Advancements in Bridge Scour Evaluation with Two-Dimensional Hydraulic Modeling using SRH-2D / SMS

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Abstract

The US Federal Highway Administration (FHWA) has promoted the use of two-dimensional hydraulic modeling for bridge hydraulic analysis for many years, and in recent years adopted the US Bureau of Reclamation (Reclamation) SRH-2D model. Reclamation and FHWA have since worked in partnership to incorporate new hydraulic structure features into SRH-2D and have facilitated a custom graphical user interface in the Surface Water Modeling System (SMS, by Aquaveo) that includes powerful tools for analyzing and communicating results to others. Most recently, FHWA developed a bridge scour tool to extract hydraulic parameters needed for bridge scour analysis and transfer them into the FHWA's Hydraulic Toolbox, where users can compute each of the scour components, generate a total scour summary table, and plot the resulting scour profiles at the bridge cross section. This paper provides a brief background of the FHWA bridge scour program and how technology has advanced to support improved bridge scour evaluations.

Introduction

In September 1988, the United States Department of Transportation's (USDOT) Federal Highway Administration (FHWA) established a national scour evaluation program. A major impetus for establishing the FHWA scour program was the April 1987 I-87 Schoharie Creek bridge failure in New York. After the failure, FHWA had immediately directed that each State should evaluate the risk of its bridges being subjected to similar damage during floods on the order of a 100 to 500-year return period or more. Where vulnerable, bridges should be evaluated for the need for additional riprap or channel protection, spur dikes, groins or other river training devices and in some cases strengthening of the foundation through addition of piles, sheeting, or other appropriate measures (FHWA, 1987). However, subsequent investigations led to recommendations of a formal and structured FHWA oversight process and associated guidance.

This resulted in the September 1988 issue of Technical Advisory (TA) T 5140.20 (FHWA, 1988) to provide guidance for program development and implementation. TA T 5140.20 included interim guidelines for evaluating scour at bridges. The TA provided scour mitigation recommendations for both new and existing bridges. TA T 5140.20 also described FHWA's intent to develop and publish a new FHWA publication Hydraulic Engineering Circular (HEC) No. 18, "Evaluating Scour at Bridges" (HEC-18).

FHWA established the scour program and issued TA T 5140.20 under its authorities associated with the National Bridge Inspection Standards (NBIS) and associated regulation (US Code of Federal Regulations (CFR), Title 23 CFR 650 Subpart C "National Bridge Inspection Standards.") All bridges in the National Bridge Inventory (NBI) were subject to the guidance of TA T 5140.20. Additionally, FHWA added a scour focused data collection item to the NBI to provide a data driven component of the scour program. The April 1989 failure of the Route 51 Hatchie River bridge illustrated how stream instability and lateral migration were also important elements that the fledging scour program needed to address.

In February 1991, FHWA published the first edition of HEC-18. At the same time, FHWA also published a companion technical reference (1991a), HEC-20 "Stream Stability at Highway Structures." These two documents provide guidance on the development and implementation of procedures for evaluating bridge scour and stream stability processes.

In October 1991, FHWA issued TA T 5140.23, that updated and superseded TA T 5140.20 (FHWA, 1991b). TA T 5140.23 specifically cited HEC-18 as FHWA's recommended procedures for addressing scour at both new and existing bridges. In turn, HEC-18 refers to HEC-20 for additional aspects of the stream stability issues and components.

In conjunction with on-going bridge scour research and significance advances in the state-of-practice over the years, HEC-18 and HEC-20 have gone through several major revisions, with the current versions being HEC-18 Fifth Edition (FHWA 2012a) and HEC-20 (FHWA 2012b) Fourth Edition. Recognizing the need for guidance in scour countermeasures, in July 1997, FHWA issued HEC-23 "Bridge Scour and Stream Instability Countermeasures" (HEC-23) (the September 2009, third edition is the latest release of HEC-23).

Currently, the FHWA scour program involves more than 509,000 bridges over water in the U.S. (NBI, 2017), or about 80 percent of U.S. bridges. The original 1988 technical advisory and subsequent documents launched a massive scour screening and evaluation program that effectively continues to this day. Scour vulnerability evaluation (evaluation) is required for all new bridges over waterways, and bridges are required to withstand the effects of scour from a "superflood," on the order of a 500-year flood, without failing (FHWA 1995).

Evolution of Bridge Scour Evaluation Technology

Bridge scour evaluations require an engineering analysis to evaluate hydraulic variables (including flow depths, velocity magnitudes, and directions) through the bridge reach and use them to compute each of the components that contribute to total scour, which include long-term degradation, contraction scour, and local scour (pier scour and abutment scour), as described in HEC-18 (FHWA 2012b). Engineers who perform infrequent scour evaluations typically follow the steps in HEC-18 by performing manual calculations; however, most who perform multiple scour evaluation, have integrated the equations into spreadsheets for efficient and consistent calculations.

Other computer programs have also been developed over the years and supported by FHWA. For example, FHWA developed the program "HY-9: Scour" in 1992, drawing upon the second edition of HEC-18 (1993) for solving numerous scour equations and documenting the results. The transportation community used HY-9 through the 1990s. In the mid-1990's, the U.S. Geological Survey (USGS) and FHWA integrated HEC-18 scour procedures into the one-dimensional (1D) hydraulic model Water-Surface PROfile computations (WSPRO) software (FHWA 1990). In 2001, the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center's River Analysis System (HEC-RAS) version 3.0.1 included bridge scour evaluation options that followed the Fourth Edition of HEC-18 (FHWA 2001), and has been used widely since 2001, but the scour options in HEC-RAS (through current version 5.0.3) have not been updated to reflect the fifth edition of HEC-18 (FHWA 2012a). Consequently, in 2013, FHWA added HEC-18, fifth edition based scour calculators for the individual scour components to the FHWA Hydraulic Toolbox (HTB) (Version 4.2) software program. Subsequently, in HTB version

4.4, FHWA added additional scour tools that allow computation of total scour, generation of scour summary tables, and plotting scour profiles.

Scour Evaluation with One-dimensional Hydraulic Modeling

Prior to 2012, most bridge scour evaluations were based on hydraulic variables that were determined from a 1D hydraulic model, such as HEC-RAS 1D (HEC 2002) and WSPRO software (FHWA 1990). The variables needed for scour evaluations include, velocity, depth, discharge, unit discharge, and flow direction, for the main channel and overbank sections at an “approach section”, located upstream of the influence of the bridge, and at the “contracted section” located at the maximum contraction beneath the bridge. The quality and accuracy of these hydraulic variables directly impact the accuracy of the scour calculations, and the variables are also dependent on the suitability of the hydraulic model to define the flow distribution (FHWA 2012c).

For 1D models, it is important to understand that the computed flow distribution is an approximation based on several assumptions, which include: flow direction, flow path, effective flow area, cross section averaged properties for water surface elevation and velocity, and flow distribution at each cross section that is based on the available incremental conveyance (FHWA 2012c). Furthermore, 1D models assume the flow distribution at each cross section is completely independent of the adjacent cross sections, up- and downstream, and continuity within the channel and overbank sections is not implicitly preserved. Bridge crossings where these assumptions are reasonable and acceptable warrant the use of 1D model results. However, many bridge crossings exhibit complex flow conditions that are overly simplified in a 1D model, resulting in the potential to incorrectly predict.

Examples of complex flow conditions include: bridges and/or road embankments that are skewed to flood flows, wide flood plains with a meandering river channel, braided channels, river crossings with multiple bridge openings, roadway overtopping, bridges with highly contracted flows, abrupt changes in channel geometry or roughness, etc. (FHWA 2012a). For bridge, hydraulic and scour analyses, these conditions would be better represented with a two-dimensional (2D) hydraulic model. However, until recent years 1D modeling has been the most practical tool available to most engineers.

Scour Evaluation with Two-dimensional Hydraulic Modeling

FHWA has been involved with 2D modeling since at least 1977, sponsoring workshops that investigated potential and actual 2D modeling application to transportation projects (FHWA 1977). However, such use typically focused on research aspects of such modeling. For project delivery, FHWA began using 2D hydraulic modeling in 1988, on a limited basis for select complex bridge design projects. FHWA recognized the many benefits of utilizing a 2D model, and has since envisioned widespread use and application of 2D hydraulic modeling within the U.S.

It has taken many years, however, for computer hardware and software to develop to a point where 2D modeling technology can be practically integrated into hydraulic engineering practice. By the early 2000s, FHWA was promoting the use of the Finite-Element Surface-Water Modeling System (FESWMS) 2D hydraulic model (FHWA 2003) for analyzing complex bridge hydraulics. Although FESWMS was successfully used by many for complex bridge hydraulics projects, it did not become integrated as a standard practice for bridge hydraulic modeling, primarily because of the difficulty in use and extended time it took to create and run a model. In the late 2000s, FHWA began supporting the development of custom graphical user interface features in the Surface Water Modeling System (SMS, 2018). SMS is a pre- and post-data processor that is used to evaluate results from hydraulic models. It also includes several powerful graphical visualization tools that are helpful in communicating modeling results to others.

After an extensive search for a new 2D hydraulic model to replace FESWMS, FHWA selected the U.S. Department of Interior's Bureau of Reclamation's (Reclamation) Sedimentation and River Hydraulics – Two-Dimensional (SRH-2D) model (Reclamation 2006). FHWA selected SRH-2D because of its advanced modeling capabilities and proven stability for riverine applications and Reclamation's interest in partnering for further development of transportation related hydraulic structures (Reclamation 2016). SRH-2D had been thoroughly tested and verified by Reclamation since their initial 2004 model creation and development. FHWA's partnership with Reclamation began in 2013 and funded the development of a custom graphical user interface in SMS (version 12). Most recently, FHWA has been promoting 2D hydraulic modeling technology through its Every Day Counts (EDC) program that seeks to identify and deploy proven but underutilized technology to improve the project delivery process and the safety and resiliency of transportation infrastructure.

Given the significant development of 2D hydraulic models and resources, and recognition that 2D hydraulic models provide more accurate representations of the flow field and flow distribution, the 2012, fifth edition of HEC-18 included FHWA's recommendation to use 2D hydraulic analysis for all bridges with complex flow characteristics. Complex flow distributions produced by channels and/or bridges skewed to the floodplain simply cannot be accurately predicted with a 1D hydraulic model. FHWA further noted, in Hydraulic Design Series (HDS)-7 "Hydraulic Design of Safe Bridges," that "Two-dimensional models should be used on all but the simplest bridge crossings as a matter of course," (2012c).

Two-dimensional hydraulic models overcome the significant assumptions required for 1D hydraulic modeling, and they improve the estimation of bridge scour by helping to identify correct locations of the "approach section" and "contracted section" that are used in scour evaluation (Figure 1). They also provide more accurate evaluation of the hydraulic variables at these locations. Flow magnitude, direction, and depth are computed for every element in a 2D hydraulic model, allowing a more accurate depiction of flow distribution. The best location for the "approach section" is often noted by the point at which the computed flow direction (noted by velocity vectors) in the overbank areas takes a marked turn toward the channel, indicating the upstream limit of the bridge encroachment influence on flow distribution. Correctly identifying the location of this section is critical in determining whether contraction and abutment scour are governed by "live-bed" or "clear-water" conditions. Furthermore, if "live-bed" conditions exist, accurate flow distribution in the main channel at the "approach section" is important in quantifying the volume of sediment that is effectively transported to the bridge (contracted) section. Subsequently, the location of the "contracted section" at the bridge opening determines the sediment transport capacity through the contraction and potential for scour, when compared to hydraulic conditions at the approach section. Without the additional insights and information offered by a 2D hydraulic model, assessing the location and orientation for the approach and contracted sections with 1D hydraulic model results can be challenging, and is much more subjective, especially for complex flow conditions.

New Scour Evaluation Tools

New features have been developed in the SMS graphical user interface, through FHWA, which may be used to conveniently and efficiently extract the hydraulic variables needed for bridge scour computations. Within the SMS software package, users create a bridge scour specific coverage (layer) and draw arcs along the “approach section” and “contracted section” locations, as shown in Figure 1.

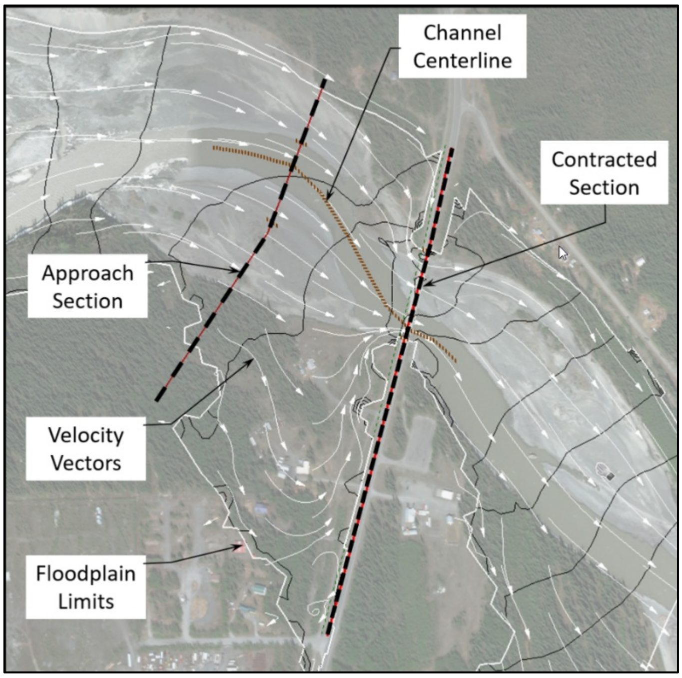

Figure 1. Example of the approach and contracted section arcs drawn in an SMS bridge scour coverage (Image source: ESRI World Imagery)

Additional shorter arcs are also drawn to note channel bank locations, pier locations and alignment, and the locations of the toe of slope at the bridge abutments. After the user specifies a gradation for the channel bed material and selects the model results for a specific flood simulation (e.g., 100-year), the hydraulic variables, along with bridge cross section geometry, are extracted and copied into a Hydraulic Toolbox (HTB) input file. In the Hydraulic Toolbox, users select the appropriate scour calculators for contraction scour, pier scour, and abutment scour, and the HTB computes each of the

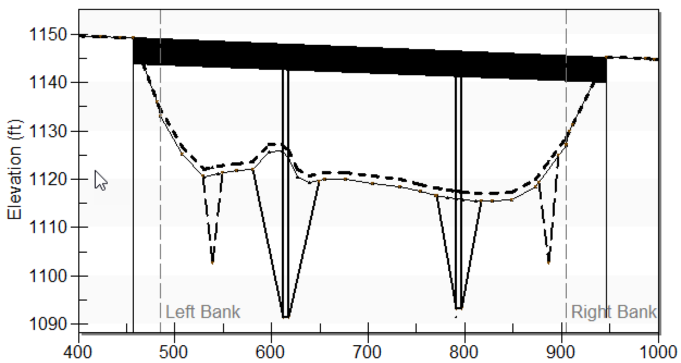

Figure 2. Example bridge scour plot from the Hydraulic Toolbox. (Image source: FHWA)

scour components. With the bridge contracted section geometry as reference, the total scour elevations can be computed and displayed in a summary table and bridge cross section plot, as shown in Figure 2.

An additional benefit of using 2D hydraulic modeling, is that users can gain better insights into the hydraulic flow patterns by viewing continuous lateral coverage of the results (scalar and vector) through the model limits, in contrast to viewing results only at cross section locations in a 1D hydraulic model. The SRH-2D standard output variables include velocity, depth, water surface elevation, Froude number, and shear stress, but additional parameters may also be computed using a data calculator tool in the SMS package. The energy grade line (EGL) and the "critical velocity index" are two example parameters that can be beneficial to hydraulic analysis. The 'critical velocity index' is a ratio of the computed flow velocity to the critical velocity for a specific sediment size, as computed using Equation 6.1 in HEC-18 (2012a). With a known material gradation and model results for depth and velocity, users can develop a critical velocity index coverage that can show whether the material in transport at the "approach section" is maintained in transport through the bridge section. In the example provided in Figure 3, the critical velocity index (CVI) shows that the velocity in the main channel exceeds the critical velocity (CVI>1) from the "approach section", through the "contracted section" at the bridge, therefore confirming a "live-bed" scour condition for the specified flow.

Conclusion – Future Developments

These bridge scour tools were developed to take advantage of the improved information available with 2D hydraulic models and to help reduce the subjective judgement needed by engineers when assessing hydraulic variables for bridge scour calculations, and ultimately to improve the consistency of calculations between different engineers. FHWA plans continue to improve and enhance these tools in the years to come.

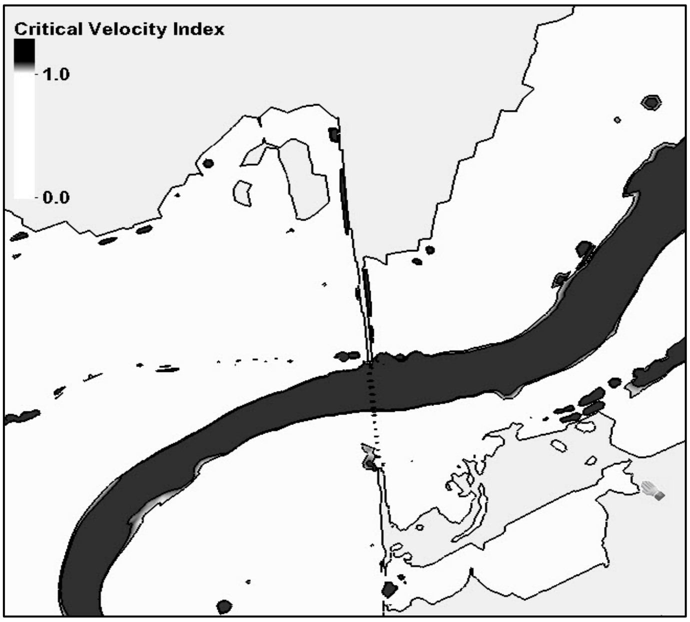

Figure 3. Example of critical velocity index plot confirming "live-bed" conditions in the channel through the bridge. (Image source: FHWA)

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