TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 3. GRADE CONTROL STRUCTURE DESIGN

3.1 INTRODUCTION

The term grade control may be broadly applied to any alteration in the watershed which provides stability to the streambed. The most common method of establishing grade control is the construction of in-channel grade control structures. Other methods include control of sediment supply and/or surface runoff to the streambed.

There are two basic types of grade control structures. One is referred to, by Biedenharn and Hubbard [2001], as a bed control structure, as it is designed to provide a hard point in the streambed that is capable of resisting the erosive forces of the flow in a degradational reach. The structure is built at grade and does not change the upstream or downstream flow conditions. The other type is referred to as a hydraulic control structure, as it is designed to reduce the energy slope to the point that the stream is no longer capable of scouring the bed. The structure is built above grade and will cause a backwater effect to the upstream flow. The difference of these two types of structures will be illustrated in the next section.

The design considerations for these two types of structures will be described first. Because of the District's intent to provide green design, materials such as concrete and gabions will not be used unless it's necessary for safety and constructability reasons. Because of our commitment to provide fish passage whenever possible, large drop structures which are fish barriers will not be considered. The design procedures that follow will provide a step by step guide to the analysis and design of grade control structures that meet our design requirements. The type of concrete drop structure that may be used at dam outlets will be discussed in Chapter 5.

3.2 DESIGN CONSIDERATIONS

The bed control structure may be made of rocks or logs anchored into the channel bed. Since its top elevation is made to level with the bed, the transition needs to be smooth to avoid pitting or flow induced erosion. The hydraulic control structure will protrude from the bed, raise the upstream water level and will need a plunge pool downstream to dissipate the extra potential energy. The structure is functionally a drop structure made of logs or rocks.

Design considerations for grade control structures include determination of the type, location, spacing of structures, and detailed design of the structures themselves. These considerations cover hydraulics, geomorphology, geotechnical, construction, maintenance and operation, and environmental impacts. Through these considerations, the design of grade control structures is performed. These considerations are explained in the following.

3.2.1 Design Flow

This is a design criterion that has not been made clear in the literatures and is worthwhile to clarify the concepts behind it.

A grade control structure is usually made as part of the bankfull channel geometry. Since we have established that the bankfull flow is the channel-forming flow that shapes the bankfull channel, intuitively one would design a grade control structure using the bankfull discharge, as suggested by *California Salmonid Stream Habitat Restoration Manual* [California 2006]. This approach is appropriate only if the project reach is composed of a bankfull channel and <u>wide</u>

floodplains. Calculations of channel-bottom shear stress (Figure 9-12b) have shown that the channel bottom will experience the maximum shear stress at the bankfull flow, when wide floodplains are present. Higher flows will result in reduction of the energy slope and bottom shear in the bankfull channel.

When the floodplain size is limited, or not present at all as in an incised channel, the bottom shear will continue to rise with flow, as shown in Figure 9-12b(3). In that case, which design flow to use becomes a question of risk management. The higher is the design flow, the higher the construction cost will be, but the lower the risk of failure will be.

Hence, the design flow for a project should be determined based on the channel geometry in the project reach. We have simplified the selection to the following approach:

$$\begin{aligned} \frac{W_{fp}}{W} &\geq 1 \qquad\qquad Q_{design} = 1.5 Q_{bf} \\ \frac{W_{fp}}{W} &< 1 \qquad\qquad Q_{design} = Q_{1\%} \, or \, Q_{Project\,design} \end{aligned} \tag{3-1}$$

where W_{fp} is the floodplain width and W is the bankfull channel width as defined in Figure 9-12b(1).

The grade control structure should not suffer significant damage under the 1% flow, or project design flow, nor should it cause significant damage to the upstream or downstream reaches. Hence, if the Q_{design} is less than $Q_{1\%}$, the project should still check the integrity of the grade control structure using the latter.

For grade control weirs, the design flow is used to size the rock of the weir and design the riffle blanket for both log and rock weirs. This design flow is separate from the fish-passage flow which will be discussed in Chapter 5.

3.2.2 Hydraulic Considerations

The hydraulic siting of grade control structures is a critical element of the design process, particularly when a series of structures is planned. It involves the determination of the equilibrium slope, which has been discussed in Sections 9.1.2 and 2.2.1. The intent is to install the grade control structures to allow the existing slope to gradually evolve into the equilibrium slope which will be stable so long as the flow and sediment conditions remain.

Heede and Mulich [1973] suggested that the optimum spacing of grade control structures is such that the upstream structure does not interfere with the deposition zone of the next downstream structure. As shown in Figure 3-1, the desirable spacing (X) can be determined by extending a line from the top of the downstream structure at a slope equal to the equilibrium slope (S_f) until it intersects the existing slope (S_o).

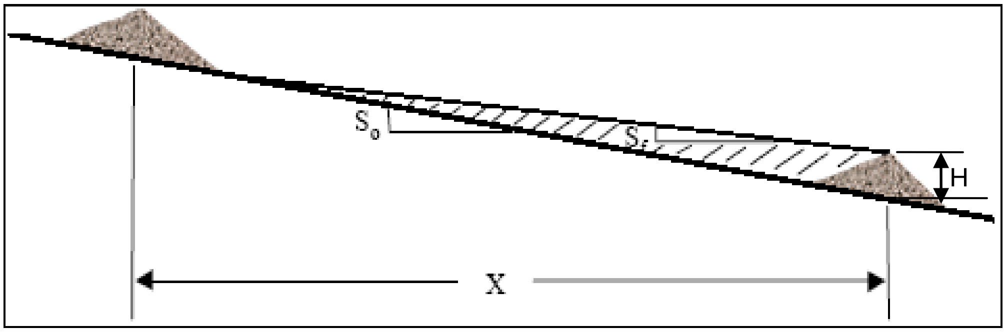


Figure 3-1. Spacing of Grade Control Structures
(Adapted From Mussetter 1982)

The amount of drop, H, to be removed from a given reach may be calculated by

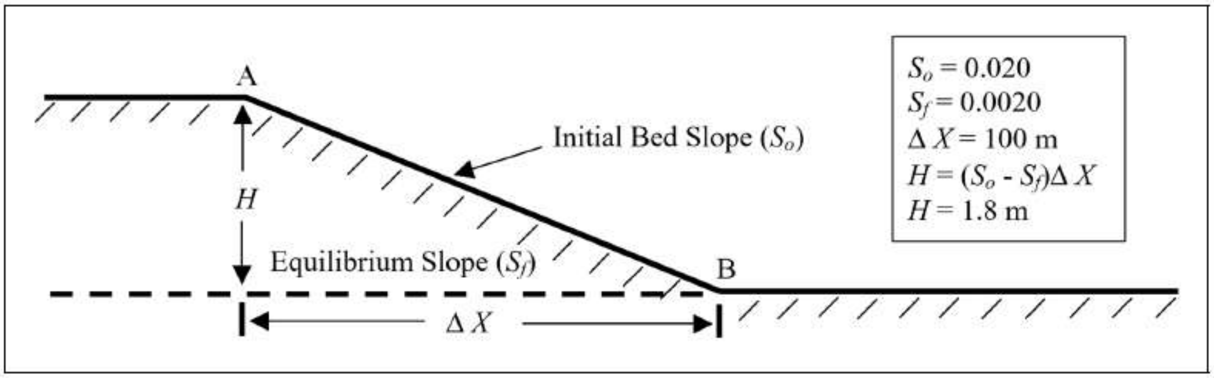
$$H = (S_o - S_f)\ X \qquad (3\text{-}2)$$

And if H is larger than the allowable height of a drop structure (h), the number of structures (N) required for this reach can be determined by

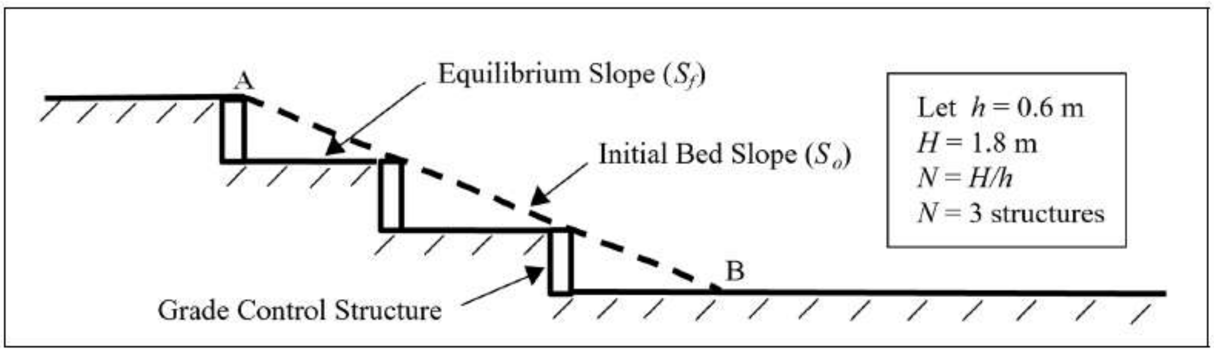
$$N = H/h \qquad (3\text{-}3)$$

Bed Control Structure

Using the above method, the example in Figure 3-2 illustrates how the bed-control type of grade control structures is designed hydraulically.



a. Initial condition of streambed showing degradational zone between points A and B. Total anticipated drop in reach is calculated to be 1.8 m



b. Stabilization of degradational zone using three bed control structures. Each structure has a design drop of 0.6 m

Figure 3-2. Siting of Bed Control Structures
(Adapted From Biedenharn and Hubbard, 2001)

Figure 3-2a shows an initial bed slope (S_o) higher than the equilibrium slope (S_f), indicating that the reach is prone to degradation. The total drop required (H) is computed to be 1.8 m. With each drop height (h) limited to 0.6 m, 3 grade control structures are required. Each bed control structure is laid at grade, and these are the only 3 points in the reach which remain at the original elevation.

A characteristic of this method of grade control is that it does not intercept sediment from the upstream. The only sediment it deprives from the downstream is the sediment in this reach that may otherwise erode with time. The long-term effect of that may be studied, using a program such as HEC-6.

Hydraulic Control Structure

The same example may be used to design hydraulic control structures, as is shown in Figure 3-3.

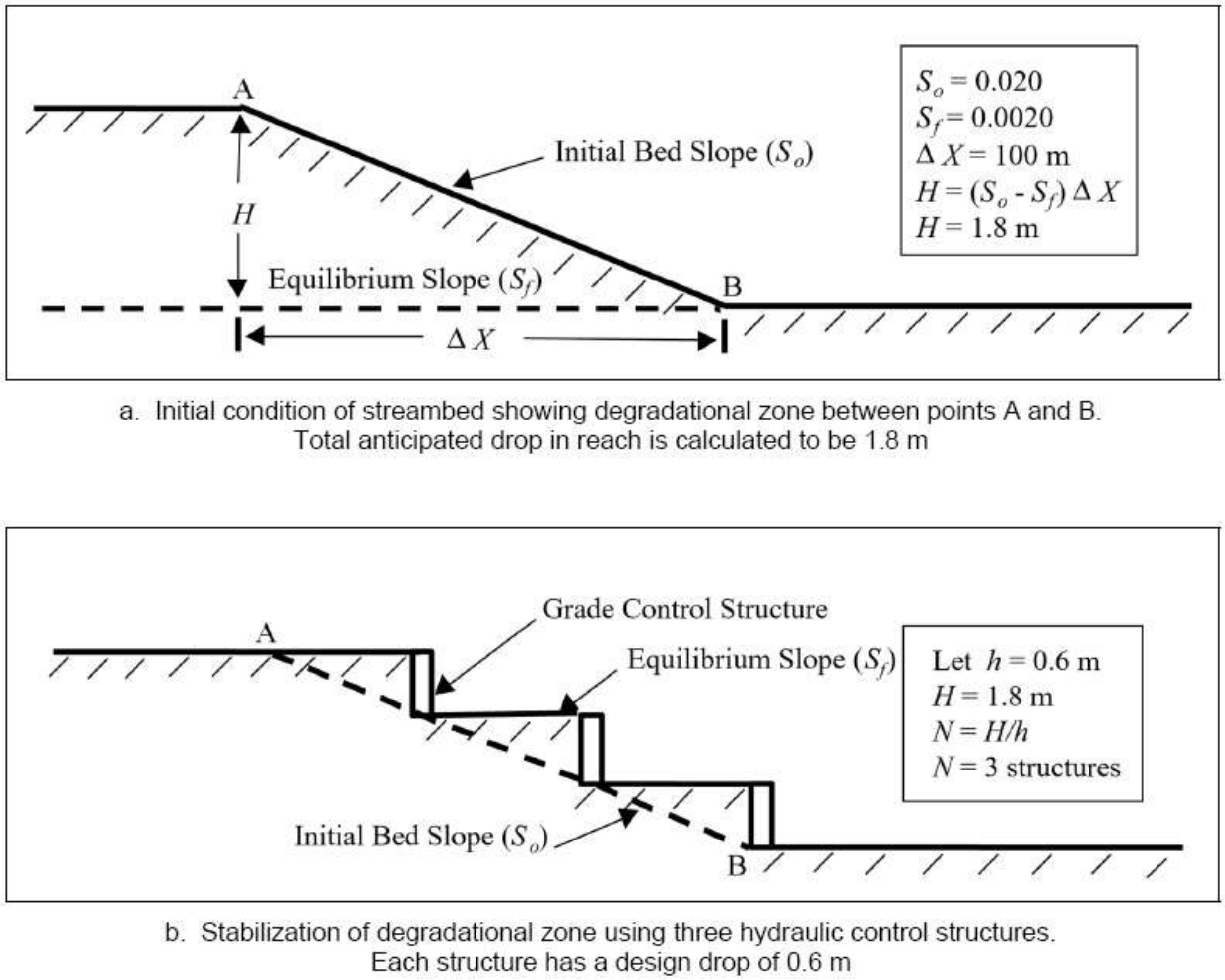


Figure 3-3. Siting of Hydraulic Control Structures
(Adapted From Biedenharn and Hubbard, 2001)

The hydraulic calculation is exactly the same, as for the bed control structure, to determine the number and size of structures. The difference is that the structures are installed above the original grade. They will intercept upstream sediment supply to develop the equilibrium slope, and for that reason they may starve the downstream from sediment supply.

This type of grade control structure requires a sediment transport analysis using HEC-6 to determine the effect of grade control. One common practice is to stage installation of the structures into several seasons to minimize impact on downstream sediment supply.

3.2.3 Geomorphologic Considerations

Because the design of grade control structures requires determination of the equilibrium slope, which in turn requires sediment characteristics, sediment load, and channel characteristics. If a channel is in the process to reach dynamic equilibrium, its present state and the sediment and channel characteristics will change with time. It is essential then to realize this fact, and design considering this potential change.

The selection of a grade control structure may also depend on the geomorphic state of a stream. In a channel with well developed bankfull and floodplain geometry, it will be straightforward to fit a rock weir (Section 3.3.2) into the cross-section. However, a rock weir will be cumbersome to key into an incised channel, and an at-grade rock bench or log bottom may be used to minimize impact to the channel.

3.2.4 Geotechnical Considerations

The stability of channel banks will affect selection and design of grade control structures. When the critical bank height (Section 9.4) is exceeded due to degradation, bank instability may be widespread throughout the reach, rather than restricted to the outside banks in channel bends. For those cases, bank erosion protection may not be feasible, and grade control is more appropriate.

Also for banks that are near critical height, the grade control structure should be designed to reinforce stability by increasing toe protection and reducing bank slope. In most cases, the geotechnical data on soil material and bank stability are required to design grade control and bank protection structures.

3.2.5 Flood-Control Considerations

Channel improvements for stability reasons should always try to minimize impact to flood capacity. This requires that the grade control structures not encroach into the flow area. This is not an issue for bed control structures, but is a valid consideration for hydraulic control structures. The selection of a particular design should consider and quantify impacts to flow capacity and water level in the reach.

As a minimum the water surface profiles for the bankfull flow and maximum design flow should be examined to determine the effect of the grade control structure.

3.2.6 Environmental and Ecological Considerations

Sometimes at the location of a grade control structure determined from hydraulic calculations there are protected species of vegetation or wildlife such that construction of the grade control structure will incur significant environmental impact. Under these circumstances, it may be advisable to relocate the structure a short distance downstream or upstream to avoid or minimize environmental impacts. A field investigation is required after initial hydraulic calculations to determine if the site condition is feasible or optimal for locating a grade control structure.

Given our mission to preserve and protect the environment, fish passage is also an implicit assumption in our flood protection work. This assumption excludes large drop structures from being considered in design (see Section 3.3.2 for more detail). It also precludes concrete, gabion, and sackcrete from being used as materials of the grade control structure. Only the environmentally friendly materials such as gravels, rocks and tree logs are considered for grade-control purpose in this manual.

3.3 DESIGN PROCEDURE

The following procedure describes the sequence of technical analyses that are required to take place to produce the data needed for grade control structure design. It is assumed that land survey, basic water surface profile analysis (HEC-RAS, Sections 2.3.4 and 2.4.1) and sediment material characterization (Section 10.1) have been completed. Some of the analyses described below have already been discussed in Chapters 10 and 2. They are included here to address the relations to grade control structure design.

3.3.1 Sediment Transport Analysis

Since the purpose of grade control structures is to maintain or create a stable channel, the design has to prove a balance in sediment transport, i.e., sediment-in equal to sediment-out. To achieve this end, we need to determine the transport capacity, annual sediment yield, and equilibrium slope.

If the project reach is short and regular, or may be represented with a uniform slope and a constant cross-sectional geometry, use SAM for these calculations, as described in Section 2.4. The procedure is as follows:

(1) Develop a representative cross-section, longitudinal slope and sediment characteristics for the reach immediately upstream from the project reach.

(2) Calculate the transport capacity and sediment yield for this upstream reach using the methods described in Section 2.4.

(3) Develop a representative cross-section, longitudinal slope and sediment characteristics for the project reach.

(4) Calculate the transport capacity and sediment yield for the project reach.

(5) Compare results of Steps (2) and (4) and adjust the longitudinal slope of the project reach until the sediment yield from the project reach matches that of the upstream. This is the equilibrium slope.

Take this equilibrium slope and go to the next section to determine the need for grade control structures.

3.3.2 Hydraulic Siting Calculation

By comparing the equilibrium slope and the existing slope using Eq. (3-2) and (3-3), we can determine the need for grade control structures. The allowable drop height in most cases is defined based on the type of fish whose passage the design must accommodate. Both California Department of Fish and Game [2002] and NOAA [2001] require the maximum drop to be less than 1 ft for adult anadromous salmonids and 6 in. for juvenile salmonids. If the drop height exceeds this limit, opening may be considered through the drop structure. There are also requirement for the depth of the plunge pool which will be discussed in Chapter 5.

Hence, the procedure of hydraulic calculations is as follows:

(1) Develop the maximum drop height (h) based on fish passage and other criteria

(2) Use Eq. (3-2) to compute the required drop height (H)

(3) Use Eq. (3-3(to determine the number of drops (N) required and the spacing

(4) Layout the locations of drop structures on an aerial photograph

3.3.3 Field Data Collection

With tentative locations of the grade control structures determined, we are ready to go to the field for data collection. Bring a copy of the aerial photograph with tentative locations of the grade control structures marked on it, tape measure, and a note pad.

(1) Examine each of the tentative sites for constructability. The considerations include type of soil, vegetation that will be impacted by construction, channel geometry and bank stability, access for equipment and personnel, and construction lay-down and staging areas. If possible, locate grade control structures in straight channel sections to avoid nonuniform flow distributions intrinsic to channel bends.

(2) If a site is not suitable for construction, walk upstream and downstream to select another location in the close vicinity.

(3) After all locations are examined and confirmed, determine if additional geotechnical investigation should be conducted to assess bank stability and soil conditions. If the bank slope is steep and the terrace height is significant, there may be a potential of bank failure during excavation. Have a geotechnical engineer review the situation and make recommendations.

3.3.4 Type of Grade Control

With the location of the grade control structures identified, we can now determine which type of grade control best fits the project reach.

Generally there are two situations where grade control structures are needed. The first is when channel degradation has occurred or is in the processing of occurring, and we wish to install grade control structures to maintain the existing or future stable invert slope. The second is when degradation has generated a large invert drop at a specific location, e.g., a culvert or bridge crossing where the hardscape has stopped the degradation, and we wish to install grade control structures in the reach downstream from the drop to replace the large drop with several small drops.

Bed Control Structure

In the first situation, since the grade we are trying to control is at or lower than the existing grade, the bed-control type of structure is better suited for this application. This may be achieved by constructing a rock or log structure at grade. The design is provided in Section 3.4. No additional sediment transport analysis is required before design can proceed.

Hydraulic Control Structure

In the second situation, we will be trying to restore channel invert to a previous, higher elevation. The hydraulic-control type of structure will suit this purpose. To determine effect of sediment trapping on downstream reaches, and to determine timing of installation to minimize impact, the following analysis shall be performed:

(1) Construct a HEC-6 model to include the grade control project reach, an upstream reach to provide sediment inflow boundary condition, and a downstream reach long enough to extend into the depositional region, if this model has not been developed already.

(2) Using historical flow and invert profile data, calibrate the HEC-6 model.

(3) Develop flow record to simulate future creek flow condition.

(4) Run the HEC-6 model staging the installation of grade control structures to determine the optimal installation schedule and impact to the downstream.

Through this analysis the temporal and physical effects of grade control structures are determined. Now we can perform detail design of the grade control structures.

3.4 GRADE CONTROL STRUCTURE DESIGN

The main consideration in designing a grade control structure is the site cross-sectional geometry. In incised channels the flow area is usually restricted by steep banks. This situation requires a design that minimizes encroachment into the flow area. On the other hand, in channels with floodplains, a grade control structure may be integrated with the bankfull geometry without exacerbating flood conditions. Several different designs that can meet these considerations of the Santa Clara Valley are described below.

3.4.1 Incised Channel

If the stream is seriously incised, with high and steep banks and a terrace that has lost touch with the normal flow regime, the design should strive to minimize impact to the steep banks, but at the same time minimize encroachment into the flow area. These requirements limit the selection to simple log weirs and rock weirs as described below.

3.4.1.1 Log Weir

Using logs salvaged from the local watershed may best fulfill the purpose of grade control and habitat restoration in an incised environment. Logs have been used successfully for toe protection at SCVWD in the past, but relatively little experience exists for grade control. The design below was developed based on our own analysis and guidelines provided in the *California Salmonid Stream Habitat Restoration Manual* [California 2006] and *Integrated Streambank Protection Guidelines* [Washington State 2003].

A log weir is a drop structure made of logs or logs in combination with rocks. It may be a straight weir, downstream-V weir, upstream-V weir or diagonal weir. Sketches of these weirs are illustrated in Figure 3-4. More details on the design will follow later. A straight weir is perpendicular to the direction of flow, usually installed in a riffle section with flow uniformly distributed across the channel. A downstream-V weir has the tip of the V pointing in the downstream direction. Since it forces flow toward the banks, it is effective in dissipating energy, but should only be used in areas of stable banks that can withstand flow impact and shear accompanying such a design. The upstream-V weir, on the other hand, directs the flow toward the center and can develop a scour pool that enhances the aquatic habitat. A diagonal weir with a lower upstream end helps directing flow away from the bank of the downstream end. Designs of these log weirs are similar, and that is why only the straight-log-weir design is provided in detail here.

The longevity of log structures has always been a concern. It is partly dependent on tree species. Redwood, western red cedar, and Douglas fir may be expected to last the longest. Spruce, hemlock, white fir and pine are the least durable. The longevity will be improved when the barks are removed. Keeping the log wet or submerged will also prolong its life. Frequent wetting and drying accelerates the rotting process.

When designing log weirs, the main consideration is anchorage. Most species of wood are lighter than water and will float or move if not anchored properly. Reported failures of log toe or grade control projects [Cousins and Storesund, 2005] were mostly due to insufficient anchor design. The log weir design below was developed to address this consideration.

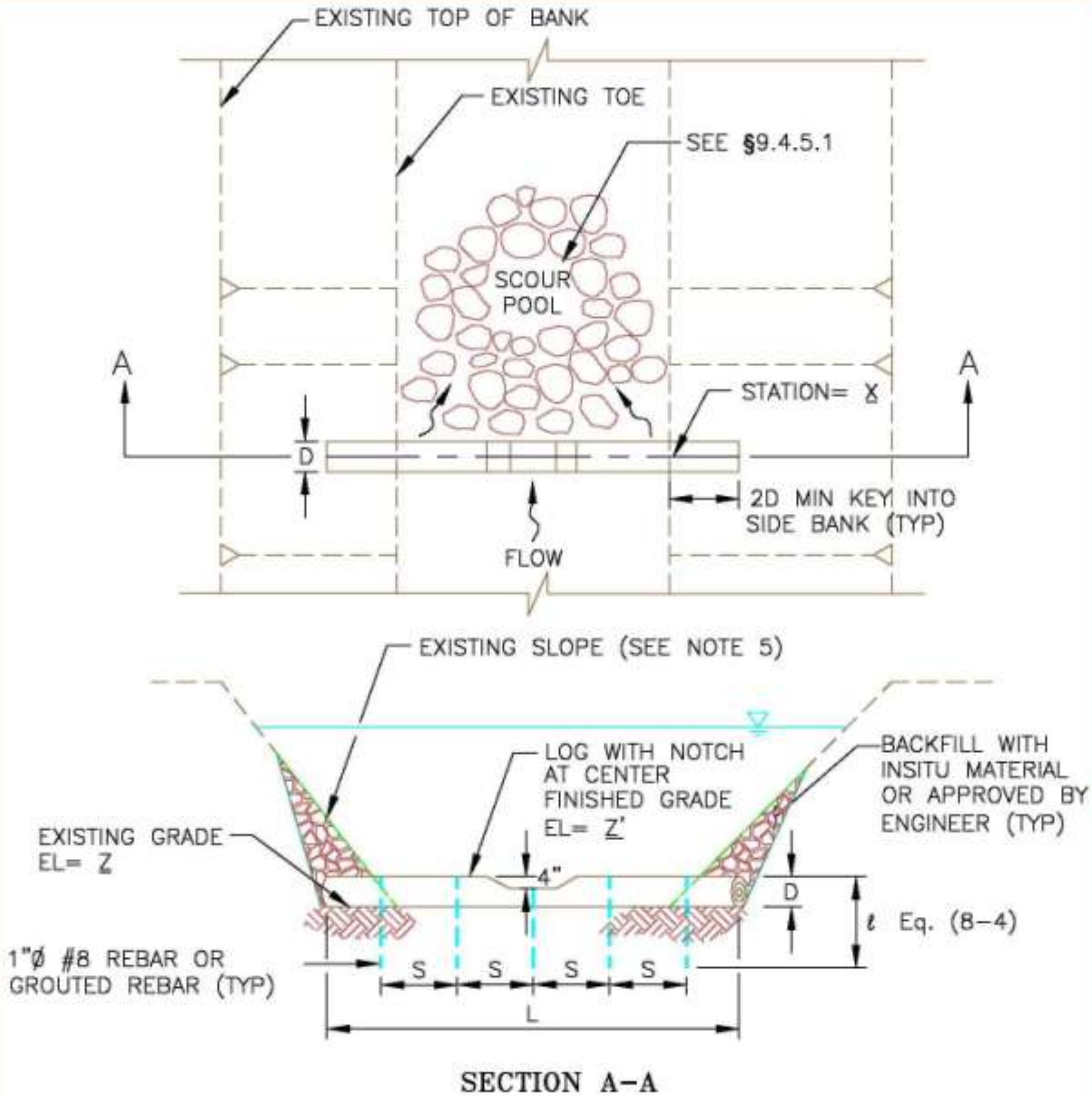
Common anchoring designs [California 2006 and Washington State 2003] include cabling, chaining, pinning to rocks, deadman anchoring on floodplain, piling and ballast. Our goal is to use easily obtained materials, be constructed easily, be fish and environmental friendly, and be cost effective. The selected method is to use steel rebars anchored into soil to act as friction piles to resist the uplift and impact forces, as depicted in Figure 3-4. We will use #8 rebar, with a diameter of 1 inch. This size provides sufficient stiffness to allow using the bucket of a front-end loader to press the steel into soil. The rebar is equipped with a threaded end and is recess-bolted to the top of the log.

Since the buoyancy force on the log has to be balanced with the friction force between soil and rebar, the weight of the log comes into play. The weight of the log also varies with tree species. Table 3-1, excerpted from http://waynesword.palomar.edu/plsept99.htm, shows the density of some trees commonly seen in California.

Table 3-1
Specific Gravity of Dry Wood

Wood	**Specific Gravity**	**Wood**	**Specific Gravity**
Bay, California	0.65	Pine, Ponderosa	0.46
Cedar, red	0.38	Redwood, Coast	0.40 – 0.45
Cottonwood	0.42	Spruce, Engelmann	0.35
Fir, Douglas	0.53	Sycamore	0.59
Oak, Canyon live	0.85	Walnut, California black	0.63
Oak, Coast live	0.83	Willow	0.42

Note that the specific gravities provided were based on dry weight of the wood. When submerged, the specific gravity will be higher which improves stability of the log. Typically a log of 12-inch diameter may be used.



NOTES

1. USE #8 REBAR OR GROUTED REBAR EVENLY SPACED AT CENTER TO CENTER.
2. PLACE LOG ON LEVELED SITE AND KEY ENDS OF LOG INTO SIDE BANK.
3. BACKFILL SHALL BE INSITU MATERIAL OR APPROVED BY ENGINEER.
4. BACKFILL SHALL BE COMPACTED TO MINIMUM 90% RELATIVE COMPACTION.
5. EXISTING SLOPE MAY REQUIRE SITE SPECIFIC DESIGN TREATMENT TO STABLIZE BACKFILL.
6. ALL ELEVATIONS AND STATIONS SHALL BE STAKED AND APPROVED BY ENGINEER BEFORE CONSTRUCTION.

Figure 3-4a. Straight Log Weir

(Not To Scale)

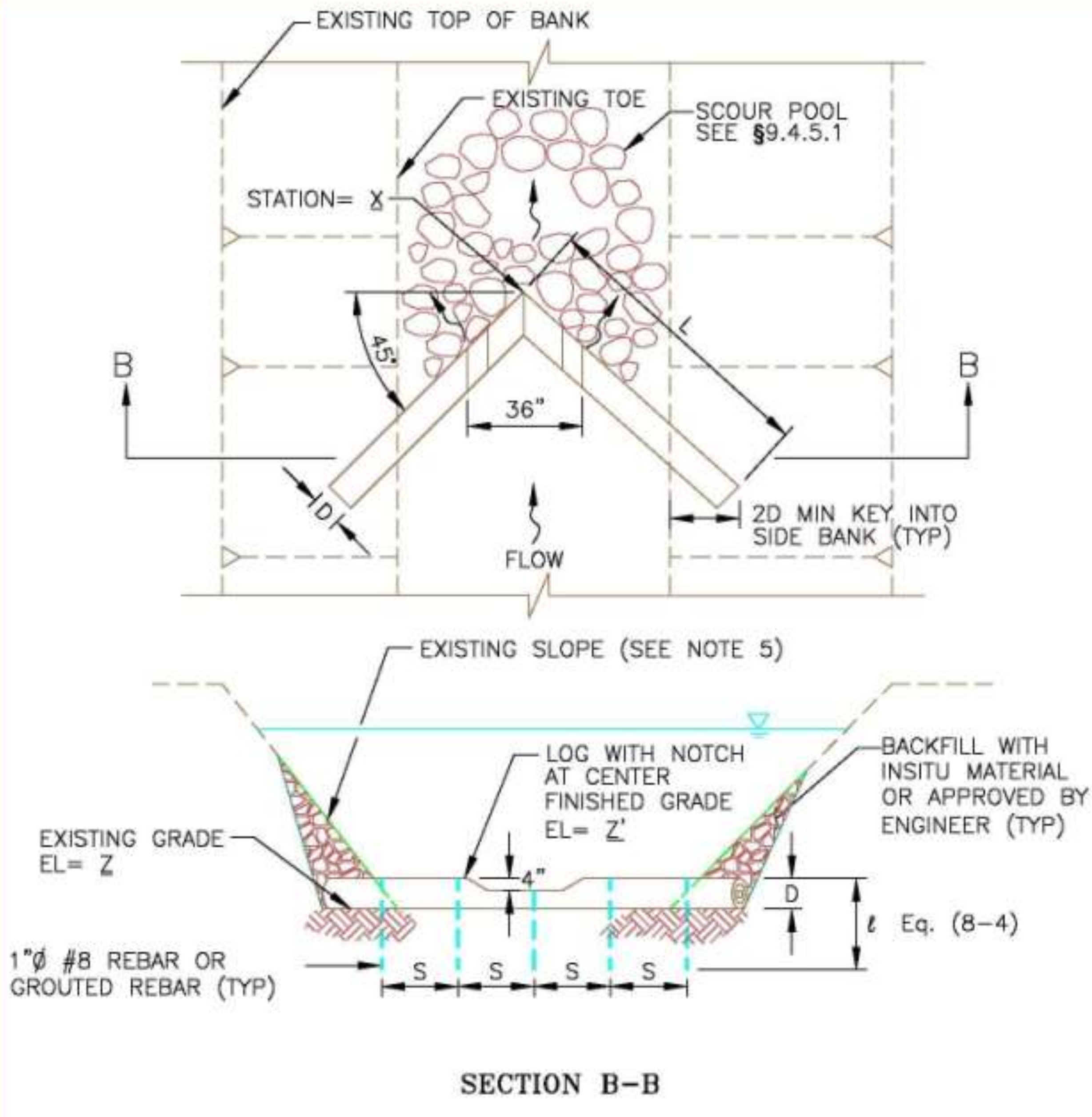


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Figure 3-4b. Downstream – V Log Weir

(Not To Scale)

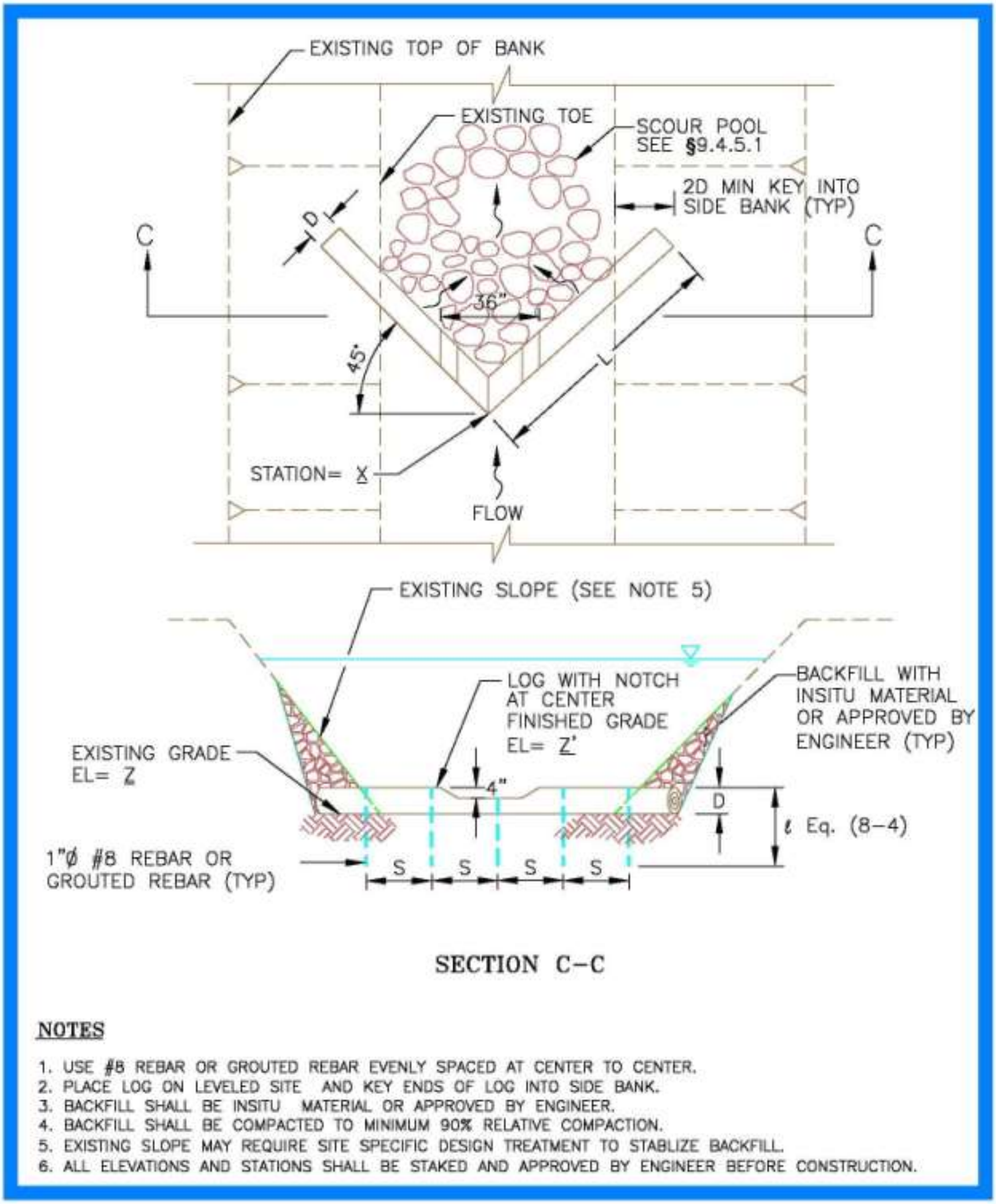


Figure 3-4c. Upstream – V Log Weir

(Not To Scale)

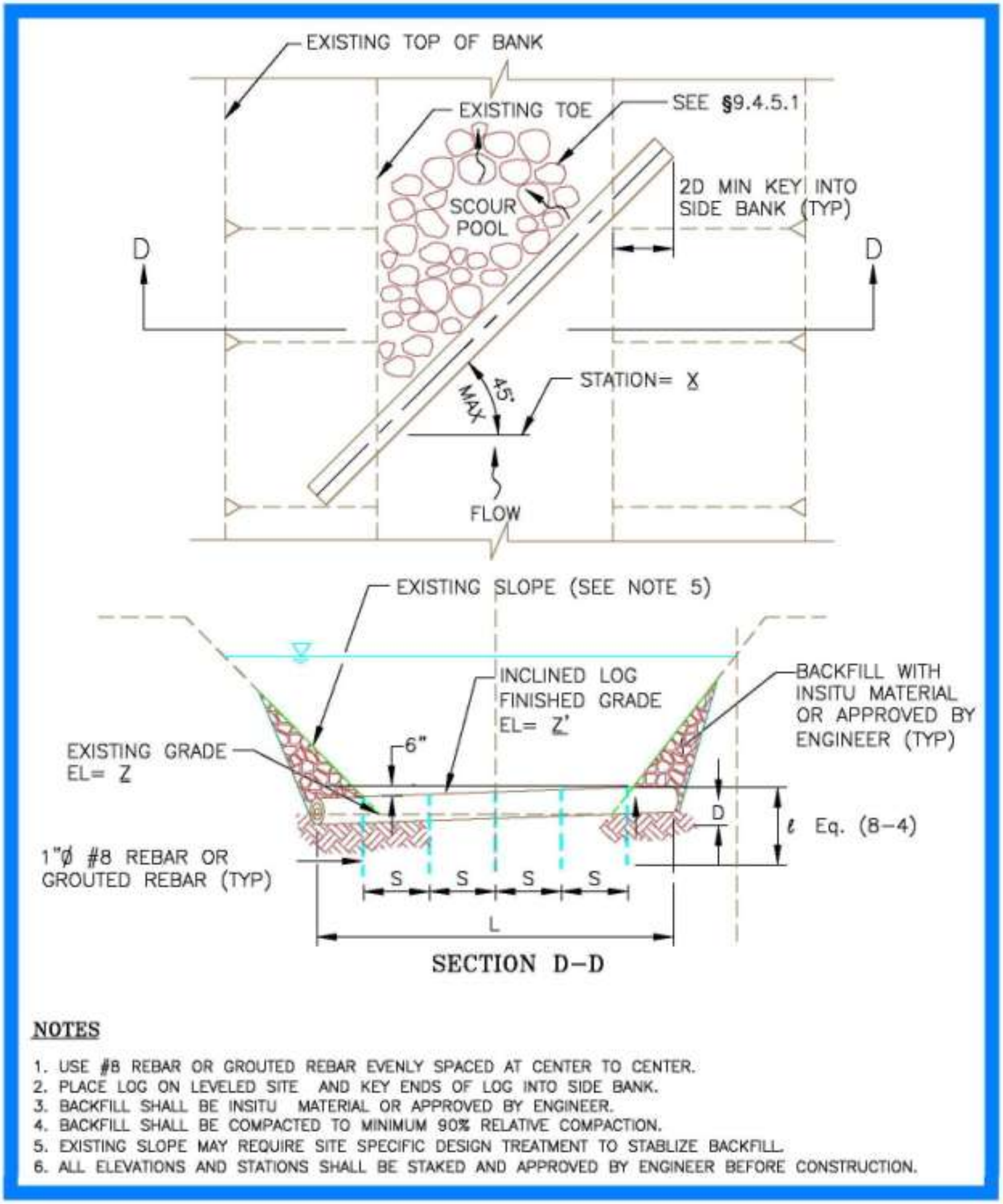


Figure 3-4d. Diagonal Log Weir

(Not To Scale)

Balancing the buoyancy force on the log and the resistive force on the rebar, we can compute the required length of the rebar in soil as:

$$l = \frac{(1 - sg)\gamma_w S D^2}{4 f d} \qquad (3\text{-}4)$$

where l = length of rebar embedded in soil, ft

sg = specific gravity of log

γ_w = specific weight of water, lb/ft^3

S = center-to-center spacing between rebars, ft

D = diameter of the log, ft

f = skin friction between soil and rebar, lb/ft^2

d = rebar diameter, ft

The skin friction is a characteristic of the soil. The value should be determined by a geotechnical engineer from boring samples. Typically this value is higher than 300 lb/ft^2 in our creeks except the muddy tidal reaches.

As an example, using #8 rebar, d = 1 inch = 0.083 ft, a Douglas Fir log of 1 ft diameter and specific gravity of 0.53, a rebar spacing of 4 ft, and a soil skin friction of 300 lb/ft^2, the required anchor length is 1.2 ft. Allowing a safety factor of 2 and 5 ft of development length, a nominal anchor length of 10 ft is appropriate, as suggested by California [2006].

The impact or shear force on the log will be withstood by the anchor design with sufficient factor of safety.

Design Procedure

(1) Consult a geotech engineer to determine the site-specific skin friction of the soil.

(2) If the skin friction is higher than 300 lb/ft^2, use #8 size rebar and an appropriate spacing of approximately 4 ft, and a suitable log size of approximately 12 inches to compute the required anchor length. The 12-inch diameter log, #8 size rebar and 4 ft spacing are elements of a standard design applicable to most situations in the Santa Clara Valley.

(3) If the skin friction is less than 300 lb/ft^2, grout #8 rebars in 4-in-diameter predrilled holes. This will entail the application of a concrete pump truck and a boring rig. If this equipment is not feasible to the site, consult a geotech engineer and perform analysis to evaluate other alternatives or the risk of using the standard design.

(4) Design the scour pool, including dimensions, rock size, gradation and filtering layer, as described in Sections 5.2 and 5.4.

(5) Prepare design drawings similar to Figure 3-4.

If multiple layers of logs are used, replace the single-log diameter D in Eq. (3-4) with an equivalent log diameter that provides the same cross-sectional area for the multiple logs. In this case, bolt the logs together with #6 rebars at 4 ft spacing.

A scour pool will, in most cases, accompany a weir type of drop structure. It provides the necessary energy dissipation and prevents undermining of the weir structure. The scour pool design is provided in Section 5.4. Backfill the upstream side of the weir from the top of log down on a 1V:20H slope. This should be included as part of the construction scope of work to prevent piping from being developed through the bottom of the log. Further deposition will occur naturally afterwards to fill to an equilibrium slope.

A few requirements to prepare the site, logs and rebars for construction are provided in the technical specifications below:

Technical Specifications

(1) The site of the log weir shall be cleared and grubbed to remove any organic matters the presence of which may affect the integrity or longevity of the weir structure. The weir foundation shall be leveled to the design elevation and form a continuous contact surface with the log. The contact between foundation and log shall be inspected by the Engineer before rebar anchors are installed.

(2) The banks shall be excavated to key 3 ft of log inside the bank. After the log(s) are anchored, the keys shall be filled with gravel and soil and compacted to conform to the existing side slope.

(3) Install a scour pool downstream of the weir according to design.

(4) The Engineer shall inspect the anchored and keyed-in log(s) to ensure smooth transition to the side slopes and scour pool. The upstream side of the weir shall then be filled with soil from the top of log toward upstream on a 1:20 slope. The backfill material shall have a size gradation similar to that of the native soil. Excavated material from the scour pool area may be used for this fill, unless otherwise directed by Engineer.

(5) Prior to installation, all barks from the log shall be removed. The log shall be shaved to provide a smooth surface. The bottom face of the log which will be in contact with the foundation shall be shaved to a flat surface of 3-inches wide. The logs shall be pre-drilled to provide 1 inch holes for rebar anchors. At the top of the log where the anchor terminates, recessed bolt holes shall be provided to prevent the rebar from protruding into the flow.

(6) The rebars shall be ribbed, epoxy coated, and threaded at the top end to be bolted to the log. The last 4 inches of the bottom end may be tapered to facilitate penetration into soil. A typical design of the bolt connection is shown in Figure 3-4e.

(7) The finished elevation of the weir and scour pool shall be surveyed, recorded, reviewed and approved by Engineer, and incorporated into as-built drawings.

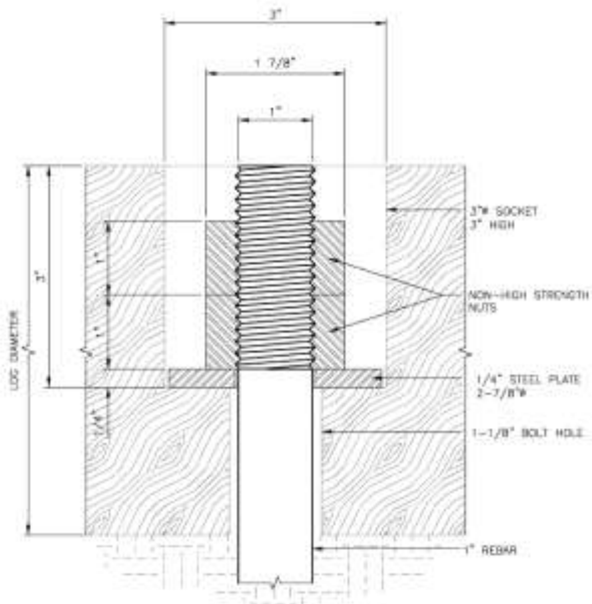


Figure 3-4e. Typical Design of Bolt Connector for Log Anchors

3.4.1.2 Straight Rock Weir

A simple straight rock weir may be designed to control grade in an incised channel. The consideration again is to minimize intrusion into the flow area and stability of the rocks.

Use the USACE [1994] equation for steep-slope channel to size the rock. Refer to details of the USACE equation in Section 5.2. The approach is to build the weir using a fairly uniform size of rock that is stable under the design flow condition. The specification on gradation will provide a size distribution that is practical for the contractor to supply the material. Because of limitations imposed by the incised channel, this design does not require key-in into the side slopes. Instead two rows of rocks interconnected horizontally will be used to provide sheltering and aid stability. A smooth transition to both banks and the downstream scour pool is critical to avoid erosion caused by flow separation around blunt edges.

Design Procedure

(1) Determine the design flow for the weir using Eq. (3-1) and compute the corresponding average velocity in the channel using HEC-RAS.

(2) Use the USACE Eq. (5-7) provided in Section 5.2.1.2 to determine the minimum rock size (D_{min}) under the design flow condition. If the D_{min} rock size is less than the drop size, use the drop size as D_{min} for the weir. If D_{min} is larger than the drop size, excavate the foundation to allow placement to the controlled elevation.

(3) Determine gradation for the weir rocks: $D_{85}/D_{15}<1.4$.

(4) Design the scour pool as described in Section 5.4.5.1.

(5) Size the scour pool rocks as described in Section 5.2.1.3.

(6) Design the filter layer for the weir and scour pool as described in Section 5.2.2.

(7) Provide design drawings as shown in Figure 3-5.

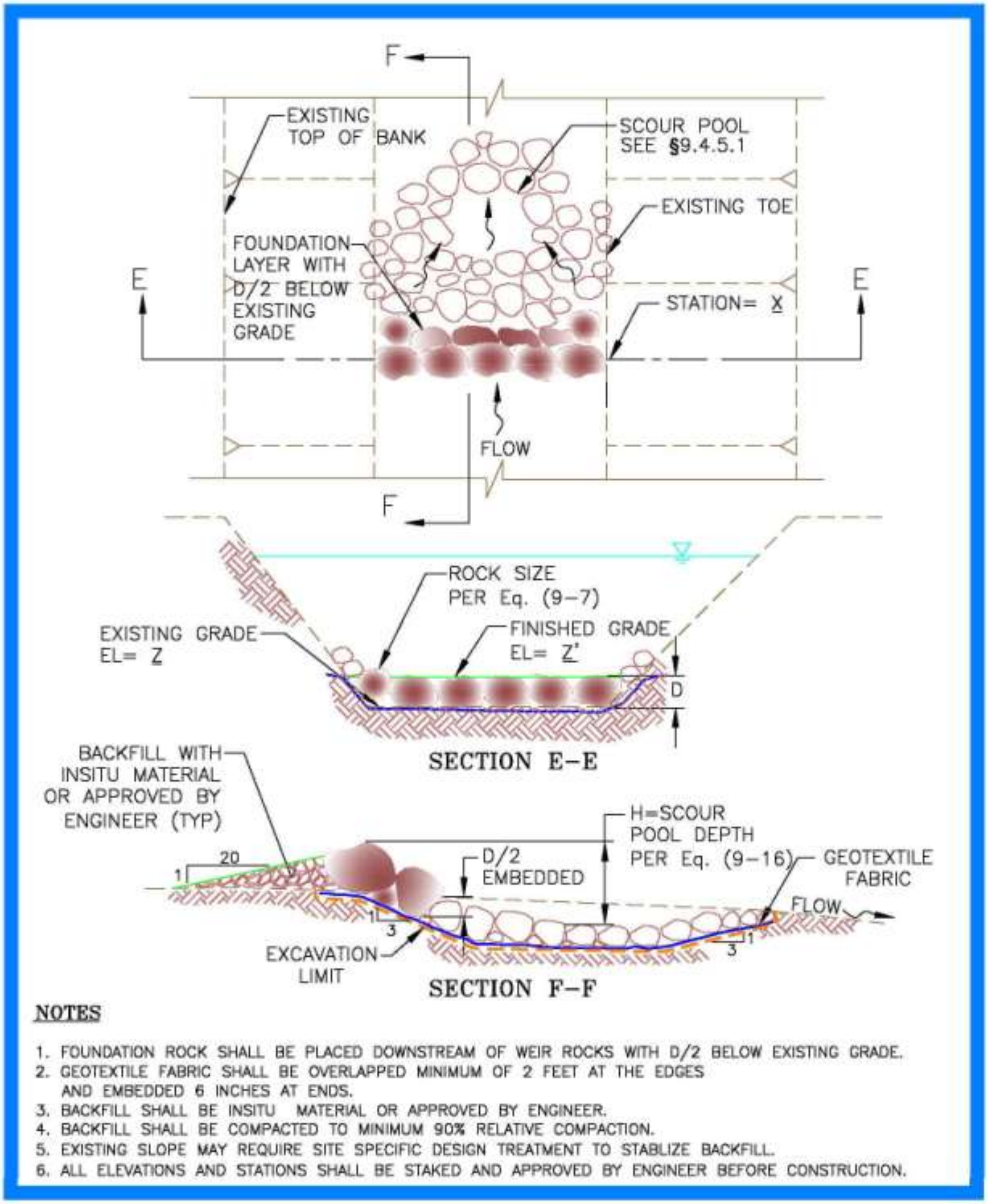


Figure 3-5. Straight Rock Weir

(Not To Scale)

Technical Specifications

(1) The rocks used to build the weir shall be quarry stone, angular, with no axis greater than 1.5 times any other. It is preferable to have a relatively flat surface on the long axis. The rocks shall be of good quality with no observable fracture lines.

(2) Clear, grub and level the channel bottom to prepare for rock weir foundation. Remove any organic material.

(3) The rocks of the weir shall be placed individually with the aid of a front-end loader. The top of rock elevation shall conform to the controlled elevation shown on the drawings.

(4) Excavate, if necessary, the channel downstream in the scour pool area, in accordance with the drawings, to prepare for scour pool construction. The rocks of the scour pool may be placed by machine, but positioned and leveled according to design.

(5) Smooth the transition to channel banks. Fill voids with gravel. Fill the top, upstream and downstream edges of rock with graded cobbles and gravels to make a smooth transition to the natural channel boundary.

(6) Fill the upstream reach from the top of rock on a 1:20 slope with natural, in-situ bed materials. The same material excavated from the scour pool may be used for this fill.

The finished elevation of top of weir, center of scour pool, and end of scour pool shall be surveyed, recorded, reviewed and approved by Engineer, and incorporated into the as-built drawings.

3.4.2 Bankfull-and-Floodplain Channel

When the channel cross-section in the project reach includes a bankfull channel (with or without a low flow channel) and floodplains, the shear force exerted on the channel boundary may reduce as flow spills onto the floodplains. This phenomenon was illustrated in Figure 9-12b(3). The reduction in shear stress may also provide relief to the design flow requirement of Eq. (3-1). In addition, expansion of the physical boundary from bankfull to floodplain affords constructability to certain types of grade control structure that were not suitable in incised channels. Two examples of these grade control structures are the vortex weir and Newberry riffle, which will be described in the following. The grade control structures described in Section 3.4.1 for incised channels may also be used in a bankfull-and-floodplain type of channel geometry.

3.4.2.1 Vortex Weir

A vortex rock weir is weir of rocks forming a V shape with the apex pointing upstream. The two legs slope down from the bankfull level to the apex at the desired bed elevation. Sketches of a vortex rock are shown in Figure 3-6. Similar designs were also called porous weir [Washington State 2003] and cross-vane weir [Rosgen 1996].

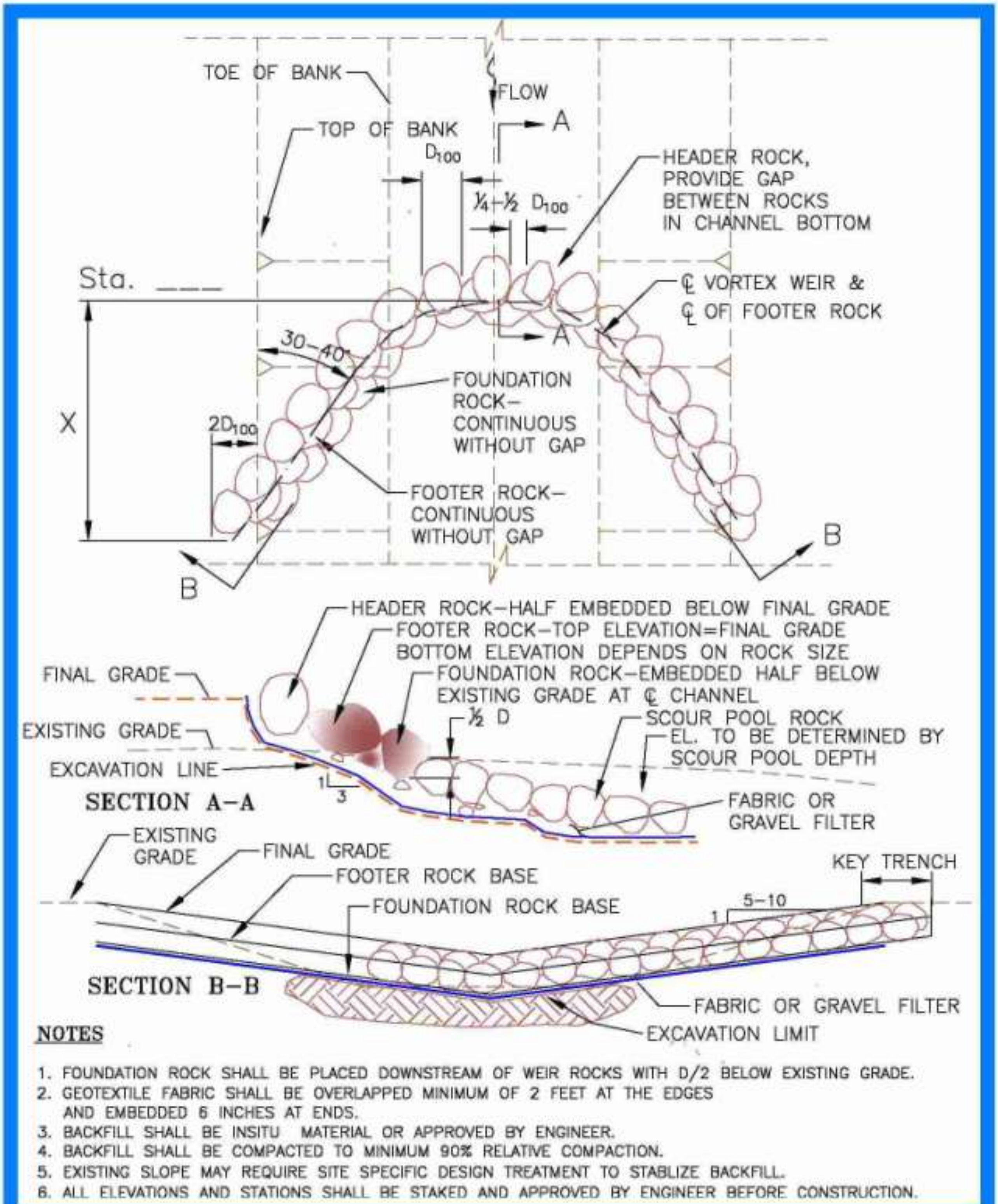


Figure 3-6. Vortex Rock Weir

(Not To Scale)

As shown in Figure 3-6, the weir is composed of a row of header rocks, a row of footer rocks and a row of foundation rocks. The header rocks are installed with half of its size embedded below the final grade. The header rocks within the bottom of the bankfull channel are spaced with a gap to facilitate low flow and fish passages. The footer rocks are installed downstream of and at a lower elevation than the header rocks to provide support. They form a continuous row, without gaps. The top of the footer rocks are positioned at the final grade. The foundation rocks are installed downstream of and at a lower elevation than the footer rocks. They also form a continuous row without gaps. Half of the foundation rocks are embedded below the existing grade. The foundation rocks are also connected to the scour pool to prevent undermining from turbulence generated in the pool.

Because of the depressed apex at the center, a vortex weir helps concentrating flow toward the middle of the stream and away from the banks. Its two legs are designed to terminate at the floodplain level. Hence, it will block off some flow area in the bankfull channel and raise the water level. But because of the existence of floodplains, the raised water level is absorbed quickly by the floodplains without causing significant impact to the flood hydraulics. This is generally the case when $W_{fp}/W \geq 1$. In any case, the flow velocity and increased shear stress as a result of raised water level shall be analyzed in the 60% design to determine the effect of the weir and finalize the design.

With the channel boundary opening up at the floodplain level, the weir may be properly keyed into the side slopes, an advantage not easily afforded by incised channels. Each leg of the weir typically makes an angle of 30 – 40 degrees with the bank.

Design Procedure

(1) Determine design flow using Eq. (3-1). Compute the average existing channel velocity using HEC-RAS.

(2) Size the rocks and gradation using the Isbash method described in Section 5.2.1.2.

(3) Design the filter layer as described in Section 5.2.2.

(4) Based on thickness of the filter layer and size of weir rocks, layout location and elevation of the header and footer rocks in accordance with details of Figure 3-6.

(5) Update the HEC-RAS model using the design cross-section to re-compute the channel velocity, and repeat Step 2 to check rock design. Repeat the procedure until a consistent design is obtained.

Design Considerations

The vortex rock weir designed in this way has a fairly uniform gradation that can withstand the shear force of the design flow condition. The 3-row design allows partial embedment and interlocking to provide support for the weir structure. The alignment and final elevation of the weir are determined by the footer rocks. The top of the footer rock conforms to the final grade that we want to achieve. The rock size, existing grade elevation, final grade elevations and weir alignment then determine the overall weir design. The final grade, footer rock baseline, foundation rock baseline and excavation limit shall be clearly identified in the drawing. It is this design detail that is lacking in most references but is crucial to the stability of the weir structure.

3.4.2.2 Newberry Riffle

The Newberry riffle is a design that uses rocks to form a shallow riffle area to control grade as well as enhance the aquatic habitat. It is also called grade-control rock ramp in some references.

The design sketches for a Newberry riffle is shown in Figure 3-7. These sketches follow closely that prepared by APWA [2006]. They present the information that needs to be provided through design and shown on construction drawings.

The design includes a rock crest, a mild (1:20) downstream ramp, and a steeper (1:4) upstream slope. The crest also extends from the top of bank toward the center of the channel in an upstream-oriented V or arch shape. This feature is similar to the vortex weir design. The downward slope of the crest depends on the stream width, weir height and bankfull channel depth, but typically varies from 1 on 5 to 1 on 10. The crest is also keyed into an excavated key trench. The detailed requirements are shown in Figure 3-7. The design procedure is described below.

Design Procedure

1. Determine design flow using Eq. (3-1). Compute the existing average channel velocity using HEC-RAS.

2. Size the D_{50} stone using Eq. (5-8) and (5-2).

3. Determine thickness of the ramp using Eq. (5-9). Determine the depth and width of the key trench under the crest in accordance with Figure 3-7.

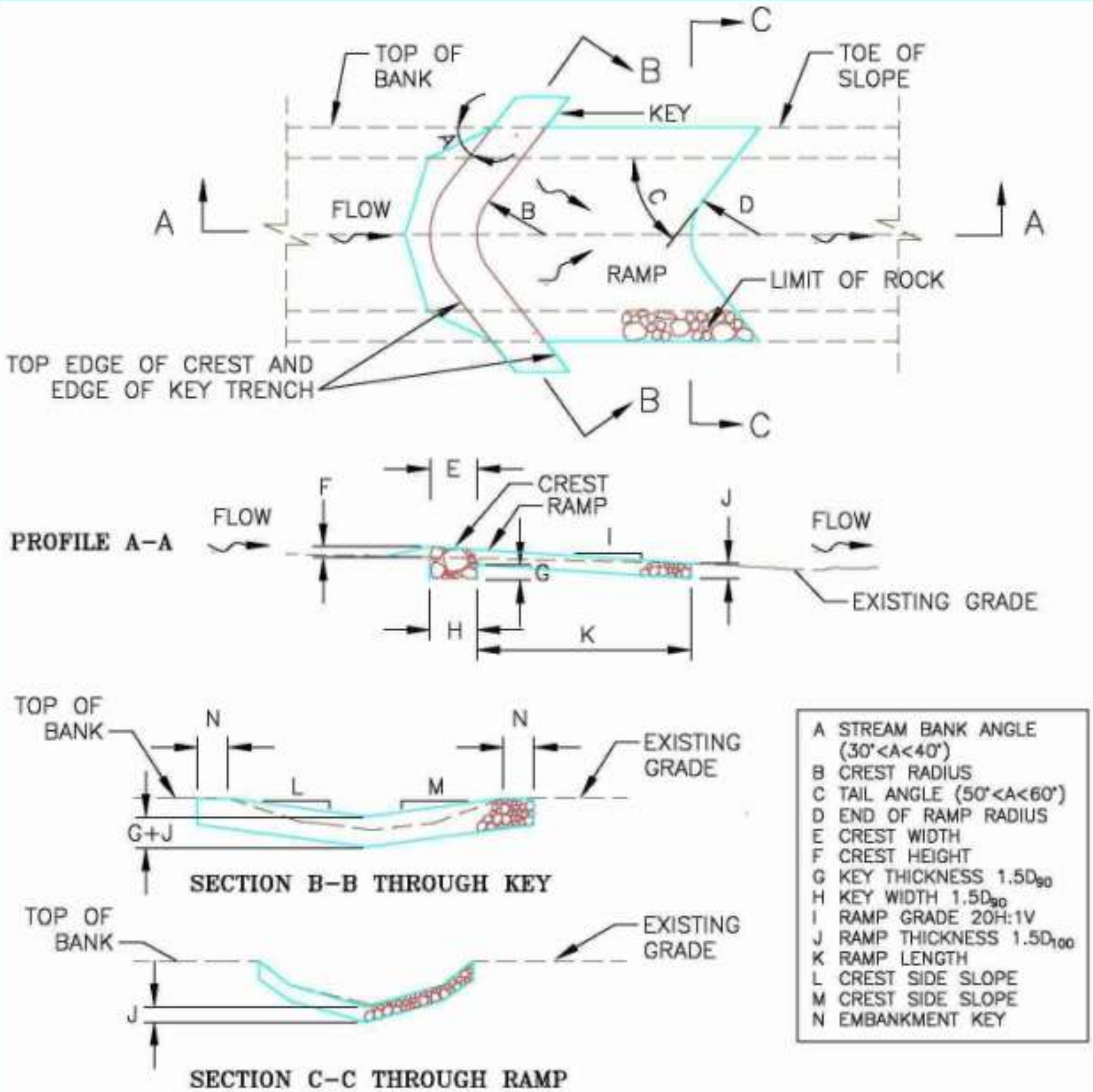
4. Specify gradation as provided in Table 5-1.

5. Lay out the design in accordance with Figure 3-7.

6. Incorporate the design cross-section into the HEC-RAS model, compute the average velocity over the as-designed riffle structure, and update rock design as necessary.

Design Considerations

The Newberry Riffle is a structure composed of one gradation of rocks laid out in a pre-designed form. There is no distinction in rock sizes among different parts of the structure. Hence, it is suitable for cross-sections with wide (Wfp/W>1) floodplains where the bottom shear stress is enveloped by the bankfull condition and the required rock size is not out of proportion. For cross-sections with narrow floodplains, the design flow is likely much higher than the bankfull discharge, and the rock size will then be large. In that case, it is reasonable to go with a design for incised channel, as described in Section 3.4.1.



NOTES

1. THE DEPTH OF KEY TRENCH SHALL BE A MINIMUM OF 1.5 D_{90}. THE CREST SHALL SLOPE DOWNWARD FROM THE STREAM BANK TO THE CENTER OF THE STRUCTURE TO FOCUS THE FLOW TO THE CHANNEL CENTER. THE TAIL RAMP IS GENERALLY SLOPED AT 20 HORIZONTAL TO 1 VERTICAL AND DISSIPATES ENERGY GRADUALLY OVER ITS LENGTH. THE UPSTREAM FACE IS NOT PERPENDICULAR TO THE FLOW BUT HAS AN UPSTREAM ORIENTED "V" OR ARCH SHAPE IN PLAN FORM.
2. FOR ITEM A, STREAM BANK ANGLE, AND ITEM C TAIL ANGLE, THE LOWER END OF THE RANGE SHOULD BE USED FOR SOFTER SOILS.
3. FOR ITEMS L AND M, CREST ANGLE, THE TYPICAL RANGE IS 5 TO 1 TO 10 TO 1.

Figure 3-7. Newberry Riffle

(Not To Scale)

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