Challenge Creek Example Problem
Chutes and Pools Roughened Channel Design

This example demonstrates some of the calculations used in design of a chutes and pools roughened channel for profile control downstream of a baffled culvert outlet.

Background

A 5.5 foot diameter corrugated metal culvert on a highway in Northwest California has a failing floor (**Figure 1**). Rehabilitation will be to slipline it with a 5 foot diameter welded steel pipe that contains steel corner baffles (**Figure 2**). The corner baffles have already been designed to meet fish passage criteria. A chutes and pools roughened channel will be used to increase the slope of the channel profile downstream of the baffled culvert outlet to eliminate any water surface drop at the outlet. The focus of this exercise is design calculations for the chutes and pools roughened channel.

The stream supports **target species of juvenile and adult anadromous steelhead trout**. The existing culvert is a velocity, depth, and outlet drop barrier for both age groups. The rehabilitation project must improve passage for both. The project is in California and under the regulatory control of the California Department of Fish and Game, so in this case the State of California culvert passage criteria and guidance were applied (CDFG, 2002; CDFG, 2009).

Pre-Design

The culvert outlet apron is at an elevation of 100.0 ft and is perched 1.3 ft above the downstream tailwater control (**Figure 3**). During pre-design it was determined that there may be as much as 0.5 feet of incision throughout the downstream channel in the future. This sets the ***lower vertical adjustment profile*** for the project.

Downstream channel dimensions:
Bankfull Width = 10 feet
Bank Heights = 3 to 4 feet
Average Channel Slope = 2.2%.
Highly entrenched channel (100-yr flow contained within banks)

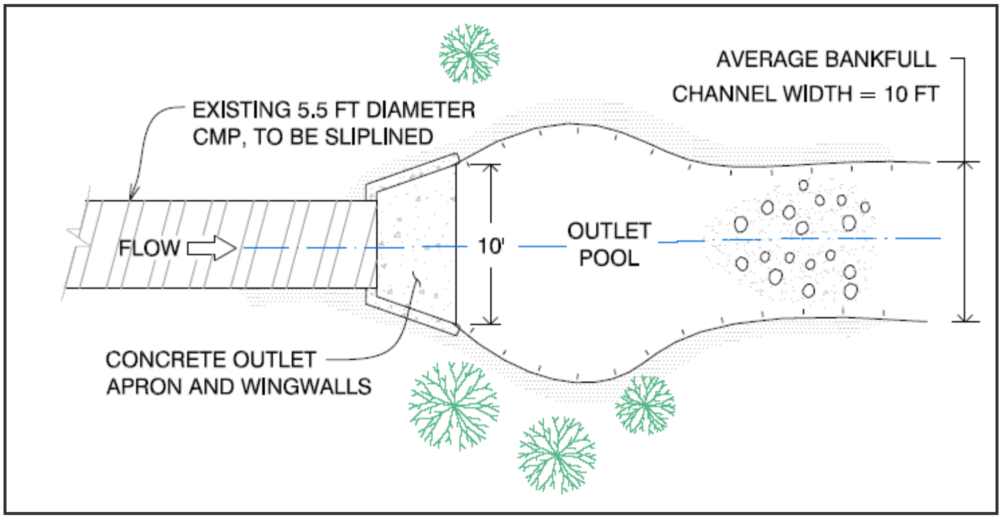

Figure 1. Plan view of existing 5.5 ft diameter CMP with concrete outlet apron.

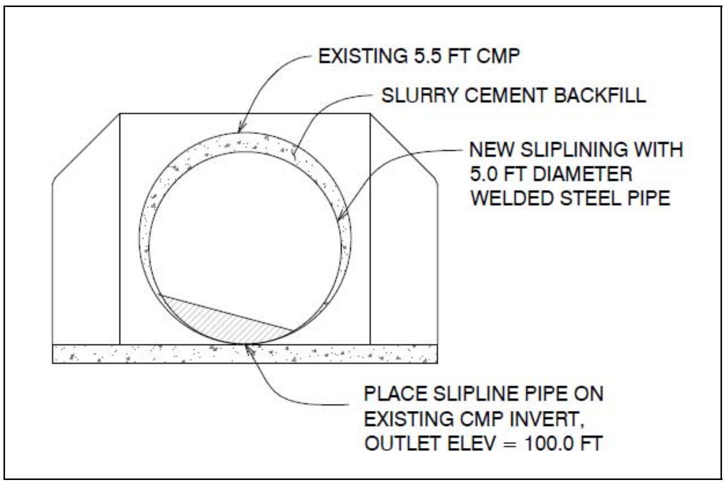

Figure 2. Section view of the culvert outlet showing the proposed slip-lining.

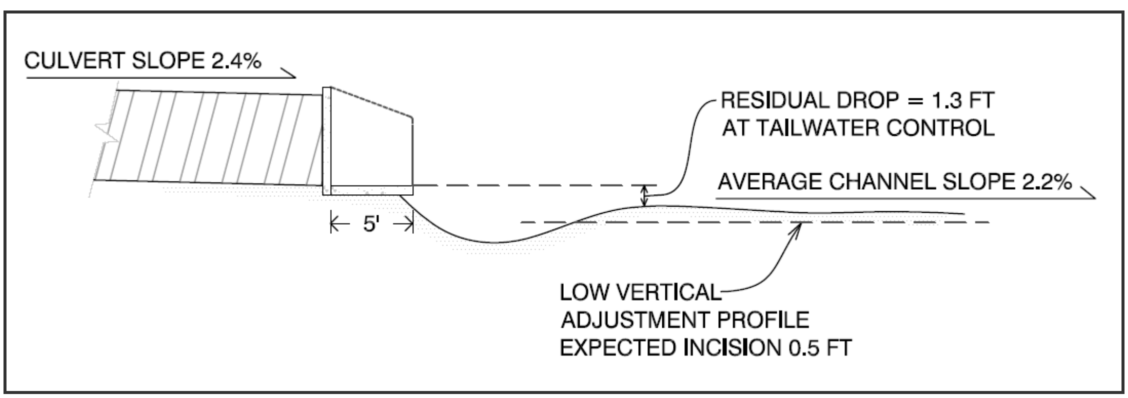

Figure 3. Profile of existing CMP to be slip-lined. Outlet scour pool is 15 ft long.

Design Criteria and Design Flows

The following design guidance and criteria are applied to roughened channels:

<u>Minimum Water Depth</u>
Juvenile Steelhead: 6 inches
Adult Steelhead: 12 inches

<u>Minimum Depth for Resting Pools</u>
Adult Steelhead: 2.0 ft

<u>Maximum Water Velocity</u>
(distance between resting pools $\leq$ 60 ft)
Juvenile Steelhead: 1 ft/s
Adult Steelhead: 6 ft/s

<u>Maximum EDF for Adult Steelhead</u>
In Flowing Water: 7 ft-lb/s/ft^3 (guidance)
In Resting Pools: 4 ft-lb/s/ft^3

<u>Maximum Roughened Channel Slope (guidance)</u>
Chutes and Pools (with armored pools): 4% (overall slope)
Maximum Drop across a Chute: 2 feet

<u>Calculated Fish Passage Design Flows for the Project Site</u>
Juvenile Steelhead: Low = 1.0 cfs High = 4.3 cfs
Adult Steelhead: Low = 3.0 cfs High = 15.5 cfs

<u>Stable-Bed Design Flow for the Roughened Channel</u>: 110 cfs

Initial Channel Layout

Problem No. 1: Chutes and Pool Lengths

Given the following dimensions for the chutes and pools roughened channel (**Figure 4**):
:

- Overall design slope (measured from chute crest to chute crest) of 4%,
- Chute Slope = 6%
- Drop across the chute (from top to bottom of chute) = 2 feet

How long is one chute-pool sequence? How long of a pool will this provide between chutes?

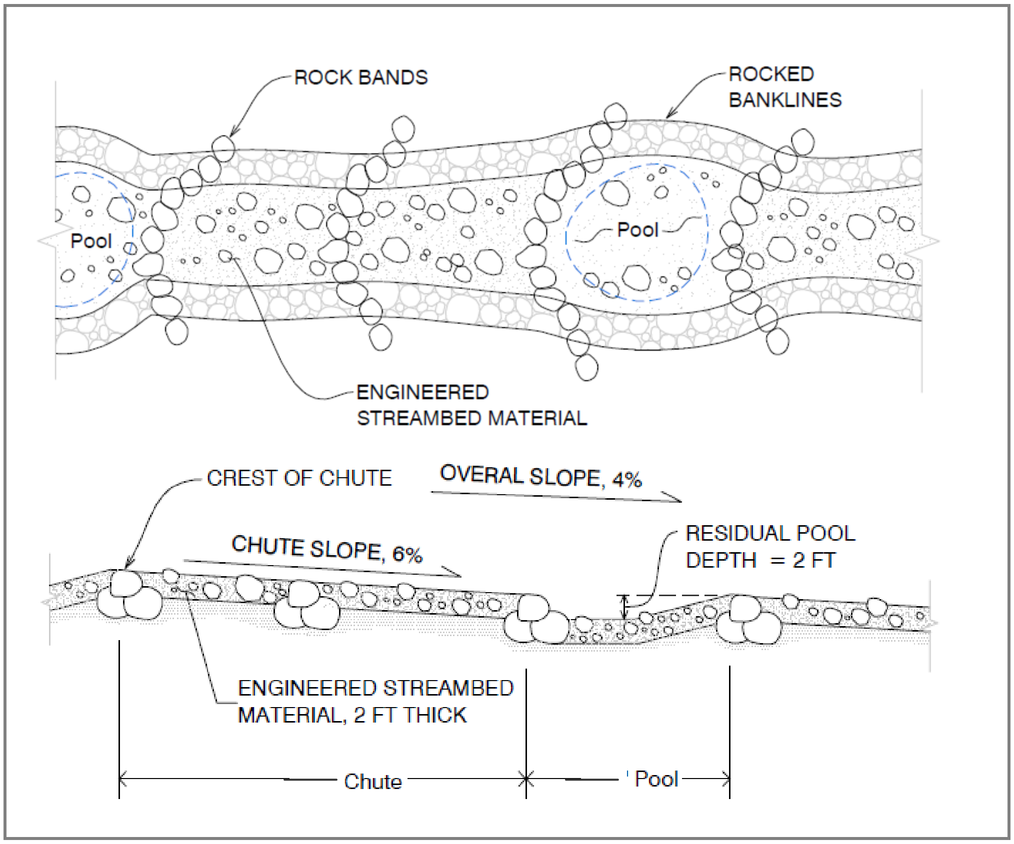

Figure 4. Dimensions of the chutes and pools in plan and profile.

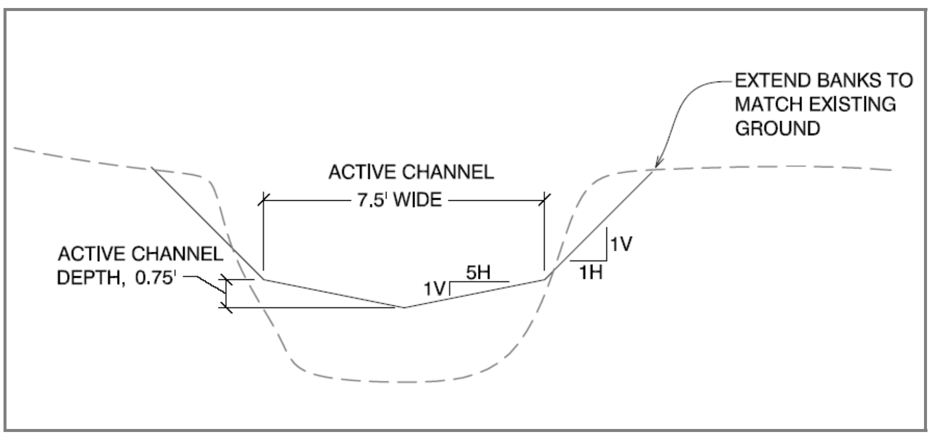

Figure 5. Cross sectional dimensions of chutes.

Channel Shape for the Chute

Development of the cross sectional shape of the roughened channel chute is an iterative process to identify a shape that results in reasonably sized stable rock at the stable-bed design flow and meets passage criteria at fish passage flows.

As a first cut, we will try a cross sectional shape for the chute that is similar to the existing channel shape (**Figure 5**).

Active channel width = 7.5 ft
Active Channel side-slope = 5H:1V (generally max recommended for chutes)
Active channel depth = 0.75 ft.
Bank side-slope = 1H:1V

Problem No. 2: Estimate Unit Discharge in Chute

Estimate of the unit discharge, *q*, at the stable-bed design flow, $Q_{\text{stable-bed}}$. Assume all the flow is contained within the banks. **As a first approximation, estimate the unit discharge conservatively as the total flow divided by the active channel width:**

Engineering Streambed Material (ESM) Gradation

Problem No. 3: Develop ESM Gradation Portion for Framework Rock

Use the ACOE (2004) rock sizing equation to estimate the stable D_{30} particle size for a riprap channel at the stable bed design flow.

For a first cut at estimating the water surface slope at this flow, use the overall slope of the roughened channel rather than the slope of the chute.

$$D_{30-Riprap} = \frac{1.95S^{0.555}1.25q^{\frac{2}{3}}}{g^{\frac{1}{3}}}$$

$D_{30\text{-Riprap}}$	D_{30} (30th percentile) stable particle size based on riprap rock gradation provided in ACOE, 1994 (ft)
S	hydraulic slope (ft/ft)
g	gravitational acceleration (32.2 ft/s^2)

Next, calculate the D_{84} D_{50} and D_{100} for the Engineered Streambed Material (ESM) using the following ratios recommended in CDFG (2009). This is the framework portion the ESM

$D_{84\text{-}ESM} = 1.5\ D_{30\text{-}Riprap}$ $D_{50\text{-}ESM} = 0.4\ D_{84\text{-}ESM}$ $D_{100\text{-}ESM} = 2.5\ D_{84\text{-}ESM}$

As a sensitivity check, what would the gradation for the ESM framework rock be if we used a water surface slope equal to the chute slope (6%)?

Problem No. 4: Develop Portion of ESM Gradation for Filling Voids (>D50)

To fill the interstitial voids between the larger rocks, the gradation of the material smaller than the $D_{50\text{-}ESM}$ is determined using a modified form of the Fuller-Thompson equation.

The coefficient, *n,* should be adjusted until the $D_{8\text{-}ESM}$ is roughly 2mm (0.0066 ft), which is characterized as coarse sand. This is to ensure that between 5 and 10 percent of the ESM consists of sands and silts. **Through trial-and-error find *n*, and then calculate the $D_{16\text{-}ESM}$. Use the $D_{50\text{-}ESM}$ using a water surface slope of 4%.**

$$D_{8-ESM} = 0.16^{\frac{1}{n}} D_{50-ESM} \qquad D_{16-ESM} = 0.32^{\frac{1}{n}} D_{50-ESM}$$

This gives us our gradation for the ESM:

Percent Finer	**Size**
8	> 2 mm (Sand/Silt)
16	
50	
84	
100	

Fish Passage Hydraulics

For initial design, fish passage hydraulics of the chutes and pools are evaluated using the typical cross section of the chute (**Figure 5**), assuming uniform flow across the chute. In this example, Manning's equation for uniform flow will be used.

Problem No. 5: Hydraulic Roughness at a High Fish Passage Flow

The hydraulic roughness of the chutes depends on the size of bed material in the chutes and the depth of flow. CDFG (2009) provides several hydraulic roughness equations appropriate for chute design. The equation developed by Mussetter (1989) is suitable for fish passage flows, where relative submergence (water depth/D_{84}) is low.

Calculate the Manning's Roughness Coefficient (*n*) when the depth of flow is 1.37 feet in the chute.

<u>**Hydraulic Geometry**</u>

At a depth of 1.37 ft, cross sectional hydraulic geometry of the chute is as follows:

Wetted Area, A = 7.85 ft^2 Wetted Perimeter, P = 9.40 ft

Wetted Top Width, T = 8.74 ft

Hydraulic Radius, R = A/P = (7.85 ft^2/9.40 ft) = 0.83 ft

Hydraulic Depth, d = A/T = (7.85 ft^2/8.74 ft) = 0.90 ft

<u>**Roughness Equations**</u>

The equation by Musetter (1989) predicts the Darcy friction factor, *f*:

$$\left(\frac{8}{f}\right)^{0.5} = 1.11\left(\frac{d}{D_{84}}\right)^{0.46}\left(\frac{D_{84}}{D_{50}}\right)^{-0.85} S_0^{-0.39}$$

Solving for *f*:

$$f = \frac{8}{\left[1.11\left(\frac{d}{D_{84}}\right)^{0.46}\left(\frac{D_{84}}{D_{50}}\right)^{-0.85} S_0^{-0.39}\right]^2}$$

To convert the Darcy friction factor i to a Manning's roughness coefficient, *n*:

$$n = 0.0926 R^{1/6}\sqrt{f}$$

Problem No. 5: Uniform Flow using Manning's Equation

Using Manning's equation for uniform flow, calculated the flowrate (Q) in the chute at a depth of flow = 1.37 ft. Use the 6% slope of the chute for S_o.

<u>**Manning's Equation**</u>

$$Q = \left(\frac{1.49}{n}\right) AR^{\frac{2}{3}} S_0^{\frac{1}{2}}$$

Is this flow approximately equal to one of the fish passage design flows?

Problem No. 6: Water Velocity in Chute

Calculate the cross sectional water velocity, U_{Chute} within the chute at the flowrate calculated in Problem No. 5

$$U_{Chute} = Q / A$$

Does it satisfy the design criteria?

Problem No. 7: Turbulence in Chute

The Energy Dissipation Factor (EDF) is a measure of turbulence. **Calculate the EDF within the chute at the flowrate calculated in Problem No. 5**

$$EDF_S = \gamma Q S_0 / A$$

Where γ is the unit weight of water (62.4 lbs/ft^3).

Does the EDF exceed the adult steelhead recommended threshold for chutes and rock ramps of 7.0 ft-lb/s/ft^3? What changes in the design of the chute could reduce the EDF?

Select Elevations of Chutes

Problem No. 8: Hydraulic Transition at Top Chute

A design objective is to eliminate any water surface drop at the culvert outlet. This is accomplished by setting the crest of the upstream most chute at an elevation that backwaters the baffled culvert outlet at all fish passage design flows. Depths are listed in the table below. **Given that the culvert outlet invert is at Elevation 100.00 feet, what is the lowest elevation the chute crest can be placed to avoid a water surface drop at the outlet?**

	Juvenile Steelhead		Adult Steelhead	
	Low Flow	**High Flow**	**Low Flow**	**High Flow**
Streamflow	1.0 cfs	4.3 cfs	3.0 cfs	15.5 cfs
Normal Depth in Baffled Culvert	0.90 ft	1.23 ft	1.09 ft	1.67 ft
Depth in Chute	0.57 ft	0.91 ft	0.82 ft	1.37 ft
Chute Crest Elevation to Match Culvert Outlet Depth				

Problem No. 9: Hydraulic Transition at Bottom Chute Elevation

Determining the length of the chutes and pools roughened channel is best done graphically (**Figure 7)**. The downstream end of the bottom chute ("End of Chute") should extend below the low vertical adjustment profile so a drop does not form at the end of the chute. **Assuming that a 20 foot long pool will scour and form downstream of the last chute, what is the minimum depth the end of the chute be placed below the low vertical adjustment profile.**

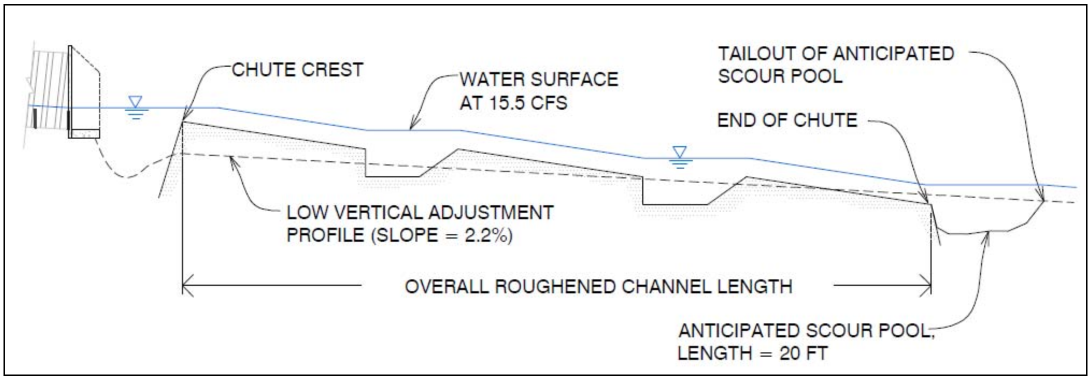

Figure 6. Profile of the chutes and pools roughened channel.