OFFICE OF STRUCTURES
MANUAL ON HYDROLOGIC AND HYDRAULIC DESIGN

CHAPTER 10 BRIDGES

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10.1 Introduction

10.1.1 Definition

Bridge structures are defined as:

- Structures that transport vehicular traffic over waterways or other obstructions,
- Any highway structure over a waterway placed on footings
- Part of a stream crossing system that includes the approach roadway over the flood plain, relief openings, and the structure itself,
- Legally, all structures with a centerline span of 20 feet (6.1 m) or more. This chapter addresses structures designed hydraulically as bridges, regardless of their length. The design of culverts that meet the definition of a bridge structure is addressed in Chapter 13 and (for bottomless culverts) Chapter 11, Appendix C

As a general rule, the Office of Structures is responsible for structures with a drainage area of one square mile or greater while the Office of Highway Development handles structures with smaller drainage areas. However, the Office of Structures will normally handle cast-in-place box culverts, structures placed on footings and certain small culverts as described in Chapter 13, Culverts

101.2 Purpose of Chapter

- To establish policies and procedures for the location and hydraulic design of bridge structures over waterways and to promote early, active and continuing involvement and coordination in the project development process by structural, geotechnical and hydraulic engineers.
- To emphasize the need for full consideration of public safety and traffic service, and in particular the consequences of catastrophic loss through bridge collapse or failure.
- To emphasize the importance of stream geomorphology and environmental considerations in the selection, location and design of bridge structures.
- To present a design approach which emphasizes a comprehensive investigation of field conditions, an appropriate level of hydrologic, hydraulic and geomorphologic analyses, and thorough evaluation and verification of study results.

Chapters 8 (Hydrology), 9 (Channels), 10 (Hydraulic Design of Bridges), Chapter 11 (Evaluating Scour at Bridges), Chapter 13, Culverts and Chapter 14, Stream Geomorphology are closely related and need to be considered as a unit for purposes of defining the process of locating and designing bridges in flood plains. Cross-references are provided to appropriate policies or guidelines in these other chapters to avoid redundant text in this chapter.

10.2 Policy

10.2.1 General

Policy is a set of goals and/or a plan of action. Federal and State policies that broadly apply to the hydraulic design of structures are presented throughout the various chapters of this manual. Policies that apply to the hydraulic design of bridges are presented in this section.

The policies and procedures described in this chapter establish the design process representative of the present "normal engineering practice" or "State of Practice" for the Office of Structures. They outline the approach to be followed by a "reasonably competent and prudent designer" in evaluating, selecting, and approving a final design.

The mission of the Office of Structures is to design safe, economical and aesthetic highway structures for the traveling public through a dedicated work force committed to teamwork, communication, professionalism and customer service.

10.2.2 Type, Size and Location of Structures (TS&L)

The detail of location and design studies should be commensurate with the risk associated with the structure, its approach roads and with other economic, engineering, social or environmental concerns. Consideration of safety, traffic service, waterway adequacy, structural stability, environmental compatibility and cost-effectiveness are to be addressed throughout the project development stage through:

- hydrologic, geomorphologic, hydraulic, scour and structural engineering studies,
- use of a team effort of engineers with expertise in the study areas described above.
- development of alternative designs, and selection and approval of the final design in accordance with the project development procedures in Chapters 3 Policy and 5 Project Development.

Hydrologic studies are to be carried out in accordance with the procedures in Chapter 8.

Geomorphology studies are to be conducted using the procedures set forth in Chapter 14, Stream Morphology.

Hydraulic studies are discussed in this chapter as well as in Chapters 3, 9 and 13.

The primary responsibility of the Engineer is to provide for the public safety. Structures are to be designed to accommodate the design flood and to remain stable in resisting damage from scour and hydraulic forces for extreme flood events in accordance with the procedures in Chapter 11. Bridge deck drainage systems are to be designed to limit the spread of water onto the traveled way in accordance with the policy and guidance in Chapter 12, Bridge Decks.

10.2 Policy

An important aspect of susceptibility to flood damage is channel stability. Structures over streams should be designed, to the extent practicable, to enable the stream to transport its water and sediment discharges over long periods of time without significantly changing its plan form, profile or cross-sectional characteristics. Stream restorations and enhancements should be considered to help to stabilize degraded streams or to maintain existing stable streams. Procedures for accomplishing this goal are set forth in Chapter 14, Stream Geomorphology, Chapter 3, Policy, Chapter 13, and Chapter 13, Culverts.

The H&H Team Leader needs to form a team with the requisite experience, knowledge and skills discussed in this section, and to utilize these individuals throughout the project development process as described in Section 10.4.1. This project development process is described at greater length in Chapters 3 and 5:

10.2.2.1. Location of Structure

The location of structures should be supported by analyses of alternatives with consideration given to safety, engineering, economic, social and environmental concerns, as well as costs of construction, operation, maintenance and inspection associated with the structures and with the relative importance of the above noted concerns.

The Office of Structures reviews and approves the proposed horizontal and vertical alignments of bridge structures and approach roads in flood plains prior to development of the TS&L. This preliminary attention to the location of acceptable crossing and encroachment locations serves to promote the selection of safe and cost effective alternatives consistent with other design objectives and constraints. The selection of the alignment and grade of the structure and its approach roads needs to consider initial capital costs of construction and flood hazards including:

- The hydrologic and hydraulic characteristics of the waterway and its flood plain including channel stability, flood history and, in coastal areas, tidal ranges and periods,

- The effect of the proposed structure on flood flow patterns, stream geomorphology and stream stability, and the resulting scour potential at bridge foundations,

- The effect of the proposed structure (particularly culverts) on fish and wildlife passage.

- Avoidance of locations which create or augment hazardous hydraulic flow conditions that may endanger the stability of the structure or adversely affect adjacent development. Other concerns include delays and detours to traffic and disruption of the commerce and transportation systems of the region as a result of closure of a structure and its approach roads due to overtopping by floods or damage due to scour,

- Availability of routes for emergency evacuation,

- Flood hazards to adjacent properties,

10.2 Policy

- Consideration of environmental impacts and benefits of the proposed project as set forth in Chapter 3, Policy.

The evaluation of these factors is considered to constitute an assessment of risk for the specific site, and should be summarized in the hydraulic design report. A similar assessment should be made for temporary structures built by the contractor for use in the construction of the highway project.

For locations involving severe flood hazards, a more detailed risk analysis (See Reference 3) may provide a means of evaluating these flood hazards with respect to other environmental, regulatory or political considerations. A detailed risk analysis is seldom necessary for highway structures in Maryland since the application of State flood plain regulations has served to minimize the potential for severe flood hazards.

10.2.2.2 Structure Type and Size

The hydraulic analyses prepared during project development shall consider various stream crossing locations and alternatives; and structure designs to determine a cost effective alternative consistent with other design objectives and constraints:

- Structures and their approach roadways shall be designed for the passage of a design year flood in accordance with the criteria in Section 10.3.1 so that flood waters do not encroach upon the edge of the traffic lane of the approach roadways or the bridge deck. A written request must be submitted for the approval of the Deputy Chief Engineer, Office of Structures to obtain a design exception for selection of a design flood with a lesser recurrence interval.

- The structure shall be designed to be stable for anticipated worst case conditions of scour in accordance with the provisions of Chapter 11. In some cases, the Engineer may determine that an initial scour assessment at the TS&L stage will serve adequately to determine the acceptability of the proposed preliminary design. For this situation, the final scour report can be developed at a later stage of project development in accordance with the provisions of Chapter 5.

- The size of the waterway opening provided for structures over waterways shall be adequate to meet the requirements of Federal and State regulations for flood plain management (See Chapter 9), and for resistance to scour (See Chapter 11).

- Where diversion of flow to another watershed is expected to occur as a result of increased backwater or modification of existing flood flow patterns due to the highway construction, an evaluation of the flow diversion needs to be carried out. This study should serve to ensure compliance with regard to any legal requirements pertaining to flood hazards in the other watershed.

10.2 Policy

10.2.3 Flood Plain Management

Bridges and their approaches on flood plains shall be located and designed with regard to the goals and objectives of flood plain management including:

- prevention of uneconomic, hazardous or incompatible use and development of flood plains,

- avoidance of significant transverse and longitudinal encroachments, where practicable,
- minimization of adverse highway impacts and mitigation of unavoidable impacts, where practicable,

- consistency with the intent of the standards and criteria of the National Flood Insurance Program, where applicable. Coordination with FEMA (Federal Emergency Management Agency) shall be carried out through the local community as described in Chapter 5, Appendix B; consistency with the intent of State Regulations as set forth in COMAR 08.05.03, Waterway Construction (See Chapter 9).

- The predicted values of the 2, 10 and 100-year flood, <u>based on ultimate development</u> <u>in the watershed</u>, serve as the present engineering standard for evaluating and regulating flood plain uses under the flood plain regulations of the State of Maryland (See Chapter 8, Hydrology). Water surface profiles for these flood discharges and the design discharge (Section 10.3.1) shall be developed using the policies and procedures described in this chapter and in Chapter 3, Policy and Chapter 9, Channels.

- The predicted value of the 100-year flood, based on existing development in the watershed, serves as the present engineering standard for evaluating and regulating flood plains under the National Flood Insurance Program managed by FEMA.

- The final design shall be consistent with State Regulations (COMAR 08.05.03 Waterway Construction) and the National Flood Insurance Program regarding permissible increases in flood water elevations, unless exceedence of such limits can be justified by special hydraulic conditions (See Chapter 9, Stream Channels).

- Hydrologic and Hydraulic Reports are to be prepared and submitted to the Maryland Department of the Environment (MDE) and the Federal Emergency Management Agency (FEMA), where appropriate, for the necessary reviews and approvals. These reports shall demonstrate consistency with the Federal and State flood plain regulations. Chapter 3 describes the detailed information to be considered in preparing Hydrologic and Hydraulic Reports for the MDE. Chapter 5 describes the procedures to be used and the information to be included in reports submitted to FEMA. It is productive to submit hydraulic reports to MDE and FEMA for concurrent review so that the concerns of both agencies can be addressed in an efficient manner.

10.2.4 Tidal Bridges: Special procedures are required in the design tidal bridges as described in Section 10.4.5

10.3 Design Criteria

10.3.1 General Criteria

Design criteria are the tangible means for placing accepted policies into action and become the basis for the selection of the final design configuration of the stream-crossing system. Criteria are subject to change when conditions so dictate and when approved in writing by the Deputy Chief Engineer, Office of Structures. The following general criteria of the State Highway Administration apply to the hydraulic analyses for the location and design of bridges.

Structures and their approach roadways shall, as a minimum, be designed for the passage of the design year flood (based on ultimate development in the watershed) in accordance with the information in Table 2. The water surface elevation along the approach roadways for the design year flood (which should be coincident with the energy line of flow at the crossing for 1-D models) should not exceed the elevation of the bridge deck or the edge of the traffic lane. Designs for a higher recurrence interval flood may be used where justified to reduce the flood hazard to traffic or to adjacent properties. Where appropriate, consideration should be given to providing freeboard to facilitate passage of debris. Water surface profiles shall be developed for each structure (1) for the design year flood, (2) for evaluation of scour as described in Chapter 11, and (3) for the 2, 10 and 100 year floods, based on ultimate development in the watershed as described in Chapters 8 and 9. *A design exception will be necessary in order to design for a flood with a lower recurrence interval than those listed in Table 1 below:*

Table 1 Recurrence Interval for Design Flood

Highway Classification (See Highway Location Manual)	Recurrence Interval for Design Flood (years)
Interstate, other Freeways and Expressways, and Rural, Urban and Other Principal Arterials	100
Intermediate and Minor Arterials	50
Major and Minor Collectors	25
Local Streets	10

Table 1 Notes

- Interstate, Freeway, Expressway and Arterial ramps and frontage roads should be assigned a design flood recurrence interval consistent with the crossroad being serviced by the ramps and frontage roads; however, the hydraulic design of ramp structures must not interfere with or compromise the designs of the structures carrying the higher class traffic lanes.

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- *Any on-system structure that will be overtopped by flood waters having a recurrence interval smaller than the 25 year flood shall be posted for flooding.*
- In addition to the design flood, floods with the following recurrence intervals shall be evaluated during the design process:
    - bankfull stage for geomorphology studies
    - 2, 10 and 100 year floods as explained in Section 10.2 Flood Plains,
    - Overtopping ,100- year and 500-year floods for scour evaluation

10.3.2 Guard Rail and Median Barriers

Open guard rail and median barrier sections should be considered for approach roads to structures within the limits of the 100-year flood plain. If roadway or bridge designers intend to specify use of solid barriers within flood plain limits, this condition should be determined at an early stage in the project development process so that the effect of the barrier rails can be taken into account in the hydraulic design and the TS&L plans.

10.3.3 Fish and Wildlife

Full consideration is to be given to providing reasonable conditions for the passage of fish and wildlife, and for providing opportunities to enhance habitat for local species. Such considerations routinely include evaluation of channel alternatives and opportunities for stream restoration and other enhancements.

10.3.4 Structure Type

The following items should be considered in the selection of the structure type for a stream crossing:

1) Typical structure types are listed below. See Chapter 13 for a discussion of the relative advantages of culverts vs. bridges:
    - pipe culverts
    - steel pipe arch culverts
    - box culverts or rigid frames
    - bridges and bottomless arch structures

2) Use of continuous spans, where feasible, instead of simple spans to provide for a greater measure of redundancy and safety (See Chapter 11, Evaluating Scour at Bridges).

3) Use of stub abutments with spillthrough slopes, where practicable, in lieu of vertical wall abutments to provide an open design less susceptible to damage from scour (See Chapter 11).

4) Use of streamlined shapes for the superstructure (especially where overtopping by flood waters is to be expected) as well as substructure elements to minimize the extent of

horizontal hydraulic forces acting on the structure and to facilitate passage of ice and debris.

5) Consider clearances of the superstructure (freeboard) above design high water for passage of ice and debris based on the structure type and the characteristics of the stream being crossed. For navigation channels, horizontal and vertical clearances conforming to Federal and State requirements are to be provided.

6) Location and design of piers and abutments in accordance with the guidance in Chapter 11. to minimize the scour potential and to maintain the existing flow distribution in the channel and on the flood plain.

10.3.5 Structure Size and Location

The size of the waterway opening provided for structures over waterways shall be adequate to meet the requirements of Federal and State regulations) for flood plain management (Chapter 9). In addition, the following standards should be considered in the selection of the size of the structure, consistent with other structural, geometrical, and cost considerations and limitations:

1) Set the bridge deck elevation as high above the stream bed as is practical, to facilitate passage of ice and debris.

2) Set the bridge abutments well back (ten feet or more) from the channel banks to minimize problems with lateral migration of the channel and with passage of ice, debris and wildlife.

3) Eliminate or limit the number of piers in the main channel; where feasible, avoid placement of a pier at the channel thalweg.

4) The design of the waterway area and the location of substructure elements should be carried out to accomplish the following objectives for the design year flood:

   - Backwater should not increase flood damage to developed properties upstream of the crossing (See Chapter 9).

   - Velocities through the structure(s) should damage neither the highway facility nor adjacent property.

   - The existing flow patterns should be maintained to the extent practicable.

   - Changes to the flow depth and velocity in the channel upstream of the structure should not be modified to the extent that they create a problem with sediment deposition.

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- Ecosystems and values unique to the flood plain and stream should be preserved and enhanced, where practical to do so.

- Pier spacing and orientation, and abutment type and location should be selected so as to minimize (1) obstructions to the flow; (2) the disruption of existing flood flow patterns (Chapters 9 and 14); and (3) the collection of debris. Please refer to Appendix C of Chapter 10 for guidance in sizing bridge support elements to facilitate the passage of debris.

5. The "crest-vertical curve profile" should be considered as the preferred highway crossing profile when designing for embankment overtopping since this design serves to provide for relief from the hydraulic forces acting at the bridge.

10.3.6 In-Kind Replacements

In some cases, it may be advantageous to replace an existing structure using the "in-kind" replacement procedure developed by the Maryland Department of the Environment (MDE). The types of "in-kind" replacements and the procedures to follow for this design approach are described in detail in Chapter 5. One advantage of an in-kind replacement is the acceptance by MDE of simplified hydraulic studies for purposes of granting the necessary permits. However, this approach should not be used if the Engineer determines that:

- The existing waterway area is inadequate,

- The existing structure is vulnerable to damage from scour,

- The roadway profile is too low to provide for safe and adequate traffic service, or

- A modified design would result in a safer, more cost-effective structure.

Where one or more of the above conditions are found to exist, the recommended design approach is to conduct a full hydrologic and hydraulic study and to design the structure in accordance with the policies and procedures described in this manual.

10.4 Design Procedures

10.4.1 Overview

The design for a stream crossing system requires a comprehensive engineering approach as presented in Table 10- 2 below.

10.4.1.1 Typical Steps Involved in the Design of a Bridge

Table 10-2 below sets forth the steps involved in the design process for a typical bridge design project (See also Chapter 3, Policy).

Table 10 – 2 Design Process

1. Establish Design Objectives and Priorities,
2. Hydrologic Analysis
3. Existing Condition Hydraulics
4. Geomorphology and Environmental Studies (including stream stability and consideration of channel restoration and enhancement opportunities),
5. Conceptual Design for Channel Stability
6. Assessment of Structure/ Stream Channel Alternatives
7. Proposed Condition Hydraulics
   - Pre-TS&L
   - Semi-final channel stability design
   - Scour Evaluations
   - FEMA studies when required
8. Design Plans
   - Includes temporary measures during construction to maintain channel flow.

9) Documentation of the final design, including the filing of the H&H Sheet with project plans.

The study effort and scope for each of these steps can be expected to vary to a considerable degree from project to project; however, these nine steps are common elements of the design of most bridges. (See also Chapter 3 Policy). These elements are discussed below:

1. Establish Design Objectives and Priorities. It is not possible to achieve all design objectives to the same degree because some objectives may dictate significantly different designs than others. It is important to meet and reach agreement with the regulatory and review agencies on priorities at an early stage of project development. Also, at this stage of project development, the engineers conducting the various

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2. H&H studies should meet with the SHA staff in order to review the design process and to establish the scope of the work required to complete each step in the design process.

3. Hydrologic Analysis (Chapter 8). Determine and evaluate/verify the bankfull flow and various flood flows ranging from the flow selected for assessing fish passage to the 2-year flood and the 500-year flood.

4. Existing condition hydraulics. Collection and analyze information needed to prepare water surface profiles of bankfull flow and of various flood flows for the existing conditions at a bridge site. The flood flows selected for evaluation typically include the 2, 10 and 100-year discharges as well as the design flood. Water surface profiles developed for these flood flows establishes the baseline conditions for evaluating the effects of the proposed bridge at the site. In most cases, a one dimensional hydraulic analysis will be adequate using the HEC-RAS program of the Corps of Engineers. In some instances, special studies may be necessary to evaluate the site conditions. An example would be using a two-dimensional analytical program such as the FHWA program FESWMS-2dh for a site with complex hydraulic features. Important considerations in the existing system hydraulics include:

- Existing flood insurance studies and flood hazard mitigation investigations (Chapter 9)
- Existing development on the flood plain
- Evaluation of the waterway area and highway profile of the existing bridge for purposes of providing for traffic service and safety. (Performance of the existing structure and roadway in accommodating flood flows).

5. Geomorphology Study (Chapter 14). Evaluate the stability of the existing channel and its flood plain using the guidance in Chapter 14, Stream Morphology.

6. Conceptual Design for Channel Stability. This step is a follow-up to the geomorphology study. Its purpose is to develop studies to the point that the location of the stream channel and the installation of any channel controls necessary to stabilize the channel are clearly defined. It also includes consideration of opportunities for channel restoration and enhancement. This work needs to be completed in order to evaluate the performance of alternative channel and structure designs. It is at this stage that the extent of work in the channel is determined. If work beyond the presently proposed highway right-of-way is found to be necessary, such work must be approved and the ROW personnel notified of the need for additional acquisitions or easements.

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7. Assessment of Structure and Stream Channel Alternatives. Assess the compatibility with the stream geomorphology, evaluate project benefits and impacts and evaluate and compare water surface profiles of the proposed structure with those of the existing structure.

8. Proposed Condition Hydraulics (Pre-TS&L Studies). Finalize the stream channel design to the extent practicable and select a structure that is consistent with the stream morphology and the hydraulics of the site. After the most appropriate structure is selected, finalize water surface profiles to document compliance with applicable State (MDE) and Federal (FEMA) regulations. Conduct scour studies to assure that the structure remains stable for the worst-case scour conditions as determined from the guidance in Chapter 11.

9. Design Plans. This process of completing the plans extends from the TS&L to PS&E. The plans for the channel are completed and channel control structures for vertical and horizontal controls are detailed on the plans. Design plans for the structure, including any scour countermeasures, are completed. Erosion control features are evaluated and included on the plans along with detailed information for any temporary stream diversions during construction.

10. Documentation. The Structures H&H Sheet is completed and filed with the PS&E plans. All computations and reports are submitted to the Structures H&H Unit in hard copy and on computer CD disks

10.4.1.1 Evaluation of Errors

Water surface profiles (typically computed by the HEC-RAS model) have a variety of technical uses including:

- Design of the bridge waterway area and bridge and roadway profiles (Chapter 10),
- Evaluation of the substructure design for resistance to scour damage (Chapter 11).

The water surface profiles serve to depict the effect of a bridge opening on water surface levels upstream and downstream of the bridge.

Errors associated with computing water surface profiles with the step backwater profile method can be classified as:

- Data estimation errors resulting from incomplete or inaccurate data collection, estimation or correlation,

- Errors due to use of a one-dimensional model for a bridge site with complex hydraulic flow characteristics where the concept of one-dimensional flow is invalid,

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- Errors involving selection or estimation of input parameters such as Manning's n values, energy loss coefficients, starting water surface elevations, limits of ineffective flow areas, etc.

- Errors resulting from selection of an inadequate length of stream downstream or upstream from the structure being analyzed,

- Significant computational errors resulting from using improper locations or spacing of cross-sections.

- Errors due to inaccurate integration of the energy loss-distance relationship that is the basis for profile computations. This error may be reduced by adding interpolated sections (more calculation steps) between surveyed sections.

These errors can be minimized or eliminated by careful evaluation of the procedures used during the collection of field and office data and during the preparation of the input for the computer model. The Assistant Division Chief of the Plats and Survey Division is available to provide assistance regarding the use of survey data. Attention should be given to addressing the error statements in the computer output of the HEC-RAS model

New surveys for the purpose of developing or determining water-surface profiles are to be referenced to mean sea level using the North American Vertical Datum (NAVD) of 1988. Prior to the use of this datum, surveys were referenced to mean sea level using the National Geodetic Vertical Datum (NGVD) of 1929. The new datum was established primarily to account for distortions in the 1929 survey network. The difference between these two datums varies depending on the geographical location. The NAVD datum may be either higher or lower than the NGVD datum. In Maryland, the NAVD datum is typically about 0.7 foot lower than the NGVD datum. If the NAVD datum is 0.7 foot lower than the NGVD datum for a specified point, it means that the elevation of the point will be 0.7 foot higher when it is converted from the NGVD datum to the NAVD datum.

In tidal waters, depth soundings are normally referenced to mean low water or mean low tide. The relationship between mean low water and mean tide level can be found from NOAA tide tables. To minimize the chance of errors due to erroneous correlation of different datums, the engineer is encouraged to prepare a Chart of Datums prior to commencement of work (See Chapter 10 Appendix A)

10.4.2 Design Procedure Outline

When using information from an SHA survey book, the book should be reviewed to establish the datum used in the survey.

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The developed water surface profiles for a proposed design need to be evaluated for conformance to the State requirements addressed in this Chapter and in Chapter 9. Factors to consider in this evaluation include:

- Changes in flood water elevations upstream and downstream attributable to the highway project,

- Changes in flow distribution and velocities due to the bridge and its approaches, and

- The flood hazards to highways users and abutting property owners. Engineering judgment is necessary to evaluate flood hazards affecting the safety of road users or abutting property owners

10.4.3 Hydraulic Performance of Bridges

The following Figures 1 through 4 have been excerpted from the FHWA Manual Hydraulics of Bridge Waterways, HDS 1 dated 1978

- Figure 1 depicts converging and diverging flow lines which may occur at a bridge for a typical normal bridge crossing which creates a contraction in the flow. Figure 1 illustrates the location of the approach section 1, the bridge section 2, the downstream bridge section 3 and section 4, the downstream limit of the stream reach affected by the bridge constriction.
- Figure 2 is of interest in the schematic representation of how bridge backwater is measured <u>at the approach section</u> as the rise in the water surface elevation due to the bridge constriction. It depicts a bridge with wingwall abutments
- Figure 3 is similar to Figure 2 for a bridge with spillthrough slopes at the abutments.
- Figure 4 depicts the types of flow encountered at a bridge constriction.

Backwater is measured relative to the normal water surface elevation without the effect of the bridge at the approach cross-section (Section 1). It is the result of contraction and re-expansion head losses and head losses due to bridge piers and abutments. Backwater can also be the result of a "choking condition" in which the channel width under the structure is constricted to the point where critical depth occurs in the contracted opening. Backwater is the result of an increase in depth and specific energy upstream of the contraction in order to develop the additional energy required to push the flow through the bridge. This condition is illustrated in Figure 4 for different flow types.

- Type I consists of subcritical flow throughout the approach, bridge, and exit cross sections and is the most common condition encountered at Maryland bridges.

- Type IIA and IIB both represent subcritical approach flows which have been choked by the contraction resulting in the occurrence of critical depth in the bridge opening. In

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- Type IIA the critical water surface elevation in the bridge opening is lower than the undisturbed normal water surface elevation. In Type IIB it is higher than the normal water surface elevation and a weak hydraulic jump occurs immediately downstream of the bridge contraction. This flow type is not desirable. Where practical, the bridge waterway area should be designed to eliminate these flow types

- Type III flow is supercritical approach flow which remains supercritical through the bridge contraction. Such a flow condition is subject to only minor increases in backwater unless it chokes and forces the occurrence of a hydraulic jump upstream of the bridge. Supercritical flow is seldom encountered in Maryland streams. If this condition is found to exist, the bridge should be designed so that there is no contraction of the flow through the bridge.

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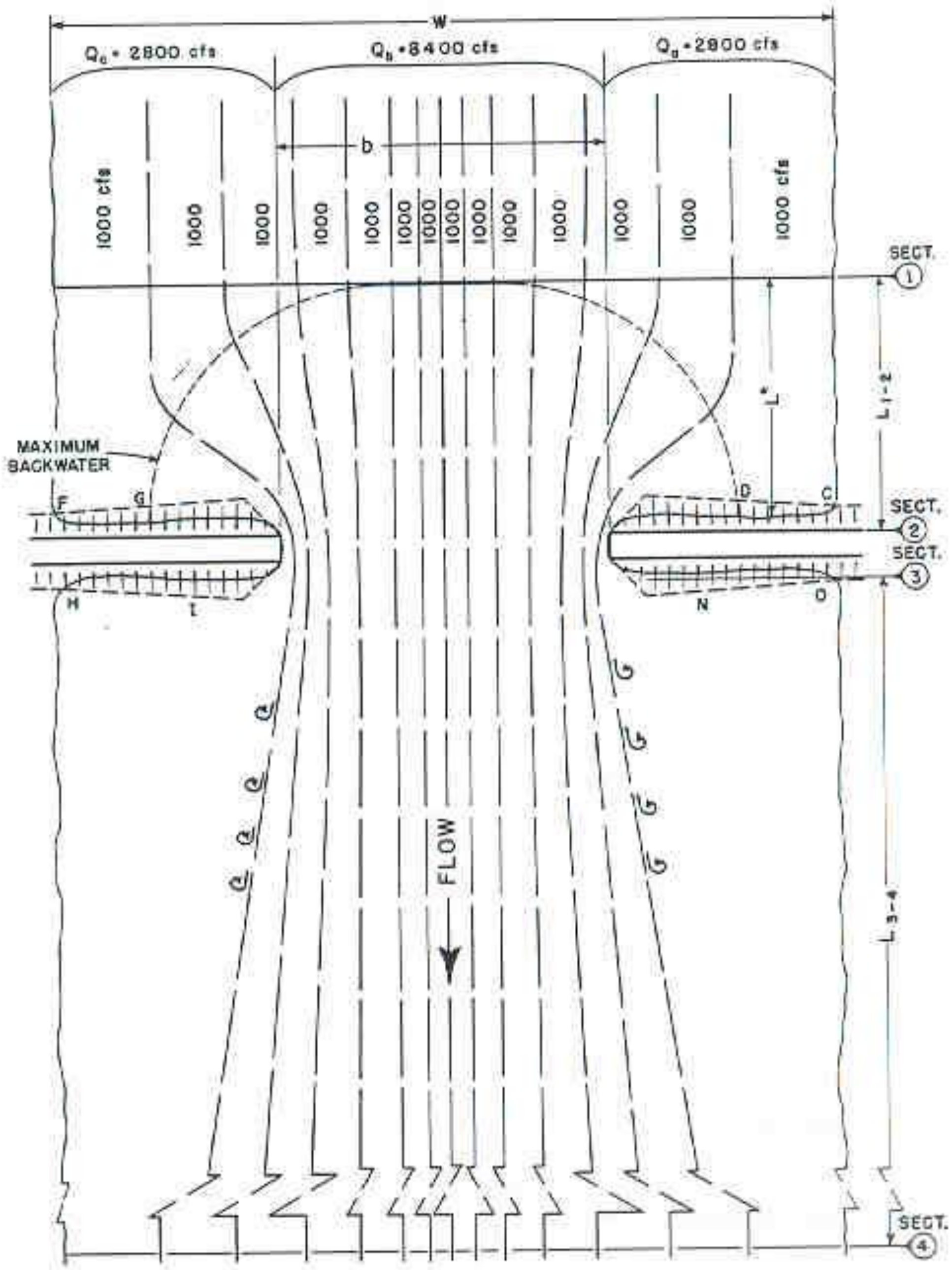

Figure 1
A Typical Pattern of Converging and Diverging Flow Lines
That Occur at a Bridge that Causes a Constriction
To the Flow

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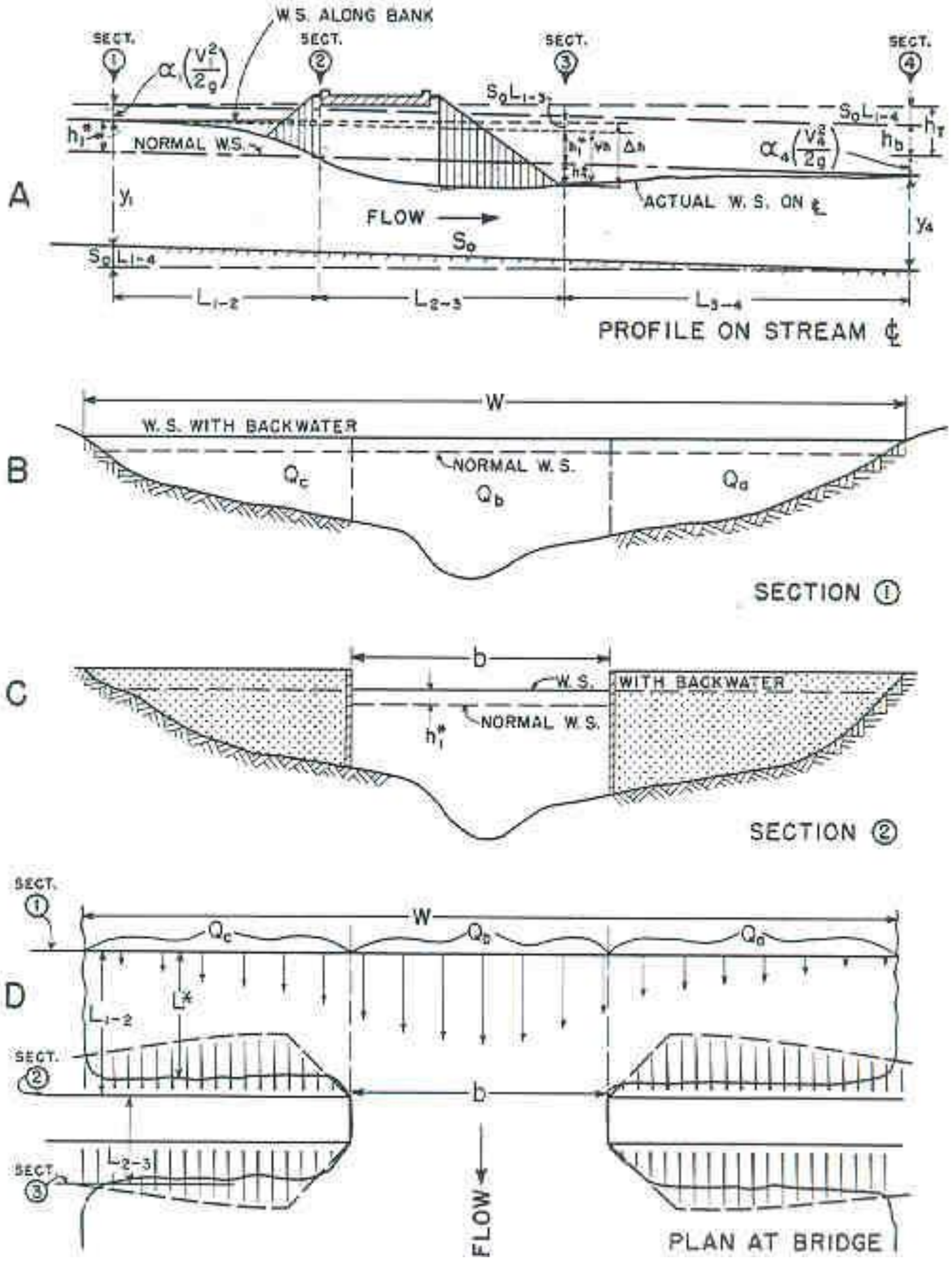

Figure 2
Schematic representation of how bridge backwater is measured <u>at the approach section</u>
for a bridge with wingwall abutments

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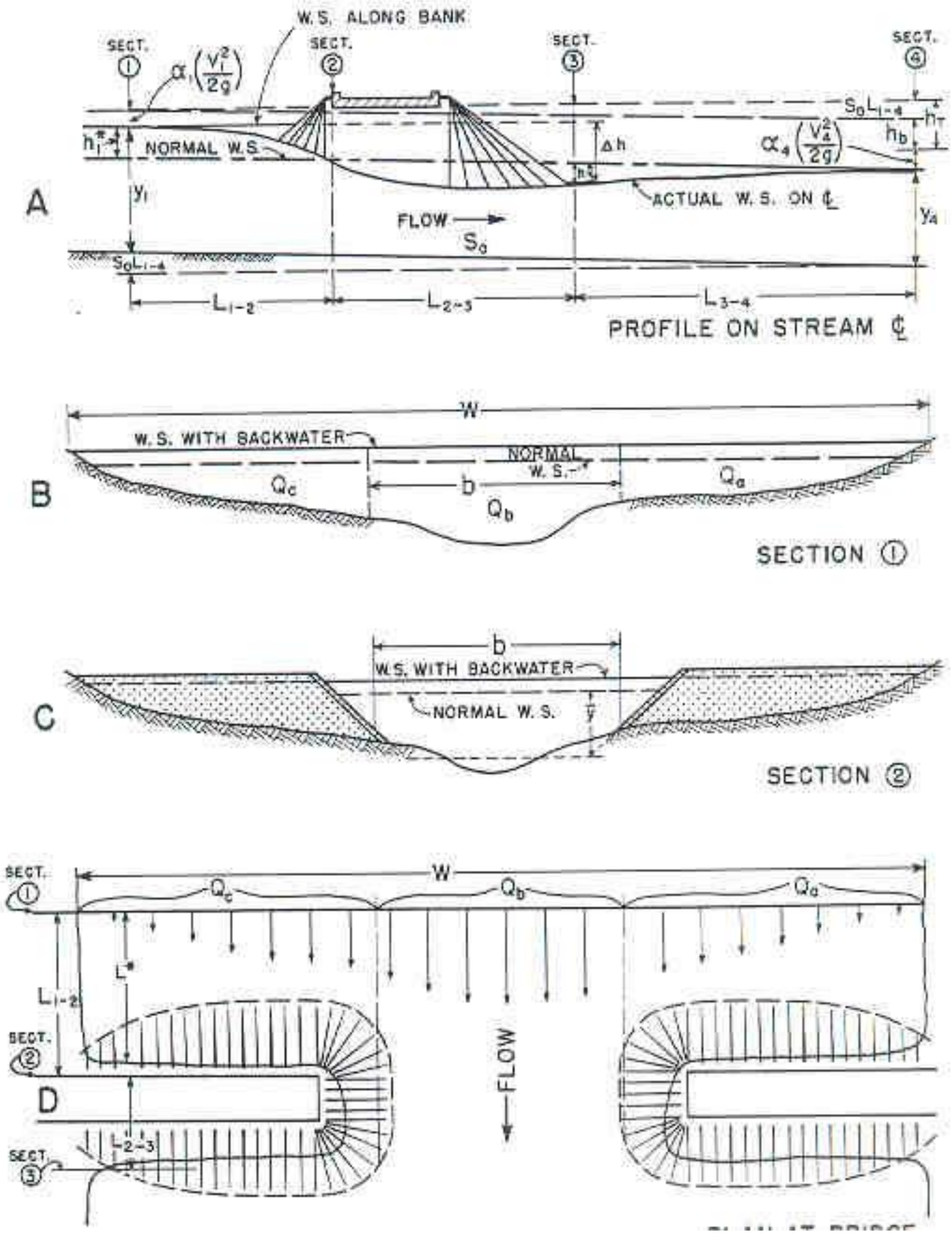

Figure 3

Schematic representation of how bridge backwater is measured <u>at the approach section</u> for a bridge with spillthrough slopes at the abutments.

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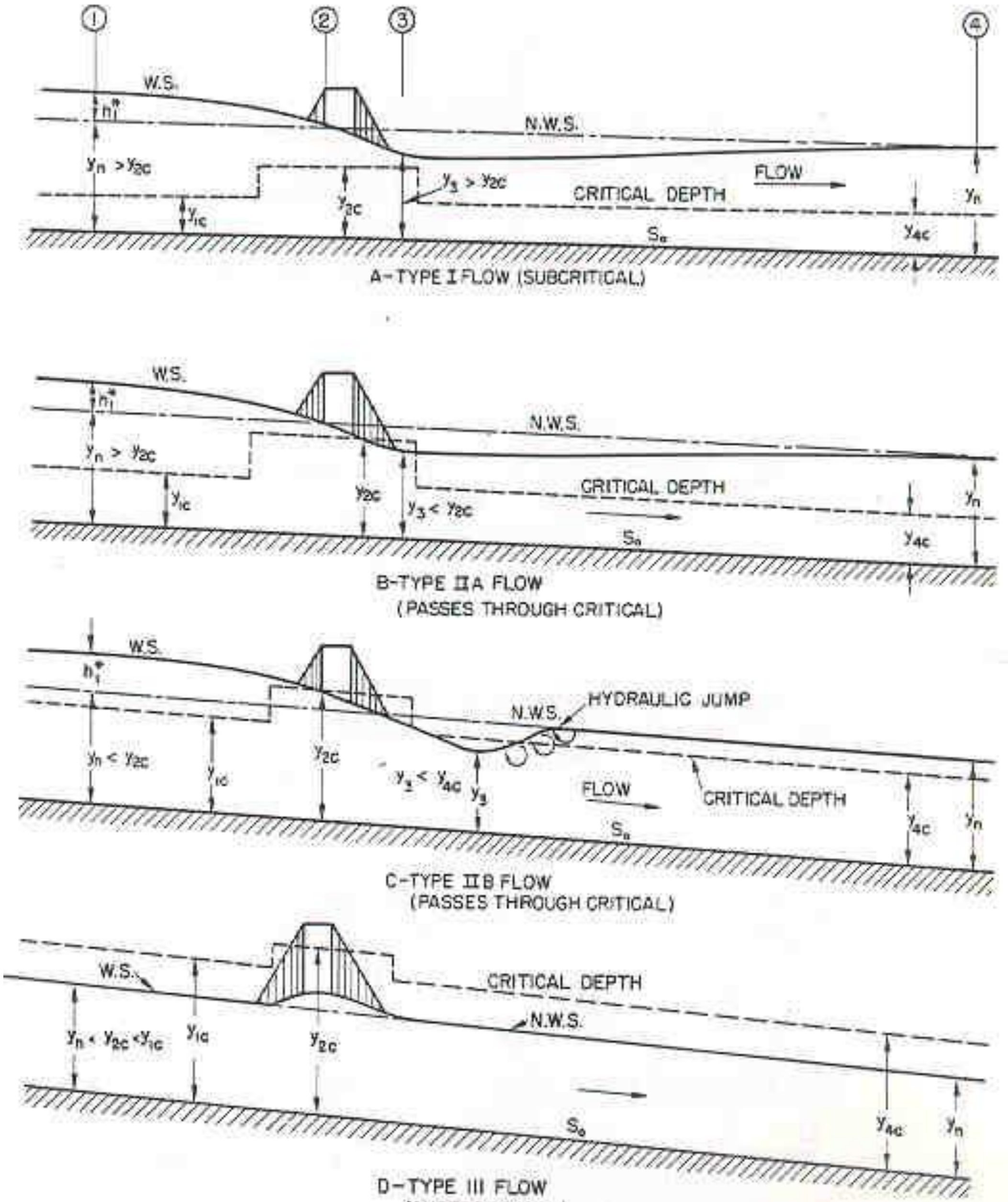

SUPERCRITICAL FLOW

Figure 4
Types of Flow Which May Occur At a Bridge Constriction.

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10.4.4 One-Dimensional Analysis

10.4.4.1 The U.S. Army Corps of Engineers HEC-RAS Model

The HEC-RAS model, Version 4.1, is the standard model in Maryland for computing water surface profiles. HEC-RAS has been developed by the Corps of Engineers Hydraulic Engineering Center at Davis, California (HEC). The initials RAS stand for River Analysis System.

HEC-RAS is menu driven and provides the user with simple, flexible procedures and choices for the input and output data. Graphical and bridge coding routines are improved and simplified. The following items highlight some of the main features of the HEC-RAS program:

- HEC-2 files can be imported to and run in HEC-RAS; however some modification of the HEC-2 files may be required to convert to the HEC-RAS format, especially for structures.
- Subcritical, supercritical and "mixed flow" regimes can be accommodated without requiring separate runs for the input data,
- A limited scour analysis using the FHWA HEC-18 methods can be performed by HEC-RAS; however, the Office of Structures uses ABSCOUR 9 for scour computations (See Chapter 11).
- The user is given the opportunity to evaluate bridge hydraulics using the concepts of (1) energy, (2) momentum, or (3) the Yarnell equations. The user also has a choice of running all three methods and allowing the program to select the method that gives the highest energy loss through the structure,
- The program handles pressure flow through use of orifice equations, and overtopping flows through use of weir equations,
- Culvert analysis procedures are improved to handle multiple culverts of various types. The program uses energy computations for outlet control conditions and the FHWA equations for inlet control conditions.
- The program can accommodate up to seven multiple openings, representing combinations of bridges, culverts and open channels,
- The cross-section output can be divided into as many as 45 segments or "slices" for purposes of determining the flow distribution in the channel and overbank areas.
- Improved graphic capabilities provide rapid, simple procedures for viewing cross-section plots to detect input errors.
- Various alternative bridge and culvert designs can be analyzed individually and then compared in a summary table.
- Output files can be presented in a wide variety of report formats
- The user can address problems of split flow or divided flow through a trial and error process. At present, this option requires the user to have an understanding of how the flow will be distributed and will require a flow separation between openings.

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Appendix A of Chapter 3 provides an extensive checklist of items to evaluate in setting up and running HEC-RAS water surface profiles. It also contains lists of items to consider in the preparation of the hydraulic report for the structure.

When a bridge project affects an existing flood plain management study of FEMA, the use of HEC-RAS is acceptable to FEMA if it is applied to the entire flood plain management study. FEMA may also accept a HEC-RAS study of a portion of the flood plain management study if it can be tied in to the existing HEC-2 model study at both the downstream and upstream ends of the reach in which the bridge is located. Either of these alternatives may require extensive work in order to get the HEC-RAS model to match precisely the existing HEC-2 FEMA study. The FEMA study could involve several miles of a stream whereas the bridge study may involve only a small portion of this distance. Therefore, the preferred method of analysis normally is to obtain the electronic file data for the original HEC-2 run and modify it to account for the changes due to the highway project.

The HEC-RAS, Version 4.1is recommended for both preliminary and final analyses of bridge hydraulics. It provides for a "template" method whereby a single section can be reproduced at several locations along a stream reach for purposes of preliminary analysis. Because of the many advantages of HEC-RAS, the single section energy models, such as those presented in the FHWA publications for Hydraulic Design Series No. 1 and HY-4 are no longer recommended either for design or preliminary analysis

10.4.4.2 The U.S. Army HEC-2 Water Surface Profile Model

The HEC-2 model has been used for the majority of the flood insurance studies performed nation-wide and in Maryland under the National Flood Insurance Program. However, it has now been superseded by HEC-RAS, Version 4.1. In some cases, it may be advantageous to utilize an existing HEC-2 study by converting it to a HEC-RAS model.

10.4.4.3 FHWA/USGS Water Surface Profile (WSPRO) Model

The FHWA/USGS WSPRO model was developed by the FHWA and the USGS and is used by these agencies as well as some highway agencies**.** It is not recommended for use in Maryland, since the HEC-RAS Program has been adopted as the SHA standard method. WSPRO combines step-backwater analysis with bridge backwater calculations. The WSPRO method analyzes pressure flow through the bridge, embankment overtopping, and flow through multiple openings and culverts. The bridge hydraulics routine relies on a one-dimensional application of the energy principle, but there is an improved technique for determining approach flow lengths and the introduction of an expansion loss coefficient. The flow-length improvement was found necessary when approach flows occur on very wide heavily-vegetated floodplains. The program also greatly facilitates the hydraulic analysis of alternative bridge lengths.

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10.4.4.4 FHWA Culvert Program HY-8

The HY-8 Culvert program developed by the FHWA is an excellent model for analyzing the complex flow patterns in culverts and multiple culvert installations and for calculating the upstream water surface elevation and energy gradient required to pass the design flow through a culvert installation. This program is approved for use in Maryland. However, the HEC-RAS program should be used (1) to determine the tailwater elevation to be used in the HY-8 program and (2) to continue the water surface profile in the stream reach upstream of the culvert.

10.4.4.5 Tidal Flows

Analysis of flow through tidal structures is also based on the principles of conservation of energy and mass as expressed by the Bernoulli and continuity equations, respectively. One of the concepts often used in the preliminary hydraulic evaluation of a structure is that the tide controls the water surface elevation on the ocean side of the structure, and therefore controls the tidal discharge through the structure. This assumption must be verified during detailed design, particularly for small structures with shallow depths, since normal depth or critical depth conditions may represent an exception to this general rule. The discharge through the structure can be determined by balancing the flow through the structure for a given time period with the change in the volume of the tidal prism (taking into consideration any upland runoff) for the same time period.

The degree of analysis required for a tidal structure depends upon the complexity of the location. Appendix A depicts the classification scheme used in Maryland for tidal structures. The computer program developed by the Office of Structures, TIDEROUT 2, can be used to analyze tidal flow for bridges where the elevation of the water surface is controlled by tides. This program also serves to evaluate the combined effect of riverine and storm tide flow, and accounts for the effect of overtopping flows. Chapter 11, Appendix B Tiderout 2 Users Manual provides guidance on the use of the TIDEROUT 2 Program.

In some cases, riverine flow will predominate and the water surface elevation will be controlled by the energy of the flow; consequently, the HEC-RAS program is used to evaluate the flow. The Woodrow Wilson Bridge is an example of this case.

Special studies may need to be carried out by persons experienced in tidal hydraulics to analyze flow through structures with certain conditions (structures that span passages between islands or an island and the mainland; structures with multiple inlets, etc). In some cases, the differences in water surface elevations across a structure may be created by wind shear forces, and this situation requires a different approach to evaluating the tidal flow. Examples of special cases of tidal flow are presented in Appendix A.

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10.4.4.6 Considerations in One-Dimensional Flow Analysis

The water surface profile used in the hydraulic analysis of a bridge should extend from a point downstream of the bridge that is beyond the influence of the constriction to a point upstream that is beyond the extent of the bridge backwater. The cross sections that are necessary for the energy analysis through the bridge opening for a single opening bridge without spur dikes are shown in Figure 10-3. The additional cross sections that are necessary for computing the entire profile are not shown in this figure. Cross sections 1, 3, and 4 are required for a Type I flow analysis and are referred to as the approach section, bridge section, and exit section, respectively. In addition, cross section 3F, which is called the full-valley section, is needed for the water surface profile computation without the presence of the bridge contraction. Cross section 2 is used as a control point in Type II flow but requires no input data. Two more cross sections must be defined if spur dikes and a roadway profile are specified.

Pressure flow through the bridge opening is assumed to occur when the depth just upstream of the bridge opening exceeds 1.1 times the hydraulic depth of the opening. The flow is then calculated as orifice flow with the discharge proportional to the square root of the effective head. Submerged orifice flow is treated similarly with the head redefined.

In free-surface flow, there is no contact between the water surface and the low-girder elevation of the bridge. In orifice flow, only the upstream girder is submerged, while in submerged orifice flow both the upstream and downstream girders are submerged. A total of four different bridge types can be treated. The help files for HEC-RAS serve as a source for more detailed information on using the computer model.

10.4.5 Two-Dimensional Flow Models (The FHWA FESWMS Model)

For one-dimensional models the computed water surface profiles and velocities in a section of river are based on the premise that the elevation of the energy line is constant across the width of each cross-section, and that the individual velocity vectors within the sub-areas of the cross-section are oriented parallel to each other. In practice, most analyses are performed using one-dimensional methods such as HEC-RAS or HEC-2. While one-dimensional methods are adequate for many applications, these methods cannot describe changes or differences in water surface elevations or flow velocity vectors which occur within a cross-section. For complex conditions involving one
or more features such as wide flood plains, river bends or river confluences, the inherent limitations of the one-dimensional model may produce results that contain significant errors.

Until recently, two-dimensional models were seldom used because of the added time and costs required to set up, calibrate and verify the model grid system. However the FESWMS (Finite Element Surface Water Model System) 2-DH/SMS Model published by the FHWA is now evolving into a more practical design tool. Refinements to the program may eventually permit construction of a two-dimensional grid pattern by the model using standard cross-sectional input data for 1-D models.

The SMS initials used in the FESWMS title above relate to a computer program developed by the Brigham Young University in Provo, Utah. It is used for constructing, editing and displaying finite element networks (meshes) used in the hydraulic modeling. It has an interface that is specifically designed to interact with the FESWMS-2dh model.

The FESWMS model is flexible and may be applied to many types of steady and unsteady flow problems including multiple opening bridge crossings, spur dikes, floodplain encroachments, multiple channels, and tidal flow around islands or in estuaries.

The SHA has utilized the FESWMS Model in several instances. Our experience has been that use of the model requires additional time and expense as compared to the use of HEC-RAS. Application of the model requires the services of persons who have received extensive training and experience with the program. At this time, the selection of the FESWMS Model has been limited to those locations where the HEC-RAS model will not be able to do a satisfactory job of developing a water surface profile.

10.4.6 Physical and Numerical Models

Complex hydrodynamic situations often defy accurate or practicable mathematical modeling. Physical/numerical models should be considered when:

- Hydraulic performance data is needed that cannot be reliably obtained from standard design models, such as HEC-RAS
- Risk of failure or excessive over-design is unacceptable, and
- Research is needed.

Constraints on physical modeling which need to be considered include size or scale of the site as compared to the model, cost, time and the availability of facilities and qualified personnel to accomplish the model study.

The SHA developed a major physical modeling study in cooperation with the

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FHWA in regard to the design of the river piers for the new Woodrow Wilson Bridge. The problem involved in estimating scour at these piers met all of the criteria noted above.

There has been considerable recent progress in developing the use of numerical models to augment the use of physical models. A major consideration in the use of numerical models is to obtain adequate information from physical models or other sources to calibrate the numerical models for design conditions.

10.5 References

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