9.4 Design Procedure

9.4.1 Survey Accuracy (Computation Method)

The design for a stream crossing system requires a comprehensive engineering approach that includes formulation of alternatives, data collection, selection of the most cost effective alternative according to established criteria and documentation of the final design.

Water surface profiles are computed for a variety of technical uses including:

- flood insurance studies
- flood hazard mitigation investigations
- drainage crossing analysis
- longitudinal encroachments

The completed profile can affect the highway bridge design and is the mechanism for determining the effect of a bridge opening on upstream water levels. The step backwater profile method is commonly used for developing water surface profile. 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 and inaccurate data estimation
- errors in accuracy of energy loss calculations depending on the validity of the energy loss equation employed and the accuracy of the energy loss coefficients
- inadequate length of stream reach investigated
- computational errors due to poor cross sectional spacings. These errors can be significant due to inaccurate integration of the energy loss-distance relationship that is the basis for profile computations. These errors may be reduced by adding interpolated or actual sections to the analysis.

9.4.2 Design Procedure Outline

Although the scope of the project and individual site characteristics make each design an unique one, this procedure shall be applied unless indicated otherwise by the Hydraulics and Drainage section.

I. Data Collection
  A. Survey
    - Topography/channel cross sections
    - Geology
    - Highwater marks
    - History of debris accumulation, ice and scour
    - Review of hydraulic performance of existing structures
    - Maps, aerial photographs
    - Rainfall and stream gage records
    - Field reconnaissance
  B. Studies by other agencies
    - FEMA Flood Insurance Studies
    - Federal Floodplain Studies by the ACOE, NRCS, etc.

- Local Floodplain Studies
- Hydraulic performance of existing bridges
- ConnDEP Inland Water Resources Division
- Stream Channel Encroachment Line Reports

C. Influences on hydraulic performance of site
- Other streams, reservoirs, water intakes
- Structures upstream or downstream
- Natural features of stream and floodplain
- Channel modifications upstream or downstream
- Floodplain encroachments
- Sediment types and bed forms (Scour, Site Data, Level I Qualitative Analysis — FHWA HEC-20)

D. Environmental impact
- Existing bed or bank instability
- Floodplain land use and flow distribution
- Environmentally sensitive areas (fisheries, wetlands, etc.)
- Level I Qualitative Analysis (FHWA HEC-20)

E. Site-specific Design Criteria
- Preliminary risk assessment
- Application of ConnDOT criteria

II. Hydrologic Analysis (See Chapter 3, Section 3.5, Design Development and Chapter 6, Hydrology.)

A. Watershed morphology
- Drainage area (attached map)
- Watershed and stream slope
- Channel geometry

B. Hydrologic computations
- Discharge and frequency for historical flood that complements the high water marks used for calibration
- Discharges for specified frequencies

III. Hydraulic Analysis (See Chapter 3, Section 3.5, Design Development and Section 9.4.3.)

A. Computer model calibration and verification
B. Hydraulic performance for existing conditions – including floodway analysis, if appropriate
C. Hydraulic performance of proposed designs – including floodway analysis, if appropriate
D. Hydraulic analysis of "natural" condition
E. Scour computations (See Section 9.5 and Appendix B – Amended Local Abutment Scour Equations for Connecticut)

IV. Selection of Final Design

A. Risk assessment/Least-cost alternative (LTEC) (if required see Section 9.6.7)
B. Measure of compliance with established hydraulic criteria
C. Consideration of environmental and social criteria
D. Design details such as riprap, scour abatement, river training

V. Documentation (See Section 9.3.10)
   A. Complete project records, permit applications, etc.
   B. Complete correspondence and reports
   C. Requirements in the ConnDEP IWRD "Model Hydraulic Analysis" document for report format
   D. Hydraulic Data Sheet presented in Appendix A.

9.4.3 Hydraulic Performance Of Bridges

The stream-crossing system is subject to either free-surface flow or pressure flow through one or more bridge openings with possible embankment overtopping. These hydraulic complexities should be analyzed using a computer program such as HEC-RAS, HEC-2 or WSPRO unless indicated otherwise by the Hydraulics and Drainage section. The hydraulic variables and flow types are defined in Figures 9-1 and 9-2.

Backwater (h_1) is measured relative to the normal water surface elevation without the effect of the bridge at the approach cross section (Section 1). Backwater is the result of contraction and re-expansion head losses and head losses due to bridge piers. Backwater can also be the result of a "choking condition" in which critical depth is forced to occur in the contracted opening with a resultant increase in depth and specific energy upstream of the contraction. This is illustrated in Figure 9-2.

The following are the three types of flow which may be encountered in bridge waterway design illustrated in Figure 9-2:

- Type I consists of subcritical flow throughout the approach, bridge and exit cross sections and is the most common condition encountered in practice.
- 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 Type IIA the critical water surface elevation in the bridge opening is lower than the undisturbed normal water surface elevation. In the Type IIB it is higher than the normal water surface elevation and a weak hydraulic jump immediately downstream of the bridge contraction is possible.
- Type III flow is supercritical approach flow and remains supercritical through the bridge contraction. Such a flow condition is not subject to backwater unless it chokes and forces the occurrence of a hydraulic jump upstream of the contraction.

9.4.4 Methodologies

No single method is ideally suited for all situations. If a satisfactory computation cannot be achieved with a given method, an alternate method should be attempted. However, it has been found that, with careful attention to the setup requirements of each method, essentially duplicate results can usually be achieved using both momentum and energy methods.

Momentum

- HEC-2

The Corps of Engineers HEC-2 model uses a variation of the momentum method in the special bridge routine when there are bridge piers. The momentum equation between cross sections 1 and 3 is used to detect Type II flow and solve for the upstream depth in this case with critical depth in the bridge contraction.

This model has been used for the majority of the flood insurance studies performed under the National Flood Insurance Program (NFIP). However, some feel that the bridge analysis routines in HDS-1 and WSPRO may yield a better definition of actual hydraulic performance.

- HEC-RAS

The Corps of Engineers Hydrologic Engineering Center (HEC) has developed the HEC-RAS (River Analysis System) program package. It operates under WINDOWS and has full graphic support. The finished package includes all the features inherent to HEC-2 and WSPRO plus program selected friction slope methods, mixed flow regime capability, automatic "n" value calibration, ice cover, quasi 2-D velocity distribution, superelevation around bends, bank erosion, riprap design, stable channel design, sediment transport calculations and scour at bridges. In addition to momentum balance, other methods are available in HEC-RAS for computing losses through bridges. These methods include the Energy Equation (standard step method), Yarnell equation and FHWA WSPRO method.

Energy

- HDS-1

The method developed by FHWA described in HDS-1 is an energy approach with the energy equation written between cross sections 1 and 4 as shown in Figure 9-1 for Type I flow. The backwater is defined in this case as the increase in the approach water surface elevation relative to the normal water surface elevation without the bridge.

This model utilizes a single typical cross section to represent the stream reach from points 1 to 4 on Figure 9-1. It also requires the use of a single energy gradient. This method is no longer recommended for final design analysis of bridges due to its inherent limitations but it may be useful for preliminary analysis and training. Studies performed by the Corps of Engineers for the FHWA show the need to utilize a multiple cross section method of analysis in order to achieve reasonable stage-discharge relationships at a bridge.

- WSPRO

WSPRO combines step-backwater analysis with bridge backwater calculations. This method allows for pressure flow through the bridge, embankment overtopping and flow through multiple openings and culverts. The bridge hydraulics still rely on 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 required to determine the least-cost alternative.

Physical Modeling

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

- hydraulic performance data are needed that cannot be reliably obtained from mathematical modeling

- risk of failure or excessive over-design is unacceptable
- research is needed

The constraints on physical modeling are:

- size(scale)
- cost
- time

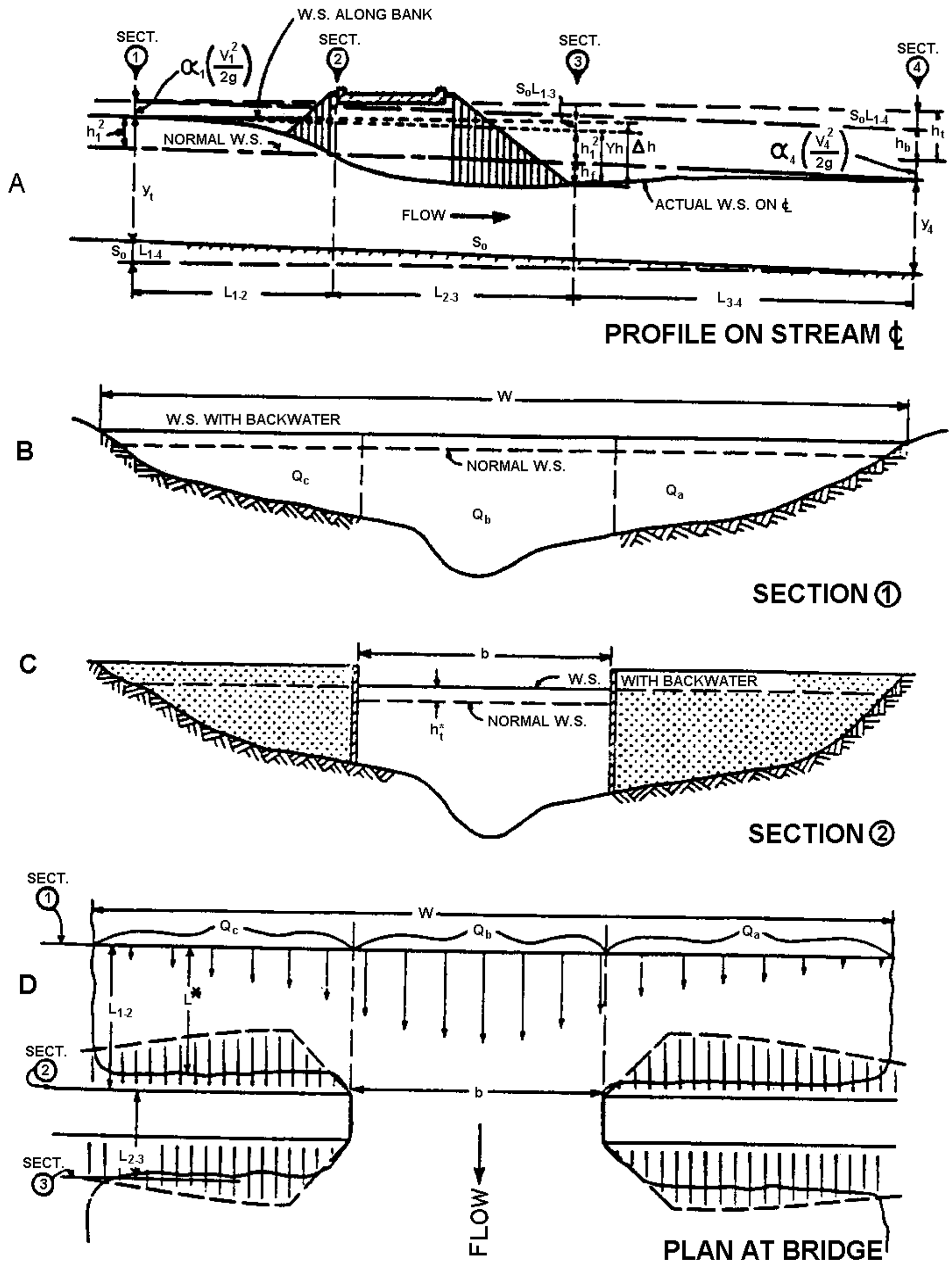

Figure 9-1 Bridge Hydraulics Definition Sketch

Source: HDS-1

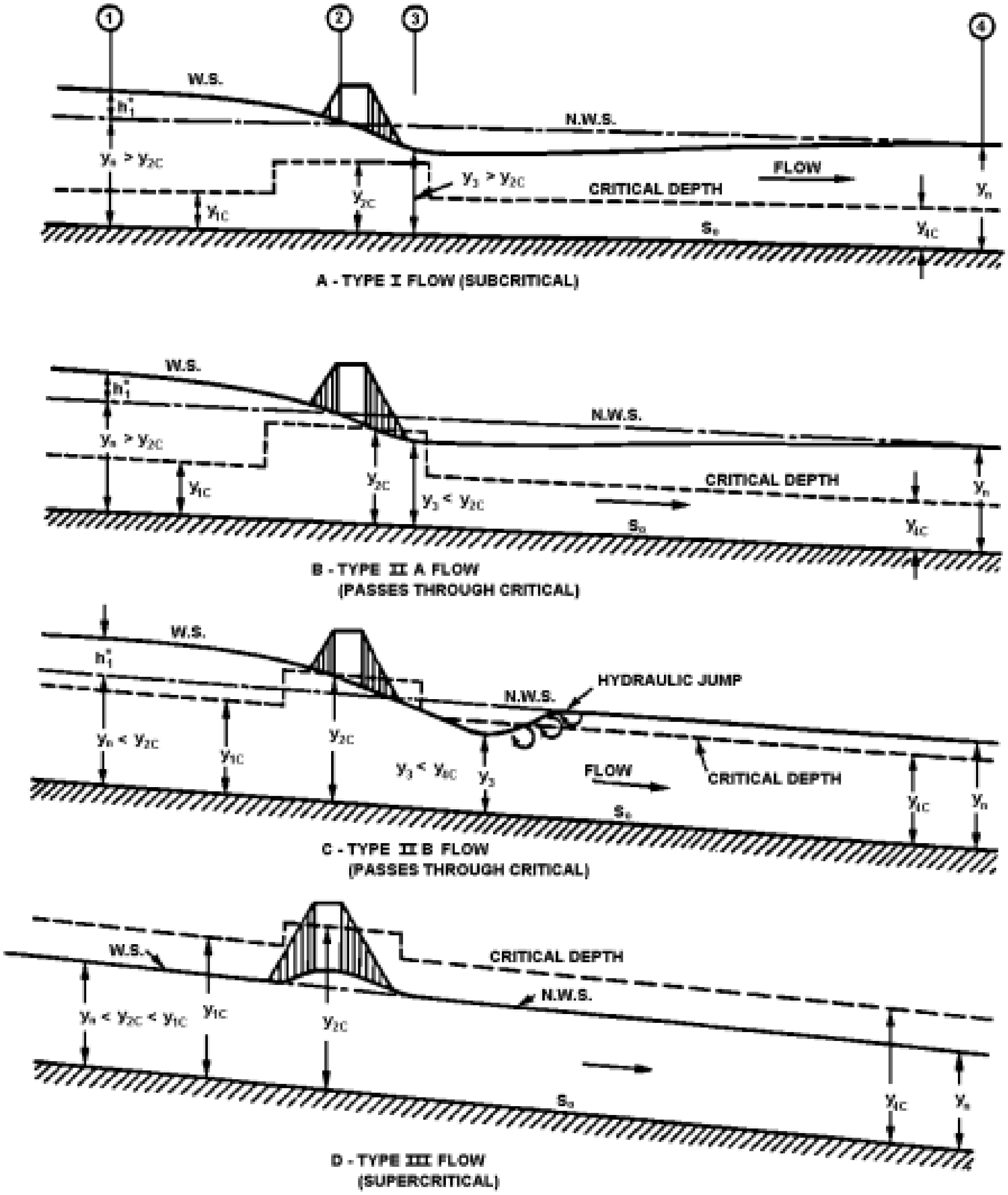

Figure 9-2 Bridge Flow Types

Source: HDS-1

9.4.5 Coastal or Tidally Influenced Waterways

Introduction

The design of coastal or tidally influenced waterway bridge openings is typically more complicated than similar designs on riverine systems. The natural system is difficult to quantify because it is typically spatially variant in two horizontal directions and it is unsteady flow. Coastal waterways are subject to storm surges and astronomical tides that play an important role in the dynamic hydraulic behavior of the system. The collection of adequate data to represent the actual condition also adds to the complexity of the problem. Data such as flows and storm surge description may be very difficult to estimate.

Tidal flow, both at flood stage and under normal conditions, may be restricted in its entrance into marshes and estuaries. Natural narrow and/or shallow passageways as well as man-made restrictions may be present. These restrictions will affect the timing cycle of high and low water, which, in turn, may affect the environmental quality of the marsh or estuary and its adjacent wetlands. The highway designer should be aware of these potential impacts, particularly when planning a new facility.

In many cases, the bridge hydraulic opening is designed to extend across the normal open water section. This may be an appropriate design from an economic standpoint, because the total cost of a larger bridge approximates the cost of a smaller bridge considering approach embankments and abutment protection measures. This design is also desirable from an environmental perspective because it results in minimal environmental impacts. In most designs, the extent of detail in the analysis must be commensurate with the project size or potential environmental impacts. However, analytical evaluation of the opening is often required and is necessary when a full crossing cannot be considered or when the existing structure and channel exhibits hydraulic problems.

HEC-18 contains several simplified methods for tidal hydraulic analysis that are applicable to many bridge crossings in tidal waterways. When the simplified methods yield unacceptably conservative results or are not applicable due to flow complexity, tidal hydraulic analyses including one- and two-dimensional hydrodynamic computer modeling will provide a more accurate hydraulic simulation of the situations.

Computer Modeling

Existing models cover a wide range from simple analytical solutions to heavily computer intensive numerical models. Some models deal only with flows through inlets, while others describe general one-dimensional or two-dimensional flow in coastal areas. A higher level includes hurricane or other storm behavior and predicts the resulting storm surges.

One-dimensional models are the most commonly used models because they demand less data and computer time than the more comprehensive models. Most analyses for tidal streams are conducted with steady state models where the tidal effects are not simulated. This may be an adequate approach if the crossing is located inland from the mouth where the tidal effects are insignificant. Computer modeling for steady state hydraulics is generally performed with the Corps of Engineers HEC-RAS, which has replaced previously used programs such as HEC-2 or the U.S. Geological Service – FHWA WSPRO (HY-7), or NRCS WSP-2.

In the event that tidal fluctuations are significant, simulation of the unsteady hydraulics is more appropriate. Dynamic modeling is recommended when complex geomorphic or hydraulic conditions make other methods unusable or when simplifying assumptions are violated to such a degree that the results are overly conservative.

In Phase 1 of the Pooled-Fund study entitled "Development of Hydraulic Computer Models to Analyze Tidal and Coastal Stream Hydraulic Conditions at Highway Structures" (Ayres Associates 1994), of which the Department was a participant, UNET (Barkau 1996) and FESWMS-2DH were recommended for dynamic tidal hydraulic modeling. UNET is a one-dimensional model, and FESWMS-2DH is a two-dimensional model. Although other one- and two-dimensional models are also applicable for tidal hydraulic modeling, the recommended models incorporate bridge, culvert and road overtopping hydraulics. Therefore, these models were deemed most applicable for tidal bridge hydraulic and scour evaluations. Detailed directions for model development for flow in tidal waterways are given by Ayres in manuals developed under the pooled fund study (see reference listing). This includes flow charts for development, calibration and model use and the use of the two-dimensional model within the modeling shell, SMS.

One-Dimensional Models

UNET is a powerful, unsteady-flow model that computes flow though a bifurcating or branching network of channels. UNET also includes storage areas and a wide variety of hydraulic structures. These features make this model useful in tidal and unsteady riverine applications where bridge hydraulics are an important component. Under agreement with Dr. Barkau, developer of the model, the USACE Hydrologic Engineering Center (HEC) maintains, distributes and provides training for UNET. Version 3.0 of HEC-RAS contains the one-dimensional model UNET developed by Barkau (1996). The input to the program consists of channel geometry as a series of cross sections comprising a channel reach, flow-resistance parameters, ineffective flow areas, structures located on or along the channels, storage areas located at the ends or adjacent to the channels, information on how the channel reaches and how storage areas are connected, and boundary conditions. Structures include bridges, culverts, roadway embankments, spillways, navigational dams and closed conduits.

Dynamic models perform hydraulic computations for channels, overbanks, bridges and culverts and include potentially filled or inundated bay, estuary and floodplain areas. Therefore, dynamic models yield the most accurate hydraulic analysis for flooding and scour computations and countermeasure design. The governing equations used in these models are the full dynamic equations for conservation of mass and momentum. One-dimensional modeling is applicable for estuaries with well-defined channels and for bays with single or multiple inlets. Where bays are crossed by numerous causeways, especially causeways with multiple bridge openings, two-dimensional modeling is recommended. Estuaries with multiple-branched channels and nearly well-defined channel flow can be modeled with one-dimensional network models (such as HEC-RAS), but the complexity often warrants the use of two-dimensional models. When it is necessary to employ dynamic modeling, it must be recognized that the development time will be significantly longer than for the one-dimensional model. However, it does provide a tool to develop complex and dynamic flow patterns.

Two-Dimensional Models

The computer program Finite Element Surface Water Modeling System: Two-Dimensional Flow in a Horizontal Plane (FESWMS-2DH) is maintained by FHWA.). In Version 3, FESWMS-2DH has been renamed to FESWMS Flo2DH. As indicated by its name, FESWMS Flo2DH uses a finite-element numerical method to solve the equations that describe the two-dimensional flow of shallow surface water. The governing equations include the conservation of mass, the conservation of momentum in two directions and boundary condition equations. The program solves for the flow depth and the x- and y-velocity components at discrete points, called “nodes,” throughout the network. The input to the program includes information on the network and the boundary conditions. The network is the discretized spatial description of the system being modeled and consists of elements and nodes. Elements are 3- or 4-sided cells that may be irregular in shape and size. Each element has an associated material type that contains the values of resistance parameters. Nodes are the points at the corners and midsides of the elements. Each 4-sided element also has a node at its center. Every node has a bed elevation assigned to it to describe the bathymetry of the system.

Another effective two-dimensional model that can be used is RMA2 (AYERS, 1994). Like FESWMS Flo2DH, this model is a two-dimensional depth, averaged finite-element hydrodynamic numerical model. It computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields. RMA2 computes a finite-element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy Equation, and eddy viscosity coefficients are used to define turbulence characteristics. The model is used to compute dynamic response to tidal, storm surge, winds and stream inflow hydrographs. Similar to FESWMS Flo2DH, the output from the model is water surface elevation and velocity throughout the domain.

Surface-Water Modeling System

Surface-water Modeling System (SMS) is a pre- and post-processor that can be used with both FESWMS and RMA2. The SMS software is a comprehensive graphical user environment for two- and three-dimensional numerical modeling. The Environmental Modeling Research Laboratory at Brigham Young University developed it in cooperation with the USACE Waterways Experiment Station, now ERDC (Engineering Research and Development Command) and FHWA. The finite-element mesh or cross section entities, plus the associated boundary conditions necessary for analysis, are created within SMS and then saved to model specific files. These files are used as input to the hydrodynamic, wave mechanic, contaminant migration and sediment-transport analysis engines of the models supported by SMS, such as RMA2 and FESWMS Flo2DH. The numerical models create solution files that contain the water surface elevations, velocities, contaminant concentrations, sediment concentrations or other functional data at each node, cell or section. Plots and animations can then be easily created within SMS to view the simulation results. SMS can also be used as a pre- and post-processor for other finite-element or finite-difference programs if the programs can read and write files in a supported format. SMS is capable of constructing large, complex meshes (up to hundreds of thousands of elements) of arbitrary shape.

SMS can also be used as a pre- and post-processor for many other surface water modeling tools for analysis and design. Supported models include the USACE-WES supported TABS-MD (GFGEN, RMA4, RMA10, SED2D-WES) in addition to the RMA2 mentioned above. It also supports ADCIRC, CGWAVE, STWAVE and HIVEL2D. Comprehensive interfaces have also been developed for facilitating the use of the FHWA-commissioned analysis packages FESWMS Flo2DH and WSPRO. SMS also includes a generic interface, which can be used to support models that have not been officially incorporated into the interface. The SMS pre- and post-processor includes two-dimensional finite element, two-dimensional finite difference, three-dimensional finite element and one-dimensional backwater modeling tools.

Method Selection

Chapter 4 of the FHWA Pooled Fund Study manual "TIDAL HYDRAULIC MODELING FOR BRIDGES" (Ayres Associates, March 2002), also provides a review of the available methods for tidal waterway hydraulic analyses, from the simple methods presented in HEC-18 to the complex modeling introduced in the preceding paragraphs of this manual. Based on the geomorphic characteristics of the waterway, recommendations are made on the selection of the most appropriate method. Chapter 5 contains guidance on HEC-RAS application for tidal hydraulics.

The hydraulic engineer is responsible for determining the most suitable method for analyzing tidal structures. The decision should be made early in the design phase with approval from the Hydraulics and Drainage Section.