# 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 Abutments on Deep Foundations and Bridge Embankment Protection

*This Technical Brief provides programmatic and technical considerations for understanding the design considerations using scour countermeasures to mitigate abutment scour at bridges supported by deep foundations. There are also considerations for protection of bridge embankments related to the provisions of the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design Bridge Design Specifications, Eighth Edition (2017) (AASHTO LRFD-8) (incorporated by reference at 23 CFR § 625.4(d)(1)(v)).*

## 1 INTRODUCTION

The Federal Highway Administration (FHWA) incorporated, by reference, the AASHTO LRFD Bridge Design Specifications (BDS), 8th edition (2017) at 23 CFR § 625.4(d)(1)(v) (hereinafter AASHTO LRFD BDS (2017)) that govern various bridge engineering design elements:

- structural (e.g., bridge superstructures, decks, piers),
- geotechnical (e.g., foundations, abutments, retaining walls, embankments, and scour),
- hydraulic (e.g., hydrology, hydraulics, and scour), and
- other elements for these types of highway infrastructure.

This Technical Brief (TechBrief) describes how scour may impact abutments on deep foundations and the associated bridge embankments at bridged waterways and provides design recommendations to protect at-risk structures from scour (scour countermeasures). This TechBrief only applies to abutments on deep foundations and does not apply to piers or other elements affected by scour.

A deep foundation (Figure 1) is a foundation that derives its support by transferring loads through piles to soil or rock at some depth below the structure by end bearing, adhesion or friction, or both (AASHTO LRFD BDS (2017)). For new bridges, analyses during the foundation selection process will determine whether shallow or deep foundations are suitable for the structural, 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.

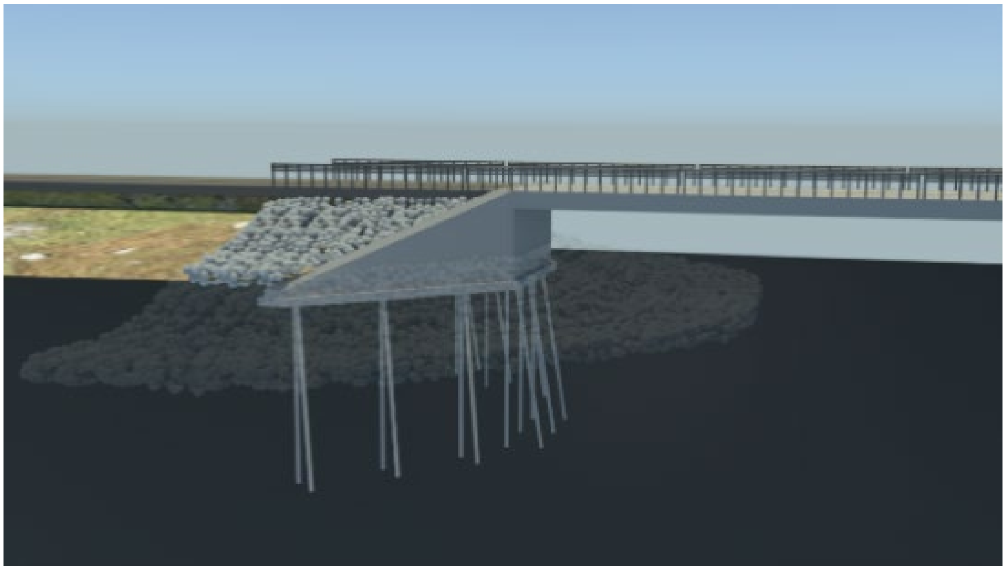

**Figure 1. Typical abutment on deep foundations.**

### 1.1 Regulatory basis

This TechBrief will help bridge owners and designers comply with the FHWA's regulations found in the Code of Federal Regulations (CFR), Title 23, Highways (23 CFR). Compliance with 23 CFR and other regulations for a project is required 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 BDS (2017) [23 CFR § 625.3(a)(1) and 23 CFR § 625.4(d)(1)(v)].
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. Project applicability [23 CFR § 650.107(a)]. Applies to all Federal-aid projects, whether on the NHS or Non-NHS.
b. Hydraulic Design Standards [23 CFR § 650.115]. Establishes the required standards to be satisfied for all Federal-aid project hydraulic designs.
c. Content of Design Studies [23 CFR § 650.117]. Requires studies to contain the hydrologic and hydraulic data and design computations [23 CFR § 650.117(b)(1)]. 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(o)(1)].
c. For those scour critical bridges, requires preparing a plan of action for deployment of scour countermeasures for known and potential deficiencies, and to address safety concerns [23 CFR § 650.313(o)(2)].

### 1.2 Technical basis

This TechBrief is based on the following research on shallow foundations and abutment scour:

a. FHWA-HRT-17-013, "Hydraulic Performance of Shallow Foundations for the Support of Vertical-Wall Bridge Abutments" (FHWA, 2017a).
b. NCHRP 24-20, Draft Final Report, "Estimation of Scour Depth at Bridge Abutments" (NCRHP, 2010).

Additionally, this TechBrief reflects other research and development efforts.

### 1.3 Related materials

This TechBrief provides clarification of FHWA's Hydraulic Engineering Circular No. 23 (HEC-23) Third Edition, 2009, Design Guide No. 14 (DG14).

## 2 ROLE OF SCOUR COUNTERMEASURES

This section of the TechBrief provides more detailed explanations of considerations and processes associated with the design of abutments on deep foundations including the use of abutment scour countermeasures and protection of their associated bridge embankments.

Engineers rely upon scour countermeasures to ensure bridge embankment stability and, for some cases, abutment foundation stability, to achieve economical abutment design and reliable abutment performance over the design life of the structure. Consequently, the importance of properly designing, installing, and maintaining the countermeasures cannot be overstated. Key points include the following:

- Abutment scour countermeasures can support one of two design approaches. One relies on the countermeasure to protect the abutment foundation from local scour. The second is designed to protect the bridge embankment to a specific level of service. For the latter scenario, the bridge foundation is designed for the total scour without consideration of a countermeasure.
- All bridge embankments should be protected against scour and erosion, regardless of abutment or foundation type.
- AASHTO LRFD BDS (2017) Article 2.6.4.4.2 states the following: "The stability of abutments in areas of turbulent flow shall be thoroughly investigated. Exposed embankment slopes should be protected with appropriate scour countermeasures."

- Horizontal aprons are a necessary component of abutment scour countermeasures to intercept the local scouring mechanism and significantly reduce the risk of countermeasure edge failure from the appropriate design or worst-case scour condition.
- Any vertical wall that is in the flow field and associated with, or serves as the abutment structure, is considered integral with the scour countermeasure and serves to partially protect the bridge embankment. The abutment wall and its wingwalls retain and protect the embankment material from erosion and scour just as any sloping countermeasure would for spill-through abutments.

### 2.1 Differentiating abutment scour countermeasures design approaches.

This TechBrief discusses two approaches owners may consider in their bridge foundation designs. In the first approach, the placement of an abutment scour countermeasure can serve to reduce the final foundation elevation by a depth equivalent to the calculated abutment scour component for the total worst-case scour. In this case, the foundation is reliant on the contribution of an abutment scour countermeasure for stability. The abutment scour countermeasure will also serve, collaterally, as the bridge embankment protection. In this case, the bridge abutment countermeasure will be placed below and provide protection to the contraction scour (CS) plus long-term degradation (LTD) elevation for the scour check flood (SCF). This use of abutment scour countermeasures to mitigate the threat of scour is more widely programmed for existing bridges. While there are always exceptions, for new bridges, it is anticipated that additional pile length needed to extend below the total worst-case scour is generally more cost effective and less environmentally intrusive than HEC-23 abutment scour countermeasures.

In the second approach, the structural designer will design the abutment on deep foundations, establishing its final elevation considering the total scour, including abutment scour. In this case, in accordance with AASHTO LRFD BDS (2017) specifications, the hydraulic engineer must design and specify a bridge embankment scour countermeasure (AASHTO LRFD Section 2.6.4.4.2). The AASHTO LRFD BDS (2017) specifications do not require a specific level of service criteria for the bridge embankment scour countermeasure to survive under flooding conditions. As such, the owner should establish the design flood frequency to protect the bridge embankment; this design flood can be independent of the hydraulic design flood, the SDF, the SCF, or the worst-case scour conditions used for the abutments' foundation design. In this case, the bridge embankment should be protected from scour down to the elevation where the apron is constructed, in accordance with the owner's published design criteria for bridge embankment protection. Countermeasure termini details for bridge locations can be found in HEC-23 at 23 CFR 650.313(o)(2)).

To determine the controlling foundation elevation, the hydraulic engineer should provide the worst-case scour elevation for the SDF as well as the worst-case scour elevation for the SCF. AASHTO LRFD considers scour as a condition caused by the loss of materials; it is not a load.

Considering the loss of scoured material, combined with the various limit state load conditions, the structural engineer and geotechnical engineers determine the final foundation elevations under 23 CFR 650.313(o)(1) (see HEC-18, Figure 1.1). For more information related to SDF and

SCF, see FHWA's TechBriefs "Scour Considerations within AASHTO LRFD Design Specifications" (FHWA-HIF-19-060) and "Scour Design within AASHTO LRFD Limit States" (FHWA-HIF-23-040).

## 2.2 Bridge embankment failure scenarios

Laboratory studies of scaled bridge abutments with countermeasures have shown that for various flow conditions, when placing the countermeasures below appropriate scour depths, abutment scour countermeasures can be effective in protecting bridge abutments and their embankments. Three scenarios are presented below to describe key conditions from those studies:

- No scour countermeasure protecting the bridge embankments
- Scour countermeasure protecting bridge embankments placed at the owner-defined elevation
- Scour countermeasure protecting bridge embankments (and abutment foundation) placed at CS (for the SCF) plus LTD

The location of a deep foundation footing/pile cap (and associated height of the vertical abutment) is generally dictated by efficiencies of design, including span arrangement, cost of substructure height vs. superstructure length, and geotechnical considerations for optimum pile cap locations.

Foundation elevations in these scenario figures are just for illustrative purposes. Similarly, the controlling flood (SDF or SCF) for each scenario is for illustrative purposes. Project design computations (sensitivity analysis) will reveal the controlling flood conditions. These scenarios assume scour condition "A" exists (see HEC-18) and that LTD and CS will be applicable.

**Scenario #1 (*No Countermeasure Option*)**

Consider the following scenario, where no countermeasure protection is installed to protect the abutment foundation, nor the bridge embankment, against scour during a flood event, as shown in Figure 2. Also, in this scenario, the elevation of the abutment scour (AS) (SCF) plus LTD is assumed to be the point at which the piles are effective when determining the required pile length. This effective pile length is that portion of the piles that extends below the total scour elevation for the scour check flood and serves to provide the additional pile load capacity to carry the design load combinations. This elevation, where deep foundation piles/shafts become effective, is consistent with guidance provided in FHWA's TA5140.23; FHWA's Geotechnical Engineering Circular No. 10 (GEC-10) (FHWA NHI-18-024) and GEC-12 (FHWA-NHI-16-009).

In this scenario, the total scour equals the AS (AS is an amplification of the CS, consistent with NCHRP 24-20 "Prediction of Scour at Bridge Abutments"; and AS includes AS plus CS calculated for the scour check flood (SCF)) plus LTD. The area surrounding the abutment illustrates the bridge embankment failure zone. The exact geometry and extent of the failure zone is a function of many factors including the soil properties, topography, and presence of any soil reinforcement or stabilization measures.

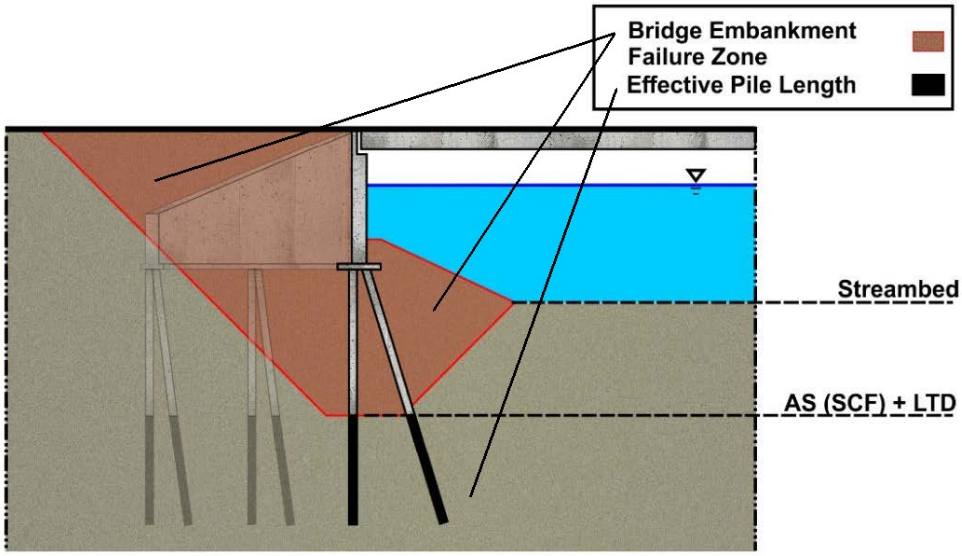


**Figure 2. Bridge embankment with no riprap countermeasure protection.**

In this scenario (Figure 2), when a flood discharge occurs that is less than or equal to the scour check flood, the unprotected bridge embankment is at risk of failure (Figure 3). Without countermeasures, local scour occurs along the abutment, eroding the soil under or around the pile cap. This triggers scour in the form of localized erosion or mass failure of the embankment material from the failure zone behind the abutment as it is eroded under or around the foundation. The abutment scour associated with the flood discharge does not reach a depth below the design AS (SCF) plus LTD elevation, so the pile length continues to satisfy the provisions for which it was designed.

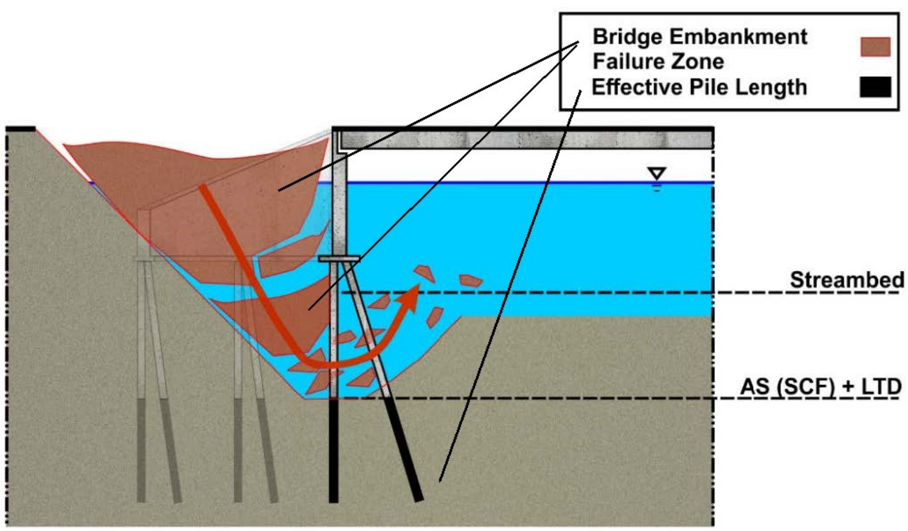


**Figure 3. Bridge embankment performance during a flood event with no riprap countermeasure protection.**

**Scenario #2 (*Countermeasure for Embankment Protection Only*)**

In a second scenario, a countermeasure is installed around the abutment to protect the bridge embankment from scour per the AASHTO LRFD BDS (2017) Article 2.6.4.4.2, to an elevation defined by the owner (owner-defined level of service); see Figure 4, which shows a bridge embankment protected by riprap countermeasures (and apron). The effective pile length is extended to the total scour elevation, AS (SCF) plus LTD.

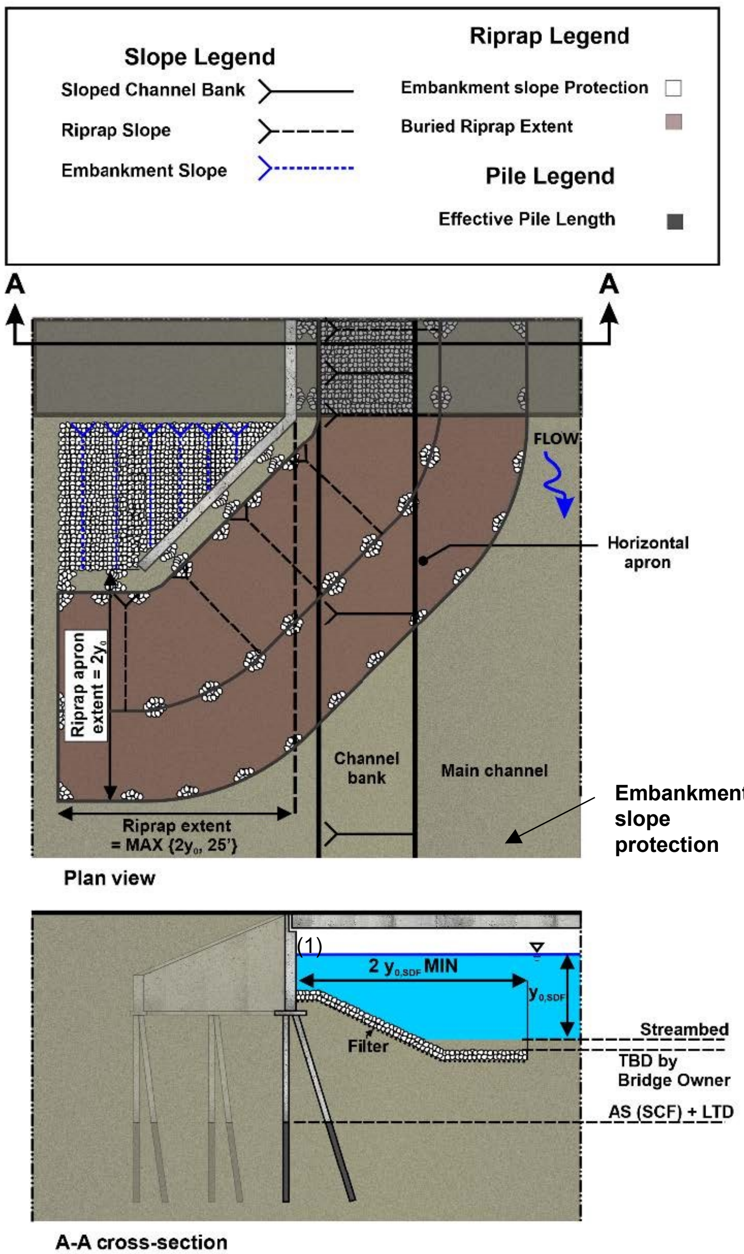


**Figure 4. Bridge embankment countermeasure elevation above total scour elevation.**

For this second scenario, the bridge embankment fill is still at risk for failure during a flood discharge event greater than the owner-defined level of service, despite the addition of the riprap countermeasure; see Figure 5. Once contraction scour extends below the countermeasure apron elevation, the integrity of the countermeasure is compromised. If the countermeasure is removed, the bridge embankment fill is at-risk of failure, similar to the first scenario, where local scour erodes the soil under the pile cap, ultimately resulting in removal of the bridge embankment material from the failure zone.

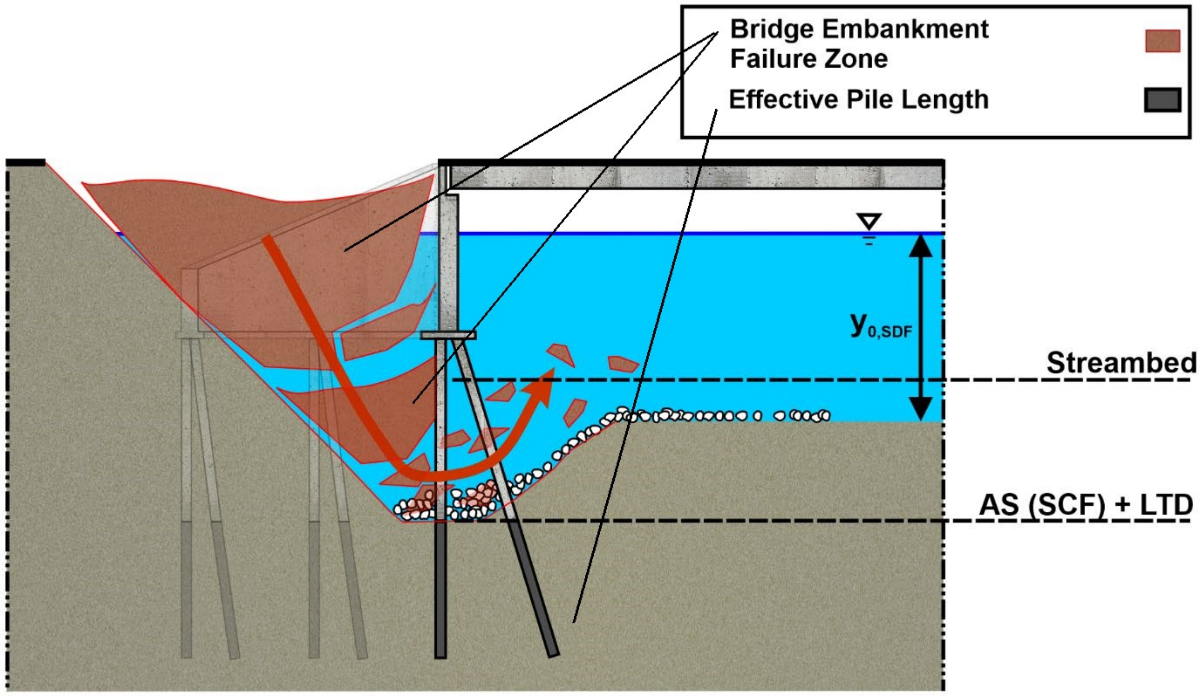


**Figure 5. Bridge embankment countermeasure placed at owner-defined elevation failure during a flood event greater than owner-defined flood frequency.**

**Scenario #3 (*Countermeasure for Abutment Foundation and Embankment Protection*)**

The third scenario involves burying the riprap countermeasures at an elevation where the top of the riprap apron equals the contraction scour elevation calculated from the scour check flood event, e.g., the SCF, plus LTD (Figure 6). With countermeasures placed below the CS (SCF) plus LTD elevation, AS can be disregarded from the total scour estimates. The "effective pile length" should begin at the CS (SCF) plus LTD. Although "effective pile length" could begin at the bottom of the stub abutment (cap beam) due to the protection provided by the properly designed countermeasure from the worst-case scour, the failure of countermeasures is not uncommon, sometimes due to non-conformance with countermeasure design and construction details.

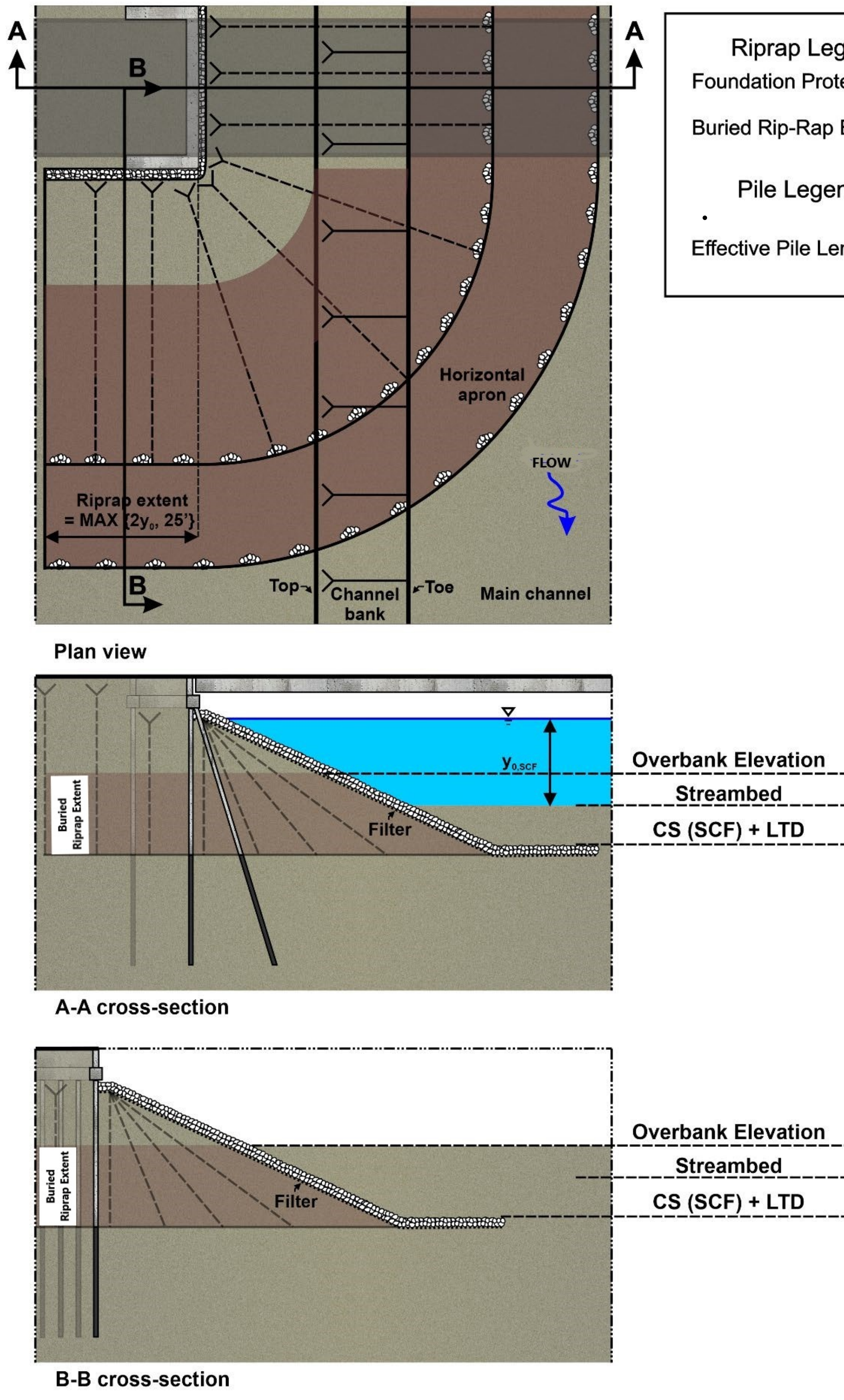


**Figure 6. Abutment countermeasure design with the riprap placed below the contraction scour (SCF) elevation plus LTD.**

# 3 SCOUR COUNTERMEASURES FOR BRIDGE EMBANKMENT PROTECTION

The following sections focus on scour countermeasures to protect bridge embankments. For abutments on deep foundations, there are few scenarios where it could be advantageous to place abutment countermeasures and horizontal aprons below the CS (SCF) plus LTD elevation. This approach would be an effort to disregard the abutment local scour component and have some reduction of deep foundation pile lengths. The more common approach is where the engineer designs the abutment on deep foundations, establishing its final elevation considering the total scour and applies the use of physical countermeasures to protect the bridge embankments adjacent to the abutments. A discussion on establishing riprap apron dimensions and elevations and other countermeasure design considerations is also provided.

## 3.1 Design of countermeasure apron elevation

Laboratory studies indicate that partial-width countermeasure aprons that are on the surface of the original streambed introduce turbulence at the apron/bed interface and redistribute flow conveyance to the unprotected portions of the streambed. This occurs whether $W_2/y_0$ is large or small, where $W_2$ is equal to the bottom width of the contracted section (i.e. the bridge opening width), and $y_0$ is equal to the flow depth in the bridge opening before scour occurs (FHWA, 2017a). These two effects result in scour depths in excess of predicted contraction scour. Buried partial-width and buried full-channel width aprons placed to the controlling flood scour depth have been shown to protect foundations. When conditions do not allow placement to the controlling flood scour depth, the countermeasures may be extended upstream and downstream beyond to limits of contraction scour while still considering the potential for LTD.

- When no contraction scour or long-term degradation is predicted and no roughness changes from riprap is considered, 2D modeling may be used to compute the contraction scour based on the difference in roughness between that found over the countermeasure as compared to the native material in the streambed.

For bridge embankment protection, countermeasures with buried aprons placed to the estimated, owner-defined flood event contraction scour plus LTD elevation have proven to be effective when owners consider the following:

- Partial-width buried riprap aprons can be effective for $W2/y0 > 6.2$ (i.e., wide openings). Concern about edge failure is significantly reduced because the apron is buried to a depth below the contraction zone associated with the owner's flood event.
- Full-width buried riprap aprons for bridges where $W2/y0 \leq 6.2$ (i.e., narrow openings) have been shown to protect foundations and can be also considered for all openings.

Some bridge owners' countermeasure policies include providing a launchable toe trench for abutment scour protection. Launchable toe trenches should only be used at streambank revetments (provided in DG4, HEC-23(2009)). The concept of launchable toe trenches used as abutment protection has not been researched or proven to be a viable alternative. The turbulence around an abutment differs from the shear forces along a sloping bank revetment where the launchable toe has been successfully applied.

### 3.2 Bridge embankment scour countermeasure design

- When scour countermeasures for bridge embankment protection are installed, the countermeasure should include a minimum-length horizontal apron. It should be designed to be stable for CS plus LTD, where appropriate, for all floods up to and including the design flood established by the owner. To avoid bridge embankment failure from local scour, the following countermeasure extents should be used:
- The countermeasure should extend 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 bridge embankment slope protection
- The countermeasure should extend up the bridge approach roadway fill to the roadway overtopping elevation (or where overtopping does not exist, use the hydraulic design flood elevation plus freeboard).
- The apron should encircle the bridge approach fill, upstream and downstream, at the defined elevation, including the zones in the overbank area; see Figure 7.

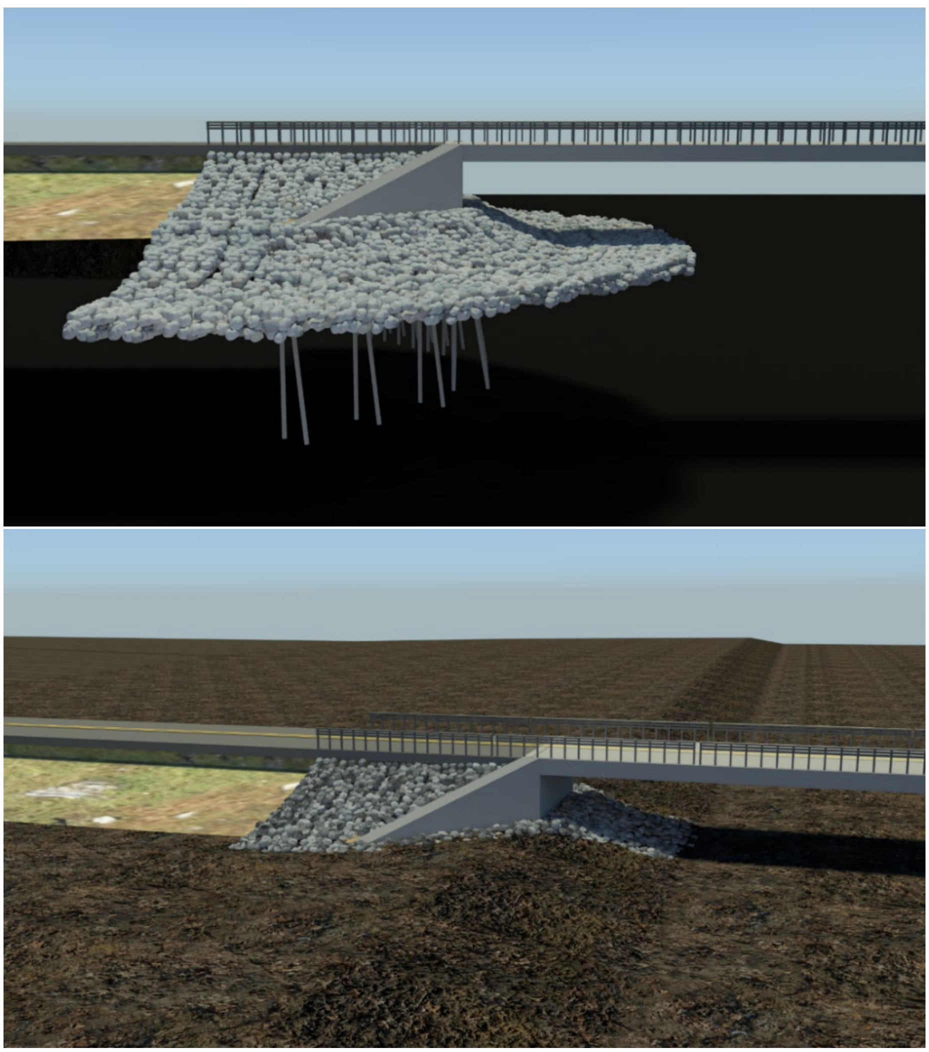

**Figure 7. 3D rendering of abutment countermeasure.**

- For abutments located near the channel bank with free-surface flow, the extensions (longitudinally upstream and downstream) should be a distance equal to twice the main channel flow depth through the bridge (2yo), minimum; see Figure 8.
- For abutments located near the channel bank that may experience pressure flow, the extensions should be a distance equal to twice the main channel flow depth at the upstream side of the bridge (2yu); see Figure 9.
- In addition, the same designed countermeasure should extend up the channel bank and protect the bridge embankment. To do this, the countermeasure should be configured to cover the bridge embankment to an appropriate height (including 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. Note, a 2D model may be necessary to provide the most representative values discussed in these bullets. See Figure 8 for location of countermeasure extents.

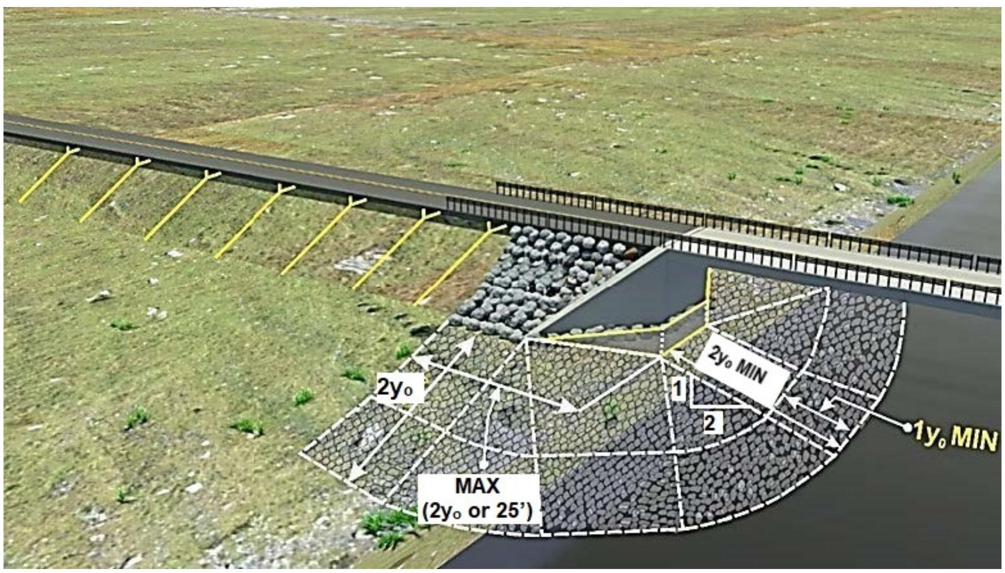


**Figure 8. Countermeasure extents.**

There are two special bridge embankment countermeasure scenarios that should be given consideration:

*Scenario 1: Countermeasures for pressure flow*. Figure 9 shows that for new bridges under pressure flow conditions, the countermeasure must extend the full width of the channel for narrow opening locations. The top elevation of the countermeasure apron should be at or below the maximum scour elevation (contraction scour plus LTD or the vertical contraction scour, whichever is greater).

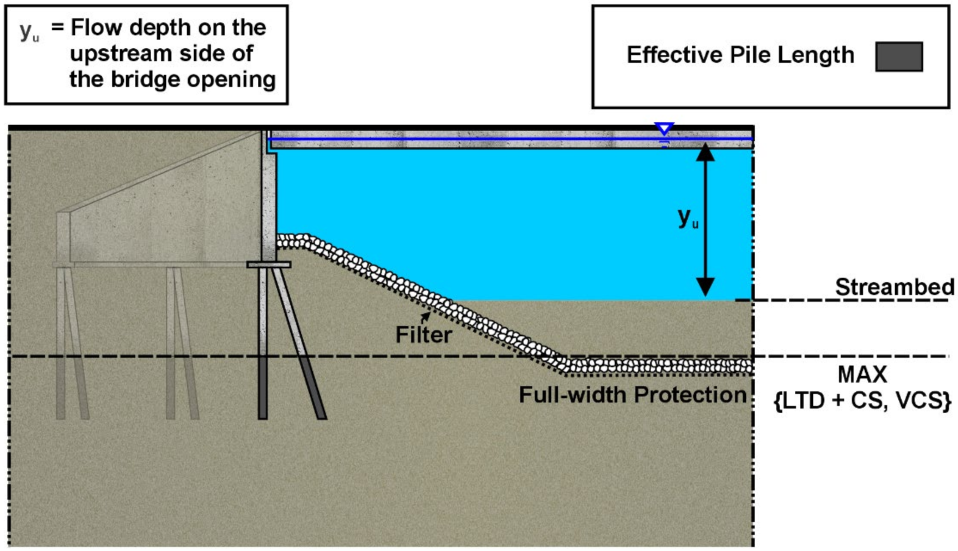


**Figure 9. Countermeasures for pressure flow.**

*Scenario 2: A pier located close to the abutment structure.* In this special case, a pier is located close to the abutment structure, which mimics the 'narrow-opening' situation described above. The special case is triggered when $W_P/y_0 \leq 6.2$, where $W_P$ is equal to the distance between the abutment toe and the pier column. To protect against edge failure, the riprap countermeasure should be fully extended between the abutment and the pile cap for the pier.

Figure 10 shows the top of the countermeasure placed below the pile cap elevation which is equal to contraction scour. The countermeasure extends fully from the pile cap to the abutment. For illustrative purposes, a scour condition "B"' location is shown.

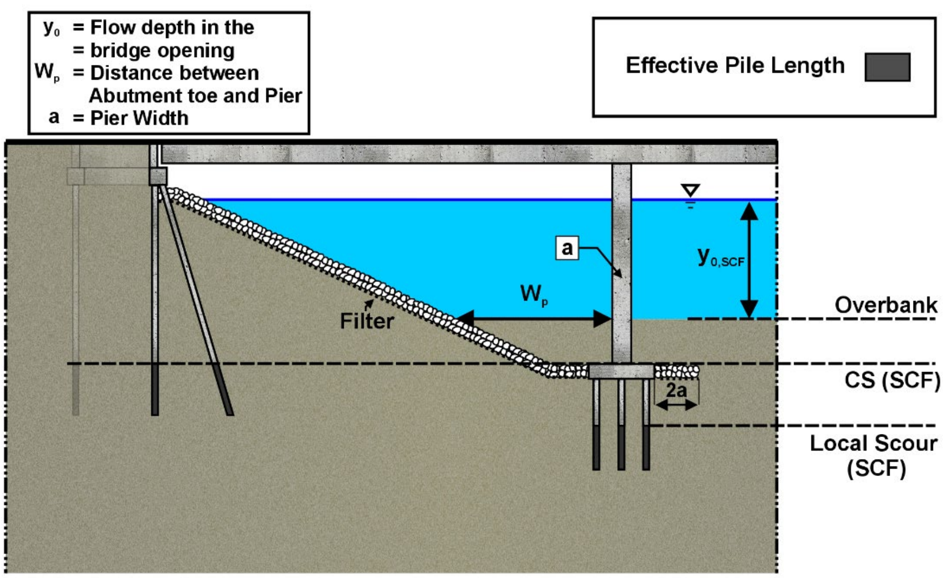


**Figure 10. Countermeasures for scour condition B and a closely located pier.**

# 4 SUMMARY

This TechBrief provides takeaways for considering scour and AASHTO LRFD BDS (2017).

- The AASHTO LRFD BDS (2017) forms the basis for nearly all recent highway bridge and structure design practices and standards. In addition, AASHTO LRFD BDS (2017) is incorporated by reference at 23 CFR 625.4(d)(1)(v) as a design standard for bridges on the National Highway System.
- To determine the controlling foundation elevation, the hydraulic engineer should provide the worst-case scour elevation for the SDF as well as the worst-case scour elevation for the SCF. Considering the loss of scoured material, combined with the various limit state load conditions, the structural engineer and geotechnical engineers determine the final foundation elevations.
- Properly designed scour countermeasures (HEC-23) may be used to eliminate the abutment local scour component of total scour when establishing the foundation elevation.
- AASHTO LRFD BDS (2017) specifications require owners to design and specify a bridge embankment scour countermeasure, although a level of service criteria for the bridge embankment scour countermeasure is not specified.
- A few hypothetical scenarios discuss how placement of countermeasures affect their long-term performance.

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# 6 GLOSSARY

This TechBrief uses and references the following terms obtained from AASHTO LRFD BDS (2017) Sections, Articles and Definitions (incorporated by reference at 23 CFR § 625.4(d)(1)(v)). The Glossary also includes specific terms from several non-regulatory FHWA TechBriefs to aid in readability and context. Finally, this Glossary provides the relevant citation of each source.

*AASHTO LRFD § 1.2 – Definitions*

**Design Life** – Period of time on which the statistical derivation of transient loads is based: 75 years for these Specifications.

*AASHTO LRFD § 3.2 – Definitions*

**Load** – The effect of acceleration, including that due to gravity, imposed deformation, or volumetric change.

*AASHTO LRFD § 10.2 – Definitions*

**Deep Foundation –** A foundation that derives its support by transferring loads to soil or rock at some depth below the structure by end bearing, adhesion or friction, or both. Examples of these foundations are driven piles and drilled shafts.

**Shallow Foundation** – A foundation that derives its support by transferring load directly to the soil or rock at shallow depth.

*HEC-18 – Definitions*

**Contraction Scour (CS)** – is equivalent to AASHTO LRFD BDS definition of Contraction Scour.

**Scour Check Flood (SCF)** – is equivalent to AASHTO LRFD BDS definition of Check Flood for Bridge Scour.

**Scour Design Flood (SDF)** – is equivalent to AASHTO LRFD BDS definition of Design Flood for Bridge Scour.

**Scour Depth or Depth of Scour** – The vertical distance a streambed is lowered by scour below a reference elevation.

**Long-term Degradation (LTD)** – The lowering or scouring of the streambed over relatively long reaches due to a deficit in sediment supply from upstream and contributes to total scour.

**Total Scour** – The sum of long-term degradation, general (contraction) scour and local scour.

*TechBrief Definitions (non-regulatory)*

**Foundation Element** – A footing, pile, or other type of foundation associated with a bridge (or culvert).

**Worst Case Scour Depth** – The conditions (e.g., discharge, velocity, depth, tailwater, geometry, orientation, type of foundation, etc.) that would produce the maximum scour depth at a particular foundation element.

## Hydraulic Considerations for Abutments on Deep Foundations and Bridge Embankment Protection

**Contact –** For more information, contact:

Federal Highway Administration (FHWA)

Office of Bridges & Structures, Paul Sharp, Senior Scour Engineer – paul.sharp@dot.gov

Office of Infrastructure Research & Development, Kornel Kerenyi, Ph.D. – kornel.kerenyi@dot.gov

Federal Highway Administration: www.fhwa.dot.gov/engineering/hydraulics/scourtech/scour.cfm

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