OFFICE OF BRIDGE DEVELOPMENT
MANUAL FOR HYDROLOGIC AND HYDRAULIC DESIGN

CHAPTER 13 CULVERTS

Guidelines for the Selection and Design of Culvert Installations

This Chapter remains in draft form pending assessment of the guidance presented For accommodating bankfull flows

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PREFACE

Please note that this manual is in final draft form. The design concept of using a combination of main channel and flood plain culverts is not standard practice, but is considered by the SHA on a case by case basis.

Incomplete items in this manual include the preparation of Figures and the development of a method for evaluating the potential for silting of culverts. The method in Appendix B is used by some hydraulic engineers to estimate this condition. It is retained in this chapter for consideration until such time as an updated method developed for Maryland streams is completed.

Guidelines for the Selection and Design of Culvert Installations

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Chapter 13
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13.1 Introduction

Various definitions for a culvert are used by the Office of Bridge Development, depending upon the purpose of the definition:

- Any structure designed hydraulically as a culvert, regardless of size, is considered as a culvert for purposes of this chapter

- Any structure that has a paved bottom is defined by the Maryland Department of the Environment as a culvert, and this definition is used by SHA in preparing permit applications.

- Structures 20 feet or wider in centerline length between extreme ends of openings are considered as bridges for purpose of the bridge inventory. These bridges may include structures designed as culverts and are therefore treated as culverts for purposes of this chapter.

- Small structures are defined as structures from 5 feet up to 20 feet in centerline length between extreme ends of openings. These may be either bridges or culverts.

Hydraulic design procedures for culverts are based on the publications and software of the Federal Highway Administration. These procedures are discussed in Appendix A

The design of a highway stream crossing involves consideration and resolution of a number of issues and concerns in order to achieve the design objectives for the site. The designer should list and prioritize these objectives at the beginning of the location/design process. This exercise will provide an opportunity to evaluate the type of design best suited for a particular location. It will also serve to highlight conflicts between objectives for a given alternative design.

These design objectives, listed in Table 1 of Section 13.2, can be categorized in the following manner:

1. Objectives regarding the structure itself such as it's structural, geotechnical and hydraulic performance and the overall effect of the design on safety, maintenance and traffic operations. This includes minimizing any effects of the stream on the structure, the highway and related flood hazards.

2. Objectives relating to minimizing any adverse effects of the structure on the stream, its flood plain, wetlands and associated habitat.

This chapter provides an approach to the selection and design of culvert installations based on consideration of the relative significance and priorities of the objectives in these categories. Objectives in both categories need to be satisfied to the extent practicable, in order to achieve a successful, cost-effective design.

This guideline addresses the collection, evaluation and application of information for culvert design. It is not intended for use as a step by step procedure, applicable under all conditions. Each location will have special features that will need to be evaluated and dealt with on the basis of engineering judgment.

The Group 1 objectives in Table 1 are determined by the SHA engineers in accordance with current state and federal regulations, SHA policies and design criteria. These engineering considerations are not normally reviewed by others except with regard to compliance with State and Federal flood plain regulations.

The Group 2 objectives in Table 1, as well as the objectives common to both groups, are addressed by SHA in consultation with representatives of other regulatory and environmental agencies. Designers and reviewers need to reach a common understanding early in the project development process with regard to what the objectives should be and what approaches should be considered in achieving these objectives.

The SHA has completed a study of Maryland streams in cooperation with the U. S. Fish and Wildlife Service, the Environmental Protection Agency, the U. S. Geological Survey, the Maryland Department of Environment Protection and other State and Federal agencies. The purpose of this study is to identify, inventory and classify the hydrologic, hydraulic and geomorphological characteristics of the streams in the various hydrologic provinces in Maryland.

The recommended guideline for the evaluation of stream morphology is the text entitled “Applied Stream Morphology” by Dave Rosgen (Reference 7). This reference serves as a companion text to the guidelines set forth in this chapter. The information from the Maryland Stream Study is being put to use to improve field investigation procedures and to facilitate achievement of the design objectives in Table 1.

Additional information regarding general design policies and procedures affecting culverts is set forth in the following chapters of the SHA Manual for Hydrologic and Hydraulic Design:

Chapter 3 - Policy
Chapter 8 - Hydrology
Chapter 9 - Channels
Chapter 10 - Bridges
Chapter 11 - Scour
Chapter 14 - Stream Morphology

13.2 Policy

The following policies of the Office of Bridge Development apply specifically to culverts.

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

- All culverts shall be hydraulically designed.

- The design flood and overtopping flood shall be selected in accordance with the criteria set forth in Chapter 10, Bridges.

- The culvert installation shall be designed, to the extent practicable, to meet the objectives in this chapter regarding stream stability, passage of fish and wildlife and other environmental concerns.

- Any culvert founded on footings shall be evaluated for resistance to scour in accordance with Chapter 11.

- Material selection shall include consideration of service life and the effects of corrosion and abrasion.

- The detail of documentation for each culvert site shall be commensurate with the risk and importance of the structure and the site conditions. Design data and calculations shall be assembled in an orderly fashion and retained for future reference as provided for in Chapter 5, Documentation. A Hydrology and Hydraulics Summary Sheet shall be completed for each culvert and included with the PS&E plans for the project (Chapter 4, Documentation).

- Consideration shall be given to the potential problems of debris and silting up of culvert barrels.

- Where practicable, means shall be provided for personnel and equipment access to facilitate maintenance (Chapter 7).

- Culverts shall be regularly inspected and maintained (Chapter 7).

These policies, along with design guidance used to implement the policies are discussed at greater length in the following sections of this chapter and in other chapters of the Manual.

13.3 Design Objectives

Table 1 below presents typical objectives for culvert design.

Table 1 - Primary Objectives to be Achieved in Culvert Design

Group 1 Objectives

Objectives relating to the structure itself such as it's structural, geotechnical and hydraulic design and the overall effect of the design on safety, maintenance and traffic operations. This includes minimizing any effects of the stream on the structure, the highway and related flood hazards.

1. Provide for the safety of the public; structure to remain stable for worst-case flood conditions.

2. Provide a cost-effective and maintainable design

3. Meet State requirements for strength and durability

4. Minimize potential for uplift, piping and pressure forces on culverts

5. Minimize maintenance problems with inorganic and organic debris

6. *Meet requirements for flood plain management

7. * Maintain the natural stream channel stability of dimension, pattern and profile so that over time the channel features are maintained and the channel neither aggrades nor degrades. (Select culvert installation to maintain bankfull geometry of width and depth).

8. *Control scour, erosion and degradation of bed and banks at culvert inlet and outlet and in downstream channel; control deposition of material in culvert barrel.

*These objectives can be considered common to both Group 1 and Group 2

Group 2 Objectives

Objectives relating to minimizing the effect of the structure on the stream, its flood plain, wetlands and associated habitat.

1. Provide for passage of fish and wildlife
2. Maintain and enhance fish and wildlife habitat
3. Create an aesthetic design
4. See objectives 6-8 above.

13.3 Design Objectives

The primary objective of the SHA is to achieve a safe, stable stream crossing that is commensurate with the risks posed to the travelling public at the site. The design criteria for use in considering the design flood and the risks associated with a proposed design are set forth in Chapters 8, 9 and 10 and will not be repeated here. The stream stability and other environmental objectives will be addressed in later sections of this chapter.

This guide introduces the concept of using a combination of main channel and flood plain culverts, when practicable, to accomplish the design objectives in Table 1 However, it is recognized that there are thousands of culverts under Maryland roads today designed as a single box or pipe that perform in a manner that substantially meets the design objectives in Table 1. It is expected that designers will continue to encounter stream crossings where site conditions permit the use of a single culvert to satisfy the design objectives. Where a culvert installation without flood plain culverts is proposed, it becomes especially important to review the proposed design in the light of the design objectives. In particular consider the flow patterns, which result from the collection of main channel and flood plain flows and their subsequent discharge into the downstream channel.

Some of the site features that may favor a main channel culvert without flood plain culverts are noted below. However, the need for flood plain culverts should be determined on a case by case basis:

- crossings of smaller streams, particularly ephemeral streams,
- replacement of an existing main channel culvert at a location where the stream is stable and has successfully adjusted to the conditions established by the existing (main channel) culvert.
- short culvert installations as is typical for low volume road stream crossings,
- locations where provision for fish passage is not required (ephemeral streams),
- crossings of streams where most of the flow for design conditions is in the channel, and where the flood plain is small or conveys little flow (Type B channels, for example),
- crossings where a large waterway opening is desired to accommodate passage of debris carried by the channel, and where provisions are made to design and maintain a stable channel section (This may be a bridge vs. culvert issue.).

13.4 Location Studies

13.4.1 Location Studies

Office of Bridge Development engineers are to be represented on study groups convened by the Office of Planning and Preliminary Engineering to assure that highway stream crossings are located, to the extent practicable, at hydraulically favorable locations (See Chapter 5).

Preliminary field and office studies and evaluations are made of the location of proposed culvert installations early in the project development process so as to enable the Office of Bridge Development to make informed decisions regarding the proposed crossing locations and the types of structures to be built.

These preliminary studies normally include consideration of the proposed line, grade and typical section of the highway, the hydrology of the watershed and the geomorphology of the stream and its flood plain. The extent of such location studies should be dependent upon the importance of the proposed structures and the flood hazards and environmental concerns involved with the site. These considerations and concerns are outlined below.

13.4.2 Highway Geometry and Stream Plan Form

Favorable crossing locations (Figure 1) are those that:

- are located on a relatively straight and stable section of the stream, typically a riffle,
- provide for a highway alignment generally normal to the flow in the channel and flood plain, avoiding locations of sharp bends, severe meanders, confluences or other areas of converging or diverging flow patterns and associated turbulence. Culvert skew should not exceed 45^0.
- are maintaining stable stream conditions in the reach of the stream affected by the highway crossing.

It may not be feasible to obtain an optimum highway alignment for every stream crossing; nevertheless, it is important that efforts be made at this early stage of project development to select the structure location and type that best fits the particular site conditions.

13.4.3 Hydrology Studies

Hydrology studies shall be performed in accordance with the policies and procedures set forth in Chapter 8. These studies provide the information to develop a flood frequency plot for the crossing site for flows from the bankfull stage (approximately 1.5-year flood for natural channels) to the 500-year flood. Hydrology studies should be initiated early in the project development process so that information on flood flows will be available for consideration when decisions are made regarding the location of the highway stream crossing and the selection of structure type. Chapter 5 discusses the project development process for projects involving structure designed by the Office of Bridge Development. A hydrology report shall be prepared summarizing appropriate information in accordance with the guidance set forth in Chapters 3, Policy and Chapter 8, Hydrology. SHA and the Maryland Department of the Environment (MDE) have agreed upon the method to be used in making estimates of flood peaks (17).

In Maryland, State regulations require that *flood* discharges be estimated on the basis of ultimate development in the watershed as determined from current zoning maps. Preliminary estimates of the magnitude of *bankfull* flows can be based on the regional curves set forth in the Maryland Stream Study report prepared by the U.S. Fish and Wildlife Service (15). These estimates are to be verified by field measurements made during the stream stability study. For sites with gaging stations, the frequency of the bankfull flow can be estimated from the station records. For ungaged sites, the bankfull flow should be plotted on the flood-frequency plot developed for the stream, using a return period between one and two years. See also Reference (15).

13.4.4 Stream Inventory and Classification

The protocols developed by the Fish and Wildlife Service (Reference 15) are to be used for measurements and inventories of stream characteristics. The stream should be classified in accordance with the Rosgen classification system (References 7 and 8). The stream stability and geomorphology study should address the following considerations:

- Stream and flood plain characteristics at the proposed highway crossing, and when necessary stream and flood plain characteristics at a reference reach determined to be a stable reach that is typical of the stream morphology in the vicinity of the highway crossing.

- Cross-sections of the channel and flood plain to provide necessary input for the preparation of water surface profiles using HEC-RAS. Note that if a “bottomless culvert” alternative is to be considered, cross-section elevations should be taken high enough to encompass the 500-year flood.

- A preliminary assessment regarding the stability of the stream bed and banks, adverse effects of urbanization, actual or potential aggradation, degradation or lateral migration, etc.

- Preparation of a Stream Inventory and Classification Report to summarize the results of the field and office studies. The report should follow the methodology set forth in Attachment A. of Reference 15. Particular attention is directed towards obtaining measurements of bankfull width and depth. The bankfull depth elevations and channel bank elevations need to be plotted on the stream profile and cross-sections in the reach of the stream under study.

13.4 Location Studies

The process described above provides for an initial classification of the stream for use in assessing the utility of a proposed culvert design. The designer will need to make an evaluation of the classification assigned to the stream as well as the extent to which the stream classification is used in the design the culvert. This will be particularly true in cases where the stream exhibits characteristics of more than one stream type or where the stream has been disturbed by changes to the channel or its watershed. Streams undergoing evolutionary change will need special consideration to decide how best to accommodate the potential stream type shifts which may occur over the life of the highway structure.

The general guidance and observations provided in the various sections of this chapter (for a C-type stream or a G-type stream, etc.) must be independently evaluated to verify that the guidance is appropriate for the given site conditions. Each stream crossing is unique. It cannot be assumed that the design approach for two different streams with the same stream classification should always be exactly the same just because the streams share the same classification of stream type.

Notwithstanding the cautions noted above, the concepts of (1) using the Rosgen stream types and (2) the consideration of bankfull flow conditions represent a significant advance in culvert design that is expected to reduce future problems with maintenance and disturbance to the stream.

13.4.5 Selection of Structure Type (Culvert vs Bridge)

Following completion of the studies discussed above, develop alternative design concepts for further evaluation for both a culvert installation and a bridge unless the choice of the appropriate structure to meet site conditions is obvious (extensions of existing structures, magnitude of flood discharge, etc).

Table 2 below provides a comparison of the advantages and disadvantages of bridges and culverts.

TABLE 2
BRIDGE vs CULVERT

Part 1 - Bridges

Advantages	Disadvantages
Less susceptible to clogging with drift, ice and debris	Requires more structural maintenance and rehabilitation over design life than do culverts
Waterway area increases with rising stage of stream until water begins to submerge superstructure	Spillthrough slopes susceptible to erosion damage from highway and bridge runoff
Scour increases waterway opening, reducing backwater.	Piers and abutments susceptible to failure from scour
Roadway widening does not usually affect	Susceptible to ice and frost formation on deck

hydraulic capacity	
13.4 Location Studies	
Less of an impact on aquatic environment and wetlands when natural channel/flood plain relationships maintained.	Bridge railing and parapets hazardous to motorists as compared to recovery areas generally provided by culverts
Easier to maintain the natural stream channel width/depth ratios under the bridge.	Deck drainage may pose a hazard to motorists; scuppers may require frequent clean out
Easier to maintain bedload (coarse sediment) transport.	Buoyant, drag and impact forces are hazards to bridges
Easier to maintain passage of fish and wildlife.	Susceptible to damage from stream meander migration
Channel under bridge can enhance habitat via scour holes at piers and abutments, etc.	
Channel under bridge may get more sunlight	

Part 2 – Culverts

Advantages	Disadvantages
Provides an uninterrupted view of the road.	Silting in one or more cells of multiple cell installations and/or accumulation of debris and ice can be a problem requiring frequent maintenance(*These problem can be reduced through the careful application of the criteria in this design guide*)
Roadway recovery area can be provided	Waterway area is fixed, once water rises above the soffit of the culvert, until overtopping occurs. May discharge flood flows to downstream channel at a higher velocity than would occur in the natural channel
Grade raises and widening projects can sometimes be accommodated by extending culvert ends	Roadway susceptible to overtopping and possible breaching of embankment if culvert clogs with drift, ice or debris
Most culverts require very little, if any, structural maintenance	Possible barrier to fish and wildlife passage due to high velocities, inadequate low flow depths, blocking of sunlight, etc.
Frost and ice usually do not form on the traveled way before other areas experience the same problem	Susceptible to erosion of fill slopes and scour at outlets due to high exit velocities; may require energy dissipation at outlets
Capacity increases with stage, and can be increased with improved inlets	Susceptible to damage from abrasion or corrosion; Susceptible to failure by piping and/or infiltration
Usually quicker and easier to build	Culvert extensions may reduce culvert capacity
Scour is localized, more predictable and easier to control	Inlets of flexible culverts susceptible to failure by buoyancy; rigid culverts susceptible to failure from

	separation of joints
13.4 Location Studies/13.5 Culvert Design Procedures	
Can be used to control headcutting or other vertical channel instabilities	Backwater caused by culvert may cause silting of upstream channel.
Storage can be used to reduce peak discharges in small channels (at interchanges, etc.) for storm water management.	Loss of sunlight and changed flow conditions can significantly reduce viability of stream for habitat within the limits of the culvert.
	May require stream diversions during construction
	May cause degradation of downstream channel through redistribution, collection and concentration of flood flows at culvert outlet.

13.5.1 Introduction

The Office of Bridge Development is involved with structures on streams having a drainage area of one square mile or more. Culvert designs for such locations often involve multi-cell boxes or multiple pipe installations. The concepts presented below represent approaches to achieving the design objectives for Type B, C, and E streams as defined by Rosgen (Reference 7). Special considerations for other stream types are discussed in Section 13.6. Section 13.5 generally applicable to culverts located on a riffle (or step or rapid for Type B streams) and on comparatively straight channel reaches. Additional considerations regarding the special problems involved in locating culverts on bends, confluences and in pools are also discussed in Section 13.6.

The design process involves the following considerations:

- design of the main channel culvert to accommodate bankfull flow with minimum change in the hydraulic characteristics of unit discharge, width, depth and velocity,

- design of an upstream transition to the culvert entrance to achieve, within practical limits, a streamlined continuity of the flow and to maintain sediment transport characteristics of velocity and shear so as to avoid deposition of material or scouring,

- design of the culvert installation, including additional flood plain culverts as appropriate, to accommodate the design discharge in the channel and on the flood plain, and

- design of the main channel culvert outlet to minimize impacts to the downstream channel and to stabilize flow conditions for passage of fish.

There is no single “standard” design method applicable to all streams. The discussion below should be considered as a guide for addressing the various objectives to be achieved in the culvert design process, consistent with the site conditions.

13.5 Culvert Design Procedures

13.5.2 Culvert Alternatives

There are many culvert types and combinations of culvert types currently available for installation at a stream crossing. A traditional engineering approach for culvert selection has been to specify the design requirements for acceptable alternatives. This allows the contractor to select from among approved alternative designs on the basis of cost. This approach works best for small pipe culvert installations. The selection process becomes more complex as the size of the stream increases due to the increasing number of factors to consider and the individual performance characteristics of different types of culverts. Because of this complexity, the SHA Office of Bridge Development will normally specify the culvert type and size to be installed. SHA typically provides detailed instructions with regard to the installation procedures to be followed for its construction.

13.5.3 Water Surface Profiles

Using information obtained from the field and office preliminary studies, utilize the HEC-RAS model to develop water surface profiles for the following discharges for pre-construction conditions:

Recurrence Interval	Existing Development Conditions in the Watershed	Conditions of Ultimate Development in the Watershed
Bankfull stage	X	
Q2	X	X
Q10	X	X
Q design	X	X
Q100	X	X
Q500 * (bottomless culverts)	X	

* The 500-year flood may need to be analyzed for culverts founded on footings to ensure that the structure is not vulnerable to damage from scour.

13.5.4 Upstream Transition Section

Concept

The purpose of the transition section is to provide a channel section where the flow can transition smoothly from the stream channel to the culvert entrance. A properly designed transition section is important in achieving various objectives of the culvert installation:

- Maintaining the natural stream channel stability of dimension, pattern and profile so that over time channel features are maintained and the channel neither aggrades nor degrades,

13.5 Culvert Design Procedures

- Minimizing scour, erosion or deposition at the culvert inlet and in the culvert barrel,
- Maintaining or enhancing fish and wildlife passage and habitat, and
- Creating an aesthetic design

Additional right-of-way may be required to properly design the transition. This need must be recognized early in the project development stage and coordinated with the Office of Real Estate. When additional ROW will be required for channel transitions, early contact should be made with affected property owners to explain the nature of the proposed work and how such work will enhance the stream quality in the transition section (See Section 13.6).

Work in the channel may be necessary to modify the channel cross-section and slope. This need must be recognized and agreed to early in the project development stage by personnel from other agencies who will review the project plans. Stream modifications can serve to provide an attractive design that enhances habitat.

Design Procedure

From the stream stability study, note the stream type of the approach channel and obtain data on the bankfull depth, width, velocity and slope. The recommended general approach is to design the culvert width to match the (stable) bankfull width of the upstream approach channel. For B, C and E type channels, this approach will tend to stabilize the channel since the culvert invert will serve to control the upstream channel elevation. In such cases, there may not be a need for much of a transition section between the culvert and the upstream channel other than to minimize any abrupt changes in the channel elevation between the channel thalweg and the depressed culvert invert. Some adjustments to the channel banks are normally required to construct the culvert and its wingwalls or headwalls. Riprap is commonly provided in the immediate vicinity of the culvert to transition to the channel banks. In some cases, such as for sand or silt channels, it may be desirable to provide riprap on the channel bed in the transition to the depressed culvert invert to limit any upstream effect of the culvert on the approach channel or adjacent wetlands. These upstream transitions are generally short, being on the order of 25 feet or less.

For a Type A, D, DA, F or G channel, there is likely to be special site conditions that will need to be taken into consideration in the design of the approach section as well as in the design of the culvert itself (See section 13.6).

There will be situations where there is inadequate ROW available to construct much of a transition section. In such cases, the culvert should be sized so that the depth and velocity at the culvert entrance for bankfull flow should approximate the depth and velocity of the flow in the approach channel. This will help to maintain the natural flow conditions at the bankfull discharge and provide for a short but functional transition section (Figure 2).

13.5 Culvert Design Procedures

The design of the main channel culvert and the flood plain culverts are described in the following sections. The design of the transition section and the culvert installation should be done concurrently.

13.5.5 Main Channel Culvert

Select a trial size of the main channel culvert:

- The culvert width should be about the same as the bankfull width for the reference section. Where practicable, accommodate the bankfull flow in a single pipe (up to 15' to 16' span) or a single box culvert cell (up to a 20' span). If the bankfull width is too great to carry in a single cell, provide a multi-cell box or pipe installation that minimizes disruption of bankfull flow. Box culverts have an advantage over pipe installations in this regard since the spacing between the box culvert cells is kept to a minimum (Figure 3). In cases where a two cell box is placed in the channel, consider the use of a "W" weir upstream of the culvert entrance (Figure 4). Some modification of the standard weir dimensions may be needed to fit the culvert site. The weir serves to divide the flow into two thalwegs while increasing the approach velocity to the culvert to accomplish the following:
  - reduced bar deposition and/or bank scour,
  - increased competence for coarse bed transport,
  - reduced debris accumulation at the center wall

- Where provision is to be made for fish passage, the main channel culvert(s) should be depressed a minimum of twenty percent below the existing channel bed. Normally, where this culvert depression is used, the stream will adjust its thalweg and cross-section so as to select one of the cells for low flows. This will minimize problems in accommodating fish passage.

- Use HEC-RAS to run the water surface profile for the bankfull discharge; adjust culvert slope, type, roughness and dimensions by a trial and error process to maintain continuity, to the extent practicable, of bankfull flow widths, depths and velocities upstream of, through and downstream of the culvert. Plot the bankfull depths along the reach of the stream in which the culvert is located. Adjust the invert elevations to maintain the selected depression depth in the culvert.

    - From the stream stability study, check the width/depth ratios and the stream type for the reference reach for agreement with the values at the culvert site.

    - assume that the depressed culvert section will fill in naturally so that the channel bed in the culvert will be continuous with the upstream and downstream channel elevations for the bankfull condition (This assumption will need to be reviewed using the procedures in Section 13.8). Filling of the culvert depression with stream bed material during construction should not be necessary. A composite "n" value

- should be used for the culvert, based on the stream bed material and the culvert material above the stream bed.

`- since the culvert geometry and roughness will differ from the stream channel, it is unlikely that any culvert selection will be able to match exactly the conveyance properties of the existing channel. The objective should be to design the culvert *system* so as to match, to the extent practicable, the existing water surface elevations for the bankfull flow upstream and downstream of the culvert as indicated in Figure 1.

- assume no scour hole occurs at the culvert outlet for the HEC-RAS run, unless the evaluation involves an existing culvert with an existing significant outlet scour hole such as a "blow hole". This assumption will need to be checked later on in the design process.

- where the continuity of bankfull flow conditions can be maintained through the culvert, the foregoing design procedure can be expected to provide reasonable assurance of fish passage for low flows. However, (1) if bankfull flow velocities in the culvert are significantly higher than in the adjacent channel or (2) if it appears that channel bed load will be swept out of the culvert for bankfull flow, design modifications (changes in culvert type or slope, addition of baffles, downstream grade control structures, etc.) may be required and should be investigated as discussed in Sections 13.8 and 13.9

13.5.6 Flood Plain Culverts

The culvert is a cost-effective hydraulic structure since it serves to collect flood flows upstream of the highway crossing from the channel and flood plains, convey the flow under the highway and discharge it into the downstream channel. However, this action of collecting the upstream flow and discharging it in a concentrated jet into the downstream channel can have an effect on the stream morphology. A small culvert that severely constricts the flow can initiate degradation and lead to the creation of an unstable channel downstream of the highway.

One way to minimize this effect is to install additional culverts on the flood plain to convey the flood plain flows from one side of the highway to the other and thereby reduce the collection and concentration of flow by the main channel culvert into the downstream channel.

An alternative approach would be to design a bridge for the crossing. However, the costs of such a solution may be high in comparison with the benefits to be obtained. Stream channels are dynamic and can adjust over time to changing conditions brought about by a highway culvert installation when careful attention is given to the stream morphology in the design of the structure. The engineer needs to determine the best method of accommodating the flood flows for the particular site conditions.

13.5 Culvert Design Procedures

The flood plain culverts may also serve to accommodate passage of wildlife. The need to provide for such passage, and the clearance or size requirements to encourage wildlife to use the culverts should be pursued with environmental specialists during the location/environmental phase of project development.

The following guidance is provided with regard to the design of the flood plain culverts. The guidance is based on the design for a box culvert, but a similar approach can be used for other culvert types and shapes as well.

Location

Where practicable, the flood plain culvert should be positioned on the flood plain well beyond the channel banks (Figure 5). This location avoids the higher velocity and boundary shear stress in the near bank region of the flood plain, and moves the culvert away from the area of convergence of the flood plain flow into the culvert. (However, SHA has successfully constructed “flood plain” culverts immediately adjacent to the main channel culvert). It also minimizes the chance for clogging with debris that is carried in the main channel. The upstream flood plain culvert invert is to be set at the water surface elevation of the bankfull flow. On wide flood plains, flood plain culverts should be used on both sides of the channel. If the flood plain is constricted, place the culvert(s) on the inside of the channel bend to avoid convergence and high velocity flows on the outside of the bend (See also Section 13.9).

Size

The culvert installation is to be sized to meet the state flood plain requirements. Since the flood plain culvert(s) and the main channel culvert will have different invert elevations, the dimensions of the various culverts must be determined by a trial and error solution.

Main channel culvert: the culvert width is determined by the procedure discussed in Section 13.4.5 to match the bankfull width; the height of the culvert needs to be established as described below.

Flood plain culvert: both the width and height of the culvert need to be determined by the procedure described below.

Appendix A discusses hydraulic design procedures for sizing the flood plain culvert(s) and the main channel culvert. Culvert design software packages such as the FHWA HY-8 program or the Corps of Engineers HEC-RAS program can be used to select the culvert sizes (See References). A primary goal is to design the main channel culvert installation to convey the main channel flows and the flood plain culvert installation(s) to convey the flood plain flows.

Judgment must be used to determine the best way to handle the flow for a specific location and flood discharge.

13.5 Culvert Design Procedures

The following criteria apply in establishing culvert size and heights:

- Provide for freeboard for *bankfull flow* (Freeboard should be equal to the thalweg or maximum depth in the channel for bankfull flow – See Figure 6).

- For pressure flow conditions, an appropriate ratio should be maintained between the main channel culvert and the flood plain culverts. As a first step where conditions warrant, it is suggested that the soffit or crown of the flood plain and main channel culverts be set at the same elevation.

- Match the existing water surface profile of the existing structure. For a structure on new location, meet the flood plain requirements set forth in Chapter 9.

- The energy line elevation for the design discharge must not exceed the elevation of the upstream edge of traffic lanes.

- A minimum cover between the pavement and the top of the box must be provided as discussed in Section 13.10.

13.5.7 Culvert Headwall and Endwall

Culverts ends shall be protected with walls designed to meet the site conditions (straight headwall or endwall, use of wingwalls, etc.). A cutoff wall at least three feet deep shall be provided below the culvert invert at the headwall and at the endwall to prevent problems of undermining, piping, scour and erosion of the culvert bedding material and the culvert fill. Culvert end sections should be designed as hydraulically efficient openings (Appendix A), should be structurally designed to resist buoyancy and uplift forces acting on the culvert, and should match the geometry of the roadway embankment.

One of the most important decisions about this aspect of the design is whether the culvert installation will share a single headwall and endwall, or whether each culvert will be protected with its own headwall and endwall. It is important to place the flood plain culverts away from the active channel to minimize the potential for undermining by degradation or migration of the main channel into the area of the flood plain culvert. If flood plain culverts can be located away from the main channel and still serve to effectively convey flood plain flows, then it is reasonable to provide for separate entrance and outlet protection for the flood plain culvert (Figure 7). If site conditions necessitate placing the flood plain culverts near the banks of the main channel, they become more vulnerable to undermining. Under this condition, consider combined headwalls and endwalls for the main channel and flood plain culverts to protect the culvert installation at its inlet and outlet. In some cases, the size of such a combined headwall can become massive and render this concept as impractical (Figure 8).

Protection of the culvert ends needs careful consideration, taking into account the likelihood of lateral migration of the upstream channel or degradation and scour of the downstream channel over the design life of the culvert installation. The stream stability study should be reviewed to consider channel characteristics such as the meander belt ratio, the stream type and the stream's ability to adjust to changing conditions.

13.5.8 Hydraulic Analysis

After selection of trial sizes and arrangements of the culvert installation to best fit the channel morphology, the culvert installation needs to be analyzed for hydraulic capacity to convey flood flows so as to meet State requirements (See Chapter 9 and Chapter 13, Appendix A). The design recurrence interval for various classes of highways is set forth in Chapter 10, Bridges.

Water surface profiles should be prepared using HEC-RAS. Adjustments need to be made in the hydraulic capacity of the culvert installation until the structure conforms to State requirements. In making these adjustments, it should be kept in mind that the width of the main channel culvert was selected to accommodate the bankfull flow. Where adjustments in capacity are required, consider increasing the area of the flood plain culverts or the height of the main channel culvert. Try to minimize changes to the width of the main channel culvert.

Field checks should be made of the development in the flood plain to assure that the culvert headwater elevations determined by the hydraulic analysis are consistent with State regulations.

13.5.9 Culvert Outlets

The design of the main channel culvert outlet is a critical aspect of the culvert installation with regard to minimizing the impact of the culvert on the stream. When flood plain culverts are effectively used, they serve to relieve the main channel culvert of much of the hydraulic load. This in turn simplifies the problem of energy dissipation at the culvert outlets. Normally, energy dissipation at the outlets of the flood plain culverts can be handled with riprap pads since the velocities of flow on the flood plain tend to be low.

A reconnaissance study should be made of the stream channel downstream of the proposed highway crossing to determine its characteristics and to evaluate its stability. If the downstream channel is steep or unstable, special considerations may need to be taken in the design of the culvert outlet. Of particular importance is the occurrence of any downstream "nick points" or channel drops which indicate that an instability downstream of the culvert is working back towards the culvert outlet. If the channel reach in the vicinity of the culvert is unstable, an early decision will need to be made as to whether restoration efforts to stabilize the stream are necessary. If so, such restoration measures should be designed and constructed as a part of the culvert installation (See Section 13.6).

Culvert outlet protection needs to be tailored for the specific conditions at the site, and no single "standard" method will be appropriate for all locations. This guide provides an overview of factors to consider in the design and provides for several examples to illustrate how the outlet protection can be designed to fit the site conditions.

Case 1 Outlets

Case 1 outlets are defined in this chapter as outlets into a downstream channel and flood plain that is stable and has a relatively flat slope such as a C-Type or E-Type stream (See Figure 1).

The design concept of the flow distribution for the Case 1 culvert installation is to pass the flow through the culverts in approximately the same manner as the flow is distributed in the upstream channel and flood plain. That is, maintain the flood plain flow on the flood plain and pass the main channel flow in the main channel culvert. Select a design that minimizes changes to the velocity of flow at the culvert outlets as compared to the velocity of flow approaching the culverts.

For this case, the flood plain culverts will often outlet onto an essentially flat flood plain. A riprap pad can be placed at the flood plain culvert outlets to protect the outlets and to minimize any local erosion on the flood plain. Another approach is to provide a riprap basin at the outlet with a pool depth designed for energy dissipation. Basins serve to dissipate energy and to redirect the outlet flow so that it spreads out and redistributes itself onto the downstream flood plain. In some developed areas, however, pools may represent a nuisance and safety hazard.

Velocities in the main channel culvert for Case 1 culverts can be expected to be higher than in the flood plain culverts, and are likely to be higher than in the upstream approach channel for the design discharge. In addition, the downstream channel banks and bed are likely to be vulnerable to scour and erosion. There are a number of alternative designs that can be considered in providing the desired protection for this case.

A riprap basin at the culvert outlet is a natural and efficient means of dissipating energy. The basin can also serve to facilitate fish passage from the downstream basin into the culvert barrel. The outlet basin is particularly effective for stable streams with flat slopes such as Type C and E streams.

The outlet basin can be pre-formed and protected with riprap to minimize future changes due to outlet scour. Alternately, a riprap blanket can be provided at the main channel culvert so that the culvert will carve the scour hole and distribute the riprap within the hole during the occurrence of future floods. For some situations, such as accommodating passage of resident or non-migratory fish species in shallow channels, the riprap blanket on the channel bed serves to facilitate the transition for the fish from the downstream channel to the culvert (Figure 9). These species of fish (chubs, minnows, etc.) are not strong swimmers and cannot traverse culverts with high outlet velocities.

Where appropriate, consideration can also be given to designing the culvert outlet as a pool using the dimensions of pool width, depth, length and other characteristics obtained from the stream inventory and classification study.

In some cases, it may be necessary to provide for a grade control on the downstream end of the basin. The purpose of the control is to maintain the outlet scour pool at an elevation to enable fish to enter the culvert. This control should also provide a means of fish passage from the downstream channel into the outlet pool. For some locations on steeper slopes, it may be necessary to design several step-pool arrangements (Figure 10).

The Rosgen cross vane can be used to advantage in some cases to provide a more positive control to anchor the downstream end of the outlet basin. These devices work well on Type B and C streams where there may be a need to design more than one outlet pool to accommodate fish passage.

Case 2 Outlets - Structural Energy Dissipators

There are a number of structural design measures that can be used to dissipate energy where there is a very high outlet velocity from a culvert. The FHWA publication HEC-14 contains details regarding outlet protection. Such devices are generally not recommended for use if there are other design approaches that can be used to reduce the outlet velocity. Alternative considerations include use of other culvert materials and shapes, modification of culvert slopes or design of a bridge in lieu of a culvert.

In some cases, particularly for A, DA, F and G Type streams, stream morphology becomes of paramount importance to the culvert design, requiring the services of engineers with specialized experience and knowledge. The discussion below addresses possible considerations affecting the design of culverts on these streams. The primary consideration for such specialized design problems should be to obtain the services of engineers with experience in working with these stream types. As noted elsewhere in this chapter, extensive work outside of the normal highway rights-of- way represents a departure from traditional design practices. Such specialized designs will need to be justified on a case by case basis.

Additional right-of-way may be required to modify the stream. This need must be recognized early in the project development stage to obtain approval of the concept and to coordinate the work with the Office of Real Estate. When additional ROW will be required for channel modifications, early contact should be made with affected property owners to explain the nature of the proposed work and how such work will enhance the stream quality.

Work in the channel may be necessary to modify the channel cross-section and slope. This need must be recognized and agreed to early in the project development stage by personnel from other agencies that will review the project plans. Stream modifications can serve to provide an attractive design that enhances habitat.

13.6.1 Type A Streams (Figure 11)

The A-type stream is a steep, entrenched and confined channel with stream slopes in the range of 4 to 10% or more. In Maryland, this stream type tends to occur mostly in small drainage basins. The recommended general concept for a highway structure on an A type stream is to span the entire channel, placing the structure footings beyond the limits of the channel banks. This approach minimizes the effect of the structure on the stream and on bankfull flow conditions. Use of a bottomless culvert, rigid frame or bridge may avoid the need for any work in the stream channel, including energy dissipation at the outlet of the structure. Typically, such structures can be constructed as a single span. If the abutment footings are located within the limits of the 500-year flood plain, appropriate measures will need to be taken to protect the abutments from damage from scour. For stream types A3, A4 and A5, particular attention should be given to evaluating the need for a grade control structure at the culvert outlet. If a culvert installation is used on a Type A stream, the culvert should be located in the area of steps, rapids or chutes.

13.6.2 Type DA Streams (Figure 12)

The DA stream types are highly interconnected channel systems developing in gentle relief terrain areas exhibiting wetland environments with stable channel conditions. The stream channels have highly variable width to depth ratios, flat slopes (< 0.005), low bedload and stable banks.

In Maryland, such streams are encountered mostly in the coastal physiographic regions. The recommended general concept for a highway structure on such streams is to maintain the existing channel system to the extent feasible and to locate the culverts in convergence regions. This can be accomplished by providing:

- a combination of bridges and culverts at the crossing (preferred approach),
- culverts to carry each of the individual stream channels under the highway, or
- a bridge to span the entire channel system.

13.6.3 Type F Streams (Figure 13)

The F stream type is an entrenched, meandering riffle/pool channel on a low gradient with a high width to depth ratio. Type F streams tend to be laterally unstable with high bank erosion rates. Studies by Rosgen have shown that the unstable nature of F type streams can lead to a reestablishment of a functional flood plain inside the confines of a channel that is consistently increasing its width within the valley. Because of the potential for the lateral instability of the F channel, an investigation should be made of the stream reach upstream and downstream of the proposed highway crossing. Consideration needs to be given to the potential for a continuing evolutionary cycle of the F channel with accompanying downcutting of the channel thalweg and building of a new flood plain level. Design alternatives for a highway stream crossing include:

1. A stream rehabilitation project to modify the Type F channel (Figure 14) to a more stable channel form such as a Type C channel. While this approach may require additional ROW purchases or easements, it may also achieve offsetting cost savings in the form of a smaller main channel culvert or bridge (to match the lower width to depth ratio of the re-established channel). Another anticipated benefit would be lower maintenance costs associated with a stable channel. The re-established channel will be more efficient in transporting sediment, and can be designed to accommodate fish passage in the reach of the stream affected by the highway crossing.

2. A bridge to span the main channel with abutments set back from the channel banks and, if necessary, placement of circular piers in the channel. A clear span without piers is preferred, since further downcutting and shifting of the channel may increase the scour potential at the piers. If the bridge width provided is of adequate length, the stream may eventually re-establish a second stage channel within the limits of the original F channel.

3. A culvert installation. The most feasible approach would be to consider the evolutionary cycle of the F channel and to design the installation with a main channel culvert (to match the lower width to depth ratio of the re-established channel) and with flood plain culverts (Alternative 1 above). If this approach cannot be worked out, a wide culvert should be

considered, having a width equal to or greater than the bankfull width of the F channel. The culvert should be of adequate size to convey the design flow assuming that an evolutionary channel will form inside the F channel and culvert. The geometry and arrangement of the culvert cells should anticipate bankfull flow in a second stage channel so that one or more of the cells can function as a future main channel culvert. Stabilization of the steep F channel banks may be needed to protect against further lateral movement of the channel that would result in outflanking of the culvert and subsequent erosion of the highway embankment (Figure 15).

13.6.4 Type G Streams

The "G" or gully stream type is an entrenched narrow and deep step/pool channel with a low to moderate sinuosity. Channel slopes generally range from 2% to 4% although "G" channels may be associated with gentler slopes where they occur as "down-cut" gullies in meadows. With the exception of channels containing bedrock and boulders, the "G" stream types have very high bank erosion rates and a high sediment supply. Channel degradation and sideslope rejuvenation processes are typical.

A culvert design on a "G" type stream should be approached with caution in recognition of the potential problems with bank erosion and sediment discharge. A bridge may be a better alternative in some cases and it is recommended that a bridge alternative always be evaluated for "G-3 to G-6" Type streams.

Prior to selecting a culvert installation for a "G" type stream, a detailed study should be conducted of the stream reach to determine whether work is necessary to stabilize the channel upstream and downstream of the culvert.

- The upstream approach channel may require stabilization in order to control bank erosion and the development and movement of meanders towards the highway. Without stabilization, the stream may outflank the culvert and attack the highway embankment. Stabilization efforts may include consideration of the conversion of the "G" channel to a "B" type channel. This is done by increasing the width to depth ratio as well as the entrenchment ratio (Figure 16).

- Upstream stabilization may require a right-of-way easement including an access road (beyond the channel banks) to maintain the channel stabilization measures.

- The design of the upstream transition section should be made with careful attention to the energy slope of the flow to minimize any deposition of bed load at the culvert entrance.

- The depth and velocity of flow for bankfull flow conditions in the culvert should be consistent with depth and flow velocity in the upstream (stabilized) channel. Accordingly, culvert longitudinal slopes should be similar to the upstream channel slopes. Any significant flattening of the culvert slope or the energy line of the flow through or upstream of the culvert may result in silting up of the culvert barrel or the approach transition section.

- Culvert outlet velocities should be consistent with existing flow velocities in the channel to the extent feasible. Significant increases in outlet velocities coupled with the formation of an outlet jet into the channel can create problems with downstream channel instability. This can

  result in channel degradation and headcutting leading to the undermining of the outlet and possible failure of the entire culvert installation.

- Stabilization of a downstream channel reach may be necessary to control degradation on G-3 to G-6 streams. Stabilization efforts may be required beyond the highway right-of-way limits. In some cases, the construction of two or three step/pools can serve effectively to stabilize the downstream channel.

In general, the stability problems with "G" type channels become more difficult as the culvert length increases. A bridge alternative has the advantage of spanning the stream entirely, thereby avoiding changes to the stream regime. Bridge abutments should be placed well back of the channel banks taking into account the potential for future channel widening and an evolution to an F ($G_c \rightarrow F$) or B ($G \rightarrow B$) type stream (Figure `17).

13.6.5 Stream Crossings at Bends, Pools and Confluences

The foregoing discussion regarding the location and design of culverts is based on the assumption of a favorable crossing location of the stream such as a straight reach on a riffle. In some cases, however, it may be necessary to construct a culvert in a bend or a pool or to deal with a stream confluence. These situations introduce a number of other considerations in the design process.

Bends (Figure 18)

Bend locations can present a number of challenges to a culvert design. It is important to assure that the reach upstream and downstream of the bend, as well as the bend itself, be reasonably stable. If it is not, consider designing upstream or downstream transition sections to reestablish a stable channel. Align the culvert entrance and outlet with the stream channel to provide for a streamlined flow pattern and accompanying efficiency in the conveyance of sediment and flood flows. To achieve the design objectives in bends, it may become necessary to adjust the location of the channel in the vicinity of the culvert inlet or outlet. Such adjustments should be made so as to maintain, to the extent practicable, the existing pattern, profile and dimension of the stream and avoid straightening of the channel.

Because of the additional problems and costs associated with designing a large culvert with a radius of curvature, this approach is not generally recommended. In some cases, however, use of a curved culvert may serve to minimize problems associated with disruption of the existing channel.

Pools (Figure 19)

When a culvert is to be located in an existing pool, the culvert design should be directed at maintaining the characteristics of the pool. The geometry of the pool can be obtained from the stream inventory data. The culvert width should be based on the average bankfull width in the pool. The bankfull depth will be much greater in the pool than it is for a riffle section. Fish passage is facilitated in a pool and the culvert invert may not need to be depressed below the stream thalweg in the pool. If the culvert extends beyond the pool into the downstream riffle, it may remove the existing control, which established the glide and the run at the end of the pool. To the extent practicable, the pool depth should be extended into the downstream riffle beyond the outlet area of the culvert a sufficient distance in order to reestablish a control for the glide and the run.

Pools and riffles tend to move downstream over time. In the event that an upstream riffle moves down into the culvert, consider a design that will still provide for sufficient flow depth for fish passage. Downstream grade control structures can be used to maintain the pool elevation.

Confluences

A recurring problem in culvert design is the treatment of a stream confluence that lies within the limits of the proposed highway alignment. The general rule for such cases is to maintain separately the natural flow pattern of each stream channel even if this involves construction of two culverts. (Bridging of the confluence is *not* generally recommended because of problems with scour, erosion or sedimentation.) The site conditions for each location will need to be evaluated to determine the best location of the confluence relative to the highway.

Relocating the stream confluence immediately upstream of the highway culvert may create future problems with sediment deposition at the confluence and culvert entrance. It is usually preferable to relocate the stream confluence downstream of the highway crossing, especially if the streams are different sizes and types (Figure 20). For example, a small tributary G Type stream emptying into a larger E Type stream is liable to carry a significant sediment load that will be deposited at the confluence and the culvert entrance. Moving the confluence downstream of the highway will require the construction of two separate main channel culverts. Where the two streams share a common flood plain, the hydraulic design will need to be developed considering the total flow in the flood plain system and the characteristics of the hydrographs (time to peak, etc.) of the two streams.

If both tributaries are of the same type and approximate size, it may be feasible to locate the confluence upstream from the culvert, provided that sediment transport can be maintained through the culvert (Figure 21). For this case, lateral stabilization of the channel banks may be needed upstream of the culvert.

13.7 Applications – Case Histories

The guidelines and criteria in this chapter provide an overview of the concepts to be applied in the design of a culvert installation in order to meet the design objectives. Since each stream crossing is unique, having its own set of conditions and considerations, it is not feasible to provide a step by step process that would serve equally well for every culvert location. However, the SHA has now constructed several culvert installations that have been designed utilizing the Rosgen stream classification system and the basic concepts presented in this chapter. Designers are encouraged to review the hydraulic reports for these culvert installations to note how the environmental, morphological, hydraulic and hydrologic conditions were evaluated and taken into account in the culvert design.

These culvert installations include:

1. Route 50 Salisbury Bypass over Wicomico River (combined bridge and culvert installation for a Rosgen DA stream type,

2. Route 25 over Beaverdam Run, Baltimore County (Rosgen C4 Channel),

3. Route 382 over Full Mill Branch and Spice Creek, Prince Georges County (Rosgen E6 channel),

4. Arena Drive over Tributary to Southwest Branch, Prince Georges County (Rosgen G4 channel),

5. Route 191 over Tributary to Cabin John, Montgomery County (Rosgen C3/B3 Channel)

13.8 Outlet Velocities, Degradation and Scour

Section 13.5, Culvert Design Procedures, presents general recommendations for the sizing and hydraulic analysis of culvert installations and their outlets. The procedure outlined in Section 13.5 serves to produce a reasonable estimate of the culvert outlet velocity for a given discharge.

Where adequately sized flood plain culverts are provided, the culvert outlet velocity in the main channel should be reasonably consistent with channel velocities for existing conditions. For culverts on mild slopes, modest increases in velocities of less than 20 percent normally will be dissipated by the formation of the outlet scour hole. Culverts on steep slopes, however, can represent more of a problem. This section expands on the guidance in Section 13.5 for the condition where there is a need to study the scour potential in greater detail.

Evaluation of three flows is recommended: bankfull flow, design flow, and incipient overtopping flow, within practical limits. Information required for the analysis includes:

- Information on the stream channel, its slope and composition of channel bars as determined from the stream inventory and classification (As noted in Section 13.5, particular attention needs to be given to the stability of the downstream channel section and any tendency towards degradation of the channel bed in this section.)

- Composition of the bed material in the outlet channel,

- Flow velocity, slope and depth at the culvert outlet and at various locations in the downstream channel.

Bankfull Flow Conditions

Compute the Manning's "n" value (bankfull flow) and critical shear stress for the bed material using the information presented in References 7 and 8, Shield's criteria or other references. Estimate the size of bedload being transported at or near the bankfull stage by sampling nearby channel bars. Compute the shear stress at several locations downstream of the culvert outlet ($\tau = \gamma RS$) where the channel is stable. By a comparison of existing and proposed conditions determine the "zone of influence" in the downstream channel where velocities and shear stresses of proposed conditions are higher than for existing conditions.

Based on the above information, determine whether outlet flow conditions are acceptable. If not, consider either (1) redesign of the culvert or (2) use of one or more riprap basins with accompanying grade control structures in the downstream channel to dissipate energy. These pools may require construction of a step-pool type of control using rock weirs, with careful attention given to passage of fish at the weirs (Figure 22).

13.8 Outlet Velocities, Degradation and Scour

Where significant problems are encountered with regard to the effect of high outlet velocities on the stability of a downstream channel, it may be prudent to evaluate an alternative design rather than to acquire easements and to construct elaborate outfall structures.

Design Flow Condition

Any culvert outlet control feature provided for bankfull flow will need to be evaluated for the design flow to assure that it will not fail and endanger the stability of the culvert. The evaluation process is similar to that used for bankfull flow. However, the estimation of Manning's "n" may need to be modified to account for the effect of vegetation and other conditions of flood flows. *It is essential that the culvert and its outlet protection system remain stable for conditions of the design flow.*

Incipient Overtopping Condition

In some cases, the incipient overtopping condition may be the design condition. In other cases, this condition may occur only for a very rare flood well in excess of a 100-year or 500-year flood. The probability of occurrence needs to be given primary consideration in the evaluation of this flood event. The incipient overtopping condition is used as a worst case scenario for evaluating culvert outlet conditions. If this flow condition will create catastrophic results due to extreme outlet velocities, a reevaluation of the culvert design is warranted.

13.9 Silting of Culverts

Main Channel Culverts

The design procedure in Section 13.5 is based on the assumptions that:

- the culvert is aligned with the upstream channel,
- the upstream channel is stable and is neither aggrading or degrading,
- the two foot depressed culvert invert will remain filled with bed load material from the upstream channel, and
- silting of the main channel culvert installation above the two-foot depression will be unlikely if the culvert is designed to maintain the dimension, pattern and profile of the stable channel morphology associated with the bankfull flow.

An important objective of the stream inventory and classification study, Section 13.4.4, is to determine the site conditions and to identify potential problems with sedimentation (stream bed aggradation or degradation, bank erosion, etc.). There will be various situations where the above assumptions will not apply. Two examples are discussed below:

Example One (Figure 23) involves flow through a box culvert on a steep slope where the Manning's "n" value in the culvert is lower than in the approach channel. In this case, there is a concern that the bed material may be swept out of the culvert, resulting in a lower "n" value and a resultant high culvert velocity. If fish passage is a design objective for this culvert, special features may need to be incorporated in the design of the culvert barrel to reduce culvert velocities and to provide resting places for fish. (Reference)

Example Two (Figure 24) involves a location where a steeper approach channel flattens out just upstream of the culvert. This is not a desirable culvert location; yet, constraints sometimes require that a culvert be located in a less than ideal stream reach. In this instance, there is a concern that the culvert will be unable to convey the bed load from the upstream channel and will silt up.

Few procedures are available for estimating sediment conveyance capacity and deposition potential in culverts. One procedure that is currently under review and evaluation by the Maryland SHA is presented in a paper written by Dennis Richards and Michael Zeller of Simons Li and Associates. This paper is included in Appendix B of this Chapter.

13.9 Silting of Culverts

The following approach is recommended in the use of the Appendix B procedure:

1. Use Method B, carefully following the steps outlined by the authors in determining the parameters contained in the Method B Equation.

2. Compute R_d on the basis that the bed load will fill in the depressed culvert section, and that the channel bed slope will be essentially the same from the outlet through the culvert barrel and up to the approach channel. This will usually involve the computation of a composite roughness "n" value in the culvert for the bankfull flow.

3. Calculate R_s the bed-material sediment-transport ratio, channel to culvert

If R_s is less than 0.8, the culvert will most likely be able to transport the sediment being delivered by the approach channel. If the value of R_s is greater than 1.0, sedimentation may occur and design modifications should be considered.

Using the same reasoning, the smaller the value of R_s, the more likely the chance that the bed load will not remain in the depressed culvert bottom for the bankfull flow. This can be checked by using the procedure discussed in Section 13.7 to see if the shear stress in the culvert exceeds the critical shear stress of the bed load for the bankfull condition. If this is the case, velocities for the bankfull condition should be based on using the "n" value of the culvert material without consideration of the roughness of the bed material.

Rosgen has pointed out (Reference 13) that the Appendix B method may be helpful for preliminary analysis, but may not always accurately reflect sediment transport processes for some stream types. For large culverts or for environmentally sensitive sites, he proposes the use of the method outlined below for gravel streams:

Compute the dimensionless shear stress for a stable (reference) reach downstream from the culvert under study.

Set this value equal to the Shield's parameter and compute the largest particle that is expected to be moved for conditions of the bankfull flow. Verify that this size particle is being moved in the reference reach by comparing the calculated size with the largest size of particle found in the lower third of a point bar in the reference reach.

Determine bankfull flow conditions in the proposed culvert and compute the Shield's parameter for these conditions leaving the particle size as an unknown. Set the Shields parameter equal to the dimensionless shear stress computed in step 1 above and solve for the largest particle size that will be moving in the culvert.

Compare the computed particle size from step 3 with the largest particle size measured and computed for the reference reach. If the culvert can pass a particle larger that the particle size in the reference reach, the culvert should not silt up. If the particle size passed by the culvert is much larger than the particle size in the reference reach, it is an indication that the culvert may be self-cleaning of its bed load.

Detailed information regarding these calculations are contained in unpublished training course material presented by Rosgen to the Maryland SHA (Reference 14)

Flood Plain Culverts

The design procedure in Section 13.5 is based on the concept that (1) the bed load carried by a stream is concentrated in the main channel and (2) that very little bed load is carried by overbank flow. This concept is applicable to many locations since the higher roughness values and lower depths of flow on the flood plain result in shear stress values that are lower than the critical shear stress of the protective vegetation. There are locations where considerable amounts of bedload material are conveyed out of the stream bed and deposited on the flood plain or along the riverbank. These locations typically introduce a major change in the sediment transport conditions due to the highway crossing or the natural flow conditions in the stream. Placement of flood plain culverts should be made with this thought in mind. Examples include:

- Formation of bars on the inside of bends,
- Goose neck bends where flood flows and sediment are transported across the flood plain neck separating the channels,
- Stream confluences,
- Diversion of flood flow due to blockage of culverts or bridges by sediment and debris.

13.10 Effects of Ice and Debris

Highway culverts should be located so as to avoid areas that have a high potential for blockage by the deposition of stream sediments and debris. Because of Maryland's location and climate, ice jams have not been a significant problem in the operation of highway culverts. Debris, on the other hand is a continuing problem, and the consequences of debris accumulation should be considered in the location and design of the culvert. Wherever practicable, access should be provided for personnel and equipment to clean the culvert entrance.

Debris is defined as any material moved by a flowing stream. This includes a combination of floating material, suspended sediment and bed load. A stream's propensity for carrying debris is based upon watershed land uses and its stream and flood plain characteristics. Debris is likely to be a problem in mountainous or steep regions. The site investigations of a proposed stream crossing should include evaluation of the following conditions:

- Stream velocity, slope and alignment,
- Presence of eroding banks and the types of trees or shrubs on the banks vulnerable to being undermined and washed away,
- Watershed land uses, particularly logging, cultivation and construction,
- Watershed response to storms, such as flash flooding in steep terrain,
- Storage of debris and materials on the flood plain (logs, lumber yards, etc.),

Debris can accumulate at a culvert inlet or become lodged in the inlet or barrel. Severe blockages can lead to the ponding of water upstream of the culvert with damage to developed properties, overtopping of the roadway and subsequent destruction of the entire culvert installation.

Some debris accumulation can be anticipated at most culvert installations. Routine maintenance operations including removal of the debris will serve in most cases to minimize the hazard of blockages. If the site reconnaissance reveals a significant potential for debris accumulation, consideration should be given to minimizing the problem and its effect on the safe operation of the highway. Alternative approaches include use of a single cell (vs a multiple-cell culvert installation) or selection of a bridge. The use of flood plain culverts will serve to provide relief openings for conveyance of the flood flows in the event the main channel culvert becomes blocked.

Debris deflectors and control structures have not been used extensively in Maryland, and they are not generally recommended for inclusion on new construction. Where debris accumulation has become a continuing maintenance problem and safety hazard at an existing culvert, a debris control structure or deflector should be considered as one way of lessening the extent of the problem. Design information for commonly employed debris control structures and deflectors can be found in the FHWA Publication HEC-9, Debris Control Structures, Reference 5.

13.11 Structural Requirements

Cast-in-place structures such as box culverts are individually designed for the given site conditions in accordance with the policies and procedures of the Office of Bridge Development.

Pre-cast boxes, pipes and pipe arch structures are to be designed in accordance with the criteria specified by the manufacturer, including provisions for minimum cover. The minimum cover for concrete and metal round pipe is three feet. The manufacturers fill height tables and specifications should be consulted when determining minimum and maximum cover for other culvert shapes and materials.

Specialized designs, such as long span culverts, are evaluated on a case by case basis.

An important requirement for metal culvert installations is to assure that the headwalls are properly anchored to resist buoyancy and up-lift forces.

SHA PPM D78-15 (4) dated July 31, 1990 entitled Length and Treatment of Culverts provides additional information on the end treatment of culverts. This directive requires that a cutoff wall with a minimum depth of 3 feet below the culvert invert be provided at headwalls and endwalls to protect the culvert from scour and erosion.

SHA PPM D84-29 (4) dated July 26, 1994 entitled End Treatment for Pipe Culverts also provides general guidance on the design of culvert end sections.

13.12 Durability Requirements

The minimum service life for a culvert designed by the Office of Bridge Development is 75 years. On a case by case basis, a longer service life of up to 100 years may be specified where the construction of a replacement structure would result in extraordinary costs or involve an extended period of disruption of traffic service. An example of this case would be a culvert under a high fill on a major arterial or Interstate highway.

The design service life of a culvert is defined as the expected maintenance free service life of each installation.

The Office of Bridge Development has adopted the durability requirements in the Highway Drainage Manual, Chapter 9, Culverts, for all concrete and metal pipe culverts. For structural plate pipe, ellipses and arches, the maintenance free service life, with respect to corrosion, abrasion and/or durability, is the number of years from installation until the deterioration reaches the point of perforation at any location. (It is noted that metal pipe with 75% or more of the invert intact can be rehabilitated in some instances by means of a concrete paved invert to extend the useful service life for years without replacement.)

For reinforced concrete structures, maintenance free service life, with respect to corrosion, abrasion and/or durability, is the number of years from installation until the deterioration reaches the point of exposed reinforcement at any point on the culvert.

All culverts are subject to deterioration from corrosion and abrasion. Corrosion may result from active elements in the soil, water and/or atmosphere. Mechanical wear depends upon the frequency, duration and velocity of flow, and the amount and character of bedload.

To assure that the maintenance-free service life is achieved, culvert materials and thicknesses should be designed for the environmental conditions existing at the site:

- Measurements of the pH and resistivity of the soil and the water at proposed culvert structures serve to provide this information. Consideration should also be given to chlorides, such as in salt-water crossings, and to sulfides. An evaluation should also be made of the potential for abrasive wear of the invert by the bed load of the stream.

- Once a site survey has been conducted, the Highway Drainage Manual can be consulted to determine the types and extent of protection needed to provide for durability of concrete and corrugated metal pipes for the site conditions.

- For structural plate pipe culverts (round, pipe-arch, and ellipse), increase the thickness of the invert plates required for structural strength by two gages in thickness.

- Use of steel pipe is generally not recommended for salt-water locations.

For severe conditions where the pH or resistivity of the stream or adjacent soil falls outside the limits specified in the Highway Drainage Manual, additional evaluation of the potential for corrosion is warranted. Alternative considerations include provision of a very heavy gage at the pipe invert, or factory or field paving of the invert. For severe conditions of acid flow, as from a mine, use of a vitrified clay lining to accommodate corrosive low flows may provide a solution to the problem.

Additional protection of the culvert invert to resist abrasion is recommended where the velocity of flow for the bankfull flow exceeds 7 fps and bed load is present. In streams carrying very heavy bedloads, it may be difficult to maintain a culvert invert in an acceptable condition for the desired service life. For such cases, consider alternative designs such as:

- placement of steel rails along the invert of the culvert,
- burying the invert of the structure by the scour depth, o*r*
- use of an alternative structure type such as a bridge or bottomless culvert

<u>Concrete Structures</u>

Where the pH or resistivity of the soil or water at the site is outside of the limits specified in the Highway Drainage Manual, additional protection from corrosion should be provided for concrete structures. This protection may consist of extra thickness of concrete cover over the steel reinforcement, high-density concrete, and/or other protective coatings. In general, cast-in-place structures should be provided with additional protective paving or coatings in environments with a low pH since they are more vulnerable to corrosion.

Reference is made to the Maryland SHA Highway Drainage Manual, Table 9.5.4.1.B, for recommendations for designing concrete structures in locations where the water has high concentrations of sulfates.

13.13 Traffic Safety Requirements

Culverts shall be designed in accordance with the AASHTO Roadside Design Guide, Reference 10, to minimize hazards to vehicles that leave the travelled way. For culverts designed by the Office of Bridge Development, provision for traffic safety is normally accomplished in one of two ways:

- Placement of culvert headwalls and endwalls at an appropriate safe distance from the travelled way as determined from Reference 10, or,

- Shielding the obstruction or hazard presented by the culvert with an appropriate roadside barrier.

SHA PPM D78-15 (4) dated July 31, 1990 entitled Length and Treatment of Culverts provides additional information on the end treatment of culverts. Placement of bars or grids at culvert ends to provide for a transversable design is not generally recommended for large culvert installations.

Where the culvert installation is similar to a bridge, the appropriate bridge barrier rail design is to be used.

13.14 Construction Details

The design plans for the culvert must contain complete information with regard to construction details. This will include:

- Bedding conditions,
- Requirements for water tightness,
- Location and description of weep holes, when used,
- Structural strength requirements, pipe class and wall thicknesses for pipe installations,
- Details of end sections including:
  - measures to anchor flexible pipe to the headwalls for protection against uplift and buoyancy,
  - strengthening of the weak leading edge of flexible pipe, particularly for a mitered condition,
  - use of bevels or improved inlets to increase hydraulic efficiency,
  - alignment of the endwalls with the roadway and embankment fill.

- Riprap protection of the culvert endwalls,
- Special designs to facilitate fish passage in the culvert barrel,
- Roadside barriers, when required.

A construction plan will need to be developed as a part of the design plans for the culvert. Elements of the construction plan should include:

- An estimate of the area to be disturbed and the activities associated with the culvert construction. This will include the staging area, materials storage, stock and spoil piles, construction access and traffic detour routes, and sediment control measures (traps, basins, earth dikes, silt fences, etc.).

- A plan for accommodating and maintaining stream flow through the project area during the construction of the culvert.

- A plan to control sediment discharge into the stream being crossed.

- A construction schedule designed to avoid disturbances to and blockages of stream flow during spawning periods.

13.15 References

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2. AASHTO Model Drainage Manual, Chapter 9, Culverts

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Appendix A

Procedures for Evaluating the Hydraulic Design Of Flood Plain and Main Channel Culverts

Appendix A

Procedures for Evaluating the Hydraulic Design Of Flood Plain and Main Channel Culverts

Procedures for the hydraulic design of culverts are set forth in the FHWA publications listed as references in the Chapter 13. The FHWA software package HY-8 and the Corps of Engineers water surface profile program HEC-RAS are two primary programs used by SHA for analysis of flows in culverts. Additional information on culvert design is contained in References 1, 2, and 3. These references contain detailed instructions regarding the hydraulic design procedures; accordingly it is not necessary to duplicate this information in this manual.

The SHA has adopted the hydraulic design procedures of the FHWA for use in culvert design, subject to (1) the limitations and constraints set forth in the design procedures themselves and (2) the policies and design criteria of the SHA as set forth in this manual.

A culvert installation, consisting of a main channel culvert and one or more flood plain culverts with inverts set at different elevations, represents a complex hydraulic structure. A design solution will normally require a number of trial and error attempts to balance the size of the main channel culvert with the size of the flood plain culverts. The HY-8 program is considered an efficient tool for conducting this analysis, using the downstream tailwater as determined from the water surface (HEC-RAS) hydraulic model. After the sizes of the various culverts have been selected, the selected culvert geometry can be included in the HEC-RAS model to get a reasonable estimate of head losses and flow distributions at the highway crossing.

Because of the various assumptions made in the analysis of the multi-cell culvert, the results of the culvert analysis need to be reviewed to see if they are reasonable. This will be particularly true when roadway overtopping is also involved in the hydraulic analysis.

Appendix B

Procedures for Evaluating the Potential For Silting Up of Culverts

Estimating Sediment Conveyance Capacity and Deposition Potential in Culverts

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Abstract

In watersheds characterized by high sediment production, culverts must be designed to adequately convey both water and sediment without causing excessive backwater upstream of the culvert or excessive sedimentation within the culvert barrel. This paper presents methods for estimating sediment conveyance capacity and deposition potential in culverts. A design example demonstrating the application of the methods is also presented.

Introduction

Erosion/sedimentation occurs within watercourses composed of erodible material, where local or general differentials in sediment transport capacity exist. Numerous factors control the erosion/sedimentation potential of channel reaches, including the size and cohesiveness of the material of which the channel is composed, the vegetation type and density in the channel, the hydraulic characteristics generated within the channel under flood events, and the presence of structures within the channel.

Placing a culvert within a fluvial system characterized by high sediment production generally results in local changes in the sediment balance within that system. This may result in near-culvert stream stability problems, including erosion at the inlet and outlet of the culvert, as well as sedimentation within the culvert barrel. The quantity of sediment that will accumulate during

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single events is of particular importance because of the potential reduction in capacity of the culvert to convey flow. The culvert must be large enough to convey both water and sediment without causing a backwater in the channel, or filling of the culvert with sediment.

A structure must be appropriately sized to minimize deposition within and immediately upstream of the culvert. If a culvert is too small, excessive headwater depths and ponded water will result with corresponding sedimentation upstream of the culvert inlet. Erosion will occur at the outlets due in part to the increased flow velocities associated with the culvert barrels when compared to normal channel conditions. In addition, the relatively sediment-free nature of the outflow from some culverts contributes to erosion at their outlets. This lack of sediment in culvert outflows is often the direct result of sediment accumulation in the vicinity of the culvert inlet.

Design procedures for the conveyance of water through the structure are well documented in such publications as the Federal Highway Administration's (FHWA) publication "Hydraulic Design of Highway Culverts," Hydraulic Design Series No. 5 (FHWA, 1982). However, procedures for quantifying the conveyance of sediment are not well documented. Development of a sediment-transport equation for an enclosed culvert is difficult, due to the complex flow conditions which often exist upstream and through the culvert.

Methods of Analysis

Estimating sediment conveyance and deposition potential in a culvert requires an analysis of the sediment-transport characteristics of both the upstream channel and of the culvert. Sediment discharge rates must be estimated for the upstream natural channel and for the culvert. The sediment discharge rate estimated for the upstream channel can then be compared to the sediment discharge rate through the culvert. If the sediment discharge rate through the culvert is less than the upstream sediment discharge rate for the channel, sedimentation of the culvert can be expected to occur. Two analytical methods are presented herein for this comparison.

Method A

There are a variety of methods for estimating the sediment discharge rate through a culvert. The following equation developed by Graf and Acaroglu (1968) has been commonly used. This equation was developed from a data base that included a large range of pipe flow and open-channel conditions.

The equation is:

$$Q_{max} = 13{,}590\ d_s^{-1.02}\ S^{2.52}\ R^{1.52}\ A$$

where:

- Q_{max} = Maximum sediment discharge rate, in cubic meters per second
- d_m = Mean sediment size, in millimeters
- S = Slope of culvert, in meters per meter
- R = Hydraulic radius, in meters
- A = Area of the culvert, in square meters

The sediment-transport characteristics of the upstream channel and the sediment supply from the upstream watershed can be determined by a variety of methods. For sand-bed channels in semi-arid regions, the sediment-discharge rate is often determined from equations such as the Zeller-Fullerton equation (1983). This equation provides the unit bed-material sediment-transport rate, and therefore the result must be multiplied by the flow width to obtain the total bed-material sediment-transport rate of the channel. The equation is:

$$q_s = \quad (0.0705\ n^{1.77}\ v^{4.32}\ G^{0.45}) \ / \ (y_h^{0.3}\ d_{50}^{\ 1.61})$$

where:

- q_s = Unit bed-material sediment-transport rate, in cms/meter
- n = Manning's roughness coefficient
- v = Velocity, in meters per second
- G = Gradation coefficient $[G = 1/2\ D_{50}/D_{15.9} + 1/2\ D_{84.5}/D_{50}]$
- y_h = Hydraulic depth, in meters
- d_{50} = Median grain size, in millimeters

If the bed-material sediment-discharge rate through the culvert is less than the upstream bed-material sediment-discharge rate for the channel, sedimentation of the culvert can be expected to occur, and an alternate culvert configuration or culvert type should be considered.

One of the disadvantages of determining the sediment-transport rate for a culvert from the equation developed by Graf and Acaroglu is that it was intended primarily for circular culverts rather than box culverts.

Method B

The above method requires the actual estimation of bed-material sediment-transport rates for both the upstream channel and the culvert. Another method that has been applied is the comparison of relative bed-material sediment-transport rates for the approach channel and the proposed culvert. This is accomplished by applying the following equation:

$$R_s = (Q_u/Q_d)\,(S_u/S_d)^{1.66}\,(n_u/n_d)^{-1.35}\,(R_u/R_d)^{0.91}$$

where:

R_s = Bed-material sediment-transport ratio (channel to culvert)

Q_u = Discharge in approach channel, in cubic meters per second

Q_d = Total culvert discharge, in cubic meters per second

S_u = Longitudinal slope of approach channel, in meters per meter

S_d = Longitudinal slope of culvert, in meters per meter

n_u = Manning's roughness coefficient for the approach channel

n_d = Manning's roughness coefficient for the culvert

R_u = Hydraulic radius of flow in approach channel, in meters

R_d = Hydraulic radius of flow within the culvert, in meters

The above equation is simply a ratio comparison of bed-material sediment-transport rates based upon the Zeller-Fullerton equation. If the value R_s is less than 1.0, the culvert will most likely be able to transport the sediment being delivered by the approach channel. However, it is recommended that the value of R_s be less than 0.8 to account for entrance losses at the culvert inlet. If the value of R_s is greater than 1.0, sedimentation may occur, and an alternate culvert or a bridge structure should be considered. The value of S_d should never exceed the critical slope of the culvert for the discharge involved. The culvert itself may be placed on a slope greater than critical, but critical slope should always be used under such circumstances. Additionally, if tailwater exceeds the top of the culvert, then a hydraulic grade line should be calculated, and the friction slope of the culvert should be used in the preceding equation.

Bed-material sediment-transport rates will vary as hydraulic flow parameters (width, depth, velocity) change as flow moves from the upstream channel, through the approach channel, and finally into and through the culvert. In order to define the bed-material sediment-transport variations through these transitions, an accurate estimate of the flow hydraulics must be performed. In steep-sloped channels characterized by high approach velocities, flow depths immediately upstream of the culvert which are defined by the ponding depths determined according to the design procedures of HDS No. 5 are overly conservative with respect to backwater depths, and thus their use will generally overestimate the resultant reduction in bed-material sediment-transport rates. In order to more accurately define these rates, more precise hydraulic parameters could be obtained by performing step-backwater calculations upstream of each individual culvert or performance charts should be adapted to include consideration of the approach velocity of the flow event.

Example

Problem

It is proposed to place 1.22-meter-diameter corrugated metal pipe culverts, with headwalls, across a wash with a bottom width of 6.0 meters, side-slopes of 3H:1V, a longitudinal slope of 0.005 m/m, a Manning's "n-value" of 0.030, and a design discharge of 12.0 cms. The median diameter (d_{50}) of the streambed sediments is 1.0 mm, with a gradation coefficient (G) of 4.0. Manning's "n-value" for the pipes is 0.024, and the pipe culverts will be placed on a 0.003 m/m slope with 0.30 meters of allowable head. The total conveyance capacity of the pipe culvert system is 10.8 cms. Determine if this pipe culvert system can be expected to experience sediment deposition when a design discharge occurs on the wash.

Solution: Method A

The flow depth and flow velocity of the upstream channel can be approximated by computing normal flow conditions, which yields:

$y = 0.8$ meters and $v = 1.7$ m/s (rounded to nearest tenth)

Using the Zeller-Fullerton Equation, the sediment-transport discharge rate for the upstream channel is computed as follows:

The "effective" flow width of the upstream channel is assumed to be 1/2(top width + bottom width), which yields $W_e = 1/2(10.9+6.0) = 8.5$ meters.

$Q_s = (q_s)(W_e)$. Then,

$Q_s = \{(0.0705)(0.030)^{-.77}(1.7)^{4.32}(4.0)^{0.45}\} / \{(0.8)^{0.3}(1.0)^{0.61}\}(8.5) = 0.024$ cms.

Using the Graf and Acaroglu Equation, the sediment-transport discharge rate in a single pipe culvert is computed as follows:

$Q_{max} = (13,590)(1.0)^{-1.02}(0.005)^{2.52}(0.30)^{1.52}(1.2) = 0.004$ cms.

Therefore, the total sediment transport discharge rate is $(4)(0.004) = 0.016$ cms.

A comparison of Q_s to Q_{max} reveals that the sediment-discharge rate of the upstream channel exceeds the sediment-discharge rate of the pipe culvert system, and therefore sediment deposition can be expected in the pipe culvert during the design flow conditions.

Solution: Method B

The upstream approach flow is assumed to be equally divided between the four pipe culverts (i.e., 4 cms is delivered to the inlet of each pipe culvert). Under this assumption, the following is computed for each pipe:

$R_s = (3.0/2.7)(0.005/0.003)^{1.66} (0.030/0.024)^{-1.55} (0.6/0.3)^{0.91} = 3.44.$

Because R_s exceeds the value of 1.0, sediment deposition can be expected in each pipe culvert during the design flow conditions.

Both Method A and Method B yield equal qualitative results. To reduce the potential for sedimentation, a different culvert type and configuration could be employed. For example, a substitute, two-cell, 2.44 meter x 1.22 meter RCBC system placed on the same slope of 0.003 with a Manning's "n-value" of 0.012 would yield the following Method B solution:

$R_s = (6.0/7.2)(0.005/0.003)^{1.66} (0.030/0.012)^{-1.55} (0.6/0.4)^{0.91} = 0.68.$

Since R_s is less than the value 1.0, as well as the recommended value of 0.8, this solution indicates that sediment deposition would not be expected to occur in the concrete box-culvert system during the design flow conditions. Based upon physical and economic constraints, refinements to the size and configuration of the culvert system can proceed accordingly.

Summary

Few procedures are readily available for estimating sediment conveyance capacity and deposition potential in culverts. The procedures presented in this paper provide a method for determining if a given culvert will be able to transport the bed-material sediment being delivered by the upstream channel. If it is determined that a given culvert is not able to transport the sediment being supplied, either a larger structure or a different type of structure may be required. In general, pipe culverts will transport less sediment than box culverts, and smooth pipes will transport more sediment than corrugated metal pipes. However, the most effective method of eliminating sedimentation problems is to utilize a culvert structure which minimizes changes to the hydraulics or geometry of the approach channel, especially head-velocity losses at the culvert inlet.

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