TABLE OF CONTENTS

LIST OF FIGURES

Figure **Title**

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 usually designed hydraulically to take advantage of submergence to increase hydraulic capacity.

2. A structure used to convey surface runoff through embankments.

3. A structure, as distinguished from bridges, which is usually covered with embankment and is composed of structural material around the entire perimeter, although some are supported on spread footings with the streambed serving as the bottom of the culvert.

4. A structure which is less than a 20 ft span length along the centerline of roadway between extreme ends of openings for multiple barrels. Figure 31-1A, Maximum Span Lengths for Culverts, provides several 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. Driveway Culvert. A structure under a driveway 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 highway culverts 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 contained in the AASHTO *Highway Drainage Guidelines*, Chapter IV.

31-1.03 Definitions

Following are definitions of concepts which are important in culvert design.

1. Backwater. 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). Critical depth is 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 crown is the inside top of the culvert.

4. Flow Type. The USGS has established seven 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 culverts having free outlets, 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 culverts. These end treatments are referred to as either side- or slope-tapered (walls or bottom tapered).

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

8. Normal Flow. Normal flow occurs in a channel reach when 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. Submerged. The following applies.

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

   b. A submerged inlet occurs when the headwater is greater than 1.2D, 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

The following policies are specific to culverts.

1. All culverts shall be hydraulically designed; however, the minimum pipe size specified in Section 31-3.05(03) will sometimes control.

2. The design storm frequency(ies) selected shall be consistent with the criteria in Section 31-3.03.

3. Survey information shall include topographic features, channel characteristics, high-water information, existing structures 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 culvert barrels.

5. Culverts shall be designed to accommodate debris or proper provisions shall be made for debris maintenance.

6. Culverts shall be located and designed to present a minimum hazard to traffic and people.

7. The detail of documentation for each culvert site shall be commensurate with the risk and importance of the structure. Design data and calculations shall 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 shall 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 shall be considered for all culvert designs.

31-3.02 Site Criteria

The following site criteria apply.

1. Structure Type Selection. Culverts are used as follows:

   a. where bridges are not hydraulically required,

b. where debris and ice are tolerable, and
c. where more economical than a bridge.

Bridges are used as follows:

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

2. Length and Slope. The culvert length and slope shall 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. Severe or abrupt changes in channel alignment upstream or downstream of culverts are not recommended. The following applies.

   a. Small culverts with no defined channel are placed normal to centerline.

   b. Large culverts perpetuating drainage in defined channels should be skewed as necessary to minimize channel relocation and erosion.

   c. Designers should locate all utilities before determining the final location of culverts to minimize conflicts.

4. Location In Profile. At most locations, the culvert profile will approximate the natural stream profile. Exceptions (which must be approved by the Hydraulics Unit) 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 shall 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 culverts that are under high fills, and

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 (Culverts), which apply to culvert design.

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 the culvert during the design flood. AHW will be limited by one or more of the following:

1. New Alignment. For new culverts on new alignment, the maximum backwater (increase in headwater elevation over the sum of TW depth plus inlet invert elevation) shall not exceed 1.5. The 1.5 in maximum may be modified for the following cases.

   a. the backwater dissipates to 1.5 in 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 any exceptions to the 1.5 in backwater allowance for new culverts on new alignment.

2. Existing Conditions. For existing (or "baseline") conditions, the IDNR essentially limits surcharge to 1 in (urban and rural). Existing conditions are defined as the water surface profile that would result 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 culvert replacements and rehabilitations 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 1 in. This will allow future widening of the structure. In addition, if the surcharge created by an existing structure is greater than 12 in., the proposed surcharge for the culvert replacement or extension must be no greater than 12 in. above the natural channel flood profile.

3. Right-of-Way. The ponding limits from the AHW cannot exceed the limits of INDOT right-of-way for structures on new alignment.

4. Upstream Channels. The ponding limits from the AHW cannot exceed the banks of any upstream channel for structures on new alignment.

5. Other. Other constraints on AHW include:

   a. grade of adjacent driveways,
   b. finished floor elevation of adjacent buildings or other improvements, and
   c. elevation of existing crop land or other property.

31-3.04(02) Roadway Serviceability

For the appropriate design storm, headwater caused by the proposed pipe cannot exceed the following:

1. If Q_{100} is the appropriate design storm, the resulting headwater elevation must be at least 2 ft 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

All culverts require outlet protection to prevent erosion. The protection used must be in accordance with the following:

1. Revetment riprap is required at all structures with an outlet velocity of 6.5 ft/s or less.

2. Class 1 riprap is required at all structures with an outlet velocity between 6.5 ft/s and 10 ft/s exclusive.

3. Class 2 riprap is required at all structures with an outlet velocity greater than or equal to 10 ft/s and less than or equal to 13 ft/s.

4. An energy dissipator is required with an outlet velocity greater than 13 ft/s. See Chapter Thirty-four for the design of energy dissipators.

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

31-3.04(04) Minimum Velocity

The minimum velocity in the culvert barrel shall result in a tractive force ($\tau = \gamma dS$) greater than critical τ of the transported streambed material at low flow rates. The designer should use 3 ft/s when streambed material size is not known.

31-3.04(05) Tailwater Relationship

For channels, the designer should:

1. evaluate the hydraulic conditions of the downstream channel to determine a tailwater depth (see Chapter Thirty),
2. calculate backwater curves at 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, and
4. use the headwater elevation of any nearby downstream culvert if it is greater than the channel depth.

For confluences or large bodies 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 shall not be considered in the hydraulic design of culverts.

31-3.05 Culvert Sizing Process

31-3.05(01) Priority System

The culvert sizing process is performed in accordance with a priority system. This 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 Pipe Installation.
5. Trial 5. Multiple Deformed Pipe Installation.
6. Trial 6. Multiple Specialty Structure Installation.

The principles of the priority system are summarized below.

1. Pipe structures are preferred to specialty structures (e.g., precast reinforced concrete box sections, precast reinforced concrete three-sided culverts, structural plate arches).

2. Circular pipes are preferred to deformed pipes.

3. Single-cell installations are preferred to multiple-cell installations.

The end of Section 31-3.0 presents 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 Speciality 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 of the culvert sizing process, 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 nomographs or computer software normally used for sizing reinforced concrete pipe. The corrugated hydraulic design is based on a Manning's n value of 0.024 and can utilize nomographs or computer software traditionally used to size 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. Refer to Figure 31-10A for typical values. Nomographs or computer software used to size structural plate pipe may be used to determine the required size for these larger structures.

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

When separate hydraulic designs are performed for smooth and corrugated interior pipe, the following scenarios are possible.

1. Case 1. The required smooth interior and corrugated interior pipe sizes are identical. In this case, the structure callout in the plans includes the required pipe size and no reference to an interior designation is made.

2. Case 2. The required smooth interior and corrugated interior pipe sizes are different. In this case, the structure callout in the plans indicates the structure requires a smooth pipe of one size or a corrugated pipe of another.

3. Case 3. An acceptable pipe size can be determined for one interior designation but not the other. When this situation occurs, the structure callout will indicate the required pipe size and interior designation.

4. Case 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 Sizes (Culverts).

31-3.05(04) Cover

In addition to the minimum pipe size requirements, cover is another factor that the designer must consider during the structure sizing process. For circular pipe structures, a minimum of 1 ft 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 1.5 ft of cover must be provided. The cover over a circular pipe structure should never exceed 100 ft, and the cover for deformed corrugated interior pipe structures should never exceed 13 ft. If the pavement grade or structure invert elevations cannot be adjusted to conform to the cover criteria discussed above, contact the Standards Section for additional instructions.

31-3.05(05) Pipe Extension Structure Sizing Process

The sizing of pipe extension structures must 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 meets all design criteria. Because the structure interior designation is known, it is only necessary to perform hydraulic calculations appropriate for that interior designation.

If the extended structure meets all required design criteria, then the structure sizing process is complete. If the extended structure does not meet 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 the construction method, traffic maintenance or other constraints, contact the Hydraulics Unit 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 extending, 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 meets all hydraulic requirements. If the analysis indicates that the extended structure does not meet 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 the construction method, traffic maintenance or other constraints, contact the Hydraulics Unit for further instructions.

31-3.06 Other Culvert Features

31-3.06(01) Culvert Skew

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

31-3.06(02) End Treatment (Inlet or Outlet)

The culvert end treatment type shall be selected from the following list based on the considerations given and the end treatment coefficient, K_e. See Section 31-10.0 for recommended values of K_e. In addition, roadside safety considerations are important to end treatment selection and design. See Section 49-3.0 for a detailed discussion on INDOT practices for the safety treatment of drainage structures.

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

1. Projecting Inlets or Outlets.

    a. Extend beyond the roadway embankment.

    b. Are susceptible to damage during roadway maintenance and from errant vehicles.

    c. Have low construction cost.

    d. Have poor hydraulic efficiency for thin materials.

    e. Shall include anchoring the end treatment to strengthen the weak leading edge for culverts 42 in. in diameter and larger. Any anchorage shall 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 falls within the roadside clear zone, the designer should consider the use of the Grated Box End Section (GBES) or Safety Metal End Section (SMES). See Chapter Forty-nine for INDOT criteria on roadside clear zones. See the *INDOT Standard Drawings* for the GBES and SMES.

2. Mitered End Treatments.

a. Are hydraulically more efficient than thin edge projecting.

b. Shall be mitered to match the fill slope.

c. Shall include anchoring the end treatment to strengthen the weak leading edge for culverts 36 in. in diameter and larger.

3. Improved End Treatments.

a. Shall be considered for culverts 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, they should only be used if economically justified.

4. Pipe End Sections.

a. Are available for both corrugated metal and concrete pipe.

b. Retard embankment erosion and incur less damage from maintenance.

c. May improve projecting metal pipe entrances by increasing hydraulic efficiency, reducing the accident hazard and improving their appearance.

d. Are 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. Wingwalls.

a. Are used to retain the roadway embankment to avoid a projecting culvert barrel.
b. Are used where the side slopes of the channel are unstable.
c. Are used where the culvert is skewed to the normal channel flow.
d. Provide the best hydraulic efficiency if the flare angle is between 30°° and 60°.
e. Shall be provided on all precast concrete drainage structures.

6. Aprons.

a. Are used to reduce scour from high headwater depths or from approach velocity in the channel.

b. Shall extend at least one pipe diameter upstream.

c. Shall not protrude above the normal streambed elevation.

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

7. Cut-off Walls.

   a. Are used to prevent piping along the culvert barrel and undermining at the culvert ends.

   b. Shall be used on all culverts with headwalls.

   c. Shall be a minimum 20 in. depth or as dictated by the INDOT *Standard Drawings* and/or *Standard Specifications.*

8. Weep Holes. Weep holes shall 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 culvert structures will be rounded to the next highest 1.5 ft.

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, shall be considered for all flexible culverts. 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 skews or mitered ends. See the INDOT *Standard Drawings* and *Standard Specifications.*

31-3.06(05) Relief Opening

Where culverts serving as relief openings have their outlet set above the normal stream flow line, special precautions shall be required to prevent headcuts or erosion from undermining the culvert outlet.

31-3.06(06) Erosion and Sediment Control

Temporary measures shall be included in the construction plans. These measures may include the use of silt boxes, brush silt barriers, filter cloth, temporary silt fence and check dams. For more information, see Chapter Thirty-seven.

31-3.06(07) Wingwalls and Headwalls for Precast Concrete Box Culvert

Designing and detailing wingwalls and headwalls for this type of structure will not usually be required. Such wingwalls and headwalls may be precast.

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

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

2. an elevation view of the end of the culvert including wingwalls and headwall if applicable. The span and rise of the culvert 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 typical section through the wingwall that shows the approximate footing configuration; and

6. the allowable soil bearing pressure. A table should be included, 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 (ø);
    c. ultimate cohesion of foundation soil (C); and
    d. ultimate adhesion between foundation soil and concrete (CA).

    These soil parameters will be provided in the Geotechnical Report for each box culvert. If the Geotechnical Report is lacking such information, it should be requested from the Materials and Tests Division’s Geotechnical Section.

The wingwalls are a separate pay item. The wingwall footing quantity will be included in the wingwall quantity. The headwalls quantities will be included in the box culvert quantities.

If a project has both reinforced concrete three-sided drainage structures and precast concrete box culverts with wingwalls, the wingwalls quantities for both types of structures may be combined.

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 *Manual* (e.g., hydrology, channels). Each of these should be consulted as appropriate. The discussion in this Section focuses on alternative analyses and design methods.

31-4.02 Alternative Analyses

Culvert alternatives shall be selected which satisfy the following:

1. topography, and
2. design policies and criteria.

Alternatives shall be analyzed for the following:

1. hydraulic equivalency, and
2. risk and cost.

Select an alternative which best integrates engineering and economic and political considerations. The selected culvert shall meet the applicable structural and hydraulic criteria and shall 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 shall choose either of the following:

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

2. to use nomographs or computer software. The Hydraulics Engineer must approve the use of nomographs not based on HDS #5.

31-4.03(01) Structure Type

The following applies to the type of structure:

1. Culvert. This is one of the following:

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

*** PRACTICE POINTER ***

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

2. Storm Drain (See Chapter Thirty-Six). 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 contained in HYDRAIN, or

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

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

3. Specialty Structures. Specialty structures can be used in either culvert or storm drain applications.

The use of details that suggest a proprietary product should be avoided when preparing plans for a three-sided drainage structure. Some examples of inappropriate details and dimensions are as follows: wing anchorage systems, wing thickness, wall thickness of precast units, corner chamfer dimensions of precast units, footing width, and footing reinforcement.

The use of brand names employed by the various manufacturers of three-sided drainage structures must also be avoided. Three-sided structures should be referred to as either flat topped or arch.

4. Oversize Box Culverts. Oversize box culverts, or megaboxes, are routinely being recommended by the Design Division's Hydraulics Unit. Megaboxes and other oversize box culverts and product information regarding these are available from several local suppliers.

The recommended layout method for an oversize box culvert, as well as a regular box culvert, is to extend the culvert to the point where a 2:1 roadway sideslope intercepts the stream flow line. Wingwalls are generally not recommended. INDOT policy requires that a 2:1 sideslope at the end of a box culvert be protected with guardrail or be located beyond the clear zone.

If the Design Division's Hydraulics Unit recommends that wingwalls be provided at the ends of a box culvert, they should be designed and detailed as cast-in-place wingwalls. There currently is no commercially available system for precast wingwalls for box culverts.

A designer wishing to submit a box culvert design incorporating precast wingwalls must provide evidence that the system is non-proprietary (i.e., more than one manufacturer exists) and must develop a unique special provision to specify the construction requirements and method of payment for the precast wingwalls.

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

An oversize box culvert should be laid out so that the total structure length works out to be 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 when determining the total structure length. The available segment masses and lengths are shown in Figure 31-4B.

31-4.03(02) Hydrology Methods

See Chapter Twenty-nine for detailed information on hydrology. A constant discharge:

1. is assumed for culvert design,
2. is always the peak discharge, and
3. will yield a conservatively sized structure where temporary storage is available but not used.

31-4.03(03) Computational Methods

Nomographs:

1. require a trial-and-error solution which is quite easy and provides reliable designs for many applications;

2. require additional computations for tailwater, outlet velocity, hydrographs, routing and roadway overtopping; and

3. are available for various culvert sizes and shapes (see HDS #5).

31-4.03(04) Computer Software

HY-8 is the only computer program allowed for the hydraulic analyses of culverts. 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. <u>HYDRAIN Microcomputer System</u>.

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

2. <u>HY8 (FHWA Culvert Analysis Software)</u>.

    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 Existing Culverts

When 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 contains 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 thoroughly inspected. See the FHWA's 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 plugged or partially plugged structures 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 given to the district operations engineer. The district operations section will slip-line or replace pipes of less than 36 in. diameter requiring excavation of less than 5 ft. See Section 31-4.04(02) Item 1 for an explanation of slip lining. This work should be done before the road-work contract is let.

Rehabilitation or replacement should be considered as part of the project work for culverts of 36 in. or greater diameter that have poor roadway geometry or that have a remaining life 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. <u>General Considerations</u>. 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.
    j. Approach erosion.

2. <u>Metal Pipe</u>. 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.
    b. Excessive deformation.

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

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

    a. Cracking, efflorescence, delamination, 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.
    e. Deterioration of structure.

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

4. <u>Jacking a Pipe</u>. 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 18 in. in diameter or larger. Slip lining is also suitable for use in some box- or arch-type culverts. 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. Many times, the capacity of a structure can 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 6.5 ft 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 50 in. or greater that will be extended 5 ft or more will require a geotechnical evaluation. See Section 31-3.05(05) for criteria regarding culvert extensions.

3. Culvert End Treatments. See Section 31-3.06(02) for desirable design criteria regarding culvert end treatments.

4. Headwalls and Anchors. Removal of headwalls or anchors usually damages the existing structure. As a minimum, 40 in. 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 are 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 50 in. 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-minute 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.

If there is 1ft or less of cover as measured from the top of a regular-sided or oversized box culvert to bottom of an asphalt of concrete pavement, the designer should show flowable backfill as the backfill material up to the top of the box.

31-5.0 DESIGN EQUATIONS

31-5.01 General

An exact theoretical analysis of culvert flow is extremely complex because the following is required.

1. analyzing nonuniform 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 procedures in this Chapter use 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 following three criteria.

   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 and/or energy dissipator design.

4. Computer Software. The following hydraulic software and design methods are acceptable for structure sizing.

   a. HY8 computer software, and
   b. FHWA Hydraulics Library CD.

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. Generally, the inlet face area is the same as the barrel area.

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

4. Inlet shape is usually the same as the shape of the culvert barrel. Typical shapes are 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 by model tests of the weir geometry or by measuring prototype discharges. These tests are then used to develop equations. Appendix A of HDS #5 contains the equations which were developed from model test data; see Figure 31-5B, Flow Type I.

2. Submerged. For headwaters 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. Appendix A of HDS #5 contains 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. Note that 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 culverts in outlet control:

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 n value. Typical Manning n values are presented 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 exit to the invert of the culvert. Because the design height of the barrel and the slope influence the actual length, an approximation of barrel length is usually 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, when 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, ft
   H_E = entrance loss, ft
   H_f = friction losses, ft
   H_V = exit loss (velocity head), ft
   H_b = bend losses, ft (see HDS #5)
   H_j = losses at junctions, ft (see HDS #5)
   H_g = losses at grates, ft (see HDS #5)

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

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

3. Velocity head. $H_V = V^2/2g$ (Equation 31-5.3)

   Where: g = acceleration due to gravity, 32.2 ft/s^2

4. Entrance loss. $H_E = K_E (V^2/2g)$ (Equation 31-5.4)

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

5. Friction loss. $H_f = [(29n^2L)/R^{1.33}] [V^2/2g]$ (Equation 31-5.5)

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

6. Exit loss. $H_O = 1.0 [(V^2/2g) - (V_d^2/2g)]$ (Equation 31-5.6)

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

$H_O = H_V = V^2/2g$ (Equation 31-5.7)

7. Barrel losses. $H = H_E + H_O + H_f$ (Equation 31-5.8)
$H = [1 + K_e + (19.63n^2L/R^{1.33})] [V^2/2g]$

8. Energy Grade Line. The energy grade line represents the total energy at any 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 following relationship results:

$HW_O + (V_U^2/2g) = TW + (V_d^2/2g) + H_L$ (Equation 31-5.9)

Where:
HW_O = headwater depth above the outlet invert, ft
V_U = approach velocity, ft/s
TW = tailwater depth above the outlet invert, ft
V_d = downstream velocity, ft/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:

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

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

2. Partly Full Flow. Equations 31-5.1 through 31-5.10 were developed for full barrel flow. The equations also apply to the flow situations which are effectively full-flow conditions, if $TW < d_C$; see Figure 31-5F, Flow Type VII. Backwater calculations may be required which begin at the downstream water surface and proceed 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 numerous backwater calculations performed by FHWA, it has been determined that the hydraulic grade line pierces the plane of the culvert outlet at a point half way between critical depth and the top of the barrel or $(d_C + D)/2$ above the outlet invert. TW should be used if 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 $(d_C + D)/2$, ft

   Adequate results are obtained down to HW = 0.75D. For lower headwaters, backwater calculations are required. See Figure 31-5G if $TW < d_C$ and Figure 31-5H if $TW > d_C$.

31-5.05 Outlet Velocity

Culvert outlet velocities shall be calculated to determine the extent of erosion protection required at the culvert exit. Culverts usually result in outlet velocities which are higher than the natural stream velocities. See Section 31-3.0 for INDOT policies 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 depths may be obtained from design aids in publications (e.g., 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

Roadways are generally designed to avoid overtopping during the appropriate design storm given for the road serviceability requirement. However, for storms that exceed the road serviceability design storm, it is necessary to calculate HW elevations and velocities.

Roadway overtopping will begin when the headwater rises to the elevation of the roadway. The overtopping will usually 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 roadway embankments are found 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:

$$Q_r = C_d L HW_r^{1.5} \quad \text{(Equation 31-5.12)}$$

Where:
- Q_r = overtopping flow rate, ft^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, ft
- HW_r = the upstream depth, measured above the roadway crest, ft

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 fall above and below the design discharge and cover the entire flow range of interest. Both inlet and outlet control headwaters shall be calculated.

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

   c. When the culvert headwater elevations exceed the roadway crest elevation, over-topping 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 culverts 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 structures which are 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 contains 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 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 at nearby structures where data is readily available.

   b. Studies and regulatory requirements by other agencies including the following:
      (1) small dams — NRCS, COE;
      (2) canals — NRCS, COE;
      (3) floodplain — NRCS, COE, FEMA, USGS, NOAA, IDNR; and
      (4) storm drain — local or private, including drains regulated by any county drainage board.

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

5. <u>Step 2: Determine Hydrology</u>.

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

6. <u>Step 3: Analyze Downstream Channel</u>.

   a. See Chapter Thirty.

b. Minimum data are cross section and slope of channel and the rating curve for 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 Qd.

   a. See Section 31-3.0 and Chapter Twenty-nine "Hydrology."
   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 magnitude(s) 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 (HWi). Use the inlet control nomograph (FHWA Hydraulics Library CD). (Note: 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 foot of width.

   c. Locate HW/D ratio:

      (1) Use a straight edge.
      (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 and read HW/D and note 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. <u>Step 8: Determine Outlet Control Headwater Depth At Inlet (HWoi)</u>.

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 (dC) using appropriate chart in HDS #5:

(1) Locate flow rate and read dC.

(2) dC cannot exceed D.

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

c. Calculate (dC + D)/2.

d. Determine (hO). hO = the larger of TW or (dC + D/2).

e. Determine (KE), entrance loss coefficient 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 range.

(2) Locate appropriate KE scale.

(3) Locate culvert length (L) or (L1):
- use (L) if Manning's n matches the n value of the culvert, or
- use (L1) to adjust for a different culvert n value.

$L1 = L(n1/n)^2$ (Equation 31-5.13)

Where:

L1	=	adjusted culvert length, ft
L	=	actual culvert length, ft
n1	=	desired Manning n value
n	=	Manning n value on chart

(4) Mark point on turning line:
- use a straight edge
- connect size with the length

(5) Read (H):
- use a straight edge
- connect Q and turning point
- read (H) on Head Loss scale

g. Calculate outlet control headwater (Hwoi):

(1) Use Equation 31-5.14, if VU and Vd are neglected:

$$HWoi = H + hO - SOL$$ (Equation 31-5.14)

(2) use Equations 31-5.1, 31-5.6 and 31-5.9 to include VU and Vd

(3) If HWoi is less than 1.2D and control is outlet control:

(a) the barrel may flow partly full

(b) the approximate method of using the greater of tailwater or (dC + 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 shall not be used

12. <u>Step 9: Determine Controlling Headwater (HWC)</u>.

a. Compare HWi and HWoi; use the higher.

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

13. Step 10: Compute Discharge Over The Roadway (Qr).

a. Choose Qt and thereby establish a TW.

b. Assume an upstream depth over the roadway (HWr), calculate the length of roadway crest (L), and calculate the overtopping flow rate using Equation 315.15:

Qr = Cd L HWr1.5 (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 Qd.

14. Step 11: Calculate Outlet Velocity (VO) And Depth (dn).

If inlet control is the controlling headwater using the design storm magnitude appropriate for the velocity,

a. Calculate flow depth at culvert exit:

(1) use normal depth (dn), or
(2) use water surface profile

b. Calculate flow area (A)

c. Calculate exit velocity (VO) = Q/A

If outlet control is the controlling headwater using the design storm magnitude appropriate for the velocity,

d. Calculate flow depth at culvert exit:

(1) use dC if dC > TW
(2) use TW if dC < TW < D
(3) use D if D < TW

e. Calculate flow area (A).

f. Calculate exit velocity (VO) = Q/A.

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

    a. the barrel must have adequate cover (refer to Section 31-3.05(04)),
    b. the length shall be close to the approximate length,
    c. the allowable backwater shall not be exceeded,
    d. the roadway serviceability must be met, and
    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 dissipators if VO is larger than 13 ft/s (see Section 31-3.0 and Chapter Thirty-four).

    c. Sediment control storage for sites 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 contains:

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

    See Figure 31-7.1 for site data.

b. Survey notes indicate:

(1) no sediment or debris problems
(2) no nearby structures

c. Studies by other agencies — none

d. Environmental, risk assessment shows:

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

e. Design criteria:

(1) HW: Q100 Maximum backwater is 1.5 in..
(2) RS: Q100 Headwater elevation must be 2 ft below the edge of pavement elevation.
(3) VEL: Q50 Maximum velocity is 13 ft/s without energy dissipator. See Section 31-3.0 for INDOT criteria on outlet protection.

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

Q50 = 134 ft3/s Q100 = 148 ft3/s

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

Point	Station (ft)	Elevation (ft)
1	12.3	194.0
2	22.3	193.0
3	28.3	192.8
4	31.0	190.4
5	43.0	190.4
6	45.7	192.8
8	62.0	197.6

The rating curve for the channel calculated by normal depth yields:

Q (ft3/s)	TW (ft)	V (ft/s)
44.5	1.73	1.97

89.0	3.13	2.90
133.5	2.57	2.47
148.3	3.30	3.00
178.0	3.60	3.20

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.

   Qd = Q100 = 148 ft3/s for HW and RS
   Q50 = 134 ft3/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 elev.	198.3 ft
Assume pavement thickness	-0.83 ft
Assume minimum cover	-1.00 ft
Pipe Thickness	-0.60 ft
Inlet Elevation	-190.7 ft
Maximum Allowable Rise	5.17 ft

   c. Try a round pipe with diameter = 60 in..

   d. Assume an end section conforming to fill slope for both RCP and CMP. Ke = 0.5 (Figure 31-10B, Entrance Loss Coefficients (Outlet Control, Full or Partly Full)).

   e. TW = 3.3 ft   AHW = Eli + TW + 0.13 = 190.7 + 3.3 + 0.13 = 194.1 ft

   f. With a very flat channel slope of 0.001 ft/ft, chances are good a culvert will operate under outlet control. However, for ease of calculations, Step 7 will calculate inlet control for the largest permissible pipe and, if a trial size is too small, Step 7 will continue on to the next trial.

7. Step 7: Determine Inlet Control Headwater Depth (HWi). Use inlet control nomograph:

   D = 5 ft, Ke = 0.5

Q = 148 ft3/s
From nomograph, HW/D = 1.16
HWi = 1.16 (5) = 5.8 ft
El.hi = HWi + Eli = 5.8 + 190.7 = 196.5 ft > 194.1 ft   No Good

Go to Trial 2, Single Deformed Pipe:

a. Maximum rise = 60 in
Maximum allowable Corrugated Metal Pipe Arch = 72 in x 48 in

b. From nomograph, HW/D = 1.55

c. HWi = 1.55 (4) = 6.2 ft

d. El.hi = 6.2 + 190.7 = 196.9 ft > 194.1 ft No Good

e. Try 100 in x 63 in Reinforced Concrete Deformed Pipe.

f. From nomograph, HW/D = 0.75   HWi = 0.75 (5.27) = 3.95

g El.h2 = 3.95 + 190.7 = 194.7 ft > 194.1 ft No Good

Go to Trial 3, Single Specialty Structure:

With a maximum of a 1.5 in increase in backwater allowed and a flat slope of 0.001 ft/ft, a wide shallow box will be necessary; therefore, try a 132 in x 48 in Reinforced Concrete Box with a wingwall 30° - 75° to barrel. Ke = 0.5 (Figure 31-10B).

Use inlet control nomograph:

D = 4 ft
Q/B = 148.3/11 = 13.48 ft3/s/ft
HW/D = 0.71
HWi = 0.71 (4) = 2.84 ft
Eli = 190.7 + 2.84 = 193.54 ft < 194.1 ft   OK

Go to outlet control.

8. <u>Step 8: Determine Outlet Control Headwater Depth at Inlet (HWoi)</u>.

TW = 3.3 ft for Q = 148.3 ft3/sec

dC = 1.73 ft from Critical Depth — Rectangular Section Chart
(dC + D)/2 = (1.73 + 4)/2 = 2.87
hO = the larger of TW or (dC + D)/2 = 3.3 ft
Ke = 0.5
Determine H from Chart 15 Outlet Control Nomograph:

a. Ke scale = 0.5
b. Culvert length (L) = 300 ft
c. n = 0.012
d. Area = 11 x 4 = 44 ft2
e. H = 0.4 ft
f. El.hO = ElO + H + hO = 190.3 + 0.4 + 3.3 = 194 ft < 194.1 ft

9. <u>Step 9: Determine Controlling Headwater Elevation</u>.

a. El.hO = 194.1 ft > El.hC = 193.5 ft
b. The culvert is in outlet control.

10. <u>Step 10: Calculate Outlet Velocity (VO)</u>.

a. Calculate flow depth at culvert exit.
Use TW if dC < TW < D   1.73 < 3.13 < 4   TW = 3.13 ft
b. Calculate flow area: 11 x 3.13 = 34.43 ft2
c. Calculate exit velocity: VO = Q50 /A = (134/34.43) = 3.9 ft/s

11. <u>Step 11: Review Results</u>. Compare alternative design with constraints and assumptions:

a. Check cover: 199 - (190.7 + 4 + 1) = 3.3 ft OK
b. L = 300 ft
c. El.hO = 194.0 ft < AHW 194.1 ft OK
d. Overtopping flood > Q100 RS = Q100
Pavement edge elevation (199 ft) - El.ho (194.0 ft) = 5 ft > 2 ft OK
e. Outlet velocity (3.9 ft/s) < 13.3.ft/s OK
Use revetment riprap (see Section 31-3.04(03)).

Note: The outlet control nomographs are designed for full flow. In this example, full flow does not exist because the TW depth (3.3 ft) is less than the rise (4 ft) and the culvert is on a flat slope. The above answer should be considered approximate. A more accurate solution is presented in Section 31-8.0 with the microcomputer analysis.

12. <u>Step 12: Documentation</u>. 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 analyses 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 could have been worked on HY8, they are not shown in this example. Trial 3, the reinforced concrete box culvert, will be shown.

Note: The screens shown in the figures in this section may not match exactly 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 222 ft^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 132 in x 48 in concrete box culvert. 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 are entered, the user is allowed to edit any incorrect entries. The above is how the screen that summarizes the culvert information will appear.

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 (0.001), number of cross-section coordinates (8) and subchannel option. The subchannel option in this case will be option (2), left and right overbanks (n = 0.08) and main channel (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 easily identify any input errors by glancing at the plot. To return to the data input screens, press any key. If data are correct, press (return). The user can then enter the roughness data for the main channel and overbanks.

31-8.03 Rating Curve

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 the following table. Selecting option (I) will permit the user to interpolate data between calculated points.

The Tailwater Rating Curve Table consists of tailwater elevation (T.W.E.) 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 148.3 ft^3/s, the tailwater elevation will be 193.7 ft. The channel velocity will be 3 ft/s, and the shear will be 0.162 lb/ft^2. This information will be useful in the design of channel linings if they are 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 when (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 50.8 ft.

31-8.05 Data Summary

All 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 any of 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 (132 x 48)

From the Culvert Program Options Menu, the culvert performance curve table can be obtained by selecting option (S). When option (S) is selected, the program will compute the performance curve table without considering overtopping in the analysis. Because this 132 in x 48 in culvert is a preliminary estimate, the performance without considering overtopping is calculated and is shown as Figure 31-8H, HY8 Performance Curve Prompt Screen, 132 in. Span by 48 in. Rise.

This 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 148.3 ft^3/s the headwater (HW) is 194.2 ft, which exceeds the design headwater of 194.1 ft. Consequently, the 132 in x 48 in box culvert is inadequate for the site conditions. The 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 shall be calculated as follows:

BW = Headwater El. - (Inlet El. + Tailwater Depth)

For example, BW @ Q = 148.3 ft^3/s is:

BW = 194.2 - (190.7 + 3.3)
= 0.2 ft

The backwater for the 132 in x 48 in is greater than allowable for 1.5 in. The next larger size of 144 in x 48 in will be analyzed.

31-8.07 Performance Curve (144 x 48)

Because the design headwater criterion was not met by a 132 in x 48 in, try a 144 in x 48 in and modify the file accordingly. The resulting performance table shown as Figure 31-8J indicates that the design headwater will not be exceeded at 148.3 ft^3/s. In addition, the designer must check the roadway serviceability at Q_{100} and the maximum velocity at Q_{50}.

It should be noted that this structure is sized to meet the INDOT criteria on new alignment of an increase of 1.5 in maximum backwater when compared to existing conditions. If the culvert had been a replacement structure, the INDOT criteria is a maximum total backwater of 12 in. It is a simple procedure to modify the box culvert size to meet this criteria.

31-8.08 Performance Curve (84 x 48)

The user can easily modify the existing program file to analyze a smaller barrel. Suppose a 84 in x 48 in culvert is tried. From the Culvert Program Options Menu, press (E) to edit the file, and then (E) to edit the culvert size. The prompts will be the same as they were for the 144 in x 48 in culvert, and the user will return to the Culvert Data Summary Table directly without going through 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, 84 in. Span by 48 in. Rise, appears.

Check the backwater for Q_{100} of 148.3 ft^3/s:

BW = Headwater Elevation - (Inlet Elevation + TW depth)
BW = 194.9 - (190.7 + 3.3) = 0.9 ft < 1 ft   OK

Therefore, a 84 in x 48 in RCB would have been adequate if the Allowable Backwater (ABW) was increased to 12 in.

31-8.09 Minimize Culvert

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 circular, box, elliptical and arch-shaped culverts based on a user's defined allowable headwater elevation, assuming no overtopping. This feature can be activated by selecting the letter 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 6 in 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. Several 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 195 ft based on the inlet of 190.7 ft, TW of 3.3 ft, and allowable backwater of 1 ft yields the results shown in Figure 31-8L.

This feature is a time saver for designers because it avoids the need for repetitively editing a culvert size to obtain a controlling headwater elevation.

31-8.10 Overtopping Performance Curve (144 x 48)

Return to the 144 in x 48 in culvert to determine the amount of overtopping and the actual headwater from the Culvert Program Options Menu select (O) for overtopping. Figure 31-8M, Summary of Culvert Flows Prompt Screen, will appear.

This computation table is used when 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. Note that the overtopping discharge of 201 ft^3/s occurs at the roadway sag point of 194.6 ft. For the maximum discharge of 222.42 ft^3/s, 215 ft^3/s will flow through the culvert and 7.42 ft^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 especially useful for comparing the effects of various combinations of culverts. See Figure 31-8 O, HY8 Overtopping Performance Curve Prompt Screen, 144 in. Span by 48 in. Rise.

31-8.11 Review

For the design criteria set forth for the example in Section 31-7.0, the design of a 144 in x 48 in RCB is selected as follows:

Q_{100} = 148.3 ft^3/s, HW = 194.1 ft, AHW = 194.1 ft, V_O = 3.93 ft/s
Channel Velocity = 3 ft/s.
Q_{50} = 134 ft^3/s, V_O = 3.73 ft/s. No energy dissipation necessary.

Road sag point elevation = 194.6 ft, Overtopping Q = 201 ft^3/s.
Therefore, Roadway Serviceability (RS) > Q_{100}.

Energy dissipators are warranted at velocities > 13.3 ft/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, improved end treatments improve culvert performance by providing a more efficient control section (the throat). Improved end treatments with FALL also improve performance by increasing the head on the throat. In addition, the following applies.

1. Improved end treatments are not recommended for use on culverts 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 rectangular box culverts and circular pipe culverts.

4. The use of an improved end treatment must be accompanied by an economic justification for use of the improved end treatment, and it must be approved by 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 (1.1D). 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, and 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. In addition, 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.

<u>31-9.03 Slope-Tapered End Treatments</u>

The slope-tapered end treatment, like the side-tapered end treatment, 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). In addition, a vertical FALL is incorporated into the end treatment between the face and throat sections. This 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 of this *Manual*. The size of the bend section is established by locating it a minimum 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 these end treatments are larger than the face sections of equivalent depressed side-tapered end treatments. 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 in this *Manual*. 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 any other configuration. Slope-tapered end treatments can be applied to both box culverts and circular pipe culverts. For the latter application, a square to round transition is normally used to connect the rectangular slope-tapered to the circular end treatment pipe.

31-9.04 Hydraulic Design

31-9.04(01) Inlet Control

Tapered end treatments have several possible control sections including the face, the bend (for slope-tapered end treatments) and the throat. In addition, 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 (Figure 31-9D, Inlet Control Performance Curves (Schematic)).

1. Side-Tapered End Treatment. The side-tapered end treatment 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 lower flow rates and headwaters, the face will usually control the flow.

2. Slope-Tapered End Treatment. The slope-tapered end treatment 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. As previously noted, the bend section will not act as the control section if the dimensional criteria in this *Manual* 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

When 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 co-efficient (K_E) is 0.2 for both side-tapered and slope-tapered end treatments. 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. These calculations are performed using the Culvert Design Form provided in Section 31-10.0. The design nomographs contained 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 and without tapered end treatments, all of which meet the site design criteria. The designer must select the best design for the site under consideration.

In the design of tapered end treatments, 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 usually minor compared with the cost of the barrel.

Performance curves are of utmost importance in understanding the operation of a culvert with a tapered end treatment. Each potential control section (face, throat and outlet) has a performance curve, based on the assumption that a specific section controls the flow. Calculating and plotting the various performance curves results in a graph similar to Figure 31-9E, Culvert Performance Curve (Schematic), containing 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; and 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 presents the figures as follows:

31-10A	Recommended Manning's n Value. These are the recommended Manning's n values typically used in the hydraulic design of culverts.
31-10B	Entrance Loss Coefficients (Outlet Control, Full or Partly Full). These coefficients (K_e) are for culverts based on the type of entrance.
31-10C	Entrance Loss Coefficients (Standard INDOT Culverts). These coefficients (K_e) are for specific culverts 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)