and design considerations for anchoring wood in waterways, including passive anchors, flexible anchors, and rigid anchors. Structures made of single or multiple pieces of large wood, boulders and other materials are commonly used in streams and rivers as habitat features, fish-passage structures and bed- and channel-stabilization features. The use of large wood can play a crucial role in habitat formation when used alone or in combination with other techniques to create natural channels and enhance bank protection projects. Properly placed and anchored large wood can assist in providing reliable bank protection as well as enhance the structural and hydraulic complexity of the channel. In contrast, poorly placed, inadequately sized, or improperly anchored large wood has a high probability of becoming dislodged during high flows, possibly resulting in failure of project objectives and potential impacts to downstream infrastructure and habitat. As discussed elsewhere in this document, disturbance plays a pivotal role in channel evolution and habitat productivity. In reference to bank protection, the movement of wood is undesirable, whereas restoration activities should accommodate and encourage disturbance where possible[1].

The selection of correctly sized large wood is fundamental to the success of a project because it minimizes the need for anchoring, although stability is enhanced by proper placement and anchoring. Naturally stable wood is discussed in the *Large Wood and Log Jam* section of these guidelines. Complex placements that emulate natural conditions are best because they have the greatest flexibility in adapting to changing channel and flow conditions with long term stability[2]. Gravel ballast of similar size to what occurs naturally in the stream bed is the first anchoring option that should be considered, followed by other types of passive anchors, flexible anchors, and finally rigid anchors. As risks associated with large wood increase, more highly engineered solutions may be required.

Successful large wood projects have used many types and methods of anchoring. Site conditions, project objectives and economic constraints govern which types are used.

2 FORCES ON WOOD IN STREAMS

The design of anchoring systems should consider the balance of forces between (1) structure buoyancy and weight, and (2) drag forces and frictional resisting forces. Structure buoyancy and weight calculations are relatively straight forward, while drag and friction calculations are prone to error, due to varying shape and orientation, and the unpredictable potential for a structure to collect additional debris. In addition, partially buried logs extending into the current are often subjected to substantial oscillation and vibration, which are complex and difficult forces to calculate. These uncertainties in

predicting forces on structures in a river lead to the necessity for a substantial factor of safety in anchoring design. A minimum factor of safety of 2.0 is recommended for situations that present risk to life or infrastructure. Factors of safety as low as 1.0 may be appropriate for enhancement projects in remote areas. Professional judgment is necessary and public safety concerns, including boat use, should always be addressed in the application of instream projects.

The analysis of wood stability is in part dependant upon the type of project, ballasting or anchoring style, and the size and character of a stream. The type of project will influence the selection of a factor of safety and the level of analysis (high for urban streams with risk to infrastructure and low for enhancement projects in rural areas). The stability of natural wood is dependant on stream order[3], something that we should recognize in the

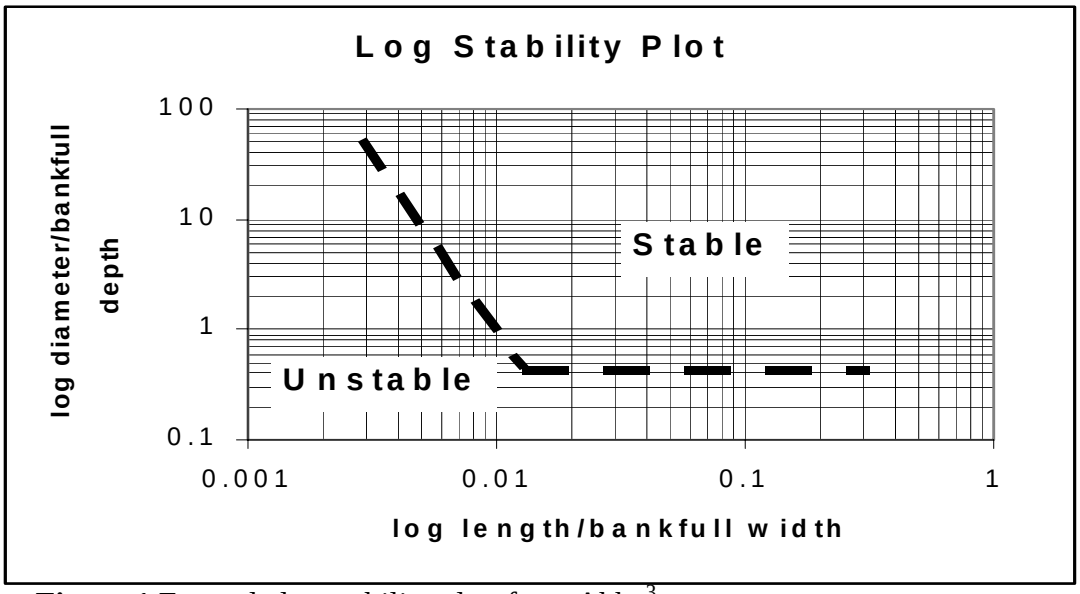

Figure 1 Example log stability plot, from Abbe[3].

design of large wood projects, especially in large rivers. In addition, an engineered approach to designing large wood projects implies a level of accuracy and predictive powers not commensurate with the materials and situation; we are working in a natural system that the simplified engineering discussed here only indirectly grasps.
For projects on major rivers, or those that involve the placement of a large number of pieces, an empirical approach used by Abbe[4] should be employed. Abbe surveyed and cataloged existing wood pieces at study sites, measuring size and channel geometry and determining stability. A dimensionless plot of log length/bankfull width vs. log diameter/bankfull depth was developed which differentiates stable and unstable zones (see **Figure 1**). Bankfull width and depth should be determined for the reach where natural, stable wood is measured. This simple relationship does not substitute for thorough stability analysis but will serve as a planning tool and will provide verification of results.

A complete analysis of forces on wood in streams can only be accomplished with

momentum and energy analysis in combination with flow studies. At present, too little is known of the various coefficients and the role of specific forces to justify such a detailed analysis. Designing and building instream structures with large wood is a rapidly evolving science, so the practitioner should stay aware of advances in modeling that could place complex analyses within easy grasp. The current standard approach to analyzing the stability of wood in streams is to view logs or log jams as flow obstructions. The various treatments of this approach have all dealt with single pieces, log and boulder combinations and simple jams[5, 6]. Large log jams have been treated as a combination of individually stable logs. **Figure 2** below shows the location and direction of some of the forces acting on a log or structure.

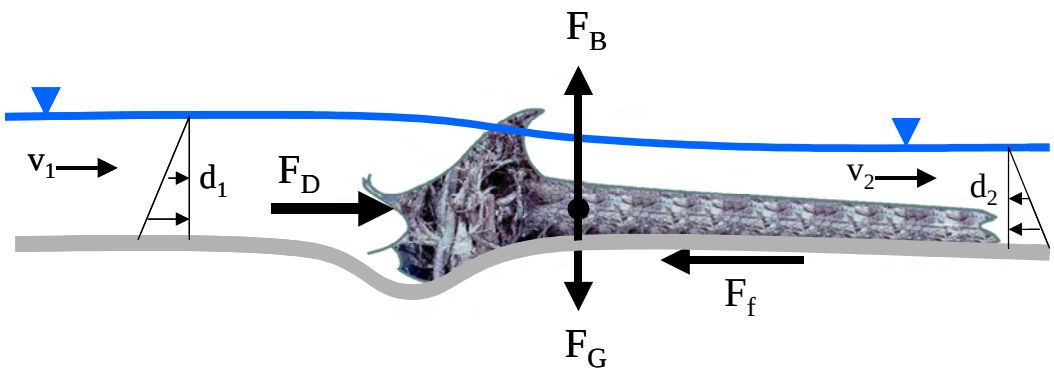

Figure 2 Forces acting on a submerged log.

where, F_B = buoyant force, F_G = the weight of the log, F_D = the dynamic fluid force, and F_f = the friction force. The buoyant force and weight of the log oppose each other in the vertical dimension. The buoyant force is equal to the weight of water displaced by the log. Wood will not float provided that the buoyant force does not exceed the weight of the log. These forces are calculated as follows:

Equation 1

$$F_G = Vol_{wood}\gamma_{wood}$$

Equation 2

$$F_B = Vol_{woodSubmerged}\gamma_{water}$$

where (γ is the unit weight of wood (ρg, or density times gravity) and water as indicated and *Vol* is the volume of total wood and submerged wood as indicated. The density of wood depends upon the species and moisture content. The range for northwest conifers in the dry condition is from 22 to 34 pounds per cubic foot. The volume of the submerged log must be determined from predicted flood elevations. Many designers have assumed the fully submerged condition for ballasted log jams in the worst-case scenario. Castro and Sampson suggest that if the weight of the log does not exceed the weight of displaced water by at least 50 percent, then some sort of ballast should be designed to hold the log in place, such as gravel ballast, boulders, cabled boulders, or anchors.

D'Aoust and Millar describe in detail ballast boulder design. Drury[7] outlines a gravel ballast design method which, though not discussed in detail here, consists of determining the depth of gravel backfill required to reduce buoyant forces and increase friction to counteract dynamic fluid forces on an individual log.

In the horizontal dimension a frictional force is balanced against fluid forces on the upstream face of the log or root wad. Friction, F_f is developed between the log and channel substrate, the submerged weight of the log acting as the normal force, F_N and the tangent of the internal angle of friction of the sediment as the coefficient of friction, $\mu = \tan\phi$:

Equation 3

$$F_f = \mu F_N$$

The coefficients of friction range from 0.4 for fine sand to 0.9 for gravel and boulders. Coefficient of friction is the tangent of the angle of repose for the material. There is no empirical data to justify the application of this model to real situations, although all of the references cited here employ this approach.

The references mentioned in this section only address the frictional contact with the bed, whether from the log itself or the ballast rock. Other anchoring mechanisms may assume part or all of this resisting function, such as cabling, pinning or pilings.

The dynamic fluid forces F_D, or drag, are determined with the empirical relationship,

Equation 4

$$F_D = \left(\frac{v^2}{2g}\right) A_{SW} C'_D \rho_w$$

where v is the mean incidental flow velocity, ρ_w, the density of water, and g the acceleration due to gravity (adapted here for English units). A_{SW} is the area of the submerged wood normal to the incident flow. Coefficient of drag, C'_D, is a function of an object's shape, orientation to flow, grouping and boundary conditions. Values range from 0.4 for a single log angled 15 degrees downstream off the longitudinal axis to 1.2 for a blunt root wad disk oriented upstream[8, 5,] . Groupings of closely spaced large wood elements, less than 2 or 4 diameters, are hydraulically efficient and may, in the case of two cylinders spaced 2 diameters apart, have a combined drag of less than a single isolated cylinder .

The drag coefficient is strongly influenced by boundary conditions, particularly when the blocking ratio, B, is greater than about 5 or 10 percent . The blockage ratio is:

Equation 5

$$B = \frac{Ld}{A}$$

where A is the cross sectional area in flow, d the diameter or width of the debris in flow and L the projected length of the debris in flow.

In flume experiments Gippel [8] developed a regression creating a resistance coefficient with up to 30% blockage. Since this empirical coefficient now takes into account other forces besides drag, notably hydrostatic forces, it should be considered a composite "resistance" coefficient, so that conceptually it is not confused with a coefficient that accounts only for drag. The resistance coefficient is a function of B and the coefficient of drag in infinite flow C'_D

Equation 6

$$C_D = 0.997C'_D\,(1-B)^{-2.06}$$

As mentioned above, this relation holds true for up to 30 percent blockage, but as B increases above that, upstream velocity decreases and drag force decreases at which point hydrostatic forces begin to dominate. In this scenario a debris structure transforms from an obstruction into a dam. Young [9] modeled wood in a flume at higher blockage ratios, although it may be difficult to apply his findings to force analysis since he looked primarily at backwater effects. In order to cause pool formation and gravel sorting, Washington Department of Fish and Wildlife (WDFW) found that in streams less than 16 feet wide, large wood had to occupy 40 or 50 percent of the bankfull channel, a situation that looks increasingly like a dam. In order to analyze a case like this the designer may need to apply momentum analysis in order to account for the role of other forces on an instream structure. The momentum equation for one-dimensional analysis is[10]:

Equation 7

$$\sum F = \rho Q(v_2 - v_1)$$

The sum of the forces, $\sum F$, acting on a control volume include all the relevant forces, notably drag, shear and hydrostatic head, which must equal the change in velocity, v, times the water mass transferred, ΔQ. Hydrostatic head may be calculated, as it would be for a dam, as the difference in the pressure force, F_P, between the up and downstream sides for any given unit width of the cross-section:

Equation 8

$$F_P = \frac{1}{2}\gamma d^2$$

where (is the unit weight of water and d the depth. Shear may be neglected if it is negligibly small, although longer, rough structures may cause a velocity gradient with

associated shear. Drag is computed as above, unmodified for constriction. Several factors complicate this approach, such as non-uniform velocity distribution[11], so that results from a simplified one-dimensional model may include substantial errors. It would be prudent to check all computations with discharge estimates using roughness as a surrogate for the obstruction[10] or modeling the large wood placement as a flow contraction modeled with empirical data (*e.g.* bridge rating curves)[12].

Shields[13] noted that drag forces are likely to be greatest during the first few major flow events and will diminish as the channel boundaries are shaped by turbulence and constriction. An increase in the specific gravity of wood (waterlogging) and the increase in ballast with sedimentation will also increase stability over time. Design charts for specific structures are shown in Slaney[14].

2.1 Types of Anchors

There are four common alternatives for the placement of large wood in a river. In order of preference for habitat formation, they are:

1. **No anchors** -- where wood is supplied to the stream and allowed to be naturally stable or, as conditions develop, moved by the flow.
2. **Passive anchors** -- where the weight and shape of the structure is the anchor, and movement at some flow level is acceptable (includes ballast).
3. **Flexible anchors** -- such as tethering the structure so there is some degree of movement flexibility with varying flows.
4. **Rigid anchors** -- holding the logs permanently in place with no movement allowed.

2.1.1 No Anchors

In the sphere of restoration activities, wood placement without the benefit of specific structure or anchoring is preferred when the restoration of ecosystem functions is a specific goal. Wood movement and the disturbance it causes are part of a productive ecosystem[15] where one looks at landscape level restoration[16]. Passive anchoring is a part of natural wood stability, but it is an anchoring method when we specifically employ it to create a stable wood structure. The no-anchors method simply states that one assumes full liability for risks incurred from mobile wood in a stream system. This approach works well in remote areas or for projects with a large land area and a single landowner (e.g. industrial timber).

2.1.2 Passive Anchors

Passive anchors use the weight and shape of a structure itself to provide resistance to movement. Logjams can be anchored by large wood pieces (whose own weight will stabilize them), rootwads, and frictional resistance with the bed (see Section 2, *Forces on Wood in Streams*). Bracing one or both ends of a log against trees or bedrock is also a form of passive anchoring (pinning, **Figure 12**). Individual boulders can be placed within a woody matrix without cabling because they provide additional weight for structural stability. Ballasting a structure with gravel is also passive anchoring (see **Figures 3, 4,** and **5**). A debris structure can be considered passively anchored as long as they are cabled or pinned in a rigid matrix but remain unattached to any exterior anchors.

The structure may become mobile at high flows, but the size and shape of the structure keeps it from moving a great distance. This may be a preferred approach for some habitat mitigation structures.

2.1.3 Flexible Anchors

Flexible anchors or tethers use materials that are similar to those used in rigid anchors, however, in this case, they allow the large wood structure to shift with changing flow stage or direction (see **Figure 9**). Tethers are appropriate where the structure is providing roughness or cover and where exact positioning of the feature is not critical. Such an approach may be used to provide a base for other debris to collect and stabilize at a specific location. The anchoring system must account for this added load. Tethered structures move with the current, scouring or "mining" erodible surfaces within their scope. In certain circumstances this may be considered a desirable outcome, although in most situations local scour is not acceptable and the tether must be designed to prevent the structure from moving near the bank. Secure tethering requires that anchors be attached at several points on the structure to prevent unlimited twisting. Tethered structures float and allow flood flows to pass under them until the depth of water exceeds the length of the tether, presumably reducing stress on the structure[17]. Gippel notes a decrease in the coefficient of drag with increasing log height over the bottom, reaching a minimum when it is floating. However, flexible anchoring introduces dynamic forces that add stress to the anchoring system. Structures are often tethered to points both on the bank and in the channel. Flexible anchors are appropriate for backwater and other low velocity areas, but should not be used in high-energy stream channels. Flexible anchors also pose the greatest risk to public safety due to floating wood and exposed cable.

2.1.4 Rigid Anchors

A rigid anchoring system is one in which wood is not allowed to move, float, or rotate. Rigid anchoring is usually desired where long-term grade control or direct bank protection is the objective. Some structures that are embedded in the bank can lead to continued bank failure if they shift or move downstream. Due to the anticipated permanence of this approach, it is important that the structure being anchored is properly designed and positioned. The anchoring methods most commonly used include cabling or pinning to a deadman, bedrock or standing trees. Rigid anchoring can also be accomplished by direct burial of part of the structure in the bank or a boulder pile. Large wood anchored tightly to bedrock is an example of a rigidly anchored restoration or mitigation project. Logs embedded in a barb, groin, rock toe and revetment are examples of rigid-anchor bank protection structures (see **Figure 11**).

2.2 Methods of Anchoring

There are seven common methods of anchoring large wood including:

1. **Ballast** -- the addition of weight to the structure.
2. **Pilings** -- trap large wood behind or between wood poles driven into the bed or banks.
3. **Cabling or Chaining** -- secures large wood to itself or other objects.
4. **Pinning --** trap large wood in existing vegetation or pin one log to another with

rebar pins or bolts.

5. **Deadman Anchors** -- buried objects secured to the large wood that resist removal by virtue of the weight of the soil mass above it.
6. **Anchoring to Bedrock and Boulders** -- large wood is held down to bedrock with chain or cable glued into holes drilled in the bedrock.
7. A **combination** of the above methods

2.2.1 Ballast

Any object that adds to the weight and frictional resistance of a structure is considered ballast. The most commonly used ballast material is rock ranging from gravel to boulders. If ballasting with gravel, risk of failure can be high, considering that if the gravel is the same size or smaller than the streambed alluvium, then it could be washed away by floods, releasing the log. This creates a risk to downstream property, a reduction in mitigation value and a loss to the restoration project at that location. Careful design reduces this risk. Sediment transport off of the structure can be minimized if the top of the structure is designed to match the floodplain elevation. By mimicking natural floodplains, vegetation will become established and sediment deposition will occur during most flood events.

Ballasting log jams with gravel has become standard practice (see **Figures 3, 4,** and **5**). Since gravel has over twice the bulk density of wood, gravel ballast placed over the jam counteracts buoyancy[18]. This leads to long-term stability by providing a substrate for plants to grow and form persistent features in the same fashion as vegetated bars or islands. Individual logs imbedded in gravel are much more stable, resisting incision and general bed scour. The factor of safety also improves over time due to saturation of the wood and a subsequent increase in density.

A log structure can also be anchored by confining it with boulders, without direct, permanent connection between the various parts. Examples include logs imbedded in a boulder cluster or in a groin (see **Figure 11**) or burying the log in the bank with added boulders for ballast (see **Figure 6**). Buoyancy as well as hydraulic forces must be accounted for in design. When calculating ballast requirements, use the submerged weight of the material. For common rock materials, the submerged weight is 60 percent of its weight in air.

Another approach to ballasting is to stack additional logs on top of a structure. Logs that remain above the designed flood elevation provide dry weight to the structure. The logs may either be attached or unattached to the structure. However, this is not appropriate for confined channels where flood flows may achieve great depths. Since this type of structure may be higher than adjacent banks and can block a significant flow area of the channel, it may not be appropriate to use next to erodible banks or high-risk areas without additional bank protection.

Boulders can be attached to the large wood using cables or chains. This increases the log's submerged weight and its friction with the bed. Concrete blocks can also be used but, because they are unnatural features, they are not preferred; if concrete blocks are

used it should be in locations where they will remain completely buried. Anecdotal information on concrete blocks in streams indicates that they are less stable than boulders. Hydraulic considerations indicate that flat surfaces increase lift and drag as compared to rounded shapes. In addition, concrete is not allowed in many bank protection or mitigation projects. See *Cabling and Chaining* below for risks.

2.2.2 Pilings

Where equipment access allows and soils are appropriate, structures can be anchored with piles (see **Figure 7**). Pilings are appropriate in streams with moderate to fine-sized bed material. Hard clays, cemented hardpan and bedrock will obstruct pilings. Very coarse, cobble/boulder substrate will prove difficult for piling placement. Pointed steel caps will aid in driving log pilings into a gravel/cobble bed. Sharpening one end of the log and driving it in with an excavator bucket may be sufficient in streams with fine-grained bed material. Pilings can also be pushed horizontally into banks as long as soil composition is able to provide appropriate structure.

In streams that have bed and bank material that is too large or compacted for this approach, pile-driving equipment can be used, although it is not a common practice. Other pile types are possible, for instance steel H-pile or pipe, but this is not frequently applied either. Pilings have also been installed by excavating a hole, installing the pile and backfilling the hole. This may lead to increased erosion of the disturbed soil and failure of the pile.

The matrix of pilings, logs, sediment and vegetation may be all that is necessary to hold a structure together. If necessary, pins or cables are used to attach materials to pilings. Logs can be wedged between pilings and held in place by water pressure or ballast. This approach has also been used successfully for building log jams. Cable strung between a number of pilings has been used to hold woody debris in place. This has been particularly successful in holding small debris in scour holes to promote the deposition of fine sediment.

Typical piling anchor designs require one-half to two-thirds of the piling length be buried below the streambed surface. This is critical for structures where the pilings are located near or in the scour zone of the structure. Piling depth must be determined with consideration for the potential scour depths resulting from the design flood and forces acting on the piles. Additional pilings away from the scour zone may be required as they are in some designs of engineered log jams (see example drawings in the discussion about Engineered Log Jams in the *Large Wood And Log Jams* Chapter). For critical applications with high risk factors, a professional engineer should determine the structural requirements for using pilings as anchors.

2.2.3 Cabling or Chaining

This method includes anchoring large wood with various materials including cable, wire rope, chain, rope and straps. Where a permanent, rigid anchor is desired, cable (wire rope) and chain are appropriate choices. If temporary anchoring is the goal, the use of hemp or other biodegradable, natural-fiber rope or strap may be the solution. Rope or straps of synthetic material may have a life expectancy somewhere between cable and

biodegradable ropes.

Cabling or chaining implies a level of control and permanence that seeks to reduce risk of failure. Cabling is often employed in high stress or high-risk situations. Yet, cable can deteriorate rapidly with constant flexing and abrasion. Cable fragments and frayed ends are a hazard to humans and animals. Cables, which snap under high tension, may have powerful recoil. Chain reduces some of these risks, but the more important underlying issue might be that the structure itself is under too high a stress and should be reevaluated. The designer should ensure that more natural methods, like ballasting, cannot be applied effectively to the situation.

Cable is available in galvanized and non-galvanized forms. Galvanized cable has the advantage of being resistant to corrosion but should still be cleaned prior to the use of adhesives such as epoxy. Cable can be cut in the field using guillotine-type cutters, which tend to leave a frayed end that can be difficult to insert into holes, or by using a skill saw with a metal cutting blade, which makes a cleaner cut. The best way to cut cable in the field is with a hydraulic shear, which can be carried in a backpack and weighs approximately 15 pounds.

Cables are typically connected to each other and to anchors and woody debris using cable clamps. Cable clamps are a weak point in cable anchors. Using a factor of safety of two to three times the estimated loading is prudent in the dynamic environment of streams. Improperly placed clamps can reduce the efficiency of the connection up to 40 percent of the cable strength. Thus, it is important to pay careful attention to clamp design and construction. Clamp efficiency is affected by orientation, tightening, spacing and the number of clamps used. The minimum number of clamps ranges from two for 3/8-inch-diameter cable to five for one-inch diameter cable. Standard wire rope clamps on a thimble eye obtain up to 80 percent of the strength of the rope when properly made. Specialty hardware can form eye loops with up to 100 percent of the cable strength. Flemish loops (a hand-formed loop) only develop up to 70 percent of the strength of the wire rope.[19]

When attaching cable to logs, always remove the bark from the area enclosed by the cable, otherwise the cable will loosen as the bark rots. To prevent the cable from slipping along the log, insert the cable through a drilled hole in the log or create a notch around the log using a chainsaw or axe. If rigid anchoring is required, a winch is necessary to tension the cable properly before tightening the attachment hardware. Following the placement of cable, any wood movement should not create slack in the cable. Staples can be used in addition to cable clamps to secure cables to large wood. When installing staples, avoid excessive crimping of the cable. When cabling to a live tree, care should be taken not to girdle the tree.

Cable leading to buried anchors through a rip rap blanket becomes abraded as the wood moves with changing flow. There are numerous instances where the cables have been severed at the rip rap surface resulting in the loss of large wood. Chains, while still subject to abrasion, are likely to fair better than cable.

2.2.4 Pinning

The word "pinning" has entered the restoration idiom with two different meanings. One is a steel pin used to connect individual pieces of large wood, to attach large wood to other anchors, or to serve as direct anchors (by being driven into the substrate). The other is a manner of anchoring a log against or between live trees or other immobile objects (see **Figure 12**). This latter meaning recognizes an often-observed natural method that should be employed whenever possible. Often, increasing hydraulic forces increase the pinning effect and resulting stability. If there are opportunities to apply this technique, it should be preferentially used.

The need for steel pins in some situations shows that either the large wood is not large enough to remain in place by itself or it is in an inappropriate situation. The main concern with steel pins is that they do not allow the structure to shift and settle, therefore fully active soil and log contact pressures are not developed. This leaves uneven stress distribution, so that one part of a large jam, or a single pinned joint carries a disproportionate amount of the load potentially causing the structure to fail catastrophically. However, the use of pins leaves less non-native material in the channel after failure.

Other concerns associated with pinning include adequate strength, durability of materials and security of attachment. Determining forces on large wood in rivers is challenging, so using conservative factors of safety in design is recommended. Durability of steel pins depends upon the corrosive or electrolytic nature of the soils and water, which may greatly reduce longevity at some locations.

Pin-attachment effectiveness depends upon the materials used. Threaded rods or rebar are the most common materials used. Rebar pinning relies on shaft friction to maintain attachment. Using a cable clamp at one or both ends or bending the protruding rebar end reduces the chance of pullout. When using threaded rods or bolts as connectors, large washers should always be used. Pilot holes are necessary for driving pins through large logs, and special, extended-shaft auger bits must be made for drilling through stacked logs.

Angle iron plates with four holes on each end for lag bolts or spikes have been used successfully in high-energy environments. These should be used to supplement cable in debris jams within higher-energy environments. Half-inch lag bolts or spikes at least six to eight inches long should be used.

Pieces of debris have also been anchored using various lengths of rebar driven into the streambed or bank. The rebar is driven through a pilot hole in the debris and into the streambed using a fence-post driver, sledgehammer or vibrator hammer with a special adapter for the rebar. These applications have had variable success due to difficulty in driving the rebar to adequate depth and the varying ability of subsoil to secure the rebar. For this reason, this method is not recommended as the sole method of anchoring treatments requiring long-term, rigid anchors.

2.2.5 Deadman Anchors

A deadman is a common form of anchor using a wide array of potential materials. The concept of a deadman is to bury an anchor in the bed or bank. The anchor pushes against a wedge of undisturbed soil when tensioned. An advantage of a deadman anchor is that it can be placed in the bank away from the potential erosion zone and keeps heavy equipment out of the stream. A structure usually requires at least two deadman anchors or a combination of a deadman and other anchors, however, a single deadman might be used as a tether anchor.

Commercial deadman anchors are available that can be driven or screwed into the soil. The driven style is set by providing tension on the anchor. The tension causes the deployment of legs or plates, which actually provide the anchorage. These anchors depend entirely on the shear strength of the soil and, therefore, are not acceptable in unconsolidated gravel beds. Much anecdotal information surrounds the use of these anchors. The main complaint deals with the connecting cables "working" in the soil as the log shifts or vibrates in the stream flow, creating a hole deep enough to release the anchor or otherwise leading to increased erosion.

Buried boulders, logs, concrete blocks or steel shapes are also used as deadman anchors. They have the advantage of their weight adding ballast, and they have more bearing area than commercial anchors. A drawback of this method is that by disturbing the native soil, erosion can take place more rapidly and gain inroads behind a structure or into undisturbed areas. In the application of concrete blocks as deadman anchors, the anchor tie should be cable- or chain-wrapped around the block, not through the lifting eye on the block.

Designing deadman anchors requires information on soil characteristics, such as the strength and tightness of soil, which will determine the style and number of anchors required. In design, a simple pullout analysis should be completed to determine the appropriate depth and style of anchor for a particular application. In addition, the manufacturer's specifications should always be followed for commercial anchor systems.

The movement of anchored debris can cause the anchoring cable or chain to slice through and loosen the soil lying between the anchor and the debris. When this occurs, the soil becomes more susceptible to erosion. For this reason, deadman anchoring systems should be designed so they minimize the range of movement of a piece of anchored debris. Multiple, strategically located anchors will typically restrict woody debris movement more effectively than a single anchor. If movement of the woody debris is desired, an alternative anchoring system, such as ballast or pilings, should be considered. Anchors can be placed at an angle between the streambed and bank material or directly in the streambed if the bank material is weak, which will also result in less erosion if the anchor fails catastrophically. An analysis of maximum scour depth should be completed if anchoring into the streambed.

2.2.6 Anchoring to Bedrock and Boulders

When structures are to be placed on or near bedrock or anchored to boulders, the rock

can be drilled and anchors set. See **Figures 8** and **9** for examples of boulders used to anchor large wood. The bedrock or boulders must be suitable and durable. The rock should be free from segregation, seams, cracks and other defects tending to reduce its resistance to weathering. Attachment to bedrock or boulders can be accomplished by inserting cable, rebar, threaded rod or rock bolt anchors into a hole filled with the appropriate grout or adhesive as required by the manufacturer. Oiled cable must be carefully cleaned with acetone or muriatic acid to allow proper bonding with the adhesive. The drilled hole must reach into unfractured rock to develop full anchor strength, and it must be of a depth and diameter as specified by the manufacturer. There are many types of anchor adhesives on the market. The type selected should take into account wet conditions, possible oversized holes, and other typical complications.

The following are steps recommended by typical product literature for attaching threaded rod or rebar to bedrock or boulders using an epoxy adhesive (similar techniques can be used for rock bolt anchors):

1. Drill the anchor hole typically 1/16 inch larger in diameter than the rod or 1/8 inch larger in diameter than the rebar. Cable has also been used as an insert, but some failures have been observed, probably due to the non-uniform surface relative to the drilled-hole alignment. If using cable, a better method would be to attach the cable to a rod or rebar;
2. Clean the hole with a wire brush. Use air to blow out the hole to remove all dust and debris;
3. If the cable or steel rod is lubricated, clean the cable using acetone or muriatic acid;
4. Inject the adhesive into the hole per the manufacturer's specifications;
5. Insert the rod or rebar, and turn it slowly until the end contacts the bottom of the hole (air pockets at the bottom of the hole reduce bonding strength);
6. Make adjustments to the fastener before specified gel times, and
7. Allow curing to occur (curing time is a function of temperature and varies from one to three hours).

Some adhesives may require dry surfaces for proper bonding. Prior to using an adhesive, it's important to verify the conditions under which the adhesive functions most effectively and to make sure the product has not reached or exceeded its expiration date. Using adhesives that require dry surfaces should not be used on structures to be cabled instream.

If applied properly, some adhesives can hold to the point of cable failure[20]. While some systems provide adhesion under water, in practice they are difficult to apply in a flowing stream with consistent success. It is important to consider how wood will be cabled during the construction and placement. Failure to consider cabling specifications during construction will reduce cabling effectiveness and structural integrity.

Another common anchoring method is to use threaded expansion anchors or rock bolts. There are a variety of commercial expansion anchors available. Advantages of rock bolts

over glued-in cable or steel rod include faster installation time and achievement of full strength upon installation (no drying time necessary). A disadvantage of mechanical anchors is that they are more susceptible to vibration effects than glued anchors. Another type of rock bolt anchor is, the groutable rebar type. This anchor is set and then pressure grouted to seal and fill all voids and cracks in the rocks. This type can be used in weaker rock.

Cable can be threaded through a hole drilled in the rock. Any large diameter hole is acceptable, although the standard rock quarry drill, which is approximately 3 inches in diameter, are economically drilled right at the pit. A length of hydraulic hose can be threaded over the cable to reduce fraying and crimping.

2.2.7 Combinations of Anchoring Methods

Anchoring methods are often used in combinations suited to the particular task at hand. For instance, a bank protection project may consist of logs cabled to each other, pinned between pilings and ballasted with boulders (see **Figure 10**) or a log jam may be piled up to an elevation above the floodplain and buried in gravel ballast (see **Figure 4**). It is up to the designer to mix and match the anchoring techniques presented here (and any other feasible techniques) to produce an effective anchoring system for a specific project. Creatively using large, standing trees, bedrock, boulders and sharp bends to passively anchor or establish large-wood accumulations are techniques used to create stable wood habitat that emulates natural habitat. The ability to visualize stream response to various flood stages during construction at low flow is necessary. Understanding the geomorphology, hydrology and hydraulics of the site during design enables one to better visualize flood stage and use what already exists on-site to help construct a solid wood habitat project.

2.3 Placement Considerations in Streambank Restoration Projects

The information below pertains to placement of large wood in conjunction with streambank protection projects. Placement considerations for stream habitat restoration projects are discussed in the Stream Habitat Restoration Guidelines (SHRG), *Logs and Log Jams technique*.

Large wood can enhance the effectiveness of bank-protection treatments while mitigating the treatments' negative effects on fish habitat. The use of rock and other bank-hardening materials in streambank-protection projects often results in the loss of fish habitat. Rock revetments create smooth banks, resulting in high near-bank velocities, loss of cover and a reduction in structural and hydraulic complexity. Structural and hydraulic complexities created by large wood are important components of fish habitat enhancement. It has been found that fish use increases when large wood is included in rock revetment projects[21, 22]. Placement of large wood is therefore considered a preferred form of mitigation. As an added benefit, some sites have shown that wood added for habitat restoration performs a bank-protection function as well. Downstream velocities are decreased and energy is dissipated in the form of turbulence around the large wood, encouraging deposition and reducing near-bank scour, while enhancing complex rearing and holding habitat for salmonids at low [23] and high flows. Whenever possible, large wood should be placed

in locations and configurations where it would be expected to occur naturally, which increases its reliability in providing fish and wildlife habitat.

The design of large wood projects must be carefully considered to ensure their success in meeting project goals. Unfortunately, the failures of some bank-protection projects involving large wood for habitat mitigation have been wrongly attributed to the wood rather than to the designer for not creating an integrated project. As designers become more adept at incorporating large wood into streambank-protection projects, its effectiveness and frequency of use will increase. **Figures 9, 10,** and **11** show several bank-protection projects successfully incorporating large wood.

A variety of strategies are available for placing wood in mitigation and restoration projects with a full range of anchoring options. The options range from simple delivery of wood to the channel[24] to fully restrained wood with cable or chain. Refer to the Stream Habitat Restoration Guidelines (SHRG), *Logs and Log Jams technique* for more information on methods and design considerations for adding wood to streams.

Large wood should not be placed during emergency conditions or for the purpose of alleviating emergency bank erosion problems. Large wood can only be anchored or placed effectively in relatively calm and/or dewatered environments. It also requires careful planning and design, which is not feasible during a true emergency.

2.3.1 Large Wood for Catching Debris

It is generally accepted that the greater the wood density found in a given reach, the greater the densities of juvenile salmonids[25] and a greater diversity of channel features with associated aquatic communities[26]. Large wood, used as mitigation, should be installed as dense clusters or have the capability of recruiting other debris from the stream. Single logs provide little habitat by themselves; and, as time passes, isolated rootwads become featureless stumps providing little cover.

Wood recruitment is the stream's habitat-revitalizing force, adding complexity and renewing cover over time. Streambank-protection techniques made of rock are not effective at recruiting wood on their own, so large wood should be incorporated since it tends to collect other debris and encourages the recruitment of even more wood. For maximum wood recruitment potential, logs with rootwads should be positioned so that a portion of the rootwad is above the flood-flow water surface. Floods recruit large wood as the banks erode, drawing large and small trees into the active channel. Small trees and wood material added to the channel float downstream and are often captured by existing downstream log jams. If logs with rootwads are installed alone and low on rock revetments, they will not collect this liberated debris as it floats by. The ideal solution is to have wood at various elevations on the bank to ensure recruitment at all flows.

In systems with high banks and infrequent out-of-bank flows, the wood stays along the thalweg in the deeper, faster moving water and does not tend to accumulate along the banks. In order to recruit debris, large wood in rock-treated banks must stick out into the flow and be high enough to capture floating debris. Wood tends to accumulate at the

downstream end of a bend as momentum resists wood transport through the lower third of the meander bend. This is a good place to expect wood recruitment on placed large wood.

2.3.2 Large Wood in Rock Toes or Revetments

Engineered log jams provide immediate, stable habitat and bank protection. Logjams that have been installed in front of rock toes or revetments as mitigation have provided some habitat value. With the effective use of wood in streambank protection on the rise, it is wise to consider using wood instead of rock if possible. Trees with rootwads are the best material to use.

Rock for bank-protection projects is frequently sized according to a minimum stable dimension or gradation. These stability equations and tables are for smooth banks with flow running on an alignment parallel to the bank. When wood is added to the revetment design, failure may result from turbulence or redirected flow unanticipated in the original rock-sizing criteria. The designer must account for these hydraulic forces in sizing stone and the determination of stone layer thickness. Experience suggests that it is best to use the largest rock available for rock revetments, toes, groins and barbs that incorporate large wood. Refer to the discussion about Riprap in Integrated Streambank Protection Guidelines (ISPG), Chapter 6, *Techniques for Rock Sizing Information*. While it may save money to use the minimum stable rock size for a particular project, the increase in risk may be unacceptable when also using wood. During floods, wood buoyancy and upstream wood collection cause shifts in hydraulic forces; and, together with impacts from large, floating logs, can quickly make conventionally-sized rock inadequate to hold wood in place. A good understanding of the worst-case flood forces that could occur at the project site enables a design that will be long-lived and emulate the size of material that would naturally occur at each site.

The use of such large rocks and logs necessitates a filter between the native material and structure, such as layered bedding, especially in fine-sediment banks and streambeds. Successful projects use progressively finer granular layers between the rock and the native bank material. Fine-grained soils may require small-diameter crushed rock or screened sand and gravel, followed by quarry spalls and light, loose riprap. Refer to the discussion about subsurface drainage in Chapter 6 for more information regarding selection of filter materials between riprap and native materials. Another approach is to use a well-graded pit run rock to provide the filter layer behind the riprap.

Based on a review of recent riprap revetment projects with large wood, two techniques show the most promise for stability and habitat. In low energy streams large logs are embedded in a boulder toe with rootwads extending in the channel. The logs are 30 feet long, placed at the elevation of the streambed, embedded 15 feet into the bank and ballasted. The upstream angle can be from 30 to 50 degrees and other logs can be attached to them to create greater complexity. In confined streams with deep flood flow, additional logs are placed higher to collect debris. The second technique involves the construction of log jams independent of the rock face to avoid jeopardizing rock placements and bank protection. See the Logs and Log Jams Technique for further

information.

2.3.3 Large Wood in Groins and Barbs

Large wood is used in groins about the same way it is used in rock toes and revetments (see **Figure 11**). However, there are a few added complications. Large logs with intact, finely branched rootwads are preferred for use in groins. They should be placed at bed level for cover purposes and also at higher stages to encourage recruitment. Logs need to be well embedded in the structure, placing one-half to two-thirds of the lower part of the tree trunk in the rock. The rock size should be increased to act as ballast; unless, as has been recommended, the largest rock available is already specified.

The positioning of large wood in the structure is the subject of some debate. It depends, in part, upon whether the structure is a barb or a groin. Barbs are positioned low and produce less scour and turbulence. As a result, sediment tends to accumulate around them and a new bankline develops. If large wood is placed near the bank upstream or down-stream of a barb, it is likely to be in a deposition zone, and its value as cover is reduced or eliminated. To enhance fish habitat, it is useful to place large wood near the tip of barbs; however, designers have expressed concerns that this is the area of highest stress, and large wood may destabilize the structure and reduce its effectiveness as bank protection. This concern applies primarily to high-energy environments. Using wood on the end of a barb could cause problems if it collects additional wood and allows hydraulic scour to be focused on the bank the barb is designed to protect. Large wood, if placed near the tip, should be positioned low in the water column to provide cover, while reducing its ability to collect debris. A good understanding of large wood transport/supply, hydrology, hydraulics and geomorphology are important. If the structure is properly designed, large wood will stay intact and improve habitat. Risk analysis and design requirements will help determine the applicability of wood in barbs at a given site.

In contrast to barbs, groins are high structures that trigger more pronounced turbulence and scour which results in the area near the bank being scoured. However, placing large wood in the area can provide good cover and complexity. Wood can also be placed near the tip on the upstream face of groins. There is usually more rock in groins than in barbs, so wood can be held more securely.

Figure 1 North Fork Stilliguamish River, Snohomish Co., log jam using gravel ballast.

Figure 2 North Fork Stilliguamish River, Snohomish Co., log jam using gravel ballast.

Figure 3 Gorst Ck., Kitsap Co., log bank protection using gravel ballast.

Figure 4 E. F. Issaquah Ck, I90 Sunset interchange, King Co., habitat logs anchored in bank with additional boulder ballast.

Figure 5 Salmon Ck, Jefferson Co., channel restoration project. Piling used to increase stability of log jam.

Figure 6 Boulder anchor. Cable should be protected from abrasion with hydraulic hose or similar protection.

Figure 7 Sauk River side channel near SR 530, Skagit co. Large wood tethered on long cables to large drilled boulders.

Figure 8 Samish River, Skagit Co. Large wood anchored using a combination of techniques; rock ballast, cabling, and pilings.

Figure 9 Cedar River, Darre Dam project, King Co. Large wood anchored in groin.

Figure 10 Bear Ck. Pacific Co. Log pinned by existing live tree.

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