Introduction to HEC-RAS Culvert Hydraulics

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Houston, Texas

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Speaker – Matthew Zeve

- Started working on HEC-RAS models in 2001
- Completed hundreds of culvert analyses over the years
- Provide technical assistance for HEC-RAS modeling worldwide

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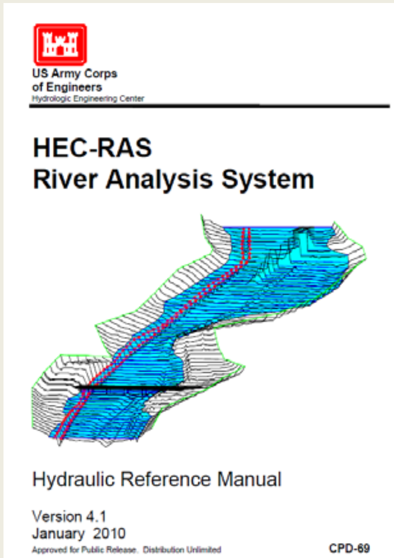
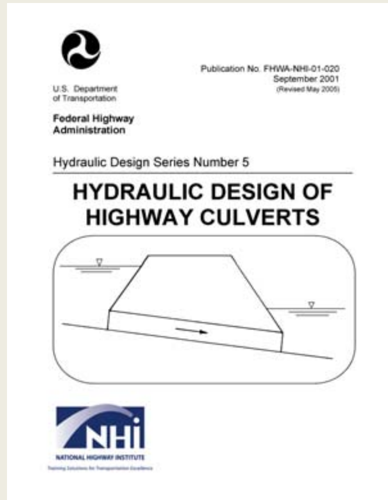
References





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Introduction

- Agenda
  - Culvert terminology
  - Inlet and outlet control
  - Chart and scale numbers
  - Solution technique in HEC-RAS
  - Examples in the software

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Culvert Terminology

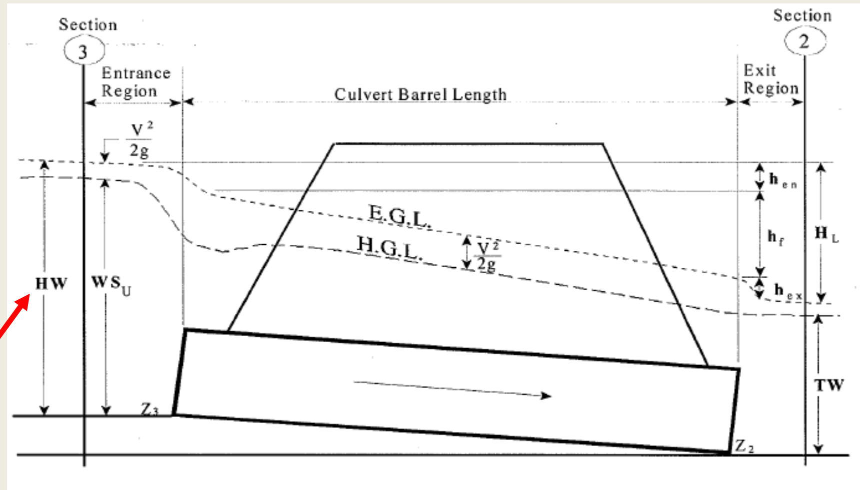

Figure 6-7 Full flowing culvert with energy and hydraulic grade lines

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Headwater

- Energy is required to force water through a culvert
- Energy takes the form of increased water surface at the upstream end of the culvert
- Headwater depth is measured from the invert of the culvert to the energy grade line

Culvert Terminology

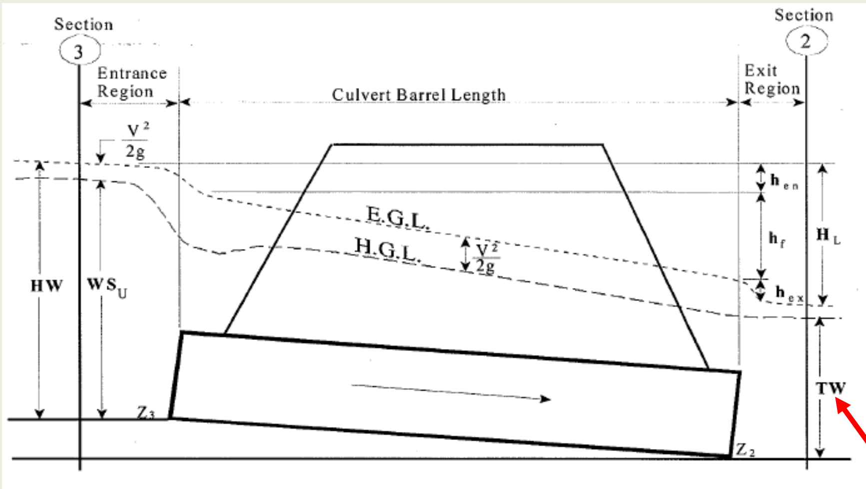

Figure 6-7 Full flowing culvert with energy and hydraulic grade lines

HEC-RAS Hydraulic Reference Manual

Tailwater

- Depth of water downstream of the culvert as measured from the invert
- Can be caused by obstruction in the downstream channel or hydraulic resistance in the channel
- Backwater

Culvert Hydraulic Calculations in HEC-RAS

- Uses FHWA HDS-5 Methodology
  - Inlet Control
    - Chart
    - Scale
  - Outlet Control
    - Exit Loss Coefficient (Default: 1.0)
    - Culvert Roughness, Slope, Length
    - Entrance Loss Coefficient

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Inlet Control

- Occurs when culvert barrel is capable of conveying more flow than inlet will accept
- Flow control section located just inside entrance
- Hydraulic characteristics downstream do not affect culvert capacity

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Typical Inlet Control

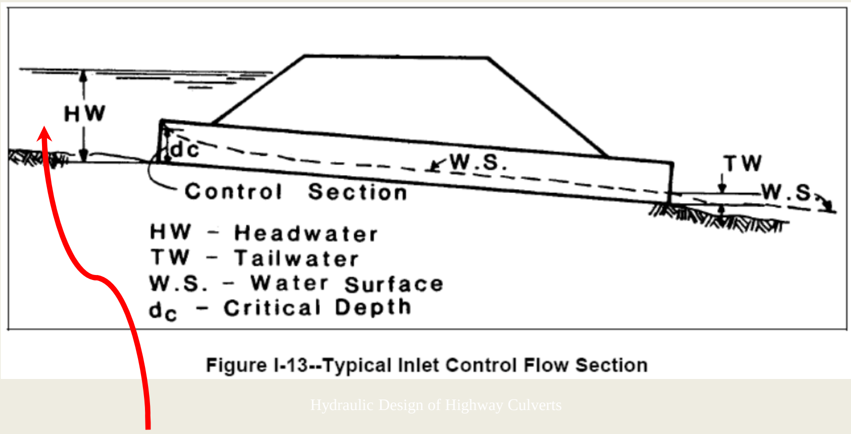
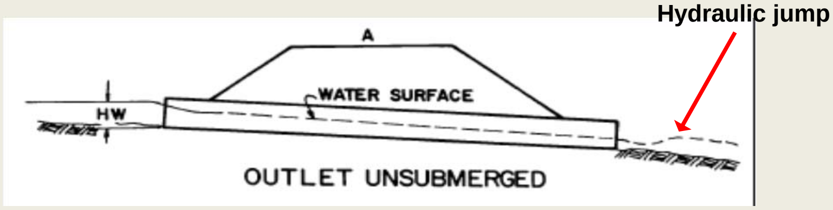


Figure I-13--Typical Inlet Control Flow Section

Hydraulic Design of Highway Culverts

Inlet Control



Hydraulic Design of Highway Culverts

Figure A:

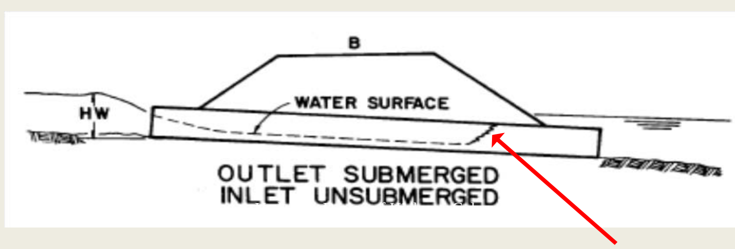
Neither inlet nor the outlet is submerged. Critical depth just D/S of entrance and flow is supercritical.

Inlet Control

Inlet Side | **_Outlet Side_**

Source: http://www.hydrocad.net/culvert1.htm

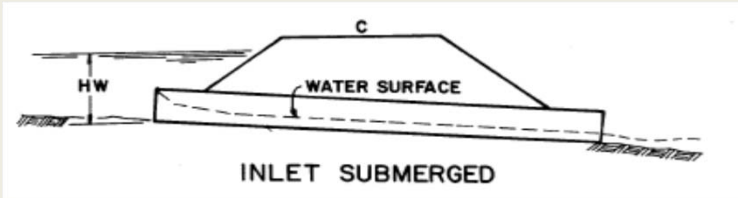
Inlet Control



Hydraulic jump

Figure B:
Submergence of outlet and hydraulic jump in barrel

Inlet Control

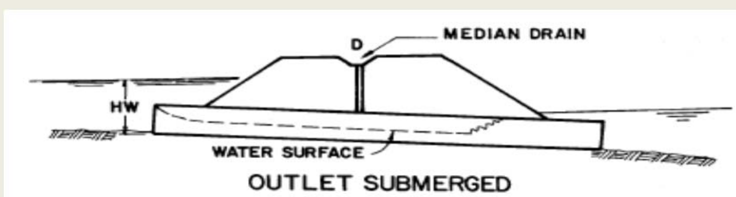


Hydraulic Design of Highway Culverts

Figure C:

Inlet submerged and open outfall. Supercritical flow in barrel and flow approaches normal depth at end of culvert

Inlet Control



Hydraulic Design of Highway Culverts

Figure D:

Inlet and outlet submerged. Vented culvert allows hydraulic jump to form

Commonly Used Inlet Configurations

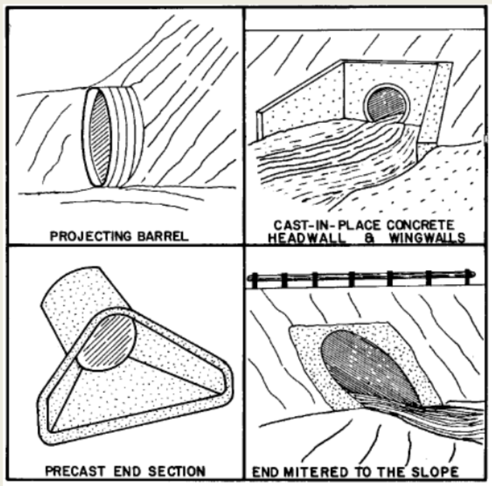


Figure I-7--Four Standard Inlet Types (schematic)

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Improved Inlet Concept

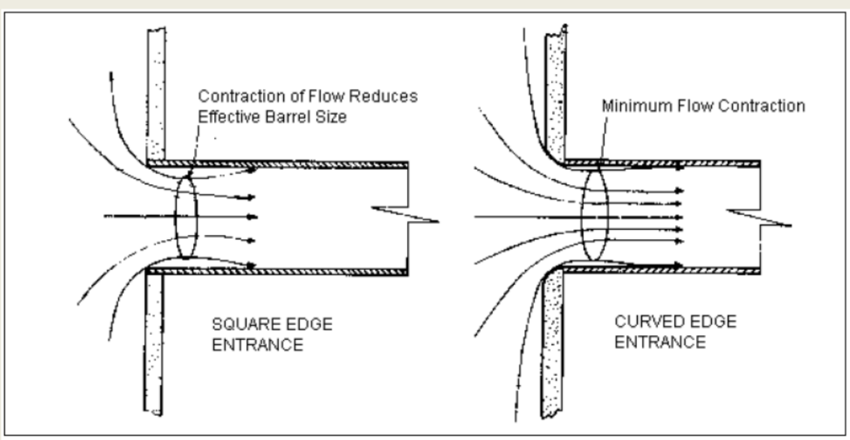

Figure I-8—Entrance Contraction (schematic)

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Improved Inlet Concept

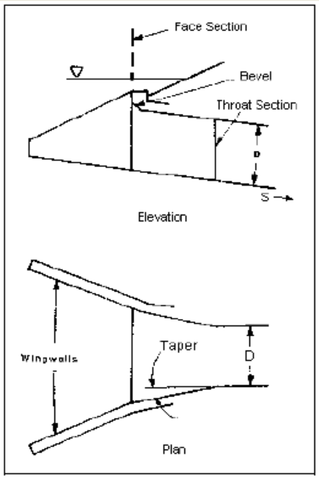

Figure I-9--Side-tapered inlet

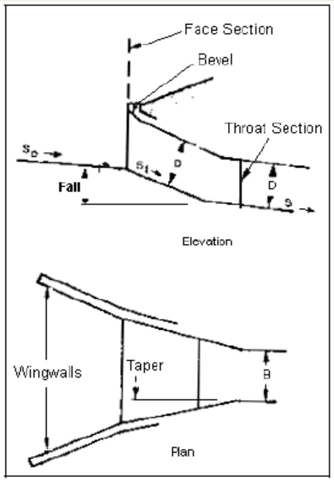

Figure I-10--Slope-tapered inlet

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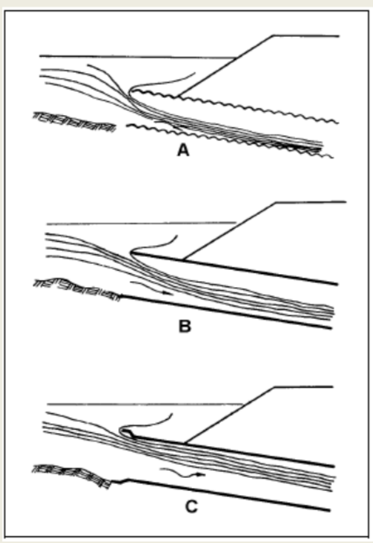
Improved Inlet Concept



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Inlet Control

- Two basic conditions of inlet control:
  - Inlet end of culvert submerged by upstream headwater
  - Inlet end of culvert not submerged by upstream headwater

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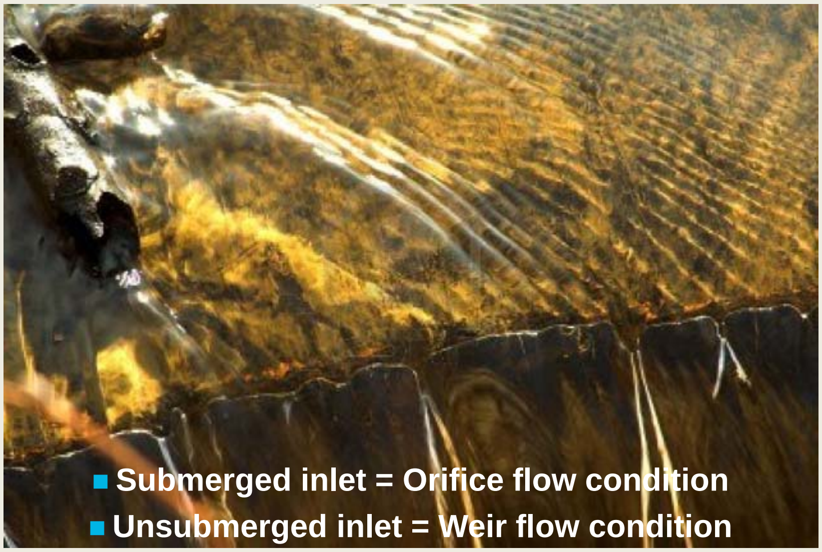
Inlet Control



- **Submerged inlet = Orifice flow condition**
- **Unsubmerged inlet = Weir flow condition**

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Inlet Control

UNSUBMERGED[1]

$$\text{Form (1)} \quad \frac{HW_i}{D} = \frac{H_c}{D} + K\left[\frac{K_u Q}{AD^{0.5}}\right]^M - 0.5S^2 \qquad (26)$$

$$\text{Form (2)} \quad \frac{HW_i}{D} = K\left[\frac{K_u Q}{AD^{0.5}}\right]^M \qquad (27)$$

SUBMERGED[3]

$$\frac{HW_i}{D} = c\left[\frac{K_u Q}{AD^{0.5}}\right]^2 + Y - 0.5S^2 \qquad (28)$$

Definitions

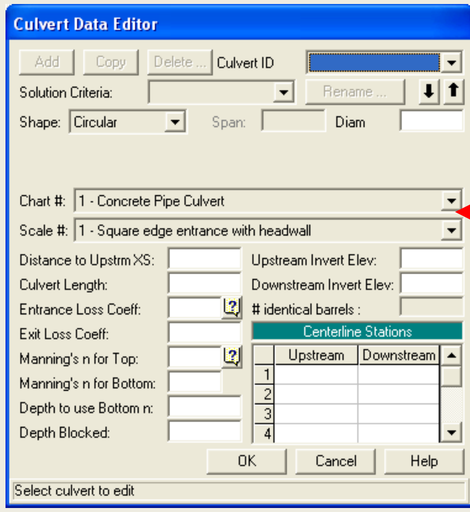
HW_i	Headwater depth above inlet control section invert, m (ft)
D	Interior height of culvert barrel, m (ft)
H_c	Specific head at critical depth ($d_c + V_c^2/2g$), m (ft)
Q	Discharge, m^3/s (ft^3/s)
A	Full cross sectional area of culvert barrel, m^2 (ft^2)
S	Culvert barrel slope, m/m (ft/ft)
K, M, c, Y	Constants from Table 9
K_u	1.811 SI (1.0 English)

Chart and Scale Numbers for Inlet Control Calcs

Table 9--Constants for Inlet Control Design Equations.

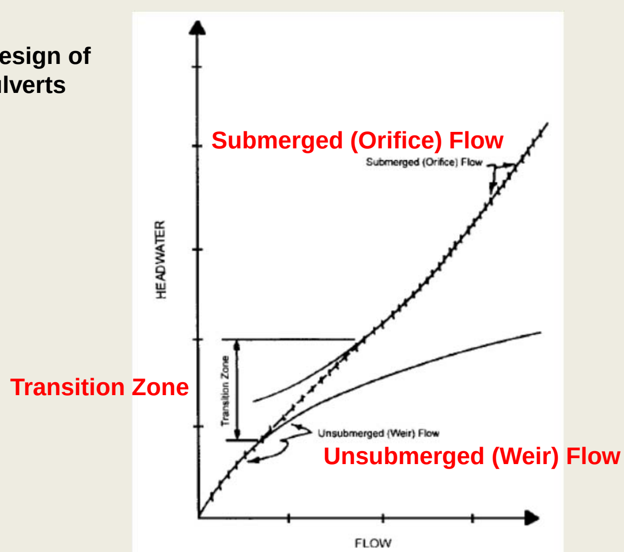
Chart No.	Shape and Material	Nomograph Scale	Inlet Edge Description	Equation Form	Unsubmerged K	Unsubmerged M	Submerged c	Submerged Y	References
1	Circular Concrete	1	Square edge w/headwall	1	.0098	2.0	.0398	.67	56/57
		2	Groove end w/headwall		.0018	2.0	.0292	.74	
		3	Groove end projecting		.0045	2.0	.0317	.69	
2	Circular CMP	1	Headwall	1	.0078	2.0	.0379	.69	56/57)
		2	Mitered to slope		.0210	1.33	.0463	.75	
		3	Projecting		.0340	1.50	.0553	.54	
3	Circular	A	Beveled ring, 45° bevels	1	.0018	2.50	.0300	.74	57
		B	Beveled ring, 33.7° bevels*		.0018	2.50	.0243	.83	
8	Rectangular Box	1	30° to 75° wingwall flares	1	.026	1.0	.0347	.81	56
		2	90° and 15° wingwall flares		.061	.75	.0400	.80	56
		3	0° wingwall flares		.061	.75	.0423	.82	8
9	Rectangular Box	1	45° wingwall flare d = .043D	2	.510	.667	.0309	.80	8
		2	18° to 33.7° wingwall flare d = .083D		.486	.667	.0249	.83	
10	Rectangular Box	1	90° headwall w/3/4" chamfers	2	.515	.667	.0375	.79	8
		2	90° headwall w/45° bevels		.495	.667	.0314	.82	
		3	90° headwall w/33.7° bevels		.486	.667	.0252	.865	
11	Rectangular Box	1	3/4" chamfers; 45° skewed headwall	2	.545	.667	.04505	.73	8
		2	3/4" chamfers; 30° skewed headwall		.533	.667	.0425	.705	
		3	3/4" chamfers; 15° skewed headwall		.522	.667	.0402	.68	
		4	45° bevels; 10°-45° skewed headwall		.498	.667	.0327	.75	
12	Rectangular Box 3/4" chamfers	1	45° non-offset wingwall flares	2	.497	.667	.0339	.803	8
		2	18.4° non-offset wingwall flares		.493	.667	.0361	.806	
		3	18.4° non-offset wingwall flares 30° skewed barrel		.495	.667	.0386	.71	
13	Rectangular Box Top Bevels	1	45° wingwall flares - offset	2	.497	.667	.0302	.835	8
		2	33.7° wingwall flares - offset		.495	.667	.0252	.881	
		3	18.4° wingwall flares - offset		.493	.667	.0227	.887	
16-19	C M Boxes	2	90° headwall	1	.0083	2.0	.0379	.69	57
		3	Thick wall projecting		.0145	1.75	.0419	.64	
		5	Thin wall projecting		.0340	1.5	.0496	.57	

Chart and Scale Numbers for Inlet Control Calcs



Hydraulics of Inlet Control

Hydraulic Design of Highway Culverts



Outline Control

- Occurs when barrel is able to convey the flow the inlet will accept
- Flow control section located at barrel exit or downstream
- Downstream conditions do affect culvert capacity (high tailwater)

Typical Outlet Control

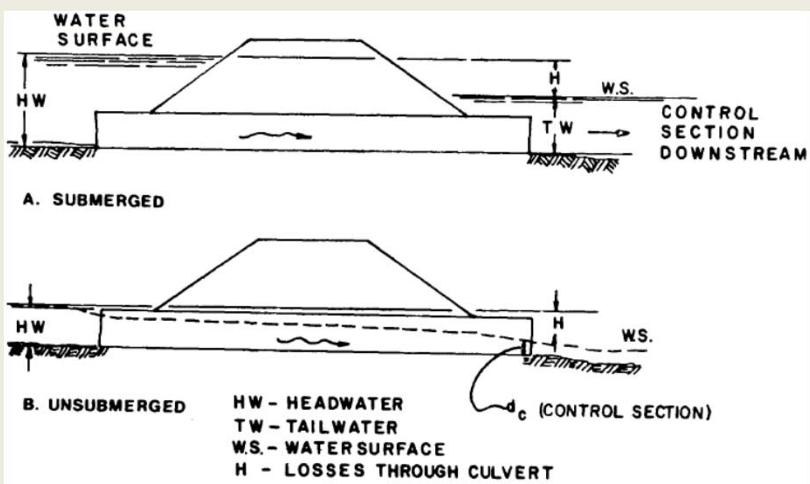


Figure I-14--Typical Outlet Control Flow Conditions

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Outline Control

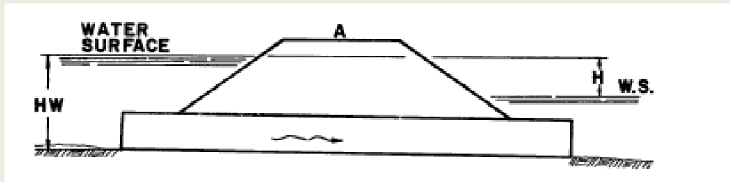

Figure A:
Classic full flow condition with inlet and outlet submerged

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Outlet Control

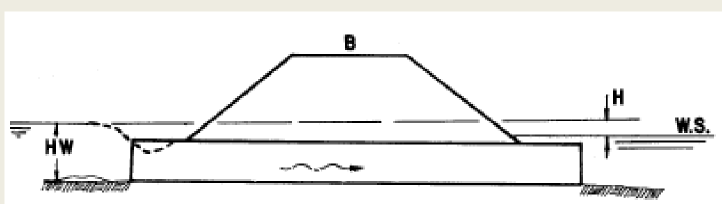

Figure B:
Outlet submerged and inlet unsubmerged. Shallow headwater allows flow to contract

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Outline Control

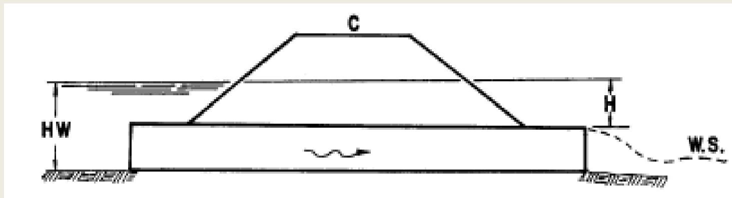

Figure C:
Inlet submerged to a degree to allow full flow through culvert.
Outlet unsubmerged

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Outlet Control

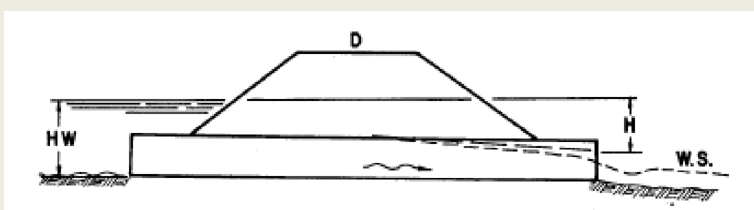

Figure D:
Inlet submerged and outlet unsubmerged.
Critical depth near culvert outlet

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Outlet Control

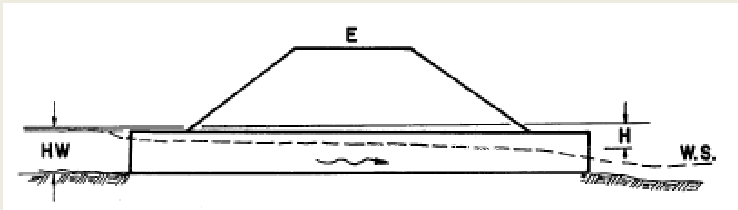

Figure E:
Neither inlet nor outlet submerged.
Partial flow through entire barrel

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Full Flow in a Culvert

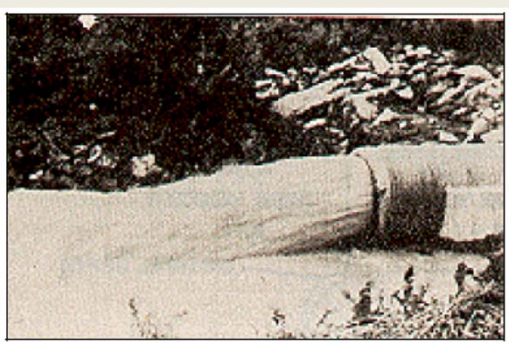

Figure I-11--Culvert Flowing Full
(No tailwater at outlet end)

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Outlet Control Headwater Calcs

$$Z_3 + Y_3 + \frac{\alpha_3 V_3^2}{2g} = Z_2 + Y_2 + \frac{\alpha_2 V_2^2}{2g} + H_L \qquad (6\text{-}$$

Where: Z_3 = Upstream invert elevation of the culvert
Y_3 = The depth of water above the upstream culvert inlet
V_3 = The average velocity upstream of the culvert
α_3 = The velocity weighting coefficient upstream of the culvert
g = The acceleration of gravity
Z_2 = Downstream invert elevation of the culvert
Y_2 = The depth of water above the downstream culvert inlet
V_2 = The average velocity downstream of the culvert
α_2 = The velocity weighting coefficient downstream of the culvert
H_L = Total energy loss through the culvert (from section 2 to 3)

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Outlet Control Headwater Calcs

$$H_L = h_{en} + h_f + h_{ex} \qquad (6\text{-}5)$$

Where: h_{en} = entrance loss (feet or meters)
h_f = friction loss (feet or meters)
h_{ex} = exit loss (feet or meters)

The friction loss in the culvert is computed using Manning's formula, which is expressed as follows:

$$h_f = L\left(\frac{Qn}{1.486\,A\,R^{2/3}}\right)^2 \qquad (6\text{-}6)$$

Where: h_f = friction loss (feet)
L = culvert length (feet)
Q = flow rate in the culvert (cfs)
n = Manning's roughness coefficient
A = area of flow (square feet)
R = hydraulic radius (feet)

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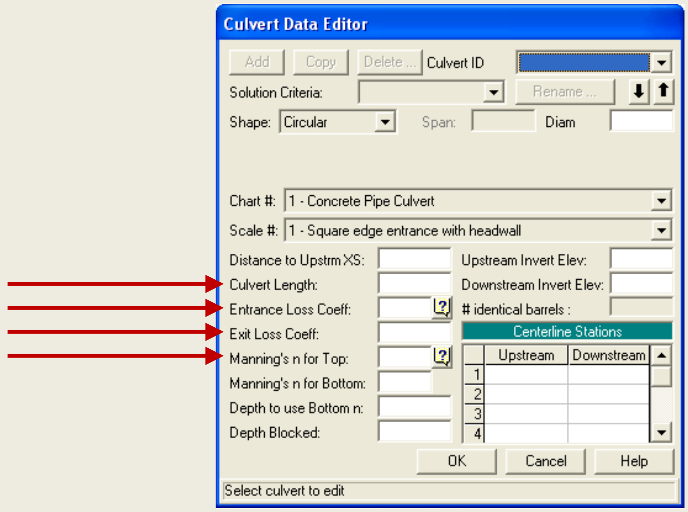
Factors for Outlet Control Calcs



HEC-RAS Outlet Control Computations

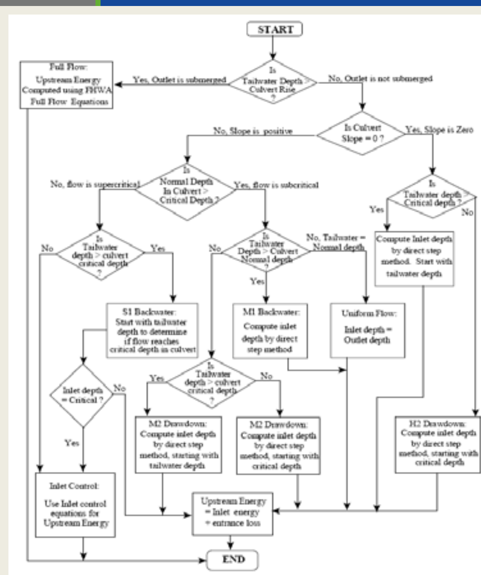


Figure 6-9 Flow Chart for Outlet Control Computations

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Factors Influencing Culvert Performance

Factor	Inlet Control	Outlet Control
Headwater Elevation	X	X
Inlet Area	X	X
Inlet Edge Configuration	X	X
Inlet Shape	X	X
Barrel Roughness		X
Barrel Area		X
Barrel Shape		X
Barrel Length		X
Barrel Slope	*	X
Tailwater Elevation		X

*Barrel slope affects inlet control performance to a small degree, but may be neglected.

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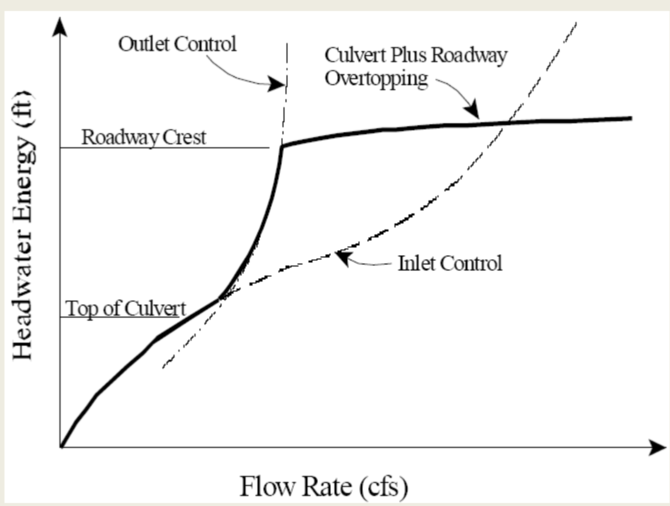
Culvert Performance Curve



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HEC-RAS Basic Culvert Analysis

- Culvert Cross-Section Layout
- Culvert Hydraulics
- Culvert Data Entry
- Culvert Analysis Results
- HEC-RAS Limitations
  - Constant Shape
  - Constant Slope
  - Constant Flowrate

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Cross Section Layout

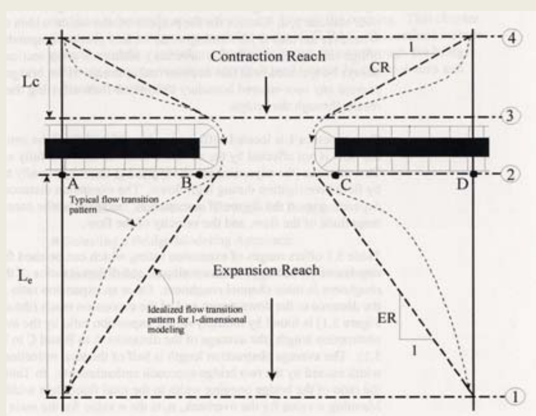
- Four Cross Section Minimum:

  1: Downstream beyond expansion

  2: 5-10 ft downstream face of culvert; valley section

  3: 5-10 ft upstream face of culvert; valley section

  4: Upstream before contraction begins



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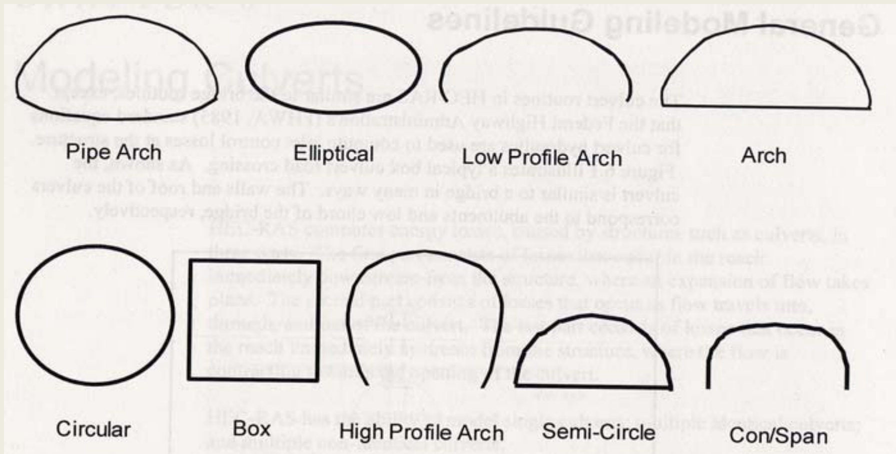
Culvert Hydraulics



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Culvert Hydraulics

Concrete Pipe n-value 0.013

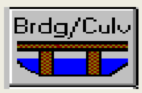
Corrugated Metal Pipe n-value 0.024

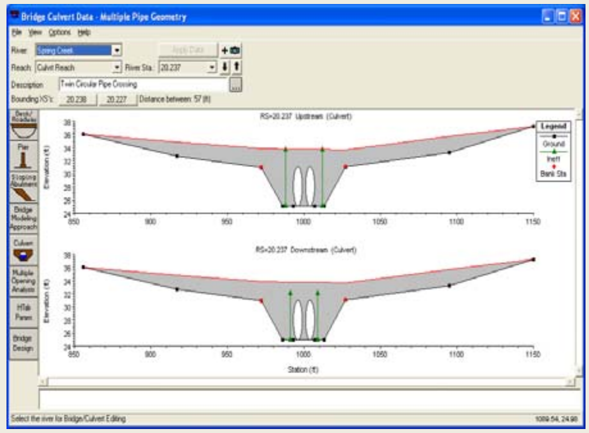
Concrete Box Culvert n-value 0.015

Manufacturer’s Specifications

Entering/Editing Culvert Data

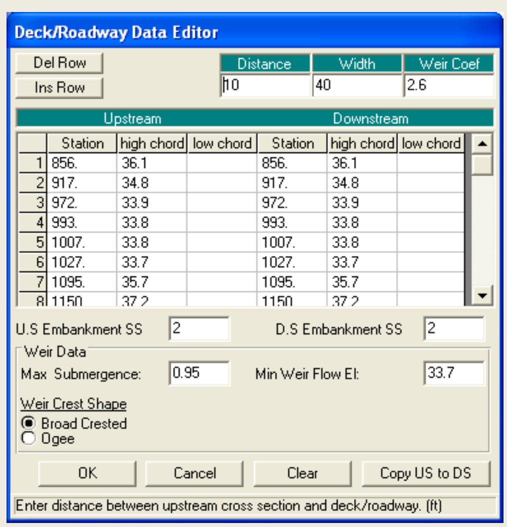
- Similar to Bridge
- Click on Bridge/Culvert Icon from Geometry Data Editor





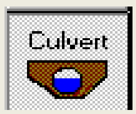
Entering/Editing Roadway Deck Data

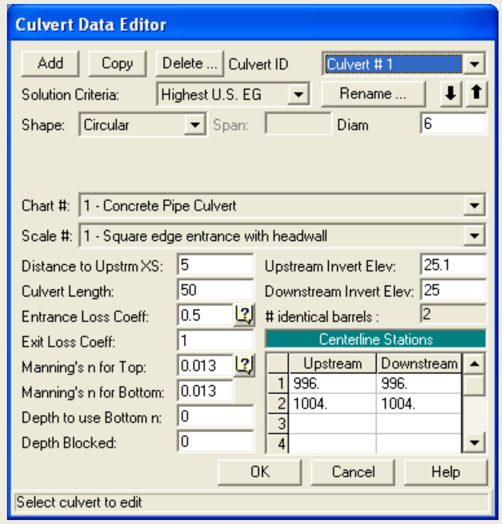
- Click on the Roadway/Deck Icon



Entering/Editing Culvert Data

- Click on the Culvert Icon from the Bridge/Culvert Screen from the Geometry Data Editor





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Viewing Culvert Output

- Four Cross Section Culvert Table
- Culvert Only Table

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Four Cross Section Culvert Table

Profile Output Table - Four XS Culvert

File Options Std. Tables User Tables Locations Help

HEC-RAS Plan: Base Plan River: Spring Creek Reach: Culvrt Reach

Reach	River Sta	Profile	E.G. Elev	W.S. Elev	Vel Head	Frctn Loss	C & E Loss	Q Left	Q Channel	Q Right	Top Width
			(ft)	(ft)	(ft)	(ft)	(ft)	(cfs)	(cfs)	(cfs)	(ft)
Culvrt Reach	20.251	5 yr	30.59	30.57	0.02	0.01	0.00		250.00		53.16
Culvrt Reach	20.251	25 yr	34.34	34.32	0.02	0.01	0.00	36.32	529.23	34.44	222.55
Culvrt Reach	20.238	5 yr	30.57	30.51	0.06				250.00		52.90
Culvrt Reach	20.238	25 yr	34.34	34.32	0.02			36.23	529.42	34.35	222.38
Culvrt Reach	20.237		Culvert								
Culvrt Reach	20.227	5 yr	30.05	29.93	0.12	0.03	0.05		250.00		50.21
Culvrt Reach	20.227	25 yr	32.19	32.13	0.06	0.03	0.00	4.19	592.43	3.38	127.60
Culvrt Reach	20.208*	5 yr	29.97	29.95	0.03	0.02	0.00		250.00		50.35
Culvrt Reach	20.208*	25 yr	32.16	32.10	0.06	0.03	0.00	3.90	592.98	3.13	125.91

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Culvert Only Table

Profile Output Table - Culvert Only

File Options Std. Tables Locations Help

HEC-RAS Plan: Mult Culvert River: Spring Creek Reach: Culvrt Reach

Reach	River Sta	Profile	E.G. US.	W.S. US.	E.G. IC	E.G. OC	Min El Weir Flow	Q Culv Group	Q Weir	Delta WS	Culv Vel US	Culv Vel DS
			(ft)	(ft)	(ft)	(ft)	(ft)	(cfs)	(cfs)	(ft)	(ft/s)	(ft/s)
Culvrt Reach	20.237 Box	5 yr	30.27	30.25	29.99	30.29	33.71	74.73		0.29	3.94	3.81
Culvrt Reach	20.237 Circular	5 yr	30.27	30.25	28.65	30.27	33.71	175.27		0.29	3.56	3.51
Culvrt Reach	20.237 Box	10 yr	31.88	31.84	31.06	31.89	33.71	145.82		0.48	4.86	4.86
Culvrt Reach	20.237 Circular	10 yr	31.88	31.84	29.55	31.87	33.71	254.18		0.48	4.49	4.49
Culvrt Reach	20.237 Box	25 yr	33.29	33.22	32.19	33.29	33.71	216.12		1.11	7.20	7.20
Culvrt Reach	20.237 Circular	25 yr	33.29	33.22	30.95	33.29	33.71	383.88		1.11	6.79	6.79

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Culvert Detailed Output Table

Culvert Output

File Type Options Help

River: Example 1 | Profile: PF 1 | Culv Group: Culvert #1

Reach: Stream | RS: 400 | Plan: Ex 1 Trial 4

Plan: Ex 1 Trial 4 Example 1 Stream RS: 400 Culv Group: Culvert #1 Profile: PF 1

Q Culv Group (cfs)	200.00	Culv Full Len (ft)	
# Barrels	1	Culv Vel US (ft/s)	12.58
Q Barrel (cfs)	200.00	Culv Vel DS (ft/s)	14.85
E.G. US. (ft)	107.93	Culv Inv El Up (ft)	100.00
W.S. US. (ft)	107.92	Culv Inv El Dn (ft)	98.00
E.G. DS (ft)	101.78	Culv Frctn Ls (ft)	2.46
W.S. DS (ft)	101.68	Culv Exit Loss (ft)	3.20
Delta EG (ft)	6.14	Culv Entr Loss (ft)	0.49
Delta WS (ft)	6.24	Q Weir (cfs)	
E.G. IC (ft)	107.93	Weir Sta Lft (ft)	
E.G. OC (ft)	107.33	Weir Sta Rgt (ft)	
Culvert Control	Inlet	Weir Submerg	
Culv WS Inlet (ft)	104.50	Weir Max Depth (ft)	
Culv WS Outlet (ft)	101.55	Weir Avg Depth (ft)	
Culv Nml Depth (ft)	3.76	Weir Flow Area (sq ft)	
Culv Crt Depth (ft)	4.04	Min El Weir Flow (ft)	110.01

Errors, Warnings and Notes

Note:	During the supercritical calculations a hydraulic jump occurred at the outlet of (leaving) the culvert.
Warning:	During the supercritical analysis, the program could not converge on a supercritical answer in the downstream cross section. The program used the solution with the least error.
Note:	The flow in the culvert is entirely supercritical.

Select Profile

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Hand Calculations (HDS 5)

- Show example problems in HDS 5

(Chapter 3, page 56)

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Hand Calculations (HDS 5)

Example Problem #1 (English Units)

A culvert at a new roadway crossing must be designed to pass the 25-year flood. Hydrologic analysis indicates a peak flow rate of 200 ft³/s. Use the following site information:

Elevation at Culvert Face: 100 ft
Natural Stream Bed Slope: 1 percent = 0.01 ft/ft
Tailwater for 25-Year Flood: 3.5 ft
Approximate Culvert Length: 200 ft
Shoulder Elevation: 110 ft

Design a circular pipe culvert for this site. Consider the use of a corrugated metal pipe with standard 2-2/3 by 1/2 in corrugations and beveled edges and concrete pipe with a groove end. Base the design headwater on the shoulder elevation with a two ft freeboard (elevation 108.0 ft). Set the inlet invert at the natural streambed elevation (no FALL).

Note: Design charts used in this example are reproduced on the following pages.

Hand Calculations (HDS 5)

PROJECT: EXAMPLE PROBLEM No. 1
CHAPTER III, HDS No. 5

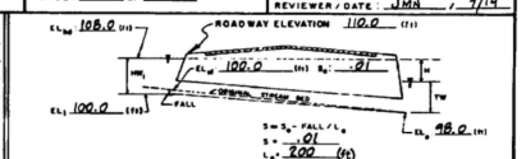
STATION: 1 + 00
SHEET 1 OF 1

CULVERT DESIGN FORM
DESIGNER / DATE: WJJ / 7/18
REVIEWER / DATE: JMN / 7/19

HYDROLOGICAL DATA
- METHOD: RATIONAL
- DRAINAGE AREA: 125 AC.
- STREAM SLOPE: 1.0%
- CHANNEL SHAPE: TRAPEZOIDAL
- ROUTING: N/A
- OTHER:

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
25	200	3.5



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CMP - CIRC. - 72 IN. - BEVEL 45° IN HEADWALL	200	200	46	58	–	105.8	3.5	3.8	4.9	4.9	0.2	2.6	105.5	105.8	9.0	TRY 60" CMP.
" " - 60 IN. - " 45°	↓	↓	1.43	7.15	–	107.2	↓	4.1	4.6	4.6	↓	6.3	108.9	108.9	11.9	TRY 60" CONC.
CONC. " - 60 IN. - GROOVE END	↓	↓	1.36	6.8	–	106.8	↓	↓	4.6	4.6	↓	2.9	105.5	106.8	15.6	TRY 54" CONC.
" " - 54 IN. - "	↓	↓	1.77	7.97	–	108.0	↓	↓	4.3	4.3	↓	4.7	107.0	108.0	15.3	OK

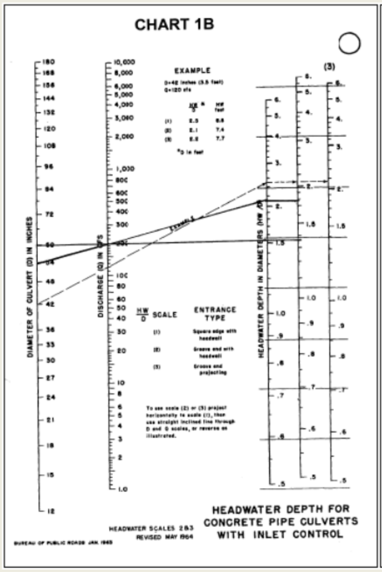
TECHNICAL FOOTNOTES:
(1) USE Q/NB FOR BOX CULVERTS
(2) $HW_i/D = HW/D$ OR HW_i/D FROM DESIGN CHARTS
(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE
(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)
(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.
(6) h_o = TW or $(d_c + D)/2$ (WHICHEVER IS GREATER)
(7) $H = \left[1 + k_e + (K_u n^2 L)/R^{1.33}\right] V^2/2g$ WHERE Ku = 19.63 (29 IN ENGLISH UNITS)
(8) $EL_{ho} = EL_o + H + h_o$

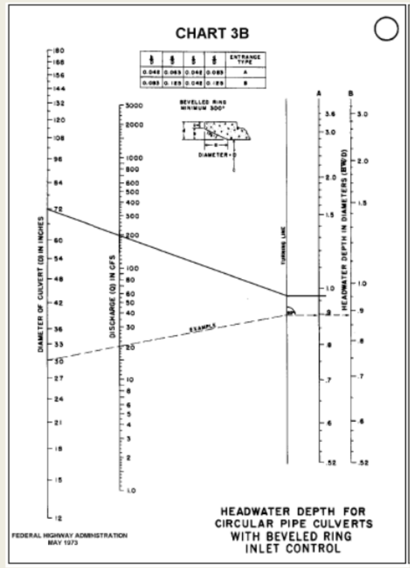
SUBSCRIPT DEFINITIONS:
a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:
HIGH OUTLET VELOCITY - OUTLET PROTECTION OR LARGER CONDUIT MAY BE NECESSARY

CULVERT BARREL SELECTED:
SIZE: 54 IN.
SHAPE: CIRCULAR
MATERIAL: CONC. n .012
ENTRANCE: GROOVE END

Nomographs – Chart 1B and 3B





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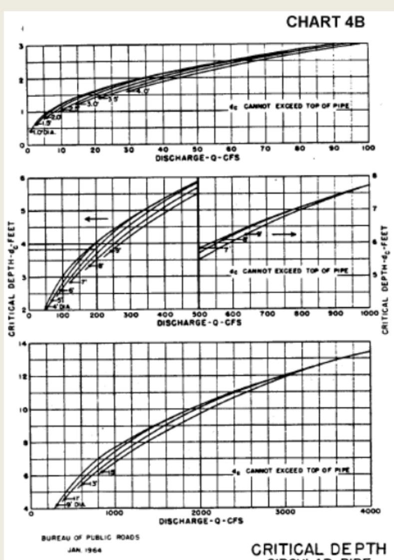
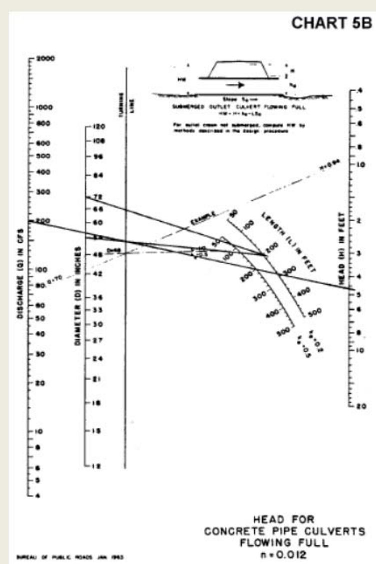
Nomographs – Charts 4B and 5B





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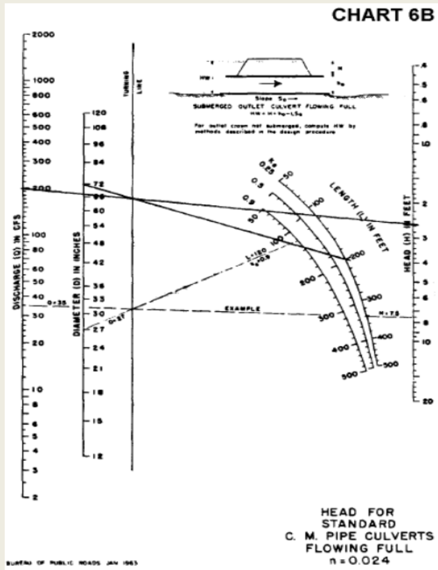
Head for Standard CM Pipe Culverts Flowing Full



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HEC-RAS Input

Example Problem #1 (English Units)

A culvert at a new roadway crossing must be designed to pass the 25-year flood. Hydrologic analysis indicates a peak flow rate of 200 ft³/s. Use the following site information:

Elevation at Culvert Face: 100 ft
Natural Stream Bed Slope: 1 percent = 0.01 ft/ft
Tailwater for 25-Year Flood: 3.5 ft
Approximate Culvert Length: 200 ft
Shoulder Elevation: 110 ft

Design a circular pipe culvert for this site. Consider the use of a corrugated metal pipe with standard 2-2/3 by 1/2 in corrugations and beveled edges and concrete pipe with a groove end. Base the design headwater on the shoulder elevation with a two ft freeboard (elevation 108.0 ft). Set the inlet invert at the natural streambed elevation (no FALL).

Note: Design charts used in this example are reproduced on the following pages.

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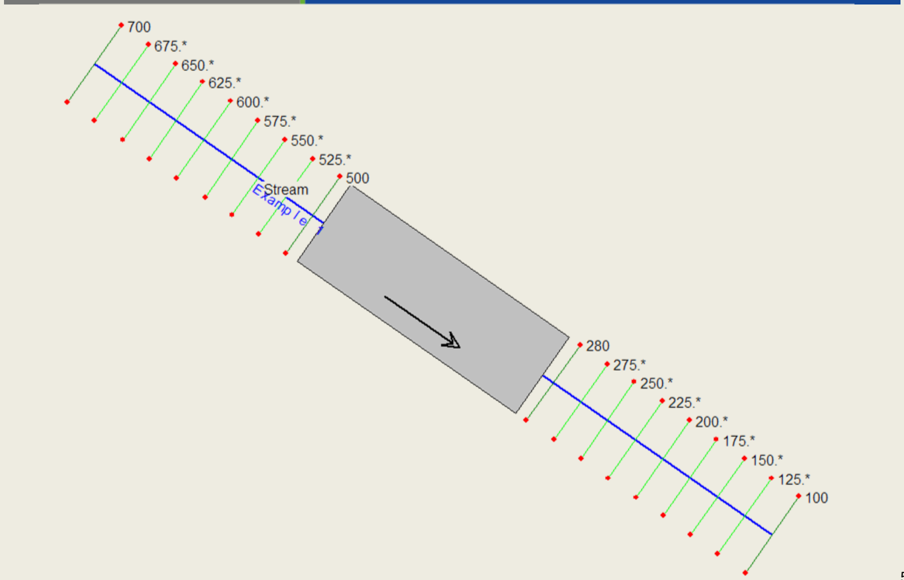
HEC-RAS Schematic



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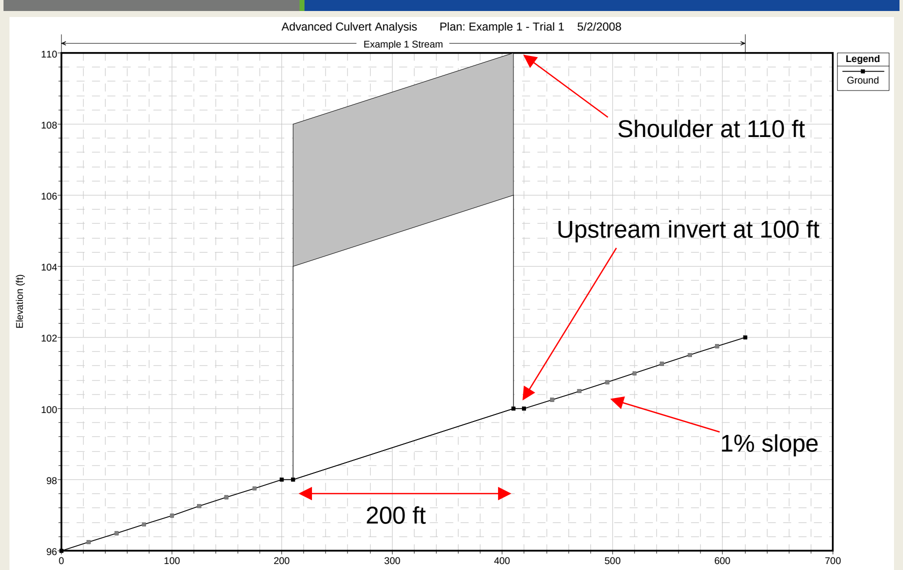
HEC-RAS Profile



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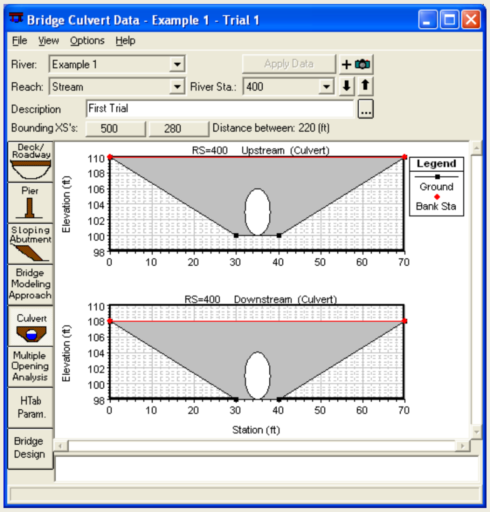
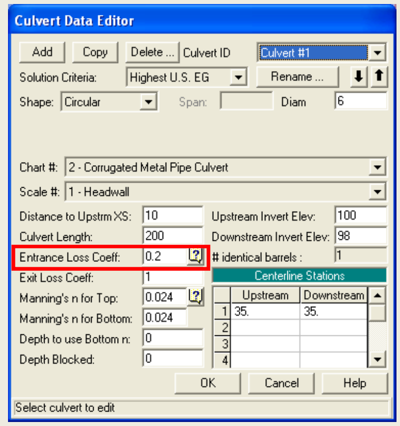
Input Data for Trial 1 – 72" Ø CMP





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Entrance Loss Coefficient Selection

Culvert Entrance loss Coefficients Information Table

Type of Structure and Design of Entrance	Coefficient (k_{en})
Pipe Culverts	
Concrete Pipe Projecting from Fill (no headwall):	
Socket end of pipe	0.2
Square cut end of pipe	0.5
Concrete Pipe with Headwall or Headwall and Wingwalls:	
Socket end of pipe (grooved end)	0.2
Square cut end of pipe	0.5
Rounded entrance, with rounding radius = 1/12 of diameter	0.2
Concrete Pipe:	
Mitered to conform to fill slope	0.7
End section conformed to fill slope	0.5
Beveled edges, 33.7 or 45 degree bevels	0.2
Side slope tapered inlet	0.2
Corrugated Metal Pipe or Pipe-Arch:	
Projected from fill (no headwall)	0.9
Headwall or headwall and wingwalls square edge	0.5
Mitered to conform to fill slope	0.7
End section conformed to fill slope	0.5
Beveled edges, 33.7 or 45 degree bevels	0.2
Side slope tapered inlet	0.2

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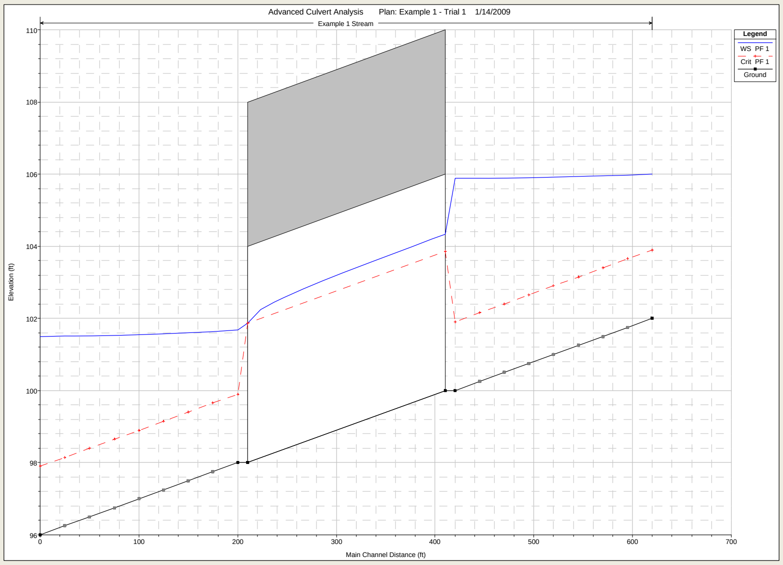
Trial 1 Profile Output



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Trial 1 Tabular Output

River: Example 1 | Profile: PF 1 | Culv Group: Culvert #1

Reach: Stream | RS: 400 | Plan: Ex1 Trial 1

Plan: Ex1 Trial 1 Example 1 Stream RS: 400 Culv Group: Culvert #1 Profile: PF 1

Q Culv Group (cfs)	200.00	Culv Full Len (ft)	
# Barrels	1	Culv Vel US (ft/s)	9.15
Q Barrel (cfs)	200.00	Culv Vel DS (ft/s)	10.39
E.G. US. (ft)	105.90	Culv Inv El Up (ft)	100.00
W.S. US. (ft)	105.88	Culv Inv El Dn (ft)	98.00
E.G. DS (ft)	101.78	Culv Frctn Ls (ft)	2.09
W.S. DS (ft)	101.68	Culv Exit Loss (ft)	1.76
Delta EG (ft)	4.12	Culv Entr Loss (ft)	0.27
Delta WS (ft)	4.20	Q Weir (cfs)	
E.G. IC (ft)	105.90	Weir Sta Lft (ft)	
E.G. OC (ft)	105.89	Weir Sta Rgt (ft)	
Culvert Control	Inlet	Weir Submerg	
Culv WS Inlet (ft)	104.33	Weir Max Depth (ft)	
Culv WS Outlet (ft)	101.86	Weir Avg Depth (ft)	
Culv Nml Depth (ft)	4.33	Weir Flow Area (sq ft)	
Culv Crt Depth (ft)	3.86	Min El Weir Flow (ft)	110.01

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	HEADWATER CALCULATIONS: INLET CONTROL HW/D (2)	HW_i	FALL (3)	EL_hi (4)	OUTLET CONTROL TW (5)	d_c	(d_c+D)/2	h_o (6)	k_e	H (7)	EL_ho (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CMP - CIRC. - 72 IN. - BEVEL 45° IN HEADWALL	200	200	.96	5.8	–	105.8	3.5	3.8	4.9	4.9	0.2	2.6	105.5	105.8	9.0	TRY 60" CMP.

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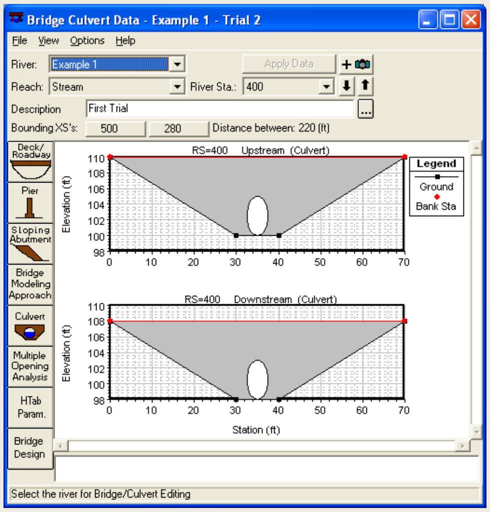
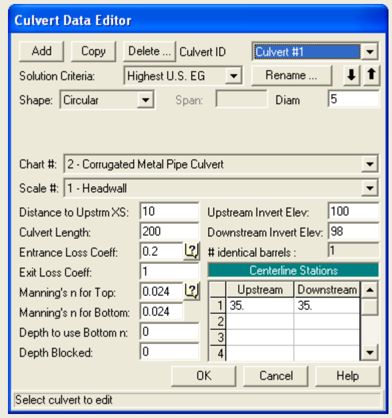
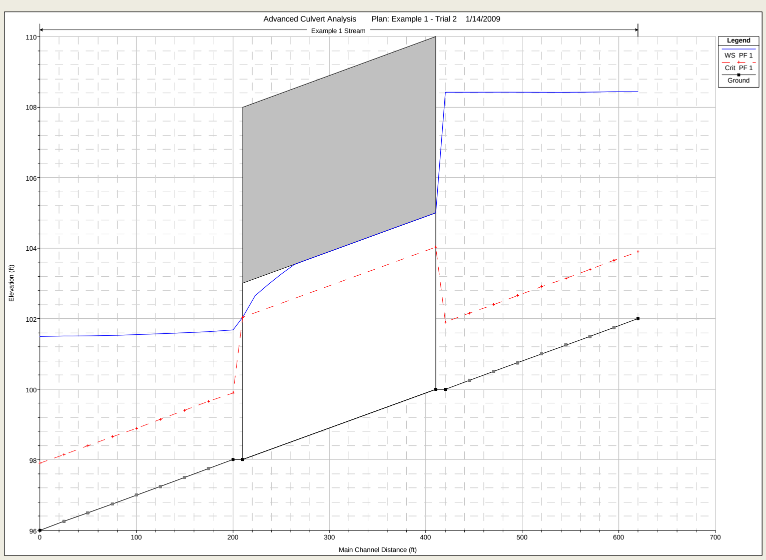
Input Data for Trial 2 – 60” Ø CMP





Trial 2 Profile Output

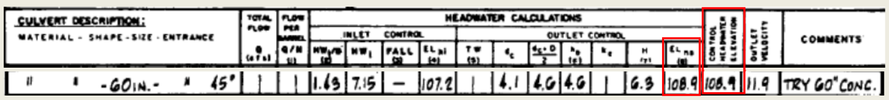


Trial 2 Tabular Output

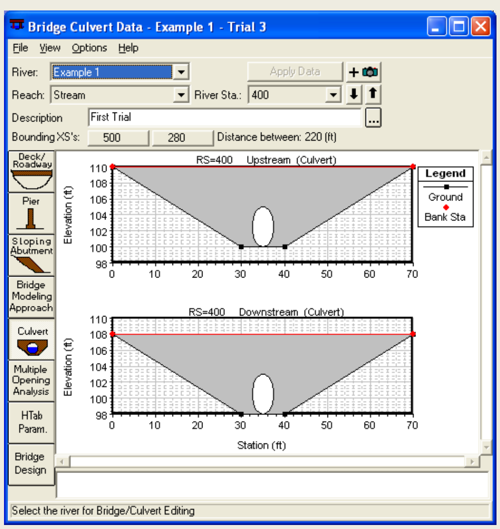
River: Example 1 | Profile: PF 1 | Culv Group: Culvert #1
Reach: Stream | RS: 400 | Plan: Ex 1 Trial 2

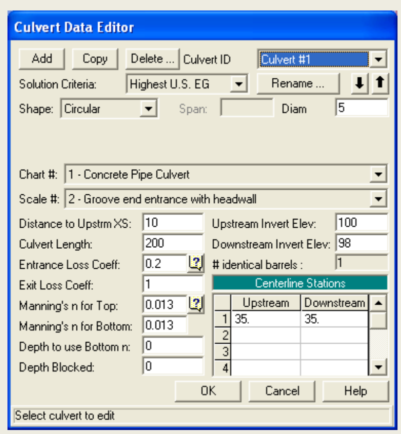
Plan: Ex 1 Trial 2 Example 1 Stream RS: 400 Culv Group: Culvert #1 Profile: PF 1

Q Culv Group (cfs)	200.00	Culv Full Len (ft)	147.28
# Barrels	1	Culv Vel US (ft/s)	10.19
Q Barrel (cfs)	200.00	Culv Vel DS (ft/s)	11.78
E.G. US. (ft)	108.42	Culv Inv El Up (ft)	100.00
W.S. US. (ft)	108.41	Culv Inv El Dn (ft)	98.00
E.G. DS (ft)	101.78	Culv Frctn Ls (ft)	3.91
W.S. DS (ft)	101.68	Culv Exit Loss (ft)	2.41
Delta EG (ft)	6.64	Culv Entr Loss (ft)	0.32
Delta WS (ft)	6.74	Q Weir (cfs)	
E.G. IC (ft)	107.36	Weir Sta Lft (ft)	
E.G. OC (ft)	108.42	Weir Sta Rgt (ft)	
Culvert Control	Outlet	Weir Submerg	
Culv WS Inlet (ft)	105.00	Weir Max Depth (ft)	
Culv WS Outlet (ft)	102.04	Weir Avg Depth (ft)	
Culv Nml Depth (ft)	5.00	Weir Flow Area (sq ft)	
Culv Crt Depth (ft)	4.04	Min El Weir Flow (ft)	110.01

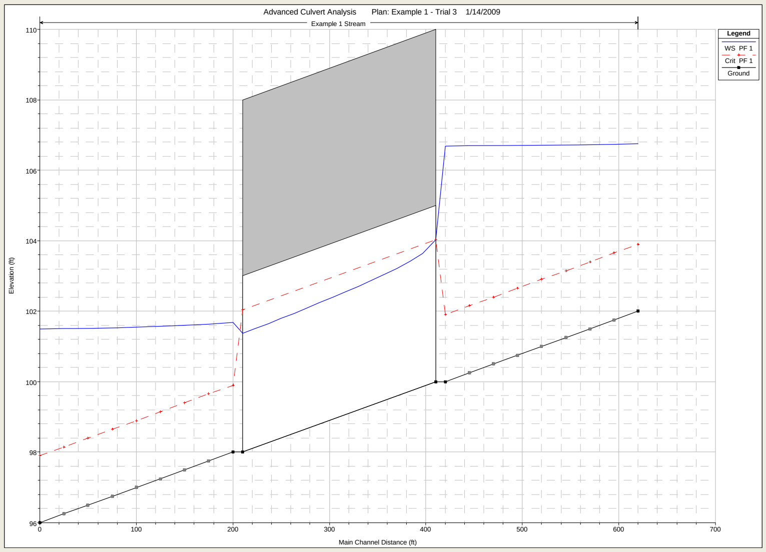


Input Data for Trial 3 – 60" Ø RCP





Trial 3 Profile Output



Trial 3 Tabular Output

River: Example 1 | Profile: PF 1 | Culv Group: Culvert #1

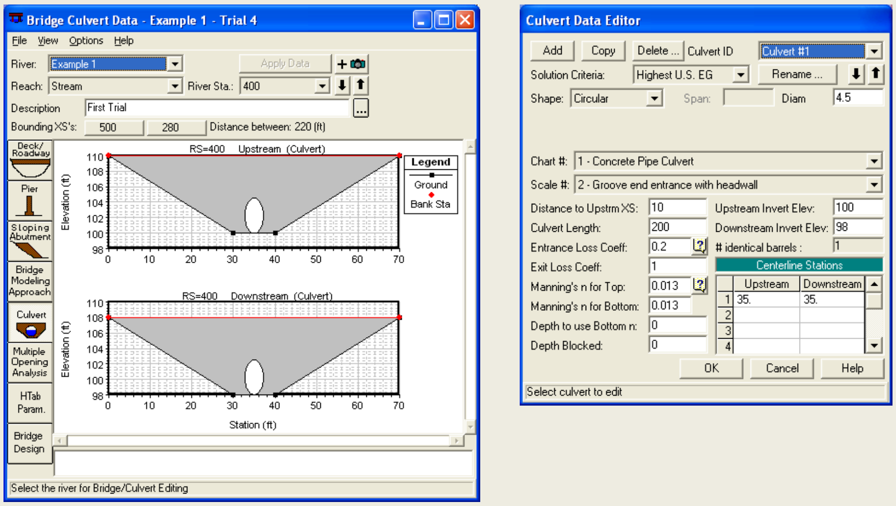
Reach: Stream | RS: 400 | Plan: Ex 1 Trial 3

Plan: Ex 1 Trial 3 Example 1 Stream RS: 400 Culv Group: Culvert #1 Profile: PF 1

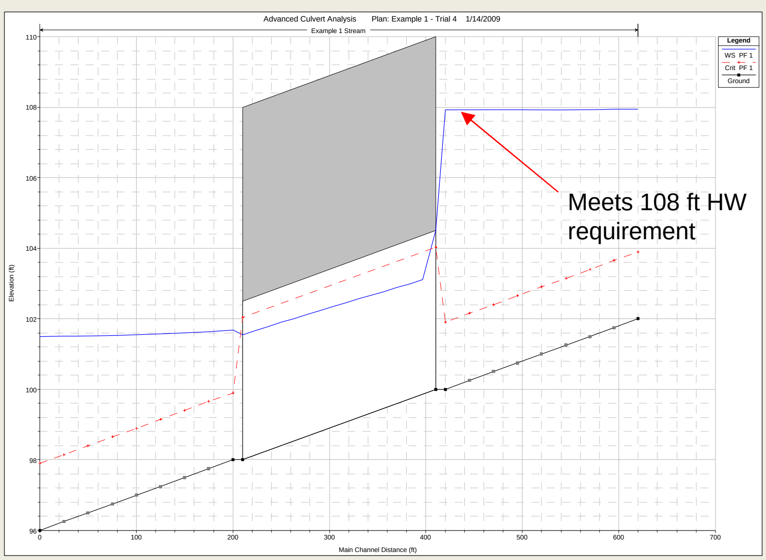
Q Culv Group (cfs)	200.00	Culv Full Len (ft)	
# Barrels	1	Culv Vel US (ft/s)	11.78
Q Barrel (cfs)	200.00	Culv Vel DS (ft/s)	14.22
E.G. US. (ft)	106.70	Culv Inv El Up (ft)	100.00
W.S. US. (ft)	106.69	Culv Inv El Dn (ft)	98.00
E.G. DS (ft)	101.78	Culv Frctn Ls (ft)	1.68
W.S. DS (ft)	101.68	Culv Exit Loss (ft)	2.73
Delta EG (ft)	4.92	Culv Entr Loss (ft)	0.51
Delta WS (ft)	5.01	Q Weir (cfs)	
E.G. IC (ft)	106.70	Weir Sta Lft (ft)	
E.G. OC (ft)	106.62	Weir Sta Rgt (ft)	
Culvert Control	Inlet	Weir Submerg	
Culv WS Inlet (ft)	104.04	Weir Max Depth (ft)	
Culv WS Outlet (ft)	101.37	Weir Avg Depth (ft)	
Culv Nml Depth (ft)	3.28	Weir Flow Area (sq ft)	
Culv Crt Depth (ft)	4.04	Min El Weir Flow (ft)	110.01

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	HEADWATER CALCULATIONS – INLET CONTROL HW/D (2)	HW	FALL (3)	EL hi (4)	OUTLET CONTROL TW (5)	dc	(dc+D)/2	ho (6)	ke	H (7)	EL ho (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CONC. " - 60 IN. - GROOVE END			1.36	6.8	–	106.8			4.6	4.6		2.9	105.5	106.8	15.6	TRY 56" CONC.

Input Data for Trial 4 – 54” Ø RCP



Trial 4 Profile Output



Trial 4 Tabular Output

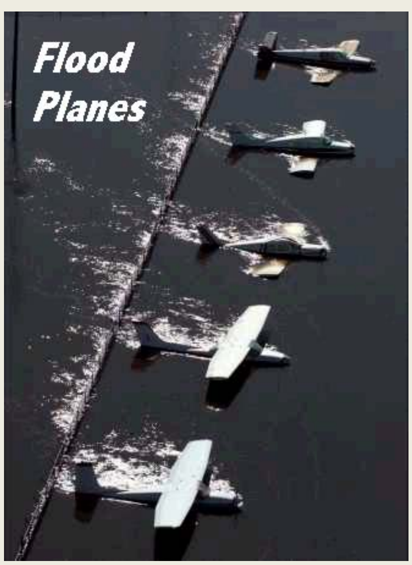
River: Example 1 | Profile: PF 1 | Culv Group: Culvert #1
Reach: Stream | RS: 400 | Plan: Ex 1 Trial 4

Plan: Ex 1 Trial 4 Example 1 Stream RS: 400 Culv Group: Culvert #1 Profile: PF 1

Q Culv Group (cfs)	200.00	Culv Full Len (ft)	
# Barrels	1	Culv Vel US (ft/s)	12.58
Q Barrel (cfs)	200.00	Culv Vel DS (ft/s)	14.85
E.G. US. (ft)	107.93	Culv Inv El Up (ft)	100.00
W.S. US. (ft)	107.92	Culv Inv El Dn (ft)	98.00
E.G. DS (ft)	101.78	Culv Frctn Ls (ft)	2.46
W.S. DS (ft)	101.68	Culv Exit Loss (ft)	3.20
Delta EG (ft)	6.14	Culv Entr Loss (ft)	0.49
Delta WS (ft)	6.24	Q Weir (cfs)	
E.G. IC (ft)	107.93	Weir Sta Lft (ft)	
E.G. OC (ft)	107.33	Weir Sta Rgt (ft)	
Culvert Control	Inlet	Weir Submerg	
Culv WS Inlet (ft)	104.50	Weir Max Depth (ft)	
Culv WS Outlet (ft)	101.55	Weir Avg Depth (ft)	
Culv Nml Depth (ft)	3.76	Weir Flow Area (sq ft)	
Culv Crt Depth (ft)	4.04	Min El Weir Flow (ft)	110.01

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	HEADWATER CALCULATIONS: INLET CONTROL HW/D (2)	HW	FALL (3)	EL hi (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL ho (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
" " - 54 IN. - "	↓	↓	1.77	7.97	-	108.0	↓	↓	4.3	4.3	↓	4.7	107.0	108.0	15.3	OK

Questions?



Houston, TX
mattzeve@gmail.com