

CHAPTER 6

BRIDGE HYDRAULIC DESIGN



NOTE: For trunkline projects, direct questions and comments to the Hydraulic Unit Supervisor, Environmental Services Section.

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If you require assistance accessing this information or require it in an alternative format, contact the Michigan Department of Transportation's (MDOT) Americans with disabilities Act (ADA) coordinator at [Michigan.gov/MDOT-ADA](https://www.michigan.gov/MDOT-ADA).

6.1 INTRODUCTION/PURPOSE

The purpose of this chapter is to provide guidance in the hydraulic design of a bridge stream crossing system through appropriate design practice and design criteria and technical aspects of hydraulic design. It also presents non-hydraulic factors that influence design including environmental concerns, emergency access, traffic service, and consequence of catastrophic loss.

Proper hydraulic analysis and design are as vital as the structural design. Bridge stream crossing systems should be designed for minimum cost subject to criteria, desired level of hydraulic performance, mitigation of impacts on stream environment and accomplishment of social, economic and environmental goals.

This chapter provides guidance for the hydraulic design of a bridge stream crossing through:

- Appropriate policy and design criteria
- Technical aspects of hydraulic design

Non-hydraulic factors that influence design include:

- Environmental considerations
- Emergency access, traffic service
- Consequence of catastrophic loss
- Navigation (refer to “Clearance” in **Section 6.3.2.4**)
- Coastal Impacts (refer to Chapter 9, Coastal Engineering)

The design procedure presented emphasizes hydraulic analysis using the computer program USACE Hydrologic Engineering Center River Analysis System (HEC-RAS) or Aquaveo Surface-water Modeling System (SMS).

A more in-depth discussion on design philosophy is presented in the current edition of the *AASHTO Highway Drainage Guidelines (2007)* and *AASHTO Drainage Manual (2014)*.

6.2 DEFINITIONS

Aggradation - General and progressive buildup (long term) of the longitudinal profile of a channel bed due to sediment deposition.

Annual Exceedance Probability (AEP) - The probability that the magnitude of the random variable (e.g., annual maximum flood peak) will be equaled or exceeded each year, often expressed as a percentage.

Annual Recurrence Interval (ARI) - The average time interval between occurrences of a hydrologic event of a given or greater magnitude, usually expressed in years. The ARI is the reciprocal of the AEP of a hydrologic event.

Apron - Protective material placed on a streambed to resist scour.

Backwater - The increase in water surface elevation induced upstream from a bridge, culvert, dike, dam, another stream at a higher stage, or other similar structures or conditions that obstruct or constrict a channel relative to the elevation occurring under natural channel and floodplain conditions.

Bridge - Under 23 CFR § 650.305, a bridge is defined as a structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between under copings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it includes multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening. Any three-sided (bottomless) structure is treated as a “bridge” in this chapter, regardless of span length.

Channel - The bed and banks that confine the surface flow of a stream up to the ordinary high water mark (OHWM).

Clearance - An unobstructed vertical space between the OHWM elevation and the low chord of a structure.

Clear-Water Scour - Scour at a pier or abutment (or contraction scour) when there is little to no movement of the bed material upstream of the bridge crossing at the flow causing scour. Clear-water scour occurs where there is flowing water with minimal to no sediment transport or suspended material which is not re-deposited when flows recede.

Contraction Scour - The removal of material from a channel bed and banks across all or most of the channel width within a natural channel or at a bridge crossing. This component of scour results from a contraction of the flow area at the bridge which causes an increase in velocity and shear stress on the channel bed and banks.

Countermeasure - An action or approach intended to monitor, prevent, delay, or mitigate the severity of hydraulic and/or erosion problems.

Degradation - A general and progressive (long-term) lowering of the channel due to erosion of the channel bottom, over a relatively long channel length.

Erosion - Displacement of soil particles due to water or wind action.

Floodplain - Any land area susceptible to inundation by floodwaters.

Floodway - The channel of a river or stream and those parts of the floodplain adjoining the channel that are reasonably required to carry and discharge a 1% AEP (100-year) flood. MCL 324.3103, R 323.1311

Freeboard - The vertical distance between the design water surface elevation and a point of interest such as a low chord of a bridge beam, crown of a culvert, or specific location on the roadway grade, for example, the bottom of subbase grade.

Harmful Interference - Causing an increased stage or change in direction of flow of a river or stream that causes, or is likely to cause, any of the following: i) Damage to property, ii) A threat to life, iii) A threat of personal injury, iv) Pollution, impairment, or destruction of water or other natural resources. MCL 324.3103, R 323.1311g

Headcutting - Channel degradation associated with abrupt changes in bed elevation that generally migrates in an upstream direction. The occurrence can be natural or in response to channel cleanouts, dam removals, bridge/culvert installations, or increases in discharge.

Hydraulic Design Flood - The peak discharge, volume (if appropriate), stage, or wave crest elevation of the flood associated with the probability of exceedance selected for the design of a highway encroachment.

Hydraulic Length - Length of a bridge substructure unit, measured parallel to the principal flow direction. Single span bridges are measured from the ends of the wingwalls. Multiple span bridges are measured from the ends of the piers.

Hydraulic Span - Opening of the bridge between bridge substructure unit faces measured perpendicular to the principal flow direction.

Incipient Overtopping Event - The event that produces a water surface elevation where the water will begin to spill over the bridge deck.

Live-Bed Scour - Scour at a pier or abutment (or contraction scour) when the bed material in the channel upstream of the bridge has suspended streambed particles in the flow causing scour. Live-bed scour occurs where there is flowing water with sediment transport or suspended material that can be re-deposited when the flows recede.

Local Scour - Removal of material around the piers, abutments, and embankments caused by an acceleration of flow and resulting vortices induced by obstructions to the flow.

Ordinary High Water Mark - The line between upland and bottomland that persists through successive changes in water levels, below which the presence and action of the water is so common or recurrent that the character of the land is marked distinctly from the upland and is apparent in the soil itself, the configuration of the surface of the soil, and the vegetation. On an inland lake that has a level established by law, it means the high established level. Where water returns to its natural level as the result of the permanent removal or abandonment of a dam, it means the natural, ordinary high water mark. (MCL § 324.30101). On Great Lakes, the ordinary high water mark is published in Section 32502 of Part 325 of NREPA.

Overtopping Flood - The flood described by the probability of exceedance and water surface elevation at which flow occurs over the highway, over the watershed divide, or through structure(s) provided for emergency relief.

Practicable - Capable of being done within reasonable natural, social, or economic constraints.

Probability of Exceedance - The probability that the magnitude of the random variable (e.g., annual maximum flood peak) will be equaled or exceeded over a given time period, expressed as a percentage.

Riprap - Layer(s) of rock placed to protect a structure or embankment from erosion.

River Training Structure - Any structure constructed in a stream or placed on, adjacent to, or in the vicinity of a streambank to deflect current, induce sediment deposition or scour, or in some other way alter the flow and sediment regimes of the stream.

Scour - Erosion of streambed or bank material due to flowing water; often considered as being localized around piers and abutments of bridges. (23 CFR § 650.305)

Scour Check Flood - A flow (flood) of an annual exceedance probability selected to estimate scour for an evaluation of the bridge foundation. The scour check flood has a lesser flood frequency (i.e., greater flood flow rate and greater recurrence interval) than the scour design flood. If a flood event is greater than the scour design flood but less than the scour check flood and it causes greater stresses on the bridge, (e.g. incipient overtopping flood), it is used as the scour check flood.

Scour Countermeasure Design Flood - A flow (flood) of an annual exceedance probability selected to determine parameters for the design and evaluation of scour countermeasures.

Scour Design Flood - A flow (flood) of an annual exceedance probability selected to estimate scour for the design and evaluation of the bridge foundation. The scour design flood has a lesser flood frequency (i.e., greater flood flow rate and greater recurrence interval) than the hydraulic design flood. If the overtopping discharge is less than the scour design flood discharge, it is used as the scour design flood.

Set Back Ratio - The ratio of the distance from the OHWM to the face of the abutment (measured perpendicular to flow) against the hydraulic depth at the design flood in the main channel.

Spread - A measure of the transverse distance from the curb or barrier face to the limit of the water flowing on the roadway.

Stream Channelization - Anything that straightens or changes the geometry to a fixed cross-section.

Temporary Haul Road - Short-term construction access that includes fill above the existing streambed or ground elevation. Includes temporary work pads.

Total Scour - The summation of long-term degradation, contraction scour, and local (abutment and pier) scour.

Weir Flow - Flow calculation used when flow overtops the road embankment or other long hydraulic control with a well-defined head discharge relationship.

Appendix 6-A contains a list of acronyms and symbols used in this chapter with their meanings.

6.3 POLICY AND DESIGN CRITERIA

6.3.1 General Policy and Design Criteria

Federal policies and state policies that broadly apply to drainage design are presented in Chapter 2, Policy and Procedures. Policies that are unique to bridge crossings are presented in this section.

AASHTO and other criteria related to the hydraulic analyses for the location and design of bridges, as stated in the AASHTO's *Highway Drainage Guidelines* (2007) include:

- Backwater will not significantly increase flood damage to property upstream of the crossing
- Velocities through the structure(s) will not damage the highway facility or increase damage to adjacent property
- Pier spacing, pier orientation, and abutments will minimize flow disruption and potential scour
- Piers will be located beyond the immediate vicinity of the abutment embankment toe of slope
- Foundation and/or countermeasures will avoid failure by scour
- Freeboard at structure(s) will pass anticipated debris and ice
- Minimize disruption to ecosystems
- Consider impacts to upstream water surface profiles with bridge railing options
- Design structures in accordance with AASHTO's *LRFD Bridge Design Specifications*.

6.3.2 MDOT Policy and Design Criteria

MDOT policies identify specific areas for which quantifiable criteria can be developed. Refer to Part 31 of Public Act 451 of 1994, the State of Michigan Executive Order in Chapter 2, Policy and Procedures, Appendix 2-D, for additional information.

Part 31 and FHWA technical advisories dictate the size of the bridge opening. They provide specific, quantifiable values that relate to local site conditions. Various alternatives are evaluated according to these design criteria using water surface profile computer programs such as HEC-RAS.

The bridge design criteria presented in **Table 6-1** identify the design flood events used for varying road classifications. Pedestrian structures within the hydraulic influence of road facilities are required to match the design criteria of that facility.

For structures relying on a scour countermeasure for B.AP.03 scour vulnerability coding, use the AEP noted in **Table 6-1**. Otherwise use 1% AEP (100-year) for all other applications including bridge embankment protection.

Table 6-1. Bridge Design Criteria – AEP (ARI)

Roadway Classification	Hydraulic Design	Scour Design	Scour Check	Designed Countermeasure
MDOT: Interstate, Freeways (Urban/Rural)	2% (50-year)	1% (100-year)	0.20% (500-year)	0.50% (200-year)
MDOT: Principal Arterial	2% (50-year)	1% (100-year)	0.20% (500-year)	0.50% (200-year)
MDOT: Minor Arterial	2% (50-year)	1% (100-year)	0.20% (500-year)	0.50% (200-year)
Local: Minor Arterial System with ADT<3000 VPD	4% (25-year)	1% (100-year)	0.20% (500-year)	0.50% (200-year)
Local: Collector System with ADT>3000 VPD	4% (25-year)	1% (100-year)	0.20% (500-year)	0.50% (200-year)
Local: Collector System with ADT<3000 VPD	10% (10-year)	1% (100-year)	0.20% (500-year)	0.50% (200-year)
Local Road System	10% (10-year)	1% (100-year)	0.20% (500-year)	0.50% (200-year)
Pedestrian Crossings	10% (10-year)	1% (100-year)	0.20% (500-year)	0.50% (200-year)

6.3.2.1 Overtopping

Overtopping of bridges is prohibited for flood events up to and including the hydraulic design flood, except when controlled by downstream tailwater conditions, as defined by **Table 6-1**. Note, the designer may need to examine the potential of debris and hydraulic characteristics of the railing if weir flow occurs up to the 0.2% AEP (500-year) storm. Avoid alterations for crossings with overtopping that would cause harmful interference for a range of flows up to and including the 1% AEP (100-year) storm.

6.3.2.2 Backwater Increases Over Existing Conditions

Backwater impacts are required to conform to Part 31 of Public Act 451 of 1994. The statute states that the project will not produce a harmful interference to the watercourse, and it will conform to FEMA regulations for sites covered by the National Flood Insurance Program (NFIP).

6.3.2.3 Freeboard

Where practicable, provide a minimum freeboard of 2 feet between the hydraulic design flood water surface and low chord as defined in **Table 6-1** to protect bridge structures from debris and scour related failure.

6.3.2.4 Clearance

Ensure clearance conforms to federal requirements based on normally expected flows during the navigation season when used by canoes, small boats, and wading anglers. Where applicable, ensure clearance also conforms to the current edition of the AASHTO's *Guide for Development of Bicycle Facilities* and FHWA's *A Policy on Geometric Design of Highways and Streets* (2011).

6.3.2.5 Location

To establish the location of a new or replacement bridge crossing, determine the flow distribution between the channel and overbanks. The proposed facility must avoid harmful interference or vertical or lateral stream instability by aligning substructure elements with the main channel and floodplain, to the extent possible.

6.3.2.6 Vertical Wall Abutments

For deep foundations, set the top of the abutment footings at or below the design contraction scour plus long-term degradation elevation. For shallow foundations, set the top of the abutment footings at or below the check flood total scour, or lesser flood that causes deeper scour, unless limited by scour-resistant bedrock.

6.3.2.7 Spill through Abutments

Provide a minimum of 2 feet of freeboard between the hydraulic design flood water surface and the low chord as defined in **Table 6-1**. Measure the setback distance horizontally from the abutment face to the OHWM. The distance must be a minimum of 25 feet or ratio of 1V:3H of the design flood hydraulic depth (whichever is greater). Provide space to properly construct scour countermeasures following guidance in FHWA HEC-23 (2009) and *Hydraulic Considerations for Abutments on Deep Foundations* (FHWA-HIF-23-048, 2023).

6.3.2.8 Scour

Design bridge foundations based on the estimated scour design and check floods as defined in **Table 6-1**. Note, if the overtopping discharge is less than the scour design event discharge, the scour design event is the incipient overtopping event.

6.3.2.9 Design Scour Countermeasure versus Bridge Embankment Protection

Properly designed and constructed scour countermeasures allow the abutment foundation elevation to be designed assuming the soil protected by the scour

countermeasure remains in place. In this case, design the top of the apron of the scour countermeasure to be located at or below the depth of long-term degradation (LTD) plus contraction scour at the scour check flood (LRFD 2.6.4.4.3).

Many site locations will limit the practicality of installing the top of aprons at or below the depth of LTD plus contraction scour at the scour check flood. For those site locations, provide bridge embankment protection to be stable for the design contraction scour plus LTD, where possible, considering any regulatory requirements. Where bridge embankment protection is utilized, design the abutment foundation depth based on total scour (LTD + contraction + local abutment).

For either application, determine the size, thickness, and horizontal limits layout of the scour countermeasure following guidance in FHWA HEC-23 (2009), FHWA-HIF-23-048 (2023), and FHWA-HIF-19-007 (2019).

6.3.3 Coordination, Permits, and Approvals

Please reference Chapter 2, Policy and Procedures, for waterway environmental permits, policies, and regulations.

6.3.4 Bridge Deck Drainage

Pavement drainage on a bridge uses the same design criteria as a curbed approach roadway since the bridge parapets confine the runoff in a manner similar to a curbed roadway. Comply with allowable spread criteria on bridge decks as described in Chapter 7, Inlet and Enclosed Storm Drainage Systems.

Where necessary to intercept deck drainage at intermediate points along the bridge, design interceptors and erosion control using FHWA HEC-21 (1993) procedures. When deck drainage interceptors are needed, a storm sewer collection system is necessary to discharge the runoff. Considerations for this system include, but are not limited to:

- Avoid direct discharges into waterbodies
- Provide required water quality and channel protection treatment, refer to the [MDOT Stormwater Treatment Manual](#)
- Design drain systems attached to the superstructure to facilitate maintenance
- Provide erosion control underneath free drops from deck interceptors
- Provide 8-inch minimum projection beyond the lowest adjacent superstructure component
- Design and size bridge deck storm water collection piping system to ensure minimum required self-cleansing velocities are being achieved for the design storm to minimize long term maintenance requirements.
- Where lateral connections are being made to the main line drainage pipe utilize wye-fittings and provide cleanout(s) to minimize long term maintenance and ensure future serviceability.

6.4. DESIGN GUIDANCE AND PROCEDURE

6.4.1 Design Procedure Outline

The following design procedure outline is used for hydraulically analyzing and sizing a bridge opening. Although the scope of the project and individual site characteristics make each design unique, this procedure may be applied.

A. Data Collection

a. Survey

- i. Topography and bathymetry
- ii. Geology
- iii. High-water marks
- iv. History of debris accumulation, ice, and scour
- v. Review hydraulic performance of existing structures
- vi. Review all available inspection reports for existing bridges
- vii. Maps, aerial photographs, and terrain data
- viii. Rainfall and stream gauge records
- ix. Field reconnaissance

b. Studies or Plans by Other Agencies

- i. Federal Flood Insurance Studies (FIS)
- ii. Federal floodplain studies by the USACE, NRCS, etc.
- iii. State and local floodplain studies
- iv. Drain Commissioners
- v. Hydraulic performance of existing bridges

c. Influences on Hydraulic Performance of Site

- i. Other streams, reservoirs, and water intakes
- ii. Structures upstream or downstream
- iii. Natural features of stream and floodplain
- iv. Ice damming
- v. Frequent log jams or debris accumulation
- vi. Channel modifications upstream or downstream
- vii. Floodplain encroachments
- viii. If downstream water bodies or hydraulic controls are present, refer to Chapter 4, Open Channels and Roadside Ditches, Section 4.4.3.10
- ix. Sediment types and bed forms (also refer to Scour, Site Data, Level One Qualitative Analysis C, FHWA.)
- x. EFA testing for cohesive soils (**Appendix 6-D**)
- xi. Abrasion testing for rock (**Appendix 6-D**)
- xii. Review stream instability following guidance in FHWA HEC-20 (2001) (**Appendix 6-D**)

d. Coastal Impacts (refer to Chapter 9, Coastal Engineering)

- i. Wave impact
- ii. High / Low Great Lake levels
- iii. Seiche (wind induced storm surge)
- iv. Long shore current

- e. Environmental Review
 - i. Existing bed or bank instability (Level 1, Qualitative Analysis, FHWA HEC-20 (2001))
 - ii. Floodplain land use and flow distribution
 - iii. Environmental constraints (Threatened and Endangered Species, fisheries, wetlands, etc.)
 - f. Site-specific Design Criteria
 - i. Preliminary risk assessment
 - 1. Site-specific geometric concerns
 - 2. Proximity to adjoining properties or structures
 - 3. Proximity to other utilities or infrastructure
 - 4. Geomorphology (vertical and/or lateral stability of the stream)
 - 5. Scour
 - 6. Navigation
 - 7. Railing design where overtopping or weir flow occurs
 - 8. Other site-specific concerns
 - ii. Miscellaneous criteria (For additional information, refer to Chapter 2, Policy and Procedures)
 - iii. County drains
 - iv. Delegated authority for legal lake level
 - v. Dam safety concerns
- B. Hydrologic Analysis - Refer to Chapter 3, Hydrology
- C. Hydraulic Analysis
- a. For floodplain review, use original hydraulic model (Effective hydraulic model from FIS) in areas with a FEMA Zone AE floodplain
 - b. Computer model calibration and verification, when applicable
 - c. Hydraulic performance for existing conditions
 - d. Hydraulic performance of proposed designs
 - e. Scour computations for scour design and scour check floods
 - f. Scour countermeasure design
- D. Compute Deck Drain Spacing and MS4 Compliance (as applicable)
- E. Final Design
- a. Measure compliance with established hydraulic criteria
 - b. Consider environmental and social criteria, such as recreational paths
 - c. Design details such as riprap, scour countermeasures, and river training
- F. Documentation
- a. Complete project records, permit applications, etc.
 - b. Complete correspondence and reports
 - c. Plans
 - d. Specifications

6.4.2 Hydraulic Performance of Bridges

The stream-crossing system is subject to open channel flow or pressure flow through one or more bridge openings with possible embankment overtopping. These hydraulic complexities are analyzed using the HEC-RAS computer program, at a minimum, unless otherwise indicated by the Hydraulic Unit Supervisor for trunkline bridges. For complex bridge situations, a more in-depth analysis may be required. Refer to **Section 6.4.3** for more detail.

Hydraulic variables and flow types are defined in **Figure 6-1** and **Figure 6-2**. Note that:

- Symbols used in **Figure 6-1** include:
 - Q_a , Q_b , and Q_c are flows in the indicated regions of the channel
 - W and b are the width of the channel and width of the bridge, respectively
 - h^* indicates height (elevation) differences at various locations along the channel
 - $\alpha v^2/2g$ is the velocity head at various locations along the channel
 - S_0 indicates slope along the channel
 - L indicates channel lengths
- Symbols used in **Figure 6-2** include:
 - y_n is the normal water depth
 - y_c is the critical water depth (at various sections along the channel)
- Backwater (h_1) is measured relative to the water surface elevation without the effect of the bridge at the approach cross-section (Section 1). The water surface elevation in FEMA FIS is the hydraulic grade line (HGL) through the floodway portion. It is the result of head losses due to contraction and expansion of 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 6-2**.

The following flow classes are defined in Chapter 6 of FHWA HDS 7 (2024):

- Class A is the most common free-surface bridge flow condition where flow is subcritical upstream of the bridge, downstream of the bridge, and throughout the bridge waterway. Class A flow satisfies the constraints of gradually varied flow throughout the reach of interest. HEC-RAS offers four approaches to modeling Class A free-surface bridge flow at a bridge, described in detail in the following section.
- In the Class B scenario, the flow passes through critical depth within the bridge waterway, which requires that supercritical flow exist, at least for a short distance, downstream of the critical depth control section. The potential for Class B flow to occur inside a bridge waterway stems from two causes. First, the elevation of critical depth is often higher in the constriction than upstream or downstream. Second, the water surface within the constriction is dropping rapidly. Most commonly, the flow conditions upstream and downstream of a bridge in Class B flow are subcritical, and a hydraulic jump will often exist either

within the bridge waterway or a short distance downstream of the bridge. Class B flow may occur in conjunction with a supercritical stream profile. In this case, the bridge waterway is a control section with subcritical flow upstream and a hydraulic jump occurring some distance upstream of the bridge.

- In Class C flow, the regime is supercritical upstream and downstream of the bridge and through the bridge waterway. This condition is extremely rare because natural channels on steep grades, such as mountain streams, rarely support uninterrupted supercritical flow over long reaches (Jarrett, 1984). Class C flow, therefore, would be expected in engineered flood control channels on a steep slope.

Refer to Chapter 5 in FHWA HDS 7 (2024) for additional information.

Figure 6-1. Bridge Hydraulics Definition Sketch (FHWA HDS 7, 2012)

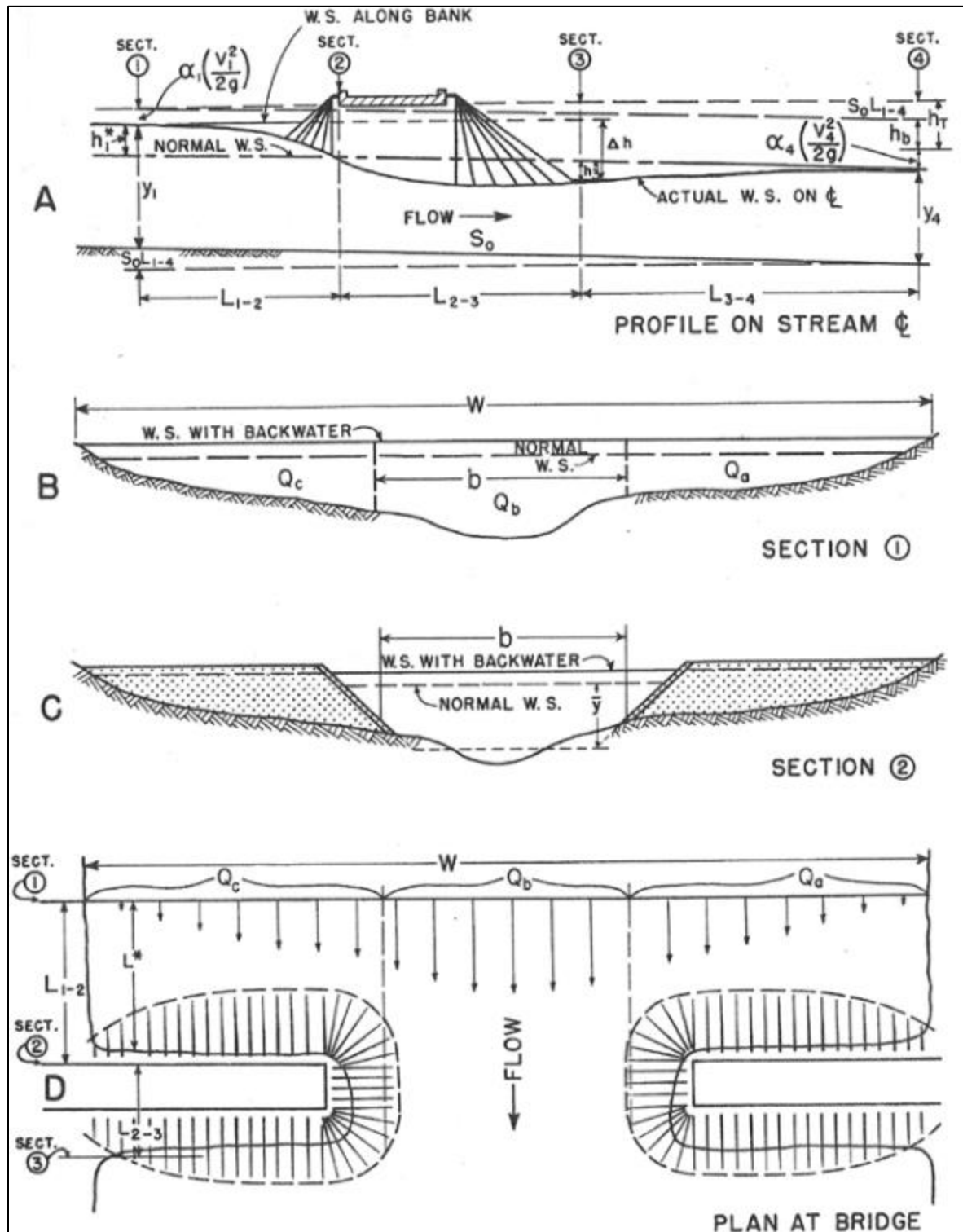
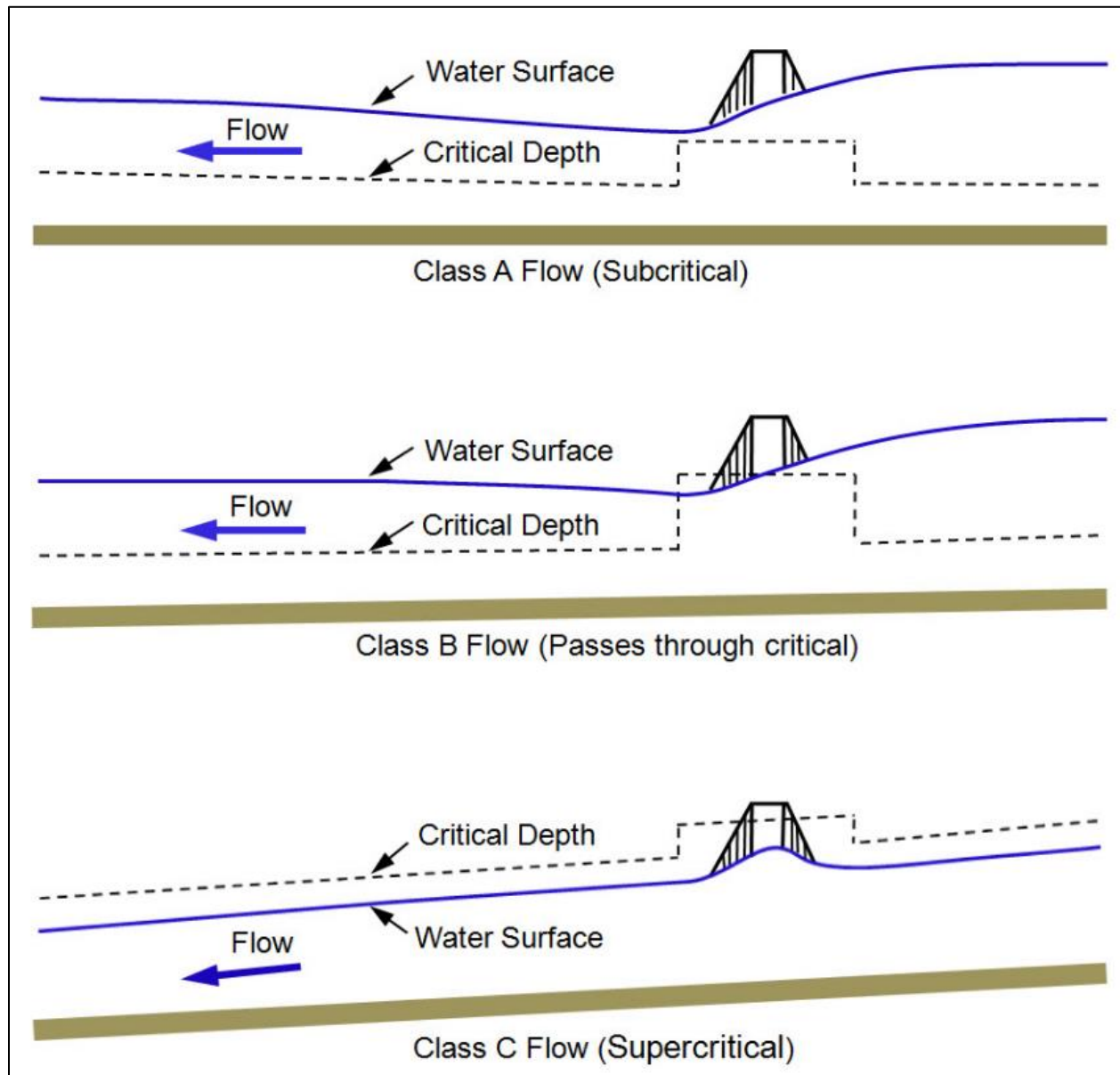


Figure 6-2. Bridge Flow Types (FHWA HDS 7, 2024)

6.4.3 Modeling Selection Rationale

Prior to commencing work on trunkline projects, contact the Hydraulic Unit Supervisor for assistance on modeling software selection. Consult an experienced hydraulic engineer for Local Agency projects. No single method is suited for all situations. If a satisfactory computation is not achieved with a given method, attempt an alternate method. Momentum and energy methods can achieve similar results with careful attention to the setup requirements of each method. **Figure 6-3** provides guidance for selecting the hydraulic modeling method for varying bridge hydraulic conditions. Refer to FHWA HDS 7 (2024) for additional information.

6.4.3.1 One-Dimensional (1D) Modeling

Most bridge hydraulic studies use one-dimensional hydraulic analysis. One-dimensional analysis encompasses detailed water surface profile calculations involving many cross-sections and sometimes multiple stream reaches (refer to Chapter 4, Open Channels and Roadside Ditches for additional information).

Although there are other 1D analysis packages, HEC-RAS is most commonly used. The package includes friction slope methods, mixed flow regime capability, automatic Manning's n calibration, ice cover, quasi two-dimensional velocity distribution, super-elevation around bends, bank erosion, riprap design, stable channel design, sediment transport calculations, and scour at bridges. Do not use the built-in scour calculator in HEC-RAS for scour computations.

A 1D approach determines the flow rate through the bridge based on the water surface elevations at the upstream and downstream sides of the structure assuming steady, gradually varied flow conditions. However, where conditions at the site depart significantly from these assumptions; where storage and acceleration effects could be substantial; or where pressure flow, in possible combination with overtopping flow, may be present, consider a 2D or Computational Fluid Dynamics (CFD) analysis.

6.4.3.2 Two-Dimensional (2D) Modeling

The water surface profile and velocities in a section of river are predicted using a computer model. While 1D methods are adequate for some applications, they cannot provide a detailed determination of the cross-section water surface elevations, flow velocities, or flow distribution. When more detail is needed, 2D modeling is used.

Finite element analysis is used to predict 2D flow components (within the horizontal plane). Consider 2D models in specialized applications such as:

- Calculation of flow distribution across a channel (such as around bends)
- Contraction and expansion at bridges
- Lateral inflow or outflow
- Crossings with extreme skew angle (> 30 degrees)

- Crossings with split flows, such as roadway overtopping and crossings with relief structures
- Multi-span bridge crossings
- Scour countermeasure sizing and designs when countermeasure is a critical component of the bridge or road embankment envelope, such as spill through abutments and existing retrofits to change the scour rating.
- Coastal applications

Figure 6-3. Bridge Hydraulic Modeling Selection (FHWA HDS 7, 2024)

Bridge Hydraulic Condition	1D Model	2D Model
Small streams	✓	✓
In-channel flows	✓	✓
Narrow to moderate-width floodplains	✓	✓
Minor floodplain constriction	✓	✓
Wide floodplains	⚠	✓
Highly variable floodplain roughness	⚠	✓
Highly sinuous channels	⚠	✓
Multiple embankment openings	✗	✓
Unmatched multiple openings in series	✗	✓
Low skew roadway (<20%)	✓	✓
Moderate skewed roadway (>20% and <30%)	⚠	✓
Highly skewed roadway (>30%)	✗	✓
Detailed analysis of bends, confluences, angle of attack	✗	✓
Multiple channels	✗	✓
Small tidal streams and rivers	✓	✓
Large tidal waterways and wind influenced conditions	✗	✓
Detailed flow distribution at bridges	✗	✓
Significant roadway overtopping	✗	✓
Upstream controls	✗	✓
Countermeasure design	✗	✓

✓ well suited, ideal use

⚠ possibly suitable, but use with caution

✗ unsuitable or not recommended

6.4.3.3 Physical Modeling and CFD Modeling

Complex hydrodynamic situations may require a more detailed modeling analysis than what 1D or 2D analysis methods accomplish. Consider physical and/or CFD models when:

- Hydraulic performance data are needed that cannot be reliably obtained from traditional modeling
- Risk of failure or excessive over-design is unacceptable
- Research is needed
- Shear stress decay from scour hole formation is present

The constraints on physical and CFD modeling are size (scale), cost, and time.

Appendix 6-D provides a more detailed discussion of physical and CFD modeling. Prior to completing a physical or CFD hydraulic model for shear stress decay analysis, contact the Hydraulic and Geotechnical Unit Supervisors to review the need on trunkline projects. Refer to additional discussion in **Appendix 6-D** regarding additional geotechnical needs.

6.4.3.4 HEC-RAS 1D Modeling

The cross-sections necessary for the HEC-RAS analysis through a single opening bridge are shown in **Figure 6-4**. Additional cross-sections are necessary upstream and downstream of the structure to compute the water surface profile.

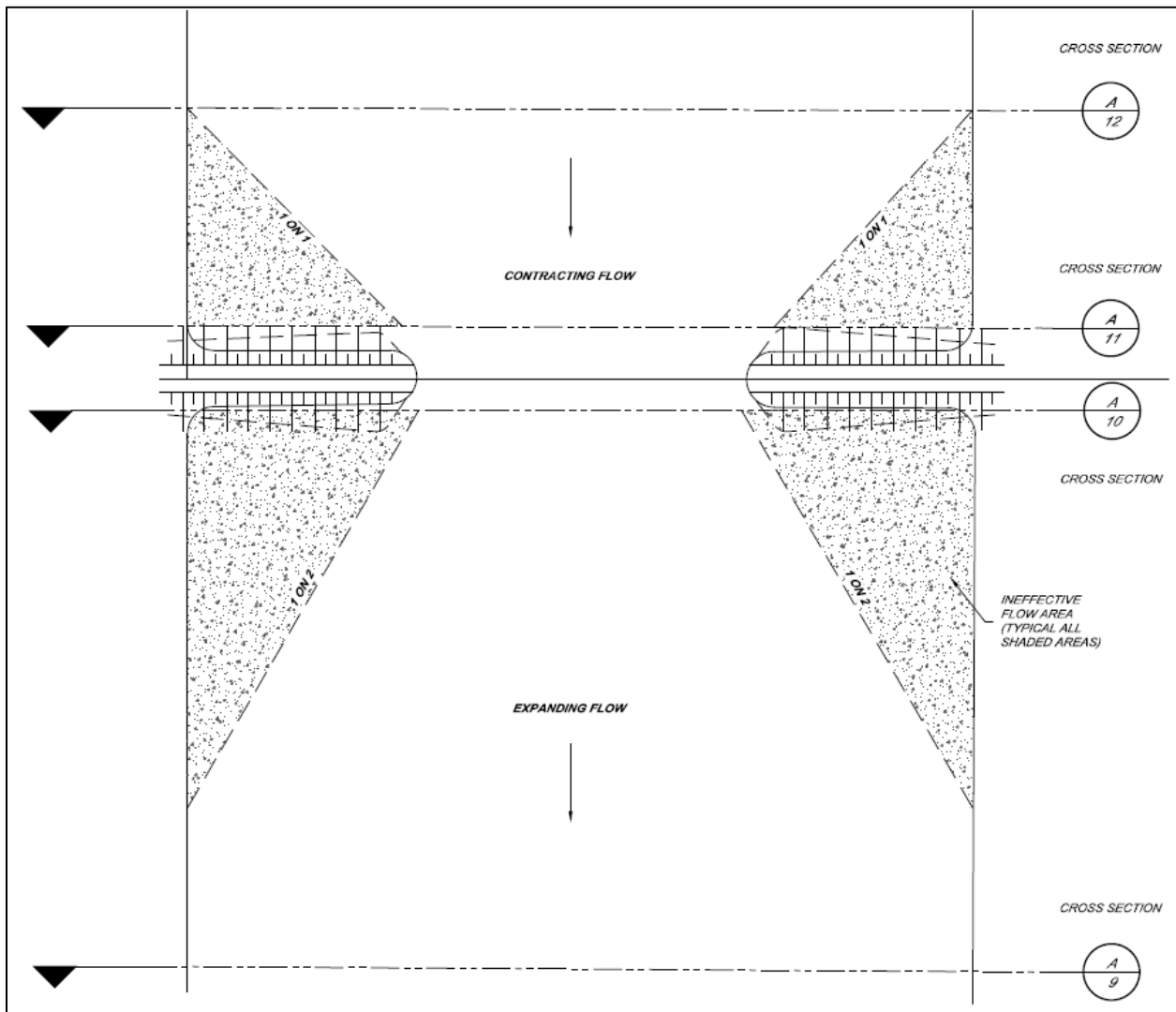
Energy losses caused by structures, such as bridges and culverts, are computed in two parts. First, the losses due to expansion and contraction of the cross-section on the upstream and downstream sides of the structure are computed in the standard step calculations. Second, the loss through the structure is computed by one of several methods.

At low flows, the losses through a bridge are computed by one of four methods: momentum balance, energy equation, Yarnell equation, or FHWA WSPRO computer model. The HEC-RAS user may select any or all of these methods for comparison.

At high flows that contact the low chord of the bridge, select hydraulic equations for pressure and weir flow. When selecting the pressure and weir flow method, HEC-RAS will automatically switch to the energy equation when the weir becomes highly submerged (the program default value is 95%).

Reference the various HEC-RAS User's and Reference Manuals included in the program help menu for more detailed information on using this computer program.

Figure 6-4. Cross-Section Locations in the Vicinity of Bridges



6.4.3.5 2D Modeling

In situations where structures create complex changes in flow direction, 1D modeling may not accurately reflect hydraulic conditions at a bridge or culvert. Therefore, 2D modeling may be required and encouraged in many scenarios. A more detailed summary of applications suitable to 2D modeling is provided in **Figure 6-3**. Refer to *Two-Dimensional Hydraulic Modeling for Highways in the River Environment* (FHWA-HIF-19-061, 2019) and the HEC-RAS 2D User's Manual for a detailed discussion of 2D modeling techniques.

6.4.4 Reporting Requirements

Reports require the following, as applicable:

- Current version of the [EGLE Hydraulic Report Guidelines](#) and **Appendix 6-C**. This includes requirements for report format, modeling setup and structure, and damage assessment certification, if needed.
- For scour requirements and reporting, refer to **Appendix 6-D**.
- Bridge deck drainage calculations.
- For Municipal Separate Storm Sewer System (MS4), refer to the [MDOT Stormwater Treatment Manual](#).

6.4.5 Bridge Scour

6.4.5.1 Introduction

Hydraulic analysis of a bridge design requires an assessment of the proposed bridge's vulnerability to undermining due to potential scour. Because of the extreme hazard and economic hardships posed by a bridge collapse, carefully select the appropriate flood magnitudes for use in the analysis.

Refer to the following FHWA publications and technical briefs for more information:

- HDS 7 (2024)
- HEC-18 (2012)
- HEC-20 (2001)
- HEC-23 (2009)
- FHWA-HIF-19-007 (2019)
- FHWA-HIF-19-060 (2021)
- FHWA-HIF-19-058 (2019)
- FHWA-HIF-23-048 (2023)

6.4.5.2 Information Needed

Items useful for completing a scour analysis include:

- Soil gradation analyses (stream and abutments) - Required
- Topographic data - Required
- Hydraulic analysis - Required
- FIS (if available)
- Bridge inspection reports and maintenance records
- Bridge construction drawings
- Aerial photographs
- Site photographs

6.4.5.3 Scour Analysis Equations

Refer to FHWA HEC-18 (2012) for a thorough discussion of scour analysis procedures. Important equations are included for reference.

Current technology dictates that bridge scour be evaluated using the following interrelated components:

- Long-term profile changes (aggradation/degradation)
- Plan form change (lateral channel movement)
- Contraction scour/deposition
- Local scour (piers and abutments)

Total scour is equal to the sum of these components, i.e., $\text{Total Scour} = (\text{degradation}) + (\text{contraction scour}) + (\text{local pier or abutment scour})$.

6.4.5.4 Long-Term Aggradation/Degradation

Long-term profile changes can occur from aggradation or degradation over the design life of a structure. Although an assessment of long-term degradation and aggradation is important to evaluate, only long-term degradation is considered when determining total scour. When and where they are identified, consider long-term degradation or aggradation when assessing effects of stream bed elevation changes at a bridge site. For most bridges, this is determined as part of the stream stability assessment. Bridge inspection reports are useful in assessing long-term degradation and aggradation at existing bridges. Refer to FHWA HEC-20 (2001) for additional discussion.

6.4.5.5 Lateral Channel Movement

Lateral migration of a stream's main channel within a floodplain may affect the stability of piers, erode abutments or the approach roadway, or change the total scour by changing the flow angle of attack at piers and abutments. Factors that affect lateral stream movement also affect the stability of a bridge foundation. These factors are the geomorphology of the stream, location of the crossing on the stream, flood

characteristics, and bed and bank material characteristics. Refer to FHWA HEC-20 (2001) for additional discussion.

6.4.5.6 Contraction Scour

Contraction scour occurs from the constriction of the flow area caused by approach fills in the floodplain or, typically to a lesser extent, by bridge piers in the waterway. Highways, bridges, and natural channel constrictions are common causes of contraction scour. Refer to Chapter 6 in FHWA HEC-18 (2012) for a detailed discussion of contraction scour. Additional information on geotechnical requirements is available in **Appendix 6-D**.

6.4.5.7 Pressure Flow Scour (Vertical Contraction Scour)

Pressure flow occurs when the water surface elevation at the upstream face of the bridge is greater than or equal to the low chord of the bridge superstructure. Pressure flow under the bridge results from a buildup of water on the upstream bridge face and a plunging of the flow downward and under the bridge. At higher approach flow depths when the bridge is submerged, the flow is a combination of plunging flow under the bridge and flow over the bridge.

Under pressure flow, the flow is directed downwards towards the streambed. The vertical contraction of flow is the primary cause of the increase in scour depth. It is recommended to design bridges that have sufficient freeboard to avoid pressure flow. However, when that is not feasible or when assessing an existing bridge, assess the effects of pressure flow. Refer to Chapter 6 in FHWA HEC-18 (2012) for a detailed discussion of pressure flow scour.

6.4.5.8 Pier Scour

The acceleration of flow around the pier and the formation of flow vortices (horseshoe vortex) causes pier scour. For piers located outside the main channel, and where there is potential for the main channel to laterally migrate over the design life of the bridge, use the main channel hydraulics to determine local scour for those piers. Under pressure flow conditions, the intensity of the horseshoe vortex increases and the local scour around piers increases. Refer to Chapter 7 in FHWA HEC-18 (2012) for a more detailed discussion of local pier scour.

For new bridges, pier foundations are designed to be stable for the calculated total scour at the scour check flood, as stipulated in AASHTO's *LRFD Bridge Design Specifications* (2024). For existing piers, contraction scour is also a critical consideration.

6.4.5.9 Abutment Scour

The constriction of flow at the sides of a channel created by the abutments of the bridge causes abutment scour. Abutment scour increases under pressure flow conditions. Refer to Chapter 8 in FHWA HEC-18 (2012) for a more detailed discussion of local

abutment scour. The NCHRP 24-20 abutment scour approach provided in FHWA HEC-18 (2012) is recommended for computing abutment scour, however, the Froelich equation may be used for sites when assumptions in 1D hydraulic modeling are valid (refer to **Section 6.4.3** for more detail) or for sites experiencing pressure flow conditions. Use a 2D hydraulic model when using the NCHRP 24-20 approach.

The NCHRP 24-20 abutment scour calculation includes the effect of contraction and local scour together. Therefore, there is no need to add contraction scour to the abutment scour depth.

The Froelich equation calculates the local scour depth. Add the contraction scour depth to the local scour depth to determine the total scour depth.

Countermeasures and aprons are designed to account for contraction scour per FHWA HEC-23 (2009), FHWA-HIF-23-048 (2023), and FHWA-HIF-19-007 (2019).

6.4.5.10 Assessment Steps

The Scour analysis procedure involves a multi-disciplinary team and uses worksheets based on FHWA HEC-18 (2012), FHWA HEC-20 (2001), and National Bridge Inspection Standards (NBIS). These worksheets, Levels 1 and 2, are included in **Appendix 6-D**.

Conduct a site visit to complete the Level 1 scour worksheet. For new bridges, proceed to Level 2 analysis. For existing bridges, if warranted from the Level 1 analysis (refer to additional detail in **Appendix 6-D**), complete a Level 2 analysis. The procedure for Levels 1 and 2 analyses can be found in FHWA HEC-20 (2001).

Assess, evaluate, and design the bridge foundation for scour using the following steps:

Step 1 Estimate the potential for long-term degradation and lateral stability of the channel.

Step 2 Evaluate the proposed bridge and road geometry for scour using the scour design and check flood events. Compare overtopping flow with design flows to determine design parameters. If the bridge overtopping flow is less than the design or check flows, evaluate overtopping flow for scour design and check floods. If the overtopping scour is determined to be greater than design scour, use the overtopping flood as the scour design flood.

Once the expected scour geometry has been assessed, consult with the Geotechnical Engineer or Geologist to understand the resistance of surface and subsurface materials and to design the foundation using guidance in AASHTO's *LRFD Bridge Design Specifications* (2024).

Use caution when determining the scour resistance of bed materials, bank materials, and the underlying strata. With sand-size material, the passage

of a single flood may result in the predicted scour depths. Conversely, in scour-resistant materials (including bedrock), the maximum predicted depth of scour may not be realized during the passage of a particular flood; however, some scour-resistant material may be lost. Commonly, this material is replaced with more easily scoured material. Thus, subsequent floods may reach the predicted scour depth. Significant scour has been observed in materials commonly perceived to be scour resistant such as consolidated soils and glacial till, so-called bedrock streams, and streams with gravel and boulder beds. The Hydraulic Engineer, in consultation with the Geotechnical Engineer, is required to assess if the bed material, bank material, and underlying strata will scour during the life of the structure or resist scour (i.e., rock-like). Refer to FHWA HEC-18 (2012) and **Appendix 6-D** for additional discussion.

- Step 3** Impose the scour check event on the proposed bridge and road geometry. The Geotechnical Engineer and Bridge Engineer reviews the foundation design for this flood using guidance in AASHTO's *LRFD Bridge Design Specifications* (2024). Set the top of proposed spread footings at the total scour for the check flood unless limited by scour-resistant bedrock (refer to **Appendix 6-D** for more information).
- Step 4** Provide scour countermeasure recommendations following guidance in FHWA HEC-23 (2009), FHWA-HIF-19-007 (2019), and FHWA-HIF-23-048 (2023) and using the annual exceedance probability for scour shown in **Table 6-1**.
- Step 5** Notify the Bridge Design Engineer and Geotechnical Engineer of findings and recommendations with a Scour Memo from Steps 1 through 4.

6.4.5.11 General Guidelines

Follow guidelines summarized in FHWA HEC-23 (2009), FHWA-HIF-19-007 (2019), and FHWA-HIF-23-048 (2023) for countermeasure selection and design.

6.4.5.12 Piers

In general, circular piers or elongated piers with circular noses and an alignment parallel to the flood flow direction reduce the impacts of scour. Spread footings are used only where the streambed is extremely stable (both horizontally and vertically) and where the top of spread footing is founded at a depth below the maximum scour computed for the scour check flood unless limited by scour resistant bedrock. Drilled shafts, drilled piers, or micropiles are possible where pilings cannot be driven. Design new bridge piers to not rely on scour countermeasures.

6.4.5.13 Abutments

Unless limited by scour-resistant bedrock, support bridge abutments on deep foundations with a properly designed and constructed scour countermeasure, as

described in AASHTO's *LRFD Bridge Design Specifications* (2024), FHWA HEC-23 (2009), and FHWA-HIF-23-048 (2023).

For non-interstate routes, embankment overtopping may be incorporated into the design provided it does not cause detrimental effects to the bridge abutments and superstructure. For large drainages with adverse channel skew angles or encroachments, or both, into wide floodplains, the most cost-effective design may be to modify the bridge waterway opening to reduce the amount of scour or the cost of the scour countermeasures. When this is not feasible, guide banks may be one approach to align the approach flow with the bridge opening and prevent scour around the abutments. Refer to FHWA HEC-23 (2009) Design Guide 15 for design of guide banks.

6.4.5.14 Scour Countermeasure Design

Where possible and practical, avoid clearing vegetation upstream and downstream of the placed scour countermeasure.

For new bridges, the most cost-effective design may be to design the bridge foundations for total scour or modify the bridge opening to reduce the amount of scour which may reduce the footprint and cost of scour countermeasures.

Where rock of sufficient size, quality, and gradation is available, use riprap to armor abutment fill slopes and the area around the base of existing piers. Protect abutment fill slopes with properly sized riprap at appropriate elevations, extents, thickness, and edge protections on top of a geotextile liner. Use articulating concrete block in lieu of riprap in locations where the ability to excavate to place a countermeasure are limited, such as installations on existing structures founded on spread footings. In certain cases, such as upstream of a dam, drop structures or grade-control structures downstream of the bridge opening can be used to protect against streambed degradation.

Refer to additional information in FHWA HEC-23 (2009), FHWA-HIF-19-007 (2019), and FHWA-HIF-23-048 (2023). Scour countermeasures are not considered permanent measures and may deteriorate with time.

Where scour countermeasures are utilized, provide access for maintenance and inspection personnel for repairs during the service life of the bridge. Evaluate the need for right-of-way and temporary construction easements early in the design process for the construction and maintenance of scour countermeasures.

6.4.6 Hydraulic and Scour Analysis Documentation

A summary of the hydraulic analysis is included on bridge construction drawings in tabular form (**Appendix 6-B**). Document the results of the hydraulic analyses in MDOT's Standard Report Form (**Appendix 6-C**). Typically, this report is included with the EGLE permit application. MDOT has developed guidelines and worksheets for Level 1 and Level 2 scour analyses (**Appendix 6-D**).

6.4.7 Scour Analysis

Refer to FHWA HEC-18 (2012) for scour calculation examples.

6.4.8 Bridge Deck Drainage

Drainage of bridge decks is similar to curbed roadway sections. It is often less efficient because cross slopes are flatter, parapets collect large amounts of debris, and small drainage inlets or scuppers have a higher potential for clogging by debris. Bridge deck construction requires a constant cross slope. Because of the difficulties in providing and maintaining adequate deck drainage systems, intercept gutter flow from roadways before it reaches a bridge. For superstructure or complete bridge replacements, do not directly discharge flow from the bridge deck to waters of the state (refer to [MDOT Stormwater Treatment Manual](#)). In many cases, deck drainage is carried several spans to the bridge end for disposal.

Drain castings/scuppers in bridge decks should be avoided where practicable. When scuppers are the best alternative, check the gutter spread to ensure compliance with the design criteria in Chapter 7, Inlet and Enclosed Storm Drainage Systems, Section 7.3.6. Avoid zero gradients and sag vertical curves on bridges. The minimum longitudinal slope for bridge deck drainage is 0.5%. In many areas of the country, scuppers are the recommended method of deck drainage because they transport a relatively large concentration of runoff in an area with limited right-of-way. They have a low initial cost and are relatively easy to maintain. Consider site-specific concerns when using scuppers. Avoid direct discharge over embankments, slope pavement, slope protection, waterway channels, driving lanes, or railroad tracks. Runoff collected and transported to the end of the bridge is collected by inlets, spillways, drainage structures, and downspouts. Sod flumes are used for extremely minor flows in some areas. Manage runoff in compliance with applicable stormwater quality regulations.

Review MS4 design and permit requirements located in the [MDOT Stormwater Treatment Manual](#) to verify that the proposed design meets all requirements.

Inlets on the bridge are not necessary if the length between inlets is longer than the bridge. To compute the inlet spacing, follow procedures in FHWA HEC-21 (1993).

6.5 TEMPORARY STRUCTURES

6.5.1 Temporary Bridges

For temporary bridges, use the minimum scour design and check floods shown in **Table 6-2**. Consider using the 1% AEP (100-year) and 0.5% AEP (200-year) return interval for the scour design and check flood events on higher road classifications, such as interstates, divided highways, and principal arterials, if monitoring and closure during higher return events is not an option.

Table 6-2. Minimum Scour Design and Check Floods AEP (ARI) for Temporary Bridges

Temporary Duration*	Scour Design	Scour Check
Less than 6 months	10% (10-year)	4% (25-year)
Less than 1 year	4% (25-year)	2% (50-year)
Less than 2 years	2% (50-year)	1% (100-year)
More than 2 years	1% (100-year)	0.5% (200-year)

**Duration is defined as the time a structure is experiencing live traffic.*

For temporary bridges in place over one winter, assume a temporary duration between 1 and 2 years.

Temporary structures with contributing drainage areas equal or greater than 2 square miles require a Part 31 permit from EGLE (refer to [EGLE Hydraulic Report Guidelines](#)).

6.5.2 Temporary Haul Roads in the Floodplain

Temporary haul roads in the 1% AEP (100-year) floodplain with contributing drainage areas equal to or greater than 2 square miles require a Part 31 permit from EGLE. If necessary, provide a water surface elevation that requires partial or full removal of the temporary haul road and limits of removal on the plans to ensure no harmful interference. In most cases, this elevation is at or below the natural channel banks.

Evaluate scour impacts to the temporary and existing structure with installation of a temporary haul road based on the duration of installation, especially with part-width construction on existing scour-critical bridges. Consider use of temporary pipes through the temporary haul road to limit backwater and scour effects.

6.6 MAINTENANCE

6.6.1 Introduction

Keep bridge piers and abutments free of obstructions. Debris and vegetative growth under a bridge may contribute to scour, create a potential fire hazard, and reduce freeboard for ice and debris during high-water flows. This creates a serious threat to the bridge. A reduced effective flow area under the bridge may result in excessive bridge backwater damage, more frequent roadway overtopping, and a hazard to the traveling public.

Maintaining a channel cross-section record and revising it as significant changes occur provides an invaluable record of the tendency toward scour, channel shifting, and degradation or aggradation. A study of these characteristics helps predict when protection of pier and abutment footings is required.

6.6.2 Inspection

Refer to the MDOT Michigan Structure Inspection Manual.

6.6.3 Maintenance Concerns

Maintenance concerns encountered at bridges and their approaches include:

- Clogging of bridge deck drains and scuppers, which create a hazard to traffic and contribute to deck deterioration.
- Discharges of bridge deck drains that are detrimental to other bridge members and elements below. In addition, discharges may cause erosion.
- Clogging of air vents in the superstructure or deck of bridges subject to overtopping which may increase buoyancy forces and the risk of bridge washouts.
- Accumulation of debris in the open space between the handrails of bridges subject to overtopping which may induce additional lateral forces on the bridges and increase the risk of bridge failures.
- Channel aggradation or degradation.
- Scour at piers and abutments caused by accumulation of debris and/or excessive velocities.
- Damage to bridge approach embankment caused by channel encroachment.
- Loss of scour countermeasures due to erosion, scour, and wave action.
- Erosion of spillways.
- Erosion below scuppers or downspouts.
- Damage to bridge elements due to debris, ice jams, and excessive velocities.
- Missing navigational signs and lights over navigable channels.

6.6.4 Maintenance Measures

Follow bridge maintenance work methods described in the MDOT Maintenance Activity Guide. Contact the MDOT Maintenance Services Section Engineer for more information.

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References in bold type are recommended reading for the engineer's library. MDOT does not claim responsibility for the information at these links or their maintenance.

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