TechBrief

The Scour Program is an integrated national effort to address or mitigate erosion of streambed or bank material due to flowing water; including erosion localized around bridge abutments and piers.

The Scour Program also addresses bridges with foundation elements that are or have the potential to be unstable for the observed or evaluated scour condition.

The Federal Highway Administration manages the Program through partnerships with state highway agencies, industry and academia.

The Program's primary goals are to improve safety and resilience of the nation's bridges.

Office of Bridges & Structures
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U.S. Department of Transportation
Federal Highway Administration

Hydraulic Considerations for Shallow Abutment Foundations

This Technical Brief provides programmatic and technical considerations for evaluating and mitigating abutment scour at bridges with shallow foundations. The information supersedes certain materials on shallow foundations in two FHWA Hydraulic Engineering Circulars (HECs) "Evaluating Scour at Bridges" (HEC-18) and "Bridge Scour and Stream Instability Countermeasures" (HEC-23), and provides an improved pressure scour method for the document "Design and Construction Guideline for Geosynthetic Reinforced Soil Abutment and Integrated Bridge Systems."

1. INTRODUCTION

This Technical Brief (TechBrief) describes how scour may impact shallow abutment foundations at bridged waterways and provides design recommendations to protect at-risk shallow abutment foundations from scour (scour countermeasures). This TechBrief does not apply to piers or other elements affected by scour.

A shallow foundation (Figure 1) is a type of structure foundation that transfers structure loads to the earth very near the surface, rather than to a subsurface layer or to a range of depths as does a deep foundation. For new bridges, analyses during the foundation selection process will determine whether shallow foundations are suitable for the hydraulic and geotechnical conditions at the site. For existing bridges, information in this TechBrief may assist bridge owners in evaluating the robustness and resiliency of their current scour countermeasure planning, design, and implementation approaches.

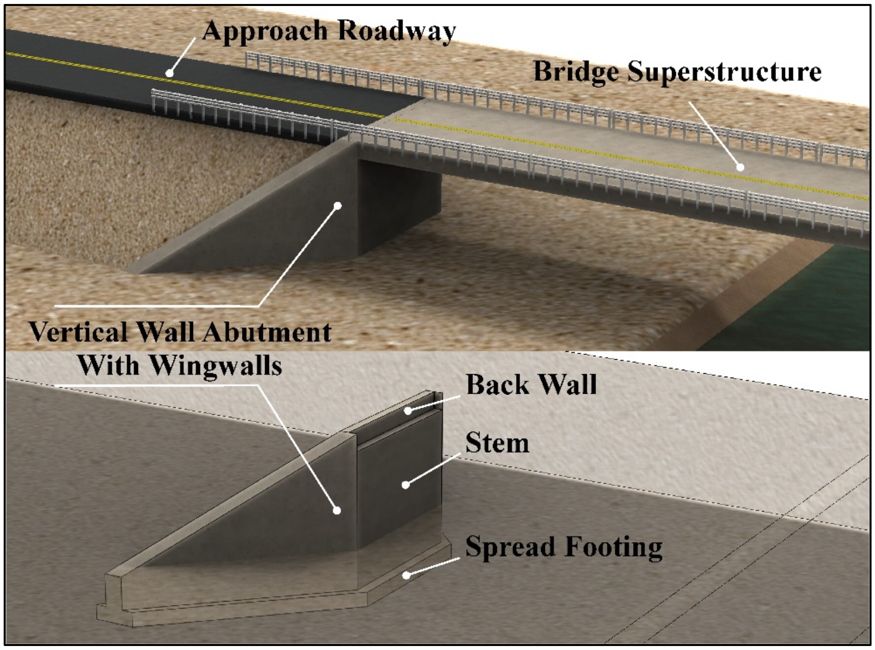

Figure 1: Typical Shallow Foundation Abutment.

1.1 REGULATORY BASIS

This TechBrief will help bridge owners and designers with compliance of the Federal Highway Administration's (FHWA's) regulations found within the Code of Federal Regulations (CFR), Title 23, Highways (23 CFR). FHWA requires compliance with 23 CFR and other regulations for a project to be eligible for Federal-aid or other FHWA participation or assistance [23 CFR 1.36].

The following Federal regulations apply to all bridges over waterways (paraphrased for brevity):

23 CFR part 625 – Design Standards

a. National Highway System (NHS) projects require following hydrologic, hydraulic, and scour related sections of the AASHTO LRFD Bridge Design Specifications [23 CFR 625.3(a)(1) and 23 CFR 625.4(b)(5)].
b. Non-NHS projects require following State DOT drainage and/or bridge standard(s) and specifications [23 CFR 625.3(a)(2)].

23 CFR 650 subpart A – Location and Hydraulic Design of Encroachments on Flood Plains

a. Hydraulic Design Standards [23 CFR 650.115] applies to all Federal-aid projects, whether on the NHS or Non-NHS. Neither Federal, State, local, nor AASHTO standards may change nor override these 23 CFR 650.115 design standards.
b. Content of Design Studies [§650.117]. Requires studies to contain the hydrologic and hydraulic data and design computations [23 CFR 650.117(b)]. As both hydrologic and hydraulic factors and characteristics lead to scour formation, such data and computations apply to scour as well. Project plans must show the water surface elevations of the base flood (i.e., 100-year flood) and overtopping flood [23 CFR 650.117(c)].

23 CFR 650 Subpart C – National Bridge Inspection Standards

a. Defines *Scour* and *Scour Critical Bridges* [23 CFR 650.305].
b. Requires bridge owners to identify bridges … that are scour critical [23 CFR 650.313(e)].
c. For those scour critical bridges, requires preparing a plan of action to … address critical findings [23 CFR 650.313(e)(3)].

1.2 TECHNICAL BASIS

FHWA primarily based this TechBrief on the following research on shallow foundations and abutment scour:

1. FHWA-HRT-17-013, "Shallow Foundations for the Support of Vertical-Wall Bridge Abutments: Interaction between Riprap and Contraction Scour" (FHWA, 2017a).
2. NCHRP 24-20, Draft Final Report, "Estimation of Scour Depth at Bridge Abutments" (NCRHP, 2010).

Additionally, the FHWA conducted and incorporated various research and development efforts that directly led to this TechBrief.

1.3 SUPERSEDED AND UPDATED MATERIALS

The TechBrief information related to shallow abutment foundations supersedes related information in:

1. Hydraulic Engineering Circular (HEC) No. 18, "Evaluating Scour at Bridges," 5th edition, (HEC-18) (FHWA, 2012a). Specifically:

   a. TechBrief section 3.1 "Scour Analyses" replaces HEC-18, Chapter 2, Section 2.2, Page 2.5, Step 7, #2 "Spread Footing on Soil – Abutment."

2. HEC No. 23 "Bridge Scour and Stream Instability Countermeasures," 3rd edition, (HEC-23) (FHWA, 2009). Specifically, for HEC-23, Volume 2, page DG 14.8, Step 4a:
   a. TechBrief Figures 6 through 10 replace HEC-23 Figure 14.7 (page DG 14.11).
   b. TechBrief eliminates the "25 foot" criteria because of the relationship of the applicable scour depth and the countermeasure fill slope.
   c. TechBrief allows the apron extension to be greater than 25 feet.
   d. TechBrief recommends that the upstream and downstream embankment coverage should extend a maximum of either $2(y_0)$ or 25 feet.

This TechBrief provides updated and improved information for:

1. FHWA "Design and Construction Guideline for Geosynthetic Reinforced Soil Abutment and Integrated Bridge Systems" (FHWA, 2017b). Specifically,
   a. TechBrief pressure scour approaches may replace pressure scour approaches in Appendix "D" (i.e., pages 190 to 191).

This TechBrief does not change nor supersede any other information of those three documents.

2. HYDRAULIC CONSIDERATIONS AND PROCESSES

This section of the TechBrief provides more detailed explanations of the new approaches and improvements, including considerations and processes, associated with shallow foundation abutments. Unless specifically cited with a regulation, these represent technical considerations and processes.

2.1 GENERAL HYDRAULIC CONSIDERATIONS

Characteristics of a bridge in a riverine or coastal environment can be very complicated because of:

1. The complex interactions between the structural components,
2. The soils in which they are founded, and
3. The moving water that imparts hydraulic loading to both structures and soils.

As recommended in HEC-18, the bridge scoping, design, and construction processes should fully engage an interdisciplinary team of structural, geotechnical, and hydraulic engineers interdisciplinary team.

As one of many potential foundation types and approaches, shallow foundations have been successfully used for many bridge abutments in riverine or coastal environments. However, when bridge owners consider using shallow foundations, it is vitally important that they fully understand the hydraulic requirements surrounding this foundation type.

This TechBrief identifies the major hydraulic components that, when properly considered, will provide greater assurance that the shallow abutment foundation will perform as intended.

2.2 SPECIFIC HYDRAULIC CONSIDERATIONS

When deciding whether a shallow or deep abutment foundation is appropriate for a waterway bridge, the bridge owner should evaluate the following specific hydraulic considerations:

1. Site Selection: The optimum stream-crossing site is one with a stable channel, which is characterized by banks and a bed that are not prone to extensive aggradation, degradation, or lateral migration over the design life of the bridge. FHWA publication HEC-20, ”Stream Stability at Highway Structures” (HEC-20) (FHWA, 2012b), contains detailed information on assessing channel stability. Shallow foundations are not recommended for unstable streams.
2. Abutment Location: Bridge abutments are typically set back from channel banks to minimize potential stability problems, scour, and impact loads[1]. If a shallow abutment foundation type is used for waterway crossings, FHWA recommends setting the abutment back from the channel bank some minimum distance (described later in this TechBrief). The interdisciplinary team should establish the hydraulic conditions at the bridge crossing using hydraulic modeling tools (i.e., software tools such as the U.S. Army Corps of Engineers' “Hydrologic Engineering Center River Analysis System” (HEC-RAS) or the Bureau of Reclamation's “Sedimentation and River Hydraulics–Two-Dimensional” (SRH-2D). If an abutment cannot be set back from the channel stream bank, the owner should consider using a deep foundation.
3. Complex Flow Conditions: This TechBrief uses the term “complex flow” to describe flow that cannot be accurately modeled by assuming it moves downstream and perpendicular to channel cross sections. Turbulence and forces resulting from complex flow conditions may increase the potential scour and stream instability at a bridge site. Complex flow conditions result from bridges that: 1) are skewed to the flow, 2) severely constrict the flow, 3) encroach on flows in steep channels, 4) have multiple embankment openings, 5) have multiple channels upstream of the bridge or 6) produce overtopping of the bridge or an approach roadway (see Hydraulic Design Series (HDS) No. 7, ”Hydraulic Design of Safe Bridges” (HDS-7) (FHWA, 2012c)). FHWA recommends evaluating crossings with one or more of these adverse conditions with two-dimensional modeling to identify flow depths and velocities at the necessary locations.
4. Risk-Based Design Approaches: In accordance with statutory provisions of the 2012 “Moving Ahead for Progress in the 21st Century” Act (MAP-21), FHWA adopted risk-based design approaches so bridge owners can better balance the flood frequency they use for bridge design with the risks associated with the crossing (e.g. cost of the bridge, importance of bridge, and traffic characteristics). Risk-based approaches factor in the importance of the structure and are defined by the need to provide safe and reliable waterway crossings and consider the economic consequences of failure (see HEC-18). Table 2.1 in HEC-18 provides one method for associating risk-based minimum scour design flood frequencies and scour design check flood frequencies based on hydraulic design flood frequencies.
5. Local Drainage: To a lesser degree, local drainage may have an impact on foundation selection. The potential for unbalanced water pressure exists when a structure becomes partially submerged by a flood, as in a “flashy” system with rapid subsidence of flood flows (as might occur in urbanized or steep-gradient watersheds), or when surface drainage is not controlled. These conditions may better lend themselves to deep foundation abutments. All abutment structures should include considerations for surface and subsurface drainage. Critical areas are: the interface between an abutment wall and

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[1] While HEC-20 and HEC-18 describe stream stability and scour (respectively), streams can experience impact loads when transporting ice, large cobbles, boulders, or large woody debris such as tree trunks. See HEC-9 “Debris Control Structures - Evaluation and Countermeasures,” 3rd edition, 2005, for more information.

the retained fill, the base of the abutment wall, and any location where a fill slope meets the abutment wall face. For example, the design needs to include provisions for surface drainage along the fill slope adjacent to abutment wing walls.

The risks associated with the above conditions should lead an interdisciplinary team to consider alternative abutment types or drainage structure types (e.g. deep foundation, reinforced concrete box culverts, or pipe culverts). This deliberation is consistent with 23 CFR 650 subpart A, which requires analyses of design alternatives with *"… consideration given to capital costs and risks; economic, engineer, social and environmental concerns; and including risk assessments or risk analyses."* [23 CFR 650.115(a)]

2.3 RECOMMENDED PROCESS

Figure 2 illustrates the recommended bridge hydraulic and scour design process applicable to shallow abutment foundations and reflects the necessary multi-disciplinary approach. The following subsections describe the required steps and considerations in this process:

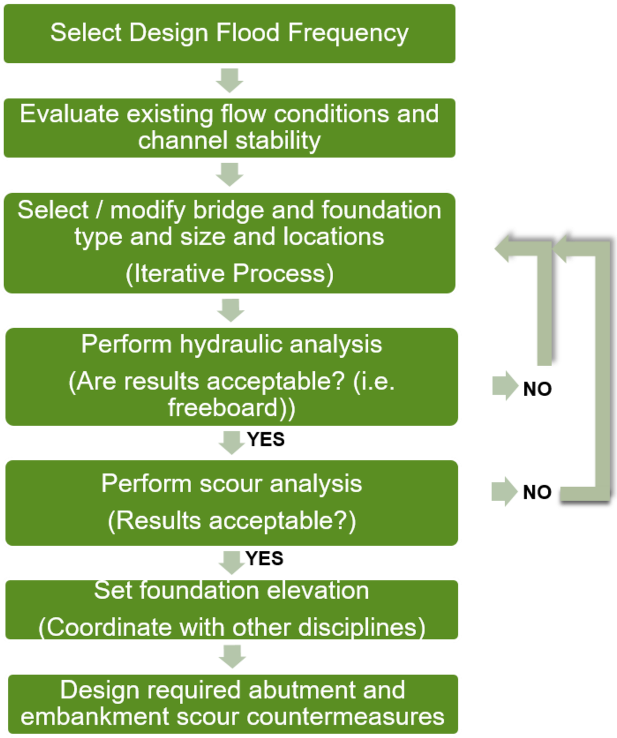

Figure 2. Steps for Bridge Hydraulic and Scour Design Process.

A) Select Design Flood Frequency

FHWA recommends that the interdisciplinary team use a minimum of three (3) flood frequencies to design/evaluate bridges and bridge foundations. These are the hydraulic design flood frequency, the scour design flood frequency, and the scour check flood frequency. The interdisciplinary team uses the hydraulic design flood frequency to identify the necessary size (i.e., length and elevation) and orientation of the bridge opening to ensure the structure is traversable with an acceptable depth of freeboard. The interdisciplinary team uses the scour design and check flood frequencies to predict scour depths, determine acceptable foundation depths, and design scour countermeasures. Hydraulic standards established by the State DOT typically define the appropriate frequencies for these floods. As noted in Section 1.2 of this document, the owners' standards must be consistent with 23 CFR part 625 and 23 CFR 650 subpart A. Refer to Chapter 2 of HEC-18 for detailed discussions of a risk-based approach and the recommended relationship between the hydraulic design flood and the scour flood frequencies.

B) Evaluate Existing Flow Conditions and Channel Stability

23 CFR 650.117(b) requires hydraulic studies to contain the hydrologic and hydraulic data and design computations. To facilitate this, the interdisciplinary team should evaluate existing and potential future flow conditions and patterns to establish a hydraulic baseline for the new or replacement bridge design. Also, as stated in the Site Selection consideration above, stream channels should be stable, both horizontally and vertically, near the bridge, for the life of the bridge. HEC-20 contains details on the evaluation of channel stability. HEC-23 provides details on stream instability countermeasure design.

C) Select/Modify Bridge Type and Size

As indicated in Figure 2, this step is the beginning of an iterative process that evaluates the hydraulics and potential scour resulting from the proposed alignment and grade of the approach roadways, as well as the size and orientation of the bridge. As part of the next step in this process, the proposed layouts of the superstructure and substructure elements will be hydraulically modeled for a range of discharges that includes the hydraulic design flood and the scour design floods to accurately estimate the hydraulic parameters (e.g. depths and velocities) impacting the bridge, the approach roadways, and the floodplain.

D) Perform Hydraulic Analysis

Any hydraulic model used must be capable of developing water-surface profiles upstream, downstream, and through the bridge to identify reasonable estimates of the key hydraulic parameters including flow distributions, water surface elevations, and velocities. At a minimum, this requires a one-dimensional water-surface profile model, such as HEC-RAS. If complex flow conditions exist, or are created by the proposed bridge type and size, the analysis should use a two-dimensional model, such as the SRH-2D model. Also, if channel geometry can change over time, the hydraulic designer should perform multiple hydraulic models to identify worst-case hydraulics and scour conditions. The designer should also evaluate possible alignments, grades, and bridge geometries with the hydraulic model(s) to find an acceptable crossing configuration for the design floods. Refer to HDS-7 for detailed guidance on one- and two-dimensional hydraulic modeling.

E) Perform Scour Analysis

This TechBrief adopts and applies the NCHRP 24-20 approach of computing abutment scour (NCHRP, 2010). The NCHRP 24-20 approach uses a contraction scour amplification factor based on the abutment type and the abutment location relative to the main channel, see HEC-18, Chapter 8. All references to abutment scour computations in this TechBrief apply this approach.

For shallow foundations, this TechBrief uses hydraulics for floods up to and including the appropriate scour check flood (1) to identify the worst-case scour depths for the applicable scour components and (2) for generating the worst-case total scour at the foundation. If a computed scour depth is not acceptable (i.e., too deep for the abutment to be economically built and/or prevented with an abutment scour countermeasure), the interdisciplinary team returns to Step "C" in this process and adjusts the bridge type, size, or even location, until the change results in an acceptable scour value. Such adjustments should be made only after in-depth consultations with the project geotechnical and structural engineers. Section 3 of this TechBrief provides more detailed guidance on conducting scour evaluations and analyses.

F) Set Foundation Elevation

As indicated in Figure 2, each project includes focused, ongoing coordination with the project hydraulic, geotechnical and structural engineers (i.e., interdisciplinary team) to establish and set the final abutment foundation elevation. For a shallow abutment foundation near a channel bank in erodible soil, there are two options for establishing the bottom elevation:

1. Set the top of the spread footing below the worst-case total scour depth at the abutment for the scour check flood (includes any long-term degradation). This option precludes the need for an abutment scour countermeasure to protect the foundation.
2. Set the top of the spread footing above the worst-case total scour elevation for the scour check flood (includes any long-term degradation). Provide a properly designed and constructed abutment scour countermeasure to protect the foundation.

An alternative to the above would be to key the shallow abutment foundation into competent rock (i.e. non-scourable rock) as determined by a geotechnical analysis. TechBrief Section 4.2 provides more detailed guidance on setting abutment foundation elevations as part of design.

G) Design Abutment Scour Countermeasures

When it is not practical to set the abutment foundation below the total scour depth, the project requires a designed abutment scour countermeasure to protect the shallow foundation and ensure bridge stability during the scour check flood. Section 4.3 of this TechBrief provides more information on the design of scour countermeasures for shallow abutments.

3. SCOUR COMPONENTS, EVALUATIONS AND ANALYSES

This TechBrief section provides explanations on the scour related components, evaluations, and analyses associated with the new approaches and improvements. Unless specifically cited with a regulation, these represent technical recommendations and not regulatory requirements.

3.1 TOTAL SCOUR COMPONENTS

Shallow abutment foundation design must compute and evaluate the following primary scour components:

1. Long-term degradation (LTD),
2. Contraction scour (CS), vertical contraction scour (VCS), if applicable, and
3. Abutment scour (AS).

Both the contraction scour and abutment scour components are sensitive to: a) the sediment transport regime that exists upstream of the bridge (i.e., live-bed or clear-water condition), and b) whether the scour floods are under free-surface flow or pressure flow conditions (i.e., superstructure is in the flow) at the bridge. Because of the dramatic increase in potential scour depth during bridge superstructure submergence, the interdisciplinary team should avoid using shallow foundations under pressure flow conditions, if possible. In addition, the abutment scour component is sensitive to the location of the abutment relative to the main channel. Abutment scour is computed differently for an abutment located in or close to the main channel, compared to the case where the abutment is located on the floodplain and is set back away from the main channel. Figures 3 and 4 depict abutment scour conditions for two abutment locations as related to the main channel.

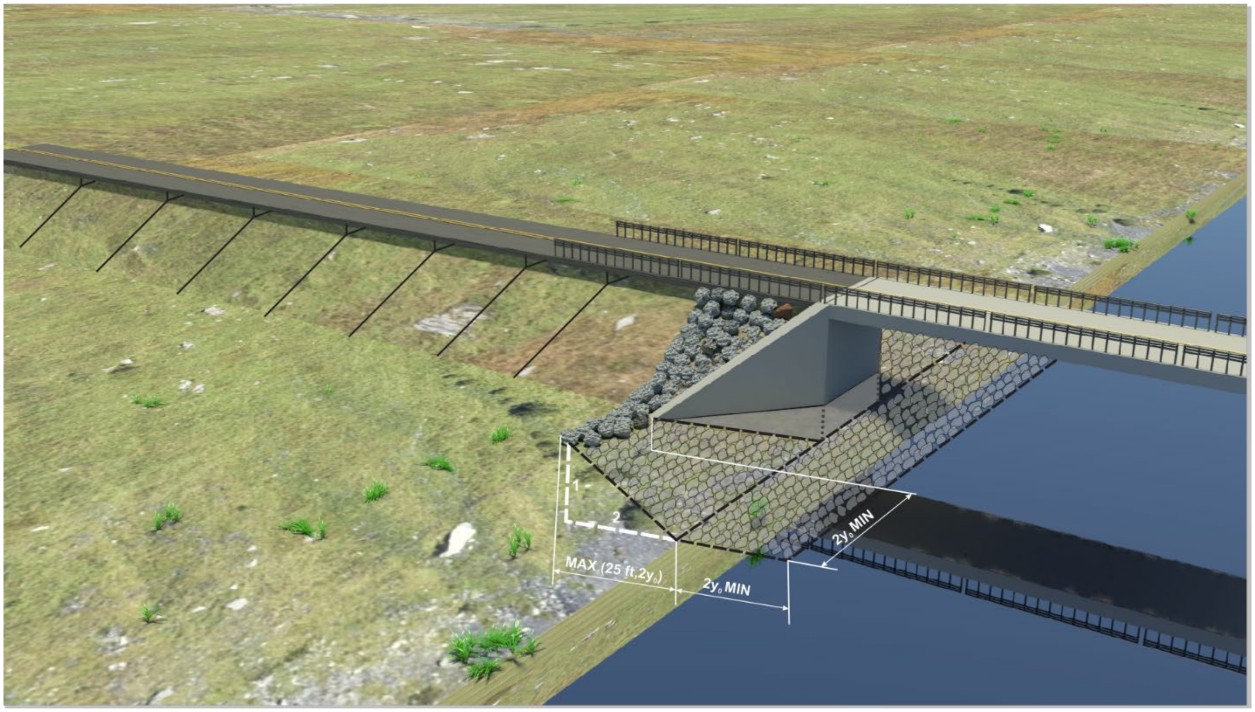

Figure 3: Scour Condition A.

Figure 4: Scour Condition B.

In Figure 3, the abutment location is at or near the main channel; designated as “Scour Condition A.” Figure 4 applies when the abutment is set back from the main channel; designated “Scour Condition B.” See HEC-18, Chapter 8, and the NCHRP 24-20 Draft Final Report for more detailed information.

The descriptions below summarize (by flow condition) the manner in which the interdisciplinary team evaluates these individual scour components for floods up to and including the appropriate scour check flood. HEC-18 provides detailed guidance on how to compute scour components.

Free-Surface Flow

1. Long-Term Degradation is equal to the greater of the two following evaluations:
   a. Computed depth from equilibrium slope or armoring analyses, based on HEC-20 guidance
   b. A specified depth for other degradation or control phenomenon, such as head cut depth, depth to a natural grade control elevation (for instance, a stable bedrock formation), or historical observation
2. Contraction Scour
   a. For Clear Water conditions use the clear-water contraction scour estimate
   b. For Live Bed conditions use the lesser of:
      i. live-bed contraction scour estimate
      ii. clear-water contraction scour estimate
3. Abutment Scour
   a. Use the Amplification Factor, based on abutment type and location, multiplied by the appropriate contraction scour estimate (either clear-water or live-bed).

Pressure Flow

1. Pressure Flow Scour is the greater of:
   a. Long-term Degradation plus Contraction Scour (same as for Free-Surface Flow computed by removing the bridge superstructure and using the resultant free-surface hydraulics)
   b. Vertical Contraction Scour (VCS)

Identification of the conditions and interaction of the above scour components can be complicated and neccesitates analysis by a qualified hydraulic engineer. Refer to HEC-18 for detailed definitions of the individual scour components and conditions that apply to abutment foundation analysis and design, and for the various methods available to compute the scour magnitude for each component.

The total scour depth used to establish the elevation of the shallow foundation or the riprap apron elevation is:

1. The worst-case combination of applicable scour components (defined above)
2. Estimated for floods up to and including the appropriate scour check flood
3. Dependent upon the flow conditions
   a. Free-surface
   b. Pressure flow
   c. Clear-water
   d. Live-bed

3.2 SCOUR ANALYSES

Laboratory studies of both “wide-opening” and “narrow-opening” bridge simulations have shown that for various flow conditions, when placed below the appropriate scour depths, several schemes of countermeasures can be effective in protecting shallow abutment foundations (FHWA, 2017a). They include:

1. No scour countermeasure required – Figure 5
2. Countermeasures for wide bridge openings – Figures 6, 7 and 8 depict buried partial-width aprons. All three figures depict the use of aprons when the length of the bridge meets the “wide-opening” criteria (i.e., $W_2/y_0 > 6.2$); where W_2 = bottom width of contracted section (bridge opening width) and y_0 is the flow depth in the bridge opening.
3. Countermeasures for narrow bridge openings – Figure 9 depicts the use of a rip-rap countermeasure for a “narrow-opening” (i.e., $W_2/y_0 \leq 6.2$).
4. Countermeasures for pressure flow – Figure 10 depicts the use of full-width rip-rap countermeasures for locations with Pressure Flow.

The summary below, along with Figures 5 through 10, describe (for each flow condition and scour countermeasure application) the manner in which to combine the individual scour components.

Free-Surface Flow

1. Option 1 (no countermeasure): Minimum depth to top of footing = Total scour at abutment = LTD + AS for the scour check flood for Scour Condition A only (Figure 5)
2. Option 2a (wide-opening countermeasure (i.e., $W_2/y_0 > 6.2$); abutment near channel bank – Scour Condition A): Top of footing below countermeasure; Minimum depth to top of abutment countermeasure apron = LTD + CS for scour check flood (Figure 6). Figure 7 shows a case were the sloping portion of the countermeasure extends into the main channel.
3. Option 2b (wide-opening countermeasure (i.e., $W_2/y_0 > 6.2$); abutment setback from channel bank such that it will never be impacted by channel migration- Scour Condition B): Top of footing below countermeasure; Minimum depth to top of abutment countermeasure apron = CS for scour check flood (Figure 8)
4. Narrow-opening countermeasure (i.e., $W_2/y_0 \leq 6.2$): Top of footing below countermeasure: Full-width countermeasure protection required from abutment to abutment; Minimum depth to top of full-width countermeasure = LTD + CS depth for scour check flood (Figure 9)

Pressure Flow

1. Pressure Flow Countermeasure: Top of footing below countermeasure; Full-width countermeasure protection required from abutment to abutment; Minimum depth to top of full-width countermeasure equals the greater of LTD + CS or the VCS depth for scour check flood (Figure 10).

It is important for the interdisciplinary team to tie scour depths to an appropriate reference elevation. For abutments located near the main channel, the interdisciplinary team should use the channel thalweg elevation as the reference elevation. For abutments set back from the main channel with no potential for lateral channel migration, the interdisciplinary team should use the overbank elevation as the reference elevation.

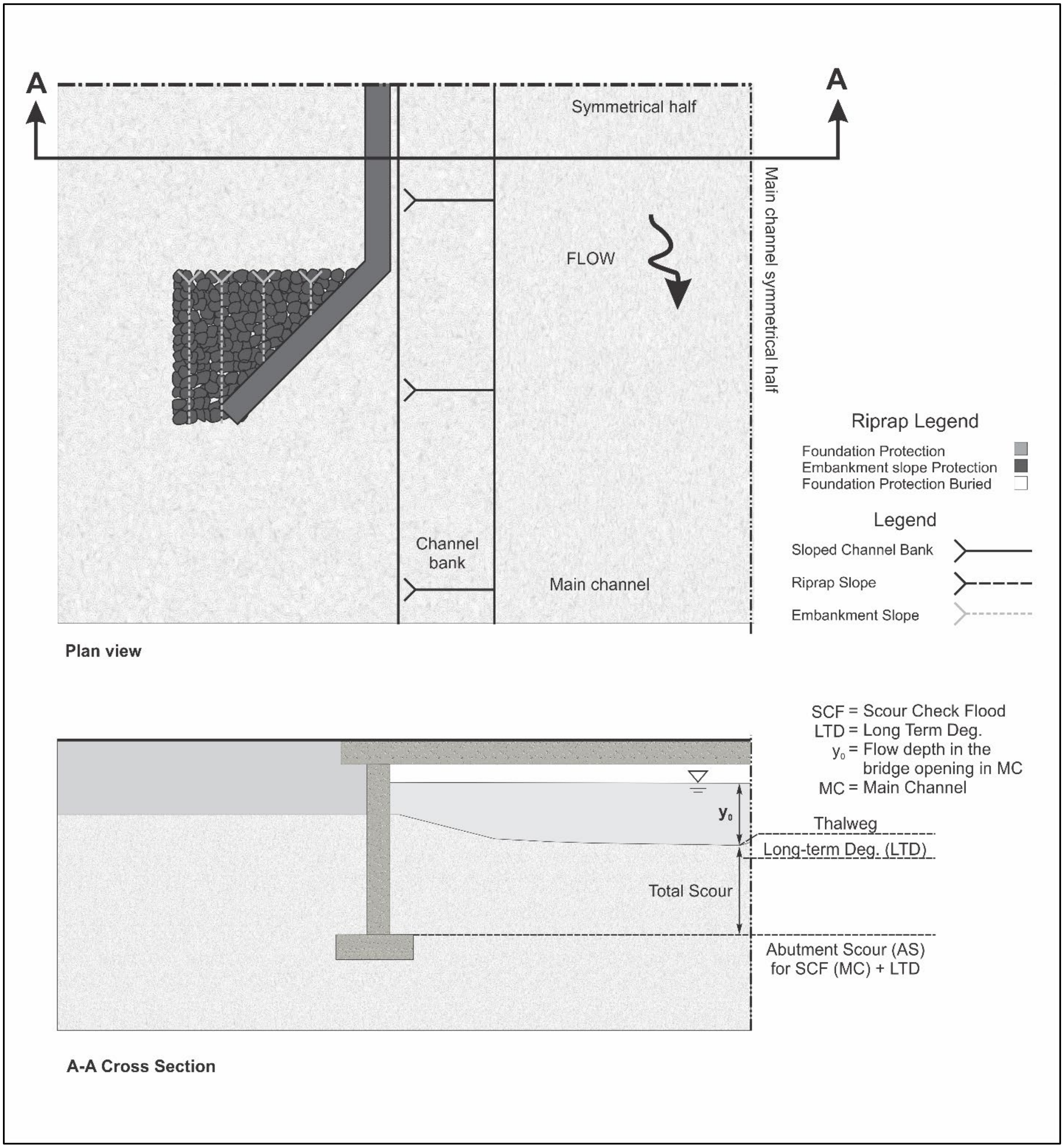

Figure 5: Free-Surface Flow, No Scour Countermeasure Required (Top of footing placed at or below the Total Scour Elevation for the Check Flood) – Scour Condition (A) (Option 1).

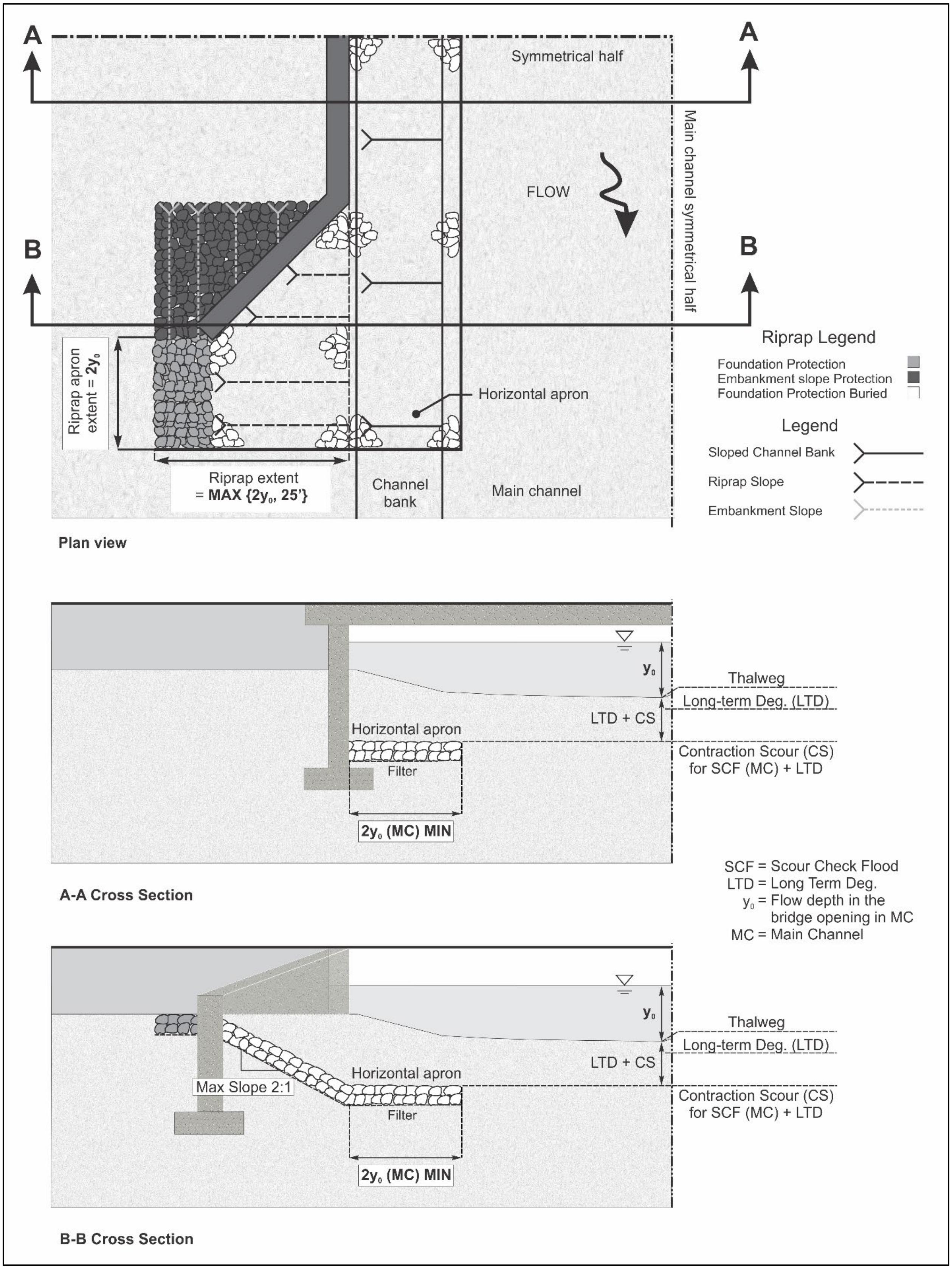

Figure 6: Free-Surface Flow, Wide-Opening Scour Countermeasure, Abutment near Channel Bank – Scour Condition (A) (Option 2a).

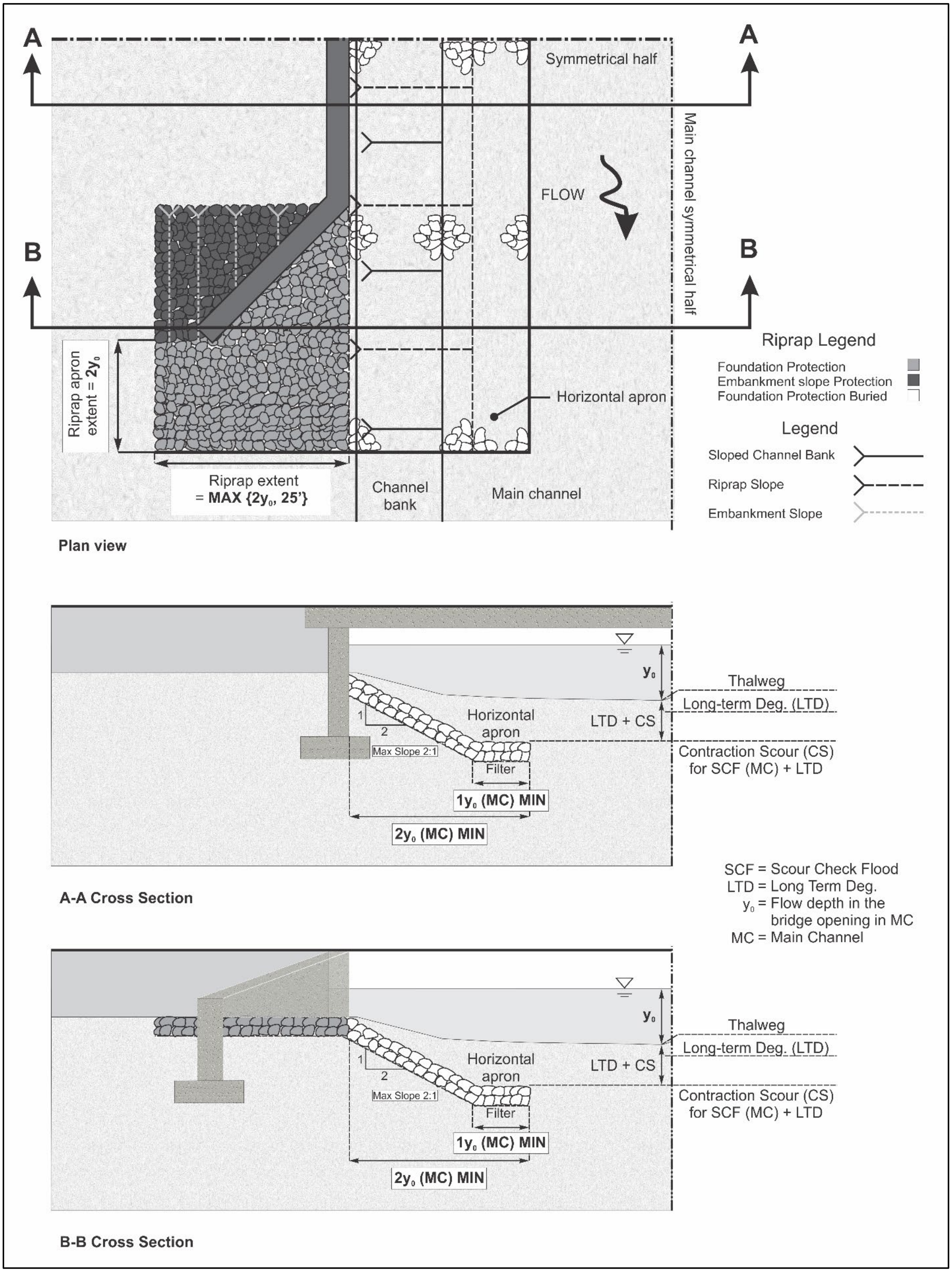

Figure 7. Free-Surface Flow, Wide-Opening Scour Countermeasure, Abutment near Channel Bank – Scour Condition (A) and sloping riprap extends into main channel (Option 2a).

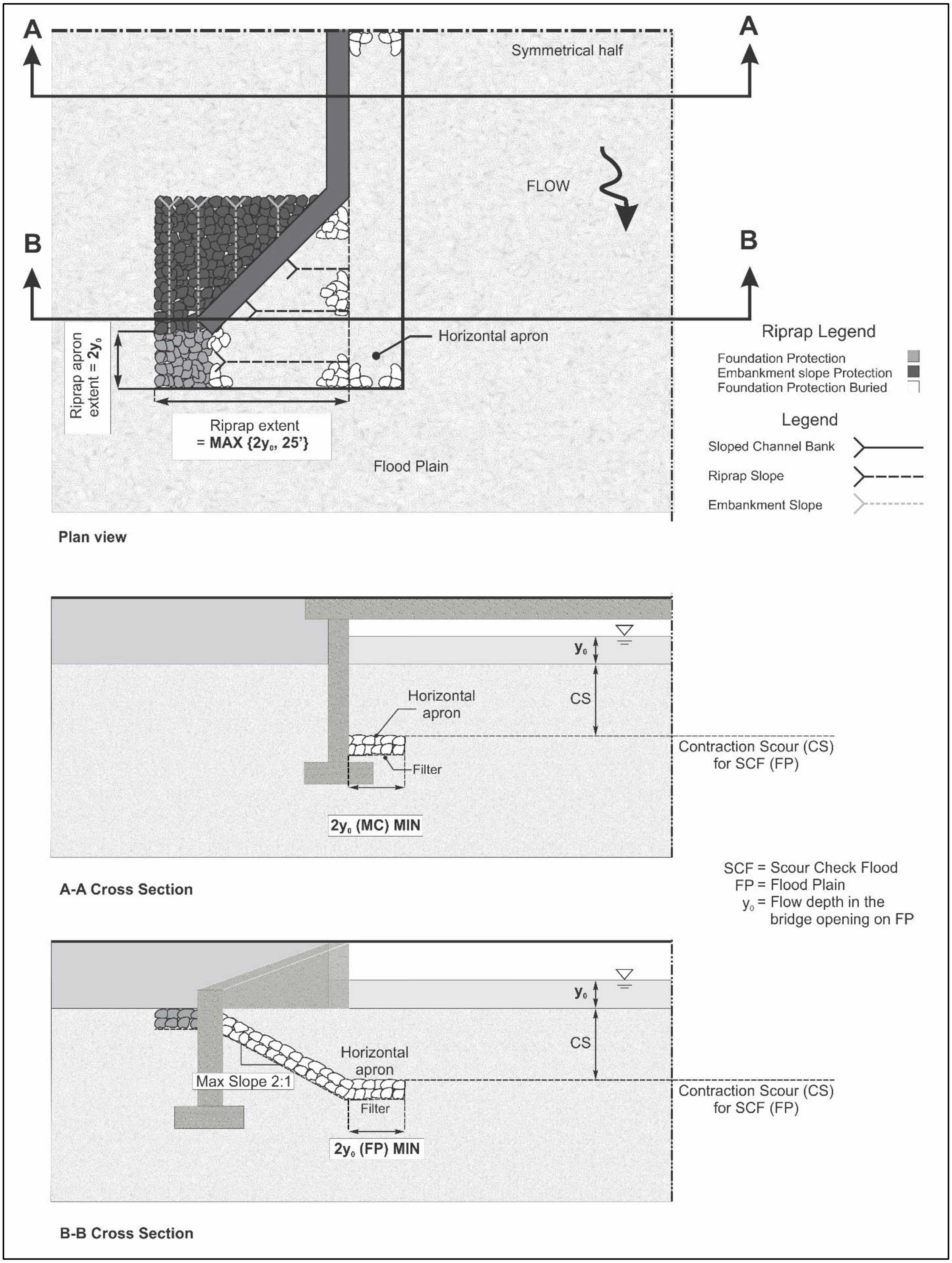

Figure 8: Free-Surface Flow, Wide-Opening Scour Countermeasure, Abutment Set Back from Channel Bank – Scour Condition (B) (Option 2b).

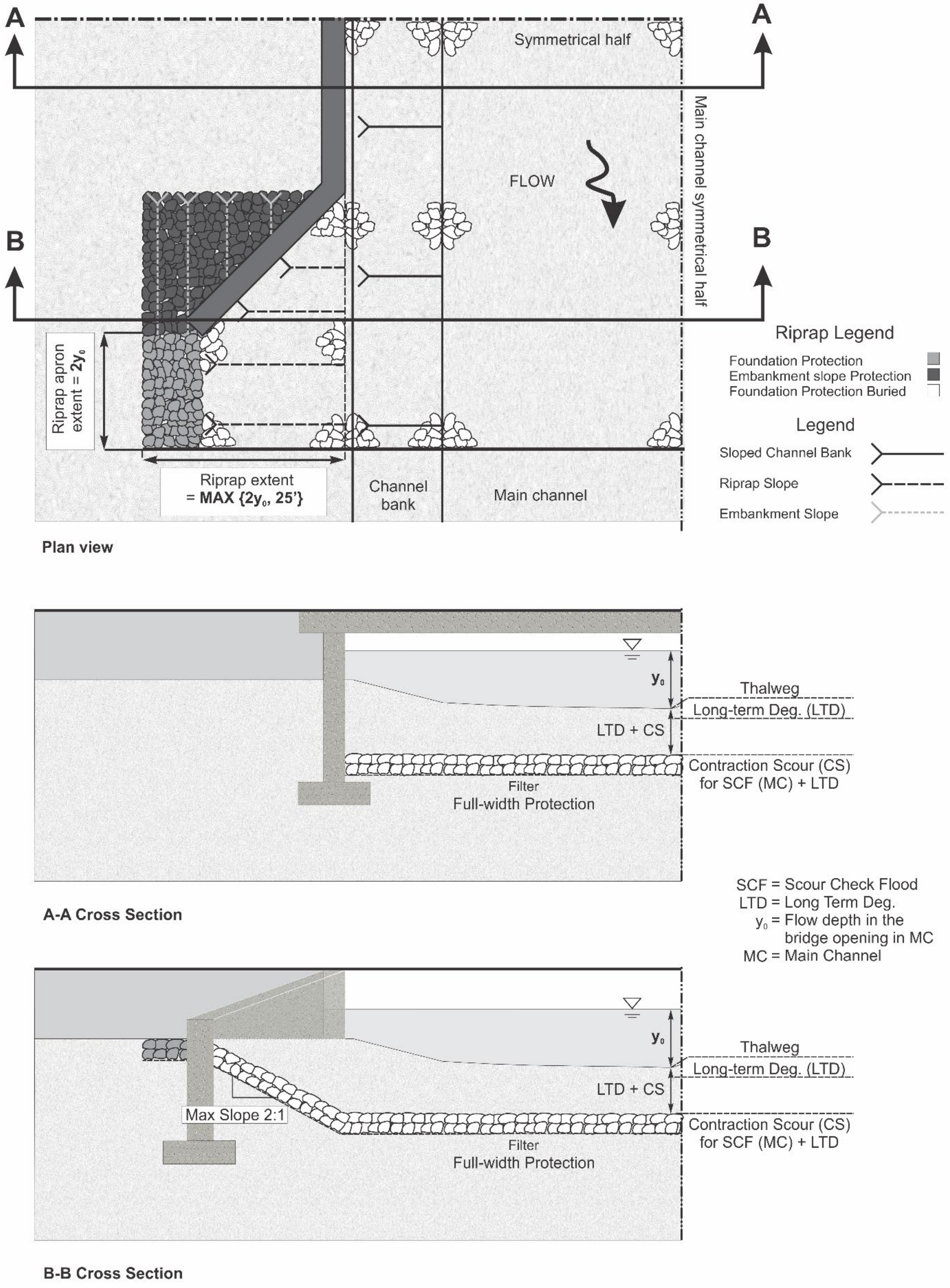

Figure 9: Free-Surface Flow, Narrow-Opening Scour Countermeasure.

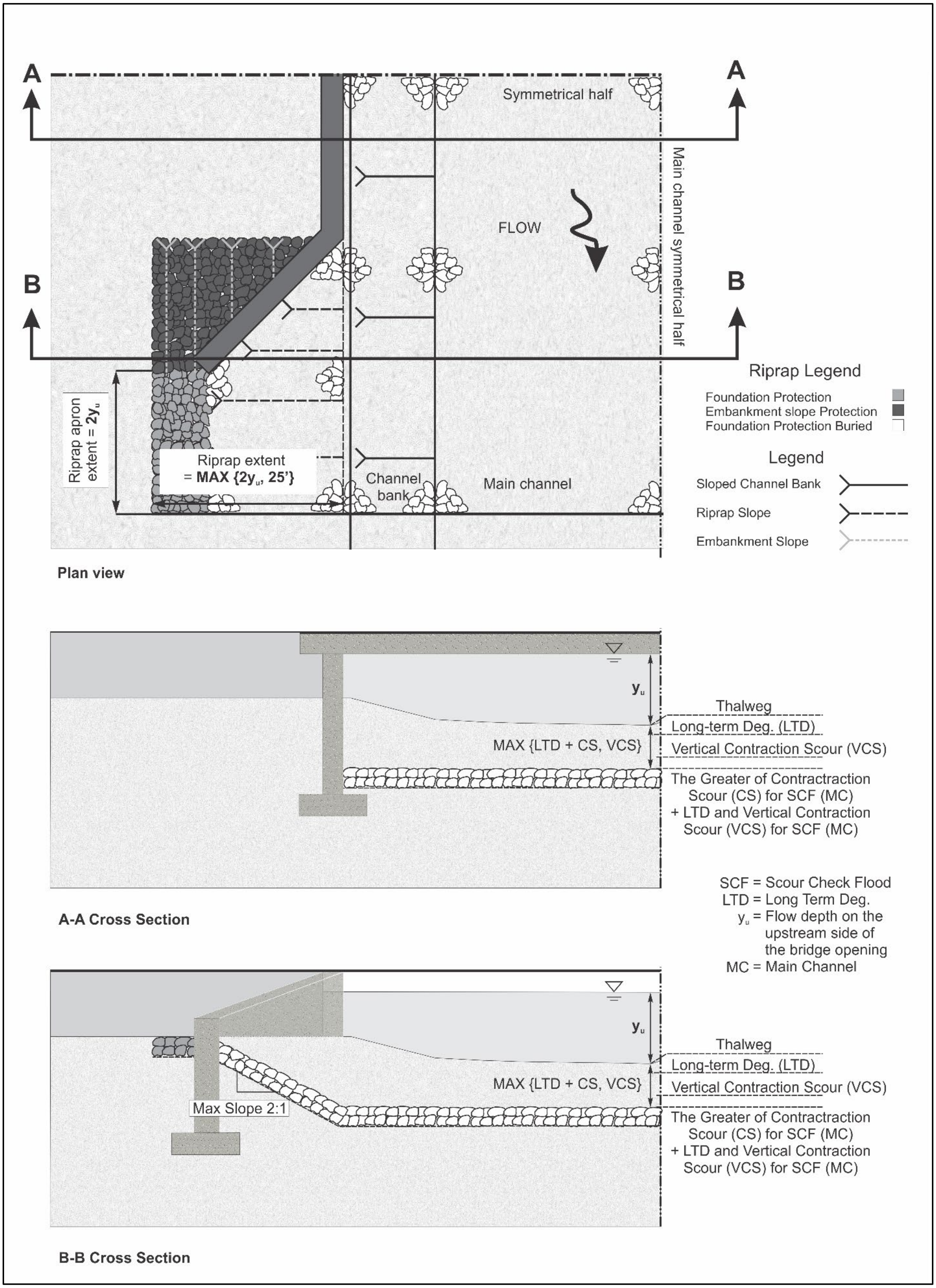

Figure 10: Pressure Flow Scour Countermeasure.

4. SCOUR COUNTERMEASURES

FHWA considers a shallow foundation abutment to be scour critical when it has been determined to be unstable for the observed or evaluated scour condition (23 CFR 650.305). To comply with regulation, addressing such situations necessitates including scour countermeasures into the design (new bridges) or (for existing bridges) developing a plan of action that involves scour countermeasures (23 CFR 650.313(e)(3)). There are three types of scour countermeasures; physical (e.g., riprap), hydraulic (e.g., guide banks for channel stability), and monitoring (in which a bridge remains scour critical). Of these three, FHWA recommends use of physical countermeasures as sufficiently addressing the particular hydraulic and scour conditions found at shallow foundation abutments.

This TechBrief section focuses on such physical countermeasures, including environmental and resource agency considerations, designing the foundation apron elevations for riprap, countermeasure design considerations, and specifications for riprap scour countermeasure design. Unless specifically cited with a regulation, these represent technical recommendations and not regulatory requirements.

4.1. ENVIRONMENTAL AND RESOURCE AGENCY CONSIDERATIONS

Bridge countermeasures such as a buried fill-slope with a buried partial-width riprap apron in the channel or buried full-width riprap across the channel necessitate installation of the countermeasures “in the dry.” This type of installation facilitates construction and reduces the downstream impacts from turbidity and sedimentation. Accomplishing this may entail use of piping or pumping the stream flow around the work area and/or the use of cofferdams.

Resource and permitting agencies typically require minimizing the construction impact to the riverine environment, so the construction of in-stream scour countermeasures may be a cause of concern or resistance for environmental or permitting agencies. If resource agencies have concerns with potential environmental impacts from scour countermeasures used to mitigate scour for near-bank abutments, the owner may need to mitigate the impacts of the bridge countermeasures.

Two possible alternatives are:

1. Extend the bridge length and move the abutments back from the channel banks
2. Change the bridge foundations from a shallow foundation to a deep foundation to alleviate the need for scour countermeasures

As per 23 CFR 650.115, such alternatives may necessitate a risk analysis or assessment to determine the final design for the project.

4.2 DESIGN OF FOUNDATION/RIPRAP APRON ELEVATION

Laboratory studies indicate that partial-width riprap aprons that are flush with the original streambed, may introduce turbulence at the apron/bed interface and redistribute conveyance to the unprotected center (FHWA, 2017a). These two effects result in scour mainfestation in excess of predicted contraction scour. Because the apron is installed within the contracted section of an opening, partial-width flush aprons will likely experience some edge failure even when W_2/y_0 is large. Therefore, FHWA does not recommend partial-width flush aprons. Potential mitigation strategies include buried partial-width and full channel width buried aprons.

For aprons buried to the estimated elevation of contraction scour, guidance is as follows:

1. Partial-width buried riprap aprons can be effective for $W_2/y_0 > 6.2$ (wide openings). Concern about edge failure is significantly reduced because the apron is buried to a depth below the contraction zone.
2. Full-width buried riprap aprons are recommended for $W_2/y_0 \leq 6.2$ (narrow opening) and can be also considered for all openings.

4.3 SCOUR COUNTERMEASURE DESIGN

When a shallow abutment foundation requires the installation of a scour countermeasure, the countermeasure must include a minimum-length horizontal apron, designed to be stable for the scour check flood. The apron protects the abutment face and extends upstream and downstream of the abutment (up to the top of bank elevation along the wingwalls for near-channel conditions or up to the floodplain elevation at the toe of the embankment slope protection) to avoid local abutment scour.

For abutments located near the channel bank with free-surface flow, the extensions should be a distance equal to twice the main channel flow depth through the bridge ($2y_o$). For abutments located near the channel bank in pressure flow, the extensions should be a distance equal to twice the main channel flow depth at the upstream side of the bridge ($2y_u$). In addition, the same designed countermeasure should run up the channel bank and protect the abutment "embankment." To do this effectively, the countermeasure should be configured to cover the embankment to an appropriate height (includes freeboard) and for a distance of twice the average main channel or floodplain flow depth (as appropriate) or 25 feet, whichever is greater, behind the abutment and parallel to the roadway.

In addition to use in scour analyses, Figures 3 through 10 illustrate the appropriate scour and countermeasure design configurations for the flow conditions and applications described above. Note that, although the countermeasure configurations are all similar, there are dimensional differences that make each case unique. Also, note that the figures reflect the use of loose rock riprap as the countermeasure type. If properly designed and constructed, a variety of countermeasure types are acceptable, including but not limited to: wire-enclosed rock, grout-filled mattresses, soil cement, and reinforced concrete. However, no project should use rubble (i.e., recycled/broken concrete) as riprap for both structural and environmental reasons and considerations. When using loose rock riprap or wire-enclosed rock as the designed countermeasure, an appropriate filter must be placed under the rock to prevent the underlying soil loss through the riprap openings.

HEC-18 provides some discussion of risk-based standards for countermeasure design at abutments. HEC-23 contains the recommended design equations for sizing rock riprap for abutment scour countermeasures in Design Guideline 14, "Rock Riprap at Bridge Abutments."

Scour countermeasure design for abutment foundations in a river environment can be a very complicated endeavor because of the complex interaction between the hydraulics, the multiple scouring mechanisms that are typically present, and the structural components. For these reasons, it is again of utmost importance that a qualified Hydraulic Engineer, experienced in river mechanics, sediment transport, and bridge hydraulics, perform the analyses required for countermeasure design.

4.3 RIPRAP COUNTERMEASURE SPECIFICATIONS

As indicated in the preceding discussions, engineers must rely upon countermeasures to ensure embankment, and at times, foundation stability during the scour design and check flood. Because of its flexibility, availability, and relative cost, the countermeasure of choice is often rock riprap. Accordingly, engineers must be aware that there are many sources of uncertainty associated with the design, manufacture, installation, performance, and maintenance of a riprap mass. Among the causes of premature riprap failure related to design and construction are the following:

1. Inadequate rock quality, size, and/or gradation
2. Inadequate embedment and/or toe-down depths
3. Inadequate thickness
4. Segregation of rock sizes
5. No or improperly installed filter
6. Damaged filter material

A designed granular or geotextile filter must be installed under all riprap installations to prevent the loss of underlying soils through the riprap openings causing premature failure.

Without comprehensive construction acceptance testing, there is little assurance that the riprap mass will perform as intended. Consequently, when using a riprap countermeasure, FHWA strongly recommends the bridge owner/interdisciplinary team develop and enforce rock quality, acceptance criteria, and sampling/testing frequency requirements within the construction contract specifications. In addition, the size and gradation test methods to be used for accepting the riprap mass must be included in, or referenced by, the contract. Including such provisions in the contract will reduce the chances of premature riprap failure. As an example, the FHWA Office of Federal Lands Highways, "Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects" (FHWA, 2014), FP-14, Sections 251 and 705 provides an approach of sampling, testing, and acceptance requirements; and material requirements, respectively, for rock riprap.

After construction, assess the riprap countermeasure condition and channel stability (1) during each regular bridge inspection and as a best practice, (2) after large flood events. Any countermeasure failure or significant change in channel stability should be noted and scheduled for repair or stabilization. Without proper inspection and maintenance, a scour countermeasure may fail or a channel may become unstable, which can lead to bridge abutment failure.

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Hydraulic Considerations for Shallow Abutment Foundations

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