TDOT DESIGN DIVISION

DRAINAGE MANUAL

CHAPTER XII
AQUATIC ORGANISM PASSAGE DESIGN

TDOT DESIGN DIVISION

CHAPTER 12 – AQUATIC ORGANISM PASSAGE DESIGN

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CHAPTER 12

Aquatic Organism Passage (AOP) Design

SECTION 12.01 – INTRODUCTION

This chapter presents the procedures and methods that will be used by the Tennessee Department of Transportation (TDOT) in the design of highway cross drains, culverts, and bridges to meet Aquatic Organism Passage requirements. This information is presented under the assumption that the designer is familiar with the essential hydraulic behavior of culverts and understands the open-channel and closed conduit flow theories needed to analyze their hydraulic performance. Additionally, the designer should also be familiar with regulations and requirements of various State and Federal agencies that regulate jurisdictional water-related construction as they may affect TDOT projects.

Aquatic Organism Passage (AOP) is defined by the US Forest Service as the ability of fish and other aquatic organisms to migrate and swim freely upstream and downstream through or beneath human infrastructure such as culverts, bridges, diversions, dams, etc.

AOP is a critical consideration in the design and implementation of roadway infrastructure, facilitating the free movement of fish, amphibians, and other aquatic organisms. Properly designed structures, such as culverts and bridges, are essential for maintaining upstream and downstream connectivity. When developing roadway projects over intermittent and perennial streams, it's crucial to prevent fragmentation of aquatic habitats to protect or improve existing ecosystems. State and federal regulations require cross-drains, side drains, bridges, box bridges, and slab bridges on perennial and intermittent streams, consider aquatic connectivity. Ephemeral streams are not required to be designed for AOP.

SECTION 12.02 – DATA REQUIREMENTS

To properly design a crossing structure for AOP, the designer should begin by assembling the data needed to support the design. This will include the general information necessary to identify and describe the existing crossing and/or stream feature provided in the Environmental Boundaries Report (EBR) and provided by the designer in accordance with the TDOT Drainage Manual. These parameters include:

12.02.01 Bankfull width

Bankfull width (BFW) is the width of a stream or river's water flow required to accommodate bankfull discharge during a storm event. Bankfull discharge is the flow that occurs when water barely overflows the adjacent floodplain during a 1–2 year, 24-hour storm event. Bankfull width is measured at a section perpendicular to the streamflow at bankfull discharge, in the narrowest part of the stream's riffles (straight sections), from bankfull elevation to bankfull elevation.

12.02.02 Bankfull flow depth

The mean depth of bankfull discharge expected during a storm event, which will cause water to flow onto the floodplain. Bankfull Discharge: The dominant channel-forming flow resulting from a 1 – 2 year – 24-hour storm event.

12.02.03 Stream bed material (e.g., sand, gravel, cobble, bedrock)

The stream bed material of a stream refers to the predominant size of rock or sand within the channel and along the streambanks. The streambed material affects the stream's capacity to resist erosion, transport and deposit sediment and the general shape of the channel. Generally, streams with gravel and sand bed material are more susceptible to changes during high flow events than streams with larger bed material such as cobble and boulders. Streams with finer bed material are more likely to erode and increase the amount of sediment in the water under high energy conditions. Similar to its slope, a stream will naturally adjust with its bed material to try to find a state of stable equilibrium.

12.02.04 D50 bed material size and particle size distribution

The particle size average (D50) is also known as the median diameter or the medium value of the particle size distribution. It is the value of the particle diameter at 50% in the cumulative distribution. It means 50% of the particles in the sample are larger than this number and 50% are smaller. Designers should use the "dominant substrate" as defined in the EBR for D50 material size determination.

12.02.05 Existing stream impediments (perched outlet, erosion, blockage)

Any material or obstruction in a channel which reduces the velocity or depth of normal flow.

12.02.06 Crossing hydrology as required in Ch. 4 of the TDOT Drainage Manual

Hydrology will consist of estimating stormwater runoff discharge rates and/or volumes from precipitation for the design of the highway drainage system and any required cross drainage structures.

SECTION 12.03 – GUIDELINES AND CRITERIA

Design criteria form the basis for the final design configuration. This section presents design standards and guidance for determining which projects require AOP designs and considerations a designer should evaluate and communicate with the project team.

12.03.01 Guidelines by Project Type

12.03.01.01 Routine Maintenance Projects

All roadway structures require routine maintenance to extend their service life and identify performance issues. Addressing minor deficiencies in drainage structures, such as removing debris, reshaping channel banks, installing rip rap or filling perched outlets, ensures they function as intended. While these activities may not fully restore lost aquatic connectivity, maintenance generally improves existing AOP impediments by removing obstructions, clearing clogged pipes, or stabilizing banks.

AOP design techniques **will not** be required on the following maintenance projects:

- Resurfacing projects
- Bridge approach projects

- Roadway signal, ITS, and lighting projects
- Retaining wall repair projects
- Rockfall/landslide projects

AOP design techniques **will** be required on the following maintenance projects:

- Bridge replacements projects
- Culvert replacements projects
- Retaining wall replacement projects
- Reconstruction projects

12.03.01.02 Rehabilitation or Reconstruction Projects (Along Existing Alignments)

Projects on existing alignments can be classified as rehabilitation (minor improvements) or reconstruction (major improvements, such as roadway widening).

During project scoping, existing structures are evaluated for bridge load rating and structural efficiency (for structures 20 feet or longer) to determine if extension or replacement is needed.

If the data in the EBR indicates that AOP design may be required and a replacement is necessary, design a new structure in accordance with both hydraulic and AOP design specifications. Designers should assess whether the existing or proposed roadway grade near the crossing provides sufficient vertical clearance (cover height) that accommodates AOP, alongside hydraulic grade considerations. Additionally, designers should consider the type of structure that meets AOP requirements (e.g., pipe, single span box, arch, clam shell box culvert, steel tub girder, etc.), as well as construction/stream phasing and traffic control stages during project development.

If an extension of the existing structure is determined to be feasible after structural evaluation, fully accommodating AOP will be limited and spanning the stream's BFW may not be possible. Instead, consider practices such as eliminating perched outlets, restoring substrate, building low flow channel, and limiting permeability to maintain flow above the stream flowline. These techniques still promote AOP but will not require a new structure and therefore cannot be designed with a natural stream bed through the structure.

AOP design techniques **will not** be required on the following rehabilitation or reconstruction projects:

- Resurfacing projects
- Bridge approach projects
- Roadway signal, ITS, and lighting projects
- Retaining wall repair projects
- Rockfall/landslide projects

AOP design techniques **will** be required on the following rehabilitation or reconstruction projects:

- Widening projects
- Relocated alignment projects
- Bridge replacements projects
- Culvert replacements projects
- Retaining wall replacement projects
- Reconstruction projects

12.03.01.03 Projects on a New Alignment

When scoping new alignment projects, stream crossing locations should be chosen with AOP design in mind to ensure minimal or no ecological impact. AOP design is required on all new alignment projects that cross an intermittent or perennial stream as specified in the EBR.

12.03.02 AOP Design Responsibility

If the design peak flow rate computed by the selected analysis method is greater than 500 ft^3/s for the 50-year storm, the designer should indicate the location of the structure on the proposed roadway layout drawing. This drawing, along with the related drainage survey and hydrologic calculations, should be forwarded to the Hydraulic Design Section of the Structures Division. The Hydraulic Design Section will then furnish all the necessary data to be shown on the plans for the particular structure. The designer will be responsible for incorporating this information into the design plans.

Designers typically use Bentley's ORD (Open Roads Design) SUDA features for stormwater system and cross-drain structure design. However, the current version of ORD cannot analyze an embedded structure. Therefore, designers must take additional steps in the following section to analyze the hydraulics with AOP design standards. Designers should consider the following structure characteristics when laying out the crossing structure:

12.03.02.01 Size

The predetermined standard size, shape, and material options for drainage pipe structures have been established, considering factors such as cost, availability, maintenance, and installation, elaborated upon in Chapter 6. In essence, designers have access to various pipe material types, with sizes up to 72 inches in diameter all of which are detailed in the Construction Specifications.

12.03.02.02 Slope

It is desired that AOP designed structures have a reasonable longitudinal slope. FHWA (Federal Highway Administration) recommends less than 5% slope for longitudinal slope for feasibility purposes.

12.03.02.03 Headwall

Standard pre-cast safety end walls are accessible solely for round pipe sizes up to 48 inches for parallel (D-SEW-series) or cross drains (D-PE-series). If proposing a pipe size larger than 48 inches, designers should consult the "Protected Endwall" standards. These must be cast in place and should undergo a roadside safety barrier treatment (Guardrail or concrete barrier) if the headwall is positioned within the clear zone as defined by S-CZ-series.

12.03.02.04 Shape

Should an oval pipe be proposed, the designer must include suitable pipe headwall details on the plan sheets. If a designer opts for concrete Arch pipes, they may refer to D-PO-1 keeping in mind cost and availability considerations.

12.03.02.05 Velocity

It is desired that AOP designed structures have an outlet velocity of about 4 fps for Q 1-2 yr.

SECTION 12.04 – DESIGN PROCEDURES

12.04.01 AOP Design steps

This section outlines the steps for selecting and designing a roadway stream crossing structure that ensures stream continuity to meet Aquatic Organism Passage (AOP) requirements. The AOP method aims to replicate the natural stream bed conditions by maintaining the Bankfull Width and flow depth through the proposed structure at the bankfull stage. The following sections will provide detailed design steps and considerations for:

1. Recessed pipe culverts, recessed box bridges, embedded box bridges, slab bridges, and bridges
2. Substrate Restoration Guidance
3. Inner berm channel design
4. Transition sections

12.04.02 Recessed Pipe Culverts

Using AOP techniques to maintain a natural stream bed and flow through pipe culverts poses constructability challenges. Placing material inside the pipe with power equipment may not be feasible or safe due to the confined space and air quality concerns. Therefore, it is recommended to only recess pipe culverts.

All pipe culverts designed to meet AOP standards will be recessed. A recessed culvert refers to a type of culvert installation where the culvert is set below the natural grade or surface level of the surrounding area. This setup allows for a more gradual transition between the culvert and the surrounding terrain, minimizing disruptions to the natural flow patterns of water and reducing the potential for erosion or blockages. Recessed culverts are often employed in areas where aesthetics, environmental considerations, or hydraulic efficiency are of particular concern.

Various approaches exist for determining the embedment amount, each based on sediment behavior within the streambed as a primary parameter. The rationale behind using sediment behavior as a model criterion is that it exposes aquatic organisms to similar forces experienced by the streambed material. The ultimate objective is to design a stream crossing with an equivalent effect. If all conditions are deemed identical, then the newly designed stream crossing should not hinder aquatic organisms.

All drainage pipes and some small box structures will be recessed, allowing natural alluvial stream bed material to deposit over time, creating a natural stream bed within the structure. Additionally, recessed culverts can pond water, promoting aquatic connectivity during low flow conditions. Only the upstream or downstream sections of the drainage structure will require the placement of natural stream bed material or substrate restoration to transition to the natural stream bed from the recessed inlet and outlet. The length of the material is calculated using the taper slope times the embedment depth.

Recessing the proposed structure is not recommended when the stream bed is composed of bedrock. In such cases, the least impactful approach is to limit disturbance by proposing a three-sided structure to maintain the natural stream bed. Additionally, substrate restoration is not needed for low gradient streams where the structure inlet and outlet are submerged or expected to be submerged.

The most convenient methods include:

12.04.02.01 HEC-26 HY-8 Method

Due to current limitations in Bentley's Open Roads Designer software, it is not recommended for use in analysis of AOP compliant crossings. The TDOT SUDA Manual should still be used in totality for non-AOP crossings. However, by utilizing the Federal Highway Administration's (FHWA) HY-8 software version 7.7 or newer, the designer can analyze pipe size and recess/embedment depth directly. Guidance for laying out a proposed culvert or box bridge crossing should be followed from Chapter 6 of the TDOT Drainage Manual. Once the horizontal alignment, vertical slope, and invert elevations are initially established from this protocol, the designer can start to input criteria into FHWA HY-8 software.

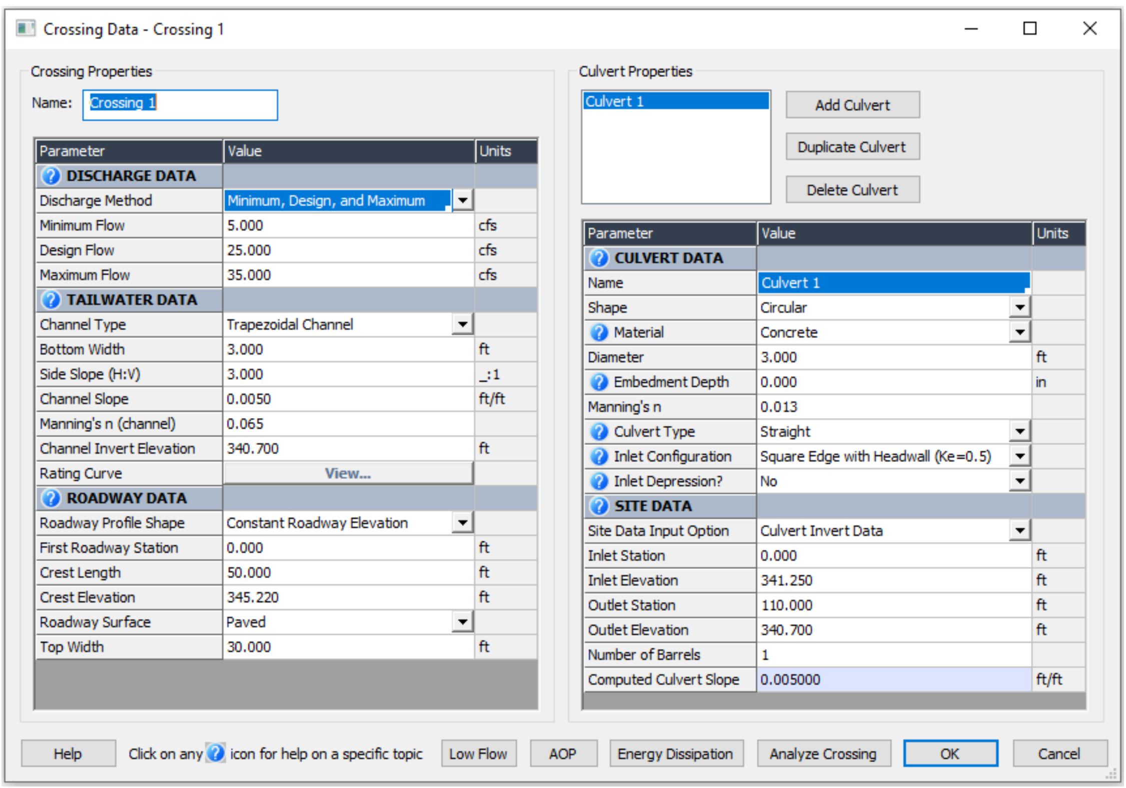
Step 1: Populate HY-8 inputs following example shown in TDOT Drainage Manual Chapter 6 Appendix 6.07.2.2. Designer should use the following flow parameters when establishing Discharge Data withing HY-8 software:

__Minimum Flow__: Designer should use 2-year flow (Q2) to analyze bankfull flow.

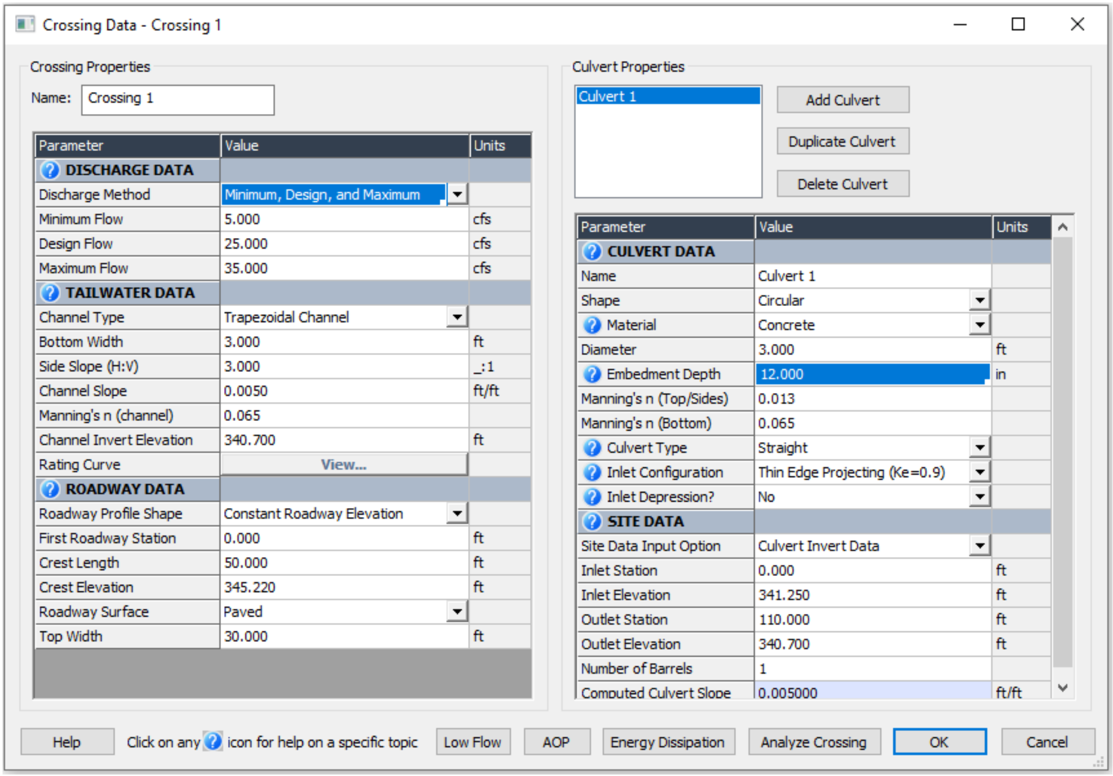
__Design Flow__: Designer should use appropriate design storm frequency based on TDOT Drainage Manual Chapter 7 Section 7.03.

__Maximum Flow__: Designer should use 100-year flow (Q100) to analyze design for adjacent property impacts and to establish appropriate right-of-way design.

__Culvert Width and Tailwater Channel width__: Designer should use the bankfull width.



Step 2: Populate embedment depth per design considerations from EBR D50 bed substrate sizing guidance. The minimum embedment depth should be 2 times the D50 found in the EBR for that stream or six inches, whichever is greater.



Step 3: Adjust the Manning's Roughness Coefficient (n) value for bottom of the proposed drainage structure. This manning's n should be consistent with the natural stream substrate as stated in the EBR. If the existing EBR does not have the necessary information, contact your Regional Environmental Technical Office.

Step 4: Analyze Crossing to determine minimum, design, and maximum (check) flow parameters including culvert discharge, headwater elevation, tailwater elevation, inlet depth, outlet depth, outlet velocity, and tailwater velocity. These parameters need to be requirements stipulated for culvert design in TDOT Drainage Manual Chapter 6.

Step 5: If culvert design meets requirements from TDOT Drainage Manual Chapter 6, designer should then check parameters as they relate to AOP design. Designer should confirm the 2-yr Flow (Q_2) is consistent with BFW parameters reported in the EBR. This includes comparing existing and proposed Q_2 outlet depth and Q_2 velocity. These parameters need to be equivalent to existing state analysis to match stream continuity and allow for aquatic organism passage in normal flow events. Designers can adjust structure type, structure size, embedment depth, and embedment

Manning's Roughness Coefficient (n) to adjust the proposed designed crossing versus the existing analysis.

Step 6: Once designer has a proposed design solution that meets both culvert design parameters established in TDOT Drainage Manual Chapter 6 and has checked for successful AOP design equivalency against existing stream conditions, the designer can populate the Hydraulic Data Table spreadsheet (shown below in Documentation Procedures) and reference or embed into the ORD Culvert Cross Sections sheets.

12.04.03 Slab Bridge and bridges

For **three-sided** slab bridge crossings, recessing or embedding typically isn't necessary. These structures are employed when a natural bedrock material is present to provide a sound foundation for the structure's footings. Naturally, three-sided structures offer minimal impact to the existing stream bed. The designer should also evaluate constructability, which may influence the type of structure proposed.

12.04.04 Box Bridge

For **four-sided** box bridge crossings, embedding them is crucial to maintain or mimic the natural stream bed material when traversing intermittent or perennial streams identified in the EBR. The smallest box of height of 6' may be installed to ensure proper working height during the placement of stream bed material inside the box. It is essential to maintain flow above the stream bed, a critical design aspect of AOP, which should be integrated with embedded crossings. Refer to section 5 for low flow considerations. If a shallow box, less than 6 ft. in height, must be used, the structure should be recessed rather than embedded, with a minimum of six inches embedment required. Ideally, increase the culvert height needed to pass the design and check storm events by 20% (rounded up to the nearest foot) to include the desired buried depth. Ensure that the cell height never exceeds the cell width for the standard culvert structures shown on STD-17 SERIES and utilize Manning's n coefficient for the stream bed. If the existing EBR does not have the necessary information, contact your Regional Environmental Technical Office. Refer to standards D-AOP-3 and D-AOP-4.

12.04.05 Bridge Crossing AOP Design Considerations

Bridge crossings become necessary when the bankfull width exceeds 18 feet. If the EBR suggests an uninterrupted crossing wider than the standard structure sizes, the designer may explore alternative structures. This could include a single span shallow box beam bridge with vertical abutments, precast arch span culvert, or tub steel arch structure. In locations where the bankfull width exceeds 40 feet, a traditional spill thru abutment girder bridge will be considered.

12.04.06 Substrate Restoration Guidance

This dynamic layer follows the stream's natural character, and even minor alterations can impact the stream's stability. Changes in features such as sinuosity, grade, channel bank depth-to-width ratio, channel width-to-floodplain width ratio, the size and gradation of stream material, and the stability of riparian material on the banks should be carefully managed.

When embedding a four-sided structure or transitioning from a stream bed to recessed drainage crossings, use natural alluvial stream bed material found on-site. If native materials are exhausted or deemed unsuitable, use coarse aggregate (#57, #3, Class A-3, or A-1) according to the substrate restoration guidance provided below.

12.04.06.01 Material Specification for Substrate Restoration

Designers should refer to the Particle Size Distribution and D50 provided with the EBR. Based on the reported nominal bed-material particle size, the following aggregate sizes for stream bed restoration can be used for sand, cobble, and gravel streams. These guidelines will help determine the appropriate stream bed type, particle size and type, layer thickness, and quantity for substrate restoration. The suggested materials are the most readily available materials, but flexibility is allowed with guidance from TDOT. This will imitate natural stream bed materials to maintain natural stream bed characteristics within the bank full width at normal flow, limiting permeability of the restored substrate. It is desirable to use the natural bed material that is removed from the stream during the initial channel excavation. Material should be temporarily stockpiled in a non-wetland/aquatic site for possible replacement in the channel.

The Substrate Restoration may be constructed in layers to minimize the amount of void space in the stream channel. Although pre-mixing the material before placement may be a desired construction alternative especially when restoring gravel stream bed. Pre-mixing must be performed outside of the BFW.

Substrate Restoration

Range of nominal particle sizes based on Stream bed type

Stream Bed Type	Nominal particle size	Restoration aggregate type	Restoration aggregate size range
Sand/silt	< 0.08”	sand	< 0.08”
Small Gravel	0.08” – 1”	# 57 stone	1/2”- 1”
Large Gravel	1” – 2.5”	# 3 stone	1” - 2”
Small Cobble	2.5” – 6”	Class A-3 Rip-Rap	2”- 6”
Large Cobble	6” – 10”	Class A-1 Rip-Rap	2”- 14”

TABLE 12-1

Stream bed types consisting of boulders (particle size 10” – 48”) or bedrock are excluded from the substrate restoration mix guidance. The EBR report provides dominate substrate type which can be used to structure the restoration aggregate mix similarly. Adding sand over the aggregate is important to limit permeability and achieve a final impervious substrate layer to maintain stream flow on the bed. The nominal thickness of layers, as shown in Table 12-2, should be no less than twice the largest diameter of the selected coarse aggregate or riprap class.

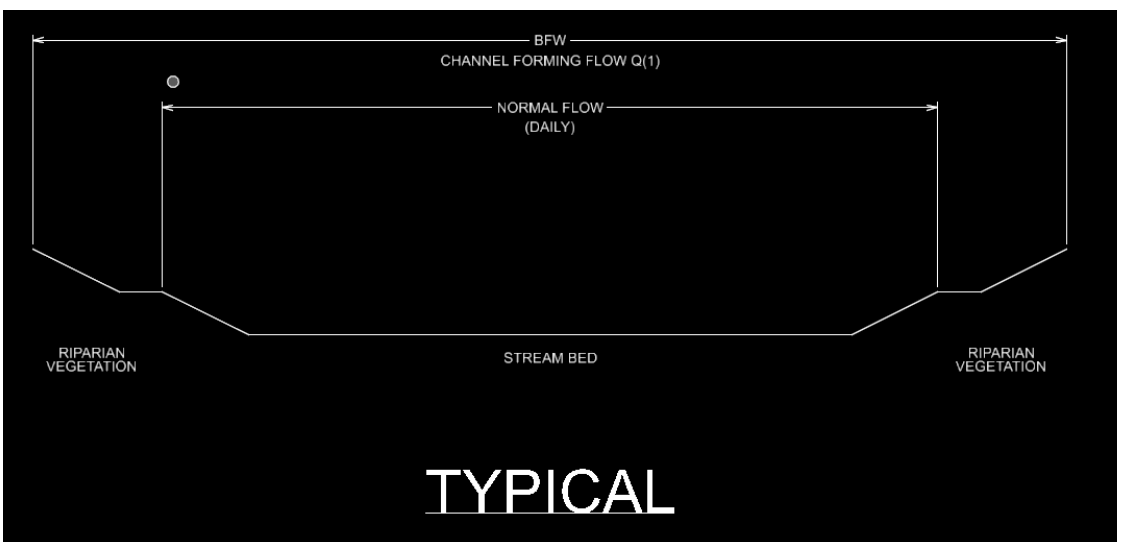
For small or large cobble stream beds, Class A-3 or A-1 riprap will be used, respectively. This coarse material will require an additional layer of #3 (with Class A-3) or #57 (with Class A-1) coarse aggregate to further limit permeability and reduce potential rock crop-outs caused by larger diameter riprap in the first layer, thereby improving the stream flow pathway. The final fine aggregate layer of sand will be placed over the coarse aggregate layers to interlock the smaller aggregate layers and further limit the permeability of the restored stream bed. Washing final sand later to assure fine materials migrated into the open graded aggregate. This step should be repeated until all fine materials densely placed confirming the restored bed could retain water on final surface. The total thickness in Table 12-2 is the amount of minimum embedment of the structure to offer stable restored stream bed under channel forming flow considerations preserving stream characteristics.

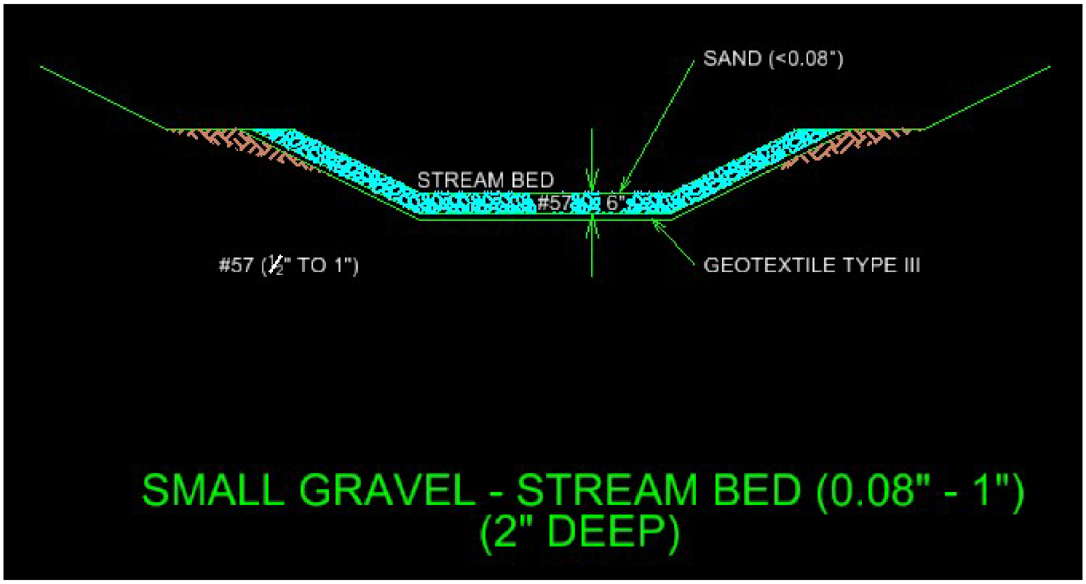
Nominal Layer thickness of restored substrate for Gravel or Cobble-bed streams

Aggregate Type	**Gravel bed**		**Cobble bed**	
	Small	**Large**	**Small**	**Large**
Sand	< 0.08”	< 0.08”	< 0.08”	< 0.08”
#57	6”	2”	2”	2”
#3		4”	4”	4”
Class A-3			12”	
Class A-1				18”
Total Thickness of layer(s)	**6”**	**6”**	**18”**	**24”**

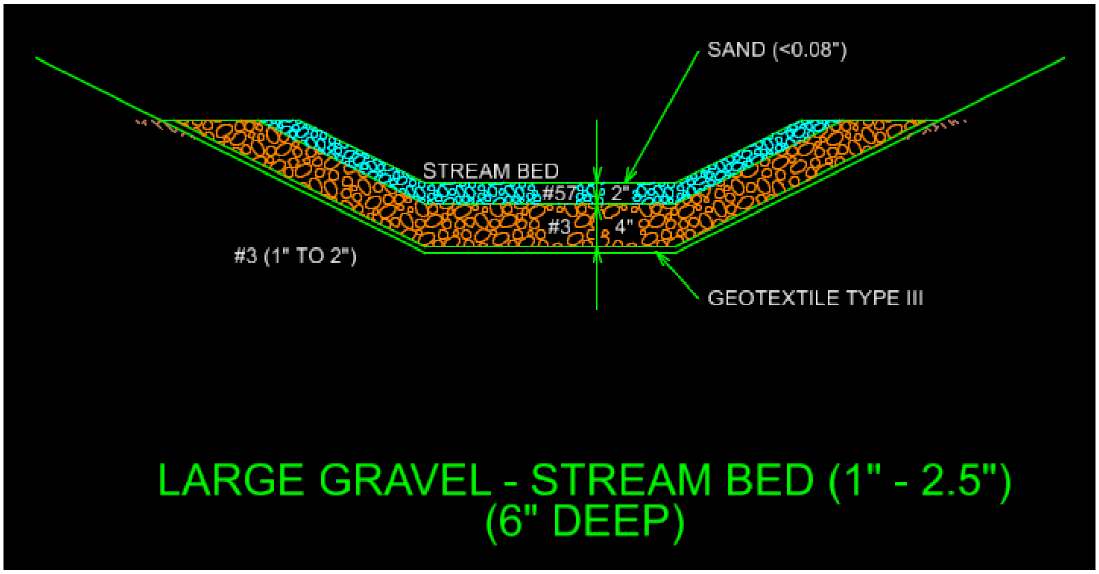
TABLE 12-2

12.04.06.02 Substrate Restoration Sequence of Construction

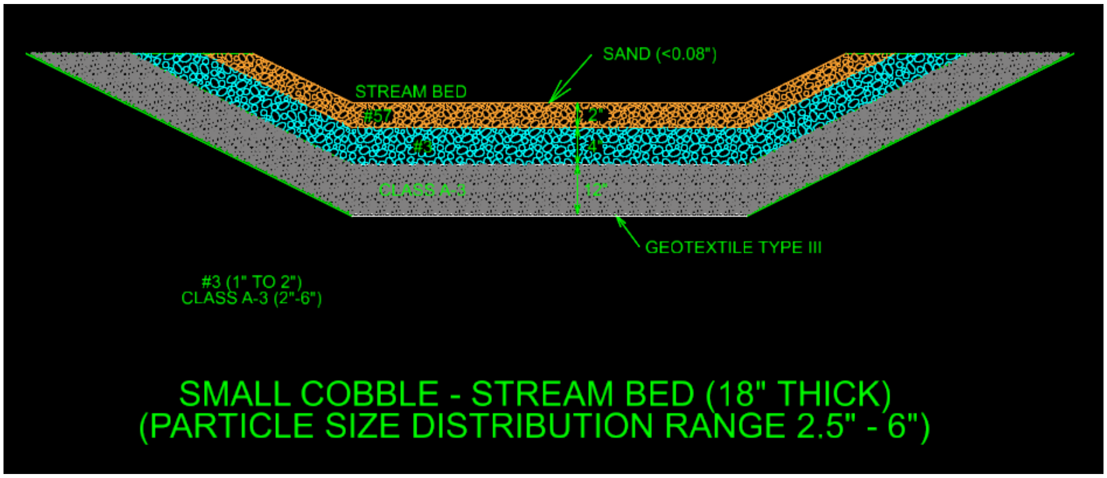


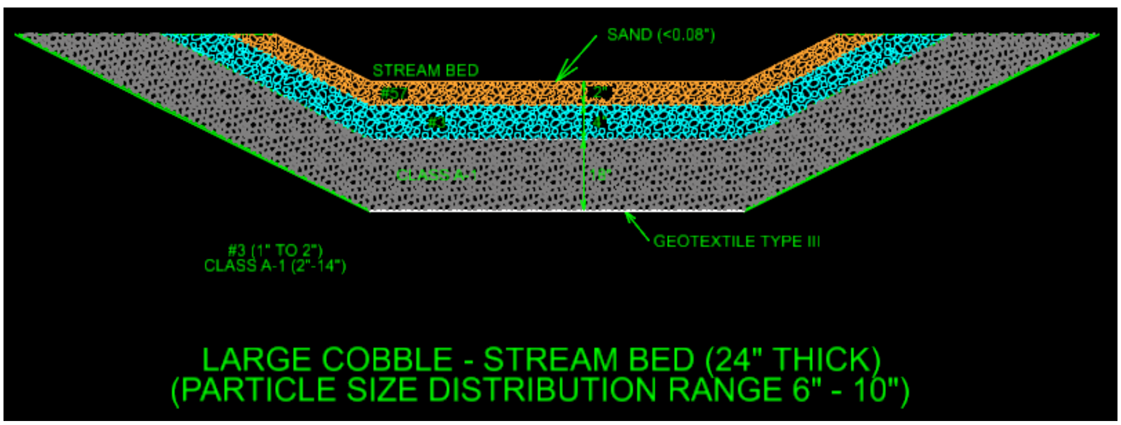


SMALL GRAVEL - STREAM BED (0.08" - 1")
(2" DEEP)



LARGE GRAVEL - STREAM BED (1" - 2.5")
(6" DEEP)





All four-sided structures should be embedded according to the above criteria unless directed otherwise by the EBR or Hydraulics design section. Embedding is not required for three-sided structures, as they do not disturb the natural stream bed and typically do not require additional substrate.

In alluvial stream beds, it is expected that the placed restoration aggregates will integrate into the live stream bed load over time, providing only initial stability at the stream-forming flow conditions. Existing streams with outlet scour holes, head cuts, or bank erosion will require natural stream stability restoration within the project limits. In some cases, addressing these existing impediments may be outside the scope of a roadway stream crossing project. At a minimum, armoring these locations with riprap material to resist forces from peak flow conditions may be necessary.

The placement of riprap at drainage structure outlets to handle high velocities during peak flow should not be considered part of the aggregate used to restore substrates. Instead, they should be placed below the restorative substrate unless otherwise directed by the Hydraulics section. Achieving impervious layer over open graded large aggregate will require an intermediate effort to limit permeability. It is important to assess the finish surface conditions of the scour protection layer before placing substrate restoration layer(s). Failure to fill in the voids will be an unacceptable practice.

12.04.07 Transitional Sections

Stream bed elevation transition sections are especially necessary when the structure is recessed. These transition sections should be carefully evaluated and constructed. The transition should not be steeper than an 8:1 taper, though this may vary based on factors such as wing wall lengths, crossing skew, the extent of riprap used for scour protection, and the inlet and outlet elevations of recessed structures. Transition zone layers include riprap below the stream bed for scour protection, variable substrate restoration aggregate layer thicknesses, and the low flow channel. While all these elements function together, they each follow different hydraulic design criteria.

12.04.07.01 Scour protection

When needed, a scour protection layer shall be designed to resist shear forces caused by design peak flow based on the structure type and outfall type.

12.04.07.02 The substrate restoration

Design follows channel forming discharge. Two-year reoccurrence interval (50%) is commonly accepted flow rate which typically occurs within the banks of a stream.

12.04.07.03 Low flow channel design

Follows channel forming flow of two-year reoccurrence interval (50%).

SECTION 12.05 – DOCUMENTATION PROCEDURES

The designer will be responsible for documenting the computations and design decisions made for the design of each AOP culvert within the roadway project. In F, the documentation should be sufficient to answer any reasonable question that may be raised in the future regarding the proposed culvert design. The documentation for each culvert should be grouped together and be organized by roadway station from the beginning of the improvement to the end.

The designer will need to provide the following output parameters for each AOP designed crossing:

12.05.01 Recessed/Embedded Pipe Culvert/Box Bridge

- Bankfull width dimension (refer to EBR)
- Bankfull flow depth (refer to EBR)
- Pipe Culvert or Box Bridge inlet and outlet invert elevations.
- Stream bed elevations at inlet and outlet (Pipe culvert Invert plus the assumed embedment depth)
- Pipe Culvert /Box Culvert Slope
- 2 year discharge velocity.
- Standards referenced. D-PE-SERIES, STD-17-SERIES, D-AOP-SERIES etc.

12.05.02 Natural Bottom Slab Bridge

- Bankfull width dimension (refer to EBR)
- Bankfull Width flow depth (refer to EBR)
- Slab Bridge inlet and outlet invert elevations match the Stream bed elevations
- Pipe Culvert /Box Culvert Slope
- 2 year discharge velocity
- Standards referenced. D-PE-SERIES, STD-17-SERIES, D-AOP-SERIES etc.

12.05.03 AOP Design Data

- The designer shall furnish the subsequent design data alongside the hydraulic information for each drainage crossing on the culvert cross sections meant for AOP design:

HYDRAULIC DESIGN DATA TABLE			
PIPE CULVERT or BOX BRIDGE			
STATION: XXX+XX.XX			
STRUCTURE: XX' OF XX PIPE CULVERT/BOX BRIDGE			
SKEW	X	DEG.	
DRAINAGE AREA	X.XX	AC.	
DESIGN DISCHARGE (Q50)	X.XX	CFS	
DESIGN DISCHARGE (Q100)	X.XX	CFS	
OVERTOPPING ELEV.	XXX.XX		
ALLOWABLE HEADWATER ELEV.	XXX.XX		
Q50 HEADWATER ELEV.	XXX.XX		
Q100 HEADWATER ELEV.	XXX.XX		
VELOCITY (Q50)	X.XX	FT/S	
VELOCITY (Q100)	X.XX	FT/S	
ENDWALLS REQUIRED:			
XXXX			
AOP ANALYSIS:			
BANKFULL WIDTH (REFER TO EBR)	X.X	FT.	
BANKFULL DEPTH (REFER TO EBR)	X.X	FT.	
DESIGN DISCHARGE (Q2)	X.XX	CFS	
PROP. INLET INVERT	XXX.XX		
PROP. INLET STREAM BED ELEV.	XXX.XX		
PROP. OUTLET INVERT	XXX.XX		
PROP. OUTLET STREAM BED ELEV.	XXX.XX		
Q2 HEADWATER ELEV.	XXX.XX		
VELOCITY (Q2)	X.XX	FT/S	
STREAM BED MATERIAL (REFER TO EBR)			
D50 BED MATERIAL SIZE (REFER TO EBR)			
STANDARD DRAWING NOS.:			
X-XX-XXX, X-XX-XXX, X-XX-XXX, X-XX-XXX			
QUANTITIES:			
CLASS "A" CONCRETE		C.Y.	
STEEL BAR REINFORCING		LB.	
BEDDING MATERIAL		C.Y.	
ENDWALL ITEM NOS.:			

SECTION 12.06 – ACCEPTABLE SOFTWARE

Please refer to TDOT Drainage Manual Chapter 6 Section 6.06 for a comprehensive list of TDOT acceptable design software.

SECTION 12.07 – APPENDIX

12.07.01 EXAMPLE PROBLEMS

12.07.01.01 EXAMPLE PROBLEM #1: RECESSED PIPE CULVERT

***GIVEN*:**

A culvert is proposed for a new roadway crossing as shown in Figure 12A-1. The culvert is intended to convey a perennial stream and therefore must be designed to AOP standards. The following information is known:

- 2-year flow rate (Q_2) = 9.6 ft^3/s
- 50-year flow rate (Q_{50}) = 15.5 ft^3/s
- 100-year flow rate (Q_{100}) = 16.8 ft^3/s
- Invert elevation at inlet = 532.09 feet
- Invert elevation at outlet = 507.25 feet
- Natural streambed slope = 3.5% (0.035 ft/ft)
- Stream bankfull width = 5 feet
- Stream D50 = 12 in.
- Normal bankfull depth = 1 foot

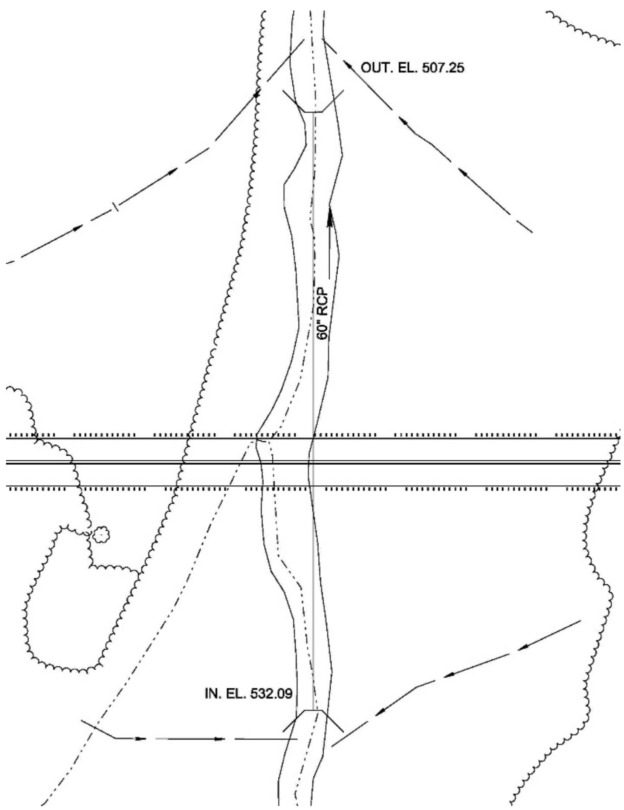


Figure 12A-1

Culvert Roadway Crossing with Perennial Stream

FIND:

Following the process shown in TDOT Drainage Manual Chapter 6 Appendix 6.07.2.2, select and analyze an appropriate pipe culvert for this site.

SOLUTION:

Step 1: Populate HY-8 inputs following example shown in TDOT Drainage Manual Chapter 6 Appendix 6.07.2.2. Designer should use the following flow parameters when establishing Discharge Data withing HY-8 software:

Minimum Flow: Designer should use 2-year flow (Q_2) to analyze bankfull flow.

Design Flow: Designer should use appropriate design storm frequency based on TDOT Drainage Manual Chapter 7 Section 7.03.

Maximum Flow: Designer should use 100-year flow (Q_{100}) to analyze design for adjacent property impacts and to establish appropriate right-of-way design.

Figure 12A-2 shows the HY-8 Discharge Data Input Screen.

DISCHARGE DATA		
Discharge Method	Minimum, Design, and Maximum	
Minimum Flow	9.600	cfs
Design Flow	15.500	cfs
Maximum Flow	16.800	cfs

Figure 12A-2

HY-8 Discharge Data Input Screen

Step 2: Enter the culvert site data for the given problem parameters. Two possibilities exist for entering this data. The user can select either the “culvert-inlet” option which prompts the user for the inlet and outlet station and elevations for the culvert along the channel, or they can enter embankment and toe data by selecting the “embankment-toe” option. HY-8 uses the embankment and toe data to create the invert data for the culvert if the “embankment-toe” option is selected. For this application, the inlet and outlet station and elevations are known; therefore, the designer will select the “culvert-invert” option. The HY-8 culvert site data (culvert-invert) screen is shown in Figure 12A-3.

SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.000	ft
Inlet Elevation	519.500	ft
Outlet Station	350.000	ft
Outlet Elevation	507.250	ft
Number of Barrels	1	
Computed Culvert Slope	0.035000	ft/ft

Figure 12A-3

HY-8 Site Data Input Screen

Step 3: Enter culvert characteristics for this site such as the shape, size, material, and inlet conditions of the proposed culvert. HY-8 provides a Manning's n-value based on the culvert material chosen by the designer. This provided Manning's n-value will be used for the top and sides of the drainage structure. A Manning's n-value for the bottom of the drainage structure will be found in Step 5. Inlet information can be for either a conventional inlet configuration or an improved inlet (side or slope tapered options are available). Designer should reference the stream bankfull width found in the EBR to determine an initial pipe diameter.

CULVERT DATA		
Name	Culvert 1	
Shape	Circular	
Material	Concrete	
Diameter	5.000	ft
Embedment Depth	24.000	in
Manning's n (Top/Sides)	0.012	
Manning's n (Bottom)	0.065	
Culvert Type	Straight	
Inlet Configuration	Square Edge with Headwall (Ke=0.5)	
Inlet Depression?	No	

Figure 12A-4

HY-8 Culvert Data Input Screen

Step 4: Populate embedment depth per design considerations from EBR D50 bed substrate sizing guidance. The minimum embedment depth should be 2 times the D50 found in the EBR for that stream.

CULVERT DATA		
Name	Culvert 1	
Shape	Circular	
Material	Concrete	
Diameter	5.000	ft
Embedment Depth	24.000	in
Manning's n (Top/Sides)	0.012	
Manning's n (Bottom)	0.065	
Culvert Type	Straight	
Inlet Configuration	Square Edge with Headwall (Ke=0.5)	
Inlet Depression?	No	

Figure 12A-5

HY-8 Culvert Data Input Screen – Embedment Depth

Step 5: Adjust the Manning's Roughness Coefficient (n) value for bottom of the proposed drainage structure. This manning's n should be consistent with the natural stream substrate as stated in the EBR.

CULVERT DATA		
Name	Culvert 1	
Shape	Circular	
Material	Concrete	
Diameter	5.000	ft
Embedment Depth	24.000	in
Manning's n (Top/Sides)	0.012	
Manning's n (Bottom)	0.065	
Culvert Type	Straight	
Inlet Configuration	Square Edge with Headwall (Ke=0.5)	
Inlet Depression?	No	

Figure 12A-6

HY-8 Culvert Data Input Screen – Manning's n

Step 6: The designer will input the downstream channel information such as shape, Manning's 'n' value of the channel (see Chapter 5 for procedures to determine channel 'n'-values), and the channel slope. The bankfull width is used for the tailwater bottom width value. Figure 12A-7 shows the HY-8 regular channel data input screen for the culvert design project. Designer should follow the same process as described in Step 6 of TDOT Drainage Manual Chapter 6 Appendix

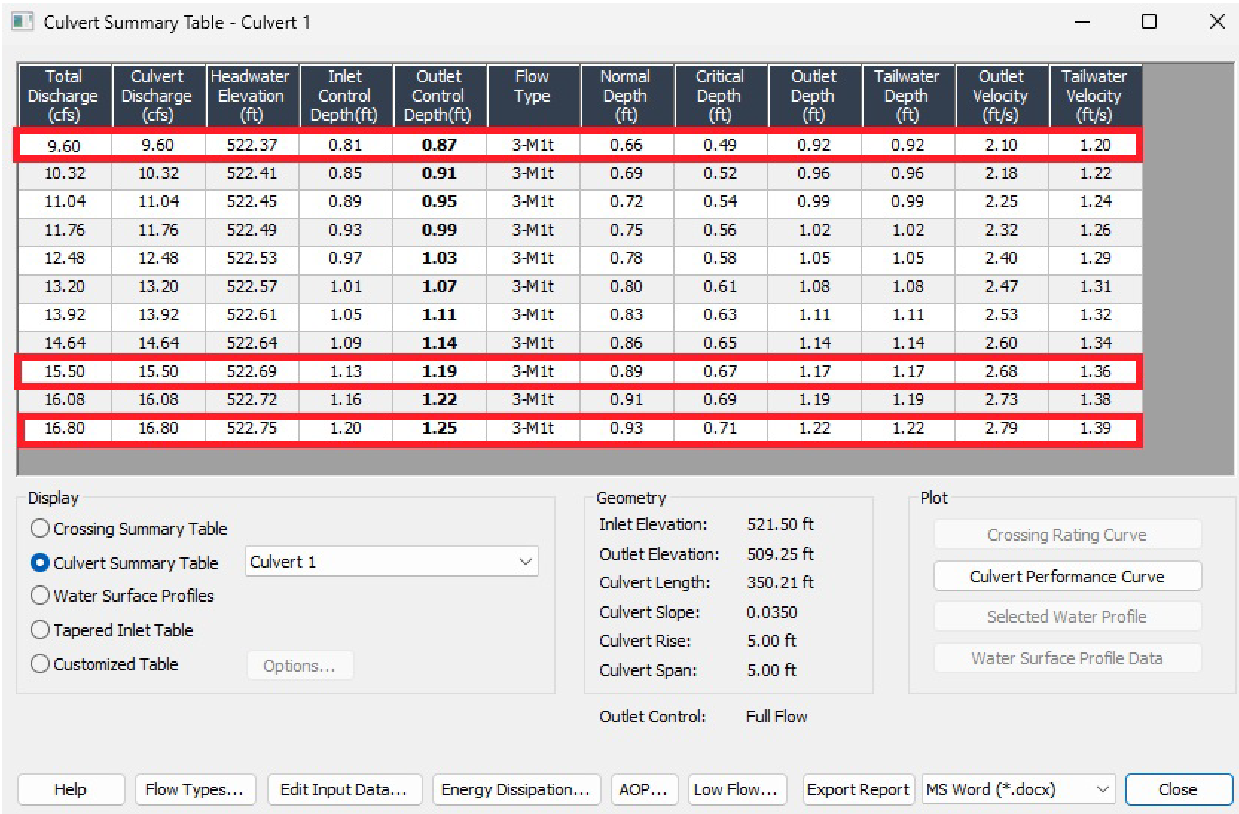
6.07.2.2, however, because this is an embedded structure, the Channel Invert Elevation must be adjusted to account for the depth of embedment. This is shown in Figure 12A-7.

TAILWATER DATA		
Channel Type	Trapezoidal Channel	
Bottom Width	5.000	ft
Side Slope (H:V)	4.000	_:1
Channel Slope	0.0050	ft/ft
Manning's n (channel)	0.065	
Channel Invert Elevation	509.250	ft
Rating Curve	View...	

Figure 12A-7

HY-8 Tailwater Data Input Screen

Step 7: Analyze Crossing to determine minimum, design, and maximum (check) flow parameters including culvert discharge, headwater elevation, tailwater elevation, inlet depth, outlet depth, outlet velocity, and tailwater velocity. Designer should select “Analyze Crossing” and then navigate to the “Culvert Summary Table.” These results are shown in Figure 12A-8.



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)
9.60	9.60	522.37	0.81	**0.87**	3-M1t	0.66	0.49	0.92	0.92	2.10	1.20
10.32	10.32	522.41	0.85	**0.91**	3-M1t	0.69	0.52	0.96	0.96	2.18	1.22
11.04	11.04	522.45	0.89	**0.95**	3-M1t	0.72	0.54	0.99	0.99	2.25	1.24
11.76	11.76	522.49	0.93	**0.99**	3-M1t	0.75	0.56	1.02	1.02	2.32	1.26
12.48	12.48	522.53	0.97	**1.03**	3-M1t	0.78	0.58	1.05	1.05	2.40	1.29
13.20	13.20	522.57	1.01	**1.07**	3-M1t	0.80	0.61	1.08	1.08	2.47	1.31
13.92	13.92	522.61	1.05	**1.11**	3-M1t	0.83	0.63	1.11	1.11	2.53	1.32
14.64	14.64	522.64	1.09	**1.14**	3-M1t	0.86	0.65	1.14	1.14	2.60	1.34
15.50	15.50	522.69	1.13	**1.19**	3-M1t	0.89	0.67	1.17	1.17	2.68	1.36
16.08	16.08	522.72	1.16	**1.22**	3-M1t	0.91	0.69	1.19	1.19	2.73	1.38
16.80	16.80	522.75	1.20	**1.25**	3-M1t	0.93	0.71	1.22	1.22	2.79	1.39

Figure 12A-8

HY-8 Culvert Summary Table Screen

Step 8: The designer should check that the culvert design meets requirements from TDOT Drainage Manual Chapter 6 and then check parameters as they relate to AOP design. Designer should confirm the 2-yr Flow (Q_2) is consistent with BFW parameters reported in the EBR. This includes Q_2 outlet depth and Q_2 velocity. These parameters need to be equivalent to existing state analysis to match stream continuity and allow for aquatic organism passage in normal flow events. Designers can adjust structure type, structure size, embedment depth, and embedment Manning's Roughness Coefficient (n) to adjust the proposed designed crossing versus the existing analysis.

Step 9: Once designer has a proposed design solution that meets both culvert design parameters established in TDOT Drainage Manual Chapter 6 and has checked for successful AOP design equivalency against existing stream conditions, the designer can populate the Hydraulic Data

Table spreadsheet (shown below in Documentation Procedures) and reference or embed into the ORD Culvert Cross Sections sheets. This is shown in Figure 12A-9.

HYDRAULIC DESIGN DATA TABLE		
PIPE CULVERT		
STATION: 150+00.00		
STRUCTURE: 350' OF 60" PIPE CULVERT		
SKEW	0	DEG.
DRAINAGE AREA	12.05	AC.
DESIGN DISCHARGE (Q50)	15.50	CFS
DESIGN DISCHARGE (Q100)	16.80	CFS
OVERTOPPING ELEV.	541.50	
ALLOWABLE HEADWATER ELEV.	541.5	
Q50 HEADWATER ELEV.	535.27	
Q100 HEADWATER ELEV.	535.33	
VELOCITY (Q50)	2.68	FT/S
VELOCITY (Q100)	2.79	FT/S
ENDWALLS REQUIRED:		
2 - TYPE "PEW" ENDWALLS		
AOP ANALYSIS:		
BANKFULL WIDTH (REFER TO EBR)	5	FT.
BANKFULL DEPTH (REFER TO EBR)	1	FT.
DESIGN DISCHARGE (Q2)	9.6	CFS
PROP. INLET INVERT	532.09	
PROP. INLET STREAM BED ELEV.	534.09	
PROP. OUTLET INVERT	507.25	
PROP. OUTLET STREAM BED ELEV.	509.25	
Q2 HEADWATER ELEV.	534.94	
VELOCITY (Q2)	2.10	FT/S
STREAM BED MATERIAL (REFER TO EBR)	Boulder Cobble	
D50 BED MATERIAL SIZE (REFER TO EBR)	12.00	IN.
STANDARD DRAWING NOS.:		
D-PB-1, D-PEW-1, D-AOP-1, D-AOP-2		
QUANTITIES:		
CLASS "A" CONCRETE	24.0	C.Y.
STEEL BAR REINFORCING	1210.0	LB.
BEDDING MATERIAL	135.1	C.Y.
ENDWALL ITEM NOS.:	611-07.01, 611-07.02	

Figure 12A-9

HY-8 Hydraulic Design Data Table

12.07.01.02 EXAMPLE PROBLEM #2: RECESSED BOX CULVERT

***GIVEN*:**

A box culvert is proposed for a new roadway crossing as shown in Figure 12A-10. The box culvert is intended to convey a perennial stream and therefore must be designed to AOP standards. The following information is known:

- 2-year flow rate (Q_2) = 38.18 ft^3/s
- 50-year flow rate (Q_{50}) = 60.18 ft^3/s
- 100-year flow rate (Q_{100}) = 64.76 ft^3/s
- Invert elevation at inlet = 489.09 feet

- Invert elevation at outlet = 481.27 feet
- Natural streambed slope = 2.8% (0.028 ft/ft)
- Stream bankfull width = 7 feet
- Stream D50 = 12 in.
- Normal Bankfull Depth = 1.5 foot

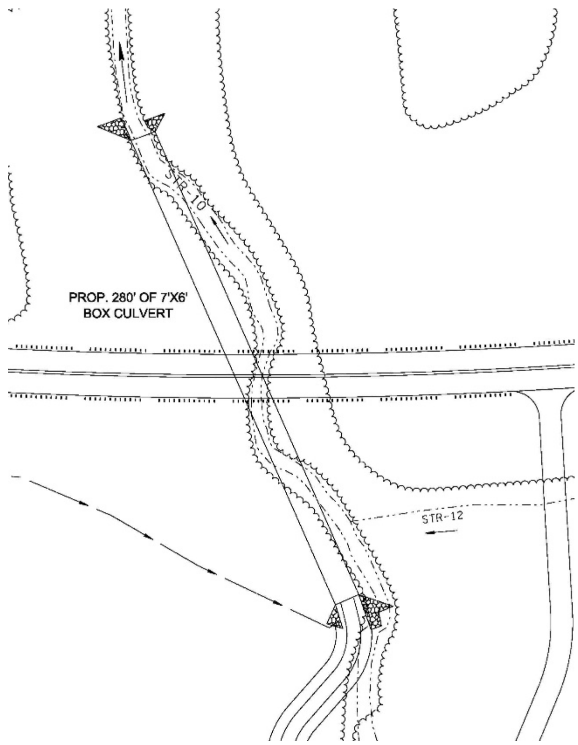


Figure 12A-10

Box Culvert Crossing with Perennial Stream

FIND:

Following the process shown in TDOT Drainage Manual Chapter 6 Appendix 6.07.2.2, select and analyze an appropriate box culvert for this site.

SOLUTION:

Step 1: Populate HY-8 inputs following example shown in TDOT Drainage Manual Chapter 6 Appendix 6.07.2.2. Designer should use the following flow parameters when establishing Discharge Data withing HY-8 software:

Minimum Flow: Designer should use 2-year flow (Q_2) to analyze bankfull flow.

Design Flow: Designer should use appropriate design storm frequency based on TDOT Drainage Manual Chapter 7 Section 7.03.

Maximum Flow: Designer should use 100-year flow (Q_{100}) to analyze design for adjacent property impacts and to establish appropriate right-of-way design.

Figure 12A-11 shows the HY-8 Discharge Data Input Screen.

DISCHARGE DATA		
Discharge Method	Minimum, Design, and Maximum	
Minimum Flow	38.180	cfs
Design Flow	60.180	cfs
Maximum Flow	64.760	cfs

Figure 12A-11

HY-8 Discharge Data Input Screen

Step 2: Enter the culvert site data for the given problem parameters. Two possibilities exist for entering this data. The user can select either the “culvert-inlet” option which prompts the user for the inlet and outlet station and elevations for the culvert along the channel, or they can enter embankment and toe data by selecting the “embankment-toe” option. HY-8 uses the embankment and toe data to create the invert data for the culvert if the “embankment-toe” option is selected. For this application, the inlet and outlet station and elevations are known; therefore, the designer will select the “culvert-invert” option. The HY-8 culvert site data (culvert-invert) screen is shown in Figure 12A-12.

SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.000	ft
Inlet Elevation	489.090	ft
Outlet Station	280.000	ft
Outlet Elevation	481.270	ft
Number of Barrels	1	
Computed Culvert Slope	0.027929	ft/ft

Figure 12A-12

HY-8 Site Data Input Screen

Step 3: Enter culvert characteristics for this site such as the shape, size, material, and inlet conditions of the proposed culvert. HY-8 provides a Manning's n-value based on the culvert material chosen by the designer. This provided Manning's n-value will be used for the top and sides of the drainage structure. A Manning's n-value for the bottom of the drainage structure will be found in Step 5. Inlet information can be for either a conventional inlet configuration or an improved inlet (side or slope tapered options are available). Designer should reference the stream bankfull width found in the EBR to determine an initial span width.

CULVERT DATA		
Name	Culvert 1	
Shape	Concrete Box	
Material	Concrete	
Span	8.000	ft
Rise	6.000	ft
Embedment Depth	24.000	in
Manning's n (Top/Sides)	0.012	
Manning's n (Bottom)	0.035	
Culvert Type	Straight	
Inlet Configuration	Square Edge (90º) Headwall (Ke=0.5)	
Inlet Depression?	No	

Figure 12A-13

HY-8 Culvert Data Input Screen

Step 4: Populate embedment depth per design considerations from EBR D50 bed substrate sizing guidance. The minimum embedment depth should be 2 times the D50 found in the EBR for that stream.

CULVERT DATA		
Name	RCBC 1	
Shape	Concrete Box	
Material	Concrete	
Span	7.000	ft
Rise	6.000	ft
Embedment Depth	24.000	in
Manning's n (Top/Sides)	0.012	
Manning's n (Bottom)	0.065	
Culvert Type	Straight	
Inlet Configuration	Square Edge (30-75º flare) Wingwall (Ke...	
Inlet Depression?	No	

Figure 12A-14

HY-8 Culvert Data Input Screen – Embedment Depth

Step 5: Adjust the Manning's Roughness Coefficient (n) value for bottom of the proposed drainage structure. This manning's n should be consistent with the natural stream substrate as stated in the EBR.

CULVERT DATA		
Name	RCBC 1	
Shape	Concrete Box	
Material	Concrete	
Span	7.000	ft
Rise	6.000	ft
Embedment Depth	24.000	in
Manning's n (Top/Sides)	0.012	
Manning's n (Bottom)	0.065	
Culvert Type	Straight	
Inlet Configuration	Square Edge (30-75º flare) Wingwall (Ke...	
Inlet Depression?	No	

Figure 12A-15

HY-8 Culvert Data Input Screen – Manning's n

Step 6: The designer will input the downstream channel information such as shape, Manning's 'n' value of the channel (see Chapter 5 for procedures to determine channel 'n'-values), and the channel slope. Figure 12A-16 shows the HY-8 regular channel data input screen for the culvert design project. Designer should follow the same process described in Step 6 of TDOT Drainage Manual Chapter 6 Appendix 6.07.2.2, however, because this is an embedded structure, the

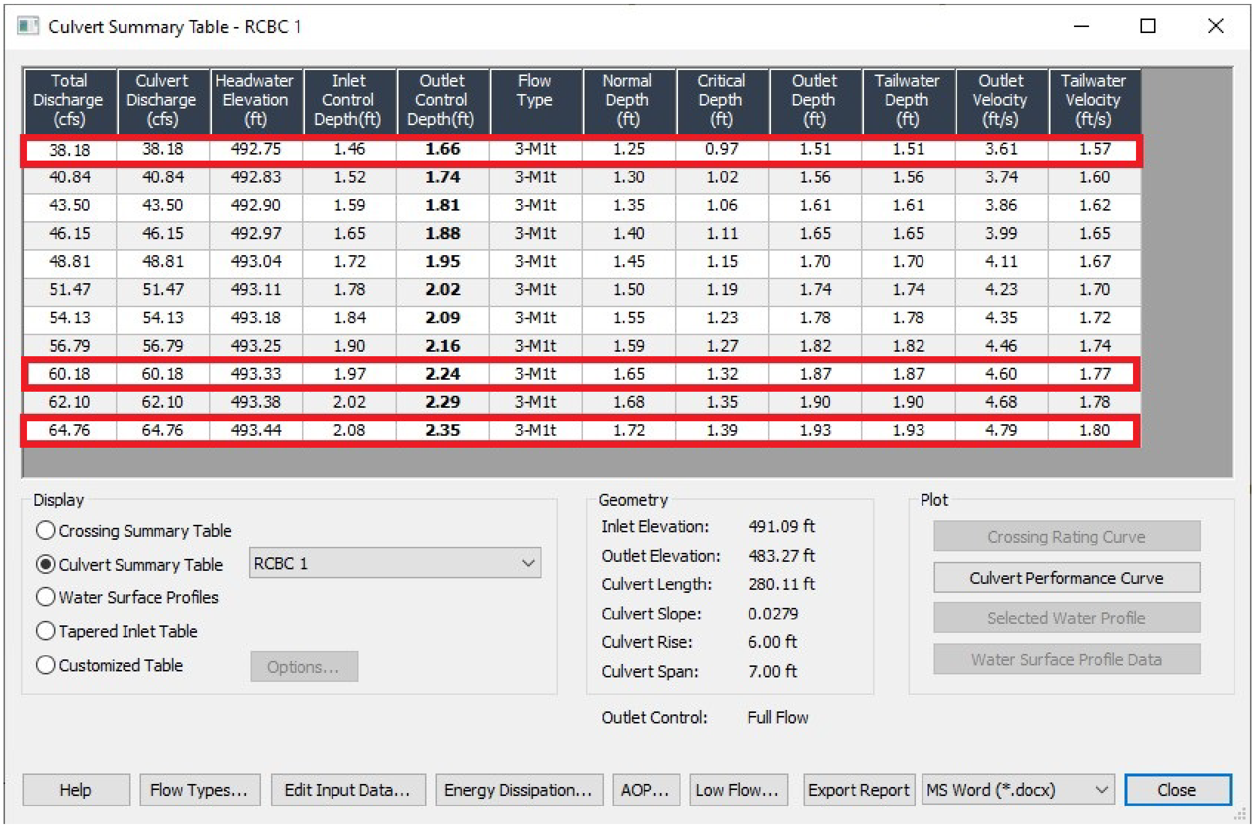
Channel Invert Elevation must be adjusted to account for the depth of embedment. This is shown in Figure 12A-16.

TAILWATER DATA		
Channel Type	Trapezoidal Channel	
Bottom Width	7.000	ft
Side Slope (H:V)	6.000	_:1
Channel Slope	0.0050	ft/ft
Manning's n (channel)	0.065	
Channel Invert Elevation	483.270	ft
Rating Curve	View...	

Figure 12A-16

HY-8 Tailwater Data Input Screen

Step 7: Analyze Crossing to determine minimum, design, and maximum (check) flow parameters including culvert discharge, headwater elevation, tailwater elevation, inlet depth, outlet depth, outlet velocity, and tailwater velocity. Designer should select "Analyze Crossing" and then navigate to the "Culvert Summary Table." These results are shown in Figure 12A-17.



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)
38.18	38.18	492.75	1.46	**1.66**	3-M1t	1.25	0.97	1.51	1.51	3.61	1.57
40.84	40.84	492.83	1.52	**1.74**	3-M1t	1.30	1.02	1.56	1.56	3.74	1.60
43.50	43.50	492.90	1.59	**1.81**	3-M1t	1.35	1.06	1.61	1.61	3.86	1.62
46.15	46.15	492.97	1.65	**1.88**	3-M1t	1.40	1.11	1.65	1.65	3.99	1.65
48.81	48.81	493.04	1.72	**1.95**	3-M1t	1.45	1.15	1.70	1.70	4.11	1.67
51.47	51.47	493.11	1.78	**2.02**	3-M1t	1.50	1.19	1.74	1.74	4.23	1.70
54.13	54.13	493.18	1.84	**2.09**	3-M1t	1.55	1.23	1.78	1.78	4.35	1.72
56.79	56.79	493.25	1.90	**2.16**	3-M1t	1.59	1.27	1.82	1.82	4.46	1.74
60.18	60.18	493.33	1.97	**2.24**	3-M1t	1.65	1.32	1.87	1.87	4.60	1.77
62.10	62.10	493.38	2.02	**2.29**	3-M1t	1.68	1.35	1.90	1.90	4.68	1.78
64.76	64.76	493.44	2.08	**2.35**	3-M1t	1.72	1.39	1.93	1.93	4.79	1.80

Figure 12A-17

HY-8 Culvert Summary Table Screen

Step 8: The designer should check that the culvert design meets requirements from TDOT Drainage Manual Chapter 6 and then check parameters as they relate to AOP design. Designer should confirm the 2-yr Flow (Q_2) is consistent with BFW parameters reported in the EBR. This includes Q_2 outlet depth and Q_2 velocity. These parameters need to be equivalent to existing state analysis to match stream continuity and allow for aquatic organism passage in normal flow events. Designers can adjust structure type, structure size, embedment depth, and embedment Manning's Roughness Coefficient (n) to adjust the proposed designed crossing versus the existing analysis.

Step 9: Once designer has a proposed design solution that meets both culvert design parameters established in TDOT Drainage Manual Chapter 6 and has checked for successful AOP design equivalency against existing stream conditions, the designer can populate the Hydraulic Data

Table spreadsheet (shown below in Documentation Procedures) and reference or embed into the ORD Culvert Cross Sections sheets. This is shown in Figure 12A-18 below.

HYDRAULIC DESIGN DATA TABLE		
BOX CULVERT		
STATION: 180+00.00		
STRUCTURE: 280' OF 7'x6' BOX CULVERT		
SKEW	66	DEG.
DRAINAGE AREA	45.67	AC.
DESIGN DISCHARGE (Q50)	60.18	CFS
DESIGN DISCHARGE (Q100)	64.76	CFS
OVERTOPPING ELEV.	537.02	
ALLOWABLE HEADWATER ELEV.	532.86	
Q50 HEADWATER ELEV.	493.33	
Q100 HEADWATER ELEV.	493.44	
VELOCITY (Q50)	4.60	FT/S
VELOCITY (Q100)	4.79	FT/S
AOP ANALYSIS:		
BANKFULL WIDTH (REFER TO EBR)	7	FT.
BANKFULL DEPTH (REFER TO EBR)	1.5	FT.
DESIGN DISCHARGE (Q2)	38.18	CFS
PROP. INLET INVERT	489.09	
PROP. INLET STREAM BED ELEV.	491.09	
PROP. OUTLET INVERT	481.27	
PROP. OUTLET STREAM BED ELEV.	483.27	
Q2 HEADWATER ELEV.	492.75	
VELOCITY (Q2)	3.61	FT/S
STREAM BED MATERIAL (REFER TO EBR)	Boulder Cobble	
D50 BED MATERIAL SIZE (REFER TO EBR)	12.00	IN.
STANDARD DRAWING NOS.:		
STD-17-52, D-AOP-1, D-AOP-4		
QUANTITIES:		
CLASS "A" CONCRETE	591.2	C.Y.
STEEL BAR REINFORCING	66121	LB.
BEDDING MATERIAL	300.0	C.Y.

Figure 12A-18

HY-8 Hydraulic Design Data Table