Extended Abstract: A Comparison of Bridge Modeling and Scour Prediction Using 1-D and 2-D Hydraulic Models

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Introduction

Scour, the leading cause of bridge collapse in the United States, is caused by three-dimensional, turbulent flow accelerating through bridge openings and around piers and abutments (Arneson et al. 2012). The threat of significant scour occurs during extreme flood events where hydrodynamic forces acting on the bed material have the greatest potential to move sediment. Estimating the extent of scour caused by extreme flow conditions is necessary to protect valuable infrastructure and ensure public safety. For the study, 100 and 500-year floods were used to estimate scour conditions between a 1-D and 2-D model. However, the most significant scour may occur with lower flow rate conditions due to a variety of reasons (e.g., complex flow conditions, varying downstream controls, and skewed approach flows). As many bridges approach the extent of their intended lifespans, climate change is further increasing the risk of bridge scour by potentially introducing increased flow intensities for design return periods.

The current state of the practice for predicting bridge scour is detailed in the Federal Highway Administration's (FHWA's) Hydraulic Engineering Circular No. 18 (HEC-18). For decades, one-dimensional (1-D) hydraulic models have been the preferred method of calculating flow conditions despite their limited ability to replicate complex flows conditions present near bridge sites. Such models predict water-surface profiles and cross section averaged flow velocities in the streamwise dimension. Two-dimensional (2-D) models, which calculate flow in both the streamwise and lateral direction, have become the preferred method of hydraulic modeling for the purpose of scour estimation. The viability of the more comprehensive 2-D modeling has increased significantly in recent years with the widespread availability of topographic LiDAR and advanced GIS bathymetry collection methods (Robinson et al. 2019). The objective of this project is to compare the methods of calculating bridge scour and their respective results using historical and contemporary geospatial data resolutions, including widespread LiDAR and improved bathymetry instrumentation. Currently, a limited number of studies have compared different modeling methods and input data resolutions for estimating bridge hydraulic conditions and associated scour (Garcia-Santiago, 2021; Yu et al. 2008; Deal et al. 2017).

Methodology

The purpose of this study was to compare different hydraulic modeling methods, results, and effects on scour magnitude estimations. One selected bridge site, Bridge A3760 of U.S. Highway 63 over the Gasconade river in central Missouri, was examined using three numerical hydraulic methods: WSPRO (1-D) (results from a 2002 USGS study with only cross sections immediately adjacent to the bridge (Rydlund and Huizinga 2002)), HEC-RAS (1-D) with increased model extent and resolution, and SRH-2D. Bridge A3760 is a 995-foot long, two-lane bridge with 11 piers, each comprised of a row of three cylindrical columns.

The 3-D topographic/bathymetric surface of the channel and floodplain was created using multiple data acquisition methods. The overbank topographic information was gathered online using Missouri's MSDIS LiDAR DEM download tool, with imagery captured under the Missouri FEMA 2017 LiDAR acquisition task order. The channel bathymetry was acquired via a multi-beam survey conducted in June 2017 by the USGS in the immediate vicinity of the bridge, while an ADCP survey of the upstream and downstream channel reaches was conducted by Saint Louis University (SLU) personnel on November 19, 2021. These three topographic/bathymetric surveys were merged into one composite surface for the hydraulic modeling analyses. The datasets were collected at varying dates and with varying data resolutions. Accordingly, the intersections of adjacent datasets were smoothed manually to create a surface that best represented field conditions.

Manning's n roughness coefficients used in the prior WSPRO scour study were also used for the comprehensive 1-D and 2-D hydraulic analysis models. The site had various surface conditions such as the channel, cornfield, and timber areas. As shown in Table 1, roughness values were assigned based on these surface conditions and flow depths.

Table 1. Manning's Roughness Coefficients

Surface Condition	Manning's Roughness Coefficients (n)	
	1-D Model	2-D Model (depth)
Cornfield	0.04	0.07 (4 ft.) - 0.04 (8 ft.)
Timber and Brush	0.08	0.1 (4 ft.) - 0.08 (8 ft.)
Channel (Upstream)	0.035	0.035
Channel (Bridge Reach)	0.033	0.033
Channel (Downstream)	0.031	0.031
Brush Covered Bluff	0.07	0.07
Moderate Underbrush	0.06	0.06

Additional bed data collection included a sediment size analysis of 22 different sample locations. An aerial photograph with bed sample locations is shown in Figure 1. Also, Figure 2 provides the grain-size distributions of the bed material samples collected in the channel. The four sediment samples taken from the channel bed returned an average D_{50} grain size of 11.25 mm. These are the yellow samples shown in Figure 1, excluding sample "B" which was acquired from the channel bank.

Figure 1. – Soil Sampling Locations for Bridge A-3760 over the Gasconade River

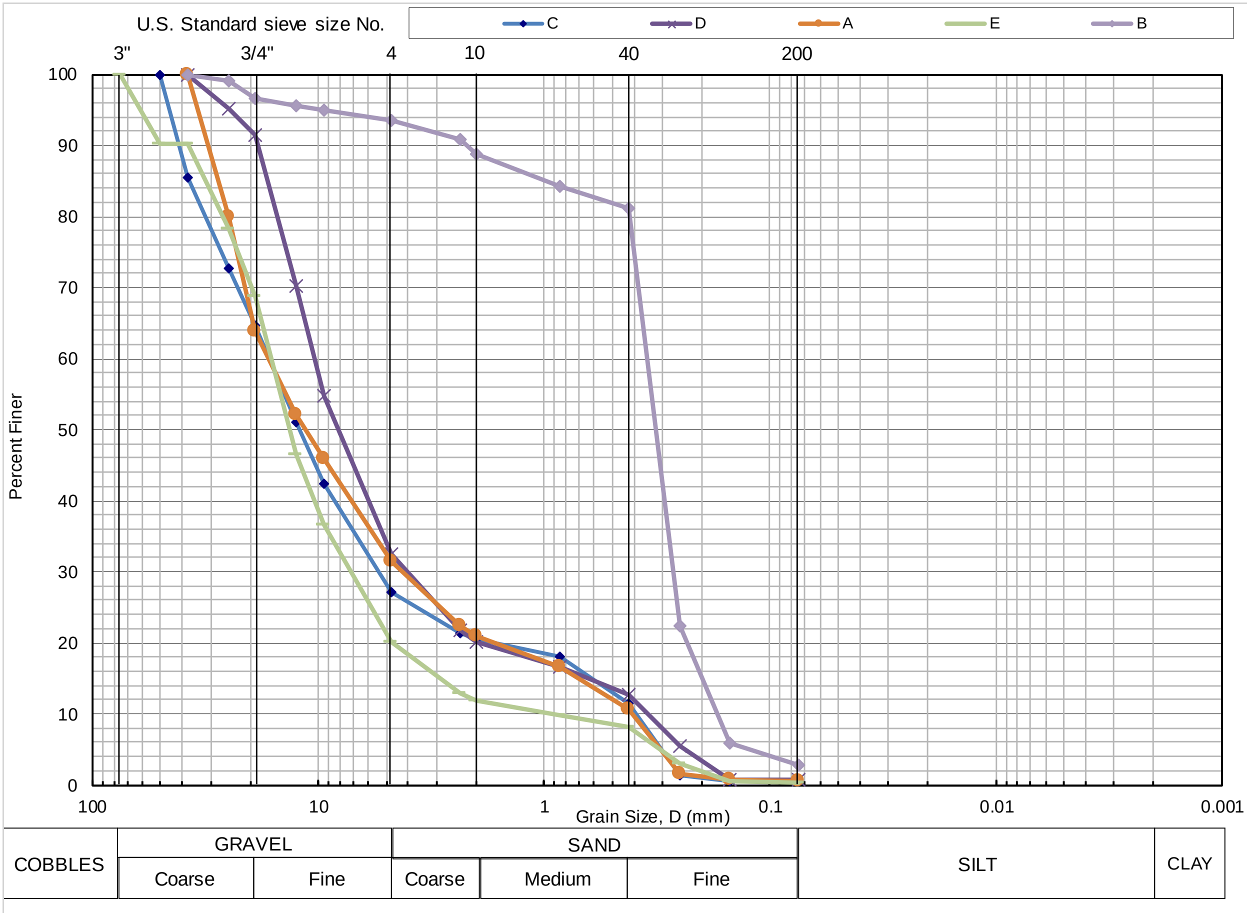

Figure 2. Grain size distributions for bed samples collected in the channel.

HEC-RAS, the 1-D numerical model used to predict hydraulic conditions and bridge scour, required many assumptions in the model construction process. It consisted of 19 cross sections across the floodplain for the 1.4-mile river reach. Ineffective flow areas were defined following the guidelines of HEC-18 – areas outside of 45-degree angles extending from the edge of the bridge opening, limited to the height of the road as any water above the road height is assumed to be moving. Normal depth downstream boundary conditions were used, with 100-year and 500-year flood flow rates, acquired using the USGS StreamStats tool. Each cross-section had roughness values assigned, which varied horizontally depending on the surface condition (channel, cornfield, timber, etc.,) across the cross-section.

For the 2-D numerical model analysis, SRH-2D was used to calculate flow conditions used to estimate scour depths. A mesh of elements of roughly 60 ft spacing in the floodplain and 30 ft spacing in the channel was constructed. Each element was assigned a roughness value dependent on the water depth and surface condition, with roughness decreasing with increasing depth. The boundary conditions were subcritical inflow with assigned flow rates of 202,500 cfs for the 100-year flood, 270,000 for the 500-year flood, and subcritical outflow with a downstream normal depth hydraulic control.

The bridge input for both models largely utilized the same level of information, with the main difference between the model types being the calculated flow conditions. Each pier was assigned a 2-D geometry of height and width, with the in-channel piers having a stepped shape and all being a group of three cylinders. The geometry of the bridge deck was also included in each model. The HEC-18 scour evaluation includes the calculation of three different types of scour: contraction, pier, and abutment scour. The WSPRO model used scour calculation methods detailed in the 4th edition of HEC-18 (Richardson and Davis 2001), while the HEC-RAS and SRH-2D models used the most up-to-date guidelines for bridge scour calculations from the 5th edition for HEC-18 (Arneson et al. 2012). The only other differences were the input hydraulic conditions such as approach flow depths, flow velocities, and Froude numbers as determined by the different modeling methods.

Results and Conclusion

The scour results predicted by the WSPRO, HEC-RAS 1-D and SRH-2D models were compared to each other. Between the two current hydraulic modeling techniques used to estimate scour (i.e., HEC-RAS and SRH-2D) HEC-RAS overall returned larger values for pier scour depth than the latter. The Hydraulic Toolbox, developed by the FHWA for the purpose of scour prediction, helped to maintain constant values such as bridge pier geometry, sediment sizes, and approach cross-section geometry. Varying inputs were applied to the scour calculator (Hydraulic Toolbox) depending on the output flow conditions of the respective numerical model. When estimating scour, each pier is subject to maximum flow depth and velocity occurring at the thalweg, as the thalweg has the potential to migrate across the channel and floodplain. Scour estimations depended mainly upon input flow depth and velocity directly upstream of each pier, which varied depending on the respective flow rate and model method. HEC-RAS, for both the 100-year and 500-year flow rates, calculated the flow velocity at the thalweg (~12 ft/s for 500-yr flow) to be roughly double that of SRH-2D (~6 ft/s for 500-yr flow). By examining the flow velocity distributions of the two model methods, it was found that for the SRH-2D model, significantly more flow was directed over the road embankment which illustrates some limitations of HEC-RAS's ability to model 2-D flows.

In addition to flow depth and velocity, the equation used to determine pier scour depth affected the estimates. Depending on whether the pile cap of each pier was exposed to flow due to contraction scour, a scour equation was chosen. The HEC-18 equation was applied to piers with pile caps buried below the surface of the riverbed; the complex pier equation was applied to piers with pile caps exposed to flow. The complex pier equation outputs more significant scour estimations as the exposure to flow of the pile cap and piles of a pier causes additional bed shear stress relative to that of the pier stem alone. This discrepancy in calculation methods caused inconsistency in the results as a trend was not able to be identified. For the HEC-RAS analysis, the pile caps were exposed for the 500-year flow and not the 100-year flow, while contraction scour for SRH-2D caused pile cap exposure for both flow rates. The resulting average scour depth estimations for the 11 piers are shown in Table 2. There was a significant increase in estimated scour depths using HEC-RAS and SRH-2d relative to the WSPRO values; this is likely due to: 1) WSPRO using local flow depth and velocity values and not the maximum values which occur at the thalweg and 2) the flow rates used for the HEC-RAS and SRH-2D models were calculated by Streamstats and approximately 20% larger than the values used in the WSPRO study.

Table 2. Pier Scour Depth Estimation Results

	Average Pier Scour Depth (ft)		
	HEC-RAS (1-D)	SRH-2D	WSPRO (1-D)
100-year Flow	14.3	15.7	8.8
500-year Flow	19.3	15.8	7.9

The scour estimation results found by the prior USGS study using WSPRO output much smaller scour depths (Rydlund and Huizinga 2002). As opposed to the two modern methods, that study used values for stream slope, and flood discharges acquired using limited data. For example, StreamStats is now available as well as increased availability of high-resolution topography/bathymetry data. The study also used a small number of cross sections (i.e., five) to calculate flow conditions, whereas, the HEC-RAS model used 19 cross sections. The results of the WSPRO study, also shown in Table 2, offer a contrast between former and current hydraulic modeling methods and data resolutions.

This study contrasts the modeling challenges, discrepancies, and scour predictions between the different methods. The use of 2-D numerical models proved to be the optimal approach given the vast availability of ground terrain data from public domain sources, limitations with establishing 1-D cross sections to accurately represent highly 2-D flow conditions, and the reasonable computational demand of 2-D modeling methods. Given the advancements in modeling tools and data access that have facilitated simulating 2-D flow conditions, this study also highlights the need for advancements in methods for estimating or modeling bridge scour in 2-D flow environments.

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