OFFICE OF STRUCTURES
MANUAL ON HYDROLOGIC AND HYDRAULIC DESIGN

CHAPTER 11
EVALUATING SCOUR AT BRIDGES

April 6, 2016

Preface

ABSCOUR 10 is the current version of the scour evaluation program used by the Office of Structures, and all previous versions should be discarded. The user is advised to check the web site below for any revisions to the program:

www.gishydro.eng.umd.edu

The material presented in Chapter 11 and the ABSCOUR User's Manual has been carefully researched and evaluated. It is being continually updated and improved to incorporate the results of new research and technology. However, no warranty expressed or implied is made on the contents of this ABSCOUR 10 program or the user's manual. The distribution of this information does not constitute responsibility by the Maryland State Highway Administration or any contributors for omissions, errors or possible misinterpretations that may result from the use or interpretation of the materials contained herein.

Questions regarding the use of the ABSCOUR Program or the interpretation of any of the policies, guidance or methodologies contained in Chapter 11 or its Appendices should be directed to the Office of Structures, Structures Hydrology and Hydraulics Division.

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APPENDICES

11.1 Introduction

11.1.1 General

Overview

The guidance in Chapter 11 recognizes and stresses that the primary responsibility of the Engineer is to provide for the safety of the public.

Chapter 11 provides policies, guidelines and methodologies for the evaluation of scour at bridges and bottomless arch culverts. This information is based on and incorporates the experience of the Office of Structures (OOS) as well as recommendations and policy guidance of various FHWA, AASHTO and ASCE manuals and guidelines. In particular, the guidance presented in FHWA Manual HEC-18, "Evaluating Scour at Bridges" Fifth Edition dated April 2012 is discussed and utilized as appropriate. For most design situations, we have found that the policies and procedures used by this office provide more reasonable estimates of scour for Maryland bridges than some of the guidance in HEC-18. ABSCOUR 10 is the computer program developed by the Office of Structures for evaluating scour, and it incorporates a number of the scour evaluating methods in HEC-18 as described below.

The Office of Structures has approved the following policies and procedures for the evaluation of scour at bridge structures.

- General HEC-18 method for evaluating scour at piers; This HEC-18 method is incorporated in the ABSCOUR 10 Pier Module. The method does not take into account the composition of the bed load material
- HEC-18 method for evaluating scour at piers in coarse bed) materials (D50>20 mm) : This method is incorporated in the ABSCOUR 10 Utilities Module. The method is recommended as a check on the General HEC-18 pier scour method for piers in coarse bed materials. It can evaluate scour at pier stems but not at pile caps or spread footings.
- HEC -18 method for Pier Scour with Debris: This method is incorporated in the ABSCOUR 10 Utilities Module
- HEC-18 Pressure Scour method: This method is incorporated in the ABSCOUR 10 Abutment Module
- MDSHA method for Evaluating contraction and Abutment scour: This method is incorporated in the ABSCOUR 10 Abutment Module
- MDSHA method for Evaluating scour in Bottomless Culverts: This method is incorporated in the ABSCOUR 10 Culvert Module
- HEC-18 method for Evaluating Pier Scour in Erodible Rock: This method is incorporated in the Erodibility Index Worksheet located with the Office of Structures software programs.
- Selection of the design flood for scour and the check flood for scour: See Section 11.4.4.
- Criteria for the design of bridge foundations for scour: See Section 11.4.5.

ABSCOUR 10 has the capability of inputting and solving other scour evaluating methodologies in HEC-18. In fact, every example problem of the scour equations in HEC-18 is listed and solved in ABSCOUR 10. While these other methods are available for use within the ABSCOUR 10 Program, the Office of Structures recommends that they be considered for conducting sensitivity analyses and for comparisons with the approved procedures listed above rather than for the design of Maryland bridges. These other HEC-18 methods for evaluating scour are listed below:

- NCHRP 24-20 Method for evaluating abutment scour
- Modified Laursen's method for evaluating contraction scour
- FHWA Method for evaluating clear water scour in bottomless culverts
- Florida method for evaluating scour at piers.

HEC-18 contains a wealth of information regarding the background and development of methodologies for evaluating scour at bridges, and should be considered as a companion manual to the Office of Structures H&H Manual.

<u>Qualifications of Personnel</u>

Personnel involved in the evaluation of scour at bridges need to possess the technical qualifications, including practical experience, education, and professional judgment, to perform the individual technical tasks assigned. Interpretation of results and conclusions of scour analyses shall be accomplished by registered engineers qualified in the appropriate disciplines. Because of the complexity of bridge scour, it is recommended that evaluations be performed by an interdisciplinary team of engineers with the requisite knowledge in structural, hydraulic, river mechanics and geotechnical engineering.

11.1.2 Definitions

The following definitions are provided to assure uniform understanding of some selected terms as they are used in this chapter:

100-Year Flood - The flood due to storm, tide or mixed population flood event having a one-percent chance of occurring in any one year. It serves for assessing flood hazards and meeting flood plain management requirements. This will also be the design flood for bridge scour unless the incipient overtopping flood is of a lesser flow magnitude.

500-Year Flood - The flood due to storm, tide or mixed population flood event having a 0.2 percent chance of occurring in any one year. This flood may also be selected for the check flood for scour unless the incipient overtopping flood is smaller. Typically, it is based on conditions of ultimate development in the watershed.

Aggradation - A long term general and progressive build-up or raising of the longitudinal profile of the channel bed due to sediment deposition.

Bankfull Flow - a discharge used to classify and evaluate stream channel morphology and stability. The bankfull flow normally occurs in natural, stable channels for a recurrence interval in the range of the 1.5-year flood. This recurrence interval can be considerably lower for unstable channels. The magnitude of the bankfull flow is usually obtained from field measurements.

Bendway Scour - Scour which occurs on the river bed near the outside of the bend due to the variable velocity distribution and the resulting secondary currents which develop across the bendway cross-section.

Check Flood for Bridge Scour - This flood serves for investigating the adequacy of the bridge to remain stable and not fail during a catastrophic flood event. This flood event represents the *ultimate loading condition*, since a bridge failure may occur for flood flows of a greater magnitude:

- If the incipient overtopping flood is less than the 500-year flood, the overtopping flood may represent the worst case condition and serve as the check flood for scour,
- If the incipient overtopping flood is greater than the 500-year flood, the 500-year flood will normally serve as the check flood for scour,
- If the site conditions are such that a more severe flood event is considered to be warranted, the Engineer may use such a flood event for the check flood for scour. This may be the case for a crossing site where the overtopping flood has a low recurrence interval and creates less of a hazard than is caused by floods with higher recurrence intervals. The Engineer may also wish to investigate special conditions caused by ice or debris dams, flows on controlled waterways, or locations near confluences involving varying tail waters.

Contraction Scour - Scour in a channel or on a flood plain that is caused by a constriction or contraction of the flow due to a naturally occurring confinement of the river or the construction of a bridge or other feature in the channel or flood plain. To satisfy the law of continuity of flow, velocities in the contracted section are higher than in the normal section; consequently, the channel bottom is subject to higher shear stress forces and tends to scour out. In a channel, contraction scour usually affects all or most of the channel width.

Degradation - A general and progressive lowering of the longitudinal profile of the channel bed due to long-term scour and erosion.

Design Flood - A flood of a specified recurrence interval used for sizing the waterway opening for the various functional classes of highways to satisfy the design policies and criteria of the SHA (See Chapter 10).

Design Flood for Bridge Scour – This event serves for estimating the total scour at the bridge and the design of the bridge foundations to resist damage from the scour. Generally, the magnitude of the design flood for bridge scour is the lesser of the 100-year flood or the overtopping flood. If the site conditions are such that a more severe flood event is considered to be warranted, the Engineer may use such a flood event for the design flood for bridge scour. This may be the case for a crossing site where the overtopping flood has a low recurrence interval and creates less of a hazard than the 100-year flood. The Engineer may also wish to investigate special conditions caused by ice or debris dams, flows on controlled waterways, or locations near confluences involving varying tail waters.

Estuary - A tidal reach at the mouth of a stream.

Flood Plain - nearly flat, alluvial lowland bordering a stream that is subject to inundation by floods.

Historic flood - A recorded past flood event that is useful for calibrating water surface profiles and evaluating the performance of existing structures.

Channel Lateral Movement Zone - The area on the floodplain that the stream channel may reasonably occupy at some future time during the service life of the crossing structure is referred to herein as the *channel lateral movement zone* (CLMZ). The boundaries of the CLMZ should envelop the extent of likely channel migration and pathways for channel avulsion.

Limit State - A condition in which the forces stabilizing a structure are equally balanced by the forces tending to destabilize the structure. This represents the ultimate loading condition for the structure, since any increase in the destabilizing forces will cause the structure to fail (no reserve capacity).

Local Scour - Scour in a channel or on a flood plain that is caused by an obstruction to the flow such as a pier or abutment, and is therefore localized in the immediate vicinity of the obstruction.

Mixed Population Flood Event - A flood event which involves the mixing of two types of flows such as tidal flow and riverine flow, or snow melt and rainfall runoff.

Overtopping Flood (Incipient overtopping flood). This flood is determined by finding the maximum flow that will be accommodated by the bridge without overtopping of the bridge, its approach roads or other drainage divide. It serves for assessing risks to highway users and damage to the bridge and its roadway approaches. The magnitude and frequency of the overtopping flood is a function of the highway/bridge design and must be determined from hydraulic analysis. The incipient overtopping flood may be designated as both the design flood for bridge scour and the check flood for bridge scour if overtopping occurs for a flood with a recurrence interval less than the 100-year event.

Preliminary Bridge Plans - For the purpose of this guide, preliminary plans are developed to the extent of depicting the type, size and location (TS&L) of a proposed structure.

Scour - Erosion due to flowing water, usually considered as being localized as opposed to general bed degradation,

Scour Prism (total scour line) - A 3-dimensional shape or solid comprised of the scourable material located above the elevation of the total scour line.

Super flood - A term used to denote a flood with a recurrence interval greater than a 100-year flood that is commonly used as the check flood for scour.

Thalweg - The line or thread extending down a channel that follows the lowest elevation of the bed.

11.2 Overview of Scour Concepts and Process

Scour is the result of the erosive action of flowing water, excavating and carrying away material from bed and banks of streams and other waterways. Different materials scour at different rates. Loose granular soils are rapidly eroded by flowing water, while cohesive or cemented soils are more scour resistant. However, ultimate scour in cohesive or cemented soils can be as deep as scour in sand bed streams. Scour will reach its maximum depth in sand and gravel bed materials in hours; cohesive bed materials in days; glacial tills, sandstones and shales in months, limestone in years and dense granites in centuries. Total scour at a highway crossing is comprised of three elements (Reference 1):

1. Aggradation and degradation. These are long term stream bed elevation changes due to natural causes or to development of the river, its flood plain or watershed. Aggradation involves the deposition of material eroded from other sections of a stream reach, whereas degradation involves the scouring or lowering of the stream bed.
2. Contraction Scour: Contraction scour in a natural channel involves the removal of material from the bed and banks across all or most of the channel width. This component of scour results from a contraction of the flow resulting from a natural constriction or a constriction caused by the bridge and its roadway approaches. Contraction scour is caused by increased velocities and the resulting increased shear stresses on the bed and banks.

3. Local scour: Local scour involves removal of material from around piers, abutments, spurs and embankments. It is caused by an acceleration of flow and resulting vortices induced by the flow obstructions.

In addition to the types of scour mentioned above, naturally occurring lateral movement of a stream may erode the approach roadway or change the total scour by changing the flow angle of attack. Factors that affect lateral movement also affect the stability of a bridge. These factors include the geomorphology of a stream, location of the crossing with respect to the stream plan form, flood characteristics, characteristics of the bed and bank materials and land use in the watershed basin (See Chapter 9).

Case studies of various bridges in the United States which have collapsed as a result of scour graphically illustrate how one or more of the elements of scour discussed above contributed to the bridge failure. For example, the collapse of the New York State Thruway Bridge over Schoharie Creek on April 5, 1987 has been attributed directly to local scour at the bridge piers. The failure of the U. S. Highway 51 Hatchie River Bridge on April 1, 1989, has been attributed to a combination of (a) lateral shifting of the stream channel induced by contraction scour and (b) local scour of bridge piers that had originally been built on the flood plain but which became river piers due to the shift in the stream channel.

Long term stream bed elevation changes may be the natural trend of the stream or may be the result of some modification to the stream or its watershed. The problem for the engineer is to estimate the long term bed elevation changes that will occur over the life of the structure. This involves assessing the present state of the stream and its watershed, and then evaluating the probable effect of anticipated future changes in the river system (See Chapter 14).

Contraction scour occurs when the shear stress created by flowing water acting on the bed and bank material exceeds the ability of the material to resist this force; consequently, the material moves downstream. There are two types of contraction scour to be considered. Live bed scour occurs when there is stream bed sediment being transported into the contracted section from upstream. Most streams and rivers carry a sediment load during floods, and bridges spanning such streams are likely to be subject to live bed scour. Clear water scour occurs when there is an insignificant amount of stream bed sediment being transported into the contracted section. Clear water scour might be expected to occur at relief bridges on flood plains or at constrictions in some tidal waterways. In Maryland, clear water scour may predominate in some watersheds where these is not enough sediment supply to maintain live bed scour conditions during floods.

Bendway scour occurs primarily on the outside of bends due to the formation of secondary currents created by the bend. For bridges located on bends subject to contraction scour, the engineer will need to use judgment in the distribution of contraction scour at the bridge section to be consistent with the anticipated bendway scour (Reference 18).

Pressure flow occurs when the water surface elevation of the upstream face of the bridge is higher than the low chord of the bridge superstructure. This condition results in a vertical contraction of the flow, causing the flow velocity to increase and to enter the bridge at a downward angle to the horizontal. Both of these factors contribute to an increase in the depth of contraction scour under the bridge.

The basic mechanism causing local scour at a pier is the formation of vortices at their base. The formation of these vortices results from the pileup of water on the upstream surface and subsequent acceleration of the flow around the nose of the pier. The action of the vortex removes bed material from around the base of the pier. When the transport rate of the sediment away from the pier caused by the vortex is greater than the transport rate of sediment into the region around the pier, a scour hole develops. As the depth of the scour hole increases and widens, the strength of the vortices is reduced, thereby reducing the transport rate of sediment out of the scour hole. At the same time, the widened scour hole is able to capture a greater amount of the bed load moving past the pier. Eventually, an equilibrium condition is established and scouring ceases.

Abutment scour is perhaps the most complex and difficult aspect of scour at a bridge to predict. The OOS methodology for computing abutment scour considers it to be a combination of contraction scour and local scour as explained in Appendix A.

The configuration of a scour hole at a bridge or abutment can be expected to change with time. The scour hole initially forms and increases in size and depth as flood flow increases at the bridge. The scour hole generally reaches its maximum depth near the peak of the flood hydrograph, and then partially refills during the recession of flow from the peak. For this reason, post flood measurements of the bed surface of the scour hole may neither reveal the maximum depth of scour experienced at the bridge nor be indicative of the maximum threat to the stability of the bridge. Maximum scour depths during floods are best obtained by on-site personnel making continuous measurements or by the installation of scour monitoring equipment that are programmed to make continuous readings during floods.

11.3 Design Philosophy

There are a number of considerations involved in the design of a bridge waterway and its roadway approaches. Each highway agency has developed its own standards and criteria for sizing of the waterway opening and for determining an acceptable recurrence interval of the overtopping flood. Higher standards are set for major interstate highways and expressways while lower standards are usually set for minor local roads with low traffic counts. Various other factors may be considered in the selection of the design flood for the bridge waterway area such as the uses of the road (school bus route and access for fire and emergency vehicles), the character and size of the river, the proximity of other river crossings and the detour routes that will be available for use in the event that the roadway and bridge are inundated and closed to traffic. Bridge owners often use some type of a formal or informal risk assessment to organize and document the decision-making process for selection of the design flood and overtopping flood. The OOS criteria is set forth in Chapter 10 Bridges

A different approach is used in the design of the bridge substructure to resist scour. All bridges should be designed to remain stable for the worst case scour condition which can reasonably be expected to occur at the crossing. The added cost of making a bridge less vulnerable to scour damage is usually small in comparison to the total costs of a bridge failure including:

- The personal costs of the injuries or deaths caused by a bridge collapse,
- Reconstruction of the bridge,
- Added time and travel costs incurred by road users on detour routes while the bridge is being repaired or reconstructed, and
- Indirect economic losses to a local community or an entire region due to lost business opportunities.

There are many sources of uncertainty in predicting the worst case scour condition and the depth of the resulting scour. These include model, parameter, hydrologic and hydraulic uncertainties.

The extent of these uncertainties can vary significantly from bridge to bridge depending upon the site conditions and the difficulties in estimating the parameters used in the scour estimate.

Model uncertainty results from using a model or equation form that may not be representative of the physical processes which occur in the river. In the case of bridge scour, most of the current models have been developed from small scale laboratory experiments which are then extrapolated to the prototype scale. Complexities in the field cannot be modeled entirely in the laboratory and the degree of accuracy of the model in predicting phenomena at prototype structures is often unknown.

If the field conditions differ significantly from the laboratory conditions used to calibrate and develop the scour estimating equations or procedures, the model uncertainty is increased to the extent that it may overshadow all other types of uncertainty.

When using scour equations developed from laboratory studies, the engineer should consider the following questions:

- What are the laboratory conditions used to develop the equations?
- Can the field conditions be represented in a way that is compatible with the laboratory conditions?

If the answer to the second question is no, then additional study and evaluation of the problem is most likely warranted.

Parameter uncertainty results from an inability to accurately assess parameters and model coefficients required in the model. For example, for many bridges, the pier width is not a simple measurement but rather an estimation of the size of the obstruction that the piles and pile caps or footings create in the flow field.

Hydrologic uncertainty results from the difficulty in accurately estimating the 100-year and 500-year flood peaks due to relatively short gaging station records or to a lack of runoff data for the watershed.

Hydraulic uncertainty is the result of attempting to estimate the flow depth and velocity for a specific discharge at a specific site. This uncertainty increases when there are limited data available for use in calibrating flood stage with discharge.

Economic uncertainty results from the large number of alternative choices and decisions involved in the location and design of a bridge and its roadway approaches. The Engineer is expected to achieve a design that is safe, compatible with the river environment and cost-effective.

It is the responsibility of the engineer to use judgment in the development and evaluation of scour estimates. This judgment should extend to the evaluation of the interactions of the uncertainties discussed above, along with the sensitivity of the scour estimate to changes in these uncertainties. The basis for decisions and assumptions relating to the predicted scour depths and the resulting foundation design should be clearly documented in the project records.

11.4 Policy

11.4.1 General Policies

The following policies apply to the preparation of scour evaluation reports and to the design of bridge foundations to resist damage from scour. Please contact the Office of Structures if you have questions regarding the interpretation or application of any of the policies presented below. Such early coordination will serve to minimize problems and delays in the preparation of project studies and plans.

1. The primary responsibility of the Engineer is to provide for the safety of the public (Section 11.1).
2. Locate and design structures, to the extent practicable, to minimize obstructions to flood flows and thereby minimize the scour potential (Section 11.6).
3. Prepare a scour evaluation report or a scour assessment report for each project involving a structure crossing of a stream. The report shall address the considerations set forth in Sections 11.6 or 11.7.
4. Prepare scour evaluations and assessments using an interdisciplinary team of engineers and specialists with the requisite knowledge in structures, hydraulics, river mechanics, geotechnical engineering and geomorphology (Section 11.1.2).
5. Conduct a stream morphology study as per the guidance in Chapter 14 and use the results in the scour evaluation study. Key information includes an evaluation of the stability of the channel, the extent of estimated degradation or aggradation; the width of the channel lateral movement zone; information on the location and properties of soil and rock at the bridge; whether the type of scour to be expected at the bridge is live-bed or clear water scour; and the classification and evaluation of debris carried by the stream.
6. Coordinate the structural, hydraulic, geotechnical and geomorphic aspects of foundation design and resolve any differences at an early date following the approval of the TS&L (Section 11.6.9).
7. The FHWA Manuals (References 1, 2, 7 and 15) serve as basic guidelines for evaluation of stream stability and scour, except for the specific policies and procedures of the SHA set forth in this chapter and its appendices, primarily with regard to scour evaluations of abutments, piers and geomorphic studies. It is the responsibility of the Engineer to assure that the hydraulic, stream stability, scour evaluation and geomorphic procedures utilize current knowledge and technology consistent with the state of practice of hydraulic engineering, are appropriate for the site conditions under consideration (Sections 11.1, 11.2 and 11.3), and are consistent with the polices set forth in this OOS manual. Design structures to be stable for worst-case conditions for the design flood for scour and verify that they remain stable for conditions of the check flood for scour (Section 11.6 and 11.8).

11.4.2 Typical Scour Evaluation

The scope of a typical scour evaluation consists of analyzing the following aspects of scour and channel morphology which may have an effect the design of the bridge foundations:

1. Estimated channel degradation;
2. Estimated contraction, abutment and pier scour elevations, taking into account the potential for future channel movement at the bridge; and
3. Measured elevations of competent bedrock.

11.4.3 Recommended Scour Evaluation Process

The Office of Structures recommends that the scour evaluation process consist of the following steps:

1. Review the Stream Morphology Report for the bridge (Reference 4). Obtain the elevation of the degraded stream bed at the bridge and the limit of potential channel movement which may affect the design of the foundation elements. This zone of potential channel movement is defined as the "lateral channel movement zone" or LCMZ.
2. Use the HEC-RAS and ABSCOUR Models to compute contraction scour for proposed conditions.
3. Use ABSCOUR and/or math computations to compute the effect of the potential lateral movement of the stream on the depth of contraction scour at the foundation elements. Compute local abutment and pier scour using this information.
4. Review the Project Boring Logs to determine the elevation of competent (scour-resistant) rock at each foundation unit. Obtain the concurrence of the interdisciplinary team regarding the quality of the rock.
5. Summarize the elevations determined from the above studies. Make a judgment as to the appropriate elevation to use in the design of each foundation element considering 1) rock elevations; 2) contraction scour, 3) local pier and abutment scour elevations, taking into account channel movement, 4) degradation and 5) a combination of the above factors. For example, in some cases it may be appropriate to consider contraction scour, channel movement and local scour along with degradation when establishing the worst case elevation for a foundation on scourable material.

11.4.4 Selecting the Design and Check Floods for Scour

The Summary Tables below provides an overview of the Office of Structures guidelines for designing bridge foundations for scour. Use Table 11.1 as a guide in selecting the design and check floods for scour. Use Section 11.4.2 as a guide in selecting the appropriate scour conditions to use in evaluating the stability of bridge foundations. Additional design criteria and guidance are provided in the comments following the Summary Tables. All foundations designs are subject to the approval of the Director, Office of Structures.

Table 11.1 Criteria for Selecting the Design and Check Floods for Scour

Magnitude of the incipient overtopping flood (Q_{ot})	Design flood for scour*	Check flood for scour*
$Q_{ot} < Q_{100} < Q_{500}$	Q_{ot} , Q_{100}	Q_{100}, Q_{500}
$Q_{100} < Q_{ot} < Q_{500}$	Q_{100}	Q_{ot} ,Q_{500}
$Q_{100} < Q_{500} < Q_{ot}$	Q_{100}	Q_{500}

*If the Engineer selects a different flood for the design flood for scour or the check flood for scour, it must be approved by the Office of Structures.

Caution should be exercised when selecting the incipient overtopping flood as the design flood for scour or the check flood for scour. It is recommended that the Engineer evaluate the incipient overtopping flood, the 100-year flood and the 500-year flood in the process of determining the worst case condition. It is recognized that available technology has not developed sufficiently to provide fully reliable scour estimates for every site condition. Engineering judgment is needed to assure that scour estimates are reasonable.

11.4.5 Designing Foundations for Scour

Design for the design flood for scour; taking into account the normal geotechnical safety factors used in design: Ensure the foundation remains stable for the specified scour condition for the check flood for scour. This flood serves for investigating the adequacy of the bridge to remain stable and not fail (structural safety factor of at least 1) during a catastrophic flood event. This flood event represents the ultimate loading condition, since a bridge failure may occur for flood flows of a greater magnitude.

Evaluate abutment, pier and contraction scour using the ABSCOUR Program. Obtain estimates of long-term bed degradation and channel lateral movement from stream morphology reports. It is likely that long-term bed degradation will not occur on the flood plain beyond the limits of the channel lateral movement zone, but this assumption should be verified during the design of the structure.

Abutments: Provide scour countermeasures whenever practicable to protect the abutment approach fill and backfill from damage for conditions created by the design flood for scour. If scour countermeasures are not provided at abutments, ensure that the abutment approach fill and backfill are not vulnerable to damage for conditions created by the design flood for scour.

Piers: Normally, the worst-case hydraulic condition (highest channel velocity) for evaluating scour will occur at or near the channel thalweg. Use the worst-case condition to evaluate scour at all piers located within the lateral channel movement zone. Design piers to be structurally stable without reliance on scour countermeasures.

Scour countermeasures: In Maryland, scour countermeasures normally consist of riprap or sheet piling. These measures need to be specifically planned to fit the conditions of the structure under design. Detailed typical examples of riprap installations are set forth in Appendix 11D.

11.4.5.1 Spread Footings within the Channel Lateral Movement Zone

Analyze scour at spread footing foundations for both the design flood for scour and the check flood for scour for the specified design conditions listed below.

Piers and abutments without scour countermeasures: Place the bottom of the spread footing at one foot below the total scour elevation computed by subtracting local scour, contraction scour, and long-term bed degradation from the existing channel elevation.

Abutments with scour countermeasures: Place the top of the spread footing at one foot below the scour elevation computed by subtracting contraction scour and long-term bed degradation from the existing channel elevation. Provide a minimum embedment of the bottom of the spread footing of six feet below the channel thalweg.

11.4.5.2 Spread Footings outside of the Channel Lateral Movement Zone

Analyze scour at spread footing foundations for both the design flood for scour and the check flood for scour for the specified design conditions listed below.

Piers, and abutments without scour countermeasures: Place the bottom of the spread footing at one foot below the total scour elevation computed by subtracting local scour, and contraction scour, from the existing overbank area elevation.

Abutments with scour countermeasures: Place the top of the spread footing one-foot below the elevation of the contraction scour. Provide a minimum embedment of the bottom of the spread footing of six feet below the elevation of the flood plain.

11.4.5.3 Spread Footings on Rock

Design and construct spread footings keyed one-foot minimum into scour resistant rock using construction practices that minimize fracturing and damage to the supporting rock. Evaluate spread footing designs on weathered or other potentially erodible rock formations using the interdisciplinary team and an experienced engineering geologist familiar with the area geology. Estimate the potential scour depth in the rock and place the footing depth below this depth. The footing should be poured in contact with the sides of the excavation for the full designed footing thickness to minimize water intrusion below footing level. Factors to consider include rock cores and analyses, local geology, rock strata, hydraulic data, structure design life and risk to the public.

Use the Erodibility Index Method (Ref. 1) as a guide in the assessment of the quality of the rock. The worksheet developed by the SHA is based on the Erodibility Index Method developed by Dr. George Annandale. See FHWA Manual HEC-18 (Ref. 1), page 7.43 for up-dated guidance on use of the method. This spreadsheet is available at the WEB site listed in the Preface to this Chapter. A geologist or other specialist familiar with rock mechanics needs to be a part of the interdisciplinary team involved in determining the Erodibility Index of the rock and in designing foundations on rock.

11.4.5.4 Deep Foundations within the Channel Lateral Movement Zone

Evaluate deep foundations (Foundations on Piles) for both the design flood for scour and the check flood for scour. Design for the design flood for scour; taking into account the normal geotechnical safety factors used in design: Ensure that the foundation remains stable for the specified scour condition for the check flood for scour.

Design abutments and piers for total scour by subtracting local scour, contraction scour, and long-term bed degradation from the channel elevation. When designing for channel movement, compute the elevation of total scour using the sketch in Figure 11.1. Design pile caps to minimize exposure of piles using the following recommendations:

Piers, and abutments without scour countermeasures: Set top of pile cap at the scour depth elevation for the design flood for scour computed by subtracting contraction scour and long-term bed degradation (as referenced to the channel thalweg) from the elevation of the existing channel bed. When designing for channel movement, compute the elevation of the pile cap using the guidance in the sketch below (Fig. 11.1). For abutments, protect the abutment backfill from damage from being undermined by scour.

Abutments with scour countermeasures: Set bottom of pile cap at the scour depth elevation for the design flood for scour computed by subtracting contraction scour and long-term bed degradation (as referenced to the channel thalweg) from the elevation of the existing channel bed. When designing for channel movement, compute the elevation of the pile cap using the guidance in the sketch below.

For all foundations, determine if exposure of piles is acceptable. A deeper embedment of the pile cap may be warranted where piles could be damaged by erosion or corrosion.

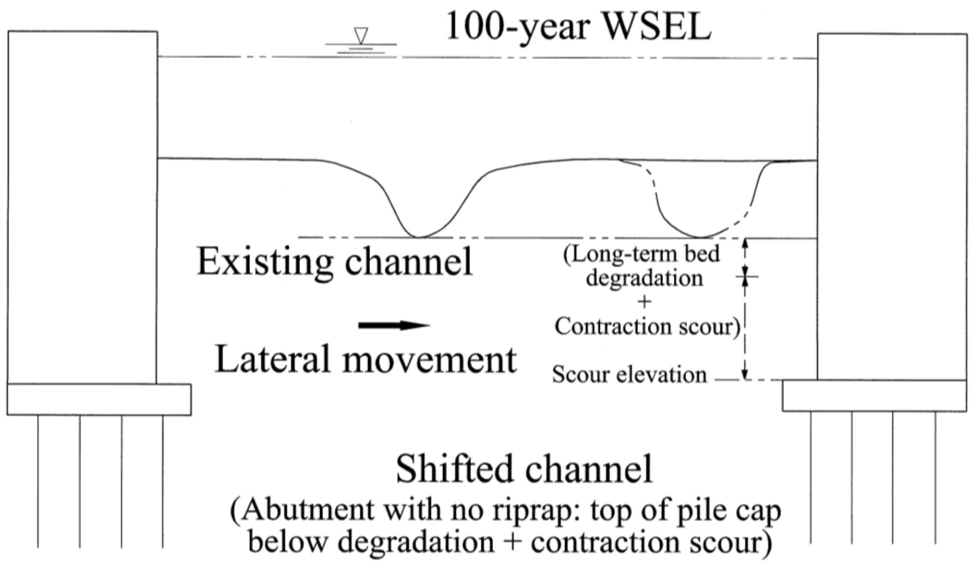


Figure 11.1. Design of Pile Cap for Deep Foundations within the Channel Lateral Movement Zone

11.4.5.5 Deep Foundations Outside of the Channel Lateral Movement Zone

Evaluate deep foundations (Foundations on Piles) for both the design flood for scour and the check flood for scour. Design for the design flood for scour, taking into account the normal geotechnical safety factors used in design. Ensure that the foundation remains stable for the specified scour condition for the check flood for scour. Design abutments and piers for total scour by subtracting local scour and contraction scour from the overbank elevation. Design pile caps to minimize exposure of piles using the following recommendations:

Piers, and abutments without scour countermeasures: Set top of pile cap at the scour depth elevation for the design flood for scour computed by subtracting contraction scour from the elevation of the existing overbank area. For abutments, protect the abutment backfill from damage from being undermined by scour.

Abutments with scour countermeasures: Set bottom of pile cap at the scour depth elevation for the design flood for scour computed by subtracting contraction scour from the elevation of the existing overbank area.

For all foundations, provide a minimum embedment of the bottom of the pile cap of six feet below the flood plain elevation. Determine if exposure of piles is acceptable. Even deeper embedment of the pile cap may be warranted where piles could be damaged by erosion or corrosion.

11.4.5.6 Deep Foundations: Stub Abutments on Spill-Through Slopes

Design stub abutments on spill-through slopes to remain stable in the event that the riprap protection is destroyed, the spill-through slope is eroded, and the piles are exposed. Two methods of analysis are recommended for consideration for this condition (see Figures 11.2a and 11.2b below). Design for the design flood for scour; taking into account the normal geotechnical safety factors used in design. Ensure that the foundation remains stable for the check flood for scour.

The angle of repose of the soil contained in the spill-through slope is an important factor in the stability analysis. Typical ranges of the angle of repose are depicted below:

Table 11.2 Typical values of the angle of repose for selected soils

Material	Typical Angle of Repose (Degrees)
Sand	30
Gravel	31-37
Cobbles	37-39
Clay	56-63

The Soils Lab should be involved in evaluating the angle of repose, since it can vary depending on such factors as density, surface area, and coefficient of friction.

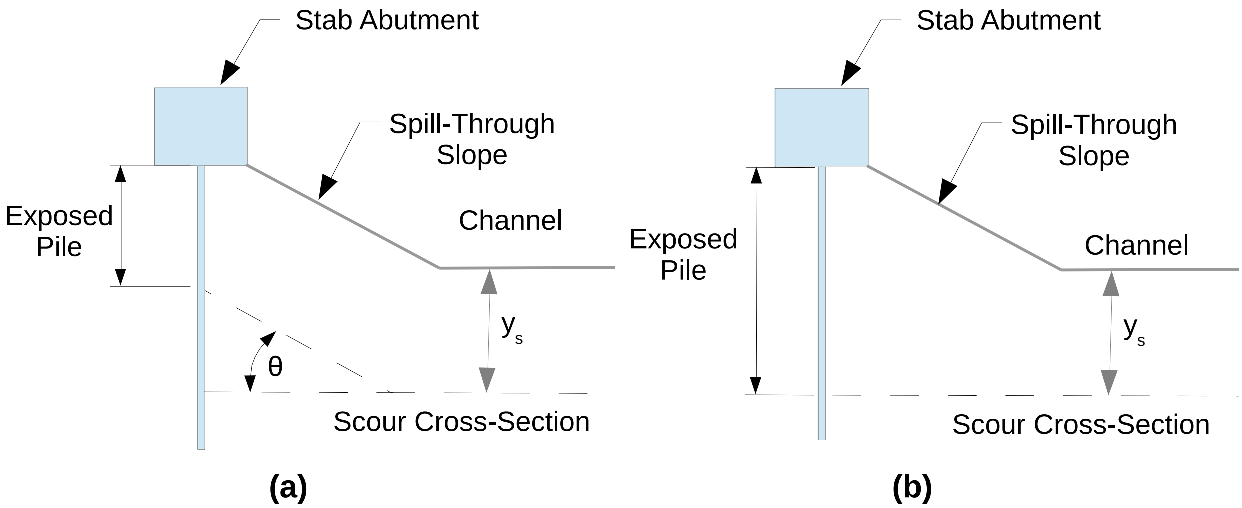
Case 1 and Case 2 described below serve to define an upper and lower limit for scour evaluation. The engineer will need to decide which case is most appropriate for the site being evaluated.

Case 1 is typical of a small stream crossing where the stream has a limited ability to erode the abutment slope.

- Compute the combined effect of contraction scour, channel movement and long-term bed degradation and plot the elevation of this scour depth at the toe of the spill-through slope.
- From this point, assume that the spill-through slope erodes at the angle of repose of the soil (typically 30 degrees for sand) and determine the elevation at which this line for the angle of repose intersects the piles.
- Evaluate the stability of the piles for this condition assuming all soil above the angle of repose has been scoured out. (See Figure 11.2a below).

Case 2 is possible for a larger stream or river with the stream power to completely erode the spill-through slope. This approach may be particularly appropriate for an abutment near the channel bank on the outside of a bend or for a location where it is reasonable to assume that the river will move into the abutment.

- Compute the combined effect of contraction scour, channel movement, and long-term degradation, and plot this total scour depth at the toe of the spill-through slope.
- From this point, draw a horizontal line to the location of the piles.
- Evaluate the stability of the piles for this condition assuming all soil above the zero angle of repose has been scoured out.(See Figure 11.2b below)



y_s = sum of contraction scour, degradation and effect of lateral channel movement. Scour cross-section elevation is used to determine the length of exposed piles for worst-case scour.

θ = angle of repose of backfill material, usually 30 degrees for sand

Figure 11.2. Stub Abutments on Spill-through Slopes

(a) Case 1: A Small Stream With A Limited Capacity To Scour The Spill-Through Slope
(b) Case 2: A Large River Where The River Moves Into The Abutment.

11.4.5.7 Abutments Utilizing Mechanically Stabilized Earth (MSE)

Under some site conditions, abutments constructed with MSE walls have been considered to be cost-effective alternatives to standard abutment designs. However, the MSE walls may be vulnerable to scour, and may need to be protected with a scour wall designed for worst case conditions of scour as described earlier in this chapter.

11.5 General Location and Design Features

11.5.1 Location Considerations

Rivers are dynamic, continually changing their dimensions, patterns and profile in response to changes in the discharge and sediment load carried by their channels. Bridges are static and remain in a fixed location. The task of the interdisciplinary team is to locate and size the structure to remain stable throughout its design service life, and to accommodate the anticipated flood discharges, sediment loads and accompanying changes in the river that will occur during this time.

It is generally safer and more cost effective to avoid hydraulic problems through the selection of favorable crossing locations than to attempt to minimize the problems at a later time in the project development process through design measures.

To the extent practicable, bridges over waterways and their approach roadways on flood plains shall be located to provide for the desired level of traffic service and safety and to:

- be consistent with flood plain management objectives and strategies, discouraging uneconomic, hazardous or incompatible use and development of flood plains,
- avoid changes to the bankfull flow conditions,
- minimize changes to existing flood flow distribution and elevations in the channel and on the flood plain, upstream, through and downstream of the bridge, particularly where such changes may adversely affect improved properties in the flood plain,
- minimize adverse changes to wetlands and other sensitive environmental features within the river's flood plain,
- select favorable crossing sites where the hydraulic flow conditions and resulting scour can be analyzed and accounted for within a reasonable degree of confidence,
- avoid locations of complex or hazardous hydraulic flow conditions (stream confluences, alluvial fans, sharp bend sections, alignments with high skew angles, sections with special problems with ice build-up or debris accumulation, etc.) conducive to the development of hazardous scouring at bridge abutments and piers.
- achieve the above objectives in a cost-effective manner, giving appropriate attention to their importance as well as the costs of construction, operation, maintenance and inspection associated with the structure.

11.5.2 Evaluation of Alternative Location Sites

The choice of location of bridges shall be supported by analyses of alternatives. The scope of such studies should be commensurate with the risks involved. Studies of alternative crossing locations should include assessments of:

- the hydrologic, hydraulic and morphological characteristics of the waterway and its flood plain, including channel stability, flood history and in estuarine crossings, tidal ranges and cycles,
- the effect of the proposed bridge on flood flow patterns and the resulting scour potential at bridge foundations,
- the potential for creating new or augmenting existing flood hazards,
- environmental impacts on the waterway and its flood plain, and
- life cycle costs of each alternative.

Experience at existing bridges in the vicinity of the project should be used to evaluate the reasonableness of all computations and conclusions regarding the proposed structure and can be helpful in selecting the type, size and location of the structure.

Further guidance on procedures for evaluating the location of bridges and their approaches on flood plains is contained in Chapter 9, Channels, and Chapter 10, Hydraulic Design of Bridges. Other references include those of the Federal Highway Administration and the American Association of State Highway and Transportation Officials (AASHTO). See References 1, 2, 3, 4, 14 and 15.

11.6 Bridge Scour Evaluation Studies and Reports

11.6.1 General

Submit Scour Evaluation Reports to the OOS for review and approval. Submit the final report both as a hard copy report and on a computer disk. In addition, fill out and date the Hydraulics and Hydrology (H&H) sheet and summary report presented in Chapter 4, and include it as a part of the final submission. The scour report and scour cross-section developed using the ABSCOUR program is also an integral part of every scour evaluation report.

Each bridge scour evaluation report should be developed to address the stability of the structure for the perceived worst case scour conditions at the site, the resulting effect on the safety of the traveling public and the measures to be taken to assure the appropriate degree of inspection and maintenance of the structure. The studies and information that should be addressed in scour reports are listed below:

- Introduction and background
- Scope of study
- Summary and Recommendations
- Hydrology study,
- Site investigation,
- Stream classification, geomorphology, and stability study. (The scope of such studies are defined by the level of detail required and may range from simple field classifications and evaluations (Level 1 analyses) to detailed stream sedimentation studies (Level 3 analyses),
- Subsurface investigation of underlying soils and rock, based on borings,
- Type, size and location of the bridge, including the geometry and dimensions of the superstructure and substructure elements and any proposed scour countermeasures,
- Line, grade and typical sections of the approach roadways,
- Hydraulic study, including evaluation of the consistency of the proposed design with the objectives of State and Federal policies and criteria regarding flood plain management,
- Scour evaluation and development of the scour cross-section under the bridge,
- Significance of scour evaluation,
- Structural and geotechnical design considerations,
- Scour countermeasures,
- Appendices, and
- Documentation

Each of these studies or report items, along with references of manuals and guidelines which provide further direction and guidance, is addressed in the following sections.

11.6.2 Introduction and Background

This section of the report should provide information on the highway section under design, the traffic it carries and other information regarding the need for the bridge project.

11.6.3 Scope of Study

The accuracy of the scour evaluation for a proposed bridge site is highly dependent upon the accuracy of the hydrologic and hydraulic data used in the equations for estimating the scour depths.

The scope of the bridge scour studies will depend upon the degree of accuracy to be achieved in the analysis. It is expected that water surface profiles will be developed for the reach of the river under study. One-dimensional hydraulic models such as the Corps of Engineers HEC-RAS model is commonly used for this purpose (See References 10 and 12). However, sites with complex flood flow patterns may warrant the use of a two dimensional model, such as the FESWMS model, to establish the hydraulic flow conditions (Reference 11). For tidal flows, different methodologies involving one and two-dimensional models are needed to define the hydraulic flow conditions. See Chapter 10 and References 11 and 13. Where conditions warrant, such as a major structure with complex hydraulic flow conditions, physical models can be used to more accurately evaluate the flow and resulting scour in the bridge opening. The selection of the study scope and the methodologies to be used in the analysis are among the most important decisions to be made in the preparation of a scour evaluation report.

One-dimensional models are based on the assumption that the slope of the energy line of the flood flow at any cross-section is the same across the entire cross-section. For many streams and rivers, this assumption provides for a reasonable approximation of the relationship between the flow in the river and the flow on the flood plain. Various techniques are built into the models to account for the more complex flow patterns which occur just upstream of a bridge crossing. One-dimensional models serve best for streams with relatively narrow flood plains where most of the flood flow is carried by the main channel.

Two-dimensional models are developed to account for changes in the energy slope longitudinally along the river and laterally between the channel and the flood plain. A two-dimensional network of triangles or quadrilaterals is established and the flow is calculated into and out of each of the network elements. The output is a plan view of the river and flood plain with vectors depicting the direction and velocity of the flow at each of the network elements. The water surface elevation and the magnitude of the flow are also provided at each network element.

While the two-dimensional model provides more information for use in a scour analysis, the cost and the time required for its application is greater. The engineer must decide which type of model is most appropriate for use based on traffic service and safety considerations, the extent of the flooding hazard and the particular site conditions at the proposed river crossing.

11.6.4 Summary and Recommendations

It is helpful to readers of the report to place the summary and recommendation section near the beginning of the report to provide an overview of the results of the scour evaluation. It should include a drawing of the scour cross-section which depicts the horizontal and vertical locations of the various foundation elements in relation to the estimated scour. Proposed scour countermeasures should also be included.

11.6.5 Hydrology Study

Appendix A presents a convenient method of summarizing hydrologic, hydraulic and bridge scour data that is currently being used by a state highway agency. SHA policies and procedures regarding Hydrology Studies are addressed in detail in Chapter 3, Policy, Chapter 8, Hydrology and in Chapter 10, Hydraulic Design of Bridges. The following discussion provides an overview of hydrologic considerations for bridge scour and stream stability study reports.

The assessment of hydrologic site conditions necessarily involves many assumptions. Key among these assumptions involves the prediction of flow magnitudes for floods with high recurrence intervals, e.g., the 500-year flood. The runoff from a given storm can be expected to change with the seasons, immediate past weather conditions and long-term natural changes or development of the watershed.

The ability to statistically predict such rare flood events is a function of the adequacy of the data base of past floods, and such predictions often change as a result of the addition of new data. The above factors make the check flood investigation of scour an important, but highly variable, safety criterion.

The assumptions used by the engineer to predict the magnitude and frequency of flood peaks used for the design and check floods for scour must be reasonable with respect to the data, conditions and projections available at the time of the bridge design. These assumptions need to be identified and documented in the hydrology study and report.

In general, use ultimate development land use, or if a TR-20 model is not available, use the upper limit of the 67% confidence interval from the Tasker Analysis.

The general trend is that the magnitude of scour increases with the magnitude of the river discharge, but this may not always be true. It is possible that the worst-case scour condition may occur for a discharge other than the design flood for scour or the check flood for scour. Such conditions may be most likely to occur at confluences or in controlled rivers with highly variable tail water. It is the responsibility of the Engineer to verify that the flows selected for analysis represent worst-case conditions for scour.

The recurrence intervals, periods and elevations of storm tides used to predict tidal scour should be correlated with the hurricane or storm tide elevations as reported in studies by the Federal Emergency Management Agency (FEMA), the Corps of Engineers (COE), the National Oceanic and Atmospheric Administration (NOAA) or other agencies.

The SHA and the Maryland Department of the Environment have jointly developed procedures for estimating peak flood flows in Maryland using the Maryland GIS Hydro 2000 Program. Detailed guidance on the methodology to be used in estimating flood peaks is presented in the publication “Application of Hydraulic Methods in Maryland dated February 1, 2001. Bankfull stages and discharges are normally obtained from field surveys as discussed in Chapter 9, Channels.

The scope of the hydrology study should be determined on the basis of the functional highway classification, the applicable federal and state requirements, and the flood hazards at the site. A range of flood flows should be determined to evaluate (1) the hydraulic adequacy of the proposed waterway opening of the bridge, (2) the effect of the bridge on the river, (3) the effect of the river on the bridge, and (4) the worst case conditions for designing the bridge foundations to resist scour. The development of a flood frequency plot is recommended to depict the magnitude of flood flows for recurrence intervals from the 1.5-year flood (typically bankfull stage for natural rivers) to the 500-year flood.

The riverine flood flows, storm tides or mixed population events listed in Section 11.1.3, Definitions, should be considered for use for the evaluation of stream stability and the design of the bridge waterway and foundations (See Reference 4). *Particular attention should be given to selecting design and check flood discharges for mixed population flood events.* For example, flow in an estuary may consist of both tidal flow and runoff from the upland watershed. If the mixed population flows are both dependent on the occurrence of a major meteorological event, such as a hurricane, the relative timing of the individual peak flow events needs to be evaluated and considered in selecting the design discharge. This is likely to be the case for flows in an estuary. If the events tend to be independent, as might be the case for floods in a mountainous region caused by rainfall runoff or snow melt, the Engineer should evaluate both events independently and then consider the probability of their occurring at the same time.

11.6.6 Site Investigation

A site-specific data collection plan should be developed for the proposed bridge crossing. Development of this plan is discussed in detail in Chapter 6, Data Collection. The following information should be considered in the preparation of the bridge scour report:

- collection of aerial and/or ground survey data for appropriate distances upstream and downstream from the bridge for the main stream channel and its flood plain,
- estimation of roughness elements for the stream and the flood plain within the reach of the stream under study,
- subsurface information including borings, soil and/or rock samples, and soil and/or rock testing,
- factors affecting water stages, including high water from streams, reservoirs, detention basins, tides and flood control structures and operating procedures,
- stream confluences,
- existing studies and reports including those conducted in accordance with the provisions of the National Flood Insurance Program or other flood control programs,
- improved properties on the flood plain,
- available historical information on the behavior of the stream and the performance of existing structures during past floods, including observed scour, bank erosion and structural damage due to scour, debris or ice,
- information on the stream channel including the bankfull cross-section, slope, plan form and materials in the stream bed and banks,
- Special studies may be warranted in some cases to collect detailed information regard the potential effect of ice, debris or bed forms to affect stream stability and the extent of scour at the bridge.
- Information obtained from field inspections and office reviews needs to be carefully identified and documented so that the source data used in the bridge scour evaluation can be identified and located at a later date.

11.6.7 Stream Classification, Morphology and Stability Study

A study is needed to evaluate the stability of the waterway and to assess the effect of the proposed highway/bridge construction on the waterway. The results of this study should include an assessment of the magnitude of the long term aggradation or degradation of the stream bed at the bridge site. It should also include an assessment and projection of the long term tendency of the stream to move laterally as a result of meander patterns, potential cutoffs of goose neck bends, etc. (See Chapter 14). This information may be of prime importance in the location and sizing of the bridge. In some instances, it may indicate that a crossing should not be attempted for the reach of the stream under study.

A stable stream can be defined as one with the ability, over time, to carry discharges and sediment loads in a manner that maintains its dimension (cross-section), pattern (plan form) and profile (slope) so that the channel neither aggrades nor degrades. If the stream to be crossed is stable, appropriate design measures need to be taken to assure that the highway/bridge construction maintains the existing flow conditions. Since minor changes in any of the above factors may cause a stream to meander and change the lateral location of its bed and banks, the likely future lateral movement of the stream needs to be considered in the bridge location and design.

If the stream is unstable, appropriate measures need to be taken to protect the structure from anticipated aggradation or degradation of the channel bed, or from lateral movement and sloughing of its banks as a result of the stream instability. The Office of Structures has developed detailed procedures for the evaluation of stream stability, as set forth in Chapter 14

11.6.8 Subsurface Study of Underlying Soil and Rock

Exploration of underlying soil and rock is essential for the geotechnical design of the bridge foundations, and subsurface exploration studies are normally planned and carried out by the geotechnical and bridge foundation engineers (See Reference 20). This information is also important in predicting the extent of scour which will occur in the channel and at the various piers and abutments. The question of the timing of the soil exploration needs to be considered early in the project development process, since the use of this information for the hydraulic and scour studies is often required at an earlier date than for the foundation design. In some cases, it may be necessary to obtain preliminary information for the scour analysis, followed up at a later date by final borings for the individual foundation elements. This type of approach requires coordination with the geotechnical engineers.

It is helpful to prepare subsurface profiles of the various soil layers and the location of the rock for purposes of evaluating the effect of the soils and rock on the total scour to be expected at the bridge crossing.

11.6.9 Type Size and Location of the Bridge (TS&L)

It is necessary to have information about the bridge dimensions and geometry for purposes of estimating contraction scour and local scour at piers and abutments. It is desirable to conduct the scour evaluation at an early stage in project development so that any needed changes to the bridge design can be more easily made to avoid serious potential scour problems. The TS&L stage of the project development process is a desirable stage for the consideration of the significance of scour. When complete information on the factors affecting scour is not available, it may be appropriate to make preliminary scour studies for purposes of establishing the significance of the scour problem. The estimates of scour can then be refined at a later date when more information becomes available.

The structural, hydraulic, and geotechnical aspects of foundation design need to be coordinated and differences resolved at the time of the foundation review.

In developing the bridge TS&L, consideration should be given to the following general design concepts to reduce the vulnerability of the bridge to scour damage:

- set deck elevations as high as practical for the given site conditions to minimize overtopping by floods, and to provide for freeboard for passage of ice and debris,
- utilize relief bridges, guide banks, dikes and other river training devices as appropriate to reduce the turbulence and hydraulic forces acting at the bridge foundations,
- utilize continuous span designs, anchor superstructures to their substructures where subject to the effects of hydraulic loads, buoyancy, ice or debris impacts or accumulations, and provide for venting and draining the superstructure,
- locate abutments back from the channel banks to minimize problems with ice/debris build up, scour or channel stability, or where special environmental or regulatory needs must be met, e.g., spanning wetlands, and
- where practical, limit the number of piers in the channel; use cylindrical piers to minimize the effect of the angle of attack; where cylindrical are not feasible, streamline pier shapes and align piers with the direction of flood flows; avoid pier types that collect ice and debris; locate piers beyond the immediate vicinity of stream banks,
- design piers on flood plains as river piers and locate their foundations at the same depth as the river piers if it is likely that the stream channel will shift during the life of the structure or that channel cutoffs are likely to occur,
- where ice or debris build-up is likely to occur, their effects should be minimized by providing for freeboard and streamlining bridge elements. Furthermore, anticipated ice and debris build-up needs to be accounted for in determining scour depths and hydraulic loads.

The stream hydrology, hydraulics and geomorphology need to be considered in the selection of a structure location, size and type that is compatible with the existing stream conditions. This includes consideration of the items listed below:

- whether the stream reach is degrading, aggrading or in equilibrium,
- for stream crossing near confluences, the effect of the main stream and the tributary on the flood stages, velocities, flow distribution, vertical and lateral movements of the stream, and the effect of the foregoing conditions on the hydraulic design of the bridge, location of a favorable stream crossing site, taking into account whether the stream is straight, meandering, braided or transitional; use of control devices to protect the bridge from existing or anticipated future adverse stream conditions,
- the effect of any proposed channel changes,
- the effect of dredging, aggregate mining or other operations in the channel,
- potential changes in the rates or volumes of runoff due to land use changes,
- the anticipated effect of the structure on the existing stream plan form, profile and cross-section and anticipated changes to the structure due to future changes in the stream geomorphology.

11.6.10 Approach Roadways

It is necessary to have information about the line, grade and typical section of the approach roads to the bridge for the entire flood plain in order to evaluate the effect of the proposed construction on flood plain flows. Highway embankments on flood plains serve to redirect overbank flow, cause it to flow generally parallel to the embankment and return to the main channel at the bridge. For such cases, the highway designs should include countermeasures where necessary to limit damage to highway fills and bridge abutments. Such countermeasures may include:

- relief bridges,
- slope protection of riprap or other types of countermeasures

Where bridges are subject to overtopping, develop the roadway/bridge profile so that one or both roadway approaches are at a lower elevation than the bridge. This provides for overtopping of the roadway approach section(s) before overtopping of the bridge, thus providing relief from the hydraulic forces acting on the bridge. This is particularly important for streams carrying a heavy ice or debris load which may clog its waterway opening.

Special hydraulic design problems may need to be dealt with on wide flood plains including the need for relief structures and the possible pocketing of flood plain waters at skewed crossings.

11.6.11 Hydraulics Study

Agreement should be reached at an early stage of project development regarding the analytical models and techniques to be used and whether they are consistent with the required level of accuracy. Where appropriate, consideration should be given to the use of laboratory studies to determine information that cannot be obtained from analytical models. The hydraulic study needs to be performed to a sufficient degree of accuracy so as to (1) size the waterway opening and (2) evaluate scour at the bridge. These two aspects of the bridge design are interdependent and should not be considered as separate, independent studies. Where use is made of existing flood studies, their accuracy should be evaluated at an early stage in the design process so that any necessary additional studies can be carried out in a timely manner.

Specific guidance and policies for the conduct of hydraulic studies are set forth in Chapter 3, Policy, Chapter 9, Channels, and Chapter 10, Hydraulic Design of Bridges.

Special procedures are set forth in Chapter 10 to define worst case scour conditions for tidal waterways. Once the worst case flow conditions are established, the scour evaluation will normally follow the same procedure used for riverine channels.

11.6.11.1 Hydraulics Considerations for Sizing the Bridge Waterway

The design process for sizing the bridge waterway should include:

- the evaluation of flood flow patterns in the main channel and flood plain for existing conditions, and
- the evaluation of trial combinations of highway profiles, alignments and bridge lengths for consistency with the design objectives.

Trial combinations should take the following into account:

- increases in flood water surface elevations caused by the bridge,

- changes in flood flow patterns and velocities in the channel and on the flood plain,
- location of hydraulic controls affecting flow through the structure or long-term stream stability,
- clearances between the flood water elevations and low sections of the superstructure (free board) to allow passage of ice and debris,
- need for relief structures on the flood plain,
- need for protection of bridge foundations and stream channel bed and banks, and
- Evaluation of capital costs and flood hazards associated with the candidate bridge alternatives through risk assessment or risk analysis procedures.

11.6.11.2 Hydraulics Considerations for Conducting Bridge Scour Evaluations

Once a preliminary bridge alternative and waterway opening has been selected, it should be evaluated for its adequacy to resist scour. In this evaluation, particular attention needs to be given to developing accurate estimates of the following hydraulic parameters at (1) the upstream approach section, (2) the bridge crossing and (3) the downstream full valley section for bridge scour studies. Estimated scour depths will be quite sensitive to these values:

- Unit flow discharges (discharge per foot) on the left overbank, right overbank and main channel,
- Flow depths and velocities for the unit flow discharges noted above,
- Vegetation, its critical shear strength and roughness for overbank areas,
- Evaluation of stream morphology and it's effect on the proposed bridge design,
- Particle size distribution and shear strength of soils in the channel bed and banks and in the overbank areas,
- Flow distribution and velocity distribution in the section immediately upstream of the bridge and in the bridge cross-section,
- Placement of foundations to minimize obstructions to the flow (spanning of channels where feasible, locating piers away from the channel thalweg, etc.)
- Tail water elevations in the downstream section,
- Superstructure geometry and its effect in the initiation of pressure scour.

Trial combinations should take the following into account:

- increases in flood water surface elevations caused by the bridge,
- changes in flood flow patterns and velocities in the channel and on the flood plain,
- location of hydraulic controls affecting flow through the structure or long-term stream stability,
- clearances between the flood water elevations and low sections of the superstructure (free board) to allow passage of ice and debris,
- need for relief structures on the flood plain,
- need for protection of bridge foundations and stream channel bed and banks, and

- evaluation of capital costs and flood hazards associated with the candidate bridge alternatives through risk assessment or risk analysis procedures.

Once a preliminary bridge alternative and waterway opening has been selected, it should be evaluated for its adequacy to resist scour. In this evaluation, particular attention needs to be given to developing accurate estimates of the following hydraulic parameters at (1) the upstream approach section, (2) the bridge crossing and (3) the downstream full valley section for bridge scour studies.

Every effort should be made to minimize changes to existing flood flow patterns and elevations in the channel and on the flood plain, upstream, through and downstream of the bridge, particularly where such changes will adversely affect improved properties in the flood plain.

11.6.12 Scour Evaluation; Development of the Bridge Scour Cross-Section

Scour at bridge foundations is to be investigated for the two conditions presented below (See Reference 4). Section 11.6.5 establishes the hydrologic definitions of these flood flows.

11.6.12.1 The Design Flood for Scour

The stream bed material in the scour prism above the total scour line shall be assumed to have been removed for design conditions. For piles and other types of deep foundations, the normal foundation design procedures and criteria are to be followed, except that no soil support is to be considered for soils in the scour prism above the total scour line.

11.6.12.2 The Check Flood for Scour

The stream bed material in the scour prism above the total scour line shall be assumed to have been removed for this condition. For piles and other types of deep foundations the normal foundation design procedures and criteria are to be followed, except that:

- no soil support is to be considered for soils in the scour prism above the total scour line. Deep foundations, such as piles, shall be designed using normal foundation design procedures, but with no soil support available above the total scour line.
- excess reserve beyond that required for stability under this condition is not necessary.

11.6.12.3 Scour Estimates

The ABSCOUR 10 Program is to be used to estimate scour at bridges and bottomless arch culverts. Detailed information on this program is contained in the program help files and in Appendix A of this chapter.

11.6.12.4 Other Considerations

When fenders or other pier protection systems are used, their effect on pier scour and collection of debris shall be taken into consideration in the design.

11.6.12.5 Scour Evaluation Procedure

The design flood for scour shall be determined on the basis of the Engineer's judgment of the hydrologic and hydraulic flow conditions at the site. The recommended procedure is to evaluate scour due to the specified flood flows and to design the foundation for the event expected to cause the deepest total scour. The recommended procedure for determining the total scour depth at bridge foundations is as follows:

- evaluate the long-term channel profile aggradation or degradation over the service life of the bridge as per Chapter 14.
- evaluate the long-term channel plan form changes over the service life of the bridge, and evaluated the extent of the Channel Lateral Movement Zone (CLMZ) as explained in Chapter 14.
- consult with the SHA on the findings of the above evaluations; determine jointly the need for any revised cross-sections to reflect anticipated long term changes,
- determine the combination of existing or likely future conditions and flood events that might be expected to result in the deepest scour for design conditions,
- determine water surface profiles for a stream reach that extends both upstream and downstream of the bridge site for the various combinations of conditions and events under consideration, and select the worst case condition for scour. Where the worst case condition is not obvious, select several cases for detailed study,
- determine the magnitude of total scour at piers and abutments,
- determine the total scour which will occur at the bridge and plot the total scour line for both the design flood for scour and the check flood for scour.

11.6.12.6 Scour Evaluation Review

The Engineer needs to decide the most appropriate method for combining the various scour elements. In most cases, a reasonable approach will be to add the long term degradation to the scour estimates obtained from ABSCOUR. If degradation values are large, additional evaluation of this simplified procedure may be necessary.

Foundation designs should be based on the total scour depths estimated by the above procedure, taking into account appropriate geotechnical safety factors. Where necessary, to minimize or avoid a hazard resulting from scour, bridge modifications may include:

- relocation of the crossing to avoid an undesirable location.
- relocation or redesign of piers or abutments to avoid areas of deep scour or overlapping scour holes from adjacent foundation elements,
- enlargement of the bridge waterway area or addition of guide banks, dikes or other river training works to provide for smoother flow transitions or to control lateral movement of the channel, or
- installation of scour countermeasures.

Foundations shall be designed to withstand the conditions of scour for the design flood and the check flood. In general, this will result in deep foundations. The design of the foundations of existing bridges that are being rehabilitated should consider underpinning or supplemental bents if the scour evaluation indicates the need. Riprap and other scour countermeasures in combination with monitoring may be appropriate if underpinning is not cost effective.

11.6.13 Significance of the Scour Evaluation

- Evaluate the results of the scour analysis, taking into account the probable accuracy of the variables in the methods used, whether or not the scour prediction equations are appropriate for the given site conditions, the available information on the behavior of the watercourse, and the performance of existing structures during past floods. Also, consider present and anticipated future flow patterns in the channel and its flood plain,
- Develop a mental picture of the existing flow patterns, how they will be affected by the bridge and how these changed conditions will affect the stability of the bridge,
- Modify the scour evaluation as necessary to assure that the evaluation is consistent and reasonable.
- Modify the bridge design or location as necessary to satisfy concerns raised by the stream stability scour analyses.

Structural and Geotechnical Design Considerations

Since the results of the scour evaluation will have an effect on the foundation design of the structure, it is important that persons conducting the hydraulics, structures and geotechnical studies work together in the conduct of their respective studies. As noted earlier in this guide, the structural, hydraulic and geotechnical aspects of foundation design need to be coordinated and differences resolved prior to the approval of the TS&L.

11.6.14 Scour Countermeasures

Scour countermeasures are features incorporated into the design of a bridge for purposes of preventing, delaying or reducing the severity of hydraulic problems and resulting scour. Specific guidance, policy and design procedures for scour countermeasures are included in Chapter 11, Appendix D and Reference 7

The recommended solutions for minimizing scour damage at new bridges include:

- Locating the bridge to avoid adverse flood flow patterns,
- Streamlining bridge elements, using features such as round piers, to minimize obstructions to the flow,
- Designing pier foundations to be stable for the worst case scour condition so that
- reliance on riprap or other similar types of scour countermeasures is not necessary (Section 5.12.3), and
- Designing abutment foundations in accordance with Section 11.6.12.4, using stone riprap, or other types of materials to protect the highway embankment and
- channel banks adjacent to the abutment.

For existing bridges, the alternatives available for protecting the bridge from scour are listed below in a rough order of cost:

- Monitoring scour depths and closing bridge if excessive,
- Providing riprap or other types of scour countermeasures at piers and abutments, when combined with monitoring,
- Constructing guide banks (spur dikes) to streamline the flow and reduce scour at the abutments,
- Constructing channel improvements,
- Strengthening the bridge foundations,
- Constructing sill or drop structures to control degradation and scour, and
- Constructing relief bridges or lengthening existing bridges

A number of considerations may affect the selection of an appropriate scour countermeasure including:

- The type of scour problem to be addressed, and the assessment of the risk involved,
- The experience in the area or region with the success or failure of various types of scour countermeasures,
- The design criteria and specifications of the bridge owner and the ability of the contractor to construct with available materials the installation envisioned by the designer, and
- The availability and cost of alternative scour countermeasures.

These factors warrant careful consideration by the engineer during the design and installation of the countermeasure. Periodic inspection and evaluation of such countermeasures are necessary to assure that the installation is intact and is able to perform its function of scour protection.

There are currently a considerable number of types of scour protection that can be used in place of riprap including sheet piling, grout bags, gabions, articulated revetment units, concrete linings, and various other types of commercially made materials. Guidance on the selection, design and installation of various types of scour countermeasures and filter materials is included in the Federal Highway Administration Publications (See References 7).

Where available, stone riprap is generally preferred as a scour countermeasure at bridges. The equations in Reference 1 are recommended for the selection of an appropriate riprap size for protecting bridge piers and abutments, since they are based on the Ishbash criteria for incipient motion of particles. The Corps of Engineers method is recommended for design of bank protection.

A recurring question with regard to the use of sheet piling is whether it should be pulled or cut off below ground elevation and left in place. This decision requires the exercise of engineering judgment with regard to the particular site conditions and the following considerations:

- pulling the sheet piling may permit the contractor to get salvage value or possible reuse at another site; however, the process of pulling the sheet piling tends to disturb the ground around the bridge foundation element and could accelerate local scour.
- Sheet piling left in place could be exposed by contraction scour and general degradation, thereby effectively increasing the width of the foundation element. This condition may cause additional local scour.
- Sheet piling left in place and backfilled and protected with an erosion resistant material may serve as an effective countermeasure, particularly if it is not exposed much above the stream bed.

There are available a number of types of natural or bio-engineering materials which, if properly designed and installed, can serve effectively as bank protection materials. These include such features as willow planting, root wads and other vegetative type treatments. Installation of natural materials requires special experience and training, and it may be prudent to use a design-build type of contract for these materials.

These natural or environmental treatments are not recommended for use at locations involving the integrity of the highway/ bridge or the safety of the persons using the highway. However, they can serve effectively in other less critical locations where a failure will not endanger lives or damage developed properties.

11.6.15 Appendices to the Scour Report

Appendices should include input to and output from computer models, plots of the location of subsurface borings along with the results of tests and measurements made of the soil and rock, scour computations, etc.

11.6.16 Documentation

Project documentation involves a system for keeping track of all significant field data, assumptions, the computer models used, input to and output from the computer models and other information on which the scour estimates are based. It is desirable to keep this information on file as hard copy as well as on computer storage disks.

The Office of Structures has developed a Hydraulics and Hydrology (H&H) Sheet and Report which is to be completed as a part of the hydrology, hydraulic and scour evaluation for bridge structures. The report is presented in Chapter 4, Documentation. The H&H Sheet is to be included as a part of the permanent bridge plans for each bridge design.

11.7 Scour Assessment Studies

In some instances, the interdisciplinary scour team may determine that a full scour evaluation report is not needed to assure that a structure can be designed and constructed in a manner that meets the intent of this guideline. An example of this type of situation might include replacement of a superstructure on an existing foundation over a stable stream when the existing piers and abutments are founded on erosion resistant rock and the footings are located below the channel thalweg. For such situations, a scour assessment report may be prepared which generally addresses the topics listed in Section 11.6 and provides the judgmental factors which serve to support the adequacy of the proposed design. If the scour assessment report cannot provide a reasonable basis on which to support the proposed design, then a more detailed scour evaluation report should be undertaken. Scour evaluations and assessments for county projects are discussed in Appendix 11F.

11.8 Changes in Foundation Conditions Due to Scour

Scour is not a force effect, but by changing the conditions of the substructure it may have a significant effect in altering the force effects acting on structures. The AASHTO Standard Specifications set forth detailed requirements for applying loads and load factors to bridge foundations (Reference 4). The consequences of changes in foundation conditions resulting from the design flood for scour shall be considered. Structures will be designed under this provision using normal design considerations and factors of safety selected by the foundation engineer. The assumption is made that all material in the scour prism has been removed and is unavailable for foundation support. The effect of the check flood for scour is to be considered with respect to the stability of structures over water. In the evaluation of this condition, the assumption is made that all material in the scour prism has been removed and is unavailable for foundation support. The structure is to remain stable for this condition, but is not required to have any reserve capacity to resist loads.

11.9 Scour in Bottomless Arch Culverts

Refer to Appendix 11C for policy and guidance on the design of culverts on footings.

11.10 Temporary Structures

Temporary structures for the Contractor's use or for accommodating traffic during construction shall be designed with regard to the safety of the traveling public and adjacent property owners as well as minimization of impacts to the stream channel and its flood plain (See References 4 and 20). The SHA may permit revised design requirements consistent with the intended service period for flood hazard posed by the temporary structure. Contract documents for the temporary structure shall delineate the respective responsibilities and risks to be assumed by the SHA and the contractor (See Chapter 19, Section 5, Temporary Structures and Flow Diversions)

References

1) Federal Highway Administration, Hydraulic Engineering Circular Number 18, *Evaluating Scour at Bridges*, Fifth Edition, April 2012.
2) Federal Highway Administration, Hydraulic Engineering Circular Number 20, *Stream Stability at Highway Structures*, Fourth Edition, 2012.
3) Federal Highway Administration, Hydraulic Engineering Circular Number 23, *Bridge Scour and Stream Instability Countermeasures*, Volumes 1 and 2, 2009
4) AASHTO LRFD Bridge Design Specifications, 2010
5) AASHTO Drainage Guidelines, Fourth Edition, 2007
6) Bridge Pressure Flow Scour for Clear Water Conditions, (See FHWA HEC-18)
7) SHA, Highway Drainage Manual and Supplements, thereto, 1981
8) Federal Highway Administration Memorandum from Chief, Bridge Division, to Regional Federal Highway Administrators dated July 19, 1991 on the subject of Scourability of Rock Formations.
9) Federal Highway Administration Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges, 2003.
10) U.S. Code of Federal Regulations, 23 CFR 650, Subpart A.
11) Corps of Engineers HEC-RAS (River Analysis System) User's Manual, Version 4.1 January 2010
12) Froehlich, D. C., Finite Element Surface-Water Modeling System, FESWMS-2DH, Version 2 User's Manual, FHWA Research Report, 1996.

13) Surface Water Modeling System (SMS) Reference Manual, Brigham Young University, Version 3.1.5, 2003

14) Corps of Engineers Hydraulic Engineering Center, UNET-- One Dimensional Unsteady Flow Through a Full Network of Open Channels, User's Manual,

15) HEC, "UNET – One-Dimensional Unsteady Flow Through a Full Network of Open Channels", User's Manual, CPD-66 Version 3.2, US Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, 1997.

16) Federal Highway Administration, HDS-6, *Highways in the River Environment*. December 2001.

17) Neill, C. R., Guide to Bridge Hydraulics, Roads and Transportation Association of Canada, 2001 Edition.

18) Maynord, Steven T., Toe Scour Estimation in Stabilized Bendways, Technical Note, Journal of Hydraulic Engineering, August 1996.

19) Applied River Morphology, David Rosgen, Wildland Hydrology, Pagosa Springs, Colorado, 1996.

20) Stream Channel Reference Sites, An Illustrated Guide to Field Techniques, United States Department of Agriculture, Forest Service, General Technical Report RM-245, April, 1994.

21) Office of Structures Manual for Hydrologic and Hydraulic Design, 2015