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CHAPTER THIRTY-ONE

CULVERTS

31-1.0 INTRODUCTION

31-1.01 Definition of a Culvert

A culvert is defined as the following:

1. a structure (pipe, cast-in-place reinforced concrete, precast reinforced concrete, structural plate arch, etc.) which is designed hydraulically to take advantage of submergence to increase hydraulic capacity;

2. a structure used to convey surface runoff through an embankment;

3. a structure, as distinguished from a bridge, which is covered with embankment and is composed of structural material around the entire perimeter, although it can be supported on spread footings with the streambed serving as the bottom of the culvert; or

4. a structure with less than a 6.1-m span length along the centerline of roadway between extreme ends of openings for multiple barrels. Figure 31-1A, Maximum Span Length for Culvert, provides schematics which define a culvert based on span length for various structural configurations. However, a structure designed hydraulically as a culvert is treated as discussed in this Chapter, regardless of span length.

In addition, the following apply to defining a culvert.

1. Mainline Culvert. A structure under a mainline roadway.

2. Public-Road-Approach Culvert. A structure under a public-road approach.

3. Drive Culvert. A structure under a drive or field entrance.

4. Concrete-Culvert Extension. New construction that extends an existing reinforced concrete slab-top, box-, or arch-culvert structure. Acceptable methods for constructing the extension include cast-in-place reinforced concrete or installation of precast reinforced-concrete box sections.

31-1.02 Purpose

This Chapter provides design procedures for the hydraulic design of a highway culvert which are based on FHWA Hydraulic Design Series Number 5 (HDS #5) *Hydraulic Design of Highway Culverts*. This Chapter also provides the following:

1. the results of culvert analysis using microcomputers which emphasizes the use of the HYDRAIN system and the HY8 culvert analysis software; and

2. a summary of the design philosophy included in the AASHTO *Highway Drainage Guidelines*, Chapter IV.

31-1.03 Definitions

The following are definitions of concepts to be considered in culvert design.

1. Backwater. The increase in water-surface elevation caused by the introduction of a culvert into an open channel or other open drainage system.

2. Critical Depth, d_C. The depth at which the specific energy of a given flow rate is at a minimum. For a given discharge and cross-section geometry there is only one critical depth.

3. Crown. The inside top of a culvert.

4. Flow Type. The USGS has established culvert-flow types which assist in determining the flow conditions at a particular culvert site. Diagrams of these flow types are provided in Section 31-5.0.

5. Free Outlet. A free outlet has a tailwater equal to or lower than critical depth. For a culvert having a free outlet, lowering of the tailwater has no effect on the discharge or the backwater profile upstream of the tailwater.

6. Improved End Treatment (Improved Inlet). An improved end treatment has an entrance geometry which decreases the flow contraction at the end treatment and thus increases the capacity of a culvert. The end treatment is referred to as side- or slope-tapered (walls or bottom tapered).

7. Invert. The flowline of the culvert (inside bottom).

8. Normal Flow. Normal flow occurs in a channel reach if the discharge, velocity, and depth of flow do not change throughout the reach. The water surface and channel bottom will be parallel.

9. Slope. The following applies.

   a. A steep slope occurs where critical depth is greater than normal depth.
   b. A mild slope occurs where critical depth is less than normal depth.

10. Submergence. The following applies.

   a. A submerged outlet occurs where the tailwater elevation is higher than the crown of the culvert.

   b. A submerged inlet occurs where the headwater is greater than 1.2*D*, where *D* is the culvert diameter or barrel height.

31-1.04 Symbols

To provide consistency within this Chapter and throughout this *Manual*, the symbols in Figure 31-1B, Culvert Symbols, will be used. These symbols have wide use in culvert publications.

31-2.0 POLICY

31-2.01 Definition

Policy is a set of goals that establish a definite course of action or method of action and that are selected to guide and determine present and future decisions. Policy is implemented through design criteria for making decisions (see Section 31-3.0).

31-2.02 Culvert Policy

The following policies are specific to a culvert.

1. Each culvert should be hydraulically designed. However, the minimum pipe size specified in Section 31-3.05(03) will sometimes control.

2. The design storm frequency/frequencies selected should be consistent with the criteria described in Section 31-3.03.

3. Survey information should include topographic features, channel characteristics, high-water information, existing-structure data, and other related site-specific information.

4. Culvert location in both plan and profile should approximate the alignment of the natural channel to avoid sediment build-up in the barrel.

5. A culvert should be designed to accommodate debris, or proper provisions should be made for debris maintenance.

6. A culvert should be located and designed to present a minimum hazard to traffic and pedestrians.

7. The detail of documentation for each culvert site should be commensurate with the risk and importance of the structure. Design data and calculations should be assembled in an orderly fashion and retained for future reference as provided for in Chapter Twenty-eight.

8. Where necessary as directed by INDOT, some means should be provided for personnel and equipment access to facilitate maintenance.

31-3.0 DESIGN CRITERIA

31-3.01 Definition

Design criteria are the standards by which a policy is implemented. They form the basis for the selection of the final design configuration. Listed below by categories are the design criteria which should be considered.

31-3.02 Site Criteria

The following apply.

1. Structure-Type Selection. A culvert is used at the locations as follows:

   a. where a bridge is not hydraulically required;
   b. where debris and ice are tolerable; and
   c. where its use will be more economical than a bridge.

   A bridge is used as follows:

a. where more economical than a culvert;
b. to avoid floodway encroachment;
c. to accommodate ice or large debris; and
d. where a culvert will generate excessive velocity, backwater, or other hydraulic deficiency.

2. Length and Slope. The culvert length and slope should be chosen to approximate existing topography and, as practical, the culvert invert should be aligned with the channel bottom and the skew angle of the stream. The roadway clear-zone requirements and the embankment geometry may dictate the culvert length. See Chapter Forty-nine.

3. Location in Plan. A severe or abrupt change in channel alignment upstream or downstream is not recommended. The following applies.

a. A small culvert with no defined channel is placed normal to the roadway centerline.

b. A large culvert perpetuating drainage in a defined channel should be skewed as necessary to minimize channel relocation and erosion.

c. All utilities should be located before determining the final location of a culvert to minimize conflicts.

4. Location in Profile. The culvert profile will likely approximate the natural stream profile. Exceptions which must be approved by the Hydraulics Team can be considered as follows:

a. arrest stream degradation by utilizing a drop-end treatment or broken-back culvert;
b. improve hydraulic performance by utilizing a slope-tapered end treatment; or
c. avoid conflicts with other utilities that are difficult to relocate such as sanitary sewers.

5. Debris Control. Debris control should be designed using Hydraulic Engineering Circular No. 9 *Debris-Control Structures*, and may be considered as follows:

a. where experience or physical evidence indicates the watercourse will transport a heavy volume of controllable debris;

b. for a culvert under a high fill; or

c. where clean-out access is limited. However, access must be available to clean out the debris-control device.

31-3.03 Design-Storm Frequency

See Figure 31-3A, Design Storm Frequency (Culvert).

31-3.04 Hydraulic Design Criteria

31-3.04(01) Allowable Headwater (*AHW*)

Allowable headwater is the depth of water that can be ponded at the upstream end of a culvert during the design flood. *AHW* will be limited by one or more of the following.

1. New Alignment. The maximum backwater (increase in headwater elevation over the sum of *TW* depth plus inlet invert elevation) should not exceed 40 mm. The 40-mm maximum may be modified as follows:

   a. the backwater dissipates to 40 mm or less at the right-of-way-line; or

   b. the channel is sufficiently deep to contain the increased elevation without overtopping the banks.

   The Hydraulics Engineer must approve exceptions to the 40-mm backwater allowance.

2. Existing Conditions. The IDNR limits surcharge to 30 mm, in an urban or rural location. Existing conditions are defined as the water surface profile that results from only those encroachments that were constructed prior to December 31, 1973. Although IDNR policy will allow for a slight increase over existing conditions, INDOT will not. INDOT policy for a culvert replacement or rehabilitation is that the surcharge created by a proposed structure must be equal to or less than the existing surcharge, unless the existing surcharge is less than 30 mm. This will allow future widening of the structure. If the surcharge created by an existing structure is greater than 300 mm, the proposed surcharge for the culvert replacement or extension must not be greater than 300 mm above the natural-channel flood profile.

3. Right of Way. The ponding limit from the *AHW* cannot exceed the right-of-way limit for a structure on a new alignment.

4. Upstream Channel. The ponding limit from the *AHW* cannot exceed the banks of an upstream channel for a structure on a new alignment.

5. Other. Other constraints on *AHW* include the following:

   a. grades of adjacent drives;
   b. finished floor elevation of adjacent buildings or other improvements; and
   c. elevation of existing cropland or other property.

31-3.04(02) Roadway Serviceability

For the appropriate design storm, headwater caused by the proposed structure cannot exceed the following for the roadway.

1. If Q_{100} is the appropriate design storm, the resulting headwater elevation must be at least 0.6 m below the edge-of-pavement elevation.

2. If the appropriate design storm frequency is less than Q_{100}, the resulting headwater elevation must not exceed the edge-of-pavement elevation.

31-3.04(03) Maximum Velocity

Each culvert requires outlet protection to prevent erosion. The protection used must be in accordance with the following.

1. Revetment riprap is required for a structure with an outlet velocity, V_o, of 2.0 m/s or lower.

2. Class 1 riprap is required for a structure with 2.0 m/s $\leq V_o <$ 3.0 m/s.

3. Class 2 riprap is required for a structure with 3.0 m/s $\leq V_o <$ 4.0 m/s.

4. An energy dissipator is required if $V_o \geq$ 4.0 m/s. See Chapter Thirty-four for the design of an energy dissipator.

If clear zone or other issues prohibit the use of the required riprap gradation, the designer must contact the Hydraulics Team for additional instructions.

31-3.04(04) Minimum Velocity

The minimum velocity in the culvert barrel should result in a tractive force, $\tau = \gamma dS$, greater than critical τ of the transported streambed material at a low-flow rate. The designer should use 0.9 m/s if the streambed material size is not known.

31-3.04(05) Tailwater Relationship

For a channel, the designer should consider the following.

1. Evaluate the hydraulic conditions of the downstream channel to determine a tailwater depth (see Chapter Thirty).

2. Calculate backwater curves for sensitive locations or use a single cross-section analysis.

3. Use the critical depth and equivalent hydraulic grade line if the culvert outlet is operating with a free outfall.

4. Use the headwater elevation of a nearby downstream culvert if it is above the channel depth.

For a confluence or large body of water, the designer should use the high-water elevation that has the same frequency as the design flood if events are known to occur concurrently (statistically dependent) to determine the tailwater.

31-3.04(06) Storage (Temporary or Permanent)

Storage should not be considered in the hydraulic design of a culvert.

31-3.05 Culvert-Sizing Process

31-3.05(01) Priority System

The culvert-sizing process is performed in accordance with a priority system. The system consists of six trials where specific installations are considered prior to evaluating other structure types. The design priority system is as follows.

1. Trial 1. Single Circular-Pipe Installation.
2. Trial 2. Single Deformed-Pipe Installation.

3. Trial 3. Single Specialty-Structure Installation.
4. Trial 4. Multiple Circular-Pipes Installation.
5. Trial 5. Multiple Deformed-Pipes Installation.
6. Trial 6. Multiple Specialty-Structures Installation.

The principles of the priority system are summarized below.

1. A pipe structure is preferred to a specialty structure (e.g., precast reinforced-concrete box section, precast reinforced-concrete three-sided culvert, structural plate arch).

2. A circular pipe is preferred to a deformed pipe.

3. A single-cell installation is preferred to a multiple-cell installation.

Section 31-3.0 provides a decision flowchart for each of the six trials in the priority system, as the following figures.

31-3C Culvert Design Process (Trial 1 - Single Circular Pipe)
31-3D Culvert Design Process (Trial 2 - Single Deformed Pipe)
31-3E Culvert Design Process (Trial 3 - Single Specialty Structure)
31-3F Culvert Design Process (Trial 4 - Multiple Circular Pipes)
31-3G Culvert Design Process (Trial 5 - Multiple Deformed Pipes)
31-3H Culvert Design Process (Trial 6 - Multiple Specialty Structures)

31-3.05(02) Pipe-Culvert-Interior Designation

During the performance of Trials 1, 2, 4, or 5, specific pipe materials will not be considered. Instead, two generic designs are required. One design will size pipes with smooth interiors and the second will size pipes with corrugated interiors. The smooth-interior hydraulic design will be based on a Manning's *n* value of 0.012 and can use the nomographs or computer software used for sizing a reinforced concrete pipe. The corrugated hydraulic design is based on a Manning's *n* value of 0.024 and can utilize the nomographs or computer software used to size a corrugated-metal pipe. If the corrugated-pipe design indicates that structural-plate pipe is required, the Manning's *n* value must be in accordance with accepted engineering practice. See Figure 31-10A for typical values. The nomographs or computer software used to size a structural-plate pipe may be used to determine the required size for a larger structure.

The two hydraulic designs for an individual structure will be based on identical pipe lengths and invert elevations.

If separate hydraulic designs are performed for smooth and corrugated interior pipes, the following situations are possible.

1. Situation 1. The required smooth-interior and corrugated-interior pipe sizes are identical. The structure callout on the plans should include the required pipe size. No reference to an interior designation is made.

2. Situation 2. The required smooth-interior and corrugated-interior pipe sizes are different. The structure callout on the plans should indicate that the structure requires a smooth pipe of one size or a corrugated pipe of another.

3. Situation 3. An acceptable pipe size can be determined for one interior designation but not the other. If this occurs, the structure callout on the plans should indicate the required pipe size and interior designation.

4. Situation 4. No acceptable pipe size can be found for either interior designation. The designer must proceed to the next trial of the culvert-sizing process.

31-3.05(03) Minimum Culvert Size

If it is determined that a pipe is acceptable for a culvert structure, the proposed pipe size must be greater than or equal to that shown in Figure 31-3B, Minimum Pipe-Culvert Size.

31-3.05(04) Cover

In addition to the minimum-pipe-size requirement, cover is another factor that the designer must consider during the structure-sizing process. For a circular pipe structure, a minimum of 0.30 m of cover (measured from the top of the pipe to the bottom of the asphalt or concrete pavement) must be provided. If the structure requires a deformed corrugated-interior pipe material, at least 0.45 m of cover must be provided. The cover for a circular pipe structure should not exceed 30 m. The cover for a deformed corrugated-interior pipe structure should not exceed 4 m. If the pavement grade or structure invert elevations cannot be adjusted to satisfy the cover criteria discussed above, contact the Hydraulics Team for additional instructions.

31-3.05(05) Pipe-Extension Structure-Sizing Process

The sizing of a pipe-extension structure should be in accordance with the following.

1. Match Existing Pipe Size and Interior Designation. If practical, the pipe extension should be the same size and material as the existing pipe. However, at this stage, it is only necessary to identify the required interior designation for the extension.

2. Perform Appropriate Hydraulic Analysis. The appropriate hydraulic calculations must be performed to verify whether the extended structure satisfies the required design criteria. Because the structure's interior designation is known, it is only necessary to perform hydraulic calculations appropriate for that interior designation.

If the extended structure satisfies the required design criteria, the structure sizing process is complete. If the extended structure does not satisfy the required design criteria, the designer must reevaluate whether the existing structure can be replaced with a new structure. If it is not practical to replace the existing pipe because of construction method, traffic maintenance, or other constraint, contact the Hydraulics Team for further instructions.

31-3.05(06) Concrete-Culvert-Extension Sizing Process

If an existing cast-in-place reinforced-concrete slab-top culvert, box culvert, or arch culvert requires extension, the designer must decide whether the extension will be constructed using cast-in-place reinforced concrete or precast reinforced-concrete box sections. Once the extension method has been determined, the appropriate culvert-design criteria must be checked to verify that the extended structure satisfies the hydraulic requirements. If the analysis indicates that the extended structure does not satisfy the hydraulic requirements, the designer must reevaluate whether the existing structure can be removed and replaced with a new structure. If it is not possible to replace the existing culvert because of construction method, traffic maintenance, or other constraint, contact the Hydraulics Team for further instructions.

31-3.06 Other Culvert Features

31-3.06(01) Culvert Skew

The culvert skew should not exceed 45 deg as measured from a line perpendicular to the roadway centerline, without the approval of the Hydraulics Engineer.

31-3.06(02) Inlet or Outlet End Treatment

The culvert end-treatment type should be selected from the list shown below based on the given considerations and the end treatment coefficient, K_e. See Section 31-10.0 for the recommended value of K_e. Roadside safety should be considered in the selection and design. See Section 49-3.0 for a detailed discussion of INDOT practices for the safety treatment of a drainage structure.

The following discusses the types of culvert end treatments and their advantages and disadvantages.

1. Projecting Inlet or Outlet.

   a. Extends beyond the roadway embankment.

   b. Is susceptible to damage during roadway maintenance or an errant vehicle.

   c. Has a low construction cost.

   d. Has poor hydraulic efficiency for thin material.

   e. Should include anchoring the end treatment to strengthen the weak leading edge for a culvert of 1050 mm diameter or larger. The anchorage should include a sufficient weight of concrete to resist buoyant forces (see the INDOT *Standard Drawings*).

   f. May be strengthened by use of a concrete collar, if necessary.

   Where a projecting inlet or outlet is within the roadside clear zone, the designer should consider the use of a grated box end section (GBES) or a safety metal end section (SMES). See Chapter Forty-nine for INDOT criteria on roadside clear zone. See the *INDOT Standard Drawings* for the GBES and SMES.

2. Mitered End Treatment.

   a. Is hydraulically more efficient than a thin edge projecting.

   b. Should be mitered to match the fill slope.

   c. Should include anchoring the end treatment to strengthen the weak leading edge for a culvert of 900 mm diameter or larger.

3. Improved End Treatment.

   a. Should be considered for a culvert which will operate in inlet control.

   b. Can increase the hydraulic performance of the culvert, but may also add to the total culvert cost. Therefore, it should only be used if economically justified.

4. Pipe End Section.

a. Is available for either corrugated-metal or concrete pipe.

b. Retards embankment erosion and incurs less damage from maintenance.

c. May improve a projecting metal-pipe entrance by increasing hydraulic efficiency, reducing accident hazard, and improving the pipe entrance's appearance.

d. Is hydraulically equivalent to a headwall, but can be equivalent to a beveled or side-tapered entrance if a flared, enclosed transition occurs before the barrel.

5. Wingwall.

a. Is used to retain the roadway embankment to avoid a projecting culvert barrel.

b. Is used where the side slopes of the channel are unstable.

c. Is used where the culvert is skewed to the normal channel flow.

d. Provides the best hydraulic efficiency if the flare angle is between 30º and 60º.

e. Should be provided for a precast-concrete drainage structure.

6. Apron.

a. Is used to reduce scour from a high headwater depth or from approach velocity in the channel.

b. Should extend at least one pipe diameter upstream.

c. Should not protrude above the normal streambed elevation.

d. May be constructed of riprap and an appropriate geotextile or concrete.

7. Cutoff Wall.

a. Is used to prevent piping along the culvert barrel and undermining at the culvert end.

b. Should be used for a culvert with headwalls.

c. Should be of minimum 500 mm depth or as shown in the INDOT *Standard Drawings* or *Standard Specifications.*

8. Weep Hole. A weep hole should not be used.

31-3.06(03) Pipe-Length Determination

After the structure size and cover have been determined, the designer must determine the required length. The design length for a culvert structure should be rounded to the next higher 0.5 m.

31-3.06(04) Buoyancy Protection

Pipe end sections or concrete anchors where a projecting end treatment or outlet is used, or other means of anchoring to provide buoyancy protection, should be considered for a flexible culvert. The seriousness of buoyancy depends on the steepness of the culvert slope, depth of the potential headwater (debris blockage may increase), flatness of the upstream fill slope, height of the fill, large culvert skew, or mitered ends. See the INDOT *Standard Drawings* and *Standard Specifications.*

31-3.06(05) Relief Opening

Where a culvert serving as a relief opening has its outlet set above the normal stream flow line, precautions should be made to prevent headcutting or erosion from undermining the culvert outlet.

31-3.06(06) Erosion and Sediment Control

Temporary measures should be shown on the construction plans. The measures may include the use of a silt box, brush silt barrier, filter cloth, temporary silt fence, or check dam. For more information, see Chapter Thirty-seven. The scour elevation to be shown on the Layout sheet is the scour elevation for Q_{500}.

31-4.0 DESIGN PHILOSOPHY

31-4.01 Overview

The design of a culvert system for a highway crossing a floodplain involves using information from other chapters in this Part (e.g., hydrology, channels). Each of these should be consulted as appropriate. The discussion below focuses on alternative analyses and design methods.

31-4.02 Alternative Analyses

A culvert alternative should be selected which satisfies the topography, and design policies and criteria.

Alternatives should be analyzed for hydraulic equivalency, and risk and cost.

Select an alternative which best integrates engineering and economic and political considerations. The selected culvert should satisfy the applicable structural and hydraulic criteria, and should be based on the following:

1. construction and maintenance costs;
2. risk of failure or property damage;
3. roadside safety; and
4. land-use requirements.

31-4.03 Design Methods

The designer should choose either of the following:

1. to use a culvert or a storm drain; or

2. to use nomographs or computer software. The use of nomographs not based on HDS #5 is subject to the approval of the Hydraulics Engineer.

31-4.03(01) Structure Type

The following applies to the structure type.

1. Culvert. This is one of the following:

    a. a covered structure with both ends open;
    b. a type of structure designed using the procedures described in HDS #5; or
    c. a type of structure which may be circular, deformed, or specialty.

*** PRACTICE POINTER ***

If twin box culverts are required, space should not be left between them.

2. Storm Drain. This is one of the following:

   a. a covered structure with at least one end in a manhole inlet or catch basin and is usually a part of a system of pipes;

   b. designed using HYDRA software included in HYDRAIN; or

   c. designed using other computer models or by hand calculations.

   See FHWA-SA-96-078 Urban Drainage Design Manual HEC #22, and Chapter Thirty-six and for more information.

3. Specialty Structure. A specialty structure can be used in either a culvert or storm-drain application. See Section 31-4.05 for more information on specialty structures.

31-4.03(02) Hydrology Methods

See Chapter Twenty-nine for detailed information on hydrology. A constant discharge is assumed for culvert design, is always the peak discharge, and will yield a conservatively-sized structure where temporary storage is available but not used.

31-4.03(03) Computational Methods

Nomographs require a trial-and-error solution which most often provides a reliable design, and require additional computations for tailwater, outlet velocity, hydrographs, routing, and roadway overtopping. They are available for many culvert sizes and shapes (see HDS #5).

31-4.03(04) Computer Software

HY-8 is the only computer program allowed for the hydraulic analysis of a culvert. The FHWA *Hydraulic Design of Highway Culverts* (HDS #5) is also acceptable. HDS #5 has also been updated and released as a CD ROM (the FHWA Hydraulics Library).

1. HYDRAIN Microcomputer System.

   a. Is recommended by AASHTO;
   b. includes HY8; and
   c. has a *User's Manual*.

2. HY8 (FHWA Culvert Analysis Software).

   a. Is an interactive program written in Basic.

   b. Uses the theoretical basis for the nomographs.

   c. Can compute tailwater, improved end treatments, road overtopping, hydrographs, routing, and multiple independent barrels.

   d. Develops and plots tailwater rating curves.

   e. Develops and plots performance curves.

   f. Is documented in the HYDRAIN *User's Manual* and HY8 *Applications Guide*.

31-4.04 Modifying or Replacing an Existing Culvert

If considering whether to modify or replace an existing culvert, the designer should first obtain a copy of the road log from the district office. The road log includes an inventory of the locations, sizes, and types of drainage structures located on each state highway. During the field data collection process, the size, location, and type of each culvert should be verified. Each structure should be inspected. See the FHWA *Culvert Inspection Manual* for information on structure inspection. See Figure 31-4A, Culvert Inspection Report Form. An editable version of this form may also be found on the Department's website at www.in.gov/dot/div/contracts/design/dmforms/. If necessary, district operations or maintenance should be contacted to clean each plugged or partially-plugged structure so an adequate inspection can be performed. The district should be notified of changes that need to be made in the road log.

Once inspection of all culverts to be addressed has been completed, a list of those requiring modification or replacement should be provided to the district Office of Highway Management.

The Office will slip-line or replace pipes of less than 900 mm diameter requiring excavation of less than 1.5 m. See Section 31-4.04(02) Item 1 for an explanation of slip lining. This work should be done before the road work is contracted.

Rehabilitation or replacement should be considered as part of the project work for a culvert of 900 mm or greater diameter that has poor roadway geometry or that has a remaining life of less than the anticipated life of the proposed road work.

31-4.04(01) Determining Need for Culvert Modification or Replacement

Each culvert to be modified or replaced should be evaluated by an individual familiar with structure inspection.

1. General Considerations. The items to check include, but are not limited to, those as follows:

    a. structure alignment with the channel and the potential for erosion or scour;
    b. erosion of the approaches, particularly the areas behind the wingwalls;
    c. loss of fill material from beneath the roadway;
    d. local and contraction scour and general channel degradation;
    e. indications of foundation undermining and the potential for foundation undermining;
    f. structure settlement;
    g. timber decay;
    h. roadway geometry;
    i. hydraulic adequacy; and
    j. approach erosion.

2. Metal Pipe. Items to check when inspecting a metal pipe include, but are not limited to, those as follows:

    a. corrosion, including holes which could cause erosion of the surrounding backfill material; and
    b. excessive deformation.

    A metal pipe found to be in poor condition should be considered for slip lining or replacement.

3. Concrete Pipe. Items to check when inspecting a concrete pipe include, but are not limited to, those as follows:

a. cracking, efflorescence, delaminating, or spalling of concrete;
b. exposed or corroded concrete reinforcement;
c. deterioration at widening joints;
d. settlement or separation of joints allowing backfill material into the pipe; and
e. deterioration of the structure.

A concrete pipe found to be in poor condition should be considered for resetting, slip lining, or possibly replacement.

4. Jacking a Pipe. If a pipe is to be jacked under a road, space should be provided for a jacking pit. Temporary right of way will be required if there is not sufficient permanent right of way. The designer should discuss this issue at the preliminary field check.

31-4.04(02) Culvert Modification

A Structure Data Table should be included in the plans for drainage structures requiring modification. Detail sheets should be provided where required.

1. Slip Lining. Slip lining is a technique for rehabilitating a culvert of 450 mm diameter or larger. Slip lining is also suitable for use for a box- or arch-type culvert. It is completed by pushing or pulling sections of polyethylene pipe through the existing structure and filling the space between the polyethylene and existing structure with grout. The capacity of a structure can often be increased due to the low friction factor of the polyethylene liner. Factors to consider when deciding whether or not to slip line a structure are as follows.

   a. The structure barrel should be relatively straight and free from obstructions.
   b. The backfill around the structure should be free from large voids.
   c. There should be sufficient room to work from at least one end of the existing structure.
   d. The structure should be under at least 2 m of fill or in a location where a road closure is undesirable or impossible.

2. Culvert Extension. A culvert that is structurally and hydraulically adequate, but of insufficient length, may be considered for an extension. Each culvert with a diameter of 1250 mm or greater that will be extended 1.5 m or more will require a geotechnical evaluation. See Section 31-3.05(05) for criteria regarding culvert extension.

3. Culvert End Treatment. See Section 31-3.06(02) for desirable design criteria regarding a culvert end treatment.

4. Headwalls and Anchors. Removal of headwalls or anchors damages the existing structure. As a minimum, 1 m of new structure should be placed for each headwall removed.

   Each protruding headwall which is not in accordance with the obstruction-free-zone criteria should be considered for removal or modification. A headwall which is shielded from impact by guardrail should not be removed unless it is located within clearance range of the guardrail as shown in Figure 49-4A.

31-4.04(03) Culvert Replacement

Each culvert with a diameter of 1250 mm or greater that is to be replaced will require a geotechnical report and a hydraulic analysis. If a legal drain is involved, the county surveyor should be contacted for the replacement-structure parameters. County soils survey and county drainage maps are available. The USGS 7.5-min series topography maps provide information regarding drainage patterns at a large scale. The topography maps show rivers, creeks, and streams which indicate the drainage pattern of the basin as a whole.

The designer should provide the flow-line elevation for the structure to be replaced. The established temporary benchmarks should be shown on the detail sheet. Cross sections should be provided where required for each culvert replacement or new installation.

If a culvert is already in the INSTIP program for replacement, the designer should attempt to incorporate the replacement into the project work.

31-4.04(04) Backfill Materials

See Section 17-2.09 for culvert-backfill requirements.

31-4.05 Specialty Structures [Revised Sept. 2009]

Specialty structures include those described below.

31-4.05(01) Precast-Concrete Box Culvert

A precast-concrete box culvert may be recommended by the Hydraulics Team. A box structure is considered oversize if its clear-span length is more than 3.65 m. The recommended layout

method for a box culvert is to extend it to the point where the roadway sideslope intercepts the stream flowline. The sideslope at the end of a box culvert should be protected with guardrail or be located beyond the clear zone.

31-4.05(02) Precast-Concrete Oversize Box Structure

A precast-concrete oversize box structure may be recommended by the Hydraulics Team. A box structure is considered oversize if its clear-span length is more than 3.65 m, but not more than 6.1 m. Product information is available from local suppliers.

The hydraulic recommendations letter will indicate if a three-sided structure with a base slab is an acceptable alternate to an oversize box structure. The designer should consult with the Hydraulics Team for guidance as to whether the two structure types are interchangeable for the specific site. A cost comparison should be used in making the final structure selection.

If the distance between the top of the structure and the top of the pavement section, is less than 600 mm as measured at the edge of travel lane, all top slab reinforcement in a box structure, or all reinforcement in a three-sided structure, should be epoxy coated. A note should be placed in the Structure Data Table's comments column indicating this.

An oversize box culvert should be laid out so that the total structure length is a multiple of the box-segment length for the given box size. It is not necessary to add a tolerance for the joints between segments in determining the total structure length. The available segment masses (weights) and lengths are shown in Figure 31-4B.

31-4.05(03) Wingwalls and Headwalls for Precast-Concrete Structure

Wingwalls and headwalls for a precast-concrete structure will be required. Such wingwalls and headwalls may b precast or cast in place.

The information to be shown on the plans is as follows:

1. a plan view showing the total length of the structure, skew angle, distance from roadway centerline to each end of structure, and the flare angle of all wingwalls.

2. an elevation view of the end of the structure including wingwalls and headwall. The span and rise of the structure should be dimensioned. The heights of the headwalls should be shown;

3. wingwalls labeled A through D with a table showing all dimensions and elevations for each wingwall;

4. a table summarizing the wingwall areas required;

5. a conceptual drawing showing a typical section through each wingwall that shows the approximate footing configuration. Footing dimensions should not be shown. The contractor is responsible for the footing design; and

6. the allowable soil bearing pressure. A table should be included on the plans listing the soil parameters for wingwall design as follows:

   a. angle of friction between wingwall footing and foundation soil, δ;
   b. angle of internal friction of the foundation soil, φ;
   c. ultimate cohesion of foundation soil, C; and
   d. ultimate adhesion between foundation soil and concrete, C_A.

   These soil parameters will be provided in the geotechnical report for the structure. vIf the geotechnical report is lacking this information, it should be requested from the Production Management Division's Office of Geotechnical Services.

The headwalls' quantities will be included in the structure quantities.

If a project has at least one precast-concrete box structure, and at least one precast-concrete three-sided drainage structure, each with wingwalls, the wingwalls' quantities for both types of structures may be combined.

31-4.05(04) Plans Details, and Design Computations and Shop Drawings

Only the conceptual layout for a precast-concrete 3-sided or 4-sided structure, or precast wingwalls and headwalls, should be shown on the plans. Once the work is under contract, the fabricator will design and detail the structure. For each 3-sided structure, or for a 4-sided structure of greater than 3.65 m span, the fabricator will provide design computations and shop drawings which are to be checked by, and are subject to the approval of, the designer.

The contractor may choose to substitute a three-sided structure as a cost-reduction incentive. Details for a hydraulically-equivalent three-sided structure should not be shown on the plans.

31-4.05(05) Structure-Size Increments

For structure box sections and structure-extension box sections, the size increments are as follows.

1. Structure of 3.65-m Span or Less. Span and rise range from a minimum of 0.91 m through a maximum of 3.65 m, in 0.61-m increments. The rise must be less than or equal to the span.

2. Oversize Structure. Span is 4.27, 4.88, 5.49, or 6.10 m. Rise is 1.22, 1.52, 1.83, 2.30, or 2.44 m.

Metric-units span and rise should be rounded to the nearer 0.01 m.

31-5.0 DESIGN EQUATIONS

31-5.01 General

An exact theoretical analysis of culvert flow is complex due the requirements as follows:

1. analyzing non-uniform flow with regions of both gradually varying and rapidly varying flow;

2. determining how the flow type changes as the flow rate and tailwater elevations change;

3. applying backwater and drawdown calculations, energy, and momentum balance;

4. applying the results of hydraulic model studies; and

5. determining if hydraulic jumps occur and if they are inside or downstream of the culvert barrel.

31-5.02 Approach

The procedure considers the following.

1. Control Section. The control section is the location where there is a unique relationship between the flow rate and the upstream water-surface elevation. Inlet control is governed by the inlet geometry. Outlet control is governed by a combination of the culvert end-treatment geometry, the barrel characteristics, and the tailwater.

2. Minimum Performance. Minimum performance is assumed by analyzing both inlet and outlet control and using the highest headwater. The culvert may operate more efficiently at times (more flow for a given headwater level), but it will not operate at a lower level of performance than calculated.

3, Culvert Sizing. The culvert sizing process must satisfy the criteria as follows:

   a. allowable headwater elevation at Q_{100};

   b. roadway serviceability for storm of specific magnitude, depending on functional classification; and

   c. maximum pipe outlet velocity or energy dissipator design.

4. Computer Software. The HY8 hydraulics computer software and FHWA Hydraulics Library CD design methods are acceptable for structure sizing.

31-5.03 Inlet Control

For inlet control, the control section is at the upstream end of the barrel (the inlet). The flow passes through critical depth near the inlet and becomes shallow, high-velocity (supercritical) flow in the culvert barrel. Depending on the tailwater, a hydraulic jump may occur downstream of the inlet.

31-5.03(01) Headwater Factors

These include the following.

1. Headwater depth is measured from the inlet invert of the inlet control section to the surface of the upstream pool.

2. Inlet area is the cross-sectional area of the face of the culvert. The inlet face area is the same as the barrel area.

3. Inlet-edge configuration describes the entrance type. Inlet-edge configurations include thin-edge projecting, mitered, square edge in a headwall, and beveled edge. See Section 31-10.0 for the edge configuration of an INDOT culvert inlet.

4. Inlet shape is the same as the shape of the culvert barrel. Shapes include rectangular, circular, elliptical, and arch. Check for an additional control section, if different than the barrel.

31-5.03(02) Hydraulics

Three regions of flow are shown in Figure 31-5A, Unsubmerged, Submerged, and Transition. These are described as follows.

1. Unsubmerged. For headwater below the inlet crown, the entrance operates as a weir. A weir is a flow-control section where the upstream water surface elevation can be predicted for a given flow rate. The relationship between flow and water surface elevation must be determined through model tests of the weir geometry or by measuring prototype discharges. These tests are then used to develop equations. HDS #5 Appendix A includes the equations which were developed from model test data. See Figure 31-5B, Flow Type I.

2. Submerged. For headwater above the inlet, the culvert operates as an orifice. An orifice is an opening, submerged on the upstream side and flowing freely on the downstream side, which functions as a control section. The relationship between flow and headwater can be defined based on results from model tests. HDS #5 Appendix A includes flow equations which were developed from model test data. See Figure 31-5C, Flow Type V.

3. Transition Zone. The transition zone is located between the unsubmerged and the submerged flow conditions where the flow is poorly defined. This zone is approximated by plotting the unsubmerged and submerged flow equations and connecting them with a line tangent to both curves.

31-5.03(03) Nomographs

The inlet-control flow versus headwater curves which are established using the above procedure are the basis for constructing the inlet control design nomographs. In the inlet control nomographs, *HW* is measured to the total upstream energy grade line including the approach velocity head.

31-5.04 Outlet Control

Outlet control has depths and velocities which are subcritical. The control of the flow is at the downstream end of the culvert (the outlet). The tailwater depth is either assumed to be critical

depth near the culvert outlet or the downstream channel depth, whichever is higher. In a given culvert, the type of flow is dependent on all of the barrel factors. All of the inlet-control factors also influence the culvert in outlet control, as follows.

1. Interior Designation. The pipe-culvert interior designation (i.e., the barrel roughness) will be either smooth or corrugated. See Section 31-3.05(02) for INDOT practice. The roughness is represented by a hydraulic resistance coefficient such as the Manning's *n* value. Manning's *n* values are provided in Section 31-10.0.

2. Barrel Area. Barrel area is measured perpendicular to the flow.

3. Barrel Length. Barrel length is the total culvert length from the entrance invert to the exit invert. Because the design height of the barrel and the slope influence the actual length, an approximation of barrel length is necessary to begin the design process.

4. Barrel Slope. Barrel slope is the actual slope of the culvert barrel and is often the same as the natural stream slope. However, if the culvert inlet or outlet is raised or lowered, the barrel slope is different from the stream slope.

31-5.04(01) Tailwater Elevation

Tailwater is based on the downstream water-surface elevation. Backwater calculations from a downstream control, a normal depth approximation, flood insurance studies, or IDNR historic flood profiles are used to define the tailwater elevation (see Section 31-3.03).

31-5.04(02) Hydraulics

Full flow in the culvert barrel is assumed for the analysis of outlet control hydraulics. Outlet-control flow conditions can be calculated based on an energy balance from the tailwater pool to the headwater pool. See Figure 31-5D, Flow Type IV.

The following equations apply.

1. Losses. $H_L = H_E + H_f + H_V + H_b + H_j + H_g$ (Equation 31-5.1)

Where:
H_L = total energy loss, m
H_E = entrance loss, m
H_f = friction losses, m
H_V = exit loss, or velocity head, m
H_b = bend losses, m (see HDS #5)

H_j = losses at junctions, m (see HDS #5)
H_g = losses at grates, m (see HDS #5)

2. Velocity. $V = Q/A$ (Equation 31-5.2)

Where: V = average barrel velocity, m/s
Q = flow rate, m^3/s
A = cross sectional area of flow with the barrel full, m^2

3. Velocity head. $H_V = \frac{V^2}{2g}$ (Equation 31-5.3)

Where: g = acceleration due to gravity, 9.81 m/s^2

4. Entrance loss. $H_E = \frac{K_E V^2}{2g}$ (Equation 31-5.4)

Where: K_E = entrance loss coefficient; see Section 31-10.0.

5. Friction loss. $H_f = \left(\frac{19.63Ln^2}{R^{1.33}}\right)\left(\frac{V^2}{2g}\right)$ (Equation 31-5.5)

Where L = length of the culvert barrel, m
n = Manning's roughness coefficient (see Section 31-10.0)
R = hydraulic radius of the full culvert barrel = A/P, m
P = wetted perimeter of the barrel, m

6. Exit loss. $H_O = \frac{V^2 - V_d^{\,2}}{2g}$ (Equation 31-5.6)

Where: V_d = channel velocity downstream of the culvert, m/s (usually neglected; see Equation 31-5.5). If neglected,

$$H_O = H_V = \frac{V^2}{2g}$$ (Equation 31-5.7)

7. Barrel losses. $H = H_E + H_O + H_f$ (Equation 31-5.8)

$$H = \left[1 + K_E + \left(\frac{19.63Ln^2}{R^{1.33}}\right)\right]\left(\frac{V^2}{2g}\right)$$

8. Energy Grade Line. The energy grade line represents the total energy at a point along the culvert barrel. Equating the total energy at Sections 1 and 2, upstream and downstream

of the culvert barrel in Figure 31-5D, Flow Type IV, the resulting relationship is as follows:

$$HW_O + \frac{V_U^{\ 2}}{2g} = TW + \frac{V_d^{\ 2}}{2g} + H_L \qquad \text{(Equation 31-5.9)}$$

Where:
- HW_O = headwater depth above the outlet invert, m
- V_U = approach velocity, m/s
- TW = tailwater depth above the outlet invert, m
- V_d = downstream velocity, m/s
- H_L = sum of all losses (Equation 31-5.1)

9. Hydraulic Grade Line. The hydraulic grade line is the depth to which water would rise in vertical tubes connected to the sides of the culvert barrel. In full flow, the energy grade line and the hydraulic grade line are parallel lines separated by the velocity head except at the inlet and the outlet.

31-5.04(03) Nomographs

The following describes the assumptions for the culvert nomographs in the FHWA Hydraulics Library CD.

1. Full Flow. The nomographs were developed assuming that the culvert barrel is flowing full and that the following apply.

   a. $TW \geq D$, Flow Type IV (see Figure 31-5D), or $d_C \geq D$, Flow Type VI (see Figure 31-5E).

   b. V_U is small and its velocity head can be considered to be a part of the available headwater, HW, used to convey the flow through the culvert.

   c. V_d is small and its velocity head can be neglected.

   d. Equation 31-5.9 becomes the following:

$$HW = TW + H - S_O L \qquad \text{(Equation 31-5.10)}$$

Where:
- HW = depth from the inlet invert to the energy grade line, m
- H = value read from the nomographs (Equation 31-5.8), m
- $S_O L$ = drop from inlet to outlet invert, m

2. Partly-Full Flow. Equations 31-5.1 through 31-5.10 were developed for full-barrel flow. The equations also apply to a flow situation which is effectively a full-flow condition, if $TW < d_C$; see Figure 31-5F, Flow Type VII. Backwater calculations may be required beginning at the downstream water surface and proceeding upstream. If the depth intersects the top of the barrel, full flow extends from that point upstream to the culvert entrance.

3. Partly-Full Flow, Approximate Method. Based on backwater calculations performed by FHWA, it has been determined that the hydraulic grade line pierces the plane of the culvert outlet at a point halfway between critical depth and the top of the barrel, or $(d_C + D)/2$ above the outlet invert. TW should be used if it is higher than $(d_C + D)/2$. The following equation should be used.

$$HW = h_O + H - S_O L \qquad \text{(Equation 31-5.11)}$$

Where: h_O = the larger of TW or $(d_C + D)/2$, m

Adequate results are obtainable down to $HW = 0.75D$. For a lower headwater, backwater calculations are required. See Figure 31-5G if $TW < d_C$, or Figure 31-5H if $TW \geq d_C$.

31-5.05 Outlet Velocity

Culvert outlet velocity should be calculated to determine the extent of erosion protection required at the culvert exit. A culvert affects an outlet velocity which is higher than the natural stream velocity. See Section 31-3.0 for the INDOT policy on outlet protection.

31-5.05(01) Inlet Control

The velocity is calculated from Equation 31-5.2 after determining the outlet depth. Either of the following methods may be used to determine the outlet depth.

1. Calculate the water surface profile through the culvert. Begin the computation at d_C at the entrance and proceed downstream to the exit. Determine the depth and flow area at the exit.

2. Assume normal depth and velocity. This approximation may be used because the water surface profile converges towards normal depth if the culvert is of adequate length. This outlet velocity may be slightly higher than the actual velocity at the outlet. Normal depth may be obtained from design aids described in publications such as HDS #3.

31-5.05(02) Outlet Control

The cross-sectional area of the flow is defined by the geometry of the outlet and either critical depth, tailwater depth, or the height of the conduit. The following applies.

1. Critical depth is used where the tailwater is less than critical depth.

2. Tailwater depth is used where tailwater is greater than critical depth but below the top of the barrel.

3. The total barrel area is used where the tailwater exceeds the top of the barrel.

31-5.06 Roadway Overtopping

A roadway is designed to avoid overtopping during the appropriate design storm given for the road-serviceability requirement. However, for a storm that exceeds the road-serviceability design storm, it is necessary to calculate *HW* elevations and velocities.

Roadway overtopping will begin once the headwater rises to the elevation of the roadway. The overtopping will occur at the low point of a sag vertical curve on the roadway. The flow will be similar to flow over a broad-crested weir. Flow coefficients for flow overtopping a roadway embankment are shown in HDS #1 *Hydraulics of Bridge Waterways* and in the documentation of HY-7, Bridge Waterways Analysis Model.

Equation 31-5.12 defines roadway overtopping as follows:

$$Q_r = C_d L H W_r^{1.5} \qquad \text{(Equation 31-5.12)}$$

Where:

Q_r	=	overtopping flow rate, m^3/s
C_d	=	overtopping discharge coefficient (weir coefficient) = $k_t C_r$
k_t	=	submergence coefficient
C_r	=	discharge coefficient
L	=	length of the roadway crest, m
HW_r	=	the upstream depth, measured above the roadway crest, m

The length is difficult to determine where the crest is defined by a roadway sag vertical curve. Either of the following may be used.

1. Subdivide the length into a series of segments. The flow over each segment is calculated for a given headwater. The flows for each segment are then added together to determine the total flow.

2. The length can be represented by a single horizontal line (one segment). The length of the weir is the horizontal length of this segment. The depth is the average depth (area/length) of the upstream pool above the roadway.

Total flow is calculated for a given upstream water-surface elevation using Equation 31-5.9. The following applies.

1. Roadway overflow plus culvert flow must equal total design flow.

2. A trial-and-error process is necessary to determine the flow passing through the culvert and the amount flowing across the roadway.

3. Performance curves for the culvert and the road overflow may be summed to yield an overall performance.

31-5.07 Performance Curves

Performance curves are plots of flow rate versus headwater depth or elevation, velocity, or outlet scour. The culvert performance curve is composed of the controlling portions of the individual performance curves for each of the following control sections (see Figure 31-5 I, Overall Performance Curve), as follows.

1. Inlet. The inlet performance curve is developed using the inlet control nomographs.

2. Outlet. The outlet performance curve is developed using Equations 31-5.1 through 31-5.10, the outlet control nomographs, or backwater calculations.

3. Roadway. A roadway performance curve is developed using Equation 31-5.12.

4. Overall. An overall performance curve is the sum of the flow through the culvert and the flow across the roadway and can be determined by performing the following steps.

    a. Select a range of flow rates and determine the corresponding headwater elevations for the culvert flow alone. These flow rates should occur above and below the design discharge and include the entire flow range of interest. Both inlet and outlet control headwaters should be calculated.

b. Combine the inlet and outlet control performance curves to define a single performance curve for the culvert.

c. If the culvert headwater elevation exceeds the roadway crest elevation, overtopping will begin. Calculate the upstream water-surface depth above the roadway for each selected flow rate. Use these water surface depths and Equation 31-5.12 to calculate flow rates across the roadway.

d. Add the culvert flow and the roadway overtopping flow at the corresponding headwater elevations to obtain the overall culvert performance curve as shown in Figure 31-5 I, Overall Performance Curve.

31-6.0 DESIGN PROCEDURES

The following design procedure provides a convenient and organized method for designing a culvert for a constant discharge, considering inlet and outlet control. The procedure does not address the affect of storage which is discussed in Chapter Thirty-five and Section 31-9.0. Storage will not be considered in the design of a structure which is not part of a detention facility. The following also applies.

1. The designer should be familiar with all equations in Section 31-5.0 before using these procedures.

2. Following the design method without an understanding of culvert hydraulics can result in an inadequate, unsafe, or costly structure.

3. The computation form has been provided in Section 31-10.0 to guide the user. It includes blocks for the project description, designer's identification, hydrologic data, culvert dimensions and elevations, trial culvert description, inlet and outlet control *HW*, culvert barrel selected, and comments.

4. <u>Step 1: Assemble Site Data And Project File</u>.

   a. See Section 28-5.0. The minimum required data are as follows:

      (1) USGS, site and location maps;
      (2) embankment cross section;
      (3) roadway profile;
      (4) channel cross section at outlet of proposed structure;
      (5) photographs;
      (6) survey (sediment, debris); and

(7) design data for nearby structures for which data is readily available.

b. Studies and regulatory requirements by other agencies including the following:

(1) small dam: NRCS, USACOE;
(2) canal: NRCS, USACOE;
(3) floodplain: NRCS, USACOE, FEMA, USGS, NOAA, IDNR; and
(4) storm drain: local or private, including drains regulated by county drainage board.

c. Design criteria.
(1) review Section 31-3.0 for applicable criteria, and
(2) prepare analysis.

5. Step 2: Determine Hydrology.

a. See Chapter Twenty-nine.
b. Minimum required data are drainage area map and a discharge.
c. Determine magnitude of each required design storm.

6. Step 3: Analyze Downstream Channel.

a. See Chapter Thirty.
b. Minimum required data are cross section and slope of channel, and the rating curve for the channel.
c. Perform analysis for each required design-storm magnitude.

7. Step 4: Summarize Data On Design Form.

a. See Chart in Section 31-10.0.
b. Data from Steps 1-3.
c. Perform analysis for each required design-storm magnitude.

8. Step 5: Select Design Discharge, Q_d.

a. See Section 31-3.0 and Chapter Twenty-nine.
b. Determine flood frequency from criteria.
c. Determine Q.

9. Step 6: Perform Structure-Sizing Process.

a. See Section 31-3.0.

b. Steps 7, 8 and 9 must be performed for each structure type analyzed in Trials 1 through 6 for the design-storm magnitudes appropriate for allowable headwater and roadway serviceability.

c. Continue with trials until hydraulic design is complete.

d. Select acceptable structure size, type, and pipe-interior designation, if applicable, and select the end treatment.

10. Step 7: Determine Inlet Control Headwater Depth, HW_i. Use the inlet-control nomograph (FHWA Hydraulics Library CD). A plastic sheet with a matte finish can be used to mark on so that the nomographs can be preserved.):

a. Locate the size or height on the scale.

b. Locate the discharge.

(1) For a circular shape, use discharge.
(2) For a box shape, use *Q* per meter of width.

c. Locate *HW*/*D* ratio.

(1) Use a straightedge.
(2) Extend a straight line from the culvert size through the flow rate.
(3) Mark the first *HW*/*D* scale. Extend a horizontal line to the desired scale, read *HW*/*D*, and identify on Chart in Section 31-10.0.

d. Calculate headwater depth, *HWi*.

(1) Multiply *HW*/*D* by *D* to obtain *HW* to energy gradeline.
(2) Neglecting the approach velocity, *HWi* = *HW*.
(3) Including the approach velocity, *HWi* = *HW* – (approach velocity head).

11. Step 8: Determine Outlet Control Headwater Depth At Inlet, HW_{oi}.

a. Calculate the tailwater depth, *TW*, using the design flow rate and normal depth (single section) or using a water surface profile.

b. Calculate critical depth, d_C, using the appropriate chart in HDS #5.

(1) Locate flow rate and read d_C.

(2) d_C cannot exceed *D*.

(3) If $d_C > 0.9D$, consult Handbook of Hydraulics (King and Brater) for a more accurate d_C, if needed, because curves are truncated where they converge.

c. Calculate $(d_C + D)/2$.

d. Determine h_O. It equals the larger of TW or $(d_C + D)/2$.

e. Determine entrance loss coefficient, K_E, from Section 31-10.0.

f. Determine losses through the culvert barrel, H.

(1) Use nomograph (FHWA Hydraulics Library CD) or Equation 31-5.8 or 31-5.9 if outside the range.

(2) Locate appropriate K_E scale.

(3) Locate culvert length, L or L_1. Use L if Manning's n matches that of the culvert. Use L_1 to adjust for a different culvert n value.

$$L_1 = \frac{2L_{n1}}{n} \qquad \text{(Equation 31-5.13)}$$

Where:

L_1	=	adjusted culvert length, m
L	=	actual culvert length, m
n_1	=	desired Manning's n value
n	=	Manning's n value from chart

(4) Mark point on turning line. Use a straightedge and connect the size with the length.

(5) Read H. Use a straightedge, connect Q and turning point, and read H on the Head Loss scale.

g. Calculate outlet control headwater, HW_{oi}:

(1) Use Equation 31-5.14, if V_U and V_d are neglected, as follows:

$$HW_{oi} = H + h_O - SO_L \qquad \text{(Equation 31-5.14)}$$

(2) Use Equations 31-5.1, 31-5.6, and 31-5.9 to include V_U and V_d.

(3) If HW_{oi} is less than 1.2D, and the outlet controls, the following apply.

(a) The barrel may flow partly full.

(b) The approximate method of using the greater of tailwater or $(d_C + D)/2$ may not be applicable.

(c) backwater calculations should be used to check the result.

(d) If the headwater depth falls below 0.75D, the approximate nomograph method should not be used.

12. Step 9: Determine Controlling Headwater, HW_C.

a. Compare HW_i and HW_{oi}, and use the higher value.

b. Compare HW_C with allowable HW and adjust culvert size if necessary.

13. Step 10: Compute Discharge Over The Roadway, Q_r.

a. Choose Q_t and thereby establish a TW.

b. Assume an upstream depth over the roadway, HW_r, calculate the length of roadway crest, L, and calculate the overtopping flow rate using Equation 31-5.15 as follows:

$$Q_r = C_d L (HW_r)^{1.5} \qquad \text{(Equation 31-5.15)}$$

See Section 31-5.06.

c. Calculate the flow in the culvert by using Equations 31-5.8 and 31-5.10 solving for V and then Q_d.

14. Step 11: Calculate Outlet Velocity, V_O, and Depth, d_n. If inlet is the controlling headwater using the design-storm magnitude appropriate for the velocity, calculate the following:

a. flow depth at culvert exit using normal depth or water-surface profile;

b. flow area, A; and

c. exit velocity, $V_O = Q/A$.

If outlet is the controlling headwater using the design-storm magnitude appropriate for the velocity, calculate the following:

a. flow depth at culvert exit;

(1) use d_C if it is greater than TW,
(2) use TW if $d_C < TW < D$, *or*
(3) use D if it is less than TW.

b. flow area, A; and

c. exit velocity, $V_O = Q/A$.

15. Step 12: Review Results. Compare alternative design with constraints and assumptions. If one or more of the following is exceeded, repeat Steps 5 through 12.

a. The barrel must have adequate cover; see Section 31-3.05(04).
b. The length should be close to the approximate length.
c. The allowable backwater should not be exceeded.
d. The roadway serviceability must be satisfied.
e. The outlet velocity should not be excessive; see Section 31-3.0.

16. Step 13: Related Designs. Consider the following options (see Sections 31-5.04 and 31-5.05).

a. Improved end treatments if culvert is in inlet control and has limited available headwater.

b. Energy dissipator if $V_O \geq 4.0$ m/s (see Section 31-3.0 and Chapter Thirty-four).

c. Sediment-control storage for site with sediment concerns such as alluvial fans (see Chapter Thirty-seven).

17. Step 14: Documentation.

a. See Chapter Twenty-eight.
b. Prepare report and file with background information.

31-7.0 NOMOGRAPH DESIGN

The following example problem follows the Design Procedure Steps described in Section 31-6.0.

1. Step 1: Assemble Site Data And Project File.

   a. Site survey project file should include the following:

      (1) USGS site and location maps;
      (2) roadway profile;
      (3) embankment cross section;
      (4) if two-lane roadway, ADT > 3000; and
      (5) new alignment.

      See Figure 31-7.1 for site data.

   b. Survey notes should indicate no sediment or debris problems and no nearby structures.

   c. Studies by other agencies: none.

   d. Environmental risk assessment shows the following:

      (1) no buildings near floodplain;
      (2) no sensitive floodplain values;
      (3) no FEMA involvement; and
      (4) convenient detours exist.

   e. Design criteria.

      (1) *HW*: Q_{100}. Maximum backwater is 40 mm.
      (2) *RS*: Q_{100}. Headwater elevation must be 0.6 m below the edge-of-pavement elevation.
      (3) *VEL*: Q_{50}. Maximum velocity is 4.0 m/s without energy dissipator. See Section 31-3.0 for INDOT criteria on outlet protection.

2. Step 2: Determine Hydrology. USGS regression equations yield the following:

   Q_{50} = 3.8 m^3/s, and Q_{100} = 4.2 m^3/s

3. Step 3: Analyze Downstream Channel. See Figure 31-7.2 for cross section of channel (slope = 0.001).

Point	Station (m)	Elevation (m)

1	3.7	58.20
2	6.7	57.90
3	8.5	57.85
4	9.3	57.11
5	12.9	57.11
6	13.7	57.85
7	15.5	57.90
8	18.6	59.27

The rating curve for the channel calculated with normal depth yields the following:

Q (m^3/s)	TW (m)	V (m/s)
1.26	0.52	0.59
2.52	0.94	0.87
3.78	0.77	0.74
4.20	0.99	0.90
5.04	1.08	0.96

4. Step 4: Summarize Data On Design Form. See Figure 31-7A, Chart 17 and Performance Curve, for design example.

5. Step 5: Select Design Discharge.

$Q_d = Q_{100} = 4.20$ m^3/s for *HW* and *RS*
$Q_{50} = 3.80$ m^3/s for outlet velocity

6. Step 6: Perform Structure-Sizing Process.

a. Start with Trial 1, Singular Circular Pipe, and proceed through the trials until the hydraulic design is complete.

b. Review site conditions to determine what limitations may be applicable.

Assume shoulder PI at approximate elevation of 59.50.
Assume pavement thickness of 0.25 m.
Assume minimum cover of 0.30 m.
Pipe thickness is 0.18 m.
Inlet elevation is 57.20.
Maximum allowable rise is 1.57 m.

c. Try a circular pipe with diameter = 1500 mm.

d. Assume an end section which satisfies the fill-slope requirement for both RCP and CMP. K_E = 0.5 from Figure 31-10B, Entrance Loss Coefficients (Outlet Control, Full or Partly Full).

e. TW = 0.99 m. AHW = El.$_i$ + TW + 0.04 = 57.20 + 0.99 + 0.04 = 58.23 m

f. With a very flat channel slope of 0.001, the culvert will likely operate under outlet control. However, for ease of calculations, Step 7 will determine inlet control for the largest permissible pipe and, if a trial size is too small, Step 7 will indicate continuing on to the next trial.

7. Step 7: Determine Inlet Control Headwater Depth, HW_i. Use inlet-control nomograph.

D = 1.50 m, K_E = 0.5
Q = 4.2 m_3/s
From nomograph, HW/D = 1.16
HW_i = 1.16 (1.50) = 1.74
El.$_{h1}$ = HW_i + El.$_i$ = 1.74 + 57.20 = 58.94 m > 58.23 m, therefore No Good.
Go to Trial 2, Single Deformed Pipe.

a. Maximum rise = 1500 mm
Maximum allowable corrugated-metal pipe-arch size = 1800 mm x 1200 mm

b. From nomograph, HW/D = 1.55

c. HW_i = 1.55 (1.2) = 1.86 m

d. El.$_{h1}$ = 1.86 + 57.20 = 59.06 m > 58.23 m, therefore No Good.

e. Try reinforced-concrete deformed pipe, 2495 mm x 1585 mm.

f. From nomograph, HW/D = 0.75. HW_i = 0.75 (1.58) = 1.19

g El.$_{h2}$ = 1.19 + 57.20 = 58.39 m > 58.23 m, therefore No Good.

Go to Trial 3, Single Specialty Structure.

With a maximum of a 40-mm increase in backwater allowed and a flat slope of 0.001, a wide shallow box will be necessary. Therefore, try a reinforced-concrete

box, 3300 mm x 1200 mm, with a wingwall 30 deg to 75 deg to barrel. K_E = 0.5 from Figure 31-10B.

Use inlet-control nomograph.

D = 1.2 m
Q/B = 4.2/3.3 = 1.27 m^3/s per meter
HW/D = 0.71
HW_i = 0.71 (1.2) = 0.85 m
El_i = 57.20 + 0.85 = 58.04 m < 58.23 m, therefore OK

Go to outlet control.

8. Step 8: Determine Outlet-Control Headwater Depth at Inlet, HW_{oi}.

TW = 0.99 m for Q = 4.2 m^3/s
d_C = 0.52 m from Critical Depth, Rectangular Section chart
$(d_C + D)/2$ = (0.52 + 1.2)/2 = 0.86
h_O = the larger of TW or $(d_C + D)/2$ = 0.99 m
K_E = 0.5
Determine H from Chart 15, Outlet-Control Nomograph.

a. K_E, scale = 0.5
b. Culvert length, L = 90 m
c. n = 0.012
d. Area = 3.3 x 1.2 = 3.96 m^2
e. H = 0.12 m
f. $El._{hO} = El_O + H + h_O$ = 57.11 + 0.12 + 0.99 = 58.22 m < 58.23 m

9. Step 9: Determine Controlling Headwater Elevation.

a. $El._{hO}$ = 58.22 m > $El._{hC}$ = 58.05 m
b. The culvert is in outlet control.

10. Step 10: Calculate Outlet Velocity, V_O.

a. Calculate flow depth at culvert exit.
Use TW if $d_C < TW < D$, 0.5 < 0.94 < 1.2, TW = 0.94 m
b. Calculate flow area: (3.3) (0.94) = 3.10 m^2
c. Calculate exit velocity: $V_O = Q_{50}/A$ = (3.80/3.10) = 1.22 m/s

11. Step 11: Review Results. Compare alternative design with constraints and assumptions.

a. Check cover: 59.7 – (57.2 + 1.2 + 0.3) = 1.0 m, therefore OK.
b. L = 90 m.
c. El.$_{hO}$ = 58.22 m < *AHW* of 58.23 m, therefore OK.
d. Overtopping flood > Q_{100}, and RS = Q_{100}
Pavement-edge elevation of 59.70 – El.$_{hO}$ of 58.22 = 1.48 m > 0.6 m, OK.
e. Outlet velocity of 1.22 m/s < 4.0 m/s, therefore OK.
Use revetment riprap; see Section 31-3.04(03).

The outlet-control nomographs are designed for full flow. In this example, full flow does not exist because the *TW* depth of 0.99 m is less than the rise of 1.2 m and the culvert is on a flat slope. The above answer should be considered approximate. A more accurate solution is provided in Section 31-8.0 with the microcomputer analysis.

12. Step 12: Documentation. Prepare a Report which includes the Culvert Design Form shown on Figure 31-7A, Chart 17 and Performance Curve for Design Example.

31-8.0 MICROCOMPUTER SOLUTION

31-8.01 Overview

Culvert hydraulic analysis can also be accomplished with the aid of the HYDRAIN software. The following example has been produced using the HY8 Culvert Analysis Microcomputer Program. It is the computer solution of the data provided in Section 31-7.0. Although Trials 1 and 2 of the culvert-design process can be worked on HY8, they are not shown in this example. Trial 3, the reinforced concrete box culvert, is shown.

The screens shown in the figures may not exactly match the version of HY8 available to the user because some editorial changes have been made to fit the screens in this text for presentation.

31-8.02 Data Input

After creating a file, the user will be prompted for the discharge range, site data, and culvert shape, size, material, and end-treatment type. The discharge range for this example will be from 0 to 6.30 m^3/s. The site data are entered by providing culvert invert data. The data input prompt screen is shown as Figure 31-8A, HY8 Data Input Prompt Screen. If embankment data points are input, the program will fit the culvert in the fill and subtract the appropriate length.

31-8.02(01) Culvert Data

As an initial size estimate, try a concrete box culvert, 3300-mm x 1200-mm. For the culvert, assume that a conventional end treatment with 1:1 bevels and 45-deg wingwalls will be used. As each group of data is entered, the user is allowed to edit incorrect entries. Figure 31-8A shows the screen that summarizes the culvert information.

31-8.02(02) Channel Data

Next, the program will prompt for data pertaining to the channel so that tailwater elevations can be determined. Referring to the problem statement, the channel is irregularly shaped and can be described by the eight coordinates listed. The channel data prompt screen is shown as Figure 31-8B, HY8 Channel Data Prompt Screen. After opening the irregular-channel file, the user will be prompted for channel slope of 0.001, number of cross-section coordinates, 8, and subchannel option. The subchannel option will be option 2, left and right overbanks with n = 0.08, and main channel with n = 0.03.

The next prompt, for channel boundaries, refers to the number of the coordinate pair defining the left subchannel boundary and the number of the coordinate pair defining the right subchannel boundary. The boundaries for this example are the 3rd and 6th coordinates. After this is input, the program prompts for channel coordinates. Once these are entered, press P and the computer will display the channel cross-section shown in Figure 31-8C, Channel Cross Section. The user can identify input errors by looking at the plot. To return to the data input screens, press any key. If data are correct, press Enter. The user can then enter the roughness data for the main channel and overbanks.

<u>31-8.03 Rating Curve</u>

The program now has sufficient information to develop a uniform flow rating curve for the channel and provide the user with a list of options. See Figure 31-8D, HY8 Rating Curve Prompt Screen. Selecting option T on the Irregular Channel Data Menu will command the program to compute the rating-curve data and display Figure 31-8D. Selecting option I will permit the user to interpolate data between calculated points.

The Tailwater Rating Curve Table consists of tailwater elevation, *TWE*, at normal depth, natural channel velocity, *Vel.*, and the shear stress at the bottom of the channel for various flow rates. At the design flow rate of 4.20 m^3/s, the tailwater elevation will be 58.10. The channel velocity will be 0.90 m/s, and the shear will be 7.76 Pa. This information will be useful in the design of a channel lining if needed. Entering P will command the computer to display the rating curve for

the channel. This curve, shown in Figure 31-8E, Tailwater vs. Flow Rate, is a plot of tailwater elevation vs. flow rate at the exit of the culvert.

31-8.04 Roadway Data

The next prompts are for the roadway profile so that an overtopping analysis can be performed. Referring to the problem statement, the roadway profile is a sag vertical curve, which will require nine coordinates to define. Once these coordinates are input, the profile will be displayed once P is entered, as illustrated in Figure 31-8F, Roadway Profile. The other data required for overtopping analysis are roadway surface or weir coefficient and the embankment top width. For this example, the roadway is paved with an embankment width of 15.24 m.

31-8.05 Data Summary

All of the data has now been entered and the summary table is displayed as shown in Figure 31-8G, HY8 Data Summary Prompt Screen. At this point, the data can be changed or the user can save the data and continue by pressing Enter, which will bring up the Culvert Program Options Menu.

31-8.06 Performance Curve for Culvert Size of 3300 mm x 1200 mm

From the Culvert Program Options Menu, the culvert performance curve table can be obtained by selecting option S. If option S is selected, the program will compute the performance-curve table without considering overtopping in the analysis. Because this 3300-mm x 1200-mm culvert is a preliminary estimate, the performance without considering overtopping is calculated and is shown as Figure 31-8H, HY8 Performance Curve Prompt Screen, 3300-mm Span by 1200-mm Rise.

The table indicates the controlling headwater elevation, *HW*, the tailwater elevation, and the headwater elevations associated with all possible control sections of the culvert. It is apparent from the table that at 4.20 m^3/s, *HW* = 58.25 m, which exceeds the design headwater of 58.23 m. Consequently, the 3300-mm x 1200-mm box culvert is inadequate for the site conditions. Figure 31-8 I, Inlet/Outlet Control Headwaters plot, can be obtained by entering P. In this example, the culvert is operating in outlet control (the upper curve) throughout the discharge range. Backwater should be calculated as follows:

$$BW = \text{Headwater El.} - (\text{Inlet El.} + \text{Tailwater Depth})$$

For this example, *BW* at Q = 4.20 m^3/s is 58.25 – (57.20 + 0.99) = 0.06 m

The backwater for the 3300-mm x 1200-mm culvert is greater than allowable for 40 mm. The next larger size of 3600 mm x 1200 mm will be analyzed.

31-8.07 Performance Curve for Culvert Size of 3600 mm x 1200 mm

Because the design headwater criterion was not satisfied by a size of 3300 mm x 1200 mm, try a size of 3600 mm x 1200 mm and modify the file accordingly. The resulting performance table shown as Figure 31-8J indicates that the design headwater will not be exceeded at 4.20 m^3/s. The designer must check the roadway serviceability at Q_{100} and the maximum velocity at Q_{50}.

This structure is sized to satisfy the INDOT criteria on new alignment of an increase of 40 mm maximum backwater if compared to existing conditions. If the culvert had been a replacement structure, the INDOT criteria is a maximum total backwater of 300 mm. The box-culvert size can be modified to satisfy this criterion.

31-8.08 Performance Curve for Culvert Size of 2100 mm x 1200 mm

The user can modify the existing program file to analyze a smaller barrel. Try a size of 2100 mm x 1200 mm. From the Culvert Program Options Menu, press E to edit the file, and then E again to edit the culvert size. The prompts will be the same as they were for the 3600-mm x 1200-mm culvert. The user will return to the Culvert Data Summary Table directly without seeing the tailwater and overtopping menus again. Press F to rename the data file, or press Enter to save the changes into the current file and return to the Culvert Program Options Menu. The performance of this culvert can be checked by selecting option S for no overtopping. The performance curve table shown as Figure 31-8K, HY8 Performance Curve Prompt Screen, 2100-mm Span by 1200-mm Rise, appears.

Check the backwater for Q_{100} of 4.20 m^3/s as follows:

BW = Headwater Elevation – (Inlet Elevation + *TW* depth)
BW = 58.46 – a(57.2 + 0.99) = 0.27 m < 0.3 m, therefore OK.

Therefore, a reinforced-concrete box culvert of 2100 mm x 1200 mm RCB will be adequate if the Allowable Backwater, *ABW*, is increased to 300 mm.

31-8.09 Minimize Culvert Span

Rather than using a series of trials to increase or reduce the culvert headwater to an acceptable level, as in the preceding examples, the Minimize Culvert Span feature of HY8 can be used. This feature is intended to allow the designer to use HY8 as a tool to perform culvert design for a circular, box, elliptical, or arch-shaped culvert based on a user's defined allowable headwater elevation, assuming no overtopping. This feature can be activated by pressing M. Once this option is selected, the user inputs the allowable headwater elevation. That elevation will be the basis for adjusting the user's defined culvert size for the design discharge. The program will adjust the culvert span by increasing or decreasing in it in 150-mm increments. It will compute the headwater elevation for the span, and compare it with the user's defined allowable headwater. If the computed headwater elevation is lower than or equal to the defined allowable headwater elevation, the minimization routine will stop, and the adjusted culvert can be used for the remainder of the program. Other hydraulic parameters are also computed while performing the minimization routine. These hydraulic parameters which are part of the output of the minimization-routine table, as shown in Figure 31-8L, HY8 Minimization Routine Table Prompt Screen, must be printed from this screen because they are not printed with the output-listing routine. The *AHW* of 58.49 based on the inlet elevation of 57.20, *TW* of 0.l99 m, and allowable backwater of 0.3 m yields the results shown in Figure 31-8L.

This feature is a timesaver, as it avoids the need for repetitively editing a culvert size to obtain a controlling headwater elevation.

31-8.10 Overtopping Performance Curve, Culver Size of 3600 mm x 1200 mm

Return to the 3600-mm x 1200-mm culvert to determine the amount of overtopping and the actual headwater from the Culvert Program Options Menu, and select O for overtopping. Figure 31-8M, Summary of Culvert Flows Prompt Screen, will appear.

This computation table is used if overtopping is used. It shows the headwater, total flow rate, the flow through each barrel and overtopping flow, and the number of iterations it took to balance the flows. The overtopping discharge of 5.7 m^3/s occurs at the roadway sag-point elevation of 58.38. For the maximum discharge of 6.3 m^3/s, 6.1 m^3/s will flow through the culvert and 0.2 m^3/s will flow over the road. From this information, a total (culvert and overtopping) performance curve, shown in Figure 31-8N, Total Performance Curve, can be obtained by selecting option P. This curve is a plot of the headwater elevation vs. the total flow rate which indicates how the culvert or group of culverts will perform over the selected range of discharges. It is useful for comparing the effects of various combinations of culverts. See Figure 31-8 O, HY8 Overtopping Performance Curve Prompt Screen, 3600-mm Span by 1200-mm Rise.

31-8.11 Review

For the design criteria set forth for the example in Section 31-7.0, the design of a reinforced-concrete box culvert of 3600 mm x 1200 mm is selected as follows:

Q_{100} = 4.2 m^3/s, HW = 58.23, AHW = 58.23, V_O = 1.18 m/s, V_C = 0.90 m/s.
Q_{50} = 3.8 m^3/s, V_O = 1.12 m/s. No energy dissipation necessary.

Road sag point elevation = 58.38, Overtopping Q = 5.7 m^3/s.
Therefore, Roadway Serviceability, $RS > Q_{100}$.

An energy dissipater is warranted at a velocity higher than 4.0 m/s. See Section 31-3.0.

31-9.0 IMPROVED END TREATMENTS

31-9.01 General

An improved end treatment is a flared culvert inlet with an enlarged face section and a hydraulically-efficient throat section. An improved end treatment may have a depression, or fall, incorporated into the end-treatment structure or located upstream of the end treatment. The depression is used to exert more head on the throat section for a given headwater elevation. Therefore, an improved end treatment improves culvert performance by providing a more-efficient control section (the throat). An improved end treatment with a fall also improves performance by increasing the head on the throat. The following also applies.

1. An improved end treatment is not recommended for use with a culvert flowing in outlet control because the simple beveled edge is of equal benefit.

2. Design criteria and methods have been developed for two basic end treatment designs -- the side-tapered end treatment and the slope-tapered end treatment.

3. Improved-end-treatment design charts are available for a rectangular box culvert or a circular pipe culvert.

4. The use of an improved end treatment must be accompanied by an economic justification for its use, subject to the approval of the Hydraulics Engineer.

31-9.02 Side-Tapered

The side-tapered end treatment has an enlarged face section with the transition to the culvert barrel accomplished by tapering the side walls (Figure 31-9A, Side-Tapered End Treatment). The face section is approximately the same height as the barrel height and the inlet floor is an

extension of the barrel floor. The end treatment roof may slope upward slightly, provided that the face height does not exceed the barrel height by more than 10 percent (1.1*D*). The intersection of the tapered sidewalls and the barrel is defined as the throat section.

There are two possible control sections: the face and the throat. HW_f, shown in Figure 31-9A, is the headwater depth measured from the face section invert. HW_t is the headwater depth measured from the throat section invert. The throat of a side-tapered end treatment is a very efficient control section. The flow contraction is nearly eliminated at the throat. The throat is always slightly lower than the face so that more head is exerted on the throat for a given headwater elevation.

The beneficial effect of depressing the throat section below the streambed can be increased by installing a depression upstream of the side-tapered end treatment. See Figure 31-9B, Side-Tapered End Treatment (Upstream Depression Contained Between Wingwalls). For this type of depression, the floor of the barrel should extend upstream from the face a minimum distance of *D*/2 before sloping upward more steeply. The length of the resultant upstream crest where the slope of the depression meets the streambed should be checked to ensure that the crest will not control the flow at the design flow and headwater. If the crest length is too short, the crest may act as a weir control section.

31-9.03 Slope-Tapered

The slope-tapered end treatment also has an enlarged face section with tapered sidewalls meeting the culvert-barrel walls at the throat section (Figure 31-9C, Slope-Tapered End Treatment with Vertical Face). A vertical fall is incorporated into the end treatment between the face and throat sections. The fall concentrates more head on the throat section. At the location where the steeper slope of the end treatment intersects the flatter slope of the barrel, a third section, designated the bend section, is formed.

A slope-tapered end treatment has three possible control sections: the face, the bend, and the throat. Of these, only the dimensions of the face and the throat section are determined by the design procedures included herein. The size of the bend section is established by locating it a minimal distance upstream from the throat so that it will not control the flow.

The slope-tapered end treatment combines an efficient throat section with additional head on the throat. The face section does not benefit from the fall between the face and throat; therefore, the face sections of the end treatment are larger than the face sections of an equivalent depressed side-tapered end treatment. The required face size can be reduced by the use of bevels or other favorable edge configurations. See Figure 31-9C, Slope-Tapered End Treatment with Vertical Face.

The slope-tapered end treatment is the most complex inlet improvement recommended herein. Construction difficulties are inherent, but the benefits in increased performance can be significant. With proper design, a slope-tapered end treatment passes more flow at a given headwater elevation than another configuration. A slope-tapered end treatment can be applied to either a box culvert or a circular-pipe culvert. For the latter application, a square to round transition is used to connect the rectangular slope-tapered end treatment to the circular end-treatment pipe.

31-9.04 Hydraulic Design

31-9.04(01) Inlet Control

A tapered end treatment's control sections include the face, the bend (for a slope-tapered end treatment), and the throat. A depressed side-tapered end treatment has a possible control section at the crest upstream of the depression. Each of these inlet-control sections has an individual performance curve. The headwater depth for each control section is referenced to the invert of the section. One method of determining the overall inlet-control performance curve is to calculate performance curves for each potential control section, and then select the segment of each curve which defines the minimum overall culvert performance. See Figure 31-9D, Inlet-Control Performance Curves (Schematic).

1. Side-Tapered End Treatment. The throat should be designed to be the primary control section for the design range of flows and headwaters. Because the throat is only slightly lower than the face, it is likely that the face section will function as a weir or an orifice with downstream submergence within the design range. At a lower flow rate and headwater, the face will usually control the flow.

2. Slope-Tapered End Treatment. The throat can be the primary control section with the face section submerged or unsubmerged. If the face is submerged, the face acts as an orifice with downstream submergence. If the face is unsubmerged, the face acts as a weir, with the flow plunging into the pool formed between the face and the throat. The bend section will not act as the control section if the dimensional criteria described herein are followed. However, the bend will contribute to the inlet losses which are included in the inlet loss coefficient, K_E.

31-9.04(02) Outlet Control

If a culvert with a tapered end treatment performs in outlet control, the hydraulics are the same as described in Section 31-5.0 for all culverts. The tapered-end-treatment entrance loss coefficient, K_E, is 0.2 for a side-tapered or a slope-tapered end treatment. This loss coefficient includes

contraction and expansion losses at the face, increased friction losses between the face and the throat, and the minor expansion and contraction losses at the throat.

31-9.05 Design Methods

Tapered end treatment design begins with the selection of the culvert-barrel size, shape, and material. The calculations are performed using the Culvert Design Form provided in Section 31-10.0. The design nomographs included in HDS #5 are used to design the tapered end treatment. The design procedure is similar to designing a culvert with other control sections (face and throat). The result will be one or more culvert designs, with or without tapered end treatments, all of which satisfy the site design criteria. The designer must select the best design for the site under consideration.

The goal is to maintain control at the efficient throat section in the design range of headwater and discharge. This is because the throat section has the same geometry as the barrel, and the barrel is the most costly part of the culvert. The end-treatment face is then sized large enough to pass the design flow without acting as a control section in the design discharge range. Some slight oversizing of the face is beneficial because the cost of constructing the tapered end treatment is minor compared with the cost of the barrel.

Performance curves should be considered in understanding the operation of a culvert with a tapered end treatment. Each potential control section (face, throat, or outlet) has a performance curve, based on the assumption that a specific section controls the flow. Calculating and plotting the performance curves results in a graph similar to that shown in Figure 31-9E, Culvert Performance Curve (Schematic), including the face control, throat control, and outlet control curves. The overall culvert-performance curve is represented by the hatched line. In the range of lower discharges, face control governs. In the intermediate range, throat control governs. In the higher discharge range, outlet control governs. The crest and bend performance curves are not calculated because they do not govern in the design range.

31-10.0 TABLES AND FORMS

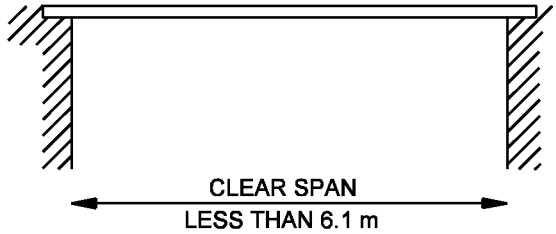
Section 31-10.0 includes the figures as follows.

- 31-10A Recommended Manning's *n* Value. These are the recommended Manning's *n* values used in the hydraulic design of a culvert.
- 31-10B Entrance Loss Coefficient (Outlet Control, Full or Partly Full). This coefficient, K_E, is for a culvert based on the type of entrance.
- 31-10C Entrance Loss Coefficient (Standard INDOT Culvert). This coefficient, K_E, is for a specific culvert as shown on the INDOT *Standard Drawings*.

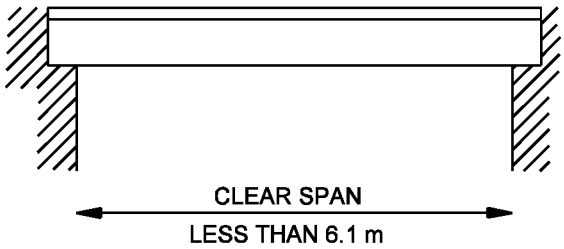
Editable versions of the following forms may also be found on the Department's website at www.in.gov/dot/div/contracts/design/dmforms/.

31-10D	Culvert Design Form, Conventional End Treatment
31-10E	Culvert Design Form, Tapered End Treatment
31-10F	Culvert Design Form, Mitered End Treatment

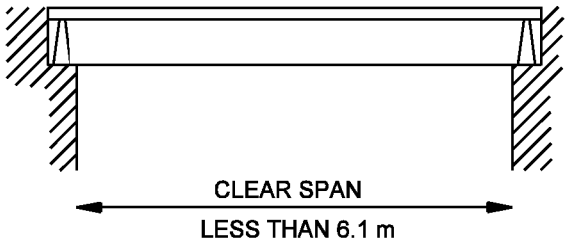
CONCRETE SLABS



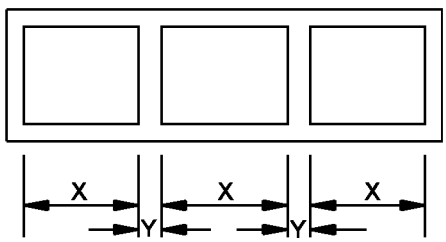
CONCRETE BEAMS OR GIRDERS
OR STEEL BEAMS EMBEDDED
IN THE BACKWALL



STEEL BEAMS OR GIRDERS OR
CONCRETE BEAMS ON BEARINGS

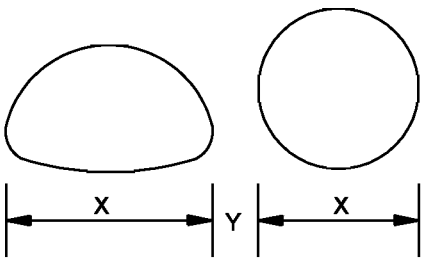


CONCRETE BOX CULVERT
AT GRADE OR UNDER FILL
(ONE OR MULTI-SPAN)



X + Y + X... = LESS THAN 6.1 m

METAL PIPE UNDER FILL
(ONE OR MULTI-SPAN)



X + Y + X... = LESS THAN 6.1 m

MAXIMUM SPAN LENGTHS FOR CULVERTS

Figure 31-1A

Symbol	Definition	Unit
A	Area of cross section of flow	m^2
AHW	Allowable headwater	m
B	Barrel width	mm or m
BW	Backwater	m
D	Culvert diameter or barrel height	mm or m
d	Depth of flow	m
d_C	Critical depth of flow	m
g	Acceleration due to gravity	m/s^2
H	Sum of $H_E + H_f + H_O$	m
H_b	Bend head loss	m
H_E	Entrance head loss	m
H_f	Friction head loss	m
H_L	Total energy losses	m
H_O	Outlet or exit head loss	m
H_V	Velocity head	m
h_O	Hydraulic grade line height above outlet invert	m
HW	Headwater depth (subscript indicates section)	m
K_E	Entrance-loss coefficient	--
L	Length of culvert	M
n	Manning's roughness coefficient	--
P	Wetted perimeter	m
Q	Rate of discharge	m^3/s
R	Hydraulic radius (A/P)	m
S	Slope of culvert	m/m
TW	Tailwater depth above invert of culvert	m
V	Mean velocity of flow with barrel full	m/s
V_d	Mean velocity in downstream channel	m/s
V_O	Mean velocity of flow at culvert outlet	m/s
V_U	Mean velocity in upstream channel	m/s
γ	Unit weight of water	N/m^3
τ	Tractive force	Pa

CULVERT EQUATION SYMBOLS

Figure 31-1B

Functional Classification	Allowable Backwater	Roadway Serviceability	Allowable Velocity
Freeway	Q_{100}	Q_{100}	Q_{50}
Non-Freeway ≥ 4 Lanes	Q_{100}	Q_{100}	Q_{50}
Two-Lane Facility			
AADT ≥ 3000	Q_{100}	Q_{100}	Q_{50}
3000 > AADT ≥ 1000	Q_{100}	Q_{25}	Q_{25}
AADT < 1000	Q_{100}	Q_{10}	Q_{10}
Drive	Q_{100}	Q_{10}	Q_{10}

Note: The design-storm frequency for a culvert-extension structure is identical to that for a new culvert structure. Traffic volume is for a 20-year projection.

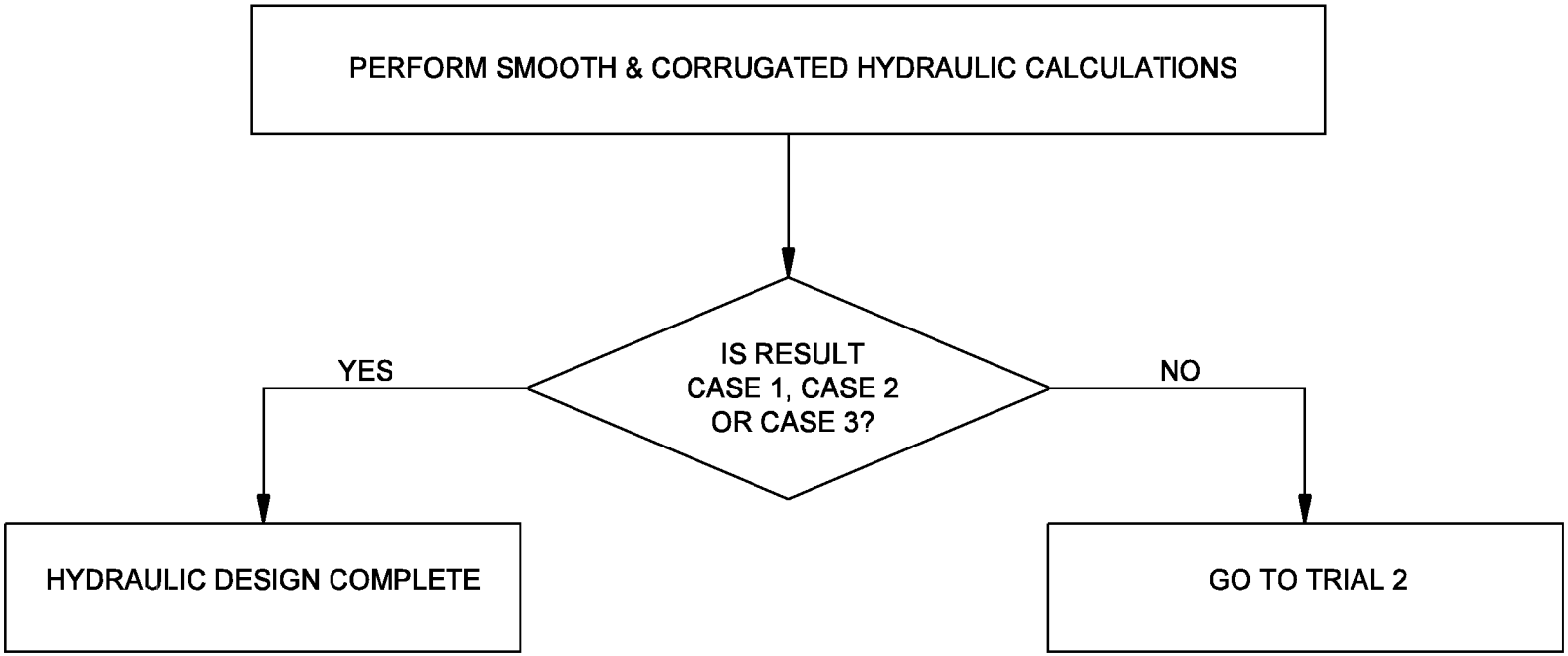
DESIGN-STORM FREQUENCY, CULVERT

Figure 31-3A

Structure Application	Minimum Circular-Pipe Size	Minimum Deformed-Pipe Area
Drive	375 mm	0.10 m^2
Mainline or Public-Road Approach (2 lanes)	375 mm	0.10 m^2
Mainline or Public-Road Approach (≥ 3 Lanes)	900 mm	0.60 m^2

MINIMUM PIPE-CULVERT SIZE

Figure 31-3B

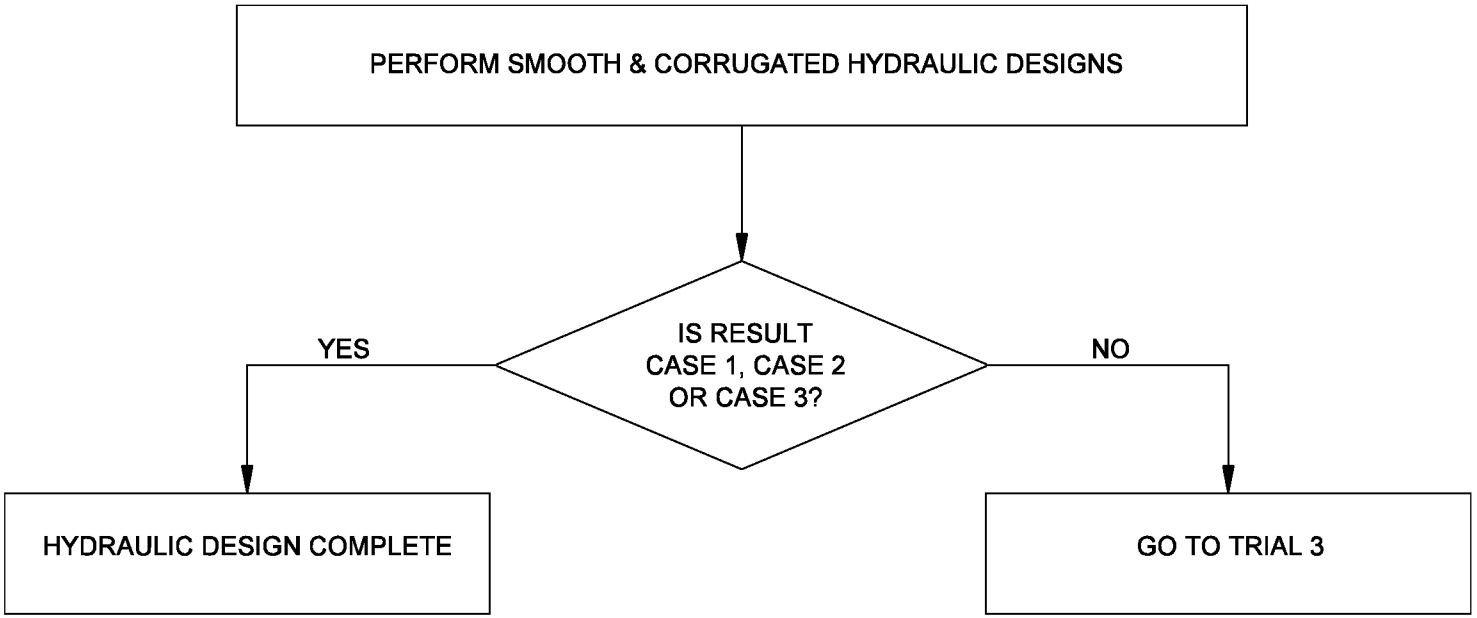


LEGEND

CASE 1 - REQUIRED SMOOTH AND CORRUGATED PIPE SIZES ARE IDENTICAL
CASE 2 - REQUIRED SMOOTH AND CORRUGATED PIPE SIZES ARE DIFFERENT
CASE 3 - THERE IS AN ACCEPTABLE PIPE SIZE FOR ONE INTERIOR TYPE, BUT NO ACCEPTABLE PIPE SIZE CAN BE FOUND FOR THE REMAINING INTERIOR TYPE

CULVERTS DESIGN PROCESS
(Trial 1 - Single Circular Pipe)

Figure 31-3C

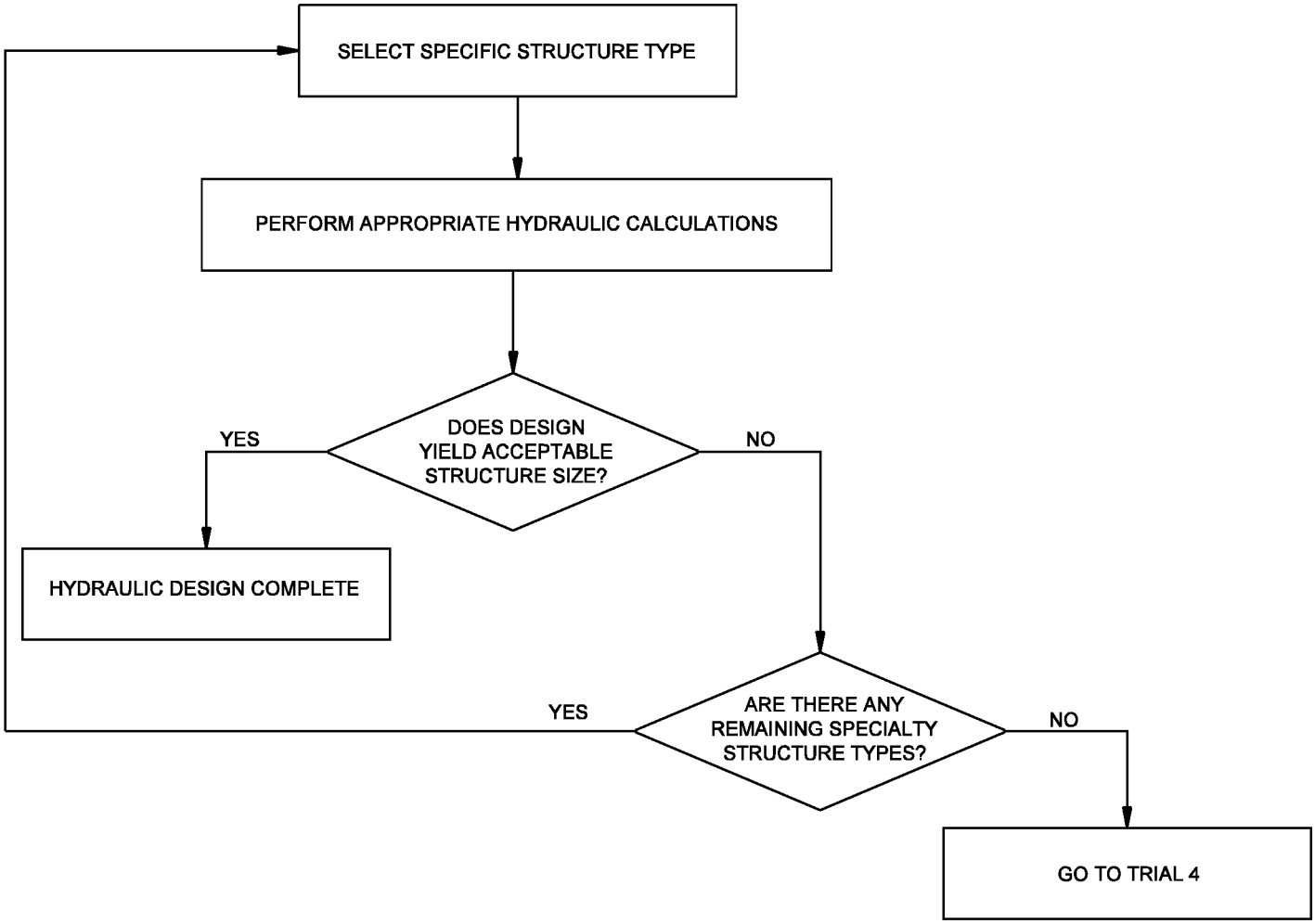


LEGEND

CASE 1 - REQUIRED SMOOTH AND CORRUGATED PIPE SIZES ARE IDENTICAL
CASE 2 - REQUIRED SMOOTH AND CORRUGATED PIPE SIZES ARE DIFFERENT
CASE 3 - THERE IS AN ACCEPTABLE PIPE SIZE FOR ONE INTERIOR TYPE, BUT NO ACCEPTABLE PIPE SIZE CAN BE FOUND FOR THE REMAINING INTERIOR TYPE

CULVERT DESIGN PROCESS
(Trial 2 - Single Deformed Pipe)

Figure 31-3D

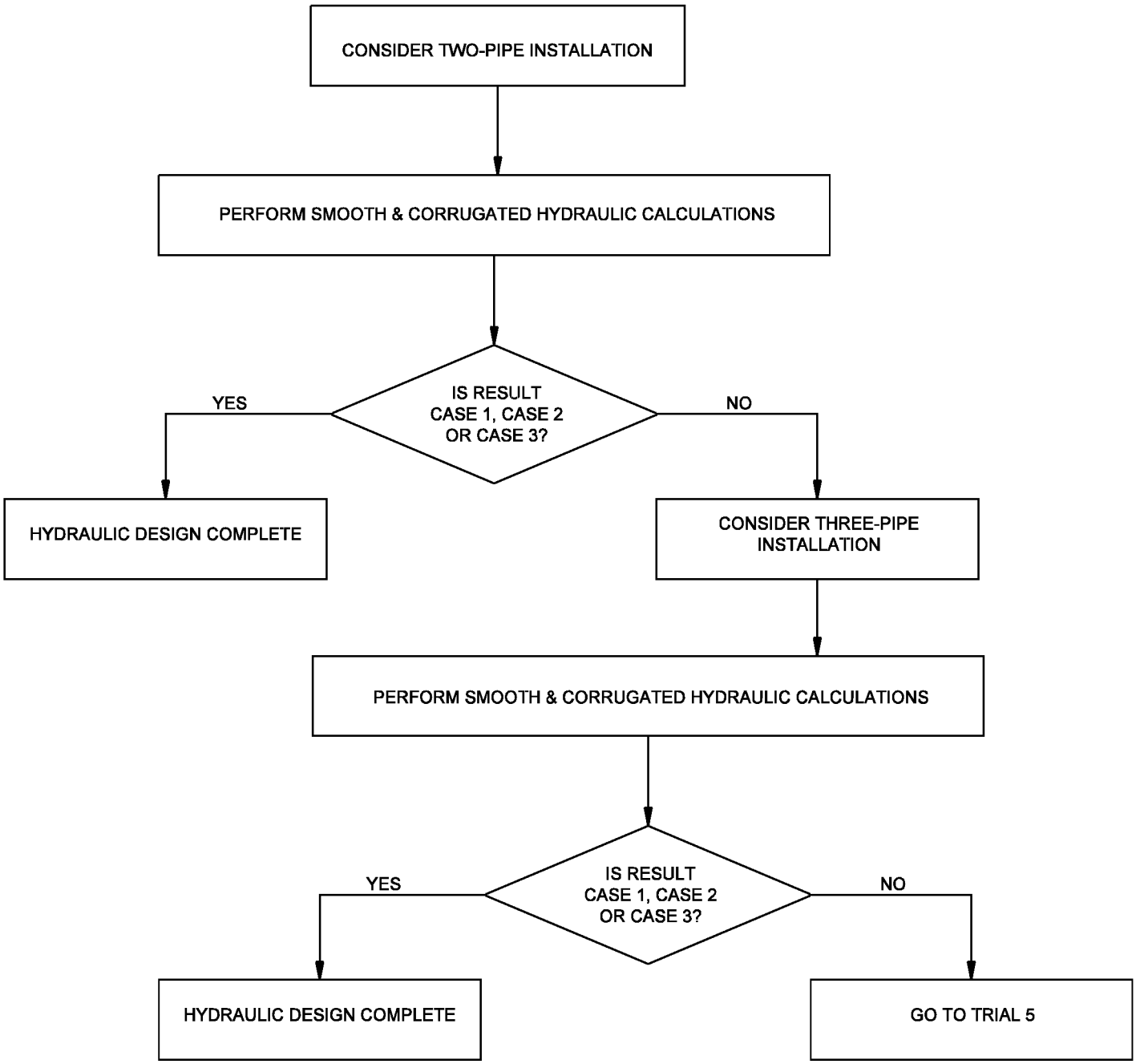


SPECIALTY STRUCTURE TYPES ARE TO BE CONSIDERED IN FOLLOWING ORDER:

1. PRECAST REINFORCED CONCRETE BOX SECTIONS
2. PRECAST REINFORCED CONCRETE THREE-SIDED CULVERT
3. STRUCTURAL PLATE ARCH
4. OTHER STRUCTURE TYPE APPROVED BY HYDRAULICS UNIT

CULVERT DESIGN PROCESS
(Trial 3 - Single Specialty Structure)

Figure 31-3E

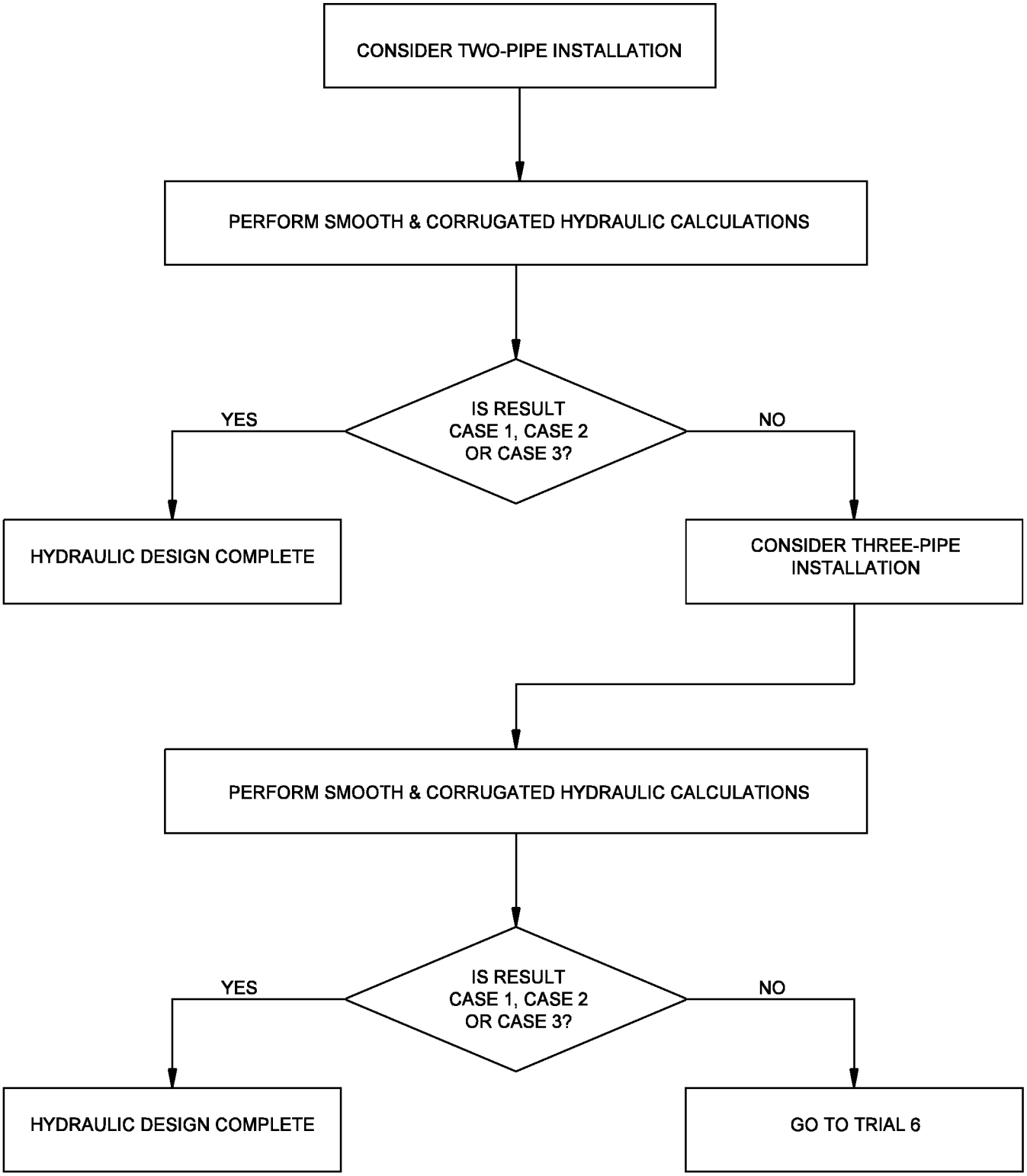


LEGEND

CASE 1 - REQUIRED SMOOTH AND CORRUGATED PIPE SIZES ARE IDENTICAL
CASE 2 - REQUIRED SMOOTH AND CORRUGATED PIPE SIZES ARE DIFFERENT
CASE 3 - THERE IS AN ACCEPTABLE PIPE SIZE FOR ONE INTERIOR TYPE, BUT NO ACCEPTABLE PIPE SIZE CAN BE FOUND FOR THE REMAINING INTERIOR TYPE

CULVERT DESIGN PROCESS
(Trial 4 - Multiple Circular Pipes)

Figure 31-3F



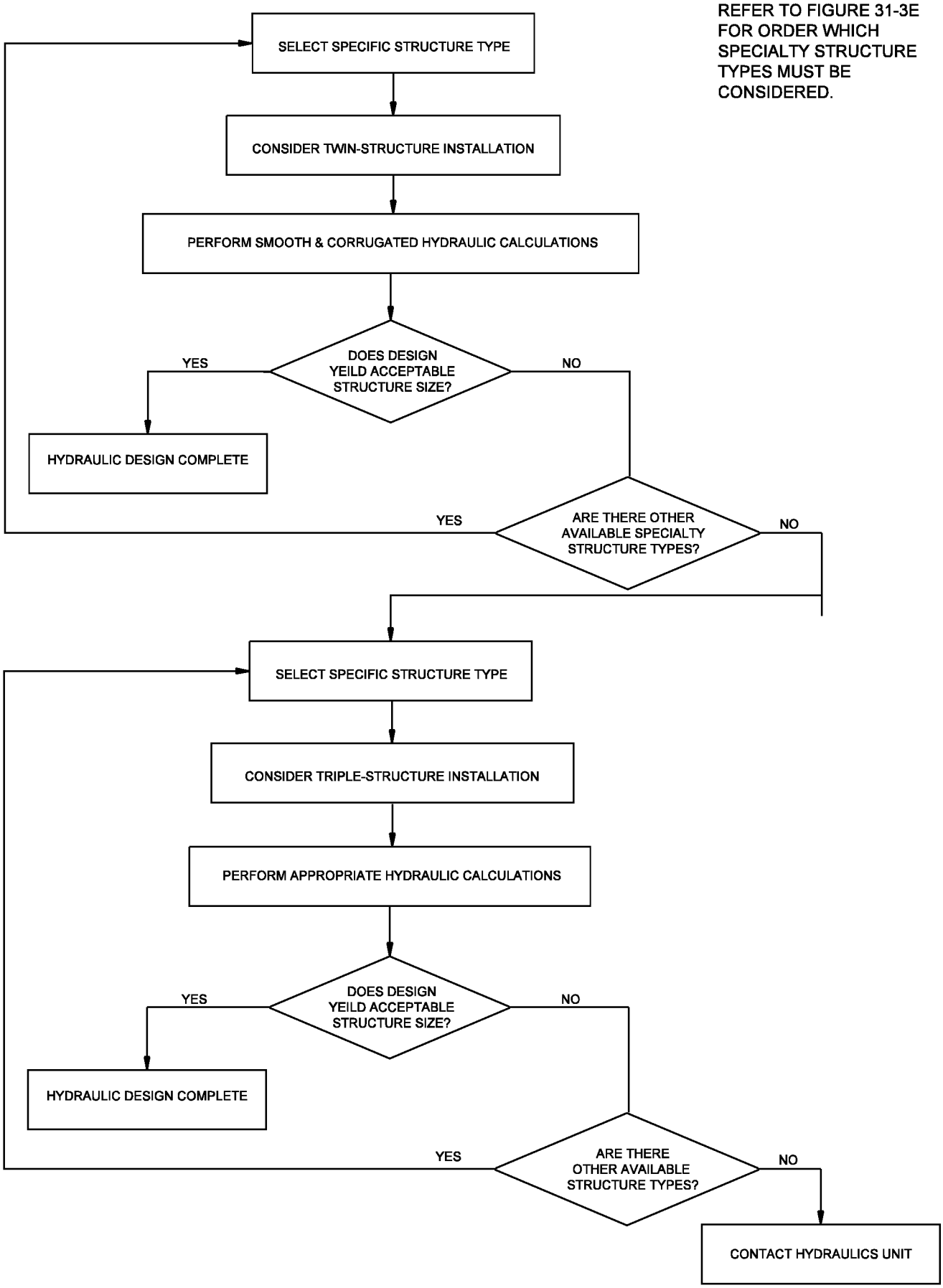
LEGEND

CASE 1 - REQUIRED SMOOTH AND CORRUGATED PIPE SIZES ARE IDENTICAL
CASE 2 - REQUIRED SMOOTH AND CORRUGATED PIPE SIZES ARE DIFFERENT
CASE 3 - THERE IS AN ACCEPTABLE PIPE SIZE FOR ONE INTERIOR TYPE, BUT NO ACCEPTABLE PIPE SIZE CAN BE FOUND FOR THE REMAINING INTERIOR TYPE

CULVERT DESIGN PROCESS
(Trial 5 - Multiple Deformed Pipes)

Figure 31-3G

REFER TO FIGURE 31-3E FOR ORDER WHICH SPECIALTY STRUCTURE TYPES MUST BE CONSIDERED.



CULVERT DESIGN PROCESS
(Trial 6 - Multiple Specialty Pipes)

Figure 31-3H

CULVERT INSPECTION REPORT

ROUTE R.P. DISTRICT:

INVENTORY DATA

NO. LANES: CLEARANCE: FILL:

DESCRIPTION:

CULVERT NO. - -

(route)-(co. no.)-(r.p.)

ROADWAY ITEMS – RATING	COMMENTS
ALIGNMENT	
PAVEMENT	
SHOULDERS	
EMBANKMENT	
OVERALL	

CULVERT ITEMS – RATING	COMMENTS
HEADWALLS	
WINGWALLS	
BARREL / BOX	
SETTLEMENT	
OVERALL	

CHANNEL ITEMS – RATING	COMMENTS
ALIGNMENT	
EROSION	
SCOUR	
DRIFT / SEDMT.	
ADEQUACY	
OVERALL	

OVERALL RATING:

MX. NEEDED

INSTIP CODE

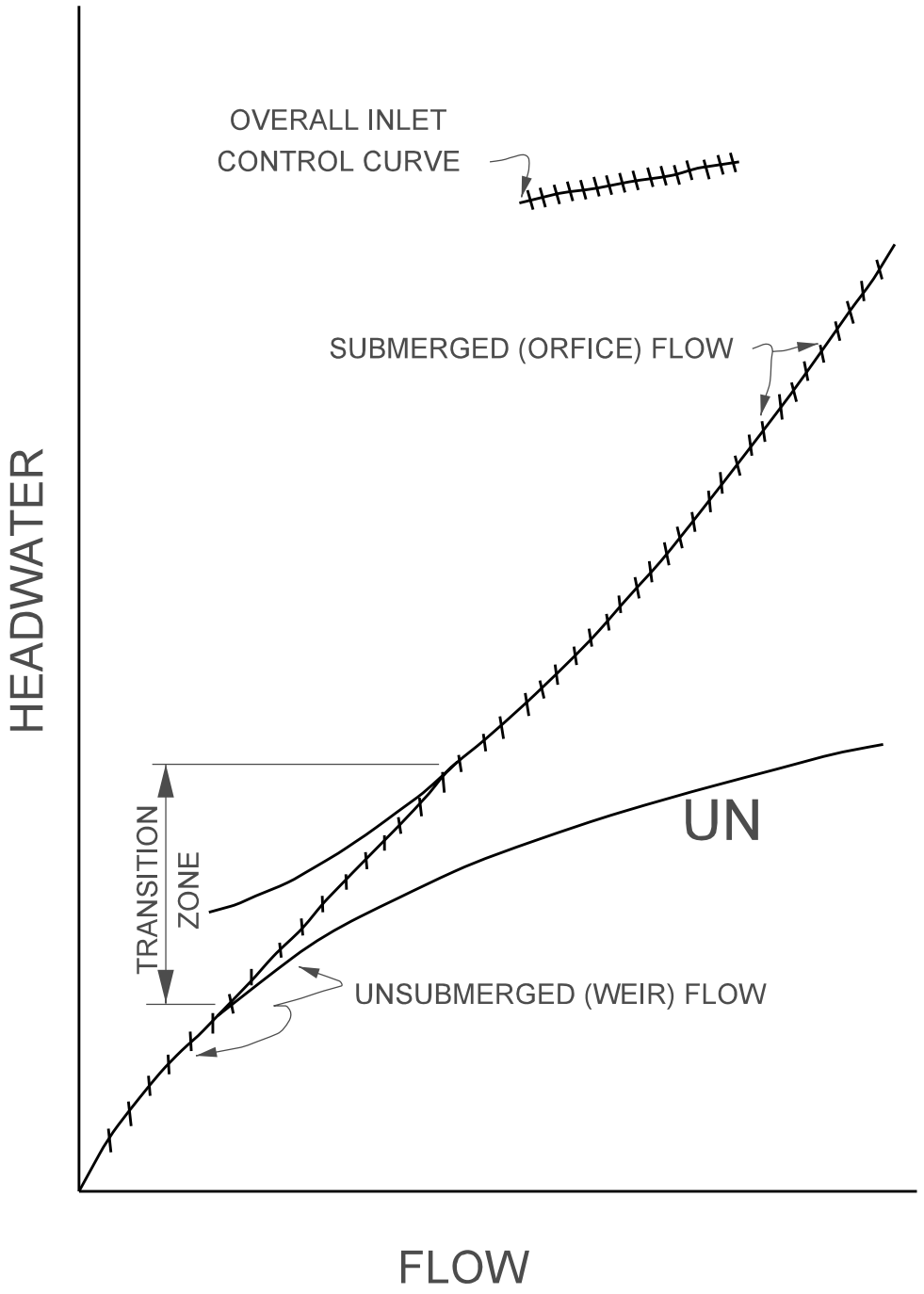
INSTIP Codes: 0 = No Work Needed. 1 = Replace Structure by Contract. 2 = Repair Structure by Contract.

INSPECTOR: DATE:

RISE	1.22 m		1.52 m		1.83 m		2.30 m		2.44 m	
SPAN	Mass, Mg/m	Lgth., m	Mass, Mg/m	Lgth., m	Mass, Mg/m	Lgth., m	Mass, Mg/m	Lgth., m	Mass, Mg/m	Lgth., m
4.27 m	9.38	1.83	9.82	1.83	11.61	1.83	10.71	1.83	12.50	1.83
4.88 m	10.27	1.83	10.27	1.83	12.05	1.52	11.16	1.52	12.95	1.52
5.49 m	11.16	1.52	10.71	1.52	12.50	1.52	11.61	1.52	13.39	1.52
6.10 m	12.05	1.52	11.16	1.52	12.95	1.52	12.05	1.52	13.84	1.22

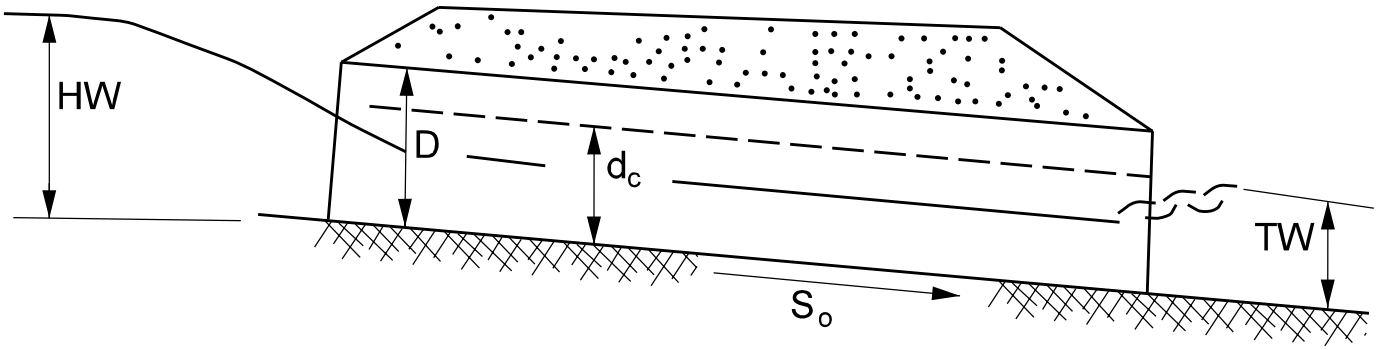
OVERSIZE-BOX-CULVERT SEGMENTS MASS AND LENGTH

Figure 31-4B



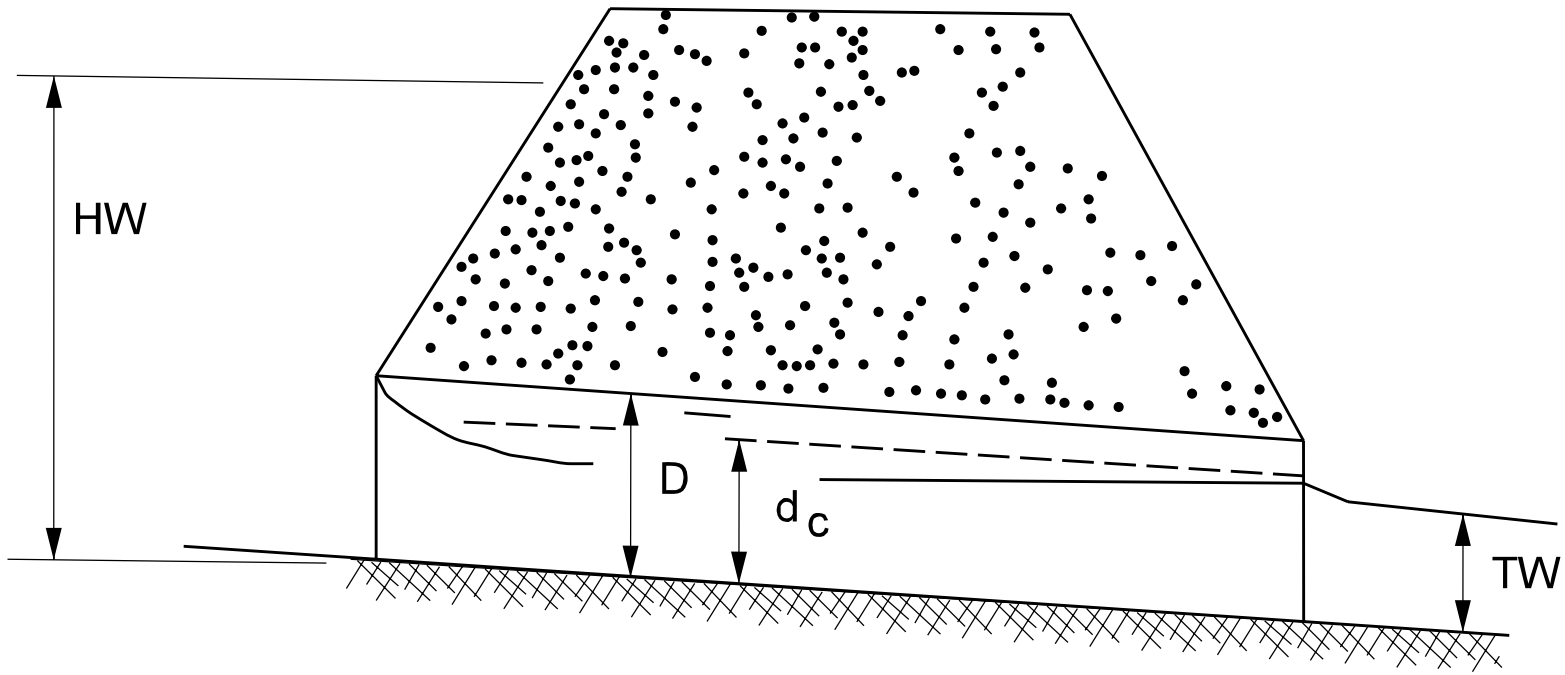
UNSUBMERGED, SUBMERGED AND TRANSITION

Figure 31-5A



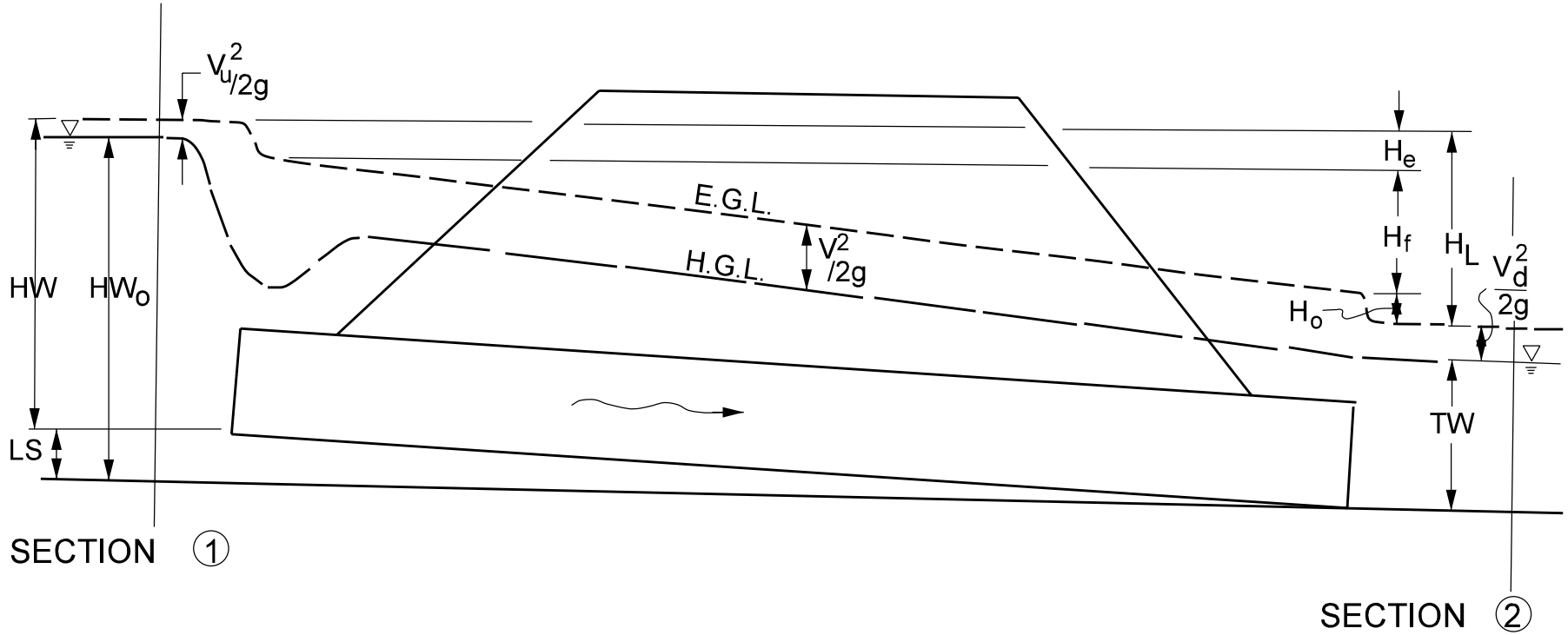
FLOW TYPE I

Figure 31-5B



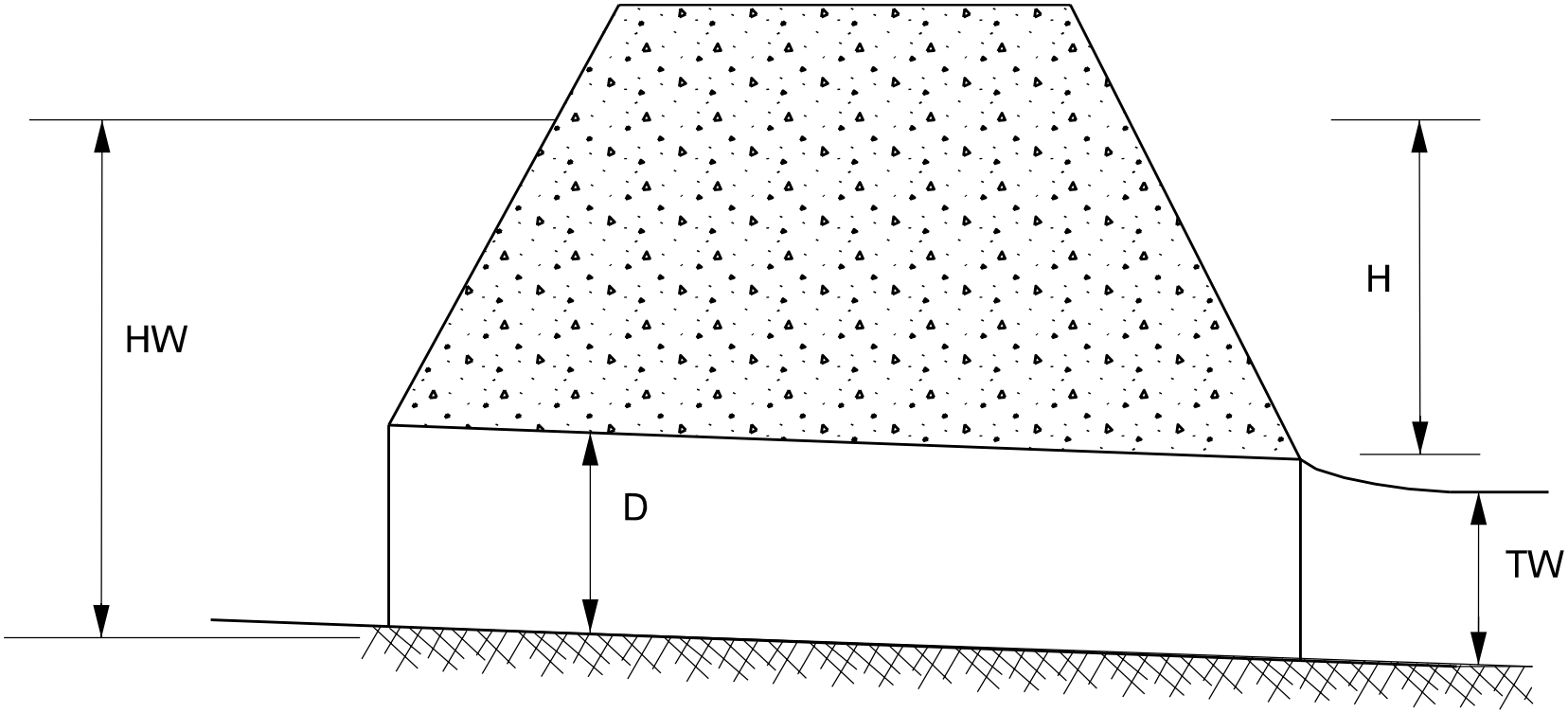
FLOW TYPE V

Figure 31-5C



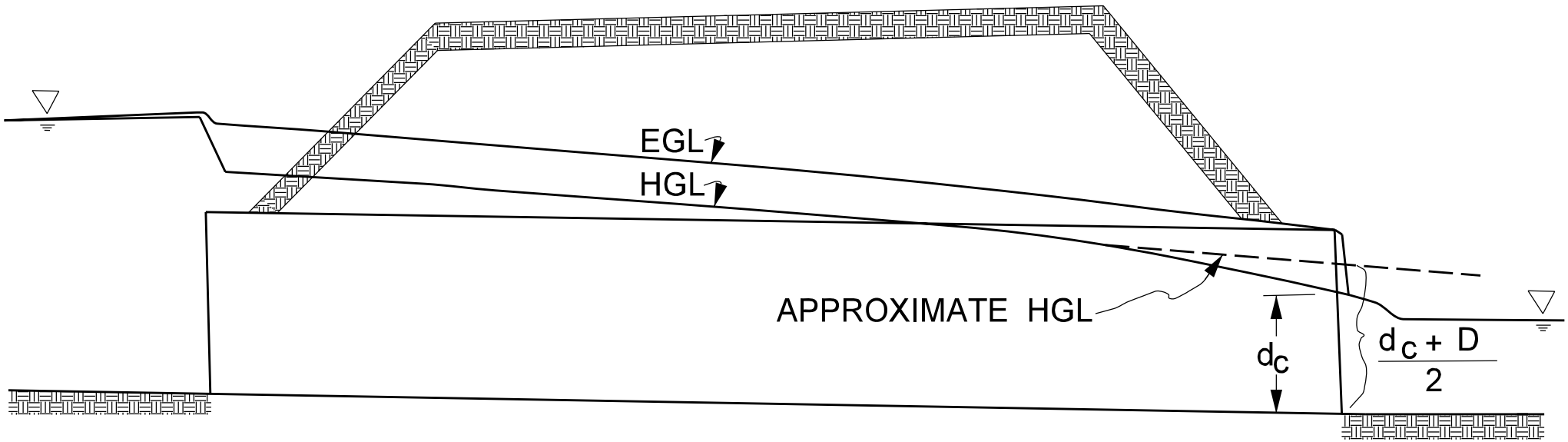
FLOW TYPE IV

Figure 31-5D



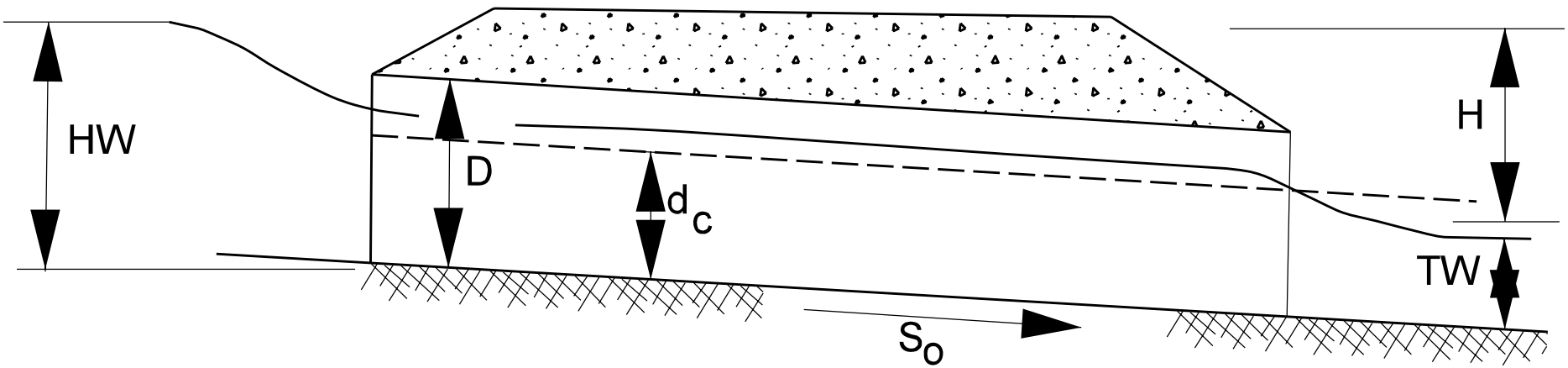
FLOW TYPE VI

Figure 31-5E



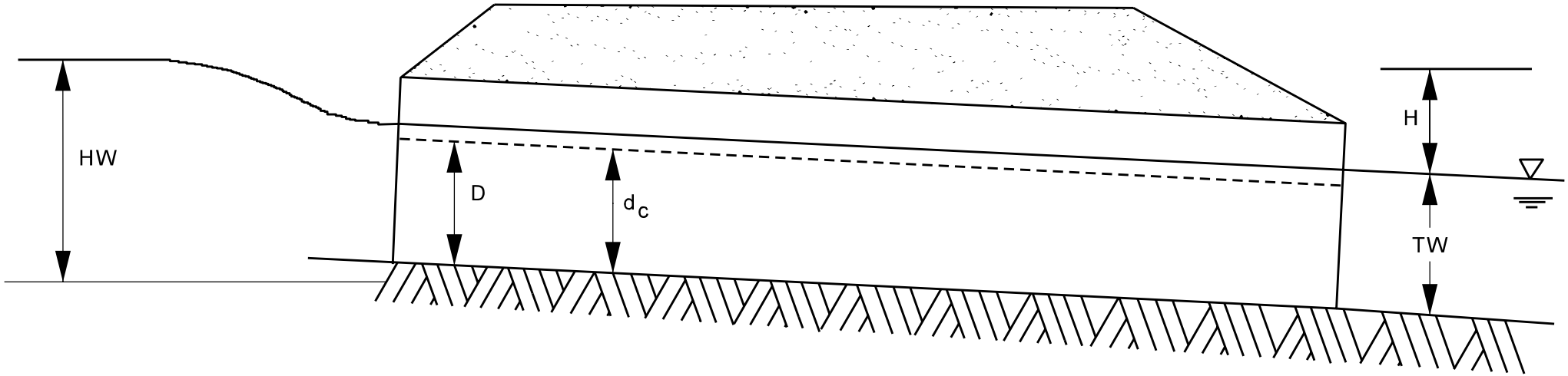
FLOW TYPE VII

Figure 31-5F



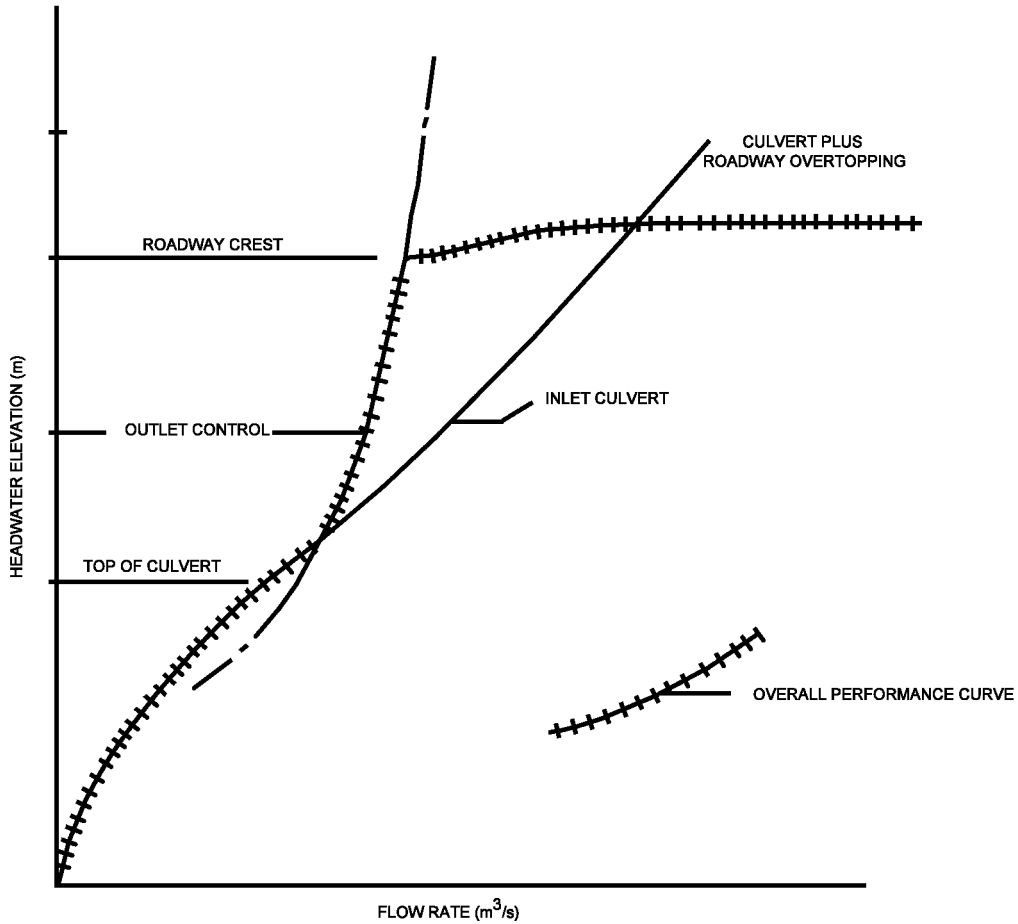
FLOW TYPE II, TW < d_C

Figure 31-5G



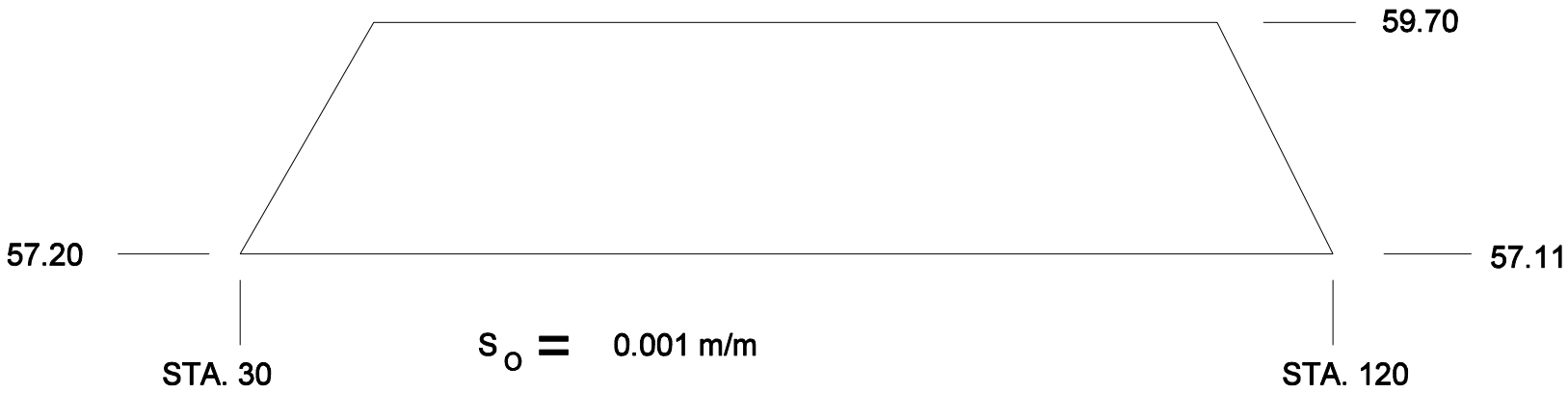
FLOW TYPE III, TW > d_c

Figure 31-5H



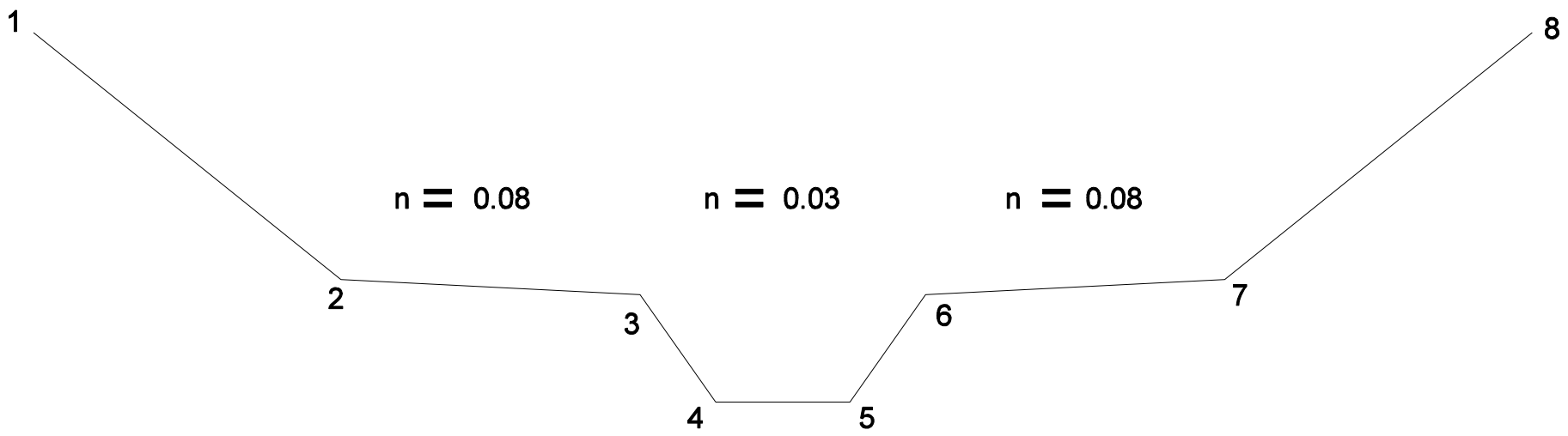
OVERALL PERFORMANCE CURVE

Figure 31-5l



NOMOGRAPH DESIGN EXAMPLE - SITE DATA

Figure 31-7.1



NOMOGRAPH DESIGN EXAMPLE DOWNSTREAM CHANNEL SECTION

Figure 31-7.2

PROJECT: Example Problem Nomograph	STATION: Test SHEET 1 OF 1	CULVERT DESIGN FORM DESIGNER/DATE: _____ OF ____ REVIEWER/DATE: _____ OF ____

HYDROLOGICAL DATA

SEE ADD=L. SHEETS

☒ METHOD: USGS
☐ DRAINAGE AREA: _____ ☐ STREAM SLOPE: _____
☐ CHANNEL SHAPE: _____
☐ ROUTING: _____ ☐ OTHER: _____

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (m^3/s)	TW (m)
50	3.78	0.94
100	4.20	0.99

See Figure 31-7A(1) for Details

CULVERT DESCRIPTION: MATERIAL-SHAPE-SIZE-ENTRANCE	TOTAL FLOW Q (m^3/s)	FLOW PER BARREL Q/N (1)	HEADWATER CALCULATIONS											CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
			INLET CONTROL				OUTLET CONTROL									
			HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	TW (5)	d_c	$\frac{d_c + D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)			
Trial 1: Single RCP or CMP 1500 mm	4.2	4.2	1.16	1.74	-	58.94		No	Good							Case 4
Trial 2: Single Deformed Conc. 2495 x 1585	4.2	4.2	0.75	1.19	-	58.39		No	Good							Case 4
Trial 2: Single CSP-A 1800 x 1200	4.2	4.2	1.55	1.86	-	59.06		No	Good							Case 4
Trial 3: RCB 3300 x 1200	4.2	4.2	0.71	0.85	-	58.05	0.99	0.52	0.86	0.99	0.5	0.12	58.22	58.22	1.29	Looks OK

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) HW_i/D = HW/D OR HW_t/D FROM DESIGN CHARTS

FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(3) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(4) TW BASED ON DOWNSTREAM CONTROL OR FLOW DEPTH IN CHANNEL

(6) h_o = TW or $(d_c + D)/2$ (WHICHEVER IS GREATER)

(7) $H = (1+k_e+(19.63\ n^2L)/R^{1.33})\ V^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUSCRIPT DEFINTIIONS:

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:

This is an approximate solution because box not flowing full. Check with microcomputer HY8 for exact solution.

CULVERT BARREL SELECTED:

SIZE: 3300 x 1200

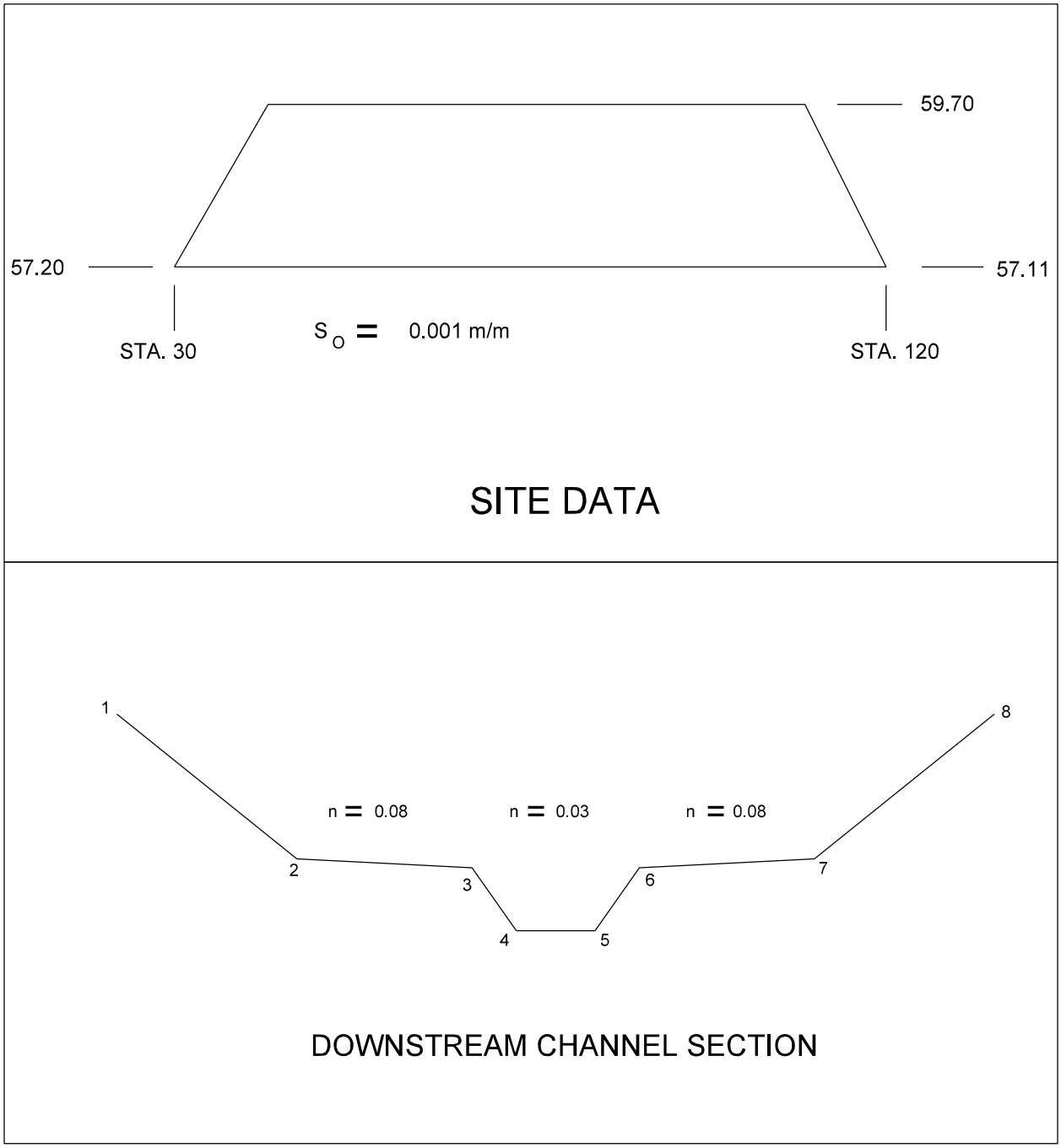
SHAPE: RCB

MATERIAL: Concrete n: 0.012

ENTRANCE: Conventional Bevel

CHART 17 AND PERFORMANCE CURVE FOR DESIGN EXAMPLE

Figure 31-7A



NOMOGRAPH DESIGN EXAMPLE

Figure 31-7A(1)

```
FILE NAME: 31833       FHWA CULVERT ANALYSIS        DATE: 10-12-1998
TAILWATER FILE: 3180   HY8, VERSION 6.0             CULVERT NO. 1 OF 1

******* CULVERT DATA SUMMARY ****************************************************

  BARREL SHAPE:            BOX
  BARREL SPAN:             3300 mm
  BARREL RISE:             1200 mm
  BARREL MATERIAL:         CONCRETE
  BARREL MANNING'S n:      0.012
  INLET TYPE:              CONVENTIONAL
  INLET EDGE AND WALL:     1:1 BEVEL (45 DEG. FLARE)
  INLET DEPRESSION:        NONE

       <ENTER> TO CONTINUE       <NUMBER> TO EDIT ITEM

1-Help   2-Prog   3       4       5-End   6       7-Edit  8       9-Dos  10
```

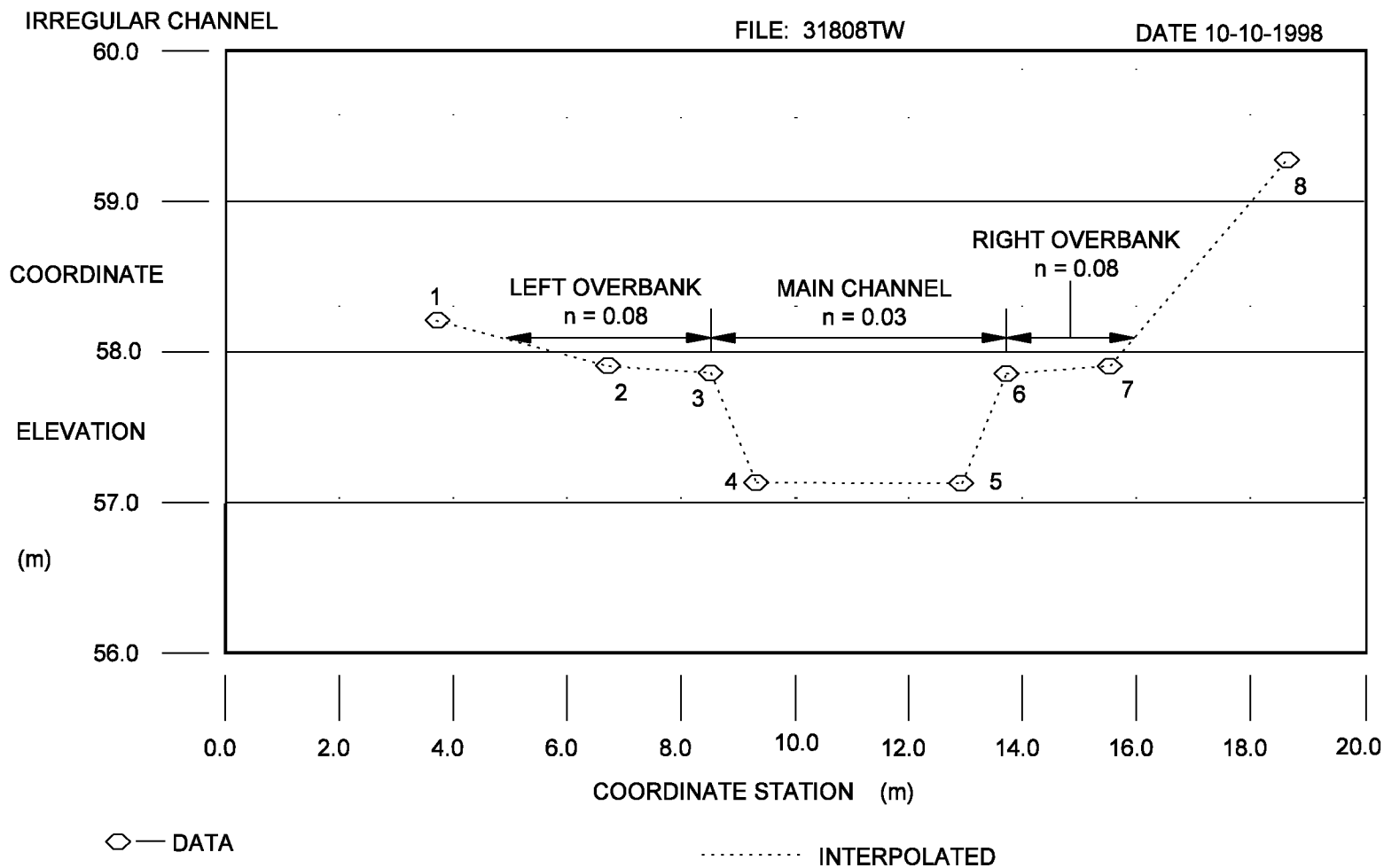
HY8 DATA INPUT PROMPT SCREEN

Figure 31-8A

```
IRREGULAR CHANNEL CROSS-SECTION

CROSS-SECTION    X        Y
COORD. NO.      (m)      (m)
       1         3.70    58.20
       2         6.70    57.90
       3         8.50    57.85
       4         9.30    57.11
       5        12.90    57.11
       6        13.70    57.85
       7        15.50    57.90
       8        18.60    59.27

<NUMBER>  TO EDIT COORDINATES
<I>  <D>  TO INSERT OR DELETE
<ENTER>   TO CONTINUE
<P>       TO PLOT CROSS-SECTION

1-Help  2-Prog  3       4       5-End   6       7       8       9-DOS  10
```

HY8 CHANNEL DATA PROMPT SCREEN

Figure 31-8B



CHANNEL CROSS SECTION

Figure 31-8C

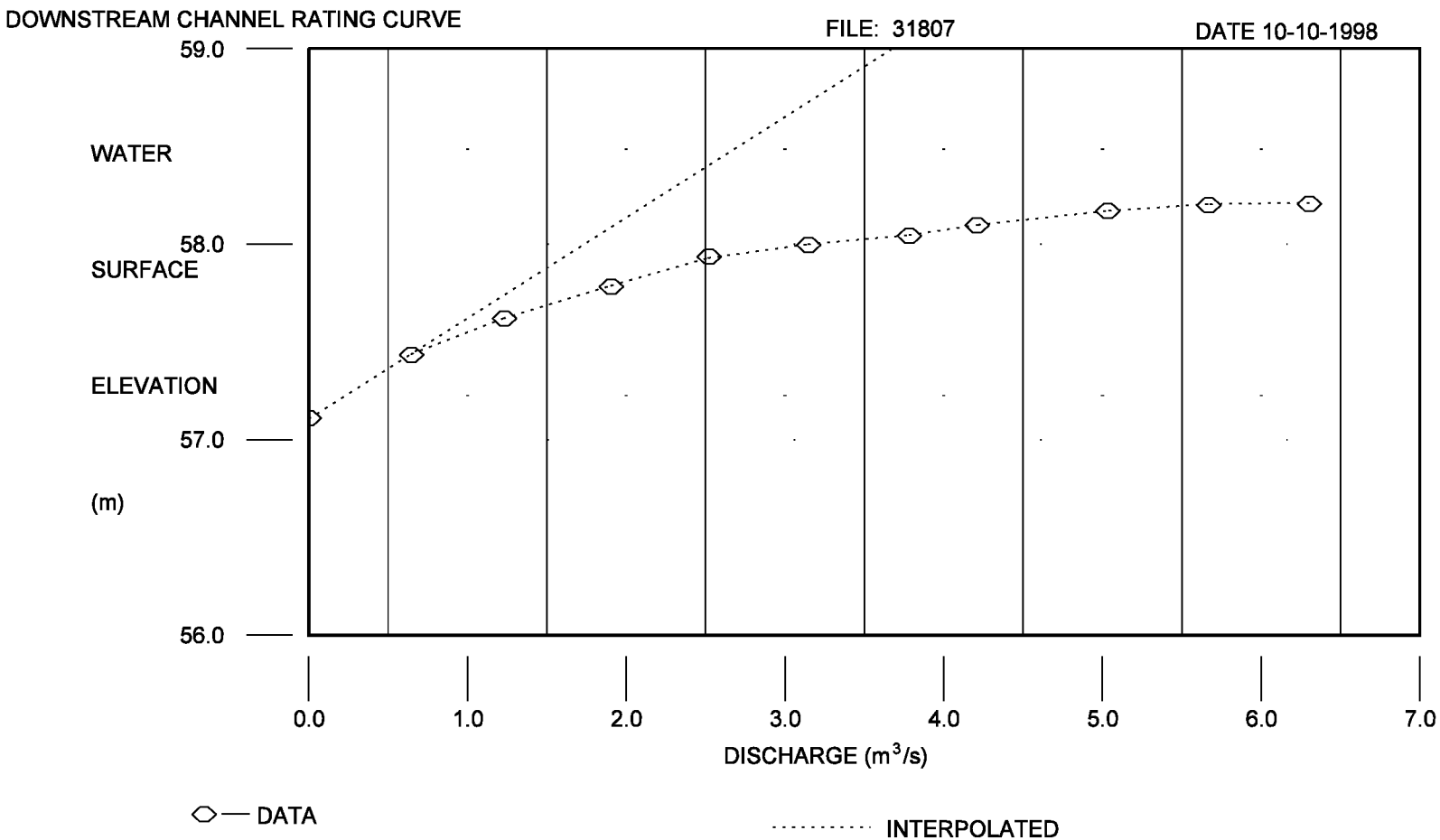
```
CULVERT FILE: EX31803      FHWA CULVERT ANALYSIS         DATE: 10-06-98
TAILWATER FILE: 3180       HY8, VERSION 6.0          CULVERT NO. 1 OF 1

******* UNIFORM FLOW RATING CURVE FOR DOWNSTREAM CHANNEL
```

FLOW (m^3/s)	W.S.E (m)	FROUDE NUMBER	DEPTH (m)	VEL. (m/s)	SHEAR (Pa)
0.00	57.11	0.000	0.00	0.00	0.00
0.63	57.46	0.267	0.35	0.47	2.97
1.26	57.63	0.280	0.52	0.59	4.17
1.89	57.77	0.287	0.66	0.68	5.03
2.52	57.88	0.293	0.77	0.74	5.84
3.15	57.97	0.299	0.86	0.81	6.61
3.78	58.05	0.304	0.94	0.87	7.28
4.20	58.10	0.307	0.99	0.90	7.76
5.04	58.19	0.312	1.08	0.96	8.52
5.67	58.20	0.312	1.09	0.97	8.57
6.30	58.20	0.312	1.09	0.97	8.57

```
Note: Shear stress was calculated using R.

PRESS  <D>    FOR DATA
       <P>    TO PLOT RATING CURVE
       <ESC>  FOR CHANNEL SHAPE MENU
       <ENTER>TO CONTINUE

1-Help  2-Progr 3       4       5-End   6       7       8       9-DOS  10
```

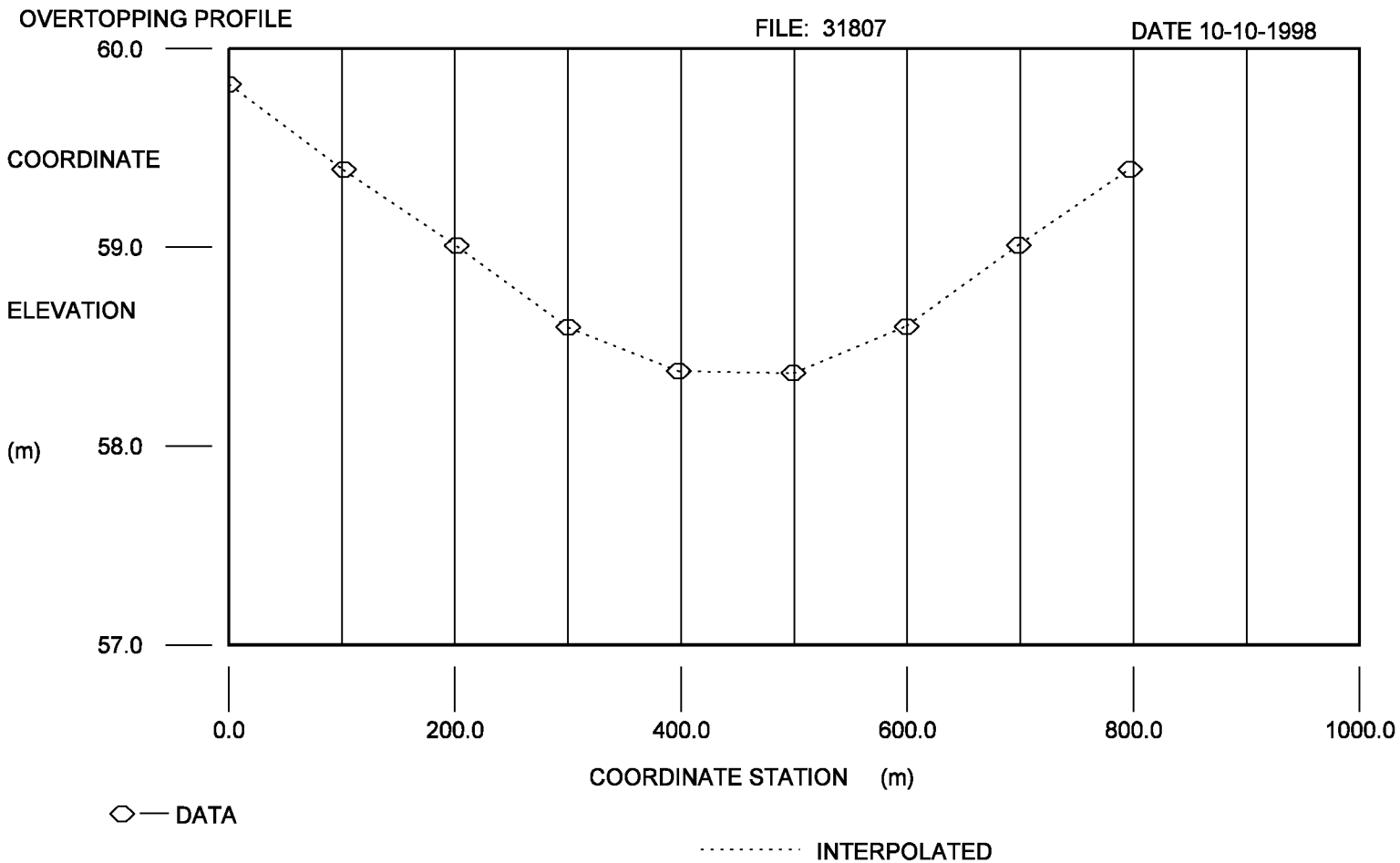
HY8 RATING CURVE PROMPT SCREEN

Figure 31-8D



TAILWATER VS. FLOWRATE

Figure 31-8E



ROADWAY PROFILE

Figure 31-8F

CURRENT DATE: 10-12-1998 FILE DATE: 10-12-1998
CURRENT TIME: 11:34:41 FILE NAME: 31833

FHWA CULVERT ANALYSIS
HY-8, VERSION 6.0

	SITE DATA			CULVERT SHAPE, MATERIAL, INLET				
CULV. NO.	INLET ELEV. (m)	OUTLET ELEV. (m)	CULVERT LENGTH (m)	BARRELS SHAPE MATERIAL	SPAN (mm)	RISE (mm)	MANNING n	INLET TYPE
1	57.20	57.11	90.00	1 RCB	3300	1200	0.012	CONVENTIONAL
2								
3								
4								
5								
6								

```
                    OPTION MENU:      PRESS <LETTER>

          CULVERT FILE                SINGLE CULVERT (NO OVERTOPPING)
          <C> Create                  <S> Calculate
          <E> Edit                    <M> Minimize Width
          <N> Name                    <R> Report - Display or Print
          <D> Directory               <F> File - Save PC and LST files

          AVAILABLE FILES             MULTIPLE CULVERTS & OVERTOPPING
          Culvert:   EX31803.INP      <O> Overtopping
           Output:   EX31803.PC       <R> Report - Display or Print
           Report:   None             <L> List - Save PC and LST files

          DESIGN OPTIONS              DEFAULT OPTIONS
          <H> Hydrograph              <U> Units Used - SI
          <I> Routing                 <W> Outlet Control - Profiles
          <J> Dissipator              <P> Paths for files & Defaults

                       <Enter> for Documentation Menu
                           <Q> Quit

1-Help   2-Progr 3       4       5-End   6       7       8       9-DOS   10
```

HY8 DATA SUMMARY PROMPT SCREEN

Figure 31-8G

PERFORMANCE CURVE FOR CULVERT 1 – One (3300 mm BY 1200 mm) RCB

DIS-CHARGE FLOW (m^3/s)	HEAD-WATER ELEV. (m)	INLET CONTROL DEPTH (m)	OUTLET CONTROL DEPTH (m)	FLOW TYPE <F4>	NORMAL DEPTH (m)	CRIT. DEPTH (m)	OUTLET DEPTH (m)	TW DEPTH (m)	OUTLET VEL. (m/s)	TW VEL. (m/s)
0.00	57.20	0.00	-0.09	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
0.63	57.51	0.23	0.31	3-M1t	0.21	0.16	0.35	0.35	0.55	0.47
1.26	57.70	0.37	0.50	3-Mlt	0.34	0.25	0.52	0.52	0.73	0.59
1.89	57.85	0.48	0.65	3-Mlt	0.44	0.32	0.66	0.66	0.87	0.68
2.52	57.99	0.58	0.78	3-Mlt	0.53	0.39	0.77	0.77	0.98	0.74
3.15	58.11	0.68	0.91	3-Mlt	0.62	0.45	0.86	0.86	1.11	0.81
3.78	58.21	0.77	1.01	3-Mlt	0.70	0.51	0.94	0.94	1.22	0.87
4.20	58.25	0.84	1.05	3-Mlt	0.75	0.55	0.99	0.99	1.28	0.90
5.04	58.37	0.95	1.16	3-Mlt	0.85	0.62	1.08	1.08	1.41	0.96
5.67	58.41	1.04	1.22	3-Mlt	0.92	0.67	1.09	1.09	1.58	0.97
6.30	58.46	1.12	1.26	3-Mlt	0.99	0.72	1.09	1.09	1.75	0.97

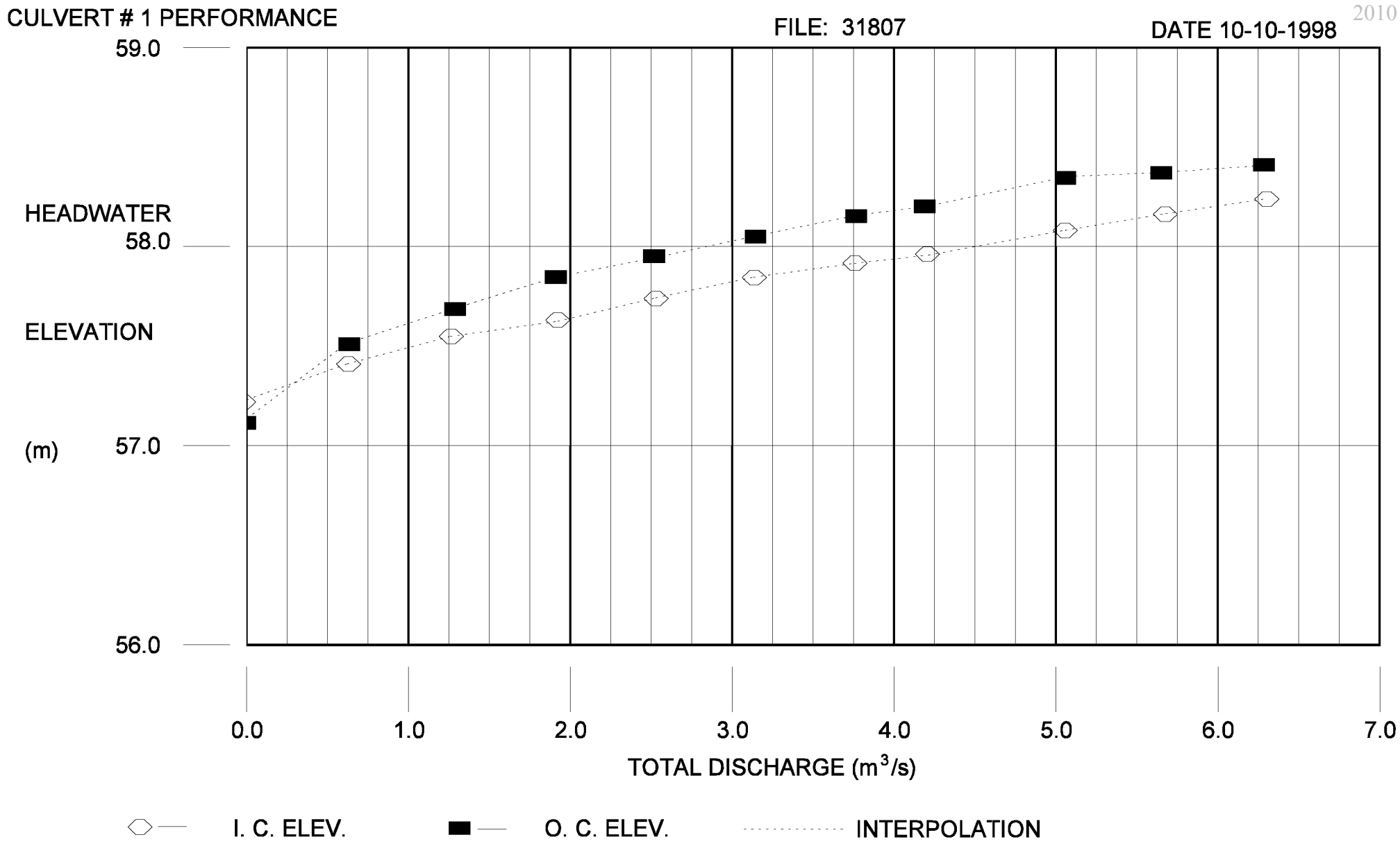
El. inlet face invert 57.20 m El. outlet invert 57.11 m
El. inlet throat invert 0.00 m El. inlet crest 0.00 m

PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
<P> TO PLOT <I> FOR IMPROVED INLET TABLE

1- Help 2 3 4-Type 5-End 6 7 8 9-DOS 10

HY8 PERFORMANCE CURVE PROMPT SCREEN
3300 mm SPAN BY 1200 mm RISE CULVERT

Figure 31-8H



INLET/OUTLET CONTROL HEADWATERS

Figure 31-8 I

PERFORMANCE CURVE FOR CULVERT 1 – One (3600 mm BY 1200 mm) RCB

DIS-CHARGE FLOW (m3/s)	HEAD-WATER ELEV. (m)	INLET CONTROL DEPTH (m)	OUTLET CONTROL DEPTH (m)	FLOW TYPE <F4>	NORMAL DEPTH (m)	CRIT. DEPTH (m)	OUTLET DEPTH (m)	TW DEPTH (m)	OUTLET VEL. (m/s)	TW VEL. (m/s)
0.00	57.20	0.00	-0.09	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
0.63	57.51	0.22	0.31	3-M1t	0.20	0.15	0.35	0.35	0.50	0.47
1.26	57.70	0.35	0.49	3-Mlt	0.31	0.23	0.52	0.52	0.67	0.59
1.89	57.84	0.45	0.64	3-Mlt	0.41	0.30	0.66	0.66	0.80	0.68
2.52	57.97	0.55	0.77	3-Mlt	0.50	0.37	0.77	0.77	0.90	0.74
3.15	58.07	0.64	0.87	3-Mlt	0.58	0.43	0.86	0.86	1.01	0.81
3.78	58.17	0.73	0.97	3-Mlt	0.65	0.48	0.94	0.94	1.12	0.87
4.20	58.23	0.79	1.03	3-Mlt	0.70	0.52	0.99	0.99	1.18	0.90
5.04	58.36	0.89	1.16	3-Mlt	0.79	0.59	1.08	1.08	1.30	0.96
5.67	58.38	0.97	1.18	3-Mlt	0.86	0.63	1.09	1.09	1.45	0.97
6.30	58.42	1.05	1.22	3-Mlt	0.92	0.68	1.09	1.09	1.61	0.97

El. inlet face invert 57.20 m El. outlet invert 57.11 m
El. inlet throat invert 0.00 m El. inlet crest 0.00 m

PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
<P> TO PLOT <I> FOR IMPROVED INLET TABLE

1- Help 2 3 4-Type 5-End 6 7 8 9-DOS 10

HY8 PERFORMANCE CURVE PROMPT SCREEN
3600 mm SPAN BY 1200 mm RISE CULVERT

Figure 31-8J

PERFORMANCE CURVE FOR CULVERT 1 – One (2100 mm BY 1200 mm) RCB

DIS-CHARGE FLOW (m^3/s)	HEAD-WATER ELEV. (m)	INLET CONTROL DEPTH (m)	OUTLET CONTROL DEPTH (m)	FLOW TYPE <F4>	NORMAL DEPTH (m)	CRIT. DEPTH (m)	OUTLET DEPTH (m)	TW DEPTH (m)	OUTLET VEL. (m/s)	TW VEL. (m/s)
0.00	57.20	0.00	-0.09	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
0.63	57.57	0.31	0.37	3-M1t	0.30	0.21	0.35	0.35	0.86	0.47
1.26	57.79	0.50	0.59	3-Mlt	0.48	0.33	0.52	0.52	1.15	0.59
1.89	57.97	0.65	0.77	3-Mlt	0.63	0.44	0.66	0.66	1.37	0.68
2.52	58.12	0.80	0.92	3-M2t	0.78	0.53	0.77	0.77	1.55	0.74
3.15	58.26	0.94	1.06	3-M2t	0.91	0.61	0.86	0.86	1.74	0.81
3.78	58.38	1.07	1.18	3-M2t	1.05	0.69	0.94	0.94	1.91	0.87
4.20	58.46	1.16	1.26	3-M2t	1.20	0.74	0.99	0.99	2.01	0.90
5.04	58.62	1.34	1.42	3-M2t	1.20	0.84	1.08	1.08	2.22	0.96
5.67	58.71	1.47	1.51	3-M2t	1.20	0.91	1.09	1.09	2.48	0.97
6.30	58.89	1.61	1.69	3-M2t	1.20	0.97	1.09	1.09	2.76	0.97

El. inlet face invert 57.20 m El. outlet invert 57.11 m
El. inlet throat invert 0.00 m El. inlet crest 0.00 m

PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
<P> TO PLOT <I> FOR IMPROVED INLET TABLE

1- Help 2 3 4-Type 5-End 6 7 8 9-DOS 10

HY8 PERFORMANCE CURVE PROMPT SCREEN
2100 mm SPAN BY 1200 mm RISE CULVERT

Figure 31-8K

CULVERT FILE: HDS5EX1 DATE: 10-10-1998
TAILWATER FILE: AP-GDEX1 CULVERT NO. 1 OF 1

FHWA CULVERT ANALYSIS
HY-8, VERSION 6.0

SUMMARY TABLE FOR FILE 2400

	<S> SITE DATA			<C> CULVERT SHAPE, MATERIAL, INLET				
CULV. NO.	INLET ELEV. (m)	OUTLET ELEV. (m)	CULVERT LENGTH (m)	BARRELS SHAPE MATERIAL	SPAN (mm)	RISE (mm)	MANNING n	INLET TYPE
1	57.20	57.11	90.00	1 RCB	2100	1200	0.012	CONVENTIONAL
2								
3								
4								
5								
6								

```
HEADWATER ELEVATION (m)
   ENTER ALLOWABLE   =   58.49
   CONTROLLING       =   58.47
   INLET CONTROL     =   58.36
   OUTLET CONTROL    =   58.47

FLOW VELOCITY (m/s)
   V CULVERT         =   2.02
   V CHANNEL         =   0.90
   Q (m3/s)          =   4.20
   SLOPE             =   0.0010

FLOW DEPTHS (m)
   CULVERT           =   0.99
   CHANNEL           =   0.99
   NORMAL            =   1.20
   CRITICAL          =   0.74

MAXIMUM HEADWATER          <ENTER> TO RETURN
                           <H> TO CHANGE HEADWATER
                           <S> TO SAVE FILE

1       2-      3       4       5-End   6       7       8       9       10
```

HY8 MINIMIZATION ROUTINE TABLE PROMPT SCREEN

Figure 31-8L

HY8, VERSION 6.0

SUMMARY OF CULVERT FLOWS (m3/s) FILE: 31808 DATE: 10-12-1998

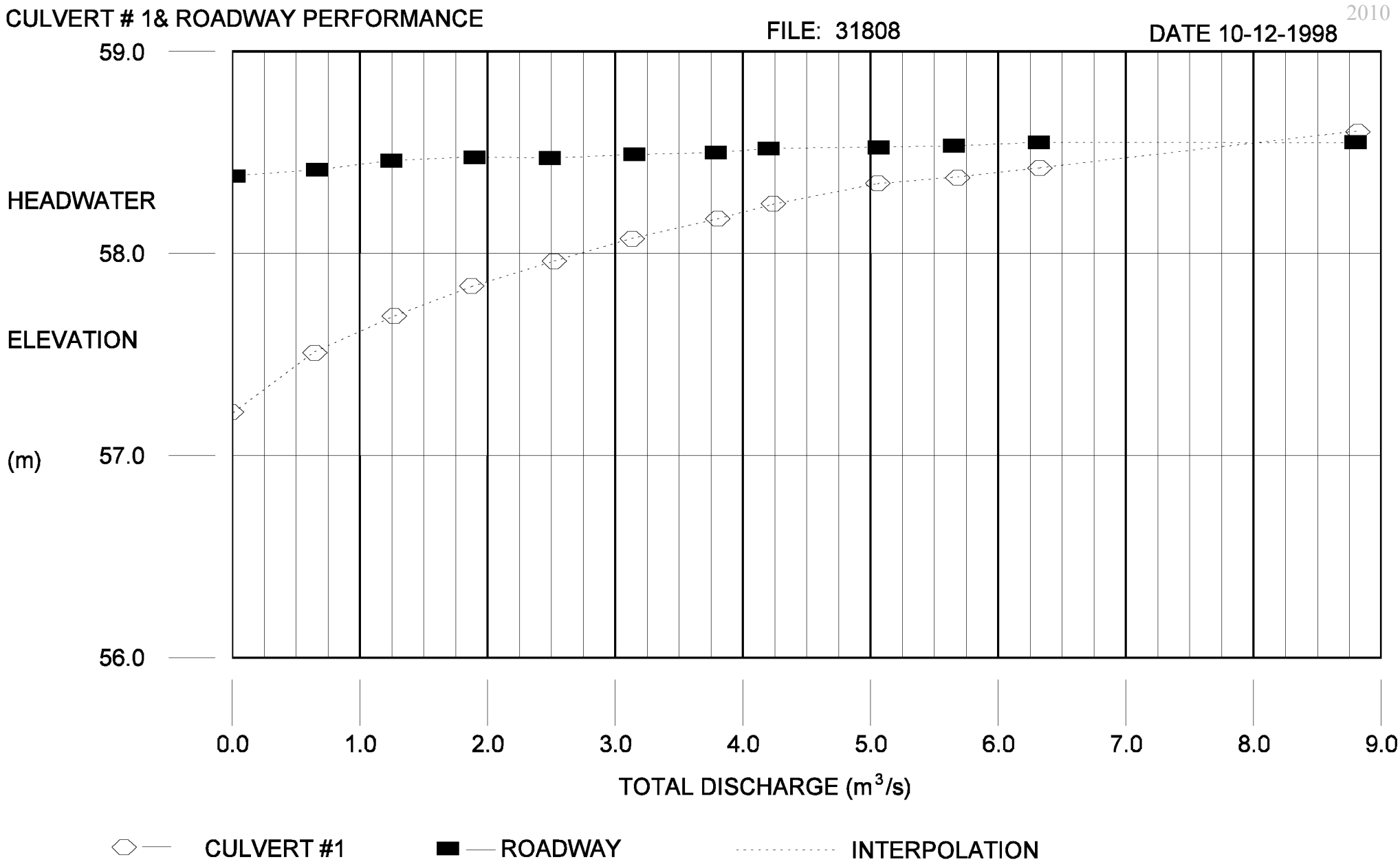
ELEV(m)	TOTAL	1	2	3	4	5	6	ROADWAY	ITER
57.20	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	1
57.51	0.6	0.6	0.00	0.00	0.00	0.00	0.00	0.00	1
57.69	1.3	1.3	0.00	0.00	0.00	0.00	0.00	0.00	1
57.84	1.9	1.9	0.00	0.00	0.00	0.00	0.00	0.00	1
57.97	2.5	2.5	0.00	0.00	0.00	0.00	0.00	0.00	1
58.07	3.2	3.1	0.00	0.00	0.00	0.00	0.00	0.00	1
58.17	3.8	3.8	0.00	0.00	0.00	0.00	0.00	0.00	1
58.23	4.2	4.2	0.00	0.00	0.00	0.00	0.00	0.00	1
58.36	5.0	5.0	0.00	0.00	0.00	0.00	0.00	0.00	1
58.38	5.7	5.7	0.00	0.00	0.00	0.00	0.00	0.00	4
58.41	6.3	6.1	0.00	0.00	0.00	0.00	0.00	0.21	6
58.38	5.7	5.7	0.00	0.00	0.00	0.00	0.00	OVERTOPPING	

PRESS: <P> TO PLOT TOTAL RATING CURVE
<T> TO DISPLAY TABLE FOR EACH CULVERT
<E> TO DISPLAY ERROR TABLE
<R> TO PRINT REPORT Output stored in HDS5EX1.PC
<H> TO RETURN TO HEADWATER TABLE
<ENTER> TO RETURN TO OPTION MENU

1-Help 2-Progr 3-Time 4 5-End 6 7 8 9-DOS 10

HY8 SUMMARY OF CULVERT FLOWS PROMPT SCREEN

Figure 31-8M



TOTAL PERFORMANCE CURVE

Figure 31-8N

OVERTOPPING PERFORMANCE CURVE FOR CULVERT 1 – One (3600 mm BY 1200 mm) RCB

DIS-CHARGE FLOW (m3/s)	HEAD-WATER ELEV. (m)	INLET CONTROL DEPTH (m)	OUTLET CONTROL DEPTH (m)	FLOW TYPE <F4>	NORMAL DEPTH (m)	CRIT. DEPTH (m)	OUTLET DEPTH (m)	TW DEPTH (m)	OUTLET VEL. (m/s)	TW VEL. (m/s)
0.00	57.20	0.00	-0.09	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
0.63	57.51	0.22	0.31	3-M1t	0.20	0.15	0.35	0.35	0.50	0.47
1.26	57.69	0.35	0.49	3-Mlt	0.31	0.23	0.52	0.52	0.67	0.59
1.89	57.84	0.45	0.64	3-Mlt	0.41	0.30	0.66	0.66	0.80	0.68
2.52	57.97	0.55	0.77	3-Mlt	0.50	0.37	0.77	0.77	0.90	0.74
3.15	58.07	0.64	0.87	3-Mlt	0.58	0.43	0.86	0.86	1.10	0.81
3.78	58.17	0.73	0.97	3-Mlt	0.65	0.48	0.94	0.94	1.12	0.87
4.20	58.23	0.79	1.03	3-Mlt	0.70	0.52	0.99	0.99	1.18	0.90
5.04	58.36	0.89	1.16	3-Mlt	0.79	0.59	1.08	1.08	1.30	0.96
5.66	58.38	0.97	1.18	3-Mlt	0.86	0.63	1.09	1.09	1.44	0.97
6.06	58.40	1.02	1.20	3-Mlt	0.90	0.66	1.09	1.09	1.55	0.97

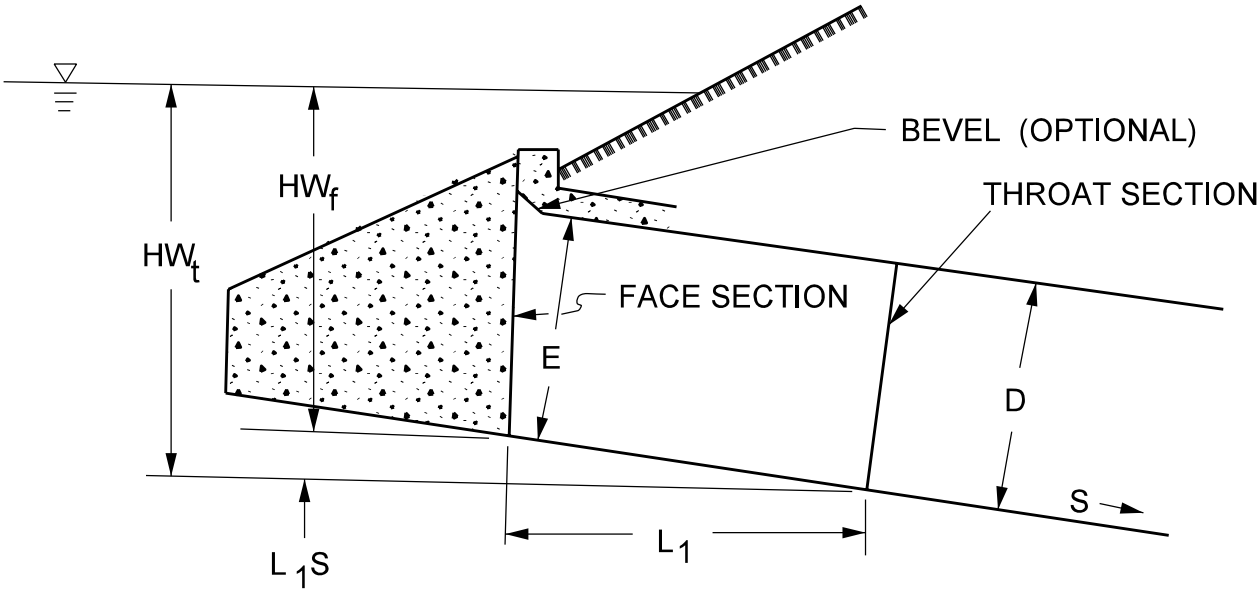
El. inlet face invert 57.20 m El. outlet invert 57.11 m
El. inlet throat invert 0.00 m El. inlet crest 0.00 m

PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
<P> TO PLOT <I> FOR IMPROVED INLET TABLE

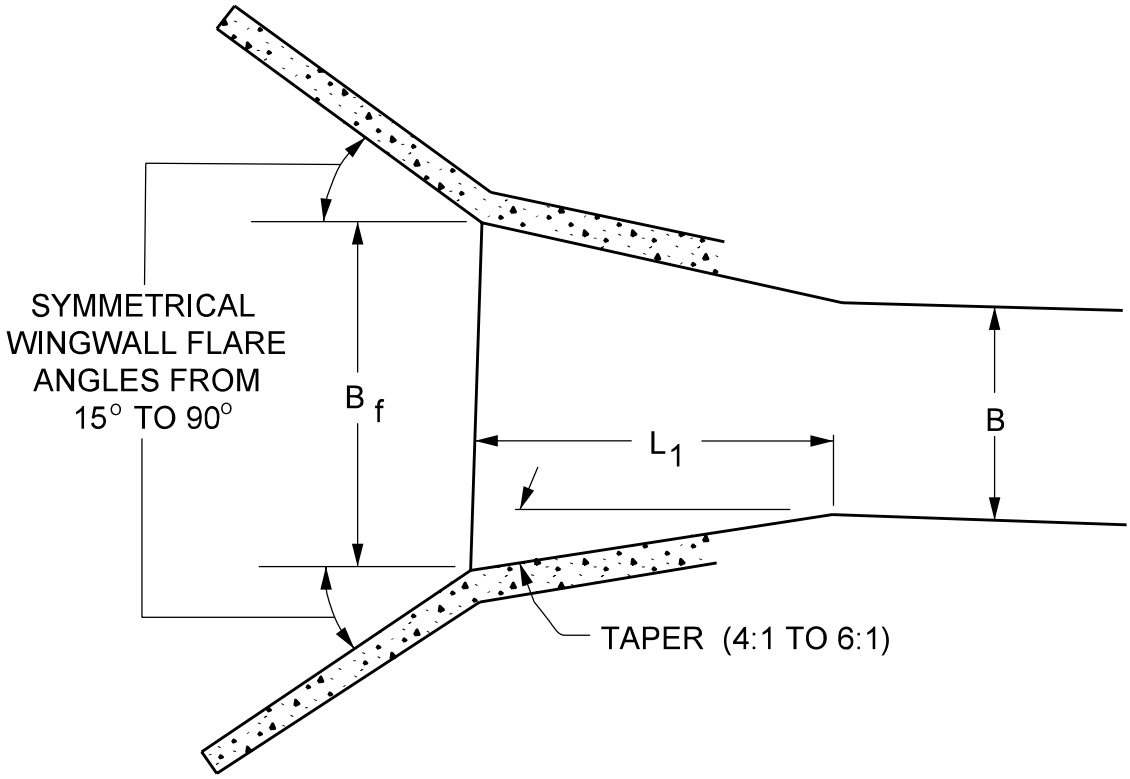
1- Help 2 3 4-Type 5-End 6 7 8 9-DOS 10

HY8 OVERTOPPING PERFORMANCE CURVE PROMPT SCREEN
3600 mm SPAN BY 1200 mm RISE CULVERT

Figure 31-8 O



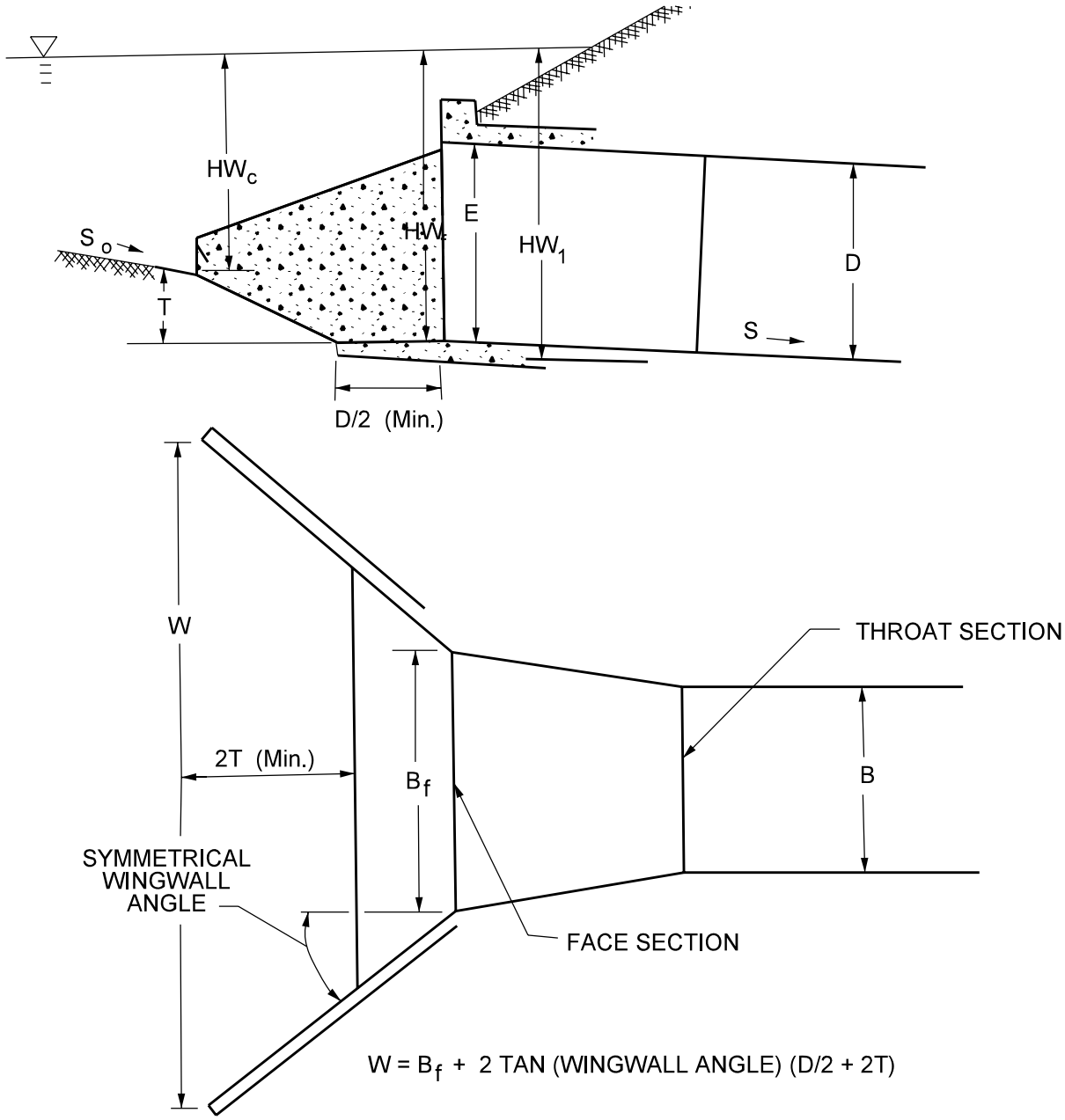
ELEVATION



PLAN

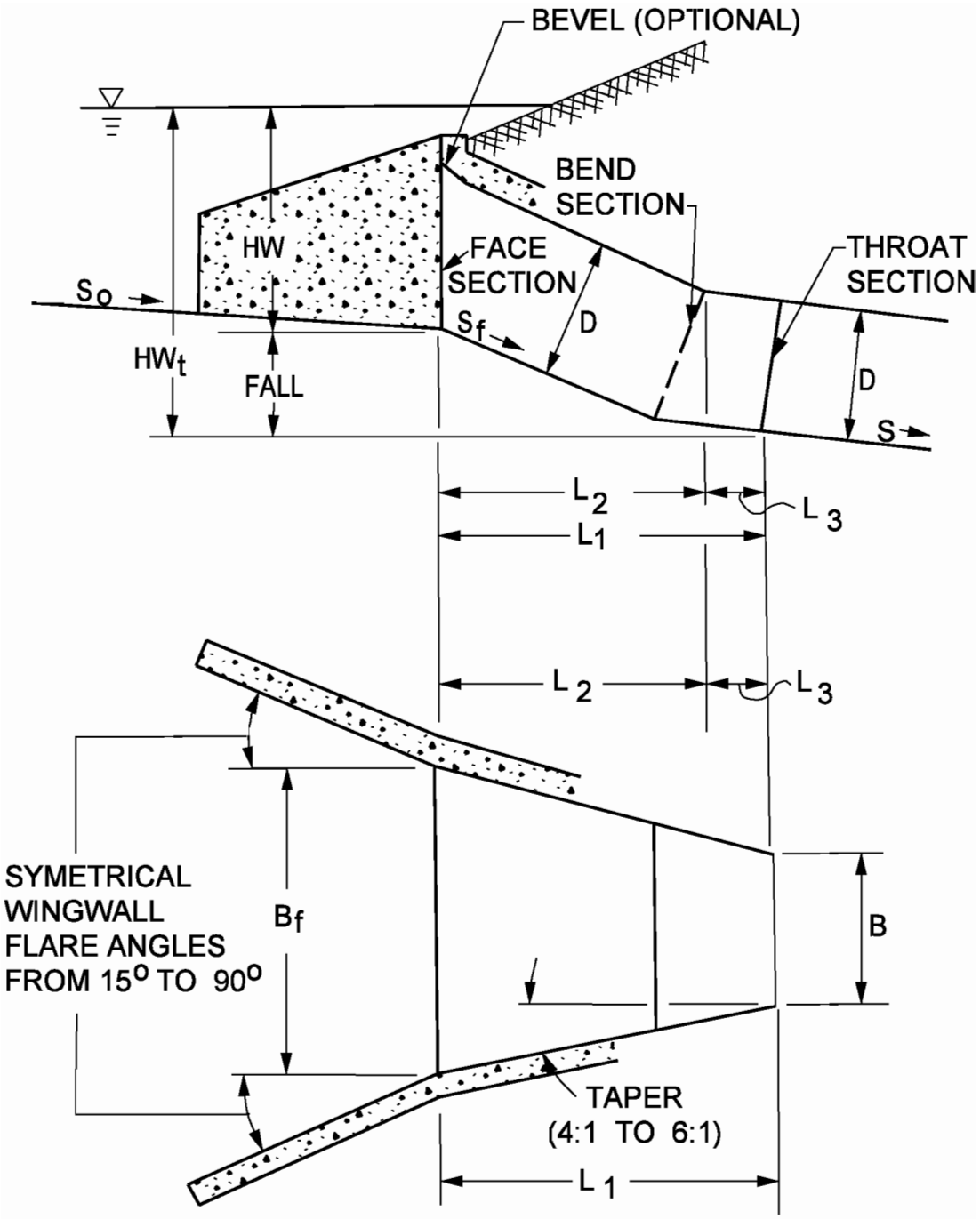
SIDE-TAPERED END TREATMENT

Figure 31-9A



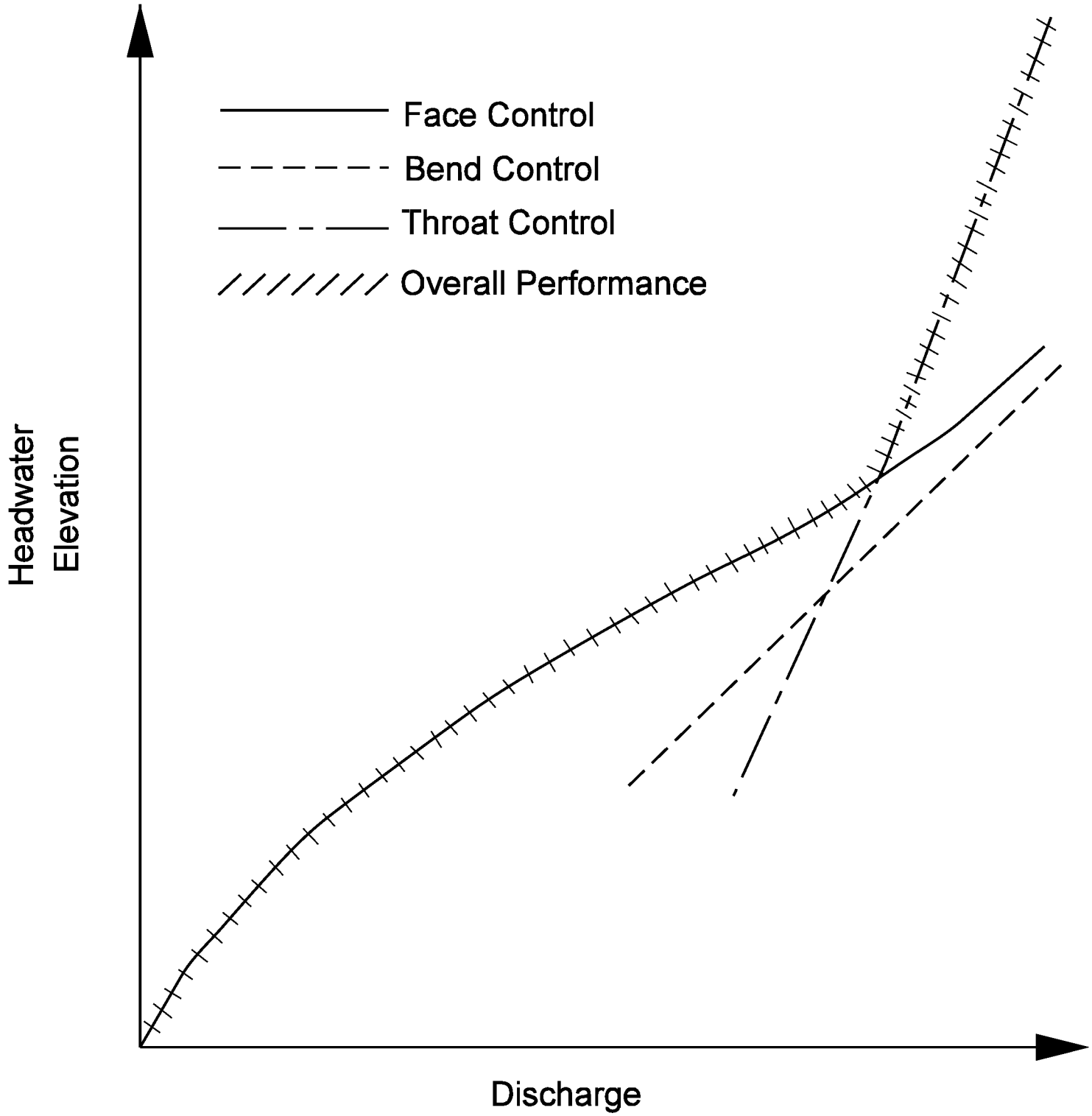
SIDE-TAPERED END TREATMENT
(Upstream Depression Contained Between Wingwalls)

Figure 31-9B



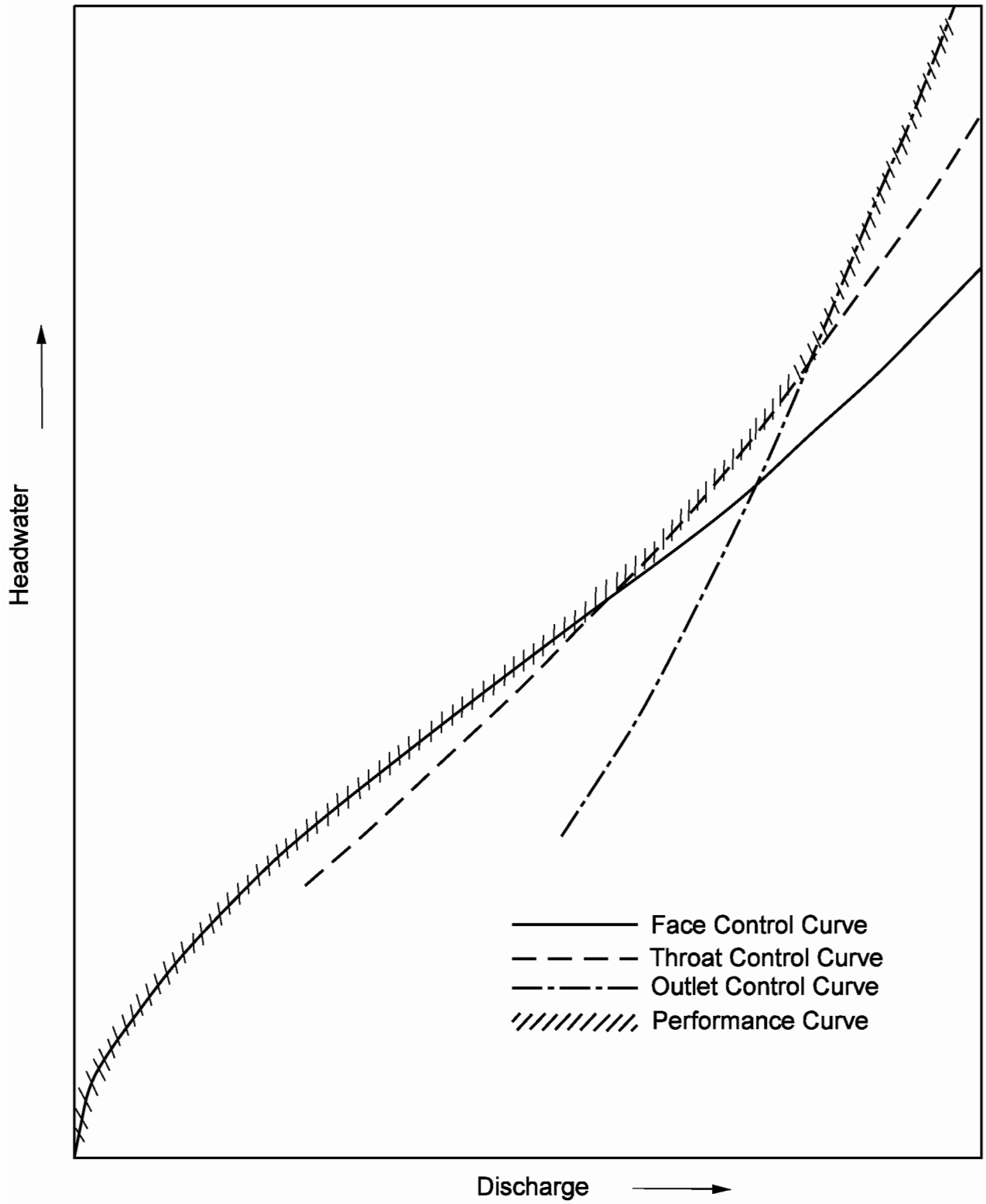
SLOPE-TAPERED END TREATMENT WITH VERTICAL FACE

Figure 31-9C



INLET CONTROL PERFORMANCE CURVES
(Schematic)

Figure 31-9D



CULVERT PERFORMANCE CURVE

(Schematic)

Figure 31-9E

Type of Conduit	Wall Description	Manning's *n*
Concrete Pipe	Smooth Interior	0.012
Concrete Box	Smooth Walls	0.012-0.015
Corrugated Metal Pipe or Box, Annular or Helical Pipe (see HDS #5)	68 mm x 13 mm corrugations 150 mm x 25 mm corrugations 125 mm x 25 mm corrugations 75 mm x 25 mm corrugations 150 mm x 50 mm structural plate 230 mm x 64 mm structural plate	0.024 0.024 0.024 0.024 0.033-0.035 0.033-0.037
Thermoplastic Pipe	Smooth Interior	0.012

1. *The values indicated in the table are the recommended Manning's* n *design values. Actual field values for an older, existing pipeline may vary depending on the effects of abrasion, corrosion, deflection, or joint conditions. A concrete pipe with poor joints or deteriorated walls may have an* n *value of 0.014 to 0.018. A corrugated metal pipe with joint or wall problems may have a higher* n *value and, may experience shape changes which can adversely affect the hydraulic characteristics of the culvert.*

2. *For further information concerning Manning's* n *values for selected conduits, consult Hydraulic Design of Highway Culverts, Federal Highway Administration, HDS #5, p. 163.*

RECOMMENDED MANNING'S *n* VALUES

Figure 31-10A

$$H_e = K_e \left[\frac{V^2}{2g} \right]$$

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, square cut end	0.5
Headwall or headwall and wingwalls	
Square-edge	0.5
Rounded (radius = 1/12*D*)	0.2
Socket end of pipe (groove-end)	0.2
Projecting from fill, socket end (groove-end)	0.2
Beveled edges, 33.7-deg or 45-deg 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, 33.7-deg or 45-deg 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 10 deg to 25 deg, or 30 deg to 75 deg 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 30 deg to 75 deg 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

* *An end section conforming to fill slope, made of either metal or concrete, is the section commonly available from manufacturers. From limited hydraulic tests, it is equivalent in operation to a headwall in both inlet and outlet control. An end section incorporating a closed taper in its design may have a superior hydraulic performance. Such a section can be designed using the information shown for the beveled inlet.*

ENTRANCE-LOSS COEFFICIENTS
(Outlet Control, Full or Partly Full)

Figure 31-10B

End-Treatment Type	Entrance Type	K_E
Grated Box End Section, Type 1	Concrete Pipe, headwall with square edge	0.5
Grated Box End Section, Type 2	Concrete Pipe, headwall with square edge	0.5
Multiple-Pipes Concrete Anchor	Concrete Pipe, projecting from fill, square cut end	0.5
Multiple-Pipes Concrete Anchor	Corrugated Metal Pipe, Projecting from fill	0.9
Metal Pipe End Section	Corrugated Metal Pipe, end section conforming to fill slope	0.5
Precast-Concrete End Section	Concrete Pipe, end section conforming to fill slope	0.5
Safety Metal End Section	Corrugated Metal Pipe, mitered to conform to fill slope	0.7
Safety Metal End Section	Corrugated Metal Pipe, end section conforming to fill slope	0.5
Safety Metal End Section	Corrugated Metal Pipe, mitered to conform to fill slope	0.7
Safety Metal End Section	Corrugated Metal Pipe, end section conforming to fill slope	0.5
Single-Pipe Concrete Anchor	Corrugated Metal Pipe, projecting from fill	0.9
Single-Pipe Concrete Anchor	Concrete Pipe, projecting from fill, square cut end	0.5
Single-Pipe Concrete Anchor	Corrugated Metal Pipe-Arch, projecting from fill	0.9
Multiple-Pipe Concrete Anchor	Concrete Pipe-Arch, projecting from fill, square cut end	0.5
Multiple-Pipe Concrete Anchor	Corrugated Metal Pipe-Arch, projecting from fill	0.9

ENTRANCE-LOSS COEFFICIENT, K_E,
FOR STANDARD INDOT CULVERT

Figure 31-10C

CULVERT DESIGN FORM

ROUTE: DES NO.:
PROJECT NO.:
PROJECT DESCRIPTION:

STATION:
SHEET OF

DESIGNER: DATE:
REVIEWER: DATE:

HYDROLOGICAL DATA

METHOD:
DRAINAGE AREA: km^2 STREAM SLOPE:
CHANNEL SHAPE::
ROUTING: OTHER:

DESIGN FLOWS / TAILWATER

R.I. (years) FLOW (m^3/s) TW (m)

See Figure 31-10D(1) for culvert-design details

CULVERT DESCRIPTION MATERIAL-SHAPE-SIZE-ENTRANCE	TOT. FLOW Q (m^3/s)	FLOW PER BAR-REL Q/N (1)	HEADWATER CALCULATIONS											CTRL. HEAD-WTR. ELEV.	OUTL. VELO-CITY	COMMENTS
			INLET CONTROL				OUTLET CONTROL									
			HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	TW (5)	d_c	$\frac{d+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)			

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERT

(2) HW_i/D = HW/D OR HW_t/D FROM DESIGN CHARTS

(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERT ON GRADE
$EL_{hi} = HW_i + EL_i$

(4) INVERT OF INLET CONTROL SECTION

(5) TW BASED ON DOWNSTREAM CONTROL OR FLOW DEPTH IN CHANNEL

(6) h_o = TW or $(d_c + D)/2$ (WHICHEVER IS GREATER)

(7) $$H = \frac{V}{2g}\left[1 + k_e + \left(\frac{19.63 n^2 L}{R^{1.33}}\right)\right]$$

(8) $EL_{ho} = EL_o + H + h_o$

SUSCRIPT DEFINTIIONS

a	Approximate
f	Culvert Face
h_d	Design Headwater
h_i	Headwater in Inlet Control
h_o	Headwater in Outlet Control
i	Inlet Control Section
o	Outlet
s_f	Streambed at Culvert Face
TW	Tailwater

COMMENTS / DISCUSSION:

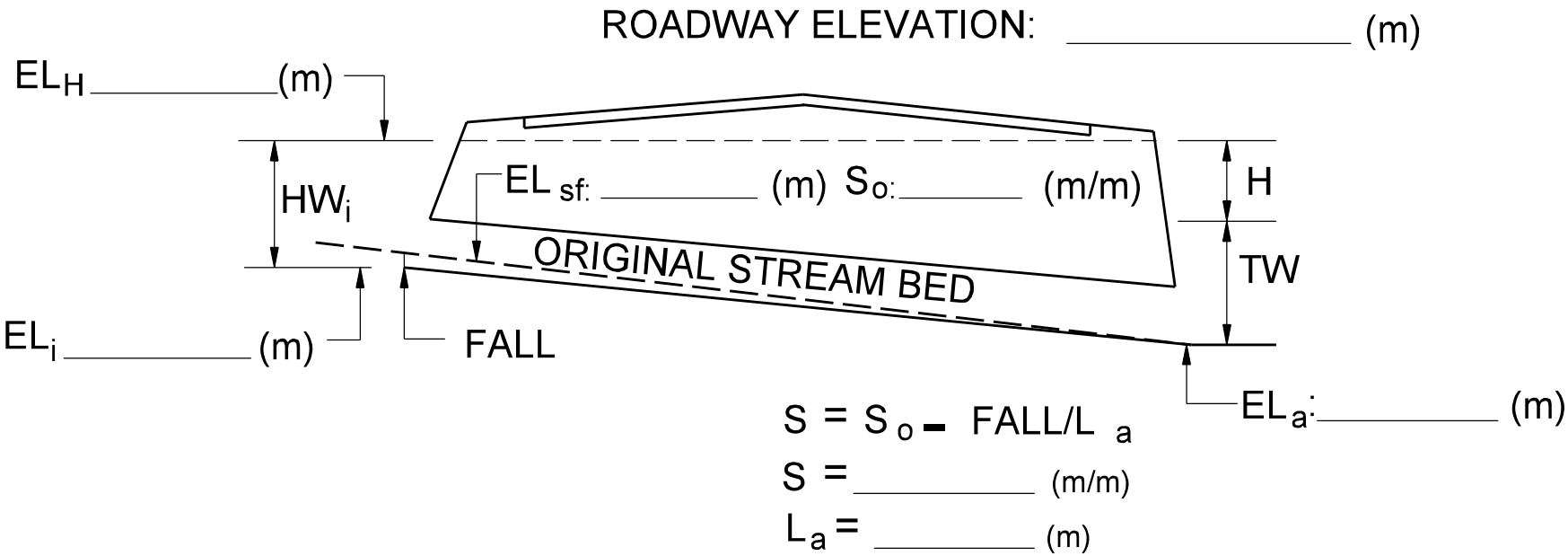
CULVERT BARREL SELECTED:

SIZE:

SHAPE:

MATERIAL: n:

ENTRANCE:



CULVERT DESIGN DETAILS
(Conventional End Treatment)

Figure 31-10D(1)

ROUTE: DES. NO.: PROJECT NO.: PROJECT DESCRIPTION:	STATION: SHEET OF	CULVERT DESIGN FORM – TAPERED INLET DESIGNER: DATE: REVIEWER: DATE:

DESIGN DATA:

Q = m^3/s; $EL._{hl}$ (m)
EL. Throat Invert (m)
EL. Stream Bed at Face (m)
FALL: (m); TAPER :1 (4H:1V to 6H:1V)
STREAM SLOPE, S_c = (m/m)
SLOPE OF BARREL, S = (m/m)
S_f :1 (2H:1V to 3H:1V)
Barrel Shape and Material:
N = ; B = ; D =
Inlet Edge Description:

COMMENTS:

Q (m^3/s)	$EL._{hl}$	EL. Throat Invert	EL. Face Invert (1)	HW_f (2)	HW_f / E (3)	Q / B_f (4)	Min. B_f (5)	Sel-Ected B_f	SLOPE-TAPERED ONLY Min. L_3 (6)	L_2 (7)	Check L_2 (8)	Adj. L_3 (9)	Adj. Taper (10)	L_1 (11)	SIDE-TAPERED w/ FALL EL. Crest Invert	HW_c (12)	Min. W (13)

TECHNICAL FOOTNOTES:
(1) Slope-Tapered: EL. Face Invert = EL. Stream Bed at Face
Side-Tapered: EL. Face Invert = EL. Throat Invert + 0.3 m (approx.)
(2) $HW_f = EL._{hl} - EL.$ Face Invert
(3) $1.1D \geq E \geq D$
(4) From Design Charts
(5) Min. $B_f = Q / (Q/B_f)$
(6) Min. $L_3 = 0.5NB$
(7) $L_2 = S_r$(EL. Face Invert – EL. Throat Invert)
(8) Check $L_2 = 0.5(B_r - NB)Taper - L_3$

(9) If (8) > (7), Adj. $L_3 = 0.5(B_r - NB)Taper - L_3$
(10) If (7) ≤ (8), Adj. Taper = $\dfrac{L_2 + L_3}{0.5(B_r - NB)}$
(11) Slope-Tapered: $L_1 = L_2 + L_3$
Side-Tapered: $L = 0.5(B_r - NB)Taper$
(12) $HW_c = EL._{hl} - EL.$ Crest Invert
(13) Min. $W = \dfrac{0.634Q}{HW_c}$

SELECTED DESIGN:
B_f =
L_1 =
L_2 =
L_3 =
Bevels Angle = °
b =
d =
Taper = :1V
S_f = :1V

ROUTE: DES. NO.: PROJECT NO.: PROJECT DESCRIPTION:	STATION: SHEET OF	CULVERT DESIGN FORM – MITERED INLET DESIGNER: DATE: REVIEWER: DATE:

DESIGN DATA:

Q = m^3/s; $EL._{hl}$ (m)
EL. Throat Invert (m)
EL. Stream Bed at Face (m)
FALL: (m); TAPER :1 (4H:1V to 6H:1V)
STREAM SLOPE, S_c = (m/m)
SLOPE OF BARREL, S = (m/m)
S_f :1 (2H:1V to 3H:1V)
Barrel Shape and Material:
N = ; B = ; D =
Inlet Edge Description:

COMMENTS:

Q (m^3/s)	$EL._{hl}$	EL. Throat Invert	y (1)	EL. Face Invert (2)	HW_f (3)	HW_f/E (4)	Q/B_f (5)	Min. B_f (6)	Sel-ected B_f	Min. L_3 (7)	L_4 (8)	L_2 (9)	Check L_2 (10)	Adj. L_3 (11)	Adj. Taper (12)	L_1 (13)	EL. Crest Inv.	HW_C (14)	Min. W (15)	W (16)

TECHNICAL FOOTNOTES:

(1) $y = \left[\frac{(S_o - S_f) - 1}{(S_o - S_f)(S_f + 1)} \right] - D$

(2) EL. Face Invert = EL. Stream Bed at Crest – y
(3) HW_f = $EL._{hl}$ – EL. Face Invert (4) 1.1D ≥ E ≥ D
(5) From Design Charts (6) Min. B_f = Q / (Q/B_f)
(7) Min. L_3 = 0.5NB (8) L^4 = yS_f + D/S_f
(9) L_2 = S_r(EL. Crest Invert – EL. Throat Invert)
If negative, do not use mitered inlet.
(10) Check $L_2 = 0.5(B_r - NB)Taper - L_3$

(11) If (10) > (9), Adj. $L_3 = 0.5(B_r - NB)Taper - L_3$

(12) If (9) ≥ (10), Adj. Taper = $\frac{L_2 + L_3}{0.5(B_r - NB)}$

(13) L_1 = L_2 + L_3 + L_4
(14) HW_c = $EL._{hl}$ – EL. Crest Invert

(15) Min. $W = \frac{0.634Q}{HW_c}$

(16) $W = NB + \left(\frac{2L_1}{Taper} \right)$ If W < Min. W, adjust taper.

SELECTED DESIGN:
B_f =
L_1 =
L_2 =
L_3 =
L_4 =
Bevels Angle = °
b =
d =
Taper = :1V
S_f = :1V