Stream Simulation Design

A Geomorphic-Based Approach for Aquatic Organism Passage at Road-Stream Crossings

Trib to Big Creek, Tongass National Forest

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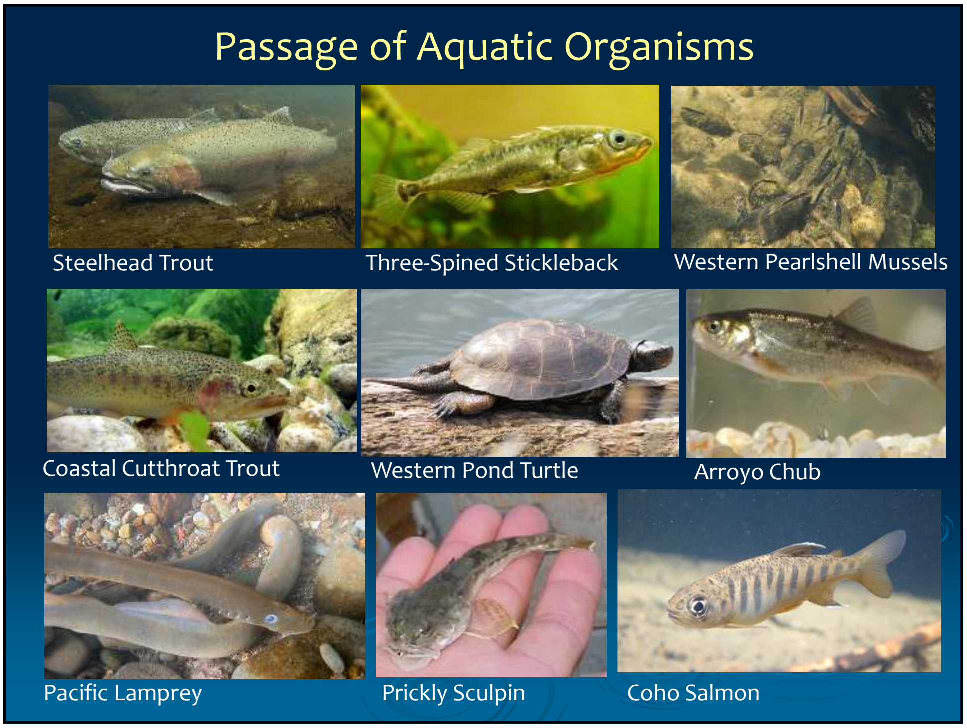
Olympia, WA



Passage of Aquatic Organisms

Steelhead Trout

Three-Spined Stickleback

Western Pearlshell Mussels

Coastal Cutthroat Trout

Western Pond Turtle

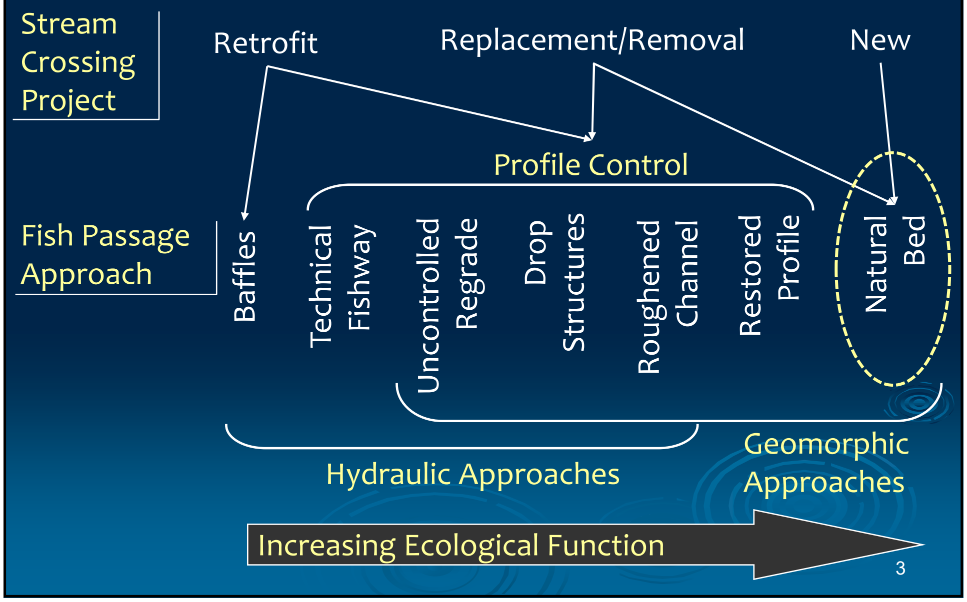
Arroyo Chub

Pacific Lamprey

Prickly Sculpin

Coho Salmon

Design Approaches for Aquatic Organism Passage



Stream Crossing Project

Retrofit

Replacement/Removal

New

Profile Control

Fish Passage Approach

Baffles

Technical Fishway

Uncontrolled Regrade

Drop Structures

Roughened Channel

Restored Profile

Natural Bed

Hydraulic Approaches

Geomorphic Approaches

Increasing Ecological Function

Stream Simulation Design Approach for Passage of Aquatic Organisms

"A channel that simulates characteristics of the natural channel will present no more of a challenge to movement of organisms than the natural channel."

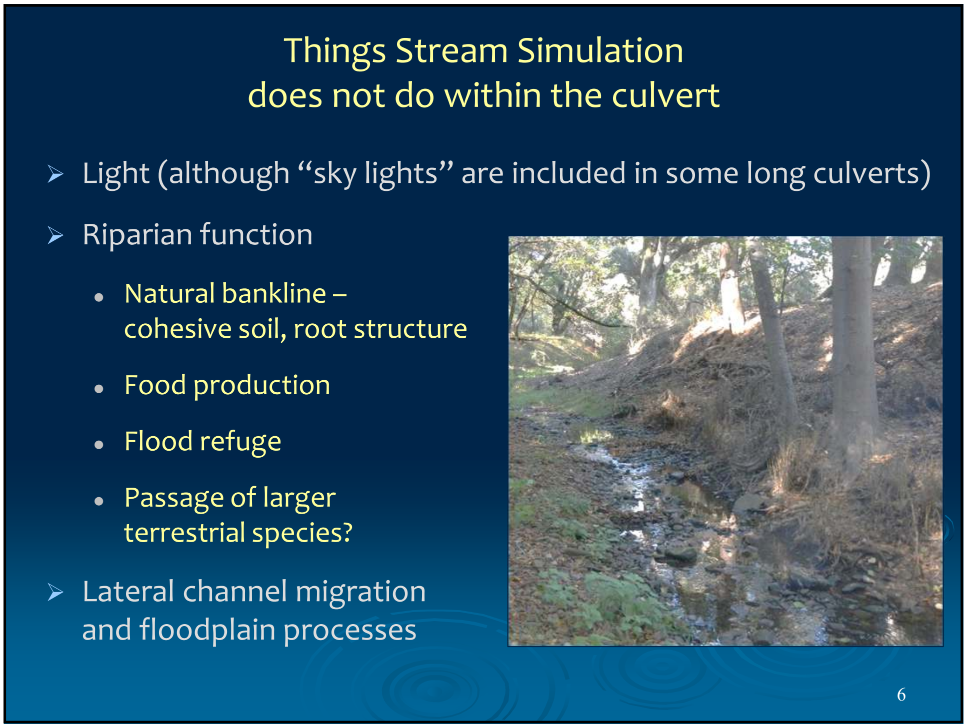
Primary Source:

USFS (2008). *Stream simulation: an ecological approach to road stream crossings*

Available at the FishXing website: **FishXing.org**

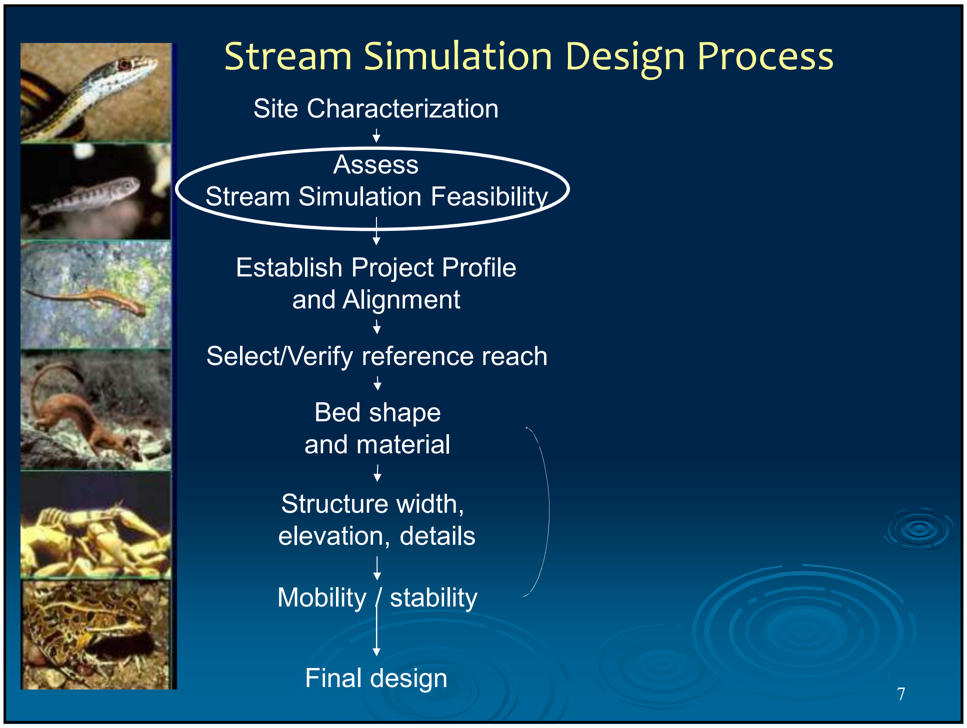
What is Stream Simulation?

- A Geomorphic Approach to Designing Stream Crossings
- Design Profile Seamlessly Connects Downstream & Upstream Channel Profiles
- Simulate A Natural Channel Reference Reach
  - Channel Slope
  - Bankfull Cross Section Dimensions
  - Channel Structure
    - Channel Bedforms
    - Mobility/Stability
  - Grade Forcing Features
  - Continuous Banks



Things Stream Simulation does not do within the culvert

- Light (although “sky lights” are included in some long culverts)
- Riparian function
  - Natural bankline – cohesive soil, root structure
  - Food production
  - Flood refuge
  - Passage of larger terrestrial species?
- Lateral channel migration and floodplain processes



Stream Simulation Design Process

Site Characterization

Assess
Stream Simulation Feasibility

Establish Project Profile
and Alignment

Select/Verify reference reach

Bed shape
and material

Structure width,
elevation, details

Mobility / stability

Final design

Site Assessment, Suitability

Suitability for a stream crossing?

- Channel stability
  - aggrading, alluvial fan, incising
- Debris flows
- Size of channel

Stream
Simulation

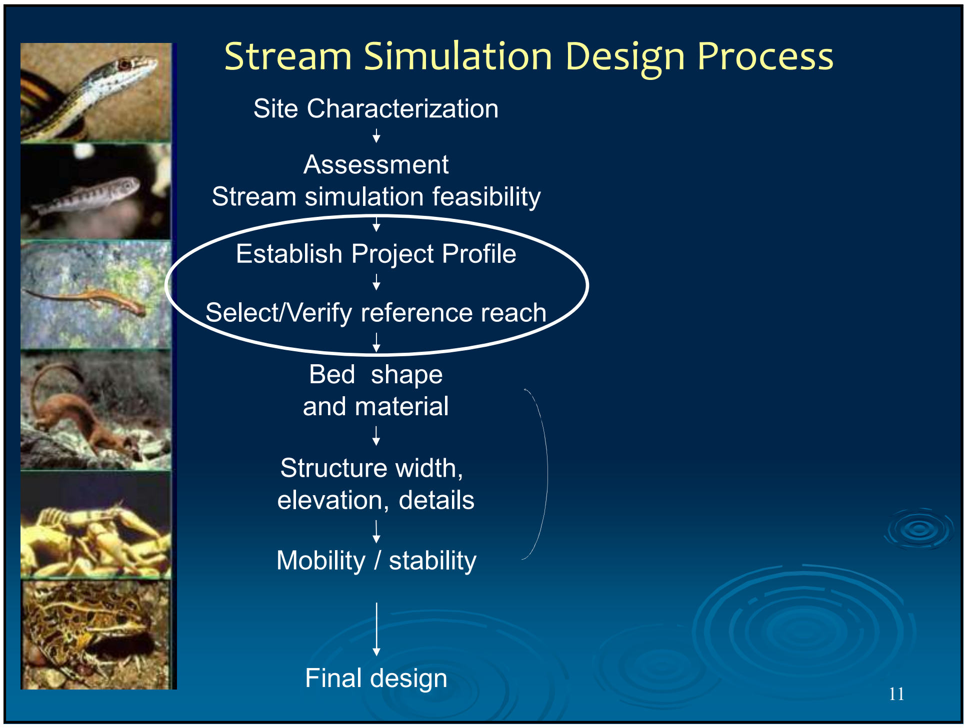
Wetland Crossings Unsuitable for Stream Simulation

Yontocket Slough

- Large culvert embedded below slough bottom
- Hydraulic Design (maintain low velocities for juvenile salmon)
- Encourage fine-grain material to deposit along bottom of culvert

Suitable for Stream Simulation

- Rock, sediment dominated
- Channel is in equilibrium



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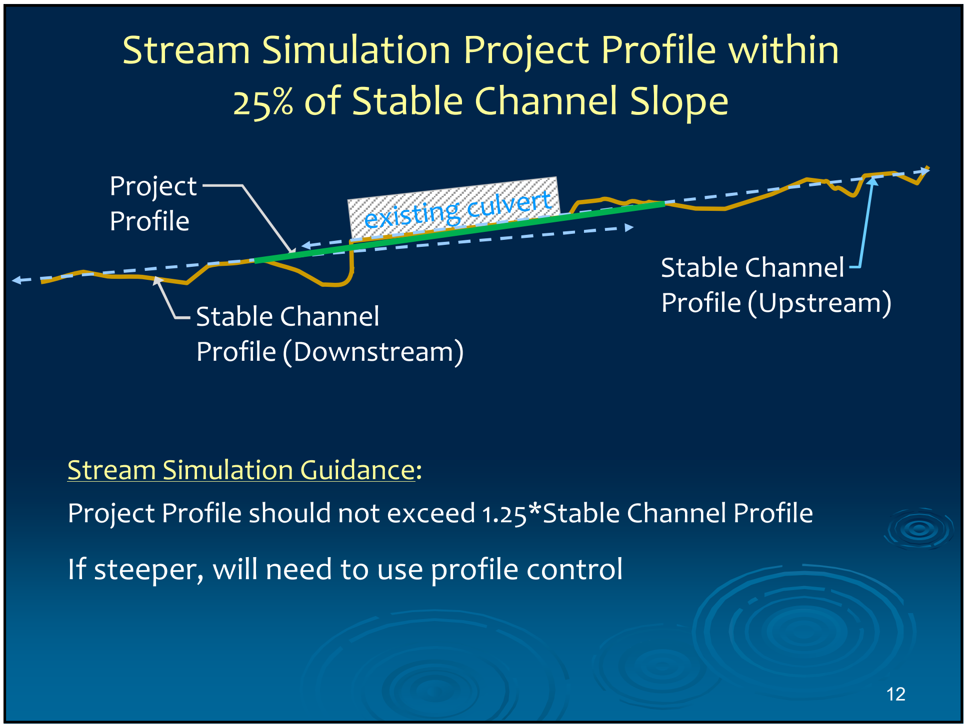
Final design

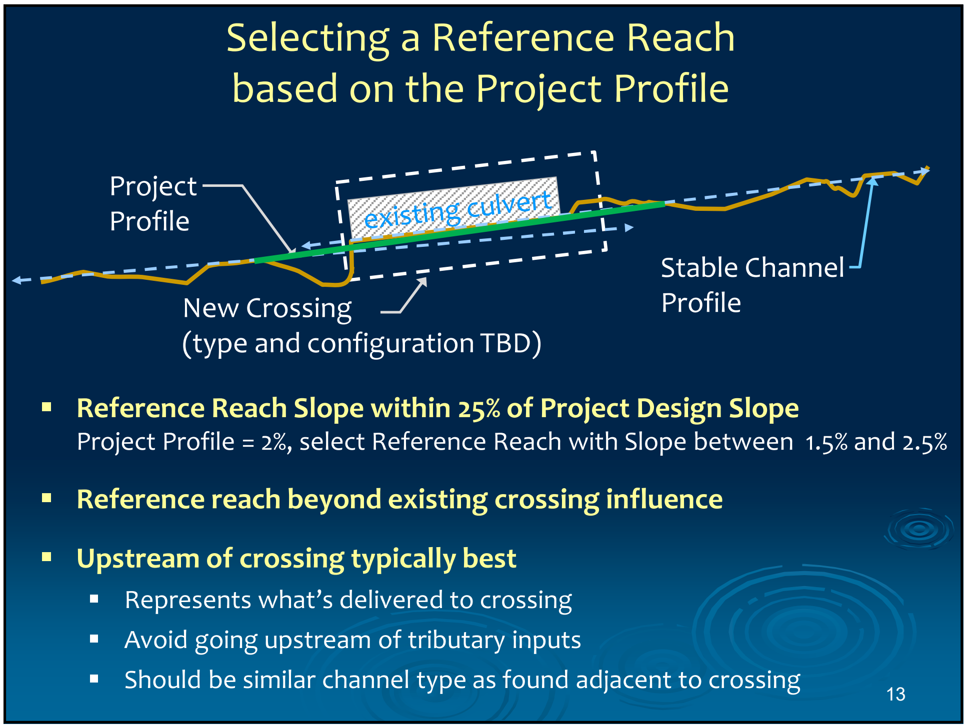


Stream Simulation Project Profile within 25% of Stable Channel Slope

Stream Simulation Guidance:

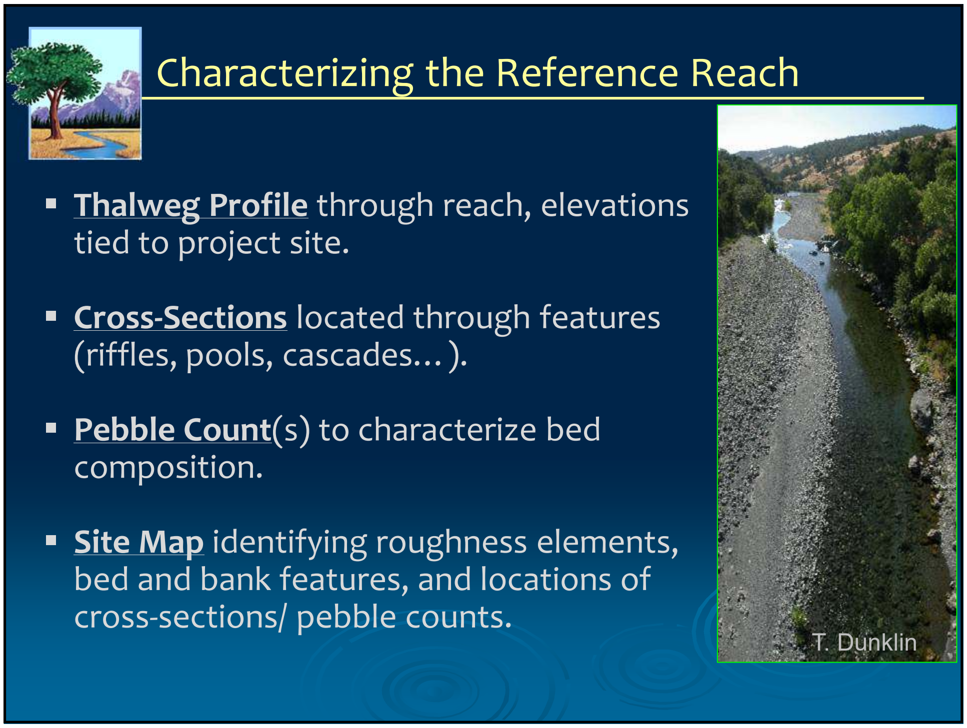
Project Profile should not exceed 1.25*Stable Channel Profile

If steeper, will need to use profile control



Selecting a Reference Reach based on the Project Profile

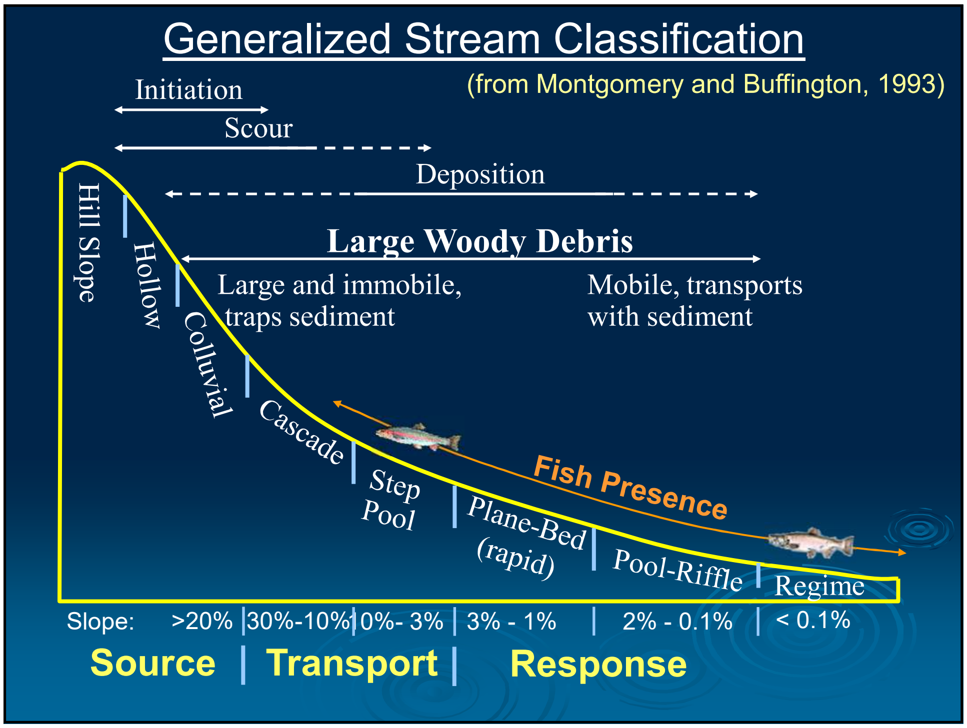
- **Reference Reach Slope within 25% of Project Design Slope**
  Project Profile = 2%, select Reference Reach with Slope between 1.5% and 2.5%
- **Reference reach beyond existing crossing influence**
- **Upstream of crossing typically best**
  - Represents what's delivered to crossing
  - Avoid going upstream of tributary inputs
  - Should be similar channel type as found adjacent to crossing



Characterizing the Reference Reach

- **Thalweg Profile** through reach, elevations tied to project site.
- **Cross-Sections** located through features (riffles, pools, cascades…).
- **Pebble Count**(s) to characterize bed composition.
- **Site Map** identifying roughness elements, bed and bank features, and locations of cross-sections/ pebble counts.

T. Dunklin



Generalized Stream Classification

(from Montgomery and Buffington, 1993)

Initiation

Scour

Deposition

Large Woody Debris

Large and immobile, traps sediment

Mobile, transports with sediment

Hill Slope

Hollow

Colluvial

Cascade

Step Pool

Plane-Bed (rapid)

Pool-Riffle

Regime

Fish Presence

Slope: >20% | 30%-10% | 10%- 3% | 3% - 1% | 2% - 0.1% | < 0.1%

Source | Transport | Response

Stream Simulation Design Process

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↓

Assessment

Stream simulation feasibility

↓

Establish Project Profile

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Select/Verify reference reach

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Bed shape and material

↓

Structure width, elevation, details

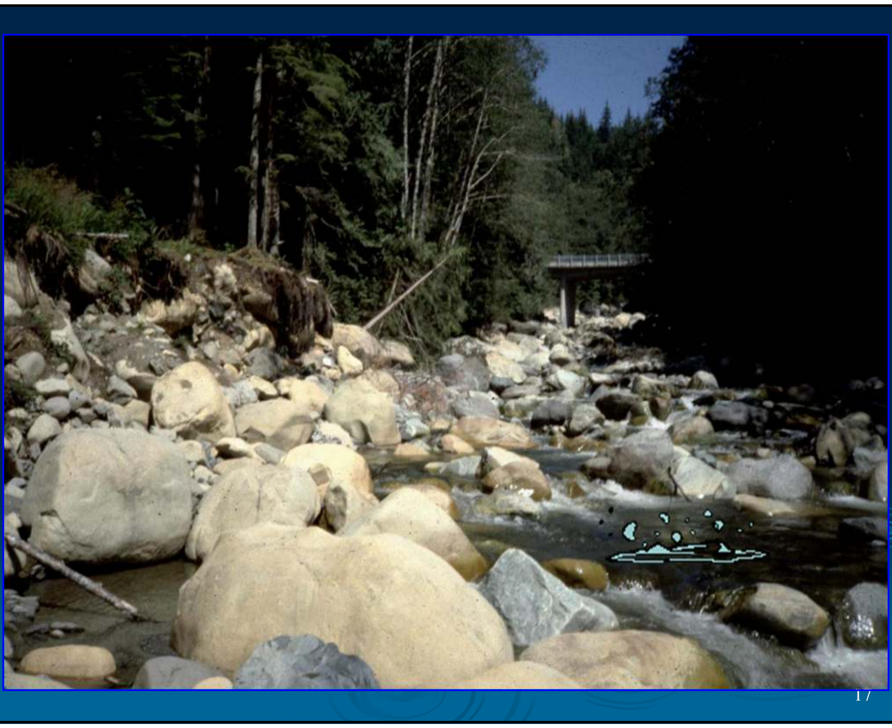
↓

Mobility / stability

↓

Final design

16



Bed Design Objectives

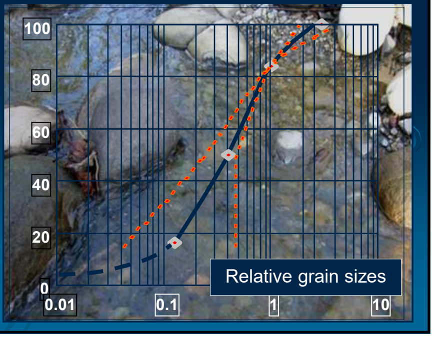
Simulate natural bed

- Bed shapes
- Diversity & Roughness
- Mobility/Stability
- Forcing features
- Control of permeability

Bed Material Design – Alluvial

Based on Reference reach Gradation:

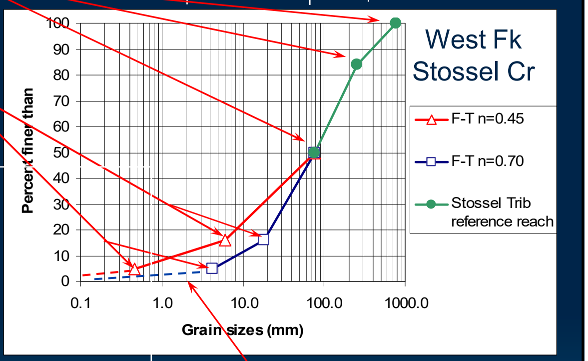
- Pebble count of reference channel for D_{100}, D_{84} and D_{50}
- Include dense gradation based on D50 for smaller material and impermeability.
- Fine-grained beds are special cases.
- Compensate for stability of initial disturbed condition.
- Account for large roughness and forcing features.



Bed Material Design – Alluvial

Larger particles sized directly from reference channel

Small grains derived by Fuller-Thompson (1907) curve based on D_{50}



Verify 5% to 10% are fines (<2mm)

Fuller-Thompson Equation:

$$P = \left[\frac{d}{D_{Max}} \right]^n$$

P = percent finer

d = diameter of particle

n = Fuller-Thompson density; varies 0.45 to 0.70

Modified to: **$D30 = 0.60^{1/n} \times D50$**

$D16 = 0.32^{1/n} \times D50$

$D5 = 0.10^{1/n} \times D50$

Bed Material Example

W Fk Stossel Cr

	Reference	Strm Sim	Fuller-Thompson n=0.64	
D100	30”	30”		
D84	10”	10”		
D50	3”	3”	3”	
D30			1.4”	$= 0.6^{1/n}$ x D50
D16			0.5”	$= 0.32^{1/n}$ x D50
D5			0.08”	$= 0.10^{1/n}$ x D50

Which is:

50% cobble and boulder

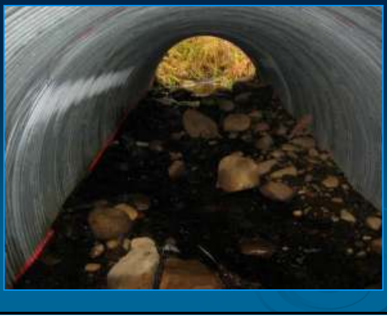
45% gravel

5% fines less than 2 mm
(sands/slits/clays)

Bed Material Example

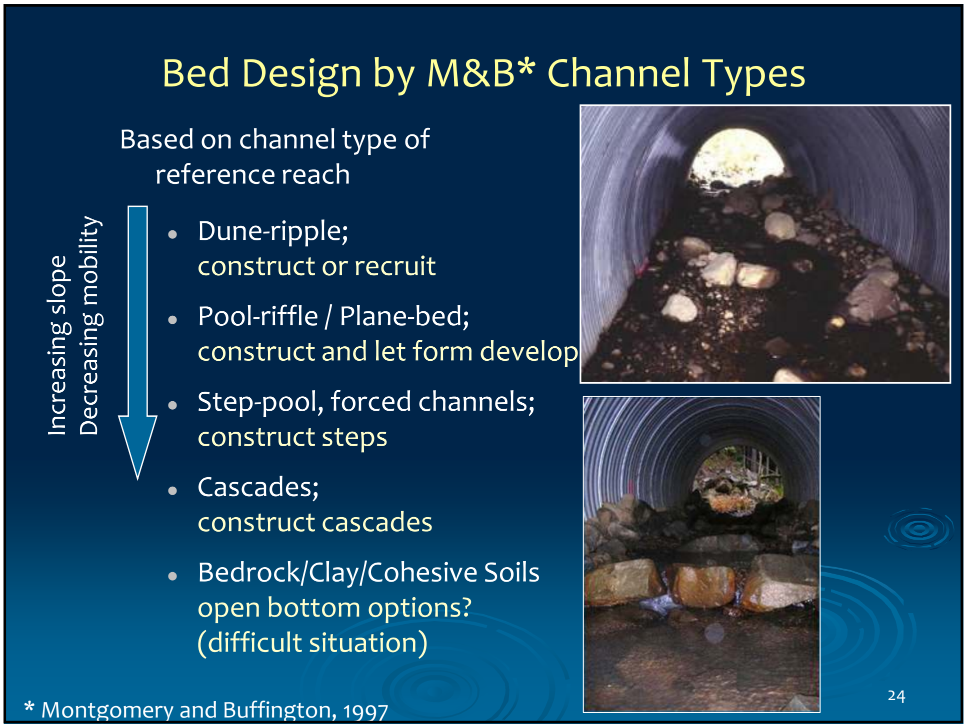
W Fk Stossel Cr - 6.4% slope

- 1 scoop bank run fines
- 4 scoops 4” minus river run
- 4 scoops 8” minus cobbles (or quarry spalls)
- 2 scoops 1.5’ minus rock
- 1.5 to 2.5 foot rock added during installation



Stream Bank Diversity

Ore Creek, Oregon
From USFS, 2006



Bed Design by M&B* Channel Types

Based on channel type of reference reach

Increasing slope
Decreasing mobility

- Dune-ripple;
  construct or recruit
- Pool-riffle / Plane-bed;
  construct and let form develop
- Step-pool, forced channels;
  construct steps
- Cascades;
  construct cascades
- Bedrock/Clay/Cohesive Soils
  open bottom options?
  (difficult situation)

* Montgomery and Buffington, 1997

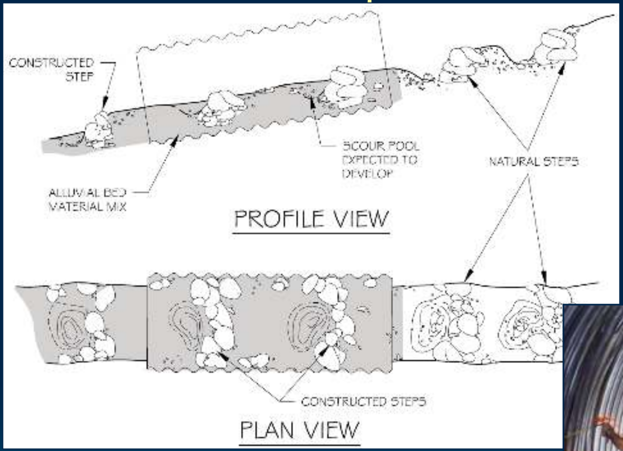
Boulder Plain-Bed Channel

< Reference Reach

Stream Simulation
Channel and Bridge
Crossing

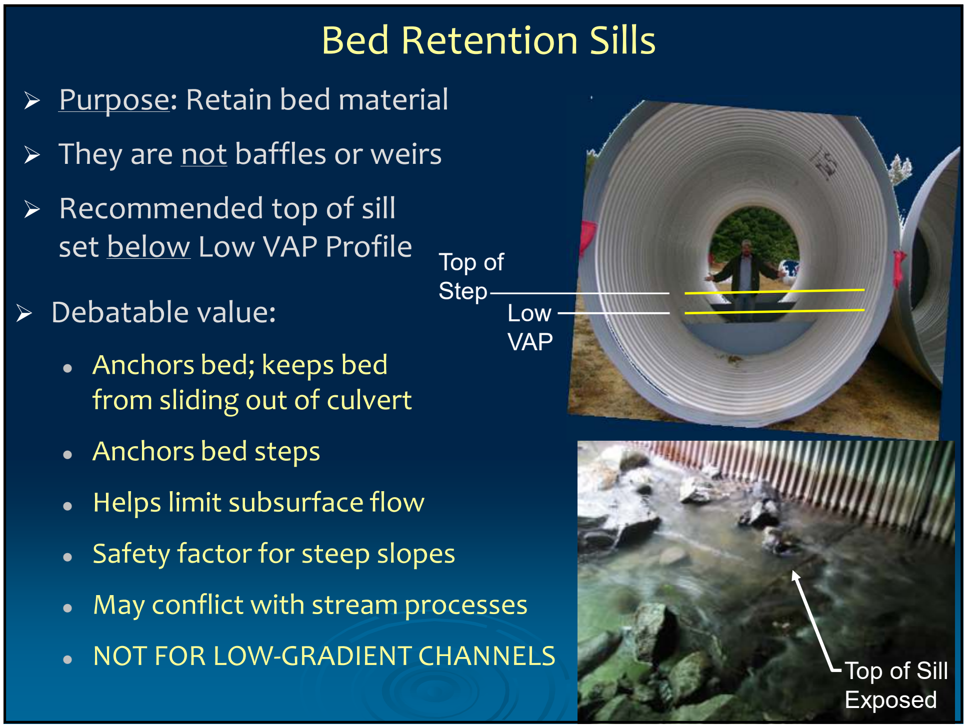
Fort Goff Creek
Highway 96

Step Pool Channels



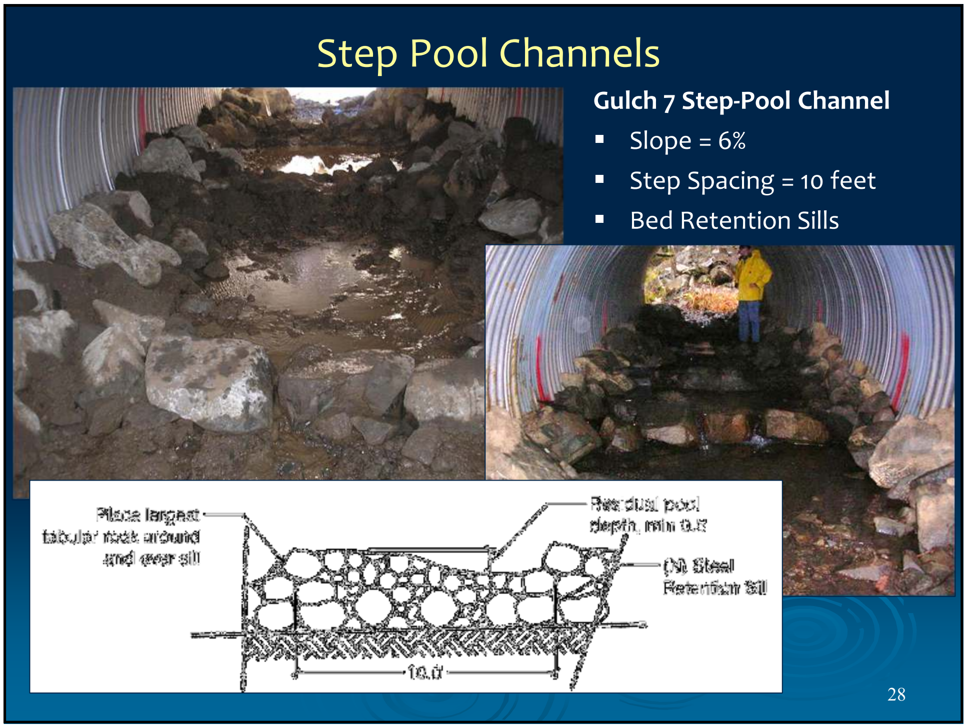
- Simulate boulder step-pools
- Simulate wood-forced step pools
- Generally considered a “stable” bed form

- Rock in steps sized to be immobile at design event (i.e. Q100)
- Design process becomes similar to roughened channel



Bed Retention Sills

- Purpose: Retain bed material
- They are not baffles or weirs
- Recommended top of sill set below Low VAP Profile
- Debatable value:
  - Anchors bed; keeps bed from sliding out of culvert
  - Anchors bed steps
  - Helps limit subsurface flow
  - Safety factor for steep slopes
  - May conflict with stream processes
  - NOT FOR LOW-GRADIENT CHANNELS



Step Pool Channels

Gulch 7 Step-Pool Channel

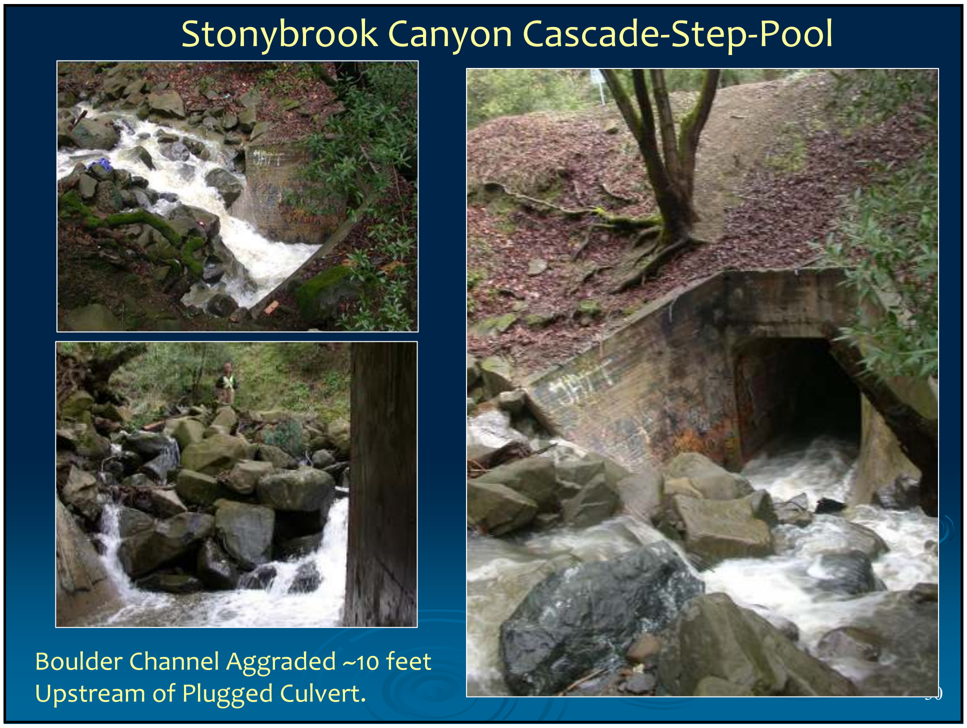
- Slope = 6%
- Step Spacing = 10 feet
- Bed Retention Sills

Wood Steps-Pool Channels

Tongass NF, AK

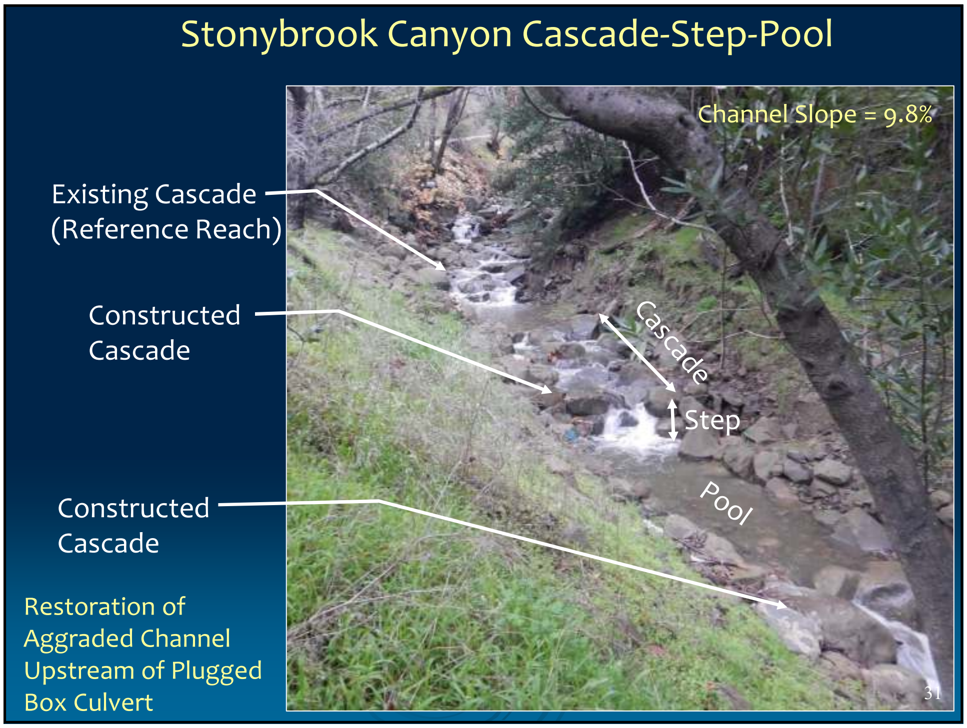
- Slope = 11%
- Used Cedar planks and "brow" logs for crests
- Filled with bed material to for sediment transport continuity
- Still functioning after 14-years

From Bob Gubernick, USFS



Stonybrook Canyon Cascade-Step-Pool

Boulder Channel Aggraded ~10 feet Upstream of Plugged Culvert.



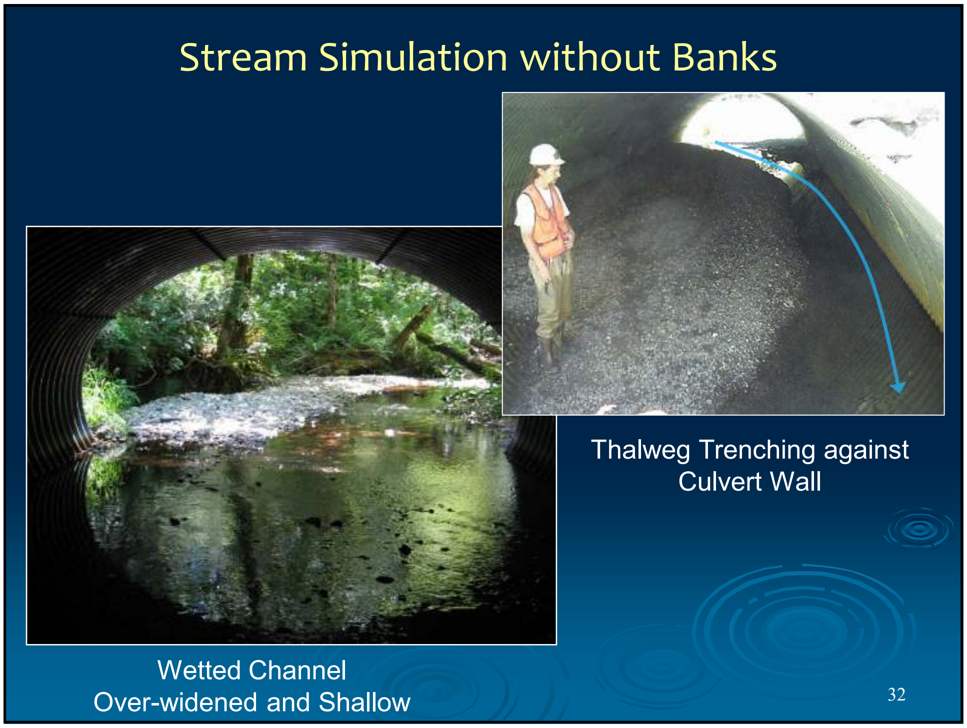
Stonybrook Canyon Cascade-Step-Pool

Existing Cascade
(Reference Reach)

Constructed
Cascade

Constructed
Cascade

Restoration of
Aggraded Channel
Upstream of Plugged
Box Culvert



Stream Simulation without Banks

Thalweg Trenching against
Culvert Wall

Wetted Channel
Over-widened and Shallow

Lack of Banklines Lead to Overwidened Channels

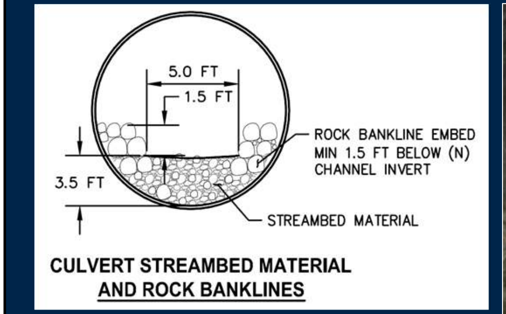
Use Banklines to Define your Bankfull Channel

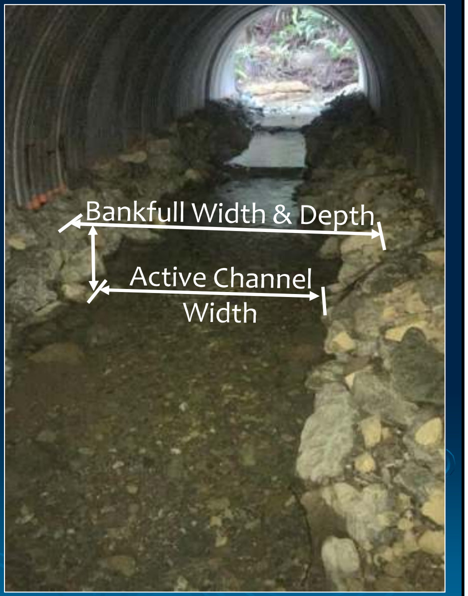
Channel width through crossing excessively wide compared to adjacent natural channel

- Lack of streambanks to create confinement
- Produces shallower flow depths than in adjacent natural channel
- Likely creating low-flow barriers to fish movement

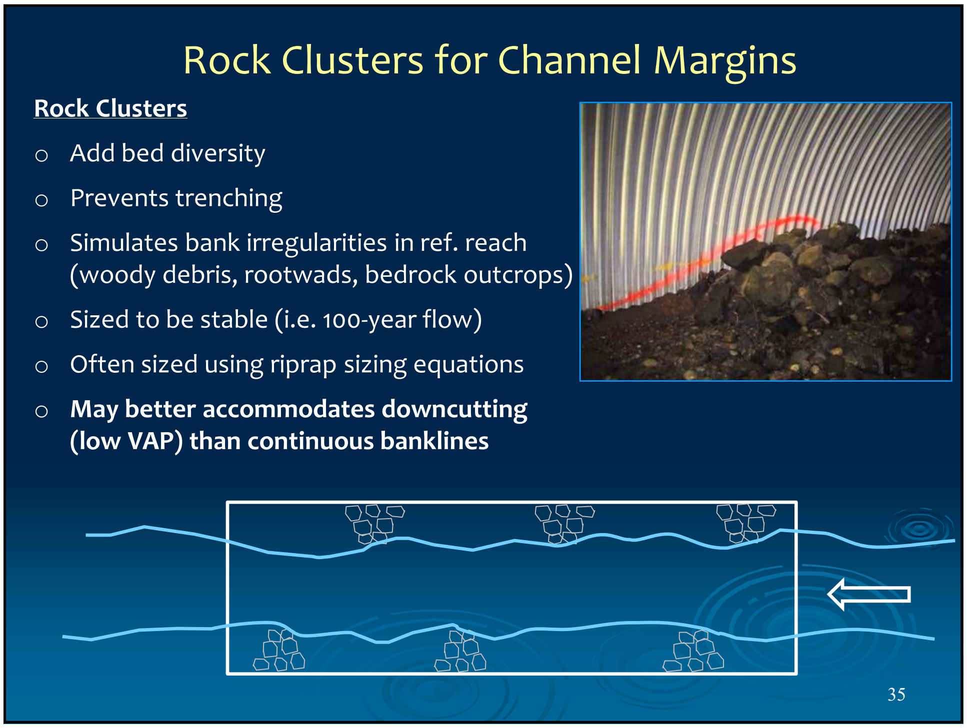
From Lang and Love (2022) – Caltrans Fish Passage Engineering Research Project

Continuous Banklines





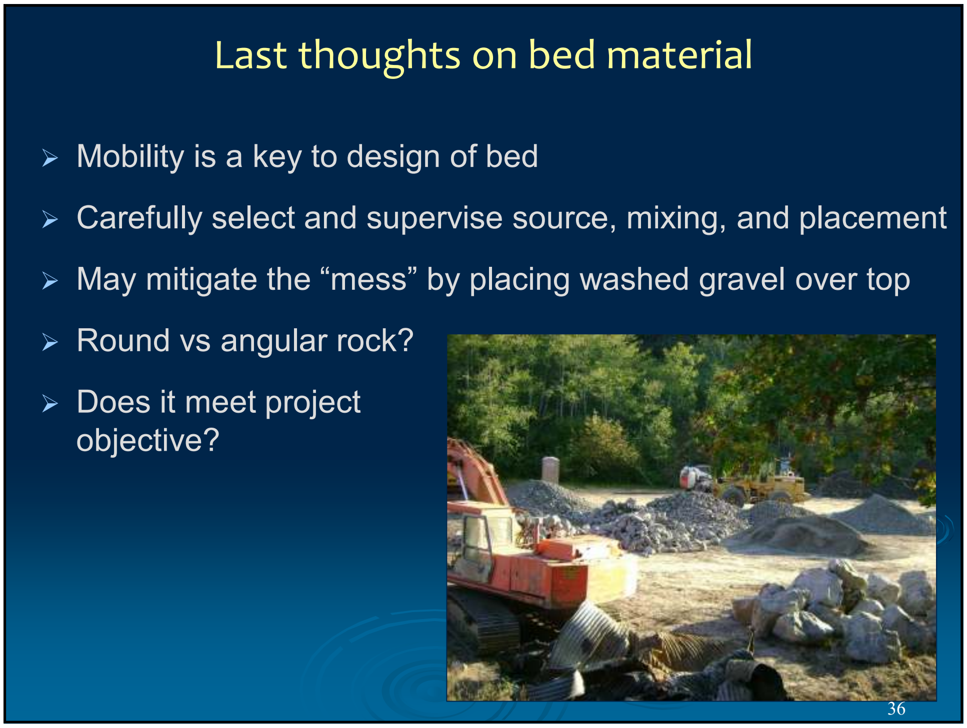
- Defines channel shape
- Edge diversity
- Terrestrial pathway
- Rock sized for stability (ie Q100)
- Fill voids with smaller material



Rock Clusters for Channel Margins

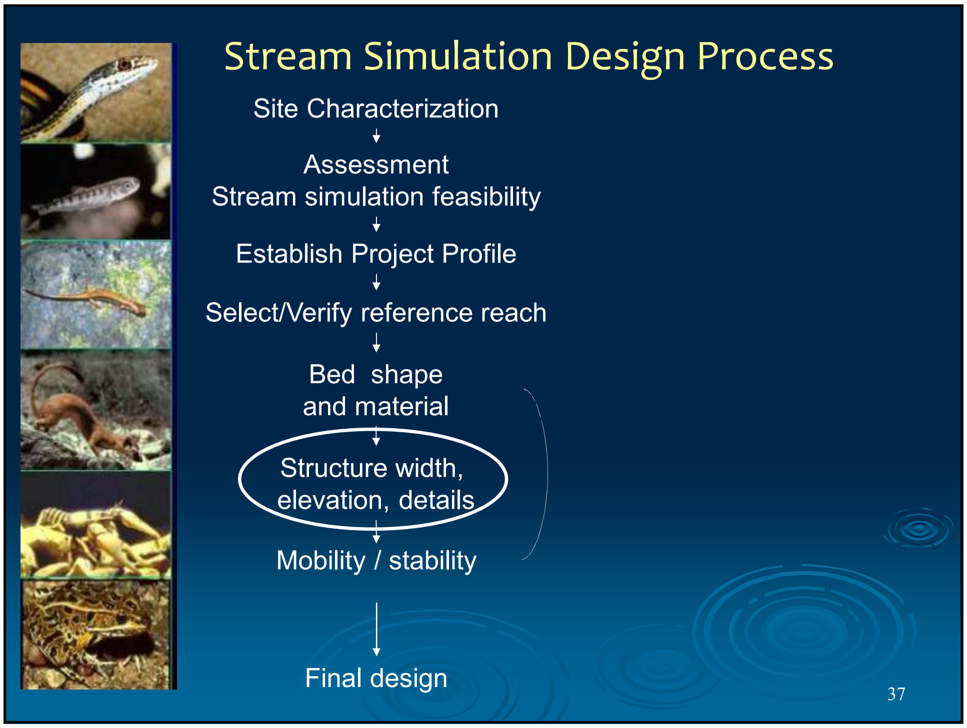
Rock Clusters

- Add bed diversity
- Prevents trenching
- Simulates bank irregularities in ref. reach (woody debris, rootwads, bedrock outcrops)
- Sized to be stable (i.e. 100-year flow)
- Often sized using riprap sizing equations
- **May better accommodates downcutting (low VAP) than continuous banklines**



Last thoughts on bed material

- Mobility is a key to design of bed
- Carefully select and supervise source, mixing, and placement
- May mitigate the “mess” by placing washed gravel over top
- Round vs angular rock?
- Does it meet project objective?



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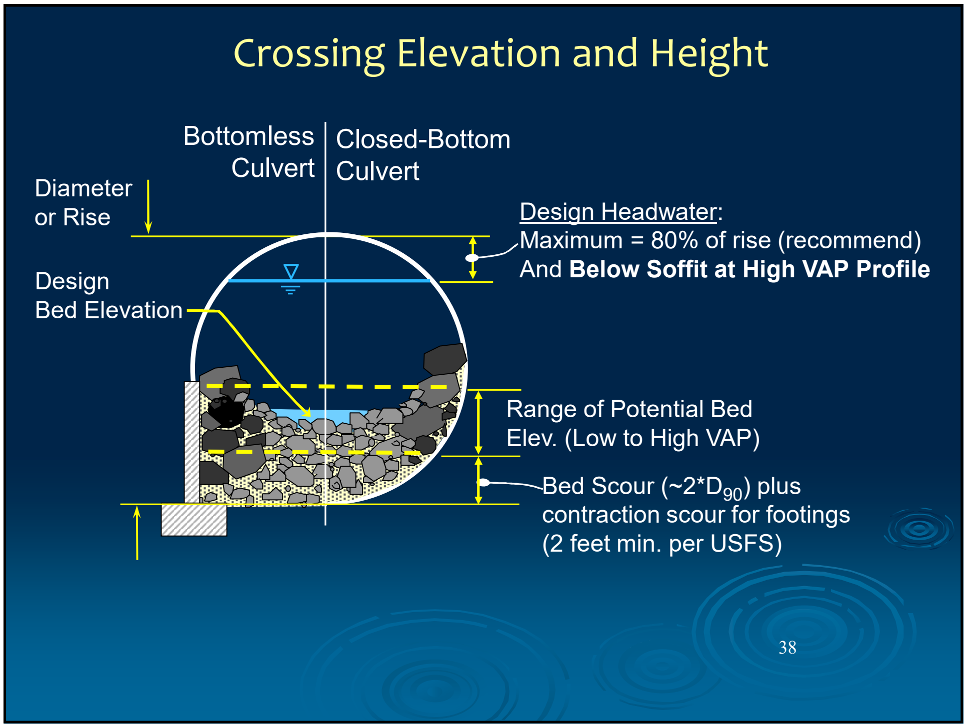


Crossing Elevation and Height

Design Headwater:
Maximum = 80% of rise (recommend)
And **Below Soffit at High VAP Profile**

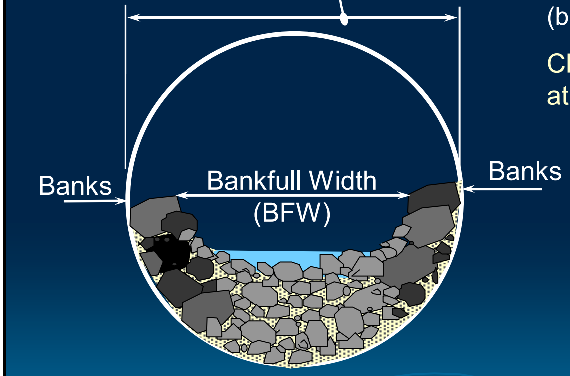
Range of Potential Bed
Elev. (Low to High VAP)

Bed Scour (~2*D_{90}) plus
contraction scour for footings
(2 feet min. per USFS)

Photo: Kozmo Bates

Stream Simulation
First Estimate of Crossing Width

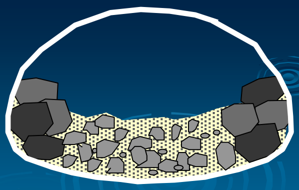
First estimate:
Culvert width to fit over-channel banks/margins

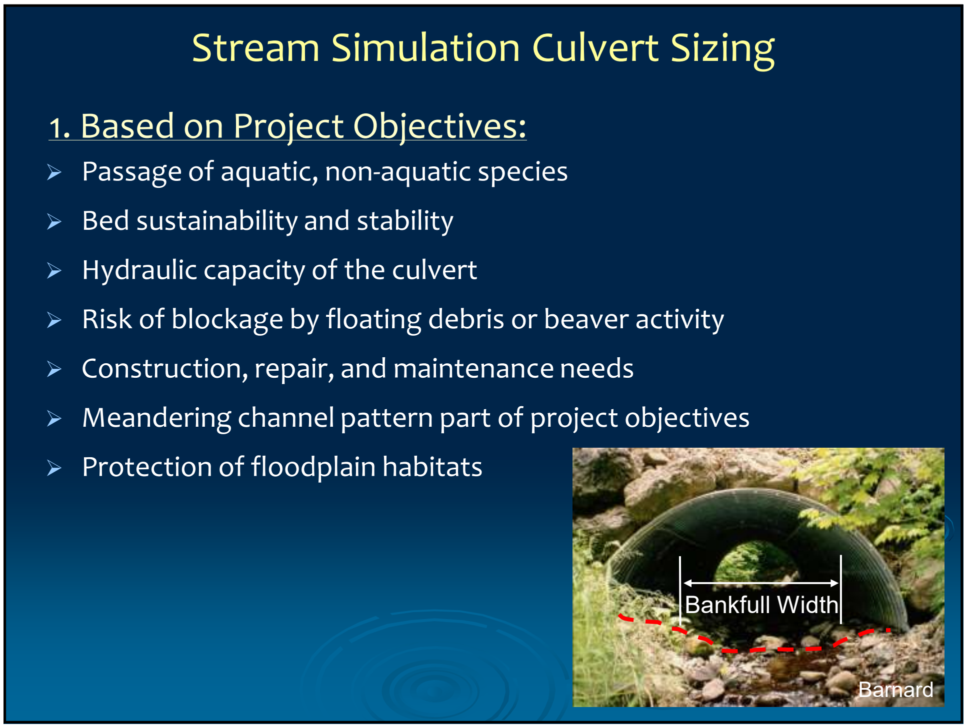


Often Applied Criteria:

Min. Crossing Width = 1.5*BFW (based on NMFS 2023 guidelines)

Chanel Width must be provided at Bankfull Depth

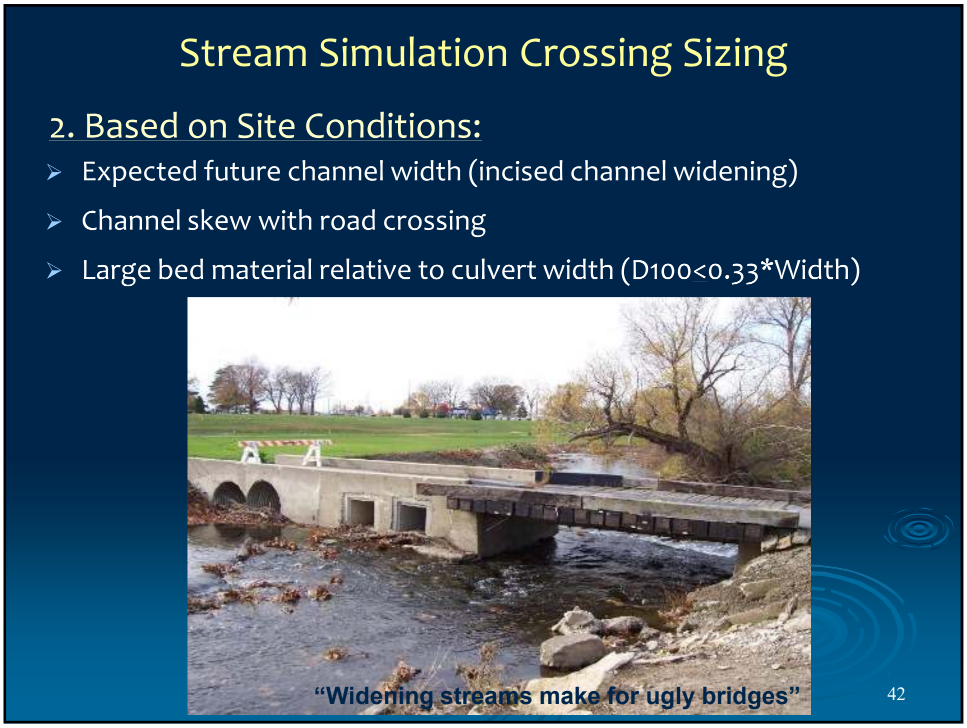




Stream Simulation Culvert Sizing

1. Based on Project Objectives:

- Passage of aquatic, non-aquatic species
- Bed sustainability and stability
- Hydraulic capacity of the culvert
- Risk of blockage by floating debris or beaver activity
- Construction, repair, and maintenance needs
- Meandering channel pattern part of project objectives
- Protection of floodplain habitats

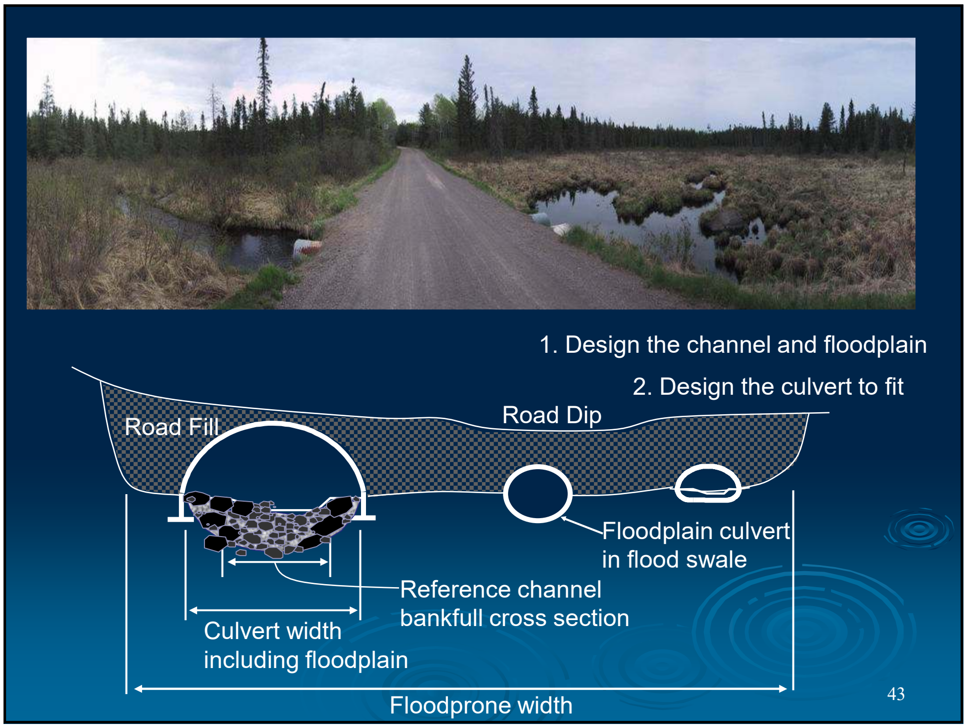


Stream Simulation Crossing Sizing

2. Based on Site Conditions:

- Expected future channel width (incised channel widening)
- Channel skew with road crossing
- Large bed material relative to culvert width (D100≤0.33*Width)

"Widening streams make for ugly bridges"



1. Design the channel and floodplain

2. Design the culvert to fit

Road Fill

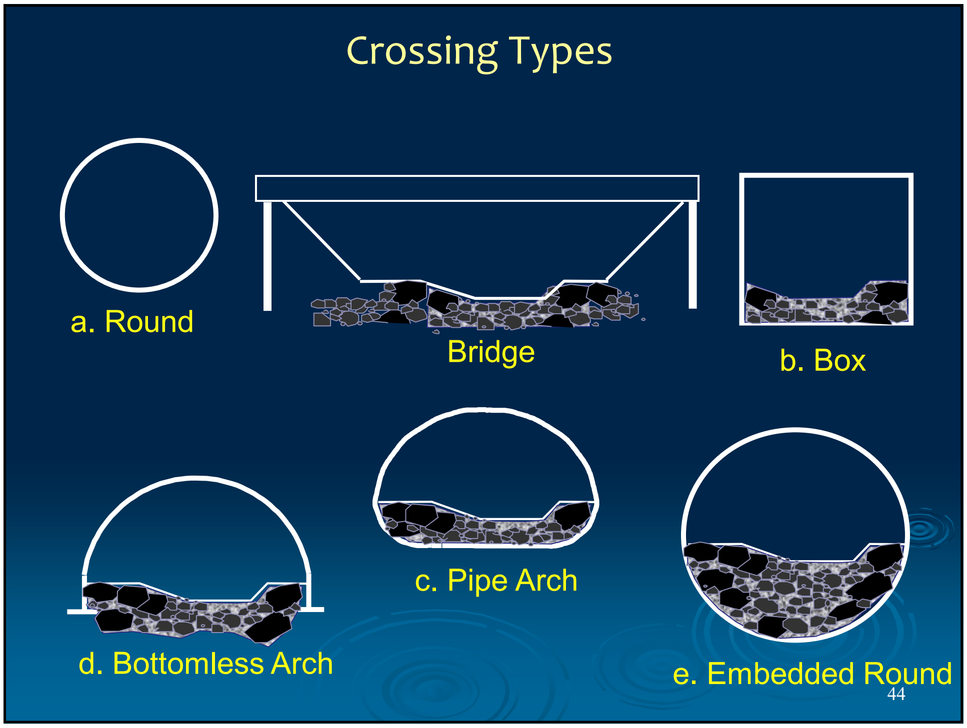
Road Dip

Floodplain culvert in flood swale

Reference channel bankfull cross section

Culvert width including floodplain

Floodprone width



Crossing Types

a. Round

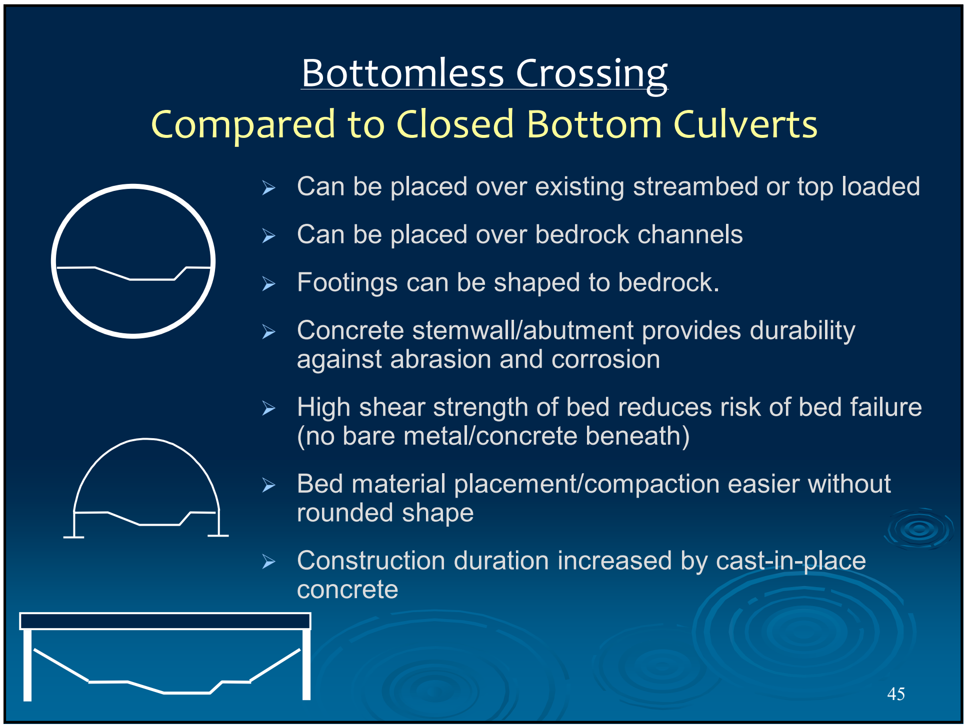
Bridge

b. Box

c. Pipe Arch

d. Bottomless Arch

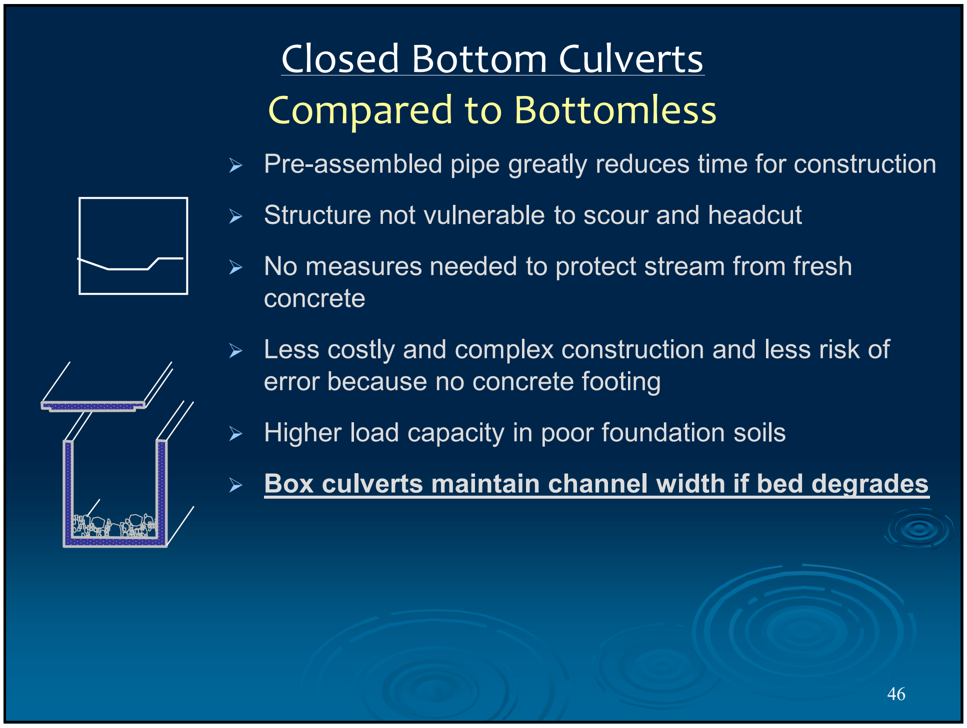
e. Embedded Round



Bottomless Crossing

Compared to Closed Bottom Culverts

- Can be placed over existing streambed or top loaded
- Can be placed over bedrock channels
- Footings can be shaped to bedrock.
- Concrete stemwall/abutment provides durability against abrasion and corrosion
- High shear strength of bed reduces risk of bed failure (no bare metal/concrete beneath)
- Bed material placement/compaction easier without rounded shape
- Construction duration increased by cast-in-place concrete



Closed Bottom Culverts

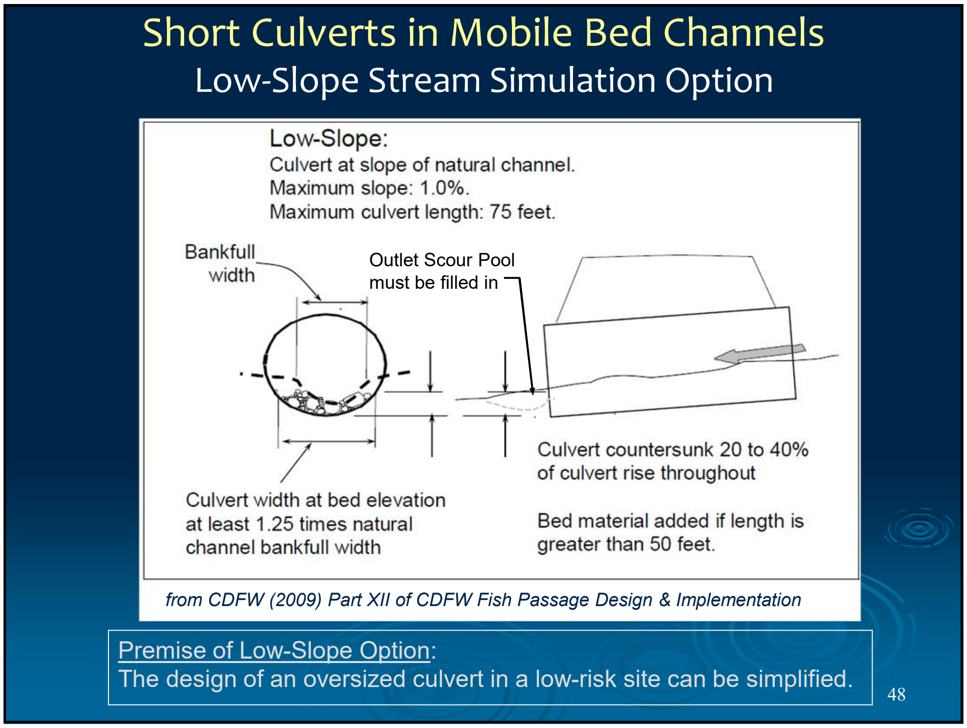
Compared to Bottomless

- Pre-assembled pipe greatly reduces time for construction
- Structure not vulnerable to scour and headcut
- No measures needed to protect stream from fresh concrete
- Less costly and complex construction and less risk of error because no concrete footing
- Higher load capacity in poor foundation soils
- **Box culverts maintain channel width if bed degrades**

Yikes!
Bad bridge

Camp 10 Ck

Not necessarily better just because it’s a bridge.



Short Culverts in Mobile Bed Channels

Low-Slope Stream Simulation Option

Low-Slope:
Culvert at slope of natural channel.
Maximum slope: 1.0%.
Maximum culvert length: 75 feet.

Bankfull width

Outlet Scour Pool must be filled in

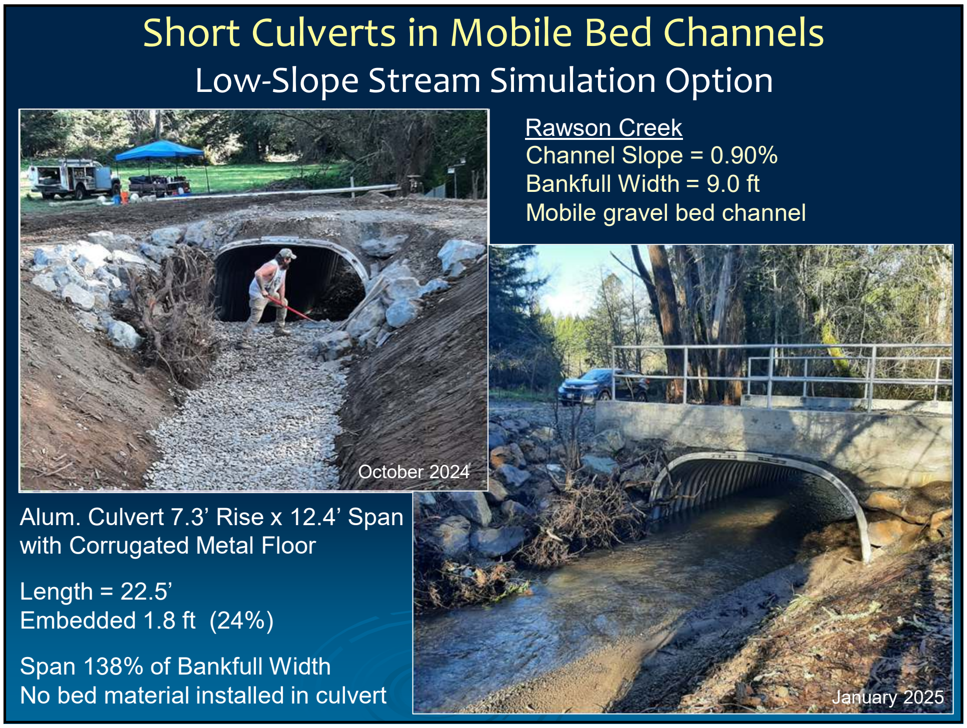
Culvert countersunk 20 to 40% of culvert rise throughout

Culvert width at bed elevation at least 1.25 times natural channel bankfull width

Bed material added if length is greater than 50 feet.

from CDFW (2009) Part XII of CDFW Fish Passage Design & Implementation

Premise of Low-Slope Option:
The design of an oversized culvert in a low-risk site can be simplified.



Short Culverts in Mobile Bed Channels

Low-Slope Stream Simulation Option

Rawson Creek
Channel Slope = 0.90%
Bankfull Width = 9.0 ft
Mobile gravel bed channel

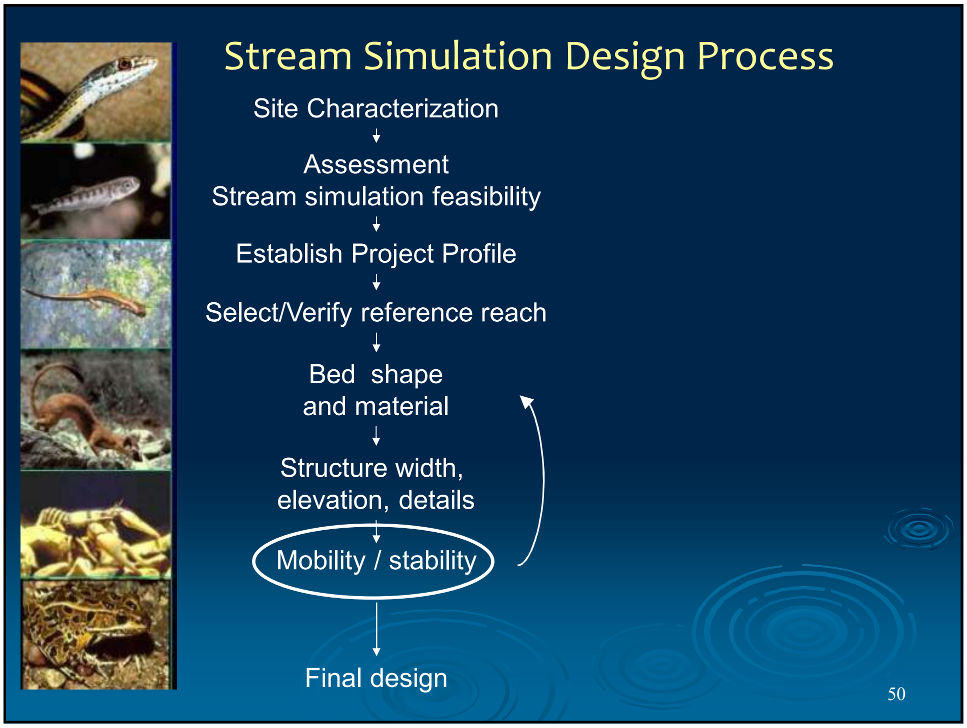
October 2024

Alum. Culvert 7.3’ Rise x 12.4’ Span
with Corrugated Metal Floor

Length = 22.5’
Embedded 1.8 ft (24%)

Span 138% of Bankfull Width
No bed material installed in culvert

January 2025



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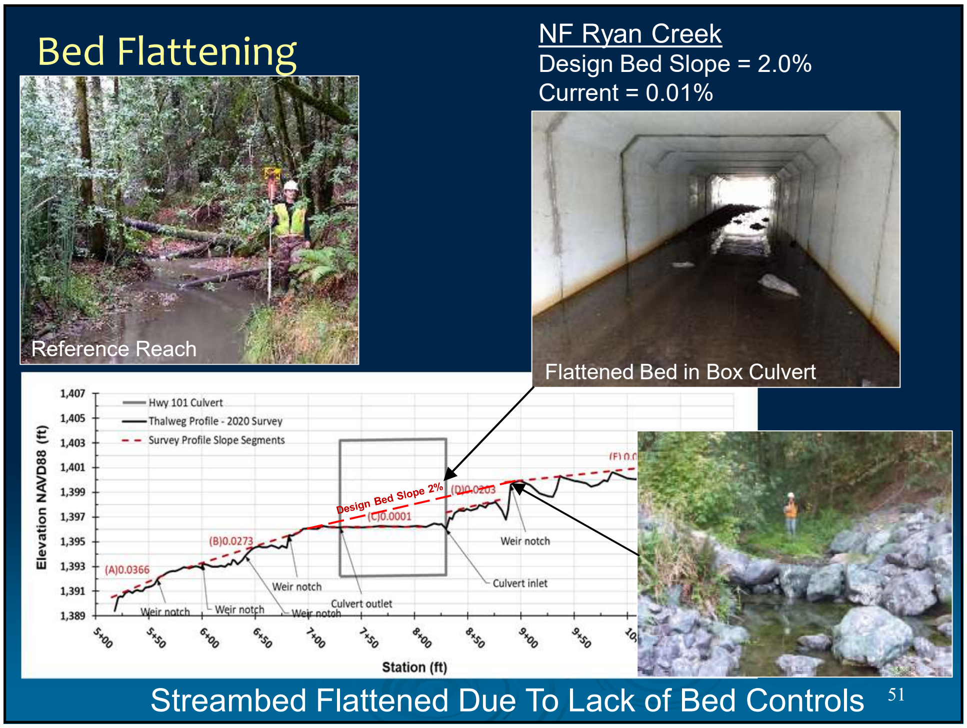


Bed Flattening

NF Ryan Creek
Design Bed Slope = 2.0%
Current = 0.01%

Reference Reach

Flattened Bed in Box Culvert

Streambed Flattened Due To Lack of Bed Controls

Bed Failure

Stimson Creek
Culvert to BF Width Ratio = 1.0
Slope = design 5%; current 2.2%

Culvert too narrow, bed material too small.
Bed slope flattens.

From: Kozmo Bates

Bed Mobility and Stability Analysis

1. Stream Simulation Objective:

   Similar sized bed particles become mobile at similar flows in Reference Reach and Stream Simulation Reach

2. Mobility Analysis Compares

   Critical Entrainment Flows (Qc) and Shear Strees (τc):

   $Qc_{culvert} = Qc_{reference\_reach}$

   $\tau c_{culvert} = \tau c_{reference\_reach}$

3. Mobility analysis typically used on higher risk sites:
   - Floodplain constrictions
   - Project Profile steeper than reference reach
4. Don’t let the analysis drive the design

Key Pieces - Stability Analysis

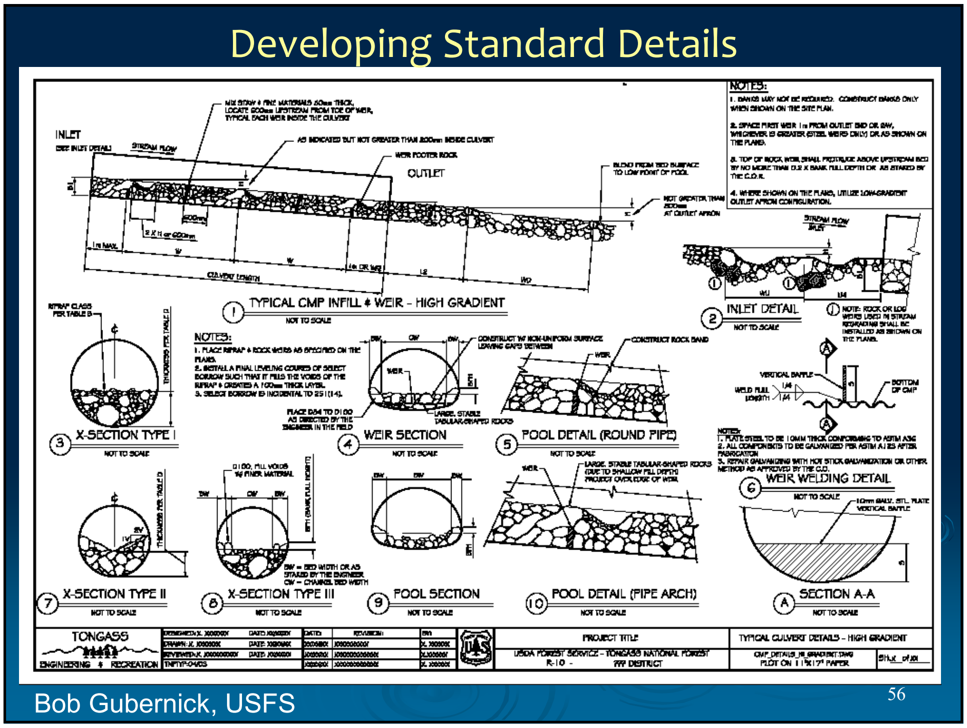
- Key pieces include banklines, clusters, steps, and others
- Key pieces are permanent (up to stability design flow)
- What is stability design flow?
- Stability models - analytical
  - Bathurst (1987)
  - USACE bank riprap (1994)
  - USACE rock chute (1994)

USACE. 1994. Hydraulic Design of Flood Control Channels 1110-2-1601. U.S. Army Corps of Engineers,

Bankfull Width Structure after 16 years

Width ratio: 1.0, slope 4.5%

Johansen



Developing Standard Details

Bob Gubernick, USFS

Bed Material Placement

- Requires vigilante on-site inspection
- Consider building the bed from downstream to upstream rather than in lifts
- Plans should indicate specific locations of Key Pieces/Forcing Features
- Pebble counts serve to check bed gradation
- Make sure the bed is compacted
  - Use flooding or jetting
  - May use vibratory means

Jetting and Flooding Critical to Sealing Bed

1. Place in lifts and jet until water ponds on surface for specified time (~30 seconds)
2. Use a rock bar to fill larger voids with smaller coarse material
3. If lift not sealed, add filler material (additional fines) on top and jet in

Stream Simulation Construction

Placing Bed Material with Standard Construction Equipment

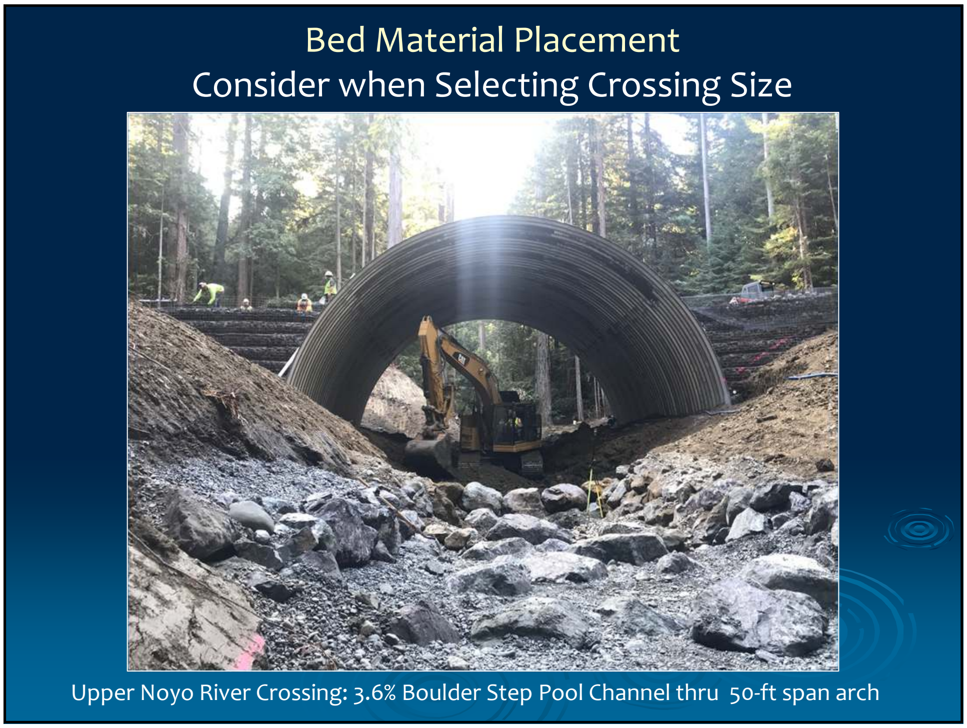
Premixed

Kim Johansen, USFS

Stream Simulation Construction

Standard Construction Equipment

Premixed



Bed Material Placement
Consider when Selecting Crossing Size

Upper Noyo River Crossing: 3.6% Boulder Step Pool Channel thru 50-ft span arch

Bed Material Placement

- Dingo Loaders
- Manually
- Trail Equipment

Bed Material Placement
Special Equipment