1D and 2D Hydraulic Modeling to Estimate Bridge Scour: A Case Study

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Abstract — *Scour is the effect of erosion of soil surrounding a bridge foundation due to fast-flowing water. This dynamic phenomenon can be categorized as the most common cause of bridge failures. Therefore, scour depth at piers and abutments should be estimated during the preliminary bridge design phase. This project will compare scour depth values for an existing bridge's foundation applying 1D and 2D hydraulic modeling. The bridge to be evaluated is located in the Municipality of San Germán, Puerto Rico and crosses the Rosario River. The 1D hydraulic model was performed using the U.S. Army Corps of Engineer's computer program, Hydrologic Engineering Center's River Analysis System, and for the 2D hydraulic model, the community version of Surface-water Modeling System from Aquaveo was used. The result of this project indicates that the use of 2D hydraulic models is the best approach to estimate scour depth in bridges.*

Key Terms — *Bridges, HEC-RAS, Hydraulic Modeling, Scour, SMS*

INTRODUCTION

The depth of the scour hole is an integral part of the bridge foundation design and it is mostly used to determine what depth should be ignored as vertical and horizontal resistance of the piles [1]. There are different methods to carry out this procedure in order to predict this important factor. In this project the methods of 1D and 2D hydraulic modeling were applied to appreciate the difference between scour depth magnitudes and conclude what is the best approach to estimate these values.

One dimensional (1D) hydraulic modeling has its limits, but it has been widely used by engineers for a long time since information regarding the two-dimensional modeling was limited and most of the computers did not have the capacity to manage the required amount of data to run the computer programs. Hydrologic Engineering Center's River Analysis System, HEC-RAS, from the US Army Corps of Engineers is the most common software to perform one dimensional hydraulic calculation. The limits of a 1D hydraulic model are mostly based on the simulation assumptions. Some of these assumptions are that the vertical and lateral fluid motion is small, the velocity is average at a cross section, and water surface elevation is constant, among others [2].

Application of 2D hydraulic modeling is rapidly becoming the preferred analytical approach, specially for bridge scour studies since its management has become more feasible for agencies and consultants [3]. In some cases, 2D hydraulic modeling seems to be the most appropriate approach to determine hydraulic variables for bridges scour calculations, such as velocity and water depth in the proximities of a bridge's foundation. These cases can be, but are not limited to, bridges that are located in a wide floodplain, in highly sinuous channels, and in multiple embankment openings situations [3].

An existing bridge is going to be the subject of analysis. Two hydraulic models were assembled to compare the scour hole depth results on the bridge's foundation elements. One of the models is a 1D simulation using the computer program HEC-RAS and the other one is a 2D simulation using the community version of Surface-water Modeling System (SMS) from Aquaveo.

LITERATURE REVIEW

The Puerto Rico Highway and Transportation Authority recommends the use of the Highway Design Manual (1979 Edition) as a guide for the basic highway design policies and procedures. In chapter 6 of this document the design policies and criteria for bridge structures are presented. One of the recommendations is to estimate scour depth at bridge's pier and abutments [4]. In order to estimate these values, we will follow the steps presented in the Hydraulic Engineering Circular No. 18, "Evaluating Scour at Bridges", published by the U.S. Department of Transportation Federal Highway Administration. One of the main objectives of the HEC-18 is to improve the state-of-practice of estimating scour at bridges [4].

There are different types of scour: the scour that is generated due to the long-term degradation of the riverbed, the contraction scour at the bridge, and the local scour at the piers or abutments. These three components are necessary to plot the total scour depth for a bridge structure. In this project, due to lack of information, the long-term streambed elevation changes are not going to be part of the analysis. The total scour will be based on the local scour at the foundation elements, and the contraction scour due to the bridge structure imposition in the river's floodplain.

METHODOLOGY

This project presents the application of computer assisted hydraulic modeling to estimate the scour depth in an existing bridge and analyze the differences of the results. One-dimensional hydraulic simulation was performed using HEC-RAS 6.0 Beta 3 and a two-dimensional hydraulic simulation was performed using SMS 13.0.14.

The main differences between both models are that the HEC-RAS computational procedure is only based on the solution of the one-dimensional energy equation, and the energy losses are evaluated by friction and the change in velocity head (contraction/expansion coefficients), while SMS solves the 2D dynamic wave equation for water surface elevation, water depth, and depth-averaged velocity using the finite volume numerical method.

For the assembly of the two hydraulic models there are several data that is needed to run both programs. Some of these input data are the resulting peak flows for different rainstorm events obtained from a previous hydrologic analysis, the bridge dimensions, a particle size distribution of the streambed soil (obtained from a geotechnical study report), the topography of the area that include the bathymetry of the river, usually provided by a licensed land surveyor, the characteristic longitudinal slope of the stream, and the surface's roughness coefficients.

The estimated peak flow is 666 cm for a 100-years recurrence interval event. This value was obtained from a hydrologic analysis that was previously performed. This river discharge value was used for both models as an inlet boundary condition. The flow regime was assumed as subcritical for what the downstream longitudinal slope was defined as 0.01 m/m. Figure 1 shows the bridge that is going to be analyzed in this project.

Figure 1
Analyzed Bridge Structure

1D HYDRAULIC MODELING

After a hydraulic model of the river reach containing the bridge to be analyzed is developed, the scour analysis can be run in the HEC-RAS program under the Hydraulic Design Function. In Figure 2 shown below, it can be observed a top view of the cross sections taken by a land surveyor on the river channel and its floodplain area. These cross sections contained topographic information of the river. Figure 3 shows one of the cross sections (the one upstream of the bridge).

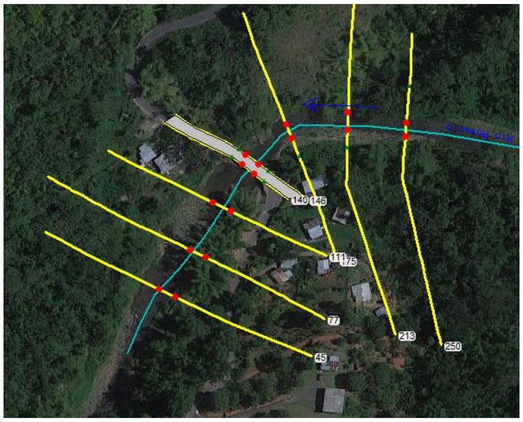

Figure 2

HEC-RAS Geometric Data Configuration

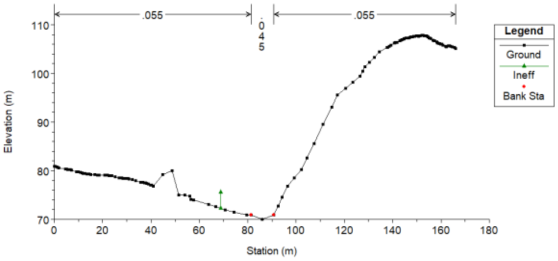

Figure 3

HEC-RAS Cross Section Upstream from the Bridge

The roughness coefficients assigned to the river channel was 0.045 following what was observed during a site visit, and the overbank areas have a roughness coefficient of 0.055 due to the dense vegetation that is characteristic of the area.

The bridge structure was modeled using an “As-built” drawing, where information about the low chord and the high chord of the bridge deck is presented, as well as the dimensions of the piers and abutments and its exact location in the cross-section stationing.

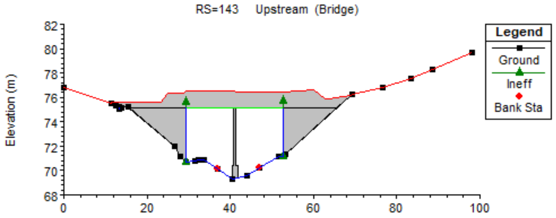

Figure 4

HEC-RAS Bridge Data

HEC-RAS bridge scour analysis is based in the methods presented in the Hydraulic Engineering Circular No. 18 (HEC No. 18, FHWA, 2001). It is important to mention that the HEC-RAS bridge’s scour analysis methods are based on the 2001 version of the FHWA HEC No. 18 manual, and this manual has been modified. The current version of this engineering circular is from 2012 (Fifth Edition) and it contains updated material from the continued research by the National Cooperative Highway Research Program, FHWA, State DOTs, among others. Different approaches to estimate scour in the bridge’s foundations are presented in the HEC-18 updated version.

With the HEC-RAS Scour at Bridges Functions, the contraction scour can be estimated applying the Laursen’s clear-water or Laursen’s live-bed equations [5]. The data needed in order for the program to calculate this value is the mean size fraction of the bed material. For the scour depth at the piers (local scour) the user can choose between the Colorado State University (CSU) equation or the Froehlich equation. The user will need to provide the information about the pier’s nose shape, the angle of attack of the river’s flows approaching the piers, the condition of the bed (clear water, plane bed, small dunes, etc.), and the size of bed material of which 95% is finer. The local scour in the abutments is calculated by either applying the HIRE equation or Froelich’s equation. The user will need to enter if the abutment is spill-through, vertical, or vertical with wingwalls. The program will automatically select all the other values needed for the computations from the hydraulic simulation output report.

The particle size distribution for the river’s bed material from a bulk sample extracted from the proximities of the bridge is shown in Table 1. Some of these values were used as input data to compute contraction scour and local scour.

Table 1
Riverbed Soil-Particle Size Distribution

Percent Finer	Particle Size (mm)
D90	20.2060
D85	17.4614
D60	9.6400
D50	7.6166
D30	4.1136
D15	1.7348
D10	0.8929

For this case the equation for contraction scour was left as “default” to allow the program to decide whether to use live-bed or clear-water equation. What the HEC-RAS program does is to compute the critical velocity at which it will be transported bed material finer than D50. If the average velocity at the approach cross section is greater than the critical velocity, the program uses the live-bed contraction scour equation. Otherwise, the clear-water contraction scour equation will be used [6].

The bridge being evaluated has round-shape nose piers and the angle of attack of the flow hitting the pier was estimated as 30 degrees. The equation chosen for this project to calculate pier’s local scour was the Colorado State University, and the condition of the bed was assumed as clear water.

To calculate the abutment local scour, information about the abutments is required. The bridge evaluated has vertical abutments with no wingwalls and the skew angles are 76 and 104 degrees for the left and right abutment, respectively. The equation applied in HEC-RAS to calculate the scour hole was the Froehlich equation.

2D HYDRAULIC MODELING

In order to assemble the 2D hydraulic model to estimate the scour depth expected in the bridge foundation, as in the 1D model, some background data needs to be imported. This data includes ground elevation data, aerial images to identify the types of surface’s materials and assign its roughness coefficients, the longitudinal slope of the river section being analyzed, and the river’s peak flow. The surface’s materials roughness for the area analyzed is presented in Figure 5 through the creation of material coverage polygons.

This spatial land cover distribution, seen in said figure, was obtained from the Coastal Analysis Program (C-CAP), which produces nationally standardized land cover data from remotely sensed imagery.

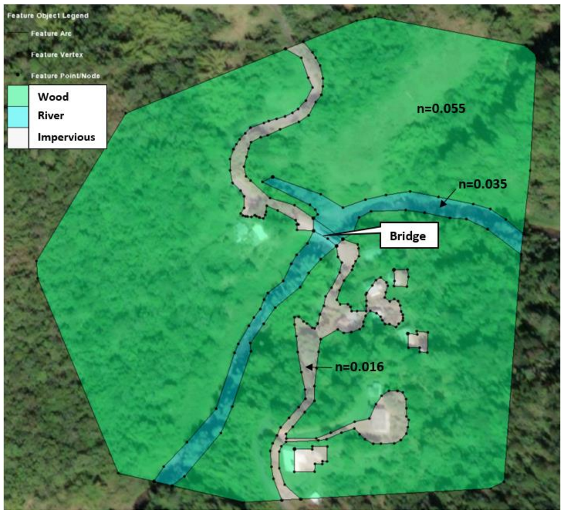

Figure 5
SMS Surface Materials

The topographic information used in the 2D simulation is the product of a merge between the ground elevation points took by the land surveyor and points from a U.S. Geological Survey LiDAR DEM from 2018. The product of the ground elevation information entered into the SMS program is shown in Figure 6.

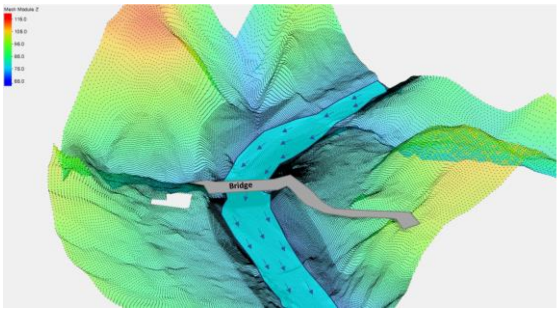

Figure 6
Site Topography

As in the 1D model, boundary conditions were assigned. An arc containing the information of the peak discharge to be evaluated, 666 cm (100-years recurrence interval), was positioned at the most upstream end of the river. The flow regime was assumed as subcritical with a constant discharge. In the downstream end of the river a constant water surface elevation of 74.34 meters was the exit boundary. This value was automatically calculated by the program when the longitudinal slope of the channel was entered.

Once all the background data is imported into the model, a mesh is generated letting holes where the bridge's piers are located to simulate an obstruction. Once the program is run, the water surface elevations and velocities are calculated at the mesh's elements centers and then these values are interpolated to the nodes, this is called finite volume-based solver. The mesh's elements with the topographic contours are presented in Figure 7.

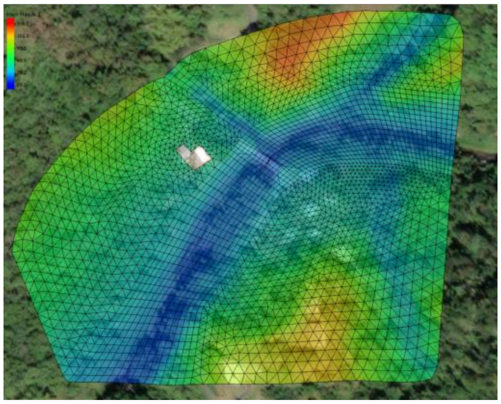

Figure 7
SMS Geometric Data Configuration

After all these components were defined, the bridge deck was simulated as a pressure zone with overtopping. The pressure zone uses the low chord and high chord elevations in the downstream and upstream face of the bridge.

Unlike hydraulic modeling in one dimension, where the angle of attack for the flow approaching the piers, the skew angle of the abutments, and the flow contraction and expansion need to be assumed by the modeler, SMS took this information from the simulation output values. A series of arcs—shown in Figure 8—that were drawn identifying the approach section, the contraction section, the bank's location, the abutment location, the pier's location, and the river's centerline were used to extract water depth and velocity values on those lines. These values are needed for the calculation of the scour surrounding the bridge's foundation. The scour values are exported to the FHWA Hydraulic Toolbox program.

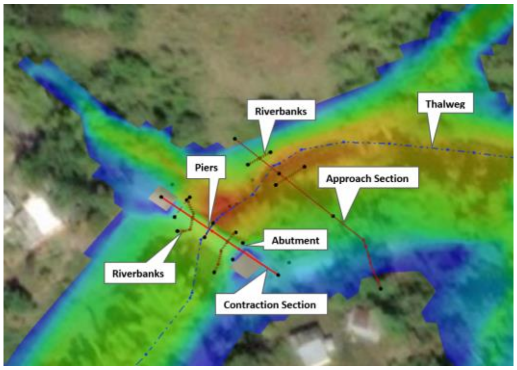

Figure 8
Bridge Scour Arcs

The SMS Program will automatically send the output values from the model to Hydraulic Toolbox software. The default equation to calculate contraction scour is the "Clear-Water and Live-Bed Scour" equation. For the bridge's piers local scour is the equation presented in the HEC-18 for clear water scour, and for the local abutment scour it is applied the new equation developed by the National Cooperative Highway Research Program, which is presented is the last version of the HEC-18.

RESULTS AND DISCUSSION

The resulting water depth and velocities in the approach section and in the bridge elements proximities for the 1D and the 2D hydraulic models are presented in the table below.

Table 2
Values to Calculate Contraction Scour (meters, mps)

	SMS 2D Model			HEC-RAS 1D Model		
	LOB	CH	ROB	LOB	CH	ROB
Ave. Depth in the App. Section	4.05	6.48	2.83	4.40	6.82	3.55
Vel. In App. Section	2.96	2.54	1.95	2.66	5.41	2.07
Ave. Depth in the Contr. Section	1.50	5.63	5.08	4.46	5.33	4.32

Table 3
Values to Calculate Pier Local Scour (meters, mps)

	SMS 2D Model	HEC-RAS 1D Model
Flow Depth Directly Upstream	7.64	7.91
Vel. Directly Upstream	3.17	4.92

Table 4
Values to Calculate Abutment Local Scour (meters)

	SMS 2D Model		HEC-RAS 1D Model	
	Left	Right	Left	Right
Depth of Flow at Toe of the Abutment	5.62	6.10	6.72	6.34

The values presented in tables 2, 3, and 4 are the most important inputs to calculate scour depth in the bridge's foundation. As it was demonstrated, there are differences between these values due to the difference in how the two types of hydraulic models (1D and 2D) calculate the distribution of velocity and depth in the proximities of an obstruction. While HEC-RAS estimates the flow depth and velocities based on an iterative solution of the energy equation from one cross section to another (standard step method), the 2D model calculates depth and velocity on each one of the mesh's elements.

The values obtained for contraction and local scour, with the HEC RAS Hydraulic Design Function (1D) and with the Hydraulic Tools (with the data extracted from the SMS model), are presented in Tables 5, 6, and 7.

Table 5
Contraction Scour Depth (m)

SMS 2D Model			HEC-RAS 1D Model		
LOB	CH	ROB	LOB	CH	ROB
0.00	1.01	0.00	0.00	0.00	0.00

There are not significant differences in the depth obtained for the contraction scour. The formulas applied in both models were the ones that recommends the HEC-18 for live bed and clear scour to calculate the scour hole because of the effects of flow contraction due to the bridge opening.

In the case of the local scour in abutments, the 1D model applied the Froehlich Equation unlike the 2D model, which by default applies the new NCHRP Equation. According to HEC-18 the advantages of using the NCHRP abutment scour equations include not using the effective embankment length—L'—which is difficult to determine in many situations, the equations are more physically representative of the abutment scour process, and the equations predict total scour at the abutment rather than the abutment scour component that is then added to contraction scour [7].

For the local scour in piers both models used the same equation—CSU—, which is also referred to as HEC-18 Equation.

Table 6
Local Scour Depth (m)

	SMS 2D Model	HEC-RAS 1D Model
Pier	5.03	4.53
Left Abutment	10.97	7.28
Right Abutment	10.29	5.50

Table 7
Total Scour Depth (m)

	SMS 2D Model	HEC-RAS 1D Model	% Diff.
Pier	6.04	4.53	25
Left Abutment	10.97	7.28	34
Right Abutment	10.84	5.5	49

The resulting scour prism for both models is presented in Figure 9 and Figure 10.

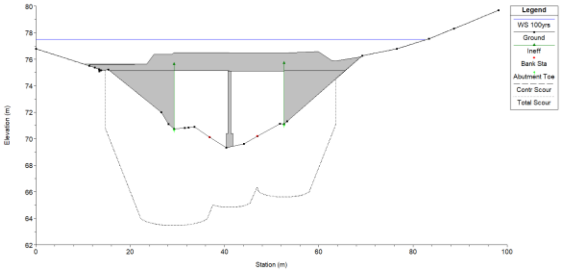

Figure 9
HEC-RAS Scour Prism

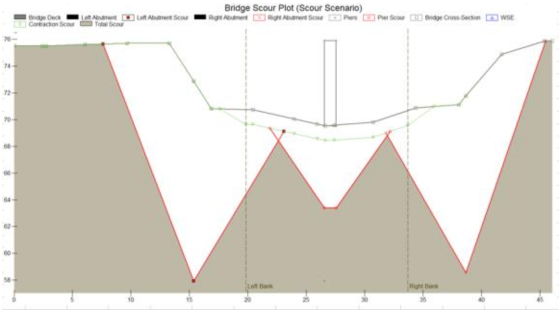

Figure 10
Hydraulic Tools Scour Prism

From these figures it can be observed that even though they present the same behavior, it was demonstrated that the scour values can be differentiated up to 50% like the scour depth for the right abutment, especially if the equations applied in each model were different, as in this case.

CONCLUSION

In the case of this river, due to its longitudinal slope and topographic conditions, there is a dominant direction of flow and forces that follows the river flow path. These circumstances may suggest that the 1D model can produce results as good as the ones obtained with a 2D model. However, since what is being evaluated is the bridge scour phenomenon, and the structure is located downstream from a meander, it can be concluded that the most accurate results were obtained with the SMS Computer Program because there can be a higher possibility of errors using a 1D model due to the data that needs to be measured and or estimated by the user, like the skew angle of the abutments, the angle of attack of the pier, the ineffective areas, the contraction/expansion coefficients, among others. These values are automatically calculated by the 2D hydraulic simulation.

It can be concluded after the completion of this project, that if the topographic data is available for the site being evaluated, and what is being analyzed is a hydraulic crossing, the best alternative is to assemble a 2D model, which will save the subjective interpretation of each parameter needed for the calculation of the scour hole in the bridge's foundation, which is greatly affected by the spatial distribution of flow.

In addition, the program used in this study for the two-dimensional modeling provides results applying the most recent developed equations by the National Cooperative Highway Research Program (NCHRP) for scour in bridges that are not included in the HEC-RAS program. While a formula completely based on laboratory data is applied in the one-dimensional model (HEC-RAS), the resulting data of the two-dimensional model are used in an equation that is more physically representative of the abutment scour process (NCHRP equation).

Everyday these programs are becoming more manageable and accessible for engineering students and practitioners and can be installed on almost any computer unlike a few years ago. Nowadays 2D models can be assembled as fast as 1D models and provide more accurate results when it comes to flows passing through a bridge opening.

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