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MDOT Hydraulics Unit
July 2022

Culvert Design

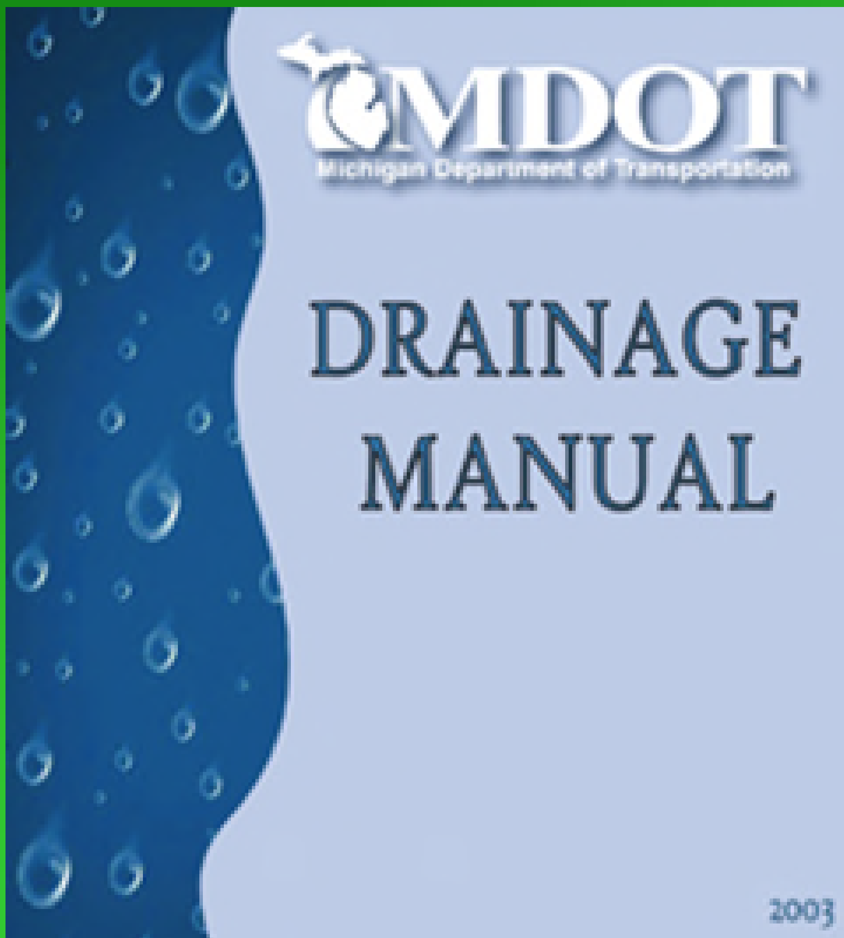
Objectives

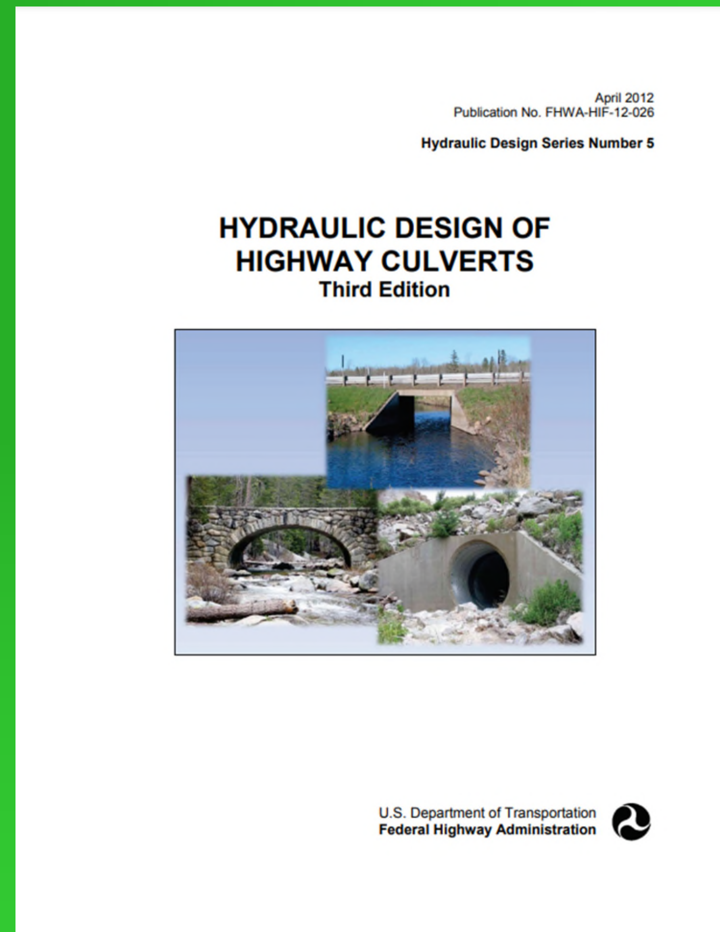
- Discuss required input data
- Discuss design criteria
- Discuss design procedures
- Answer questions

Topics Not Covered

- Basic fluid mechanics
- Hydrologic design
- Theory behind equations
- Weir flow with culverts
- Recommend taking NHI's Culvert Design Workshop

References


MDOT
Michigan Department of Transportation
DRAINAGE
MANUAL
2003


April 2012
Publication No. FHWA-HIF-12-026
Hydraulic Design Series Number 5
HYDRAULIC DESIGN OF
HIGHWAY CULVERTS
Third Edition
U.S. Department of Transportation
Federal Highway Administration

Terms

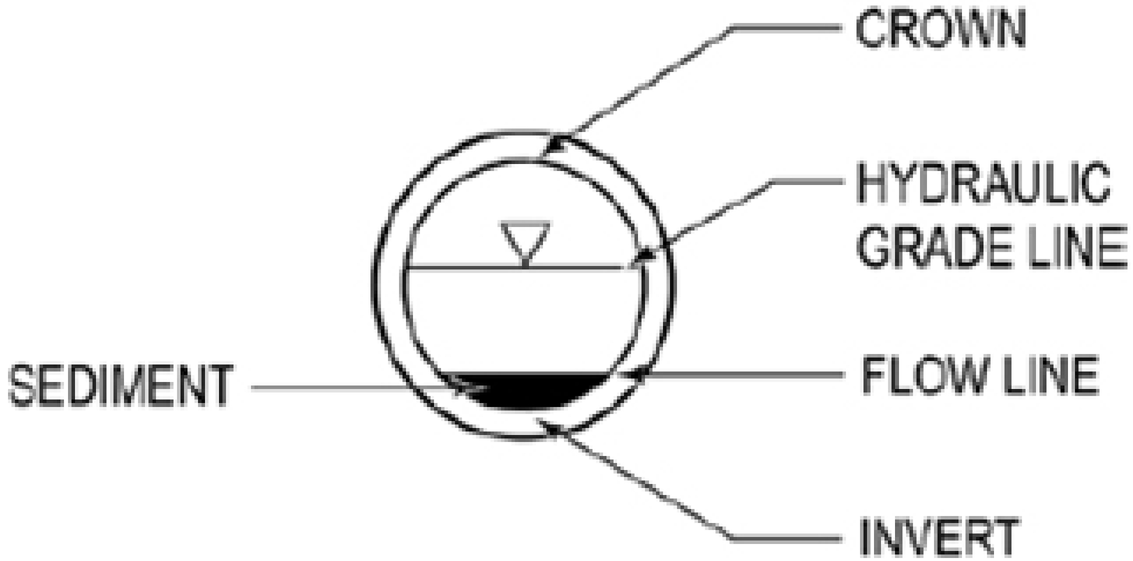


Figure 5-1 Culvert Terms

Terms

- Subcritical vs Supercritical
  - Dimensionless term
    - $Fr = V / (g * y)^{1/2}$
      - » V = velocity, ft/s
      - » g = gravitational constant = 32.2 ft/s^2
      - » y = hydraulic depth, A / W, ft.
  - Subcritical - $Fr < 1$
  - Supercritical - $Fr > 1$
  - Critical Depth – $Fr = 1$
  - Hydraulic jump when flow transitions from supercritical flow to subcritical

Terms

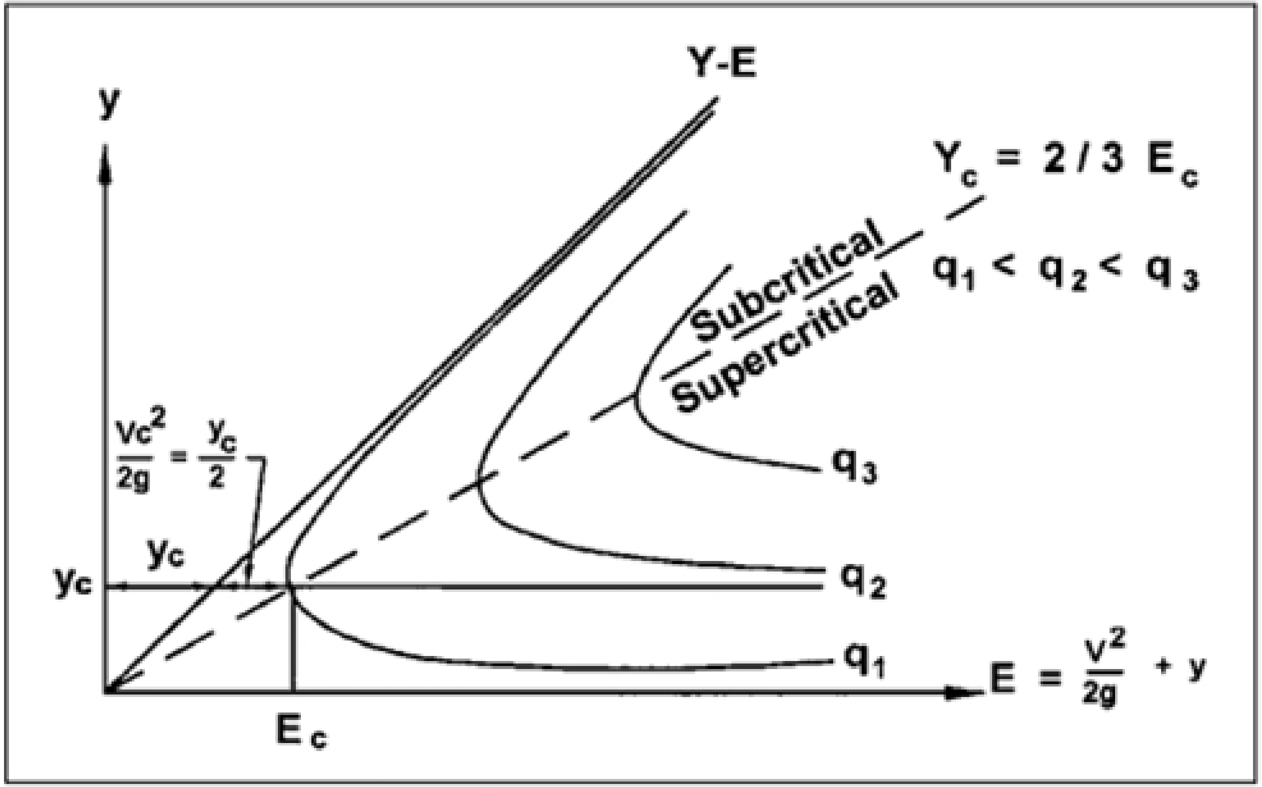


Figure 5-2. Specific energy diagram.

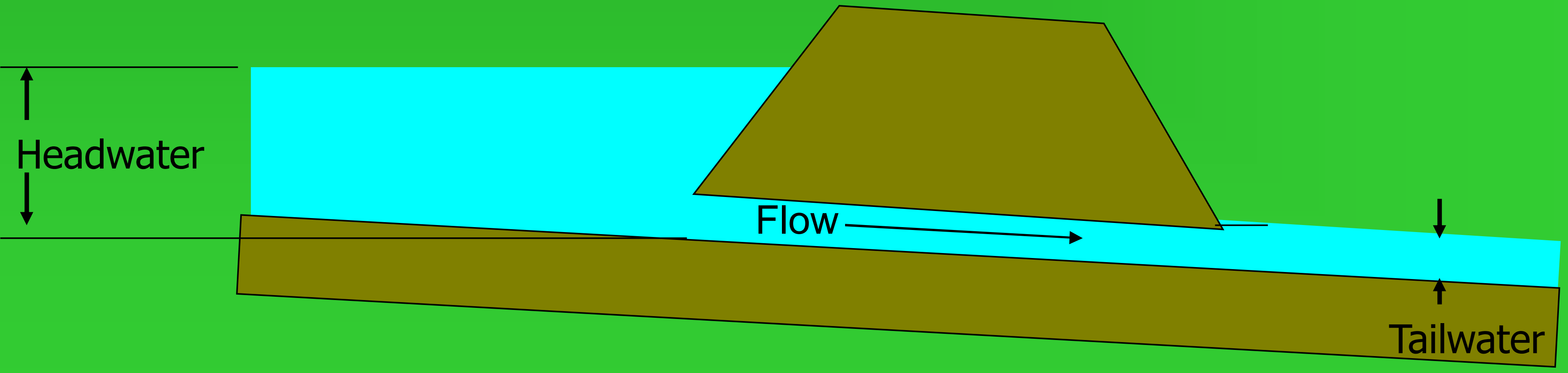
Source: FHWA HEC-22 Urban Drainage Design

Required Input Data

- Hydrologic Information
  - Drainage Area
    - If greater than or equal to 20 acres, use EGLE SCS procedures
    - If less than 20 acres, use Rational Method
    - If greater than 2 square miles, Hydraulic Unit will request discharge information from EGLE.
  - Flood Discharge Information
    - 10 year (10% chance)
    - 50 year (2% chance)
    - 100 year (1% chance)

Required Input Data

- Design Requirements
  - Site Constraints
    - Tailwater conditions
    - Headwater constraints
    - Existing culvert information
    - Discharge constraints



Design Requirements

- MDOT culverts are typically sized for a 50 year (2% chance) flood

- Check for harmful interference in a 100 year (1% chance) flood

Design Requirements

- Design headwater often controlled by site features
  - Buildings
  - Crops
  - Adjacent drainage structures (i.e. ditch culverts)
  - Road features

Design Requirements

- The design headwater should be no greater than the elevation where flow diverts around culvert (i.e. bypass flow)

Design Requirements

- Design Headwater – General Procedures

    - Target is 0.9D for circular and elliptical culverts; nearly full for box culverts for a 50-year storm (2% chance).
        - At a minimum, size to limit outlet velocities less than 6 ft/s unless consistent with downstream channel per 5.3.4 in the Drainage Manual
    - Maximum allowable headwater is 1.5 below the edge of shoulder for a 50-year storm (2% chance). <u>Use with caution for outlet velocities.</u>

Design Requirements

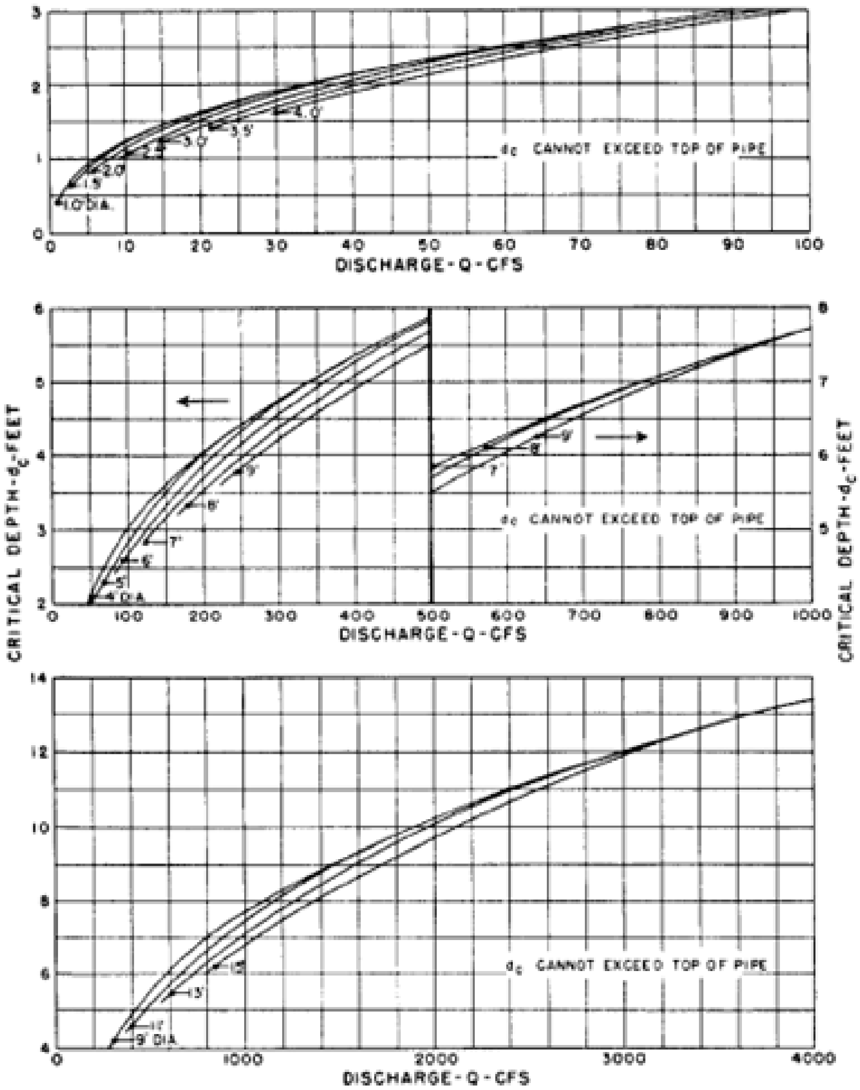
- Outlet Velocity
  - Beware of scour at outlets
  - Limit outlet velocities to 6 ft/s (unless consistent with downstream channel).

Design Requirements

- Tailwater Determination

  - Perform site visit to determine downstream controls
  - If downstream controls are present, a detailed survey will be required of the channel
    - Tailwater determined using Manning’s Equation
  - If no downstream controls are present, the tailwater may be estimated using the average of critical depth and barrel diameter.
    - – Contact Hydraulic Unit supervisor for rating curve spreadsheet for HY-8.

CHART 4B



BUREAU OF PUBLIC ROADS
JAN. 1964

CRITICAL DEPTH
CIRCULAR PIPE

Design Requirements

- Based on MDOT design, what is the design (target) headwater depth for the following?

Proposed concrete box
- Invert Upstream – 851.00 ft.
- Invert Downstream – 850.90 ft.
- Length – 56 ft.
- Roadway elevation – 860.00 ft.
- Culvert rise – 5 feet
- Discharge Info:
  - 50 year (2% chance): 120 cfs
  - 100 year (1% chance): 150 cfs
- First floor elevation of upstream building – 857.50 ft.

- Answer: 856.00 ft (+/-) for a 50-year storm

Design Requirements

- Based on MDOT Design, what is the maximum headwater depth for the following?

Proposed concrete box
Invert Upstream – 851.00 ft.
Invert Downstream – 850.90 ft.
Length – 56 ft.
Roadway elevation – 860.00 ft.
Culvert rise – 5 feet
Discharge Info:

50 year (2% chance):	120 cfs
100 year (1% chance):	150 cfs

First floor elevation of upstream building – 857.50 ft.

- Answer: 857.50 ft for a 100-year storm

Design Procedures

- Perform site visit to determine controlling features.
  - Tailwater
  - Existing culvert information (inlet type, culvert shape, culvert material, etc.)
  - Headwater constraints
  - Visible problems with existing culverts

Design Procedures

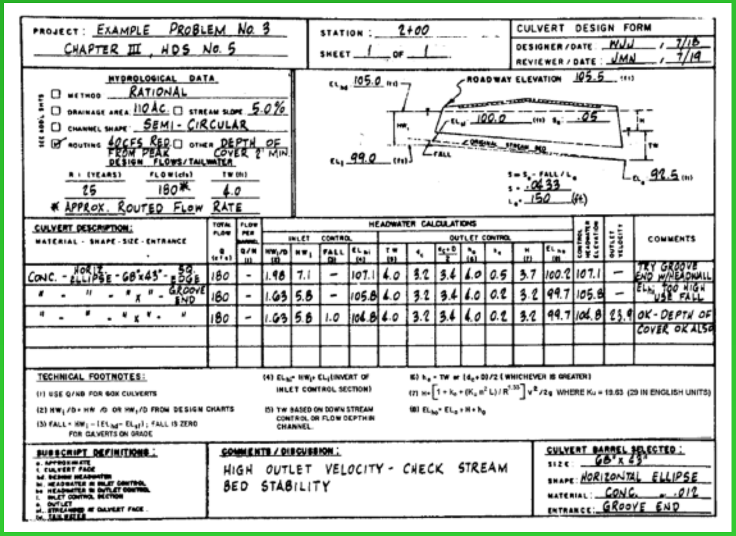
- Rules of Thumb
  - Most culverts in Michigan are designed for outlet control.
  - Culverts steeper than 1% are generally governed by inlet control.
  - Culverts in inlet control may have issues with air/cavitation and outlet velocities using conventional design.

Design Procedures

- Definitions
  - Inlet Control – Occurs when the culvert barrel is capable of conveying more flow than the inlet will accept
  - Outlet Control – Occurs when the culvert barrel is not capable of conveying as much flow as the opening will accept.

Design Procedures

- Calculations
  - Headwater values for both inlet and outlet control are calculated and compared to determine appropriate (and controlling) headwater value.



PROJECT: EXAMPLE PROBLEM No. 3 CHAPTER III, HDS No. 5

STATION: 2+00 SHEET 1 OF 1

CULVERT DESIGN FORM

DESIGNER/DATE: WJJ / 7/18

REVIEWER/DATE: JMN / 7/19

HYDROLOGICAL DATA

- ☐ METHOD: RATIONAL
- ☐ DRAINAGE AREA: 110 AC. ☐ STREAM SLOPE: 5.0%
- ☐ CHANNEL SHAPE: SEMI-CIRCULAR
- ☑ ROUTING: 40 CFS RED. FROM PEAK ☐ OTHER: DEPTH OF COVER 2' MIN.

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
25	180*	4.0

* APPROX. ROUTED FLOW RATE

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
CONC. - HORIZ. ELLIPSE - 68"x43" - SQ. EDGE	180	-	1.98	7.1	-	107.1	4.0	3.2	3.4	4.0	0.5	3.7	100.2	107.1	-	TRY GROOVE END W/HEADWALL
" - " - "x" - GROOVE END	180	-	1.63	5.8	-	105.8	4.0	3.2	3.4	4.0	0.2	3.2	99.7	105.8	-	EL_{hi} TOO HIGH USE FALL
" - " - "x" - "	180	-	1.63	5.8	1.0	106.8	4.0	3.2	3.4	4.0	0.2	3.2	99.7	106.8	23.9	OK - DEPTH OF COVER OK ALSO

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 K_u = 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 - CHECK STREAM BED STABILITY

CULVERT BARREL SELECTED:

SIZE: 68" x 43"

SHAPE: HORIZONTAL ELLIPSE

MATERIAL: CONC. n .012

ENTRANCE: GROOVE END

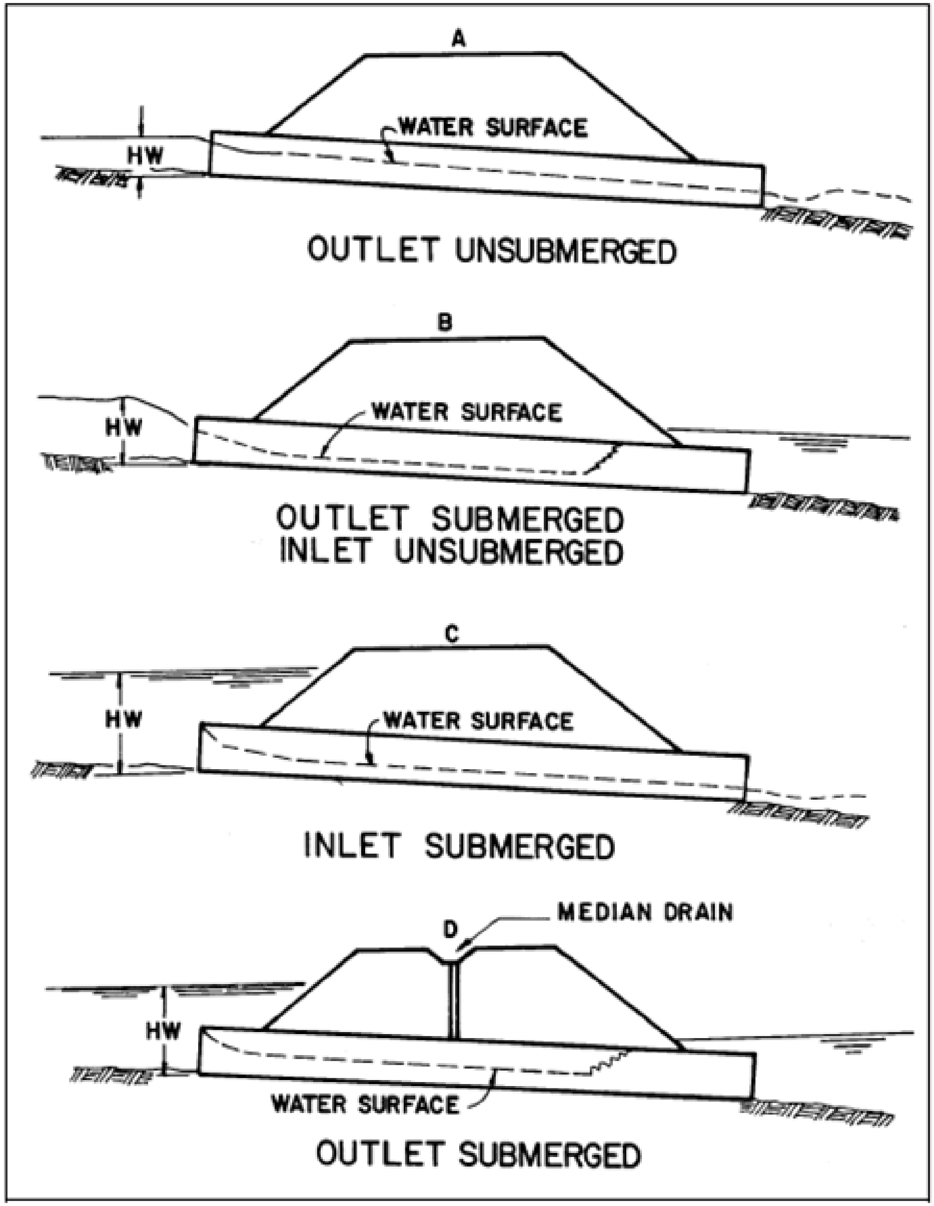


Figure III-1--Types of inlet control

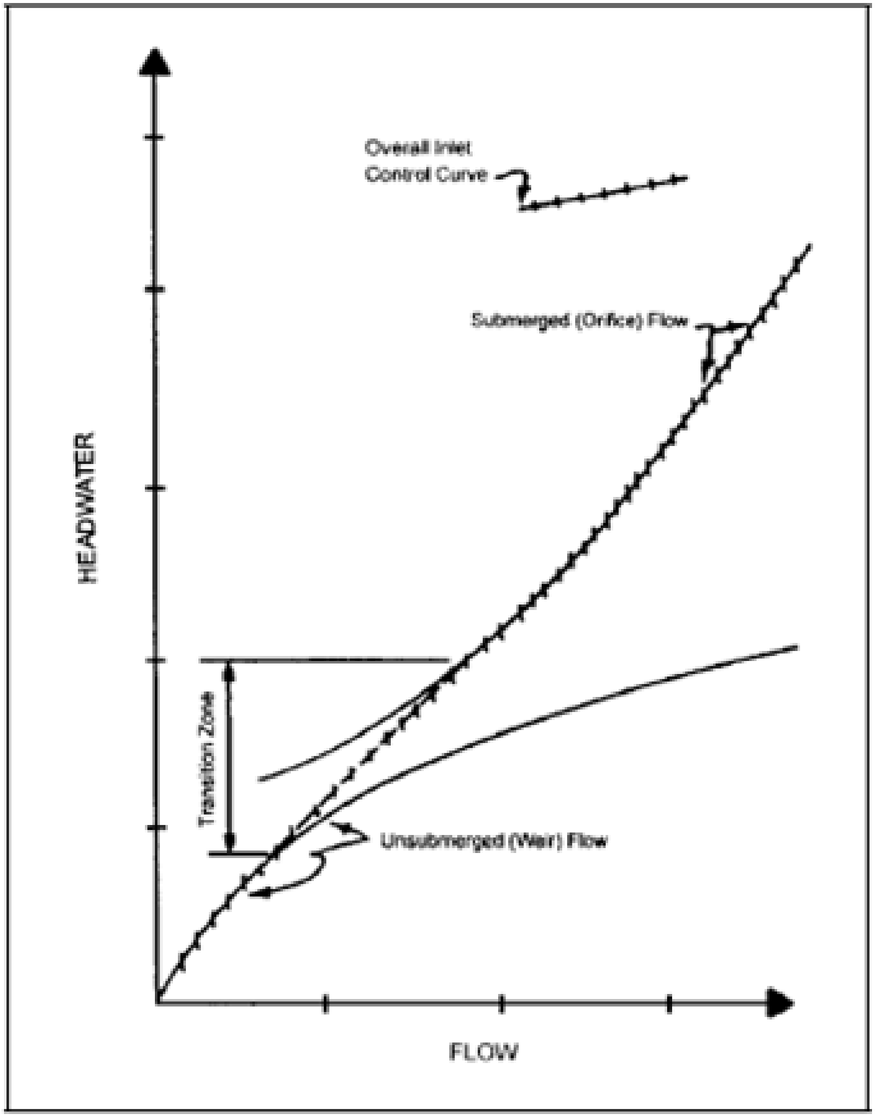


Figure III-4--Inlet Control Curves

Design Procedures

- Inlet Control
  - Factors influencing inlet control include inlet area, inlet edge configuration, and inlet shape.
  - Trapped air/cavitation may occur for submerged inlets designed in inlet control.
  - Most culverts in Michigan are not designed in inlet control.

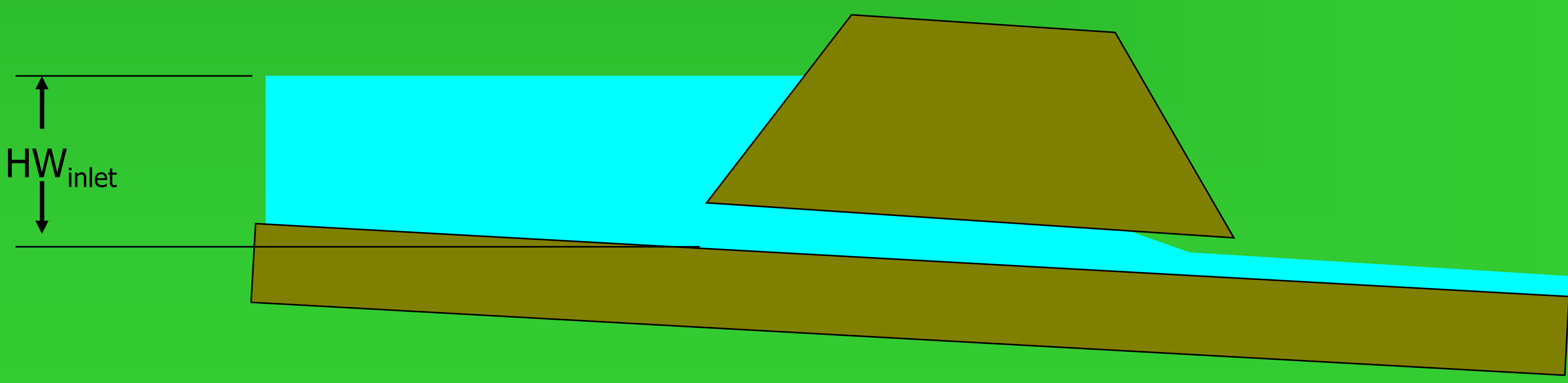
Design Procedures

- Inlet Control

    - Is the inlet control headwater affected by switching from a manufactured end section to just the pipe with the grooved end projecting?

Design Procedures

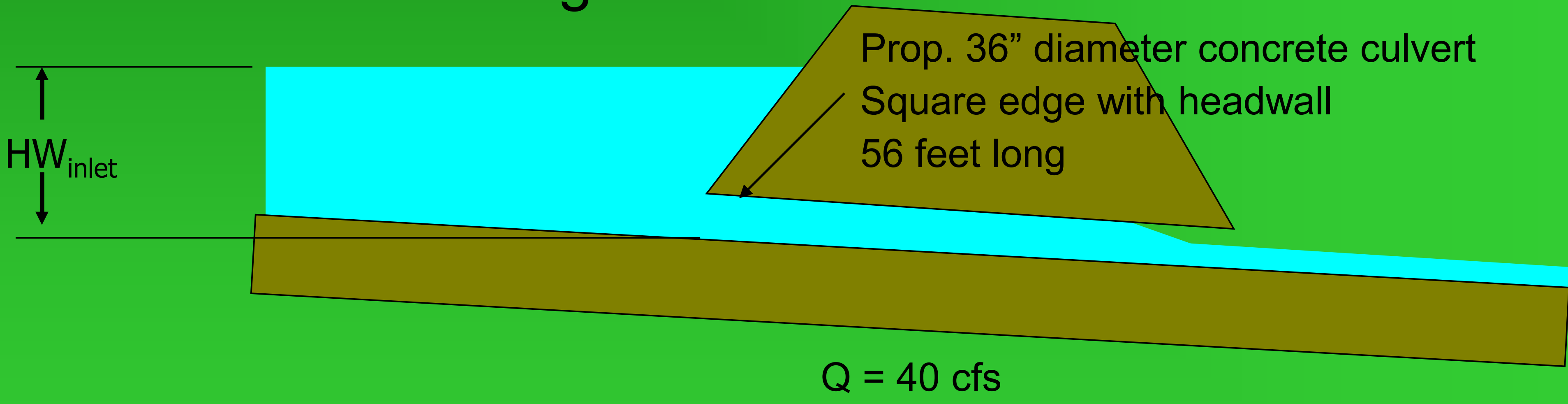
- Inlet Control
  - HW/D values found in Nomographs in HDS-5 or MDOT Drainage Manual
  - HW added to upstream invert
  - Beware of correct inlet configuration



Design Procedures

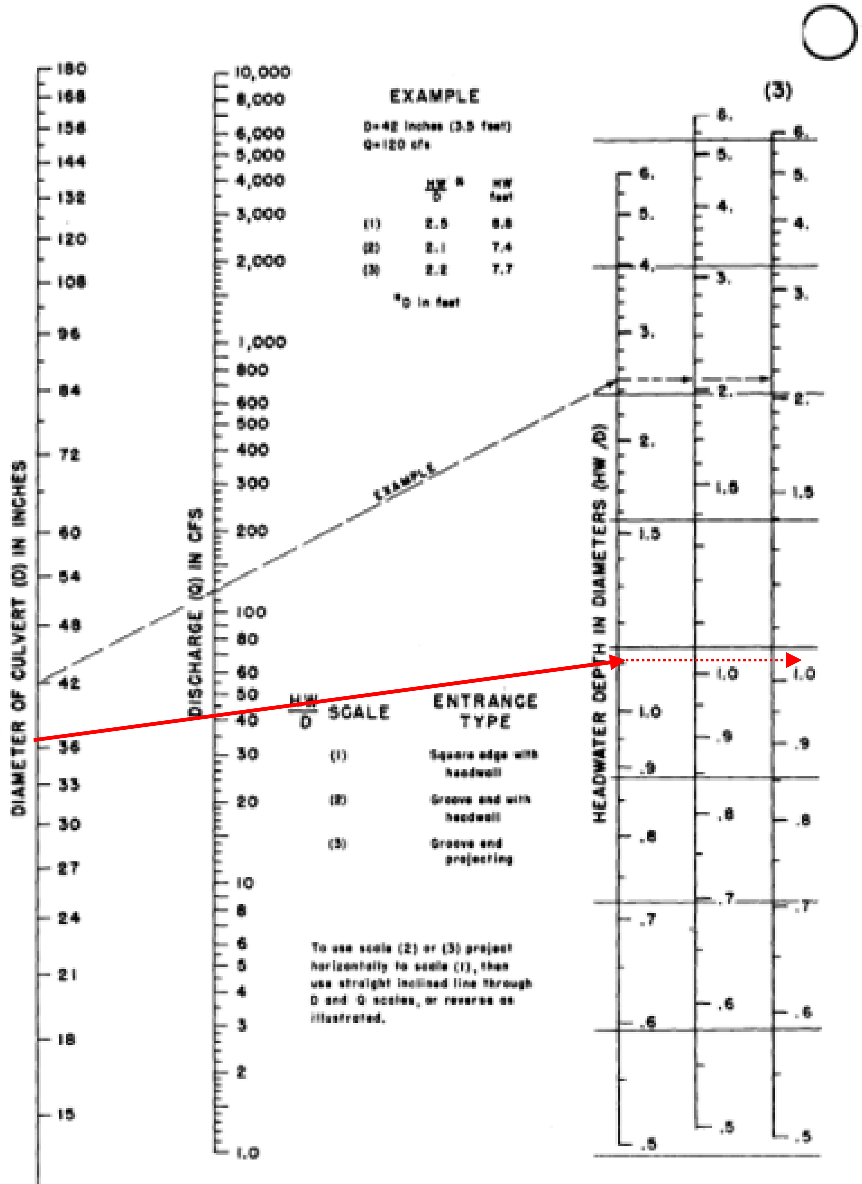
- Inlet Control

  - Find the inlet control HW value for the following:



- Answer: 3.3 feet (Chart 1B)

CHART 1B



HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL

HEADWATER SCALES 2&3
REVISED MAY 1964

BUREAU OF PUBLIC ROADS JAN. 1963

Design Procedures

- Outlet Control
  - Based on the Energy Equation
  - Factors influencing outlet control include inlet area, inlet edge configuration, inlet shape, barrel roughness, barrel area, barrel shape, barrel length, barrel slope, and tailwater elevation.
  - Most culverts in Michigan are designed for outlet control (conventional design).

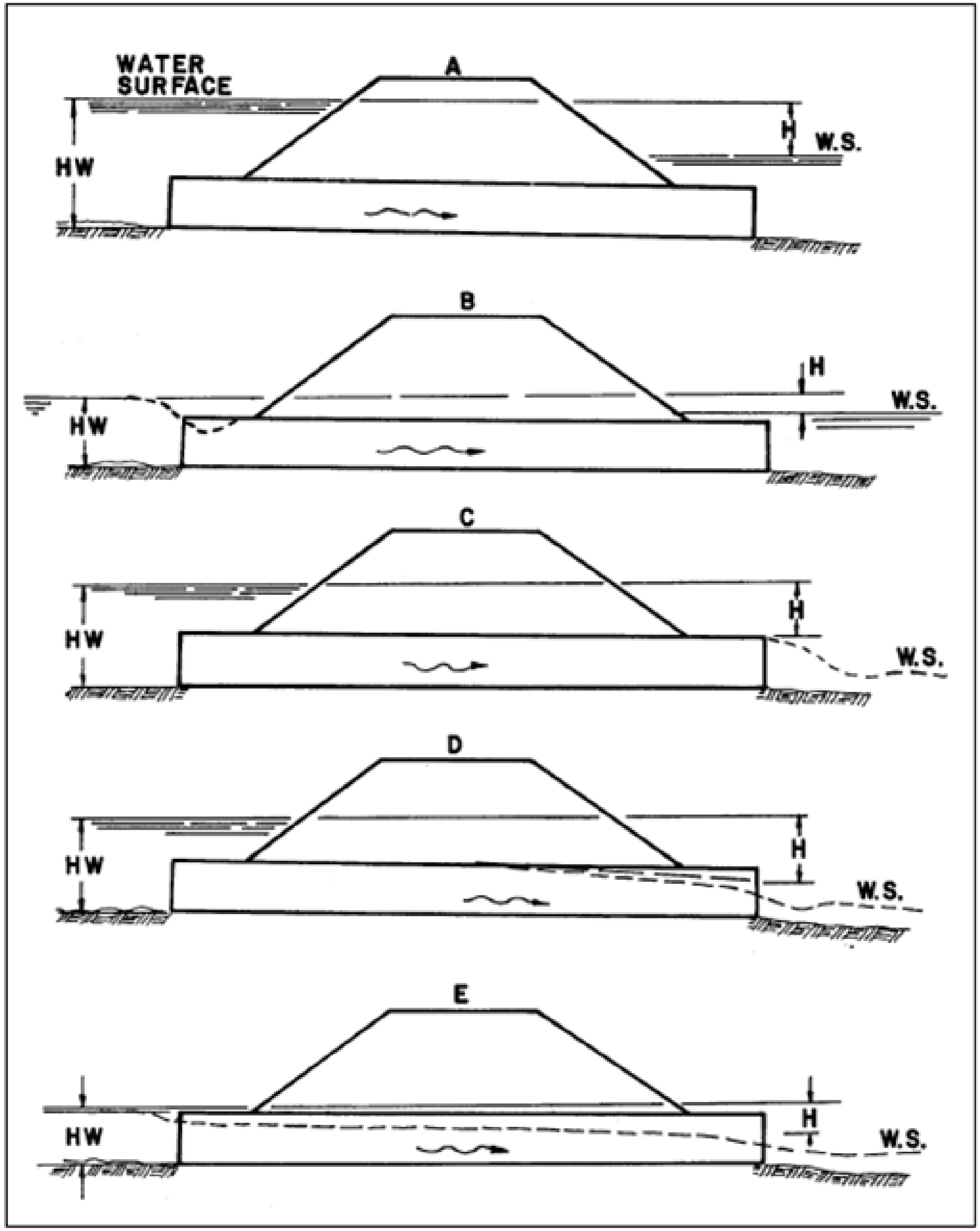


Figure III-7--Types of Outlet Control

Design Procedure

- Outlet Control
  - Equations:

$$HW_o + \frac{V_u^2}{2g} = TW + \frac{V_d^2}{2g} + H_L \qquad (HDS-5, Eq.6)$$

$$H_L = H_e + H_f + H_o + H_b + H_j + H_g \qquad (HDS-5, Eq.1)$$

$$V = \frac{Q}{A} \qquad (HDS-5, Eq.2)$$

Design Procedure

- Outlet Control

  - Typically calculated as follows:

$$HW_o = TW + H_L \qquad (HDS-5, Eq.7)$$

$$H_L = \left[1 + k_e + \frac{29n^2L}{R^{1.33}}\right]\frac{V^2}{2g} \qquad (HDS-5, Eq.5)$$

  - Bend and grate losses neglected
  - Elevations must be known

Entrance Loss Coefficients
(Outlet Control, Full or Partly Full)

$$H_e = k_e (v^2/2g)$$

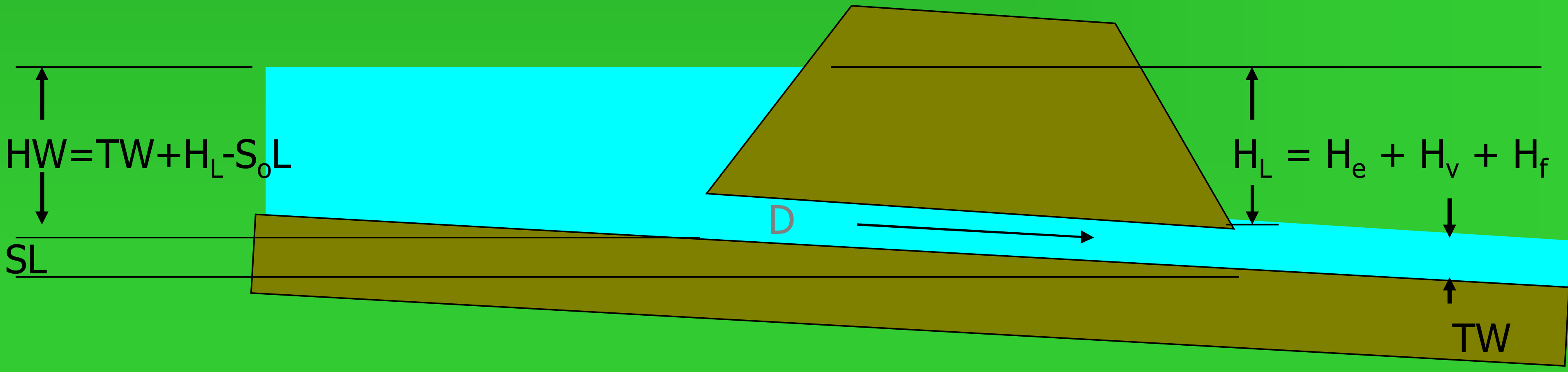
Type of Structure and Design of Entrance	Coefficient k_e
Pipe, Concrete	
Mitered to conform to fill slope	0.7
* End-Section conforming to fill slope	0.5
Projecting from fill, sq. cut end	0.5
Headwall or headwall and wingwalls	
Square-edge	0.5
Rounded (radius = 1/12D)	0.2
Socket end of pipe (groove-end)	0.2
Projecting from fill, socket end (groove-end)	0.2
Beveled edges, 33.7E or 45E bevels	0.2
Side- or slope-tapered inlet	0.2
Pipe, or Pipe-Arch, Corrugated Metal	
Projecting from fill (no headwall)	0.9
Mitered to conform to fill slope, paved or unpaved slope	0.7
Headwall or headwall and wingwalls square-edge	0.5
* End-Section conforming to fill slope	0.5
Beveled edges, 33.7E or 45E bevels	0.2
Side- or slope-tapered inlet	0.2
Box, Reinforced Concrete	
Wingwalls parallel (extension of sides)	
Square-edged at crown	0.7
Wingwalls at 10E to 25E or 30E to 75E to barrel	
Square-edged at crown	0.5
Headwall parallel to embankment (no wingwalls)	
Square-edged on 3 edges	0.5
Rounded on 3 edges to radius of 1/12 barrel dimension, or beveled edges on 3 sides	0.2
Wingwalls at 30E to 75E to barrel	
Crown edge rounded to radius of 1/12 barrel dimension, or beveled top edge	0.2
Side- or slope-tapered inlet	0.2

* Note: "End Section conforming to fill slope," made of either metal or concrete, are the sections commonly available from manufacturers. From limited hydraulic tests, they are equivalent in operation to a headwall in both inlet and outlet control. Some end sections, incorporating a closed taper in their design have a superior hydraulic performance. These latter sections can be designed using the information given for the beveled inlet.

Design Procedure

- Outlet Control
  - If elevations unknown, use the following equation:

$$HW = TW + H_L - S_0 L \qquad (MDOT, Eq. 5.7)$$



Design Procedure

- Outlet Control
  - Hydraulic radius and velocity must be adjusted for partial depth
  - Use outlet depth (TW) for partial elements

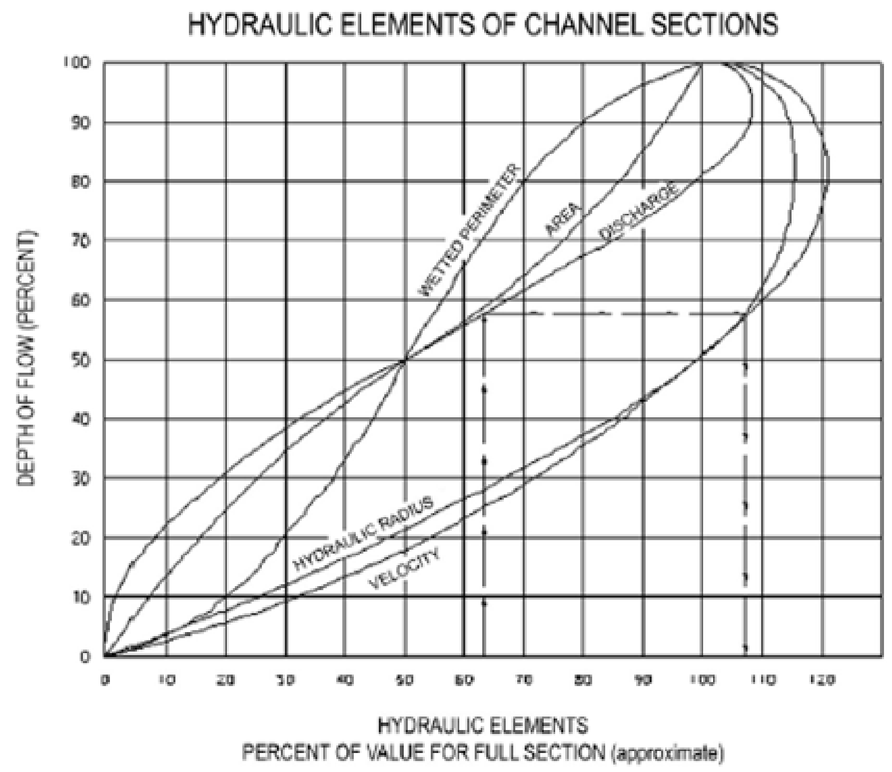
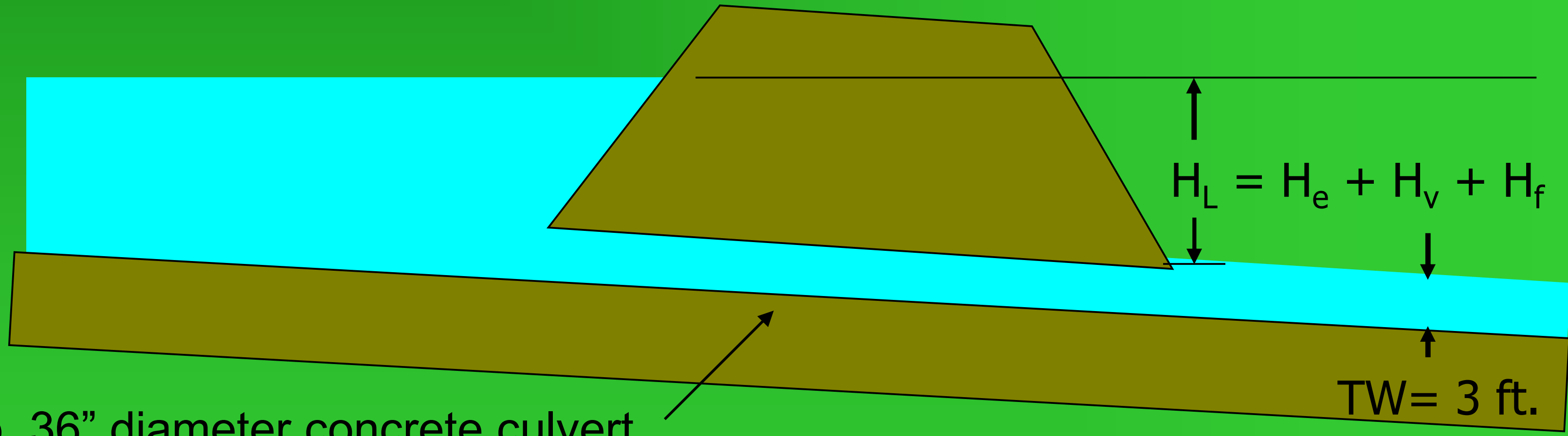


Figure 7-19 Values of Hydraulic Elements of Circular Section for Various Depths of Flow

Design Procedures

- Outlet Control
  - Find the headloss for the following:



Prop. 36” diameter concrete culvert
Square edge with headwall
56 feet long
Q = 40 cfs
Slope = 0.002 ft/ft

Design Procedures

- Outlet Control

Full flow at outlet:

$$A = \frac{\pi D^2}{4} = \frac{\pi (3)^2}{4} = 7.07 \text{ sft.}$$

$$R = \frac{A}{P} = \frac{\frac{\pi D^2}{4}}{\pi D} = \frac{D}{4} = \frac{3}{4} = 0.75 \text{ ft.}$$

$$n = 0.012$$

$$k_e = 0.5$$

$$V = \frac{Q}{A} = \frac{40}{7.07} = 5.66 \text{ ft/s}$$

$$H_L = \left[1 + k_e + \frac{29 n^2 L}{R^{1.33}}\right]\frac{V^2}{2g} = \left[1 + 0.5 + \frac{29(0.012)^2 56}{(0.75)^{1.33}}\right]\frac{(5.66)^2}{2(32.2)} = 0.92 \text{ ft.}$$

Design Procedures

Culvert Summary Table - Culvert 1

Total Discharge (cfs)	Culvert Discharge (cfs)	Headwater Elevation (ft)	Inlet Control Depth(ft)	Outlet Control Depth(ft)	Flow Type	Normal Depth (ft)	Critical Depth (ft)	Outlet Depth (ft)	Tailwater Depth (ft)	Outlet Velocity (ft/s)	Tailwater Velocity (ft/s)
0.00	0.00	3.00	0.00	**2.89**	0-NF	0.00	0.00	0.00	3.00	0.00	0.00
5.00	5.00	3.02	0.95	**2.91**	3-M1f	0.79	0.69	3.00	3.00	0.71	0.00
10.00	10.00	3.09	1.38	**2.98**	3-M1f	1.15	0.99	3.00	3.00	1.41	0.00
15.00	15.00	3.20	1.76	**3.09**	3-M1f	1.44	1.23	3.00	3.00	2.12	0.00
20.00	20.00	3.23	2.10	**3.12**	4-FFf	1.72	1.43	3.00	3.00	2.83	0.00
25.00	25.00	3.36	2.41	**3.25**	4-FFf	1.99	1.61	3.00	3.00	3.54	0.00
30.00	30.00	3.52	2.70	**3.41**	4-FFf	2.31	1.77	3.00	3.00	4.24	0.00
35.00	35.00	3.70	2.99	**3.59**	4-FFf	3.00	1.92	3.00	3.00	4.95	0.00
40.00	40.00	3.92	3.30	**3.81**	4-FFf	3.00	2.06	3.00	3.00	5.66	0.00
45.00	45.00	4.16	3.63	**4.05**	4-FFf	3.00	2.18	3.00	3.00	6.37	0.00
50.00	50.00	4.43	4.00	**4.32**	4-FFf	3.00	2.29	3.00	3.00	7.07	0.00

Display
- Crossing Summary Table
- Culvert Summary Table — Culvert 1
- Water Surface Profiles
- Improved Inlet Table
- Customized Table — Options...

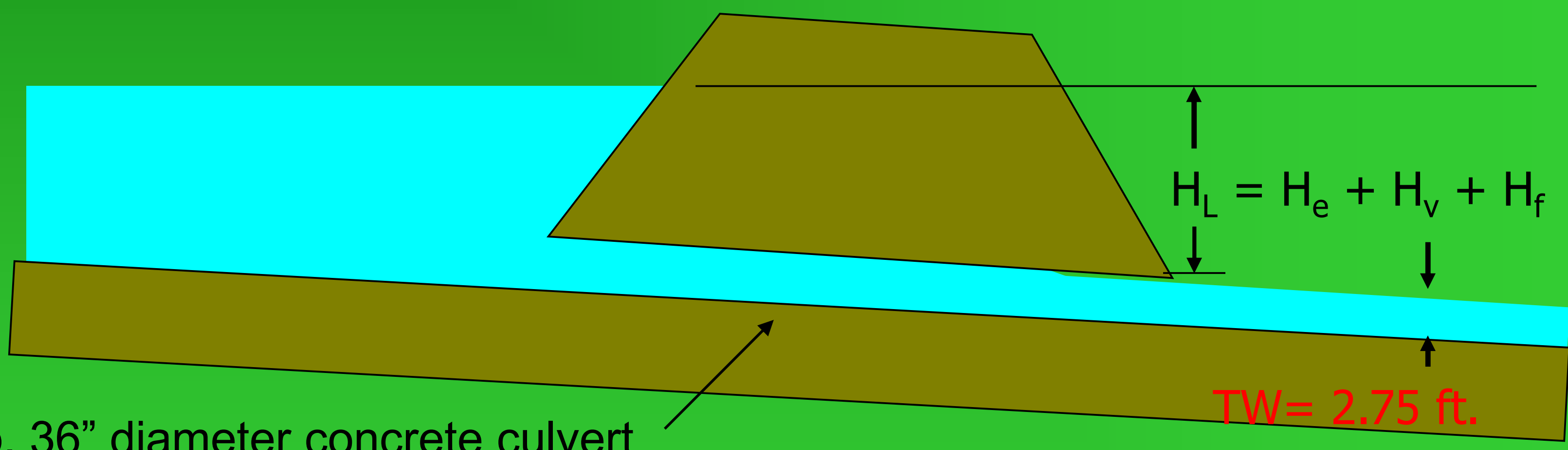
Geometry
- Inlet Elevation: 0.11 ft
- Outlet Elevation: 0.00 ft
- Culvert Length: 56.00 ft
- Culvert Slope: 0.0020
- Inlet Crest: 0.00 ft
- Inlet Throat: 0.00 ft

Plot
- Crossing Rating Curve
- Culvert Performance Curve
- Selected Water Profile

Help | Flow Types... | Edit Input Data... | Outlet Control: Profiles | Close

Design Procedures

- Outlet Control
  - Find the velocity for the following:



Prop. 36" diameter concrete culvert
Square edge with headwall
56 feet long
Q = 40 cfs
Slope = 0.002 ft/ft

Design Procedures

- Outlet Control

$$A = \frac{\pi D^2}{4} = \frac{\pi (3)^2}{4} = 7.07 \text{ sft.} \quad \text{(full flow)}$$

$$\frac{d}{D} = \frac{2.75}{3} \approx 0.92$$

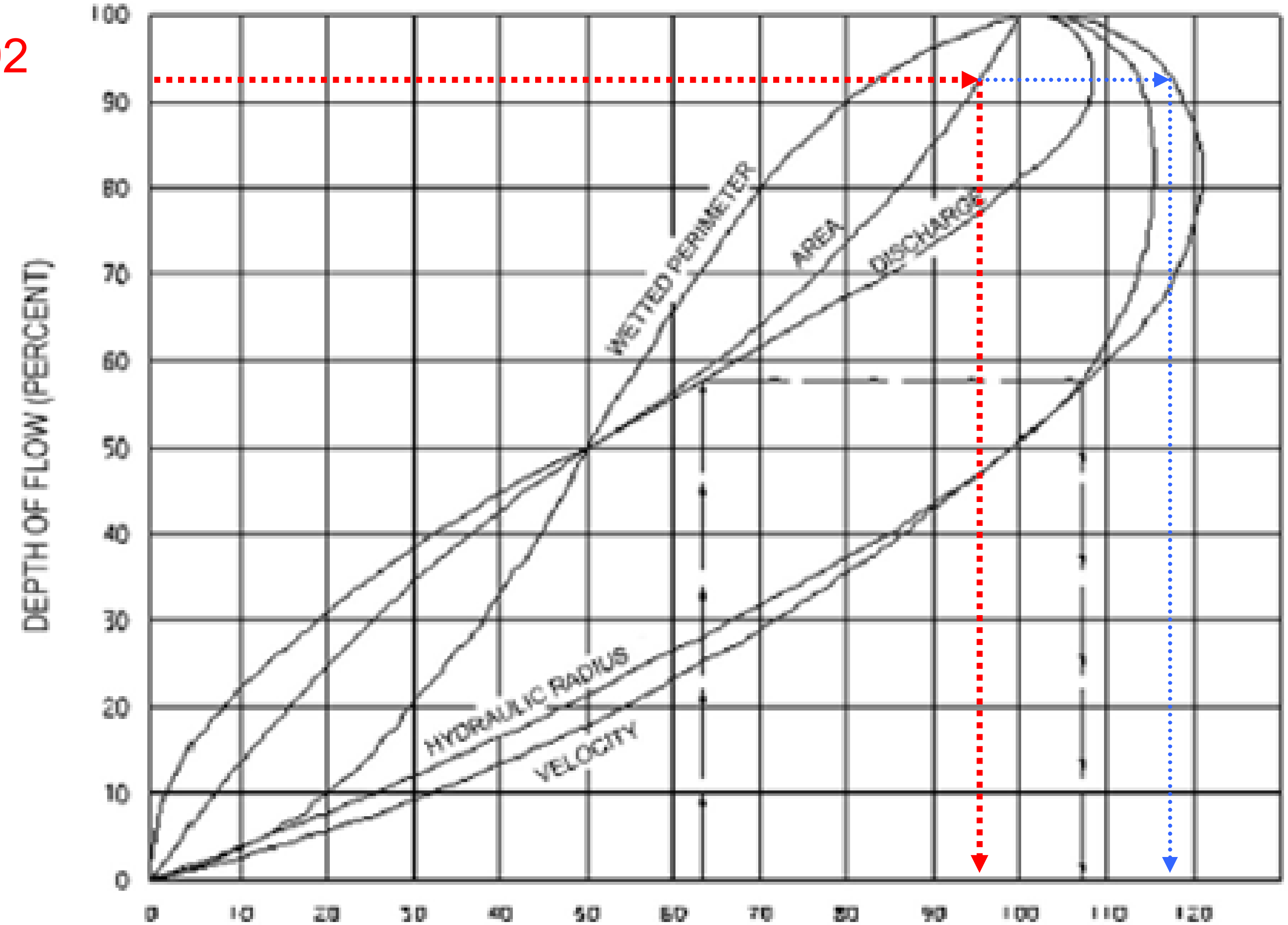
$$\frac{A'}{A} \approx 0.96 \quad \text{(Hydraulic Elements chart)}$$

$$A' = 0.96A = 0.96(7.07) = 6.79 \text{ sft.}$$

$$V = \frac{Q}{A'} = \frac{40}{6.79} = 5.89 \text{ ft/s}$$

d/D = 0.92

HYDRAULIC ELEMENTS OF CHANNEL SECTIONS



A'/A = 0.96

R'/R = 1.17

HYDRAULIC ELEMENTS
PERCENT OF VALUE FOR FULL SECTION (approximate)

Figure 7-19 Values of Hydraulic Elements of Circular Section for Various Depths of Flow

Design Procedure

- Miscellaneous Items
  - Recommend using actual surveyed elevations when sizing culverts to reduce errors.
  - Tailwater
    - Use surveyed cross-sections for all crossings with a defined bed and bank in channel (which includes “blue lines” on USGS maps).
    - Don’t forget to check for any downstream structures!

Design Procedure

- Miscellaneous Items
  - Beware of evidence of problems in the field.
    - Scour/erosion/headcuts
    - Debris lines at inlet
    - High water marks
    - Culvert damage (joint separation)
    - Road cracking over culvert

Design Procedure

- Miscellaneous Items
  - Bury the inverts below the flowline as described in 5.3.4 and on page 5-16 in the MDOT Drainage Manual

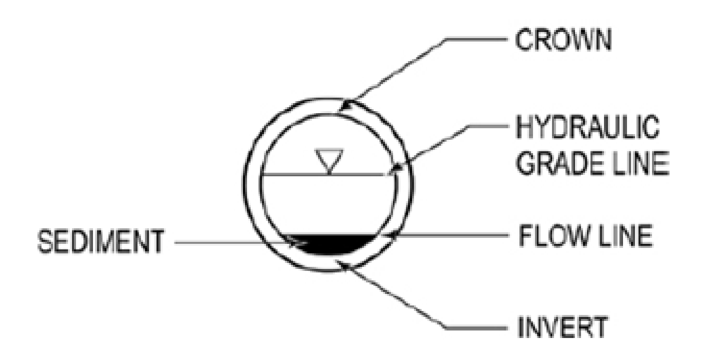


Figure 5-1 Culvert Terms

Design Procedure

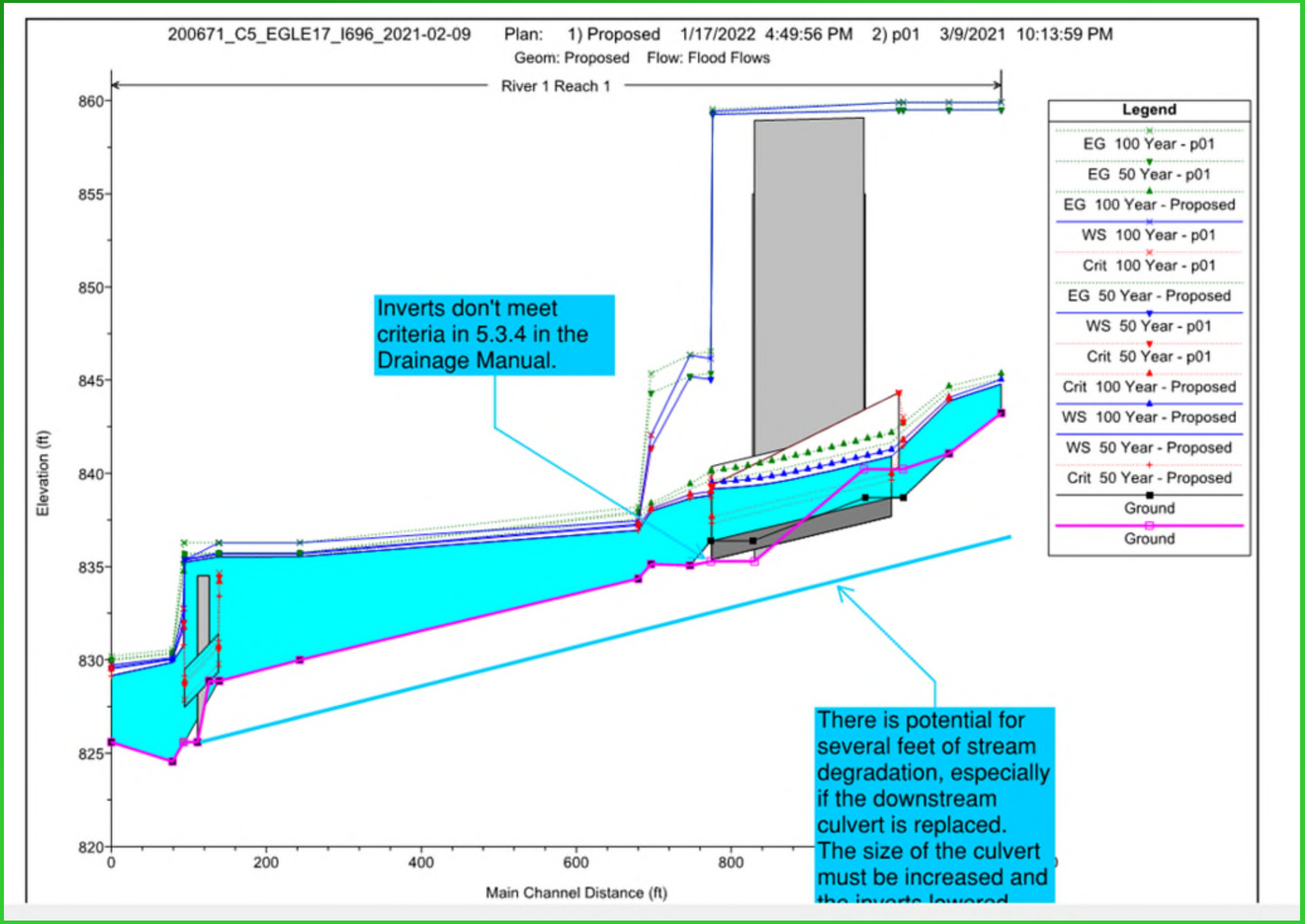
- Miscellaneous Items

Design Procedure

- Miscellaneous Items
  - Beware of long-term degradation on steep streams or future drain cleanouts or legal drain elevations on County Drain crossings

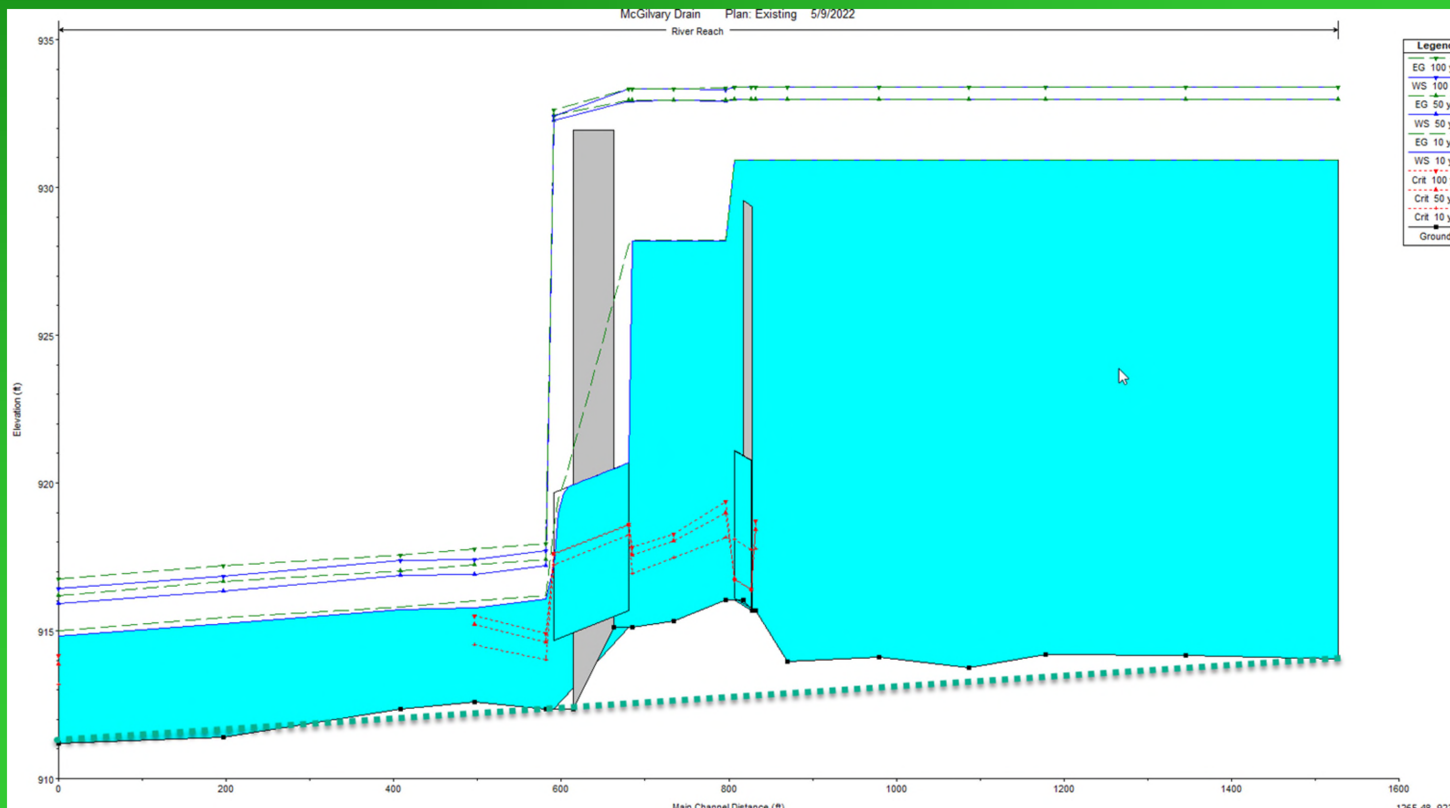
Design Procedure

- Miscellaneous Items



Design Procedure

- Miscellaneous Items



Design Procedure

- Miscellaneous Items
  - High head differential at inlet can lead to problems with buoyancy and trapped air/cavitation.
    - Can be problematic with joints on commercial ends.
    - Also problematic with cast-in-place headwalls without proper reinforcement.

Design Procedure

- Miscellaneous Items

Design Procedure

- Miscellaneous Items

Design Procedure

- Miscellaneous Items
  - Energy Dissipation
    - Required when flow transitions from supercritical to subcritical flow
    - Can be problematic for crossings requiring a Part 301 permit.
    - Common practice is to utilize manholes as drop structures for steep culverts
      - Beware of trapped air in pressure flow conditions.
    - Contact the Hydraulic Unit Supervisor for assistance

Questions?