

APPENDIX N
ROCK WEIR DESIGN

N. Rock Weir Design

N.1 Rock Weir Sizing

The rock within a rock weir must resist active forces of drag, lift, and buoyancy while subjected to flowing water in a creek. The cap layer rocks, as well as the rocks beneath in a weir, will resist the collective active forces, and must be sized accordingly. The methods for sizing rocks comprising a rock weir are Field Inspection, Rock Slope Protection (RSP) Revetment Design, Boulder Cluster Design, and Hydrostatic (Overturning Moment).

After calculating rock size using the three methods mentioned above, engineering judgment shall be incorporated in deciding which result should be used for design and construction. The most conservative or largest rock size is not necessarily the best choice, especially if a great disparity exists between the sizes calculated using the other methods.

N.1.1 Field Inspection Method

In addition to the project limits within the creek, upstream and downstream reaches should be investigated for large, stable rocks (boulders) in the stream that appear to be immobile during overtopping flows. Some stability indicators to look for in the field are salt and silt stains on a boulder, moss and lichen growth on a boulder, and bar or terrace development around a boulder or group of boulders. These bars typically contain vegetation, as well as coarse gravels and cobbles.

Once stable rocks are located in the field, their rough diameters need to be measured in the direction of at least two of the three principle axes (long, short, and middle). The measurements of each boulder should be averaged to find their approximate or rough diameter. After the rough diameters are determined, use Table N-1 to find the RSP Class corresponding to the rough D_{50} measured in the field. The information in Table N-1 is consistent with the *California Bank and Shore Rock Slope Protection Design Report (CA RSP Report)*:

RSP Class	Rough D_{50} (ft)
Cobble	0.66
Backing No. 1	0.95
Light	1.32
¼ Ton	1.79
½ Ton	2.26
1 Ton	2.85
2 Ton	3.59
4 Ton	4.50
8 Ton	5.70

Table N-1. RSP Class Rough Diameter

N.1.2 RSP Revetment Design Method

When using this method, a rock weir is analyzed as a revetment following the procedures outlined in the *CA RSP Report*. The minimum weight of rock that will resist forces from flowing water and remain stable is calculated based on a factored velocity, rock angle of repose, and rock specific gravity.

Because the *CA RSP Report* equation is being applied to the sizing of a rock weir rather than an RSP revetment, certain modifications can be made. For instance, the angle of repose of the stacked/placed rock can be simplified for rock weir analysis. When stacking or placing rock to build a weir, the steepest repose angle, recommended by the *CA RSP Report*, will be used to reduce rock quantity, as well as improve constructability. Basically, the flatter the rock weir side slope, the wider its base width will be (See Figure N-3), and the greater potential that individual weirs within a series will intersect or conflict with each other. It would be difficult to construct the weirs to the proper dimensions and tolerances if the rocks are all merged together. This would compromise the function of the weir, in addition to complicating the construction process. So, it is advantageous to have the steepest slope feasible for rock placement to avoid these problems.

In contrast, the rock for a revetment is controlled by the natural slope of the banks and will change at each project site, whereas the rock within a weir can be placed at the same angle of repose in all cases with only minor influence from each site condition. Given 1.5:1 as the recommended slope for rock weir placement for all cases, the angle of repose will be 36.3 degrees. Therefore, a modified version of the *CA RSP Report* equation can be expressed as follows:

$$W = \frac{0.00002V^6SG}{0.207(SG - 1)^3}$$

Where:

W = minimum rock mass (pounds)

*V = 1.33 V_{max} (ft/s)

SG = rock specific gravity

*In RSP revetment design, the velocity term is factored to consider parallel or impinging flow conditions. For parallel flow, the average stream velocity is multiplied by a 0.67 factor, while a 1.33 factor is applied to average stream velocity for impinging flow conditions.

For in-stream weirs, flow will be impinging on the weir in all cases and a 1.33 factor is applied to increase average stream velocity as applied in the *CA RSP Report*. Basically, the velocity vector from the stream flow will act directly on a weir in a perpendicular direction, and it will be also be subjected to secondary currents providing higher than average velocities. The average stream velocity should correspond with a 50-year flow at a minimum for rock weir sizing.

The calculated weight (W) will correspond to an RSP material class, which is summarized in Table N-2. For example, W= 1000 pounds corresponds to a ½ Ton RSP class, W= 2000 pounds corresponds to a 1-Ton weight class, etc. When sizing rock weirs, ½ -Ton RSP is the lightest rock to be used to ensure conservatism due to adapting design methods that were not developed specifically for rock weir analysis.

Caltrans RSP Class	Weight (lbs)
Backing No. 1	75
Light	200
¼ Ton	500
½ Ton	1000
1 Ton	2000
2 Ton	4000
4 Ton	8000

Table N-2. Caltrans RSP Class Weights

N.1.3 Boulder Cluster Design Method

This simplistic approach uses a table containing minimum boulder diameters and their associated critical shear stress (τ_c) and critical velocity (v_c) assuming a rock/boulder angle of repose equal to 42 degrees (approximately 1.8:1) and rock specific gravity equal to 2.65. The τ_c and v_c values were determined considering drag, lift, and buoyancy forces acting on the rocks/boulders. For the minimum diameter given in the following table, the rock/boulder will be stable during turbulent flow with it fully immersed. In other words, incipient motion will occur for a given rock/boulder diameter when stream velocities are higher than the critical velocity shown in Table N-3.

Generic Rock Class	Min. Dia. (in)	τ_c (lb/sf)	v_c (ft/s)
Very Large Boulder	>80	37.4	25
Large Boulder	>40	18.7	19
Medium Boulder	>20	9.3	14
Small Boulder	>10	4.7	10
Large Cobble	>5	2.3	7
Small Cobble	>2.5	1.1	5

Table N-3. Boulder Cluster Design Method- Minimum Rock Diameter

If an average stream velocity equals 16 ft/s, a minimum rock diameter of 28 inches can be interpolated from Table N-3. From Table N-1, a 28-inch or 2.33-foot rough diameter boulder would be classified as a ½ Ton RSP class, having weight equal to 1000 pounds.

N.1.4 Hydrostatic (Overturning Moment) Method

This analysis method is best applied to a Rock Weir (Type 2) described in Section N.8. For this method, resultant pressure and buoyancy forces are considered acting on a single rock within a weir, and this rock will resist these forces through its mass. Frictional resistance between the rock being analyzed and the stream bed would also resist these active forces, but is being ignored because this force is fairly small. Conservatism is further applied by also ignoring the mass

resistance of backfill on the downstream side of a rock. Essentially, a top layer rock is analyzed on a level, frictionless plane where only its mass will prevent movement. A free-body diagram of the hydrostatic forces is shown in Figure N-1.

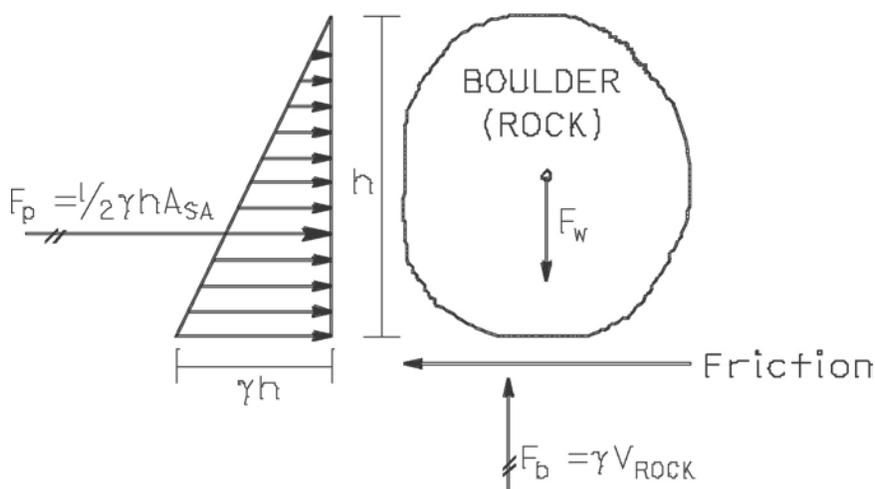


Figure N-1. Rock Free Body Diagram

F_p = Pressure Force (lb)

F_b = Buoyancy Force (lb)

F_w = Mass of Boulder (Rock) (lb)

h = Height of Water Column Associated With Design Storm Flow (ft)

γ = 70 lb/ft³ (Water & Suspended Sediment)

A_{SA} = Surface Area of Boulder (Rock) (ft²)

V_{ROCK} = Volume of Boulder (Rock) Based on Radius = $\frac{4}{3}\pi r^3$ (ft³)

The first step is to determine the height of the water column or flow depth associated with the design flow, which is typically done by developing a HEC-RAS model of the stream. Secondly, an initial estimate of rough rock diameter is performed so that mass, rock volume, and surface area can be calculated.

Once the active and resistive forces are determined for a chosen rock diameter, overturning moments can be calculated and stability analyzed based on the ratio of the sum of active and resisting overturning moments. Moment-ratios ($\Sigma M_{Resist} / \Sigma M_{Active}$) below 1 signify instability, equal to 1 indicate neutral stability, and ratios above 1 show stability. Rock diameter can be varied until proper stability results are achieved. See Table N-4 for example overturning moment and stability analysis.

f_P (LBS)	F_B (LBS)	F_W (LBS)	M_P (FT-LBS)	M_B (FT-LBS)	M_W (FT-LBS)	Σ ACTIVE: M_P+M_B (FT-LBS)	Σ RESIST: M_W (FT-LBS)
6,752	13,504	24,000	22,147	45,795	120,000	67,942	120,000

Table N-4. Example Summary of Hydrostatic Forces (F) and Overturning Moments (M)

$$\text{Factor of Safety} = \Sigma M_{\text{Resist}} / \Sigma M_{\text{Active}} = 120,000 / 67,942 = 1.8$$

N.2 Rock Weir Embedment

The depth or embedment of the rock weir is dependent upon the estimated scour potential for the site. An exact method for determining scour depth at a rock weir does not exist, but it can be estimated by one of two methods: Field Inspection/Topographic Survey and Toe-Scour Estimate Equation.

N.2.1 Field Inspection/Topographic Survey Method

Because scour depths typically are not observed during the peak of a significant storm when flow and sediment movement would be at their highest, a safety factor of 1.2 is applied to observed scour depths. As flow decreases on the descending limb of a hydrograph, suspended sediment begins to deposit. This means that scour holes found in the field during clear weather conditions are smaller than during peaks of storm events.

$$\text{Design Scour Depth} = 1.2(D_{\text{FOD}})$$

Where:

$$D_{\text{FOD}} = \text{Field Observed Depth of Scour}$$

N.2.2 Toe-Scour Estimate Method

For this method, scour depth will be calculated considering the rock weir as a stabilized bendway. Similar to a bendway section of channel, the vortex-shaped rock weir will be subjected to secondary currents, which cause higher velocities and shear stresses. These conditions will trigger greater scour around a rock weir, as well as changes in sediment transport and supply.

The toe-scour equation is empirical and was developed by synthesizing laboratory and field data. The scour depth calculation is dependent upon mean channel depth and water surface width upstream of a bend or weir, in addition to centerline bend radius and maximum water depth in bend.

Within the scour depth calculation, two ratios are incorporated. The first ratio is the centerline bend radius divided by the water surface width upstream of a bend or weir (R_c/W), while the second ratio is this same water surface width divided by the mean channel depth upstream of a bend or weir. (W/D_{mnc}). Since the equation is empirical, limits apply to its use, more specifically to the R_c/W and W/D_{mnc} ratios. Based on the range of field and laboratory data sets, R_c/W is limited from 1.5 to 10 and W/D_{mnc} limited from 20 to 125. In other words, when W/D_{mnc} is calculated to be less than 20, a value of 20 must be used. Conversely, a value of 125 must be used when W/D_{mnc} is calculated to be above 125.

As for the R_c/W ratio, it is of course dependent upon the centerline bend radius. Because the toe-scour equation is being adapted to apply to rock weir design in straight and bending channel sections, 1.5 will be used as the default value. By using 1.5 for all cases, calculated potential scour depths will be conservative.

Finally, the equations used in estimating scour depth in this method are:

$$\text{Scour Depth} = D_{mxb} - D_{mnc}$$

Where:

D_{mxb} = maximum water depth at weir (feet)

D_{mnc} = mean channel depth upstream of weir (feet)

$$D_{mxb} = 1.14D_{mnc} \left(1.72 + \frac{0.0084W}{D_{mnc}} \right)$$

Once the scour depth is calculated, this depth will be used to specify the embedment depth of the rock weir with reference to the channel bed finished grade surface. The height of rock weir above the channel bed will be determined during the hydraulics analysis.

The total height of the rock weir, equal to the height above channel bed plus the embedment depth, must be equal to or greater than the recommended RSP class thickness recommended by the *CA RSP Report* displayed in Table N-5.

Caltrans RSP Class	Minimum Thickness (ft)
½ Ton	3.40
1 Ton	4.30
2 Ton	5.40
4 Ton	6.80
8 Ton	8.50

Table N-5. Minimum Caltrans RSP Class Thickness

After the height of the weir is determined through hydraulics analysis, which is measured above the channel bed, the total rock weir thickness must be equal to or greater than the required minimum found in Table N-4. If the embedment depth plus the rock weir height is less, the minimum RSP Class layer thickness would control.

Below the rock weir, a 1.8-foot (or 2-foot) layer of Backing No. 1 RSP underlain by RSP Fabric is needed to provide filtration beneath all rock weirs. This filter layer will prevent soil movement and loss of fines from piping, and ultimately improve rock weir stability.

See Figure N-3 for embedment depth, rock weir height, and filter layer illustrations.

together with their combined mass would have to be constructed to obtain an adequate resisting moment. Using two rows of 5-foot (6-Ton) rocks, placed one behind the other in the direction of Rock Weir Geometry

The components of rock weir geometry include crest width, side slope ratio, and plan-view radius. As mentioned previously, the side slope ratio will be 1:1.5 for all rock weirs, but the crest width and plan-view radius must be calculated. The crest width is simply expressed below, where D_{50} is associated with the rock weir RSP class.

$$\text{Crest Width} = 2 (\text{Rock Weir } D_{50})$$

The other rock weir geometry element to consider is the arc, plan-view shape. See Figure N-1. The mid-chord offset of the arc is equal to 3 times D_{50} of the rock weir RSP class. The chord length will equal the distance between the left and right toes of slope. After determining the mid-chord offset and chord length, the radius of the arc can be determined with the equation below:

$$R = \frac{L^2}{8m} + \frac{m}{2}$$

Where:

R = rock weir radius (feet)

L = chord length (feet)

m = mid-chord offset = $3 D_{50}$ (feet)

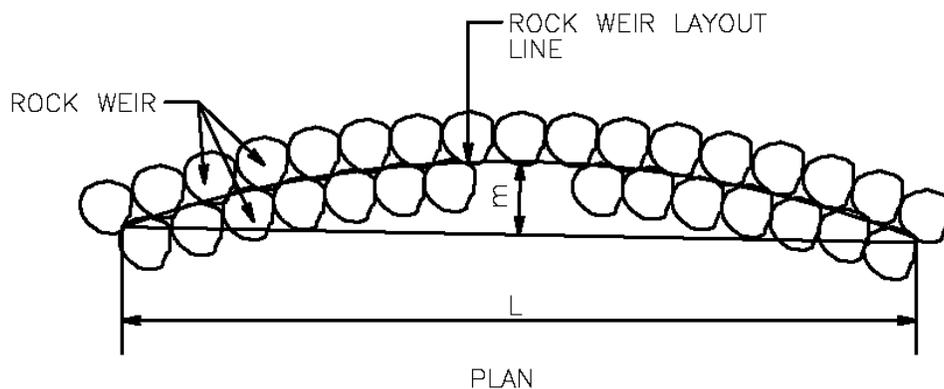


Figure N-2. Rock Weir Plan

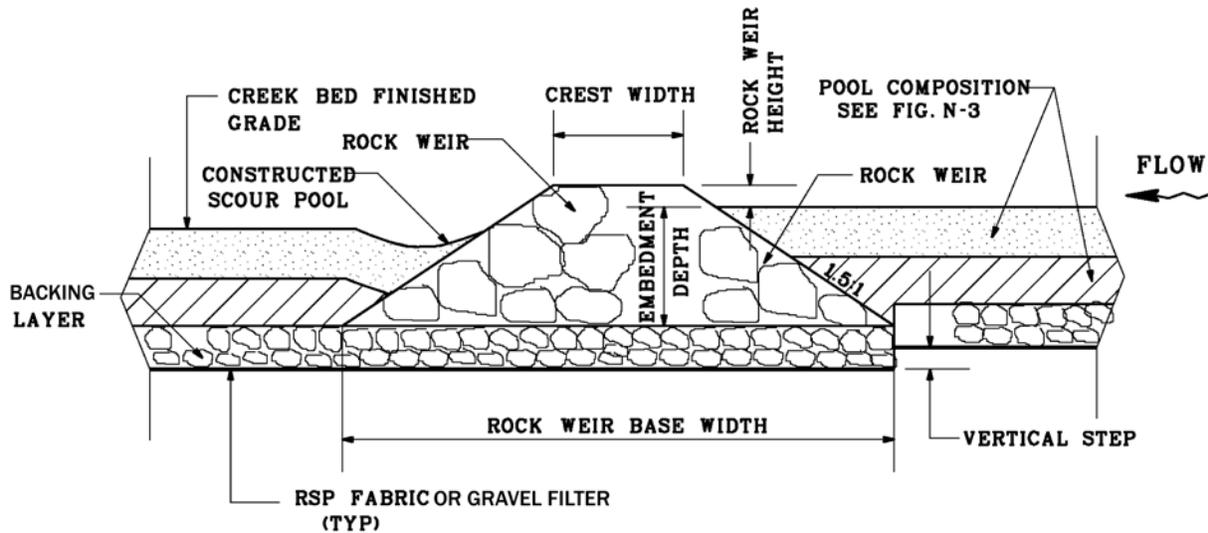


Figure N-3. Rock Weir (Type 1) Profile

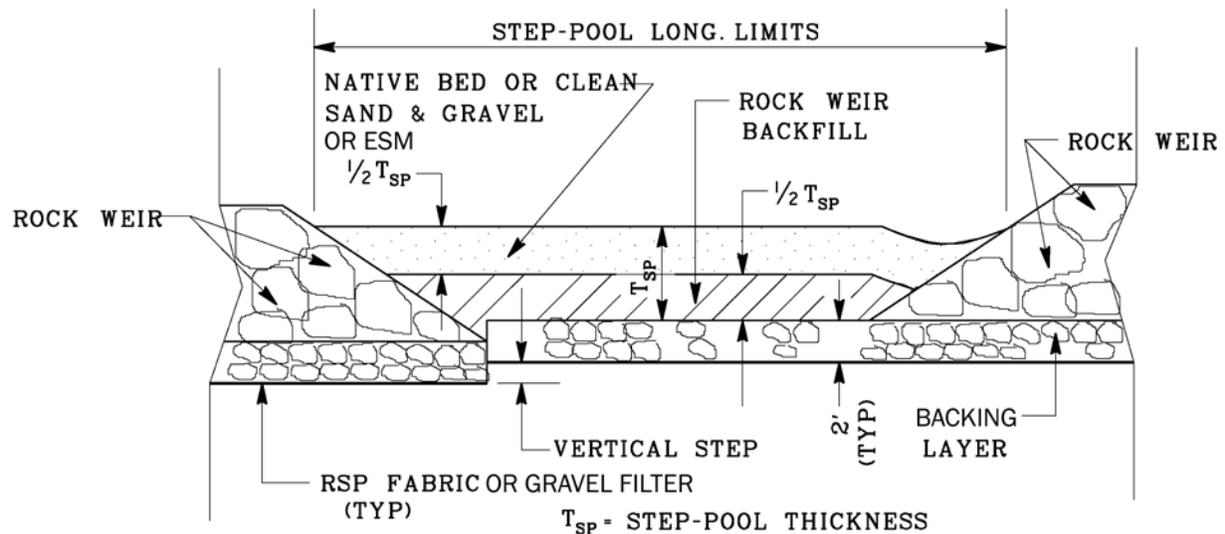


Figure N-4. Step-Pool Profile

N.3 Step-Pool Composition

The portion of the creek between rock weirs is the pool or step-pool, which has a total thickness defined in Figure N-4 as T_{sp} . The total thickness is measured from the creek bed finished grade to the top of the backing layer. T_{sp} dimensions will vary for each project depending on rock weir embedment depth and vertical step height within the pools.

As also seen in Figure N-4, the step-pool is composed of two layers of equal thickness. The top layer is either native bed material, clean sand and gravel, or engineered stream bed mix (see Section N.4), and these materials should be well compacted to 90% relative compaction during placement. The function of the top layer is to support habitat and to allow the development of various micro-pools that will promote resting areas for fish as they move through the rock weir/step-pool system.

During construction, the top 1-foot to 3-feet of the excavated creek bed can be stockpiled on site and later placed or returned to the creek as the step-pool top layer according to specified dimensions. If the excavated material is deemed unsuitable, clean sand and gravel can be imported and placed. The following is a recommended gradation for clean sand and gravel:

Sieve Size	Percentage Passing
1"	100
¾"	60-90
No. 4	25-60
No. 30	0-20

Table N-6. Clean Sand and Gravel Gradation

For bottom layer of the step-pool, a rock weir backfill is recommended that has cohesive properties and well-compacted (roughly 90% relative compaction), somewhat similar to structure backfill. The purpose of this rock weir backfill is to provide stability of the weir at its base, as well as aid in scour resistance. With its cohesive properties, the rock weir backfill will also reduce potential for surface flows becoming subsurface that can occur with a constructed streambed. The properties of the recommended rock weir backfill are as follows:

Minimum Sand Equivalent	50
Maximum Aggregate Size	3"
Maximum Plasticity Index	20
Minimum Plasticity Index	12

Table N-7. Rock Weir Backfill Properties

At the downstream end of a rock weir within the step-pool, a scour pool should be constructed. This scour pool will encourage fish to rest before jumping over the rock weir and continuing their journey. As stated previously, a 2-foot flow depth shall be provided at the downstream end of a rock weir. Even though a scour pool will form naturally over time as flow plunges over a weir, the constructed scour pool will provide immediate benefit after construction.

For recommended "Place Native Creek Bed Material", "Clean Sand and Gravel", and "Rock Weir Backfill" non-standard special provisions, see Appendix O.

N.4 Engineered Streambed Mix (ESM)

For steeper gradient streams, a roughened channel may be desired between rock weirs to provide additional energy dissipation. The ESM can replace the cap layer of clean sand and gravel or native bed material. When this is the case, the following procedure for determining key particle sizes is suggested and is based on equations from CA Fish & Wildlife's *Part XII: Fish Passage and Design Implementation* document.

Step 1: Calculate D_{30} of the ESM:

$$D_{30} = 1.95S^{0.555}(1.25q)^{2/3}g^{-1/3}$$

D_{30} = Stable particle size smaller than 70% of ESM (ft)

S= Streambed or Pool Slope (ft/ft)

g= Gravity (32.2 ft/s²)

q= Unit Discharge (ft²/s)= Q/W

Q= Full Main Channel Flow

W= Active Channel Width

Step 2: Calculate D₈₄ of the ESM:

$$D_{84} = 1.5D_{30}$$

D₈₄= Stable particle size smaller than 16% of ESM (ft)

Step 3: Calculate D₅₀ of the ESM:

$$D_{50} = 0.4D_{84}$$

D₅₀= Stable particle size smaller than 50% of ESM (ft)

Step 4: Calculate D₁₀₀ of the ESM:

$$D_{100} = 2.5D_{84}$$

D₁₀₀= Largest stable particle size of ESM (ft)

Step 5: Calculate D₁₆ and D₈ of the ESM using the Fuller-Thompson equations. In order to promote high density soil mix, use an “n-value” in below equations that will produce a D₈ particle size around 0.08” (2 millimeters).

$$D_8 = 0.16^{1/n}D_{50}$$

$$n = 0.45 \text{ to } 1.1$$

D₅₀= Stable particle size smaller than 50% of ESM (inches)

D₈= Stable particle size smaller than 92% of ESM (inches)

$$D_{16} = 0.32^{1/n}D_{50}$$

D₁₆= Stable particle size smaller than 84% of ESM (inches)

When boulder clusters are needed within the engineered stream bed mix, they are to be sized using the “Boulder Cluster Design Method” from Section N.1.3. Because boulder clusters are considered to be permanent stream features, they should be sized for the Q₂₅ to Q₅₀ storm.

N.5 Bank and Toe Stabilization

Because of energy losses caused by rock weirs, turbulent backwaters can be created, especially during overtopping and flanking conditions. The banks and toes are vulnerable to scour under these conditions, and they should be stabilized through rock slope protection (RSP) or a combination of RSP and vegetation where appropriate.

The Caltrans standard for bank and toe protection design is in the *Highway Design Manual (HDM)*, Chapter 870 Channel and Shore Protection - Erosion Control. According to Topic 873 Design Concepts, a suggested RSP design event is the 50-year storm, average stream velocity

and water surface level are calculated to determine rock size and design high water on the bank (design high water + freeboard = design height). As also stated in Topic 873, the design height estimation should, in addition, take into account other factors, such as historic high water marks, size and nature of debris, as well as construction costs. Basically, engineering judgment must be exercised in adjusting the design RSP height up or down from the calculated 50-year average flow depth, but freeboard must be considered as well.

If the combined RSP and vegetative revetment is desired, the decision for determining the minimum RSP height and design velocity is at the discretion of the District Hydraulics Engineer. The District Landscape Architect must be consulted in determining the proper plants and grasses to be specified for each project. For all projects, the toe of bank, which is highly susceptible to scour, must be stabilized with RSP to 3 feet above the toe at a minimum. See Figure N-5 for a typical step-pool cross section showing pool composition and bank protection.

N.6 Gravel Filter (Alternative to RSP Fabric)

In FHWA's HEC-23 document, discussion is presented regarding subsurface flows. As flow moves through the stream channel, the native base soil is subjected to a combination of groundwater seepage through the subsurface and turbulence from stream surface water, which causes piping beneath RSP and fine soil particles to migrate. A filter placed between the base soil and RSP layer will promote retention of fines in the base soil while still maintaining permeability and free passage of groundwater within the base soil and RSP interface.

In lieu of the common RSP fabric filter, a gravel filter can be specified and placed between the native base soil and rock or constructed stream bed channel and slopes. In general, gravel filters are preferred by resource agencies over RSP fabric because of their more natural qualities and less disruption of stream ecology.

In determination of proper gravel filter gradation, the Terzaghi method is listed as one of two recommendations in *HDM Index 873.3 (2) (a) (1) (e) Gravel Filter*. This method is well-known and is cited in many textbooks and professional papers. From Terzaghi, gravel filter design must meet two main criteria: interface stability (also known as piping) and permeability. In order to meet the piping criterion, the filter aggregate cannot be too large that would decrease base soil retention, yet to meet the permeability criterion, the aggregate cannot be too small that would inhibit seepage from the base soil subsurface through the filter. The governing equations for each Terzaghi criterion are as follows:

$$\text{Piping (Interface Stability) Criterion: } (D_{f15}/D_{b85}) \leq 5$$

D_{f15} = filter aggregate diameter that is smaller than 85% of filter aggregates, but larger than 15%

D_{b85} = base soil particle diameter that is smaller than 15% of soil particles, but larger than 85%

$$\text{Permeability Criterion: } (D_{f15}/D_{b15}) > 5$$

D_{b15} = base soil particle diameter that is smaller than 85% of soil particles, but larger than 15%

In order to use the Terzaghi method and verify the piping and permeability criterion, soil samples from the project site must be obtained for testing. A request needs to be made of the District Materials Lab for native soil samples to be collected from the streambed or banks. The request must give direction for samples to be taken every 100 feet along the length of the reference reach, or a minimum of 3 samples total. Each must contain the top 1-foot of native soil from the

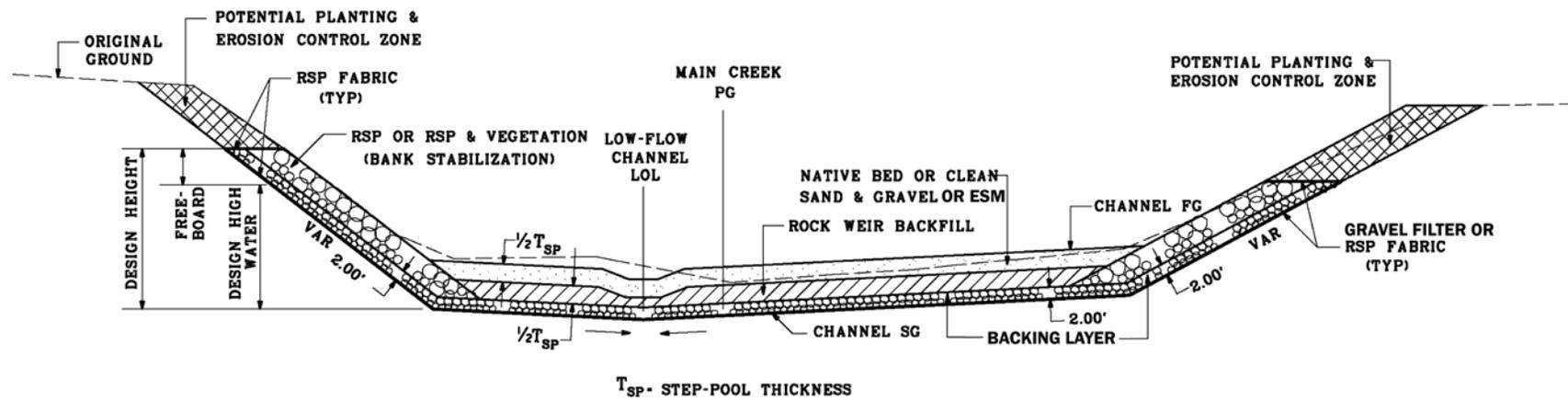


Figure N-5. Step Pool Cross Section

stream bed and/or banks. After the samples have been collected, a sieve analysis and generation of gradation curves of each sample must also be requested of the Material Lab.

For gravel filter analysis and design procedures, see Caltrans *Design Information Bulletin 87-01 (Hybrid Streambank Revetments: Vegetated Rock Slope Protection)*.

N.7 Rock Weir and Step-Pool Layout

Through an iterative hydraulics analysis, the spacing and height of the rock weirs, as well as the low-flow notch/channel dimensions are verified. These components are varied during the hydraulics modeling process until the velocity and depth requirements are satisfied as outlined in the CDFG *Culvert Criteria For Fish Passage* and the NOAA Fisheries *Guidelines For Salmonid Passage At Stream Crossings* depending on target lifestage and species. When low fish-passage flow occurs, a minimum 1-foot flow depth should be maintained within the step-pools, but a minimum 2-foot depth must be provided within the “jump” pool (constructed scour pool) at the base of each weir.

For a series of rock weirs, the minimum spacing is 25 feet. This is mainly governed by the construction process, where individual rock weirs could intersect and their physical definition could be lost if they are placed too close together. Instead of having a series of individual rock weirs, a larger pile or mass will develop without clear definition of each rock weir and the pools between them. If this occurs, the rock weirs and pools will not function properly for fish passage. This is why it is important that rock weirs are at least spaced at 25-foot intervals.

At each rock weir, a 0.5-foot to 1-foot (maximum) vertical step in the new stream profile is typically placed to minimize the longitudinal pool slope between weirs and eliminate a vertical and/or velocity barrier to fish. The rock weir will dissipate the increase of energy at a step. With a flatter pool slope, the velocity and depth criteria are more easily achieved. The use of vertical steps is especially beneficial when dealing with significant elevation changes within the project limits, which would create steep pool slopes. The overall stream gradient can be softened by having up to 1-foot grade changes at each weir location, yet provide relatively flat pool slopes or smaller grade changes between weirs. For rock weir design, the pool slope can vary between 0% and 4%, but is ultimately controlled by the velocity and depth criteria.

In order to determine the number of rock weirs, the preliminary rock weir spacing, the preliminary project length, the number of step-pools, the step-pool slope (gradient), and the number of vertical steps, the procedure below should be followed. Figure N-6 shows a vertical barrier (excessive scour pool) just below a perched culvert, which is a very common application for rock weir/step-pool system in mitigating this type of barrier or impediment.

Step 1: Assume a vertical step height (d_1) where 0.5 feet is the minimum and 1-foot is the maximum. Find d_3 , the height of the vertical barrier, by subtracting the bottom elevation of the scour pool from the upstream conform elevation (top of the excessive scour pool). Divide d_3 by d_1 and round down to the nearest whole number to determine the number of vertical steps required to overcome the vertical barrier, which is also the number of rock weirs and step-pools.

$$\# \text{ of Vertical Steps} = \# \text{ of Rock Weirs} = \# \text{ of Step-Pools} = d_3/d_1 \text{ (Round Down)}$$

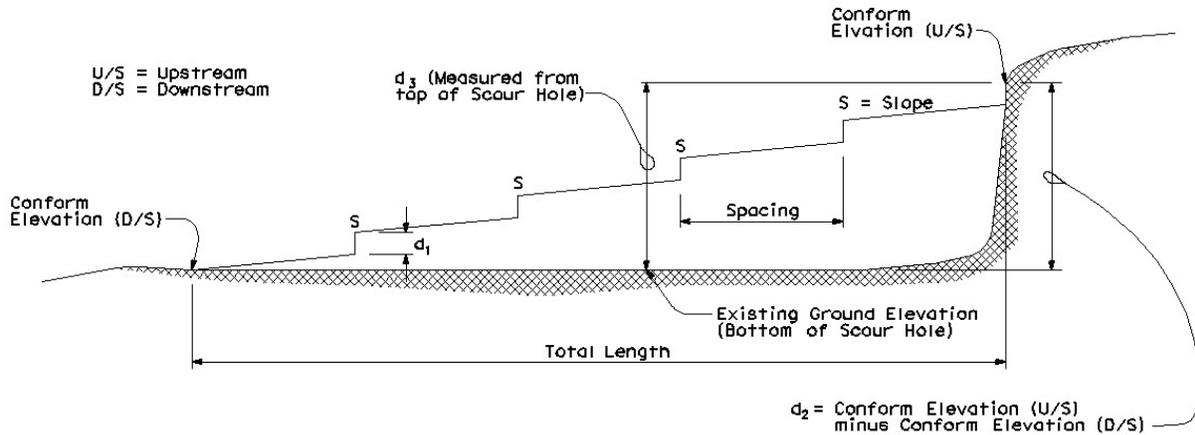


Figure N-6 Rock Weir/Step-Pool Layout

Step 2: Assume a preliminary rock weir spacing (25 feet minimum) that will also equal the step-pool longitudinal length. Calculate the total project length, in other words the longitudinal length of the rock weir/step-pool system, by multiplying the number of step-pools by the step-pool length.

NOTE: The rock weir spacing and subsequent step-pool length is preliminary until depth and velocity criteria have been met, which will be verified by the hydraulic modeling.

$$\text{Preliminary Rock Weir Spacing} = \text{Preliminary Step-Pool Length}$$

$$\text{Total Project Length} = (\# \text{ of Step-Pools}) (\text{Step-Pool Length})$$

Step 3: Find d_2 , the elevation difference in the total project length, by subtracting the downstream and upstream conform point elevations. The distance between these conform points is, of course, the total project length from Step 2. The upstream conform point is normally around the top of the scour pool.

Step 4: Determine the step-pool slope based on d_1 , d_2 , the number of vertical steps, the number of step-pools, and the step-pool length.

$$\text{Step Pool Slope (ft/ft)} = \frac{d_2 - [d_1(\# \text{ of vertical steps})]}{(\# \text{ of step pools})(\text{step pool length})}$$

After the general configuration of the rock weirs and step-pools has been found following the steps above, a preliminary rock weir height (6 inches minimum) can be determined. In the hydraulics analysis, special attention must be made to maximum drops stated in the State and Federal criteria. For all adult species, the maximum drop in water surface is 1 foot, while juvenile salmonids can only tolerate 6 inches. At the downstream base of each rock weir, a 2-foot jump pool should be provided for all species and lifestage. As can be seen in Figure N-3, the rock weir height is measured from the channel finished grade to the top of the weir crest.

By using Figure N-7 and the associated equations, a preliminary (first trial) rock weir height can be found. In this Figure, a pool between two rock weirs is shown in a creek. A line representing level water surface has been drawn from the top of the upstream side of the downstream weir to the downstream side of the upstream weir. By assuming a rock weir height (h_1) and using the preliminary step-pool length and slope determined above, h_3 can be calculated. Once h_3 is

known, h_4 can be determined, where (h_3+h_4) equals the total jump pool depth. The h_4 dimension is the height or depth of the constructed scour pool and must be at least 0.5 feet for constructability purposes. From hydraulic modeling in HEC-RAS, appropriate rock weir height and spacing will be verified if h_1 and h_2 are of minimum depth according to lifestage/species in the CDFG and NMFS criteria, and also that (h_3+h_4) is around 2 feet or greater.

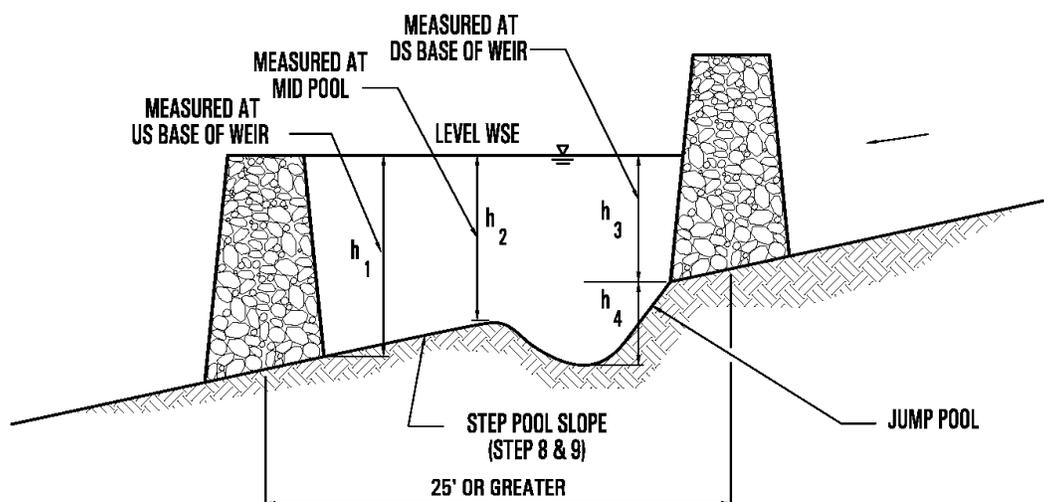


Figure N-7. Preliminary Rock Weir Height Determination

$$h_3 = h_1 - [(Step-Pool Length) (Step-Pool Slope in ft/ft)]$$

$$h_4 = (2 \text{ feet}) - h_3$$

$$h_3 + h_4 \geq 2 \text{ ft, where } h_4 \geq 0.5 \text{ ft (minimum)}$$

Once the weir height (preliminary or final) has been determined, the low-flow notch and low-flow channel can be sized using the following minimum dimensions: 6-inch depth, 2-foot base width, and 4-foot top width. Basically, the low-flow notch and channel dimensions will be consistent. As the name suggests, the function of the low-flow notch and channel is to provide minimum flow depths during low fish-passage flow. The top of a rock weir and the channel bed must have a 4% to 5% cross slope toward the low-flow notch/channel so that water will be concentrated and minimum depth is more easily attained. See Figure N-9 for cross sections of the low-flow notch and channel.

During construction, a rock weir is normally built in full without the notch in order to have proper placement and locking of rocks. After it is built, rock is removed to form the notch. Of course given the variable physical sizes of the individual rocks, the dimensions specified on the plans for a notch are somewhat approximate. Because of this situation, the D_{50} of the rock weir should also be considered in determining the dimensions of the low-flow notch. The cross-sectional dimensions of the notch cannot be less than D_{50} .

Another factor to consider in the design of the low-flow notch and channel is meandering and sinuosity of the notch and channel in plan view. By having this, channel length is increased and longitudinal slope is decreased, which further contributes to having adequate fish-passage depth and velocity especially in a steep slope environment. While a standard for the sinusoidal pattern does not exist, the engineer can use judgment in approximating a meandering low-flow channel around the creek centerline as shown in Figure N-8. The need and desire for low flow

notch/channel features should be discussed with resource agencies during preliminary design stage.

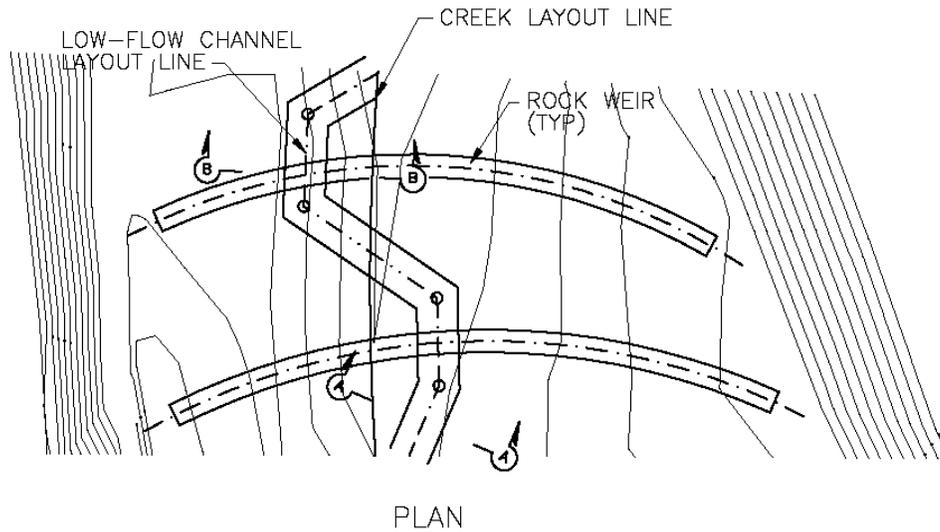
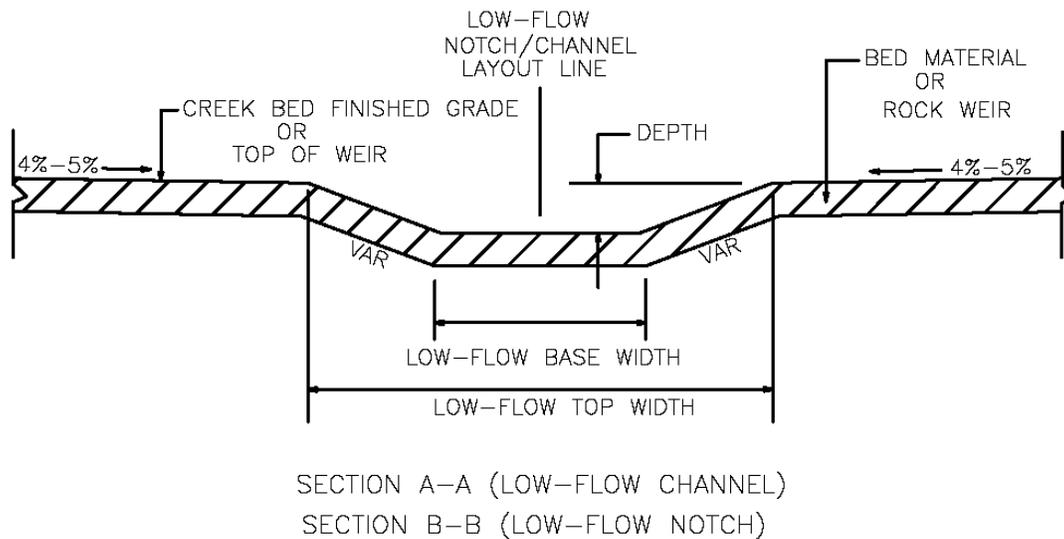


Figure N-8. Rock Weir and Low-Flow Notch/Channel Plan



SECTION A-A (LOW-FLOW CHANNEL)
SECTION B-B (LOW-FLOW NOTCH)

Figure N-9. Low-Flow Notch/Channel Cross Section

N.8 Rock Weir Types

Type 1: This type of rock weir, shown in Figure N-2, is specified by RSP Class consistent with Section N.1. Within an RSP Class, the size of the actual rock can vary according to the Standard Specifications (Section 72) mass gradation. For instance, a 1-T (Ton) RSP Class could consist of 2 Ton rock size (95-100%), 1 Ton rock size (50-100%), and ½ Ton rock size (0-5%). One of the reasons for this variability in rock size is to promote a more well-graded mix that will have less voids and more stability when placed in the field.

If a creek bed width is small (less than 25 feet), the number of rocks comprising a rock weir will also be small. With fewer rocks and smaller volumes delivered to a construction site from a

quarry, the potential is greater for receiving rocks that may be too large or too small for proper construction of the weirs considering their dimensions shown on the plans based on a specific RSP Class. For creek bed widths greater than 25 feet, the total volume of rocks required for a rock weir should be adequate enough where a reasonable gradation of rock sizes within an RSP Class will be delivered to the site. This is the reason that a Rock Weir (Type 1) is only recommended for creek bed widths greater than 25 feet.

Due to the variability in rock size, shape, and diameter associated with an RSP Class, the more difficulty the contractor will have in building rock weirs according to the typically tight weir dimensions shown on plans. This variability in size and shape is good for locking the rocks together during construction to seal the weirs, but it is harder to achieve the specified grades and elevations. In order to properly construct a rock weir, it may require the contractor several attempts at placing, removing, and placing again individual rocks of various size and shape to find the correct fit that will meet the specified grades, widths, and heights. This means that the labor and equipment costs are higher than normal RSP construction, but the material costs will be typical because the Caltrans RSP Classes are known by the commercial quarries and are usually readily available. Because of the additional labor and equipment costs, the unit price for an RSP Class will have to be higher for rock weir construction than bank revetment or energy dissipater construction. As a rule of thumb, it is recommended to increase the unit cost of a standard RSP Class item by 25-33% to account for the additional labor and equipment costs of a Rock Weir (Type 1) special BEES item.

Essentially, the positive and negative aspects of using a Rock Weir (Type 1) can be summarized by saying that their construction is labor intensive, but their material is easy to supply.

See Appendix O for a recommended Rock Weir (Type 1) NSSP.

Type 2: Instead of specifying an RSP Class, a Rock Weir (Type 2) is specified by a “rough” diameter of rock size. After an RSP Class is determined for rock sizing in Section N.1, the D_{50} of the chosen RSP Class will be used as the “rough” diameter. This type of rock weir must contain two rows of individual rocks to aid in sealing the weirs, and may have one or two layers of rock as needed based on required embedment depth. See Figures N-10 and N-11 for profile views.

When using a Rock Weir (Type 2), a rock isometric detail, shown in Figure N-12, must be used to show how the rock diameter is measured on the x, y, and z axes. This detail is essential and crucial for the contractor and quarry to use in locating the proper rocks, and also crucial for the construction inspector to verify and approve of their use.

Because the rocks comprising a Rock Weir (Type 2) will be consistent in size and relative shape, they will be much easier to place making the physical construction of this type of weir simpler than a Rock Weir (Type 1). The grades, elevations, heights, and widths will be easier to achieve with this consistent rock, but it is critical that backfill be placed and compacted in the rock weir voids to further seal the weirs. By having such consistent size and shape of rock, the potential for voids is greater than the gradation of rock in an RSP Class and must be properly dealt with during construction. In Appendix O, a recommended Rock Weir (Type 2) NSSP describes the gradation of backfill, which is called rock weir void filler, and its method of compaction.

While the physical construction of a Rock Weir (Type 2) is simpler, the difficulty for the contractor will be in selecting the consistent size rocks according to the rock isometric detail.

Basically, the positive and negative aspects of using a Rock Weir (Type 2) are the opposite of a Rock Weir (Type 1). For a Rock Weir (Type 2), the labor and equipment time will be normal for typical RSP construction, if not less, but the cost in selecting and supplying the material will be much greater. In determining a unit cost for a Rock Weir (Type 2) special BEES item, it is recommended to perform a force account analysis similar to extra work construction contract change orders for a specific project by estimating labor and equipment hours for weir construction, material costs with the additional labor in choosing the rock, delivery (trucking) of the rock from quarry to site, and applying the proper markups and surcharges.

Given this difficulty in selecting and finding the unique rock for a Rock Weir (Type 2), its availability may be questionable for large volumes. A contractor may not be able to find enough rock to construct the weirs for wide bottom creeks requiring large volumes. This is the main reason that this type of rock weir is recommended for smaller creek bed widths of 25 feet or less, where the volume of rock will be less and easier to provide this unique rock. The use of a Rock Weir (Type 2) for smaller stream widths will also eliminate the inconsistent rock gradation problem, associated with an RSP Class, discussed above for a Rock Weir (Type 1).

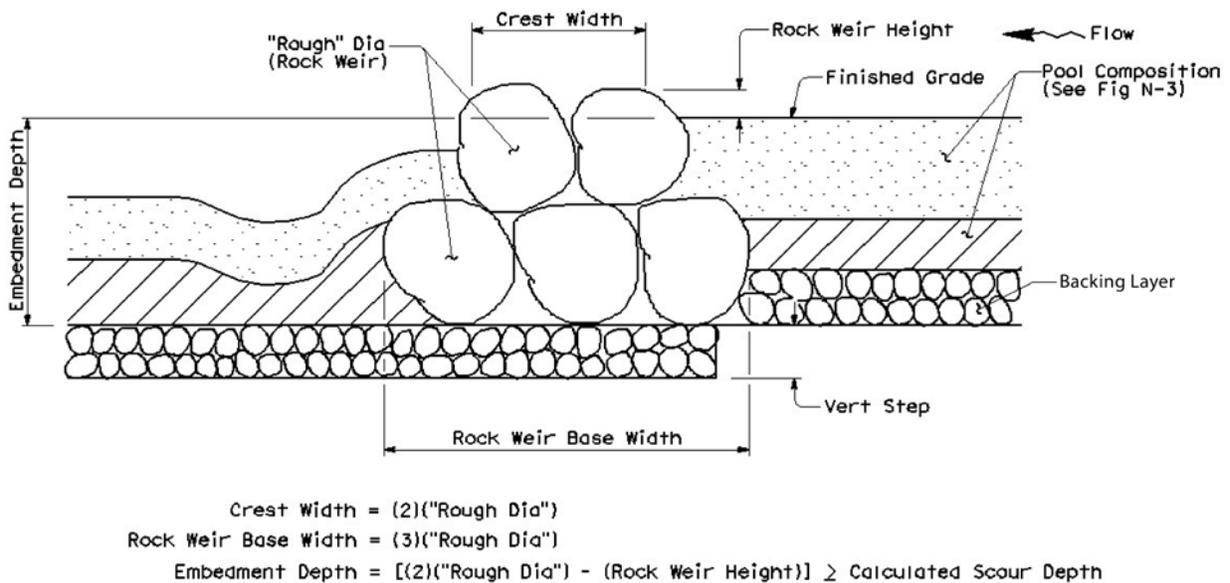
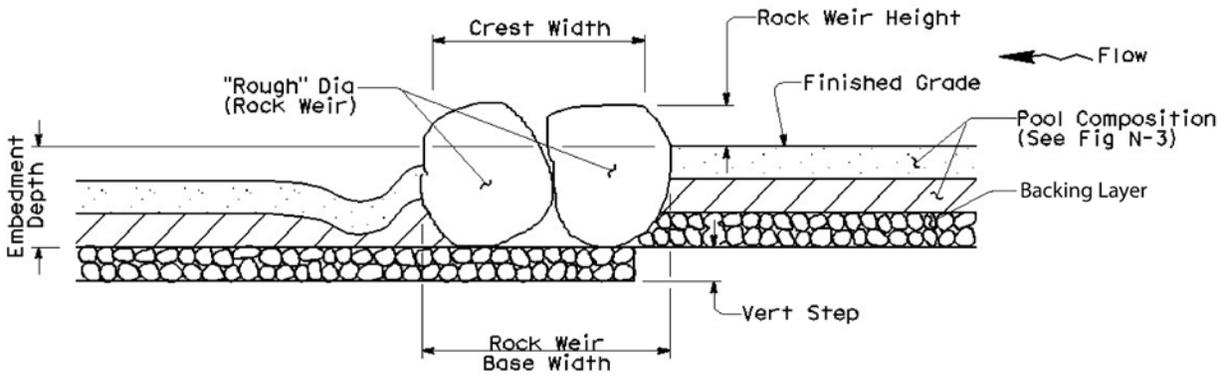
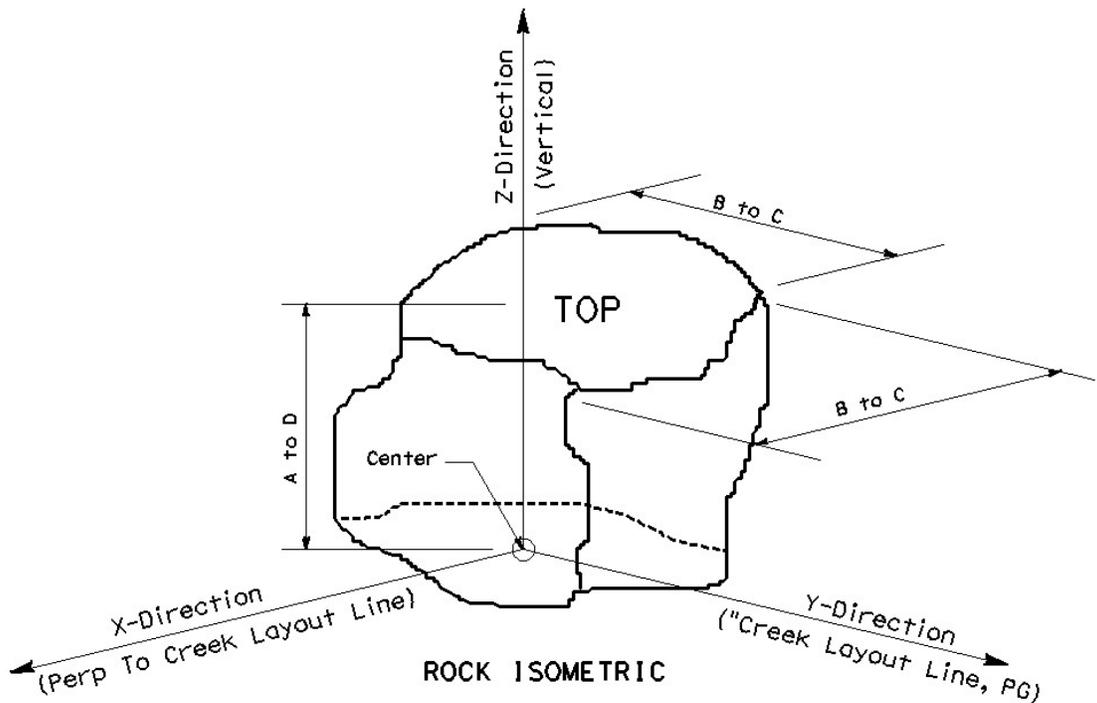


Figure N-10 Rock Weir (Type 2) Profile - Two Rock Layers



Crest Width = (2)("Rough Dia")
 Rock Weir Base Width = (2)("Rough Dia")
 Embedment Depth = [{"Rough Dia"} - {Rock Weir Height}] ≥ Calculated Scour Depth

Figure N-11 Rock Weir (Type 2) Profile - One Rock Layer



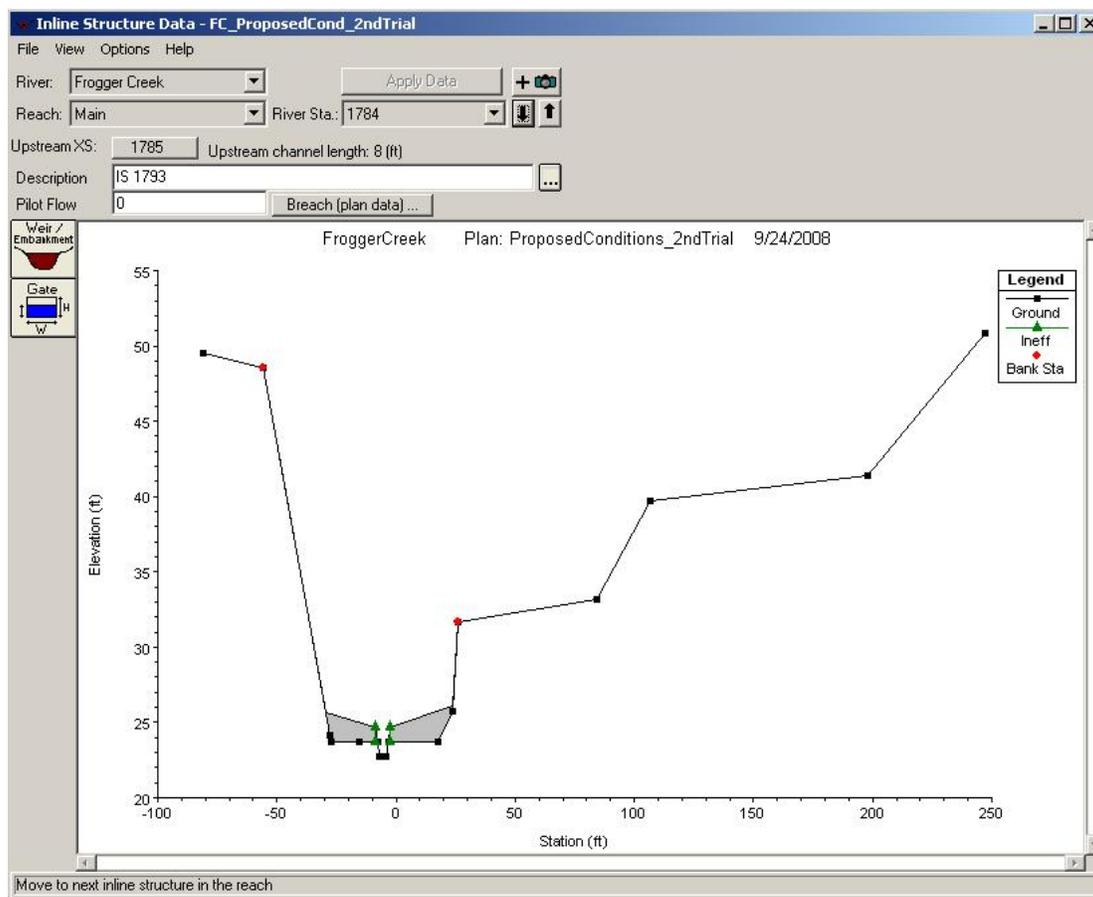
- LEGEND**
 A = Rough Diameter
 B = Rough Diameter - 1'
 C = Rough Diameter + 1'
 D = Rough Diameter + 0.5'

Figure N-12 Rock Isometric Construction Detail

N.9 Rock Weir Hydraulic Modeling

For modeling low and high fish passage flows, as well as flood flows, HEC-RAS is the software of choice given its ability to analyze in-line structures. Considering the typical crest width (breadth of crest), a rock weir is classified as broad-crested and will be analyzed in this manner by HEC-RAS. In cross section, HEC-RAS has the capability of considering a weir's theoretical shape (in-line structure), including the low-flow notch, in its analysis by entering/defining section coordinates shown in Figure N-12, but is limited in considering a weir's plan view orientation. As discussed in Section N.3, a weir should have an arc shape in plan view, but HEC-RAS will only recognize it with a perpendicular orientation associated with one specific River Station. Therefore, an arc-shaped rock weir must be entered as straight and perpendicular to the stream cross section at an identified River Station for hydraulic modeling purposes.

In order to develop an accurate water surface profile, it is recommended that at least three cross sections be created between rock weirs: one cross section immediately downstream of a weir, one cross section at the mid-point of the pool between weirs, and one cross section just upstream of a weir. The most critical cross section, which will have the lowest depth, is the one immediately downstream of a weir within the plunge/jump pool. Depth at this cross section especially, as well as the other cross sections, should meet minimum design criteria.



Del Row	Distance	Width	Weir Coef
Ins Row	11	6	2.68

Edit Station and Elevation coordinates		
Station	Elevation	
1	-30.	25.7
2	-8.5	24.7
3	-7.	22.7
4	-4.	22.7
5	-2.5	24.7
6	27.	26.25
7		
8		

U.S. Embankment SS: 0 D.S. Embankment SS: 0

Weir Data
Weir Crest Shape
 Broad Crested
 Ogee

OK Cancel Clear

Enter distance between upstream cross section and deck/roadway. (ft)

Figure N-13 Rock Weir Cross Section (HEC-RAS)

In order to determine a broad-crested weir coefficient to be used in HEC-RAS modeling, the procedure below should be followed using Table N-8. For each flow, it is recommended to determine a new weir coefficient because of its dependency on head above a weir.

Step A: Estimate the highest weir coefficient using the highest head for the previously calculated crest width (breadth of crest of weir) from Table N-8 Broad Crested Weir Coefficient.

Step B: Run the proposed HEC-RAS model and find the average head (weir average depth) over a baffle for the Low Fish Passage Flow from HEC-RAS results.

Step C: Given the average head (weir average depth) from the HEC-RAS results and the crest width (breadth of crest of weir), find a second weir coefficient from Table N-6 Broad Crested Weir Coefficient.

Step D: Run the proposed HEC-RAS model with the second weir coefficient from Step C and find the average head (weir average depth) over a baffle for the Low Fish Passage Flow from HEC-RAS results.

Step E: Given the average head (weir average depth) from the HEC-RAS results and the crest width (breadth of crest of weir), find a third weir coefficient from Table N-6 Broad Crested Weir Coefficient.

Step F: Compare weir coefficient from Step C and Step E. If weir coefficients are close in value, then use Step E weir coefficient for remaining HEC-RAS modeling. If weir coefficients are not close in value, repeat Steps C-F until an appropriate weir coefficient is found.

Head (ft)	Breadth of Crest of Weir (ft)										
	0.50	0.75	1.00	1.50	2.00	2.50	3.00	4.00	5.00	10.00	15.00
0.2	2.80	2.75	2.69	2.62	2.54	2.48	2.44	2.38	2.34	2.49	2.68
0.4	2.92	2.80	2.72	2.64	2.61	2.60	2.58	2.54	2.50	2.56	2.70
0.6	3.08	2.89	2.75	2.64	2.61	2.60	2.68	2.69	2.70	2.70	2.70
0.8	3.30	3.04	2.85	2.68	5.60	2.60	2.678	2.68	2.68	2.69	2.64
1.0	3.32	3.14	2.98	2.75	2.66	2.64	2.65	2.67	2.68	2.68	2.63
1.2	3.32	3.20	3.08	2.86	2.70	2.65	2.64	2.67	2.66	2.69	2.64
1.4	3.32	3.26	3.20	2.92	2.77	2.68	2.64	2.65	2.65	2.67	2.64
1.6	3.32	3.29	3.28	3.07	2.89	2.75	2.68	2.66	2.65	2.64	2.63
1.8	3.32	3.32	3.31	3.07	2.88	2.74	2.68	2.66	2.65	2.64	2.63
2.0	3.32	3.31	3.30	3.03	2.85	2.76	2.72	2.68	2.65	2.64	2.63
2.5	3.32	3.32	3.31	3.28	3.07	2.89	2.81	2.72	2.67	2.64	2.63
3.0	3.32	3.32	3.32	3.32	3.20	3.05	2.92	2.73	2.66	2.64	2.63
3.5	3.32	3.32	3.32	3.32	3.32	3.19	2.97	2.76	2.68	2.64	2.63
4.0	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.70	2.64	2.63
4.5	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.74	2.64	2.63
5.0	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.64	2.63
5.5	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.64	2.63

Table N-8 Broad Crested Weir Coefficient

N.10 Energy Dissipation Factor

In the pool between weirs, turbulence is created as energy is dissipated. This turbulence can be defined or measured by an Energy Dissipation Factor (EDF) having ft-lb/ft³/sec units. When turbulence is too high, it can be an impediment for fish passage. EDF criteria for pools between weirs and roughened channels are not well developed, but generally EDF should not exceed 7 ft-lb/ft³/sec.

The following equation is used to calculate EDF:

$$EDF = \frac{\gamma Q S_o}{A_{wet}}$$

Where:

EDF = Energy Dissipation Factor (ft-lb/ft³/sec)

γ = Unit weight of water (62.4 lb/ft³)

S_o = Existing culvert slope (ft/ft)

A_{wet} = Wetted cross-sectional flow area (ft²) between weirs under high fish passage flow

N.11 Rock Weir Design Steps

- Step 1: Prepare an Existing Conditions HEC-RAS hydraulic model and find the average velocity for the 50-Yr Event, check existing bridge capacity for 50-Yr and 100-Yr or existing culvert capacity for 100-Yr HDM criteria.
- Step 2: Calculate rock weir size.
- Step 3: Find potential scour depth for rock weir embedment.
- Step 4: Determine step pool composition and thickness.
- Step 5: Determine crest width.
- Step 6: Calculate plan view radius of vortex shape.
- Step 7: Size RSP for bank and toe stabilization.
- Step 8: Estimate number of steps (1 ft max per step), rock weirs, step pools, as well as linear spacing of rock weirs.
- Step 9: Develop a preliminary reach profile including longitudinal slope of step pools and vertical step height.
- Step 10: Estimate a trial rock weir height and “constructed” jump pool depth.
- Step 11: Estimate trial geometry for low flow channel and notch (depth, bottom width, side slopes) Use minimum suggested dimensions for first trial.
- Step 12: Prepare HEC-RAS plan of proposed conditions using Low and High Fish Passage Design flows and determine weir coefficient through iterative process (calibrate with Low Fish Passage Flow).
- Step 13: Find average weir depth and average channel depth for Low Fish Passage Flow. Check HEC-RAS Proposed Conditions 1st Trial plan against criteria. Perform hand calculations to check velocity through low flow notch. Note, velocity will be checked using High Fish Passage Flow. Calculate EDF.
- Step 14: Identify velocity and depth at appropriate cross-sections from HEC-RAS model and hand calculations and compare against design criteria. If velocity or depths are not met, change rock weir spacing, rock weir height, and/or low flow channel/notch geometry to ultimately meet design criteria. Re-run HEC-RAS models and perform hand calculations as needed. Once criteria have been met, summarize calculated velocities in *Velocity Criteria Versus Design (High Fish Passage Flow)* and depths in *Depth Criteria Versus Design (Low Fish Passage Flow)* tables in Form 6E.
- Step 15: Add 50-Year and/or 100-Year peak discharges to Proposed Conditions 2nd Trial Plan and evaluate results.
- Step 16: Based on final weir height, calculate rock weir base width.