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**Interim Report**

# HEC-RAS 2.2 FOR BACKWATER AND SCOUR ANALYSIS - PHASE ONE

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**Lawrence, Kansas**

## September 2000

## K-TRAN

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**THE KANSAS STATE UNIVERSITY**
**THE UNIVERSITY OF KANSAS**

**Final Report**
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# HEC-RAS 2.2 for Backwater and Scour Analysis – Phase one

by

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for

Kansas Department of Transportation

September 2000

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This study compared the HEC-RAS program with the DOS-WSPRO program and examined the HEC-RAS program with regard to scour analysis. The possibility of using the existing KDOT scour spreadsheets with output form the HR-WSPRO bridge routine was also considered. Finally, a literature review was performed to determine if any updates in the scour methods and new approaches to special conditions, such as the effect of debris or pressure flow affecting pier scour, were available.


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# Abstract

The Kansas Department of Transportation (KDOT) and most bridge consultants in Kansas have been using the DOS-WSPRO program and the KDOT scour spreadsheets to perform bridge hydraulics and scour analysis for the past several years. Unfortunately, DOS-WSPRO is a DOS program that is no longer supported and it does not support the metric system. Consequently, the newer Windows-based hydraulics program HEC-RAS appears to be a logical choice to succeed DOS-WSPRO as the basic flow model in KDOT's bridge design and scour analysis program. HEC-RAS has gained considerable popularity in the engineering community and offers many options not previously available to hydraulic modelers. It also has a scour module and has as an option, the WSPRO bridge analysis routine (henceforth called HR-WSPRO).

This study compared the HEC-RAS program with the DOS-WSPRO program and examined the HEC-RAS program with regard to scour analysis. The possibility of using the existing KDOT scour spreadsheets with output from the HR-WSPRO bridge routine was also considered. Finally, a literature review was performed to determine if any updates in the scour methods and new approaches to special conditions, such as the effect of debris or pressure flow affecting pier scour, were available.

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# CHAPTER 1

## Introduction

For the past several years the analysis of bridge scour in Kansas has been performed by the Kansas Department of Transportation (KDOT) and by bridge consultants using the FHWA sponsored DOS-WSPRO (Water Surface Profiles) software and the KDOT scour spreadsheets. Unfortunately, DOS-WSPRO is no longer supported and the windows-version of DOS-WSPRO was never usable. In addition, there is no metric version of DOS-WSPRO. As a result, there is a need to develop a scour program that is based on an “industry standard” hydraulic model that is windows based, well supported and has metric capability. The program that meets this need is the U.S. Army Corps of Engineers developed software, “Hydrologic Engineering Center River Analysis System” (HEC-RAS).

HEC-RAS Version 1.2 was introduced in 1996 and has since been updated through Versions 2.0, 2.1 and 2.2. This program is a step-backwater program that is windows based. It is a very sophisticated, user-friendly software package that is supported by the Hydrologic Engineering Center in Davis, California. The software’s capability of producing graphical displays of cross-sectional input data and plots of computed profiles almost instantaneously, greatly aids the engineer in the development of superior models. HEC-RAS also has the capability of importing GIS/CADD data to aid in model construction. The computed water surface profiles can then the exported to the GIS/CADD system for plotting. Moreover, the model is geospatially correct. It has modules for culvert flow, bridge flow, floodplain delineation, bridge design and bridge scour. (One of the bridge modeling options within HEC-RAS 2.2 is the HR-WSPRO Method Class A.) HEC-RAS also has the option to set flow distribution locations with up to 45 conveyance regions per cross section. This option is used internally to determine local depths and velocities that are used in scour analysis within HEC-RAS. It could also be used to generate input for a scour program external to HEC-RAS.

DOS-WSPRO was designed to provide data needed for scour calculations. At the time of its inception, it was probably the best program for scour analysis. That is no longer the case. HEC-RAS is the most popular backwater program among engineers today making it the "industry standard." It is an excellent tool for obtaining accurate predictions of water surface profiles in the Windows environment using either English or metric units. Moreover, it can be used to perform scour calculations either within HEC-RAS or to provide the input variables for another scour program.

This study assessed and compared the scour analysis capabilities of the current DOS-WSPRO-based KDOT scour methodology with the HEC-RAS-based methodologies. The following tasks were undertaken to achieve this.

- To compare KDOT's existing scour analysis methodology with HEC-RAS 2.2's scour analysis option.
- To compare the HR-WSPRO bridge routine in HEC-RAS 2.2 with the current DOS-WSPRO software that KDOT bridge design is using.
- To determine if the HR -WSPRO option within HEC-RAS can provide the input parameters required by KDOT's existing scour spreadsheets.
- To perform a literature search to determine pertinent updates in bridge scour research, especially pertaining to the effects of special cases.

# CHAPTER 2

## Comparison of Scour Analysis Methods

HEC-RAS 2.2 has a scour analysis option that can be used with any of the program's bridge analysis methods – HR-WSPRO, energy or momentum. Before comparing the KDOT scour analysis method with the HEC-RAS method, overviews of the two methods are presented. KDOT's current scour methodology involves using the DOS-WSPRO model with the KDOT scour spreadsheets developed by KDOT and University of Kansas (KU) engineers. The flowchart in Figure 1 illustrates the procedure. CAT.DAT is the DOS-WSPRO input file. The program POST WSP.exe is a postprocessor Fortran program written to extract the pertinent data from the DOS-WSPRO output file in the form of a text file CAT.TXT. The text file is then inserted into each spreadsheet to minimize the hand entry of data.

The contraction scour and abutment scour spreadsheets are straight-forward.

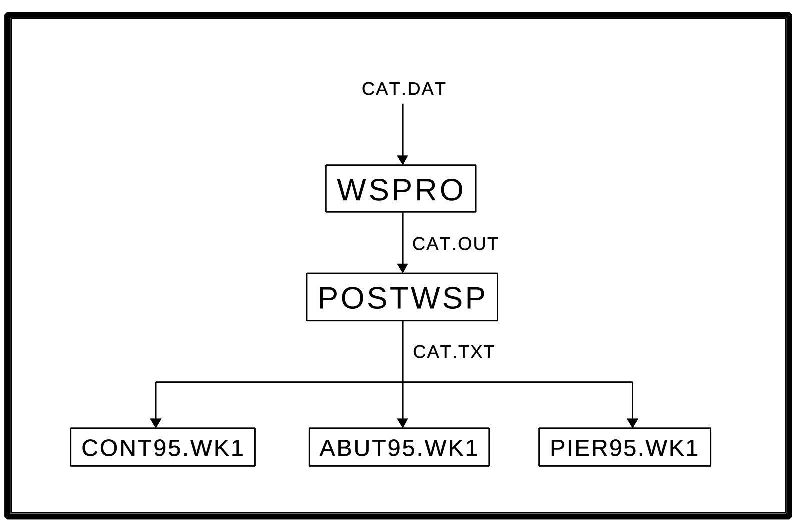



Figure 1. Flowchart of KOT Scour Analysis

They contain logic that was designed to minimize errors in the scour modeling process and to aid the modeler. For instance, for contraction scour the effective channel width used at the approach section cannot exceed three times the bridge opening based on the 1 to 1 jet contraction assumptions. The model warns if the value is exceeded and notifies the user that adjustment should be made. The contraction scour spreadsheet also tells the modeler whether clear water or live bed scour is appropriate for each overbank section and the main channel.

The pier scour spreadsheet is fairly complicated. It considers a variety of options and provides many tests within the program. Among the items considered are

Pier scour limits
Angle of attack
Multiple column angle of attack factor
$K_2$-angle of attack coefficient
Footing scour
Piling scour

DOS-WSPRO models with a bridge routine that uses 20 equal-conveyance streamtubes. The streamtube information from the DOS-WSPRO output file provides data for computation of local velocity, local depth and estimates of the local angle of attack of the approach flow. All of these parameters are important considerations for pier scour analysis. The summary sheet from PIER95.wk1 (Table 1) provides the engineer with several possible values of pier scour for each pier. The spreadsheet also allows for input of angle of attack to override the computed values. These values might be input based on field observations or results from a two-dimensional model such as FESWMS-2DH or they might be input by trial in the course of an engineer's sensitivity analysis scheme.

Table 1. Summary Table for KDOT Pier Scour Spreadsheet

SUMMARY OF PIER SCOUR RESULTS

| PIER NO. | CSU Ys ft | SINGLE PIER LIMIT Ys ft | yf ft | FOOTING (W/O FLOW ANGLE) Ys ft | PILING (W/O FLOW ANGLE) Ys ft | FLOW ANGLE ADJSTMNT PIER SCOUR Actual a, Big K2 Ys ft | FLOW ANGLE ADJSTMNT PIER SCOUR K2=1, Eff a Ys ft |
|---|---|---|---|---|---|---|---|
| 1 | 5.07 | 6.90 | 0.00 | 0.00 | 0.00 | 21.74 | 10.36 |
| 2 | 5.90 | 6.90 | 0.00 | 0.00 | 0.00 | 19.01 | 12.06 |
| 3 | 8.92 | 6.90 | 5.27 | 17.81 | 14.72 | 20.99 | 18.23 |
| 4 | 8.77 | 6.90 | 4.60 | 17.26 | 14.27 | 13.28 | 14.36 |
| 5 | 6.74 | 6.90 | 0.48 | 9.42 | 0.00 | 11.46 | 12.37 |
| 6 | 5.73 | 6.90 | 0.00 | 0.00 | 0.00 | 14.57 | 11.71 |
| 7 | 4.81 | 6.90 | 0.00 | 0.00 | 0.00 | 18.56 | 9.82 |

The limitations of the KDOT DOS-WSPRO-based method is that the DOS-WSPRO program is a DOS program that does not support metric units and does not have many of the hydraulic modeling features of the windows-based HEC-RAS 2.2 program.

HEC-RAS 2.2 is the latest version of HEC-RAS. It has a scour option that computes contraction, abutment and pier scour. This option is found under the Simulate menu as "Hydraulic Design Functions…" The main feature of the model that provides most of the parameters needed for scour calculations is the "Flow Distributions Locations…" option in the Simulate, Options toolbar menu. Essentially, it computes velocity, hydraulic depth and several other parameters at up to 45 segments of any cross sections. However, the segments are not "equal flow" segments as are the 20 stream tubes in DOS-WSPRO. After running the backwater calculations, the scour module extracts the data from the HEC-RAS input and output files and uses the pertinent values for the pier scour calculations. A plot of the all of the scour values and a scour report are produced. The scour analysis can be used with any of the program's bridge analysis routines – HR-WSPRO, energy or momentum. Figure 2 shows the scour plot.

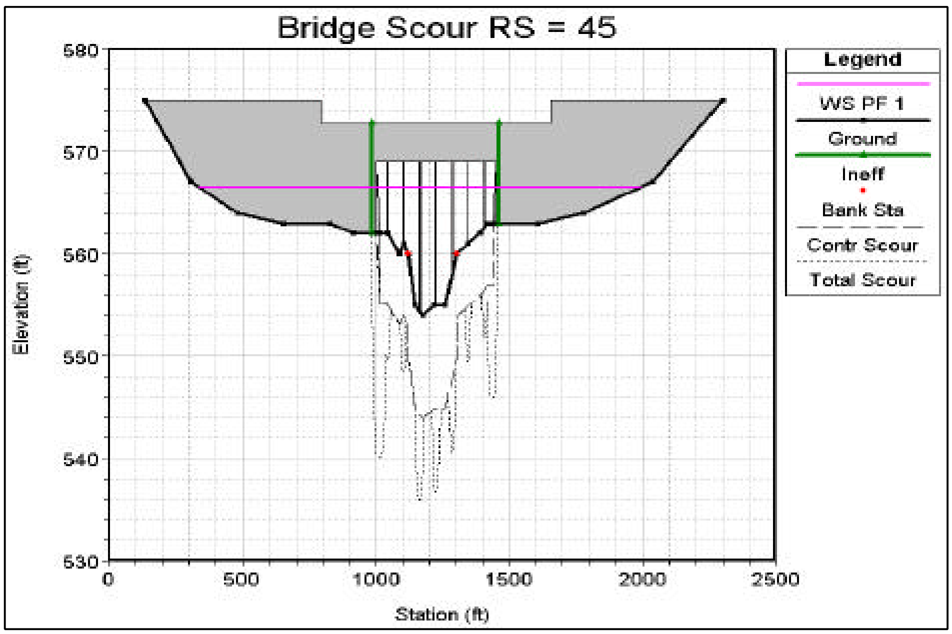



Figure 2. HEC-RAS Plot of Scour Depths

The deficiencies of the HEC-RAS 2.2 scour analysis module are

(a) The model does not compute contraction scour for overtopping flows or when the water at the section just upstream from the bridge is against the bridge face (i.e. full flow at the upstream face.)

(b) The model does not compute scour for multiple opening bridges.

(c) Neither footing scour nor piling scour is considered.

(d) The model does not use the recommended angle of attack factor for multiple columns.

(e) The scour report incorrectly computes the total of pier and contraction scour in the main channel.

(f) The flow distribution option does not correctly compute the velocity distribution at the section upstream from the bridge. This creates under-estimated approach velocities for pier scour calculations.

(g) The model does not compute scour for pressure flow.

(h) The model provides no estimates of angle of attack for the approach flow.

(i) The model does not provide the warnings included in the KDOT scour spreadsheets.

(j) The model does not have a skew option for cross sections or bridges. Consequently, station data for upstream and downstream bridge cross sections, bridges, roadways and pier need to be multiplied by the cosine of the skew angle. This is to orient the cross sections perpendicular to the flow.

These deficiencies were discovered through thorough testing of the model. In summary, **the scour portion of HEC-RAS 2.2 as it now exists should be used with a great deal of caution**.

The strengths of the HEC-RAS 2.2 model for hydraulic design are

(a) It can be used in either metric or English units.

(b) It handles the hydraulic analysis of multiple opening bridges with ease, although it does not do scour for this situation.

(c) The windows format makes the model compatible with EXCEL, which facilitates model building and tuning.

(d) The graphic capabilities of the model help reduce data input errors and aids in interpreting and tuning the hydraulic modeling of bridges.

(e) The new HEC GeoRas 1.0 program enables HEC-RAS 2.2 models to be built directly from an ArcInfo Digital Elevation Map (DEM). The user simply constructs the cross sections and the reach-length polylines on a

DEM and the program creates the geometry input file for HEC-RAS 2.2. The resulting model is geospatially correct.

An example of a bridge will be used to compare DOS-WSPRO and HR-WSPRO. The bridge is the one analyzed in Example 8 of the KDOT Scour Manual and is shown in Figs 3 and 4 herein***. (Metric units are not given in this chapter since DOS-WSPRO does not support metric units.)*** It is a bridge skewed at a 30-degree angle to the river. It has seven piers, each with three 3-ft diameter columns spaced at 19-ft intervals between column centerlines. The 4.5-ft high pier footings were 6-ft by 9-ft with the longer side parallel to the roadway. The projected width of the footings was, therefore, 10.8 ft. The bridge opening with the piers is shown below (adjusted for skew). The road was modeled as a 1000-ft long weir at a constant elevation of 572.8 ft. There are three sections downstream from the bridge – Section 10 (A-A), Section 20 (B-B), Section 30 (EXIT), Section 40 (FULLV), Section 50 (at upstream bridge face, not in DOS-WSPRO run), and Section 60 (APPRO). The HEC-RAS model requires a cross section just upstream and just downstream from the bridge. The downstream section is the one called the full valley section (FULLV) in the DOS version of DOS-WSPRO. HEC-RAS also requires a section just upstream from the bridge, even when using the HR-WSPRO option in HEC-RAS. For this example, Sections 40 and 50, downstream and upstream from the bridge, are identical. The design flow of 28,200 cfs was used with a downstream slope-conveyance boundary condition using 0.0008 as the slope of the energy grade line at Section 10. The cross section layout is shown in Figure 3 and the bridge cross sections (40 and 50) are shown in Figure 4.

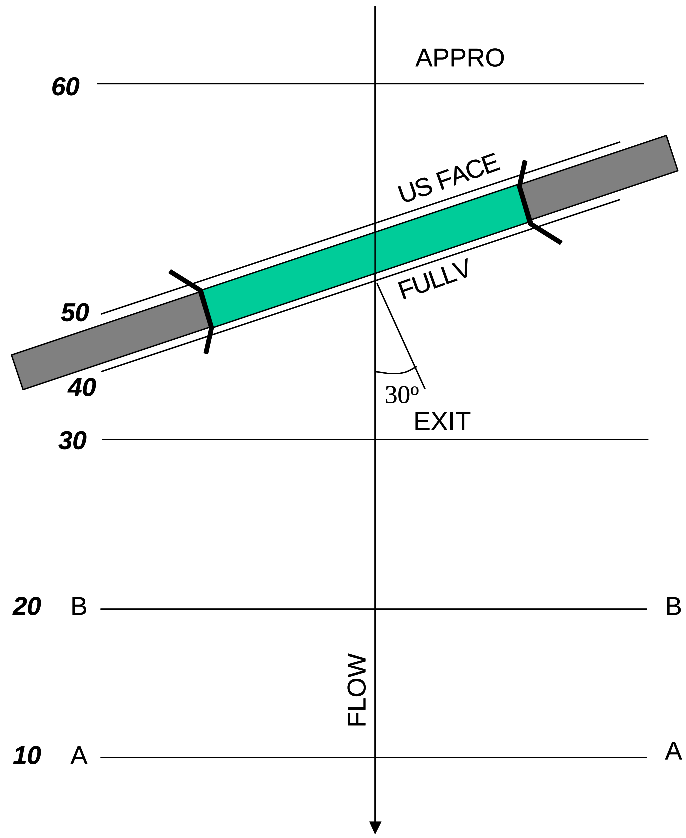



Figure 3.  Cross Section Layout for Example Bridge

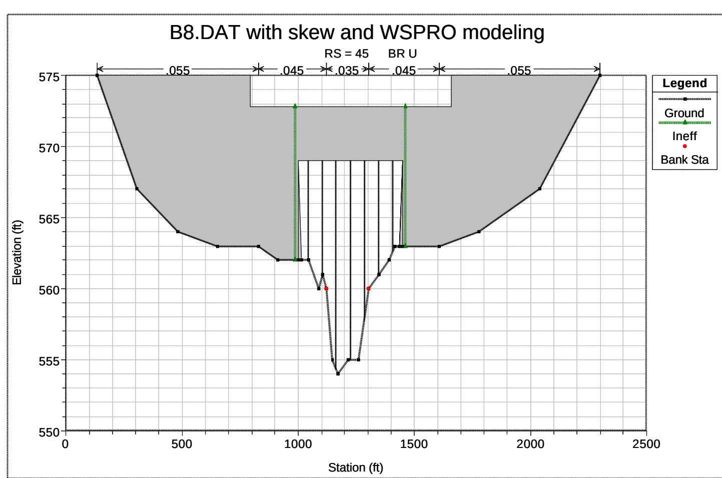



Figure 4.  Bridge Cross Section for Example Bridge

The DOS-WSPRO input file is shown on page 78-79 of the Appendix. The postprocessor file is shown on pages 80-81 and the printed KDOT scour spreadsheets are shown on pages 82-86. The same file was coded in HEC-RAS and run with the HR-WSPRO bridge modeling option. The results of the water surface elevation computations are shown in Table 2. The computed values were not much different (< 1%) at the bridge section and at Section 60, the approach section. The encircled values are the water surface elevation used to provide the local velocity and depth values for pier scour calculations. Note that DOS-WSPRO uses the bridge section velocities and HR-WSPRO uses the velocities at the cross section just upstream from the bridge, at the embankment toe.

Table 2. Water Surface Elevations from DOS-WSPRO and HR-WSPRO for the Example Problem

| | | HR -WSPRO | DOS-WSPRO | |
|---|---|---|---|---|
| Reach | River Sta | W.S. Elev | W.S. Elev | |
| | | (ft) | (ft) | |
| | | | | |
| PAW | 10 | 564.26 | 564.3 | DS 2 |
| PAW | 20 | 565 | 565.09 | DS 1 |
| PAW | 30 | 565.85 | 565.9 | EXIT |
| PAW | 40 | 565.76 | 566.29 | FULLV |
| PAW | 45 BR D | 565.7 | 565.98 | BRIDGE |
| PAW | 45 BR U | 566.52 | | |
| PAW | 50 | 567.09 | | |
| PAW | 60 | 568.78 | 568.86 | APPROACH |

The scour results from the HEC-RAS program are shown on pages 87-90 of the APPENDIX and summarized in Table 3. Note that the values of combined pier and contraction scour on page 90 are incorrect for the main channel piers. The program uses the contraction scour value for the left overbank rather than the main channel contraction scour when computing the combined scour at the main channel piers (see arrows below). The corrected values are shown below in the right hand column. The HEC-RAS plot shown in Figure 5 shows the correct values of the combined scour.

Table 3. HEC-RAS Scour Output Table for the Example Problem

| | Values in HEC-RAS Scour Report | | Corrected Values | | |
|---|---|---|---|---|---|
| | Combined Scour Depths | From Scour Report | Pier Scour Depth (ft) | Contraction Scour Depth Ys (ft): | Corrected Combined Scour Depths (ft): |
| LOB | Pier : #1 (CL = 1042.43) (Contr + Pier) (ft): | 12.24 | 5.34 | 6.9 | 12.24 |
| | Pier : #2 (CL = 1101.32) (Contr + Pier) (ft): | 12.39 | 5.49 | 6.9 | 12.39 |
| MC | Pier : #3 (CL = 1163.67) (Contr + Pier) (ft): | 15.16 | 8.26 | 9.42 | 17.68 |
| | Pier : #4 (CL = 1224.29) (Contr + Pier) (ft): | 15 | 8.1 | 9.42 | 17.52 |
| | Pier : #5 (CL = 1284.91) (Contr + Pier) (ft): | 14.1 | 7.2 | 9.42 | 16.62 |
| ROB | Pier : #6 (CL = 1345.53) (Contr + Pier) (ft): | 12.34 | 5.44 | 6.09 | 11.53 |
| | Pier : #7 (CL = 1406.15) (Contr + Pier) (ft): | 11.61 | 4.71 | 6.09 | 10.8 |

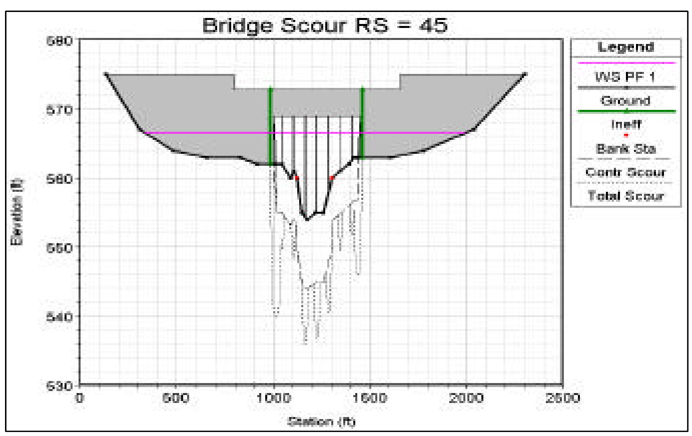



Figure 5. HEC-RAS Plot of Computed Scour Depths for Example Problem

Table 4. Comparison of Scour Values for the Example Problem using KDOT Method and HEC-RAS Method (Metric version not available for KDOT methods)

(a)

| Abutment Scour | | |
|---|---|---|
| | Left Abut | Right Abut |
| | | |
| KDOT regular | 32.44 | 14.93 |
| KDOT (Hire) | **12.01** | **9.19** |
| HEC-RAS (Hire) | **21.93** | **10.94** |

(b)

| Contraction Scour | | | |
|---|---|---|---|
| | LOB | MC | ROB |
| | | | |
| KDOT | 7.00 C.W. | 10.31 L.B. | 5.18 C.W. |
| HEC-RAS | 6.9 C.W. | 9.42 L.B. | 6.09 C.W. |

(c)

| Pier Scour | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Pier no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | | | | | | | | |
| KDOT | Ys (ft), no angle of attack | **5.07** | **5.9** | 8.92 | 8.77 | **6.74** | **5.73** | **4.81** |
| KDOT | Limit, no angle of attack | 6.9 | 6.9 | **6.9** | **6.9** | 6.9 | 6.9 | 6.9 |
| HEC-RAS | Ys (ft), no angle of attack | **5.34** | **5.43** | **8.26** | **8.1** | **7.2** | **5.44** | **4.71** |
| | | | | | | | | |
| | Angle of attack (deg) | 44.7 | 25.8 | 13.5 | 5.1 | 7.0 | 15.6 | 36.7 |
| KDOT | Factor (K2 or aeff/a) | 3 | 3 | 3 | 3.13 | 2.55 | 3 | 3 |
| KDOT | Ys(ft), with angle of attack | **10.36** | **12.06** | **18.23** | **14.36** | **12.37** | **11.71** | **9.82** |
| HEC-RAS | Factor (K2 or aeff/a) | 4.28 | 3.22 | 2.35 | 1.51 | 1.7 | 2.54 | 3.86 |
| HEC-RAS | Ys(ft), with angle of attack | **22.85** | **17.67** | **19.4** | **12.23** | **12.24** | **13.83** | **18.17** |

Where C.W. = clear water contraction scouir and L.B. = live bed contraction scour.

Tables 4 a, b and c compare the scour values for the KDOT method and for the HEC-RAS scour program using the HR-WSPRO bridge modeling option. The pier scour values were calculated for both methods with and without angle of attack considerations. The angles used in the HEC-RAS scour program were those obtained from the KDOT spreadsheets. Note that although the HEC-RAS program has a multiple columns options, it does not use the recommended projected area method of accounting for angle of attack for pier scour, which results in pier scour depths that are significantly less than they should be.

The flow distributions at and just upstream from the bridge are shown in

Figures 6 and 7. HEC-RAS has an error in the program used in the determination of the velocity distribution. For Section 50 (15-ft upstream) (4.57-m metric versions) upstream the ineffective flow option was used to eliminate conveyance to the left of station 985 (station 300.23 metric version) (approximately). The values shown in the figure and in Table 5 show that the program has water flowing out to station 923 (281.733 metric). **This is not correct.** The result of putting too much flow outside the ineffective flow boundaries is to decrease the velocities directly upstream from the bridge opening. Thus, it produces approach velocities that are too low. This error has been noted for other bridges.

HEC-RAS does not compute contraction scour when flow is not free surface flow through the bridge. This includes overtopping cases and situations where full flow occurs at the upstream bridge opening. The HEC-RAS profile, cross section and the scour plots are shown in Figures 8 and 9 for a modified version of the HEC-RAS example problem 11 that include the three cases – open channel flow, full bridge face flow and overtopping flow. Figure 10 shows the scour depths for all three cases. Note that flow attached to the upstream bridge face contraction scour was not computed.

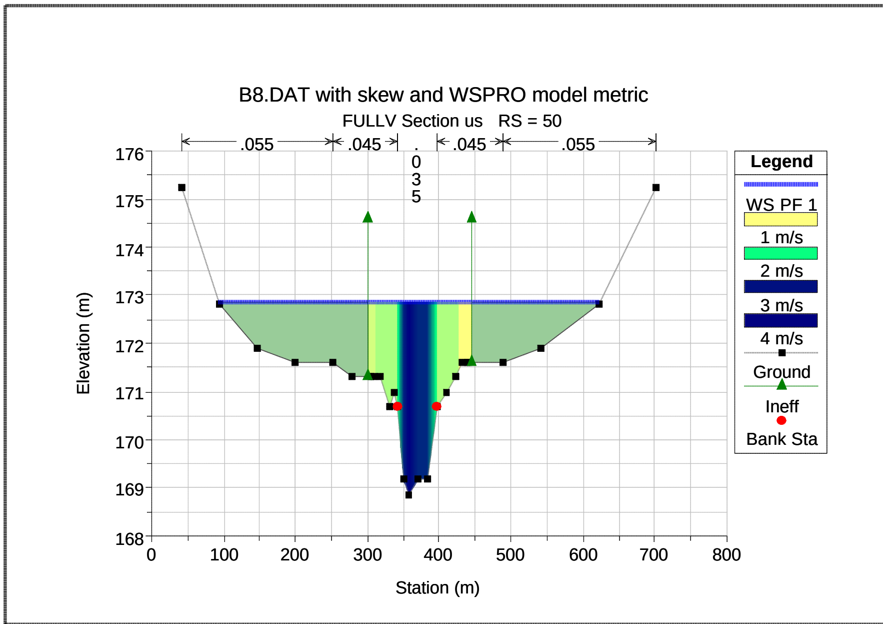



Figure 6a. HEC-RAS Plot of Velocity Distribution at Bridge for Example Problem (US Customary Units)

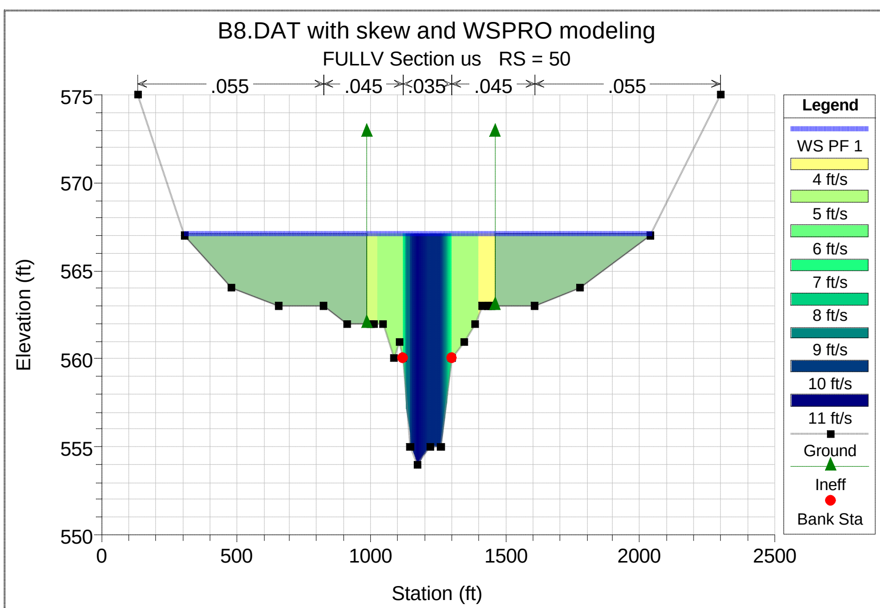



Figure 6b. HEC-RAS Plot of Velocity Distribution at Bridge for Example Problem (Metric Units)

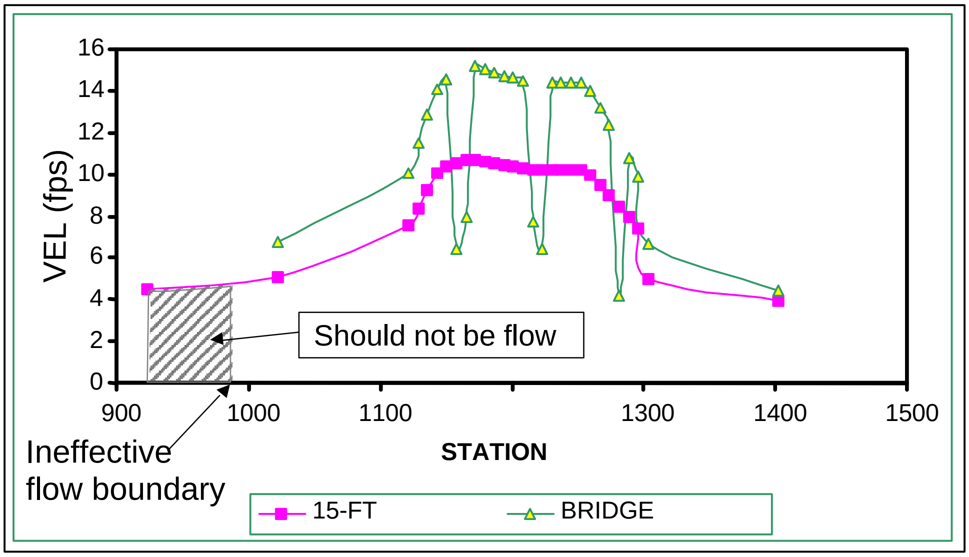



Figure 7a. HEC-RAS Plot of Velocity Distribution at Bridge and at the Upstream Cross Section for Example Problem (US Customary Units)

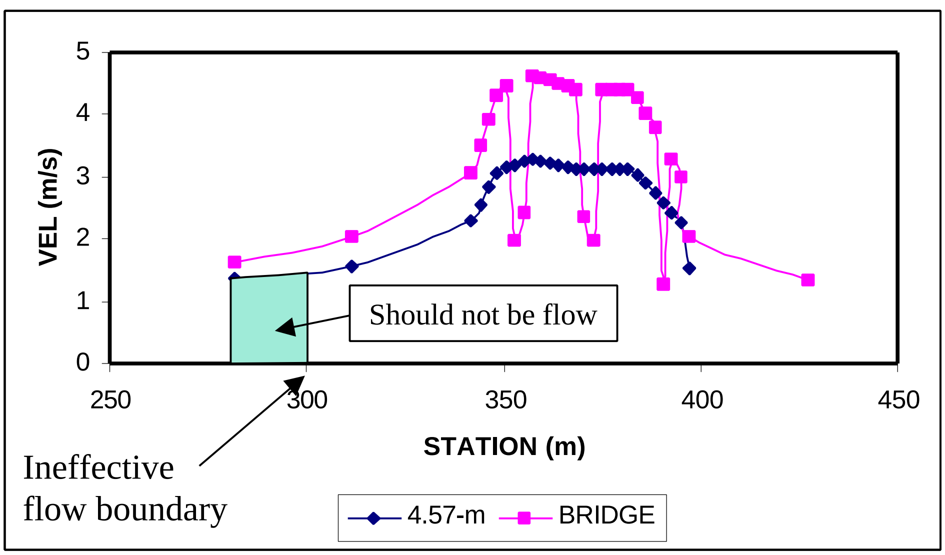



Figure 7b. HEC-RAS Plot of Velocity Distribution at Bridge and at the Upstream Cross Section for Example Problem (Metric Units)

Table 5a. HEC-RAS Table of Flow and Velocity Distributions
(US Customary Units)

985 ineffective flow

| Pier Locations | | Plan: B8 wspro River: CAT RIVER Reach:PAW Riv Sta: 50 Profile: PF 1 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Left Sta (ft) | Right Sta (ft) | Flow (cfs) | Area (sq ft) | W.P. (ft) | % Conv. | Hydr D. (ft) | Velocity (ft/s) |
| | 1 | 923.79 | 1022.52 | 865.7 | 190.93 | 37.52 | 3.07 | 5.09 | 4.53 |
| **1042 and 1101** | 2 | 1022.52 | 1121.24 | 3040.41 | 597.71 | 98.83 | 10.78 | 6.05 | **5.09** |
| | 3 | 1121.24 | 1128.51 | 426.55 | 56.66 | 7.41 | 1.51 | 7.79 | 7.53 |
| | 4 | 1128.51 | 1135.79 | 561.83 | 66.85 | 7.41 | 1.99 | 9.19 | 8.4 |
| | 5 | 1135.79 | 1143.06 | 711.62 | 77.03 | 7.41 | 2.52 | 10.59 | 9.24 |
| | 6 | 1143.06 | 1150.34 | 867.04 | 86.47 | 7.35 | 3.07 | 11.89 | 10.03 |
| | 7 | 1150.34 | 1157.61 | 930.21 | 89.83 | 7.28 | 3.3 | 12.35 | 10.35 |
| **1164** | 8 | 1157.61 | 1164.89 | 965.64 | 91.87 | 7.28 | 3.42 | 12.63 | **10.51** |
| | 9 | 1164.89 | 1172.16 | 1001.59 | 93.91 | 7.28 | 3.55 | 12.91 | 10.67 |
| | 10 | 1172.16 | 1179.44 | 1016.83 | 94.75 | 7.28 | 3.61 | 13.02 | 10.73 |
| | 11 | 1179.44 | 1186.71 | 995.7 | 93.56 | 7.28 | 3.53 | 12.86 | 10.64 |
| | 12 | 1186.71 | 1193.98 | 974.12 | 92.34 | 7.28 | 3.45 | 12.69 | 10.55 |
| | 13 | 1193.98 | 1201.26 | 952.73 | 91.12 | 7.28 | 3.38 | 12.53 | 10.46 |
| | 14 | 1201.26 | 1208.53 | 931.52 | 89.89 | 7.28 | 3.3 | 12.36 | 10.36 |
| | 15 | 1208.53 | 1215.81 | 910.5 | 88.67 | 7.28 | 3.23 | 12.19 | 10.27 |
| | 16 | 1215.81 | 1223.08 | 898.34 | 87.95 | 7.27 | 3.19 | 12.09 | 10.21 |
| **1225** | 17 | 1223.08 | 1230.36 | 898.26 | 87.94 | 7.27 | 3.19 | 12.09 | **10.21** |
| | 18 | 1230.36 | 1237.63 | 898.26 | 87.94 | 7.27 | 3.19 | 12.09 | 10.21 |
| | 19 | 1237.63 | 1244.9 | 898.26 | 87.94 | 7.27 | 3.19 | 12.09 | 10.21 |
| | 20 | 1244.9 | 1252.18 | 898.26 | 87.94 | 7.27 | 3.19 | 12.09 | 10.21 |
| | 21 | 1252.18 | 1259.45 | 898.26 | 87.94 | 7.27 | 3.19 | 12.09 | 10.21 |
| | 22 | 1259.45 | 1266.73 | 848.01 | 85.17 | 7.32 | 3.01 | 11.71 | 9.96 |
| | 23 | 1266.73 | 1274 | 748.99 | 79.07 | 7.32 | 2.66 | 10.87 | 9.47 |
| | 24 | 1274 | 1281.28 | 655.04 | 72.96 | 7.32 | 2.32 | 10.03 | 8.98 |
| **1285** | 25 | 1281.28 | 1288.55 | 566.18 | 66.85 | 7.32 | 2.01 | 9.19 | **8.47** |
| | 26 | 1288.55 | 1295.83 | 482.58 | 60.74 | 7.32 | 1.71 | 8.35 | 7.95 |
| | 27 | 1295.83 | 1303.1 | 404.41 | 54.63 | 7.32 | 1.43 | 7.51 | 7.4 |
| **1346** | 28 | 1303.1 | 1402.69 | 2964.44 | 590.21 | 99.62 | 10.51 | 5.93 | **5.02** |
| **1406** | 29 | 1402.69 | 1502.28 | 988.75 | 249.88 | 60.32 | 3.51 | 4.14 | **3.96** |

Qtotal = 28200.03

Table 5b. HEC-RAS Table of Flow and Velocity Distributions
(Metric Units)

300.23 ineffective flow

| Pier Locations | | Plan: B8 wspro River: CAT RIVER Reach:PAW Riv Sta: 50 Profile: PF 1 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Left Sta | Right Sta | Flow | Area | W.P. | % Conv. | Hydr D. | Velocity |
| | | (m) | (m) | (m3/s) | (m2) | (m) | | (m) | (m/s) |
| | | | | | | | | | |
| | 1 | 281.57 | 311.66 | 24.51 | 17.74 | 11.43 | 3.07 | 1.55 | 1.38 |
| 317.733 and 335.382 | 2 | 311.66 | 341.75 | 86.1 | 55.53 | 30.12 | 10.78 | 1.85 | 1.55 |
| | 3 | LB 341.75 | 343.97 | 12.08 | 5.26 | 2.26 | 1.51 | 2.37 | 2.29 |
| | 4 | 343.97 | 346.19 | 15.91 | 6.21 | 2.26 | 1.99 | 2.8 | 2.56 |
| | 5 | 346.19 | 348.41 | 20.15 | 7.16 | 2.26 | 2.52 | 3.23 | 2.82 |
| | 6 | 348.41 | 350.62 | 24.55 | 8.03 | 2.24 | 3.07 | 3.62 | 3.06 |
| | 7 | 350.62 | 352.84 | 26.34 | 8.35 | 2.22 | 3.3 | 3.76 | 3.16 |
| 354.69 | 8 | 352.84 | 355.06 | 27.34 | 8.54 | 2.22 | 3.42 | 3.85 | 3.2 |
| | 9 | 355.06 | 357.27 | 28.36 | 8.72 | 2.22 | 3.55 | 3.93 | 3.25 |
| | 10 | 357.27 | 359.49 | 28.79 | 8.8 | 2.22 | 3.61 | 3.97 | 3.27 |
| | 11 | 359.49 | 361.71 | 28.2 | 8.69 | 2.22 | 3.53 | 3.92 | 3.24 |
| | 12 | 361.71 | 363.93 | 27.58 | 8.58 | 2.22 | 3.45 | 3.87 | 3.22 |
| | 13 | 363.93 | 366.14 | 26.98 | 8.46 | 2.22 | 3.38 | 3.82 | 3.19 |
| | 14 | 366.14 | 368.36 | 26.38 | 8.35 | 2.22 | 3.3 | 3.77 | 3.16 |
| | 15 | 368.36 | 370.58 | 25.78 | 8.24 | 2.22 | 3.23 | 3.72 | 3.13 |
| | 16 | 370.58 | 372.8 | 25.44 | 8.17 | 2.22 | 3.19 | 3.69 | 3.11 |
| 373.16 | 17 | 372.8 | 375.01 | 25.44 | 8.17 | 2.22 | 3.19 | 3.68 | 3.11 |
| | 18 | 375.01 | 377.23 | 25.44 | 8.17 | 2.22 | 3.19 | 3.68 | 3.11 |
| | 19 | 377.23 | 379.45 | 25.44 | 8.17 | 2.22 | 3.19 | 3.68 | 3.11 |
| | 20 | 379.45 | 381.66 | 25.44 | 8.17 | 2.22 | 3.19 | 3.68 | 3.11 |
| | 21 | 381.66 | 383.88 | 25.44 | 8.17 | 2.22 | 3.19 | 3.68 | 3.11 |
| | 22 | 383.88 | 386.1 | 24.01 | 7.91 | 2.23 | 3.01 | 3.57 | 3.03 |
| | 23 | 386.1 | 388.32 | 21.21 | 7.35 | 2.23 | 2.66 | 3.31 | 2.89 |
| | 24 | 388.32 | 390.53 | 18.55 | 6.78 | 2.23 | 2.32 | 3.06 | 2.74 |
| 391.64 | 25 | 390.53 | 392.75 | 16.03 | 6.21 | 2.23 | 2.01 | 2.8 | 2.58 |
| | 26 | 392.75 | 394.97 | 13.67 | 5.64 | 2.23 | 1.71 | 2.54 | 2.42 |
| | 27 | 394.97 | RB 397.18 | 11.45 | 5.07 | 2.23 | 1.43 | 2.29 | 2.26 |
| 410.12 | 28 | 397.18 | 427.54 | 83.94 | 54.83 | 30.36 | 10.51 | 1.81 | 1.53 |
| 428.60 | 29 | 427.54 | 457.89 | 28 | 23.21 | 18.39 | 3.51 | 1.26 | 1.21 |

Qtotal = 798.55

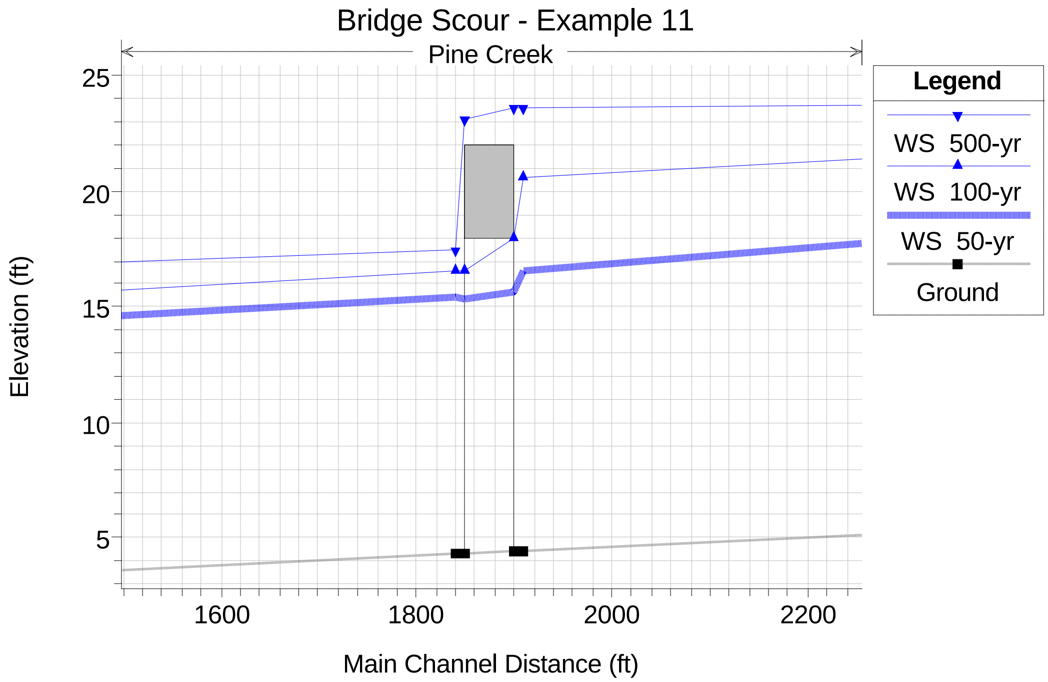



Figure 8a. HEC-RAS Profile Plot of Bridge for Overtopping, Attached and Open Channel Flow (US Customary Units)

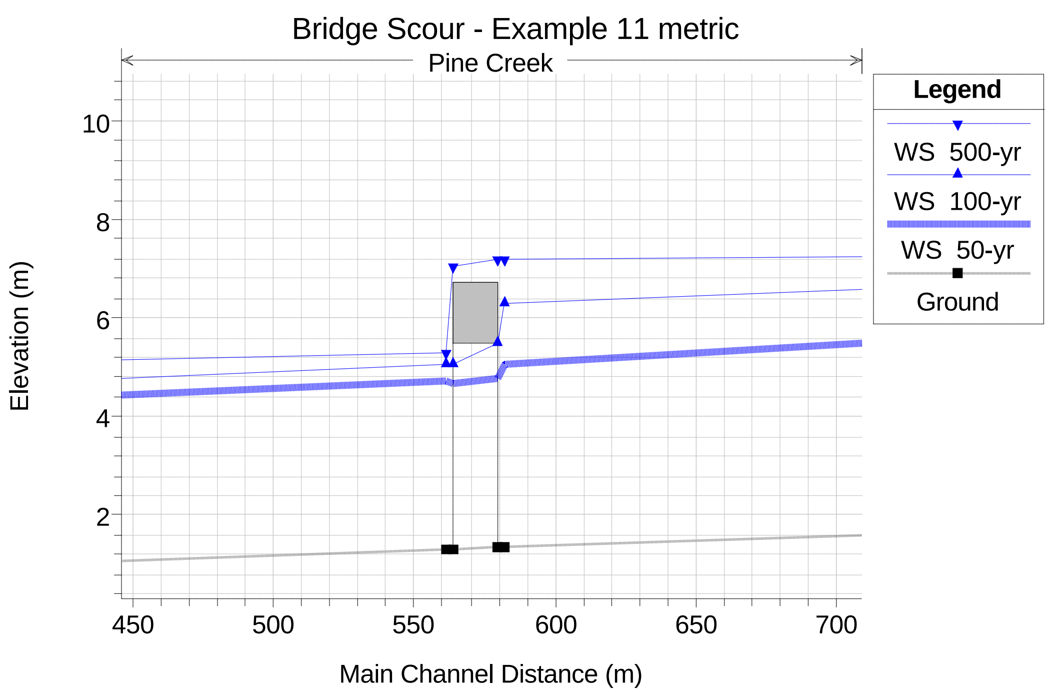



Figure 8b. HEC-RAS Profile Plot of Bridge for Overtopping, Attached and Open Channel Flow (Metric Units)

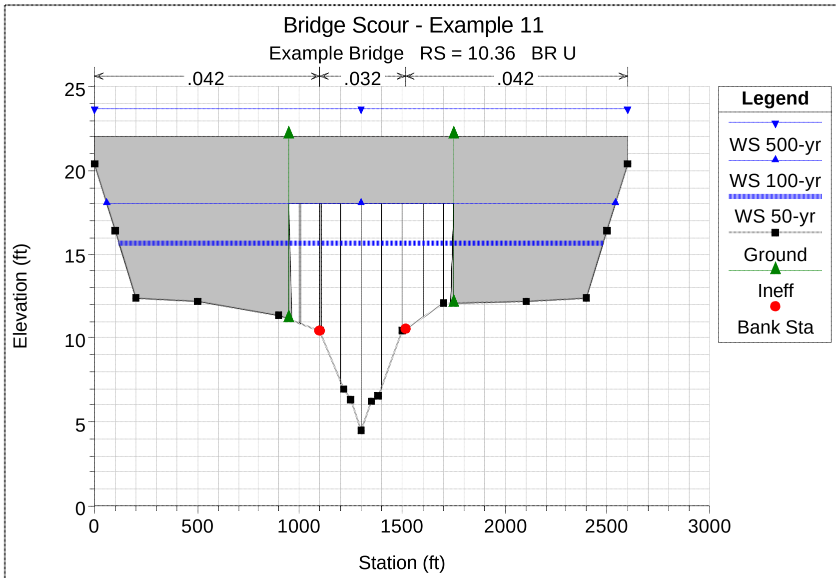



Figure 9a. HEC-RAS Profile Plot of Bridge Section for Overtopping, Attached and Open Channel Flow (US Customary Units)

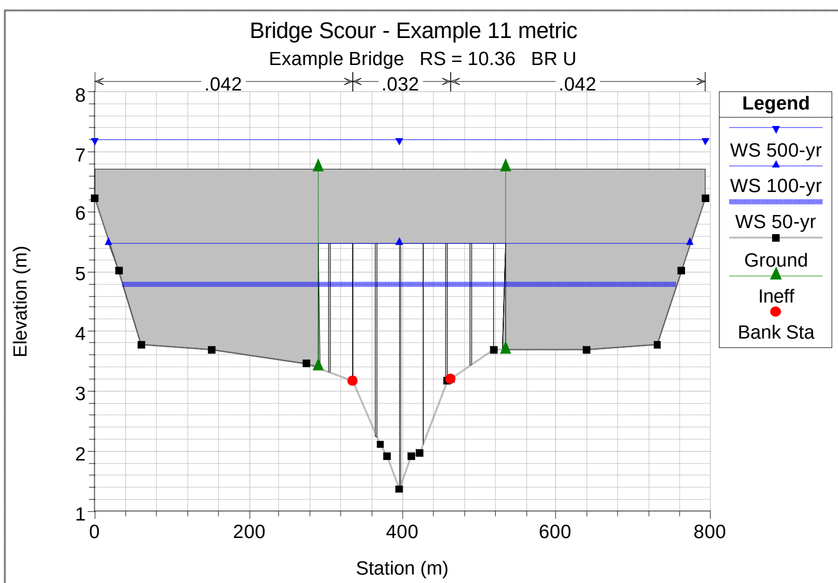
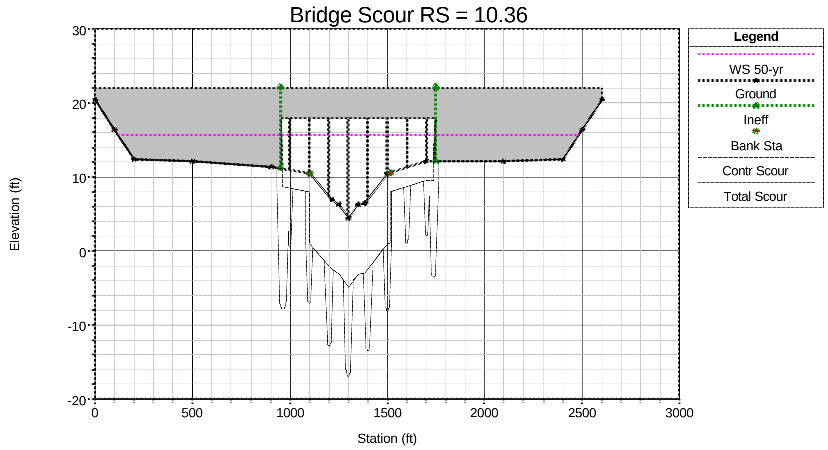
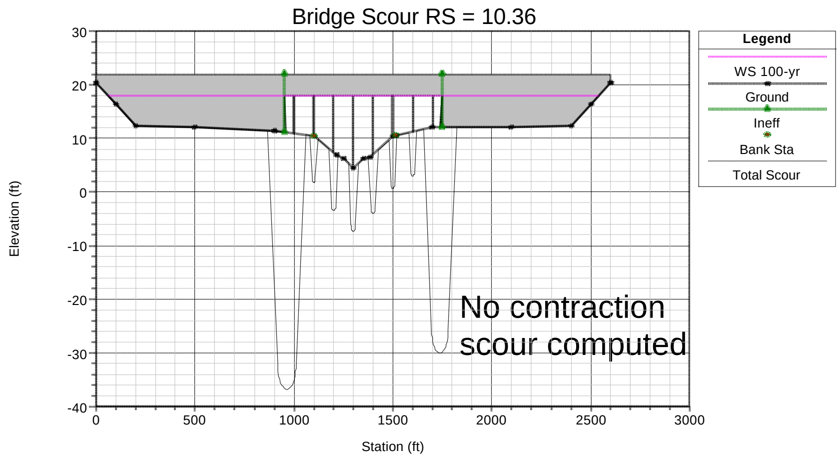



Figure 9b. HEC-RAS Profile Plot of Bridge Section for Overtopping, Attached and Open Channel Flow (Metric Units)

50-yr




100-yr




500-yr

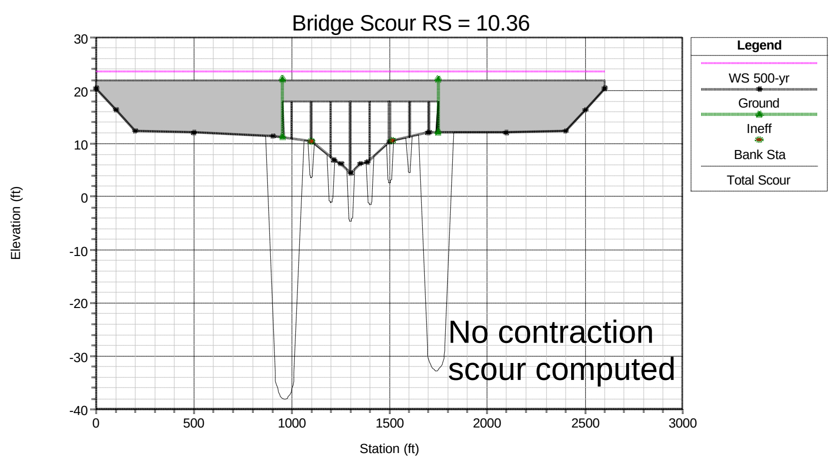



Figure 10a. Scour Plots of Bridge for Overtopping (500-yr), Attached (100-yr) and Open Channel Flow (50-yr) (US Customary Units)

50-yr

100-yr

500-yr

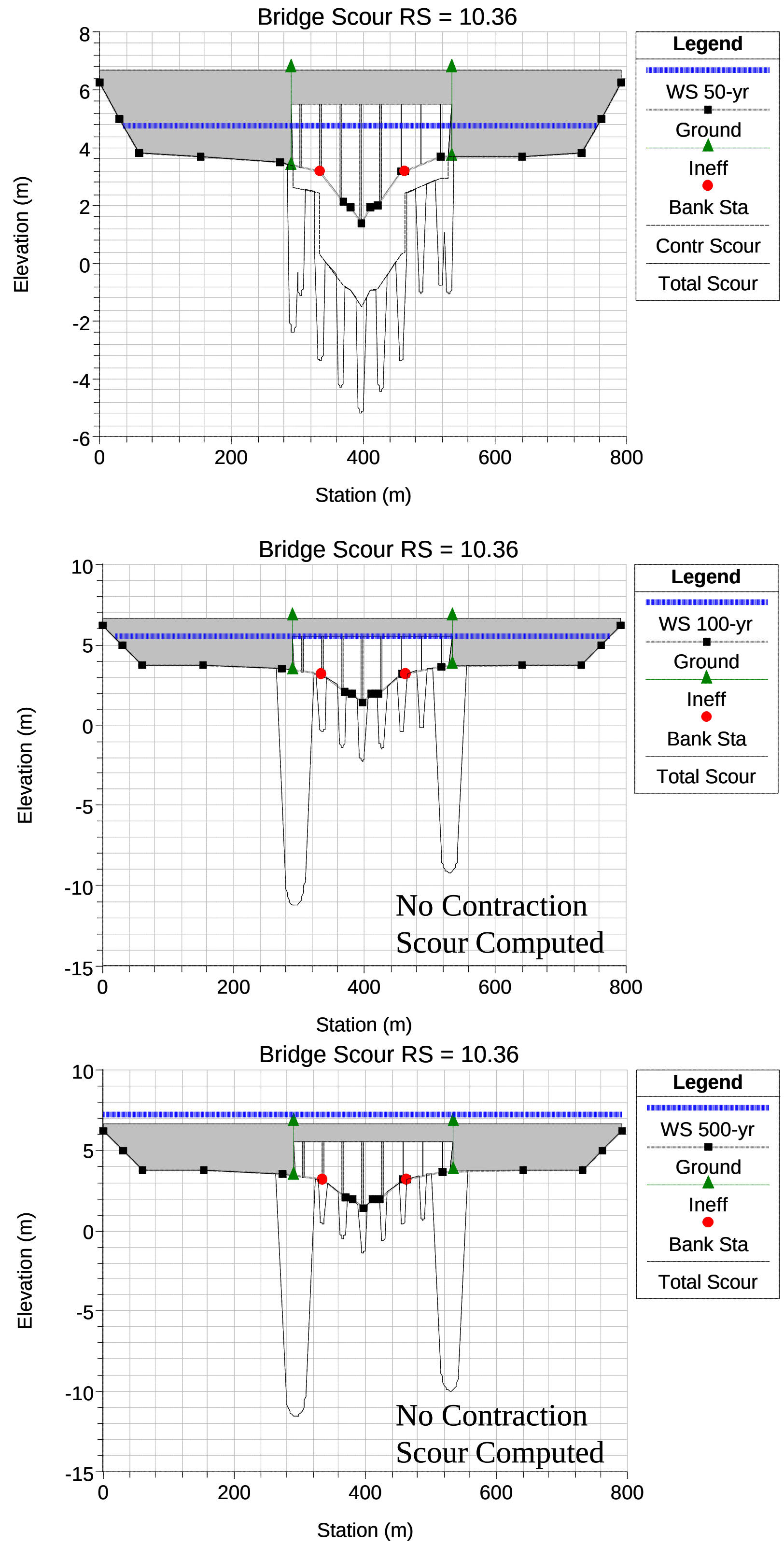



Figure 10b. Scour Plots of Bridge for Overtopping (500-yr), Attached (100-yr) and Open Channel Flow (50-yr) (Metric Units)

# CHAPTER 3

### Comparison of DOS-WSPRO with HEC-RAS Bridge Analysis Methods (HR-WSPRO, Energy and Momentum)

The HR-WSPRO method used in HEC-RAS 2.2 is not precisely the same as the method used in DOS-WSPRO. The additional cross section just upstream from the bridge that is required in HEC-RAS modeling is not required in the old DOS-WSPRO program. Consequently, the results should be somewhat different. While the DOS-WSPRO streamtubes are used to determine the average length, $L_{av}$, in Eq. 5-13 of the HEC-RAS Hydraulic Reference Manual, the values within the streamtubes are not given in the HEC-RAS output report. Several bridges were tested by both the old DOS-WSPRO program and by HR-WSPRO within HEC-RAS. The differences were small (on the order of 0.01 ft.) and are, thus, equivalent within reasonable tolerance.

Example 13 in the HEC-RAS 2.2 example problems models a bridge using the HR-WSPRO modeling option within HEC-RAS. This example also uses the energy method and the momentum method to model the bridge. A comparison table of the three methods – HR-WSPRO, energy and momentum - is shown in Table 6. The differences are quite small (< 1%) for the three methods. That is as expected since the tailwater elevation (Section 52.29) is very important and should be (and is) the same for all of the models.

Table 7 shows the scour values for Example 13 as reported by the HEC-RAS scour report and the corrected values. Note the large error in the combination pier and contraction scour depths from the scour report as stated previously. The HEC-

RAS scour report computes the combined pier scour and contraction scour for each main channel pier by adding the contraction scour for the right-most pier in the left over bank and the correct main channel pier scour value. It should also be noted that the large main channel contraction scour depths are too large. This is because the channel widths chosen by the HEC-RAS scour model are inappropriate. You do have the option to override the default values selected by the program and in this case you would choose to do this. As always, sound engineering judgment must be exercised when using any scour software. The same judgment was, of course, required in using the KDOT scour spreadsheets effectively.

Table 6a. Comparison of HR-WSPRO, Energy and Momentum Methods for HEC-RAS Example 13 (US Customary Units)

| | | HEC-RAS | HEC-RAS | | HEC-RAS | |
|---|---|---|---|---|---|---|
| | Reach | WSPRO | Energy | | Momentum | |
| River Sta | Length | W.S. Elev | W.S. Elev | Diff (3-4) | W.S. Elev | Diff (3-6) |
| | (ft) | (ft) | (ft) | (ft) | (ft) | (ft) |
| *1* | *2* | *3* | *4* | *5* | *6* | *7* |
| | | | | | | |
| 50 | | 326 | 326 | 0 | 326 | 0 |
| 50.1642* | 867 | 326.94 | 326.94 | 0 | 326.94 | 0 |
| 50.3284 | 867 | 327.59 | 327.59 | 0 | 327.59 | 0 |
| 50.4927* | 867 | 328.02 | 328.02 | 0 | 328.02 | 0 |
| 50.6570* | 867 | 328.51 | 328.51 | 0 | 328.51 | 0 |
| 50.8213* | 867 | 329.02 | 329.02 | 0 | 329.02 | 0 |
| 50.9856* | 867 | 329.54 | 329.54 | 0 | 329.54 | 0 |
| 51.15 | 867 | 330.07 | 330.07 | 0 | 330.07 | 0 |
| 51.32* | 894 | 330.71 | 330.71 | 0 | 330.71 | 0 |
| 51.49* | 894 | 331.59 | 331.59 | 0 | 331.59 | 0 |
| 51.66* | 894 | 332.59 | 332.59 | 0 | 332.59 | 0 |
| 51.83* | 894 | 333.57 | 333.57 | 0 | 333.57 | 0 |
| 52 | 894 | 334.45 | 334.45 | 0 | 334.45 | 0 |
| 52.29 | 1530 | 336.04 | 336.04 | 0 | 336.04 | 0 |
| 52.36 | 426 | 336.82 | 336.29 | 0.53 | 336.29 | 0.53 |
| 52.37 | Bridge | | Bridge | | | |
| 52.38 | 26 | 337.11 | 337.05 | 0.06 | 336.91 | 0.2 |
| 52.46 | 380 | 338.63 | 338.73 | -0.1 | 338.64 | -0.01 |
| 52.67 | 1130 | 338.93 | 339.06 | -0.13 | 338.98 | -0.05 |
| 52.8542* | 971 | 339.12 | 339.25 | -0.13 | 339.17 | -0.05 |
| 53.0385* | 971 | 339.34 | 339.45 | -0.11 | 339.38 | -0.04 |
| 53.2228* | 971 | 339.59 | 339.69 | -0.1 | 339.63 | -0.04 |
| 53.4071* | 971 | 339.88 | 339.97 | -0.09 | 339.92 | -0.04 |
| 53.5914* | 971 | 340.22 | 340.29 | -0.07 | 340.25 | -0.03 |
| 53.7757* | 971 | 340.61 | 340.67 | -0.06 | 340.63 | -0.02 |
| 53.96 | 971 | 341.05 | 341.09 | -0.04 | 341.06 | -0.01 |
| 54.14* | 950 | 341.47 | 341.5 | -0.03 | 341.48 | -0.01 |
| 54.32* | 950 | 341.89 | 341.92 | -0.03 | 341.9 | -0.01 |
| 54.5* | 950 | 342.32 | 342.34 | -0.02 | 342.33 | -0.01 |
| 54.68* | 950 | 342.75 | 342.77 | -0.02 | 342.76 | -0.01 |
| 54.86* | 950 | 343.17 | 343.19 | -0.02 | 343.18 | -0.01 |
| 55.04* | 950 | 343.59 | 343.61 | -0.02 | 343.6 | -0.01 |
| 55.22* | 950 | 344.01 | 344.02 | -0.01 | 344.01 | 0 |
| 55.4 | 950 | 344.42 | 344.43 | -0.01 | 344.42 | 0 |
| 55.5744* | 922 | 344.81 | 344.82 | -0.01 | 344.81 | 0 |
| 55.7488* | 922 | 345.24 | 345.25 | -0.01 | 345.24 | 0 |
| 55.9233* | 922 | 345.71 | 345.71 | 0 | 345.71 | 0 |
| 56.0977* | 922 | 346.19 | 346.19 | 0 | 346.19 | 0 |
| 56.2722* | 922 | 346.69 | 346.69 | 0 | 346.69 | 0 |
| 56.4466* | 922 | 347.2 | 347.2 | 0 | 347.2 | 0 |
| 56.6211* | 922 | 347.7 | 347.71 | -0.01 | 347.7 | 0 |
| 56.7955* | 922 | 348.21 | 348.21 | 0 | 348.21 | 0 |
| 56.97 | 922 | 348.71 | 348.71 | 0 | 348.71 | 0 |

**Maximum Difference**

Table 6b. Comparison of HR-WSPRO, Energy and Momentum
Methods for HEC-RAS Example 13
(Metric units)

| River Sta | Reach Length (meters) | HEC-RAS WSPRO W.S. Elev (meters) | HEC-RAS Energy W.S. Elev (meters) | Diff (3-4) (meters) | HEC-RAS Momentum W.S. Elev (meters) | Diff (3-6) (meters) |
|---|---|---|---|---|---|---|
| *1* | *2* | *3* | *4* | *5* | *6* | *7* |
| | | | | | | |
| 50 | 0.00 | 99.36 | 99.36 | 0.00 | 99.36 | 0.00 |
| 50.1642* | 264.25 | 99.65 | 99.65 | 0.00 | 99.65 | 0.00 |
| 50.3284 | 264.25 | 99.84 | 99.84 | 0.00 | 99.84 | 0.00 |
| 50.4927* | 264.25 | 99.98 | 99.98 | 0.00 | 99.98 | 0.00 |
| 50.6570* | 264.25 | 100.12 | 100.12 | 0.00 | 100.12 | 0.00 |
| 50.8213* | 264.25 | 100.28 | 100.28 | 0.00 | 100.28 | 0.00 |
| 50.9856* | 264.25 | 100.44 | 100.44 | 0.00 | 100.44 | 0.00 |
| 51.15 | 264.25 | 100.60 | 100.60 | 0.00 | 100.60 | 0.00 |
| 51.32* | 272.48 | 100.80 | 100.80 | 0.00 | 100.80 | 0.00 |
| 51.49* | 272.48 | 101.06 | 101.06 | 0.00 | 101.06 | 0.00 |
| 51.66* | 272.48 | 101.37 | 101.37 | 0.00 | 101.37 | 0.00 |
| 51.83* | 272.48 | 101.67 | 101.67 | 0.00 | 101.67 | 0.00 |
| 52 | 272.48 | 101.94 | 101.94 | 0.00 | 101.94 | 0.00 |
| 52.29 | 466.32 | 102.42 | 102.42 | 0.00 | 102.42 | 0.00 |
| 52.36 | 129.84 | 102.66 | 102.50 | 0.16 | 102.50 | 0.16 |
| 52.37 | Bridge | | Bridge | | | |
| 52.38 | 7.92 | 102.75 | 102.73 | 0.02 | 102.69 | 0.06 |
| 52.46 | 115.82 | 103.21 | 103.24 | -0.03 | 103.21 | 0.00 |
| 52.67 | 344.41 | 103.30 | 103.34 | -0.04 | 103.32 | -0.02 |
| 52.8542* | 295.95 | 103.36 | 103.40 | -0.04 | 103.37 | -0.02 |
| 53.0385* | 295.95 | 103.43 | 103.46 | -0.03 | 103.44 | -0.01 |
| 53.2228* | 295.95 | 103.50 | 103.53 | -0.03 | 103.51 | -0.01 |
| 53.4071* | 295.95 | 103.59 | 103.62 | -0.03 | 103.60 | -0.01 |
| 53.5914* | 295.95 | 103.69 | 103.72 | -0.02 | 103.70 | -0.01 |
| 53.7757* | 295.95 | 103.81 | 103.83 | -0.02 | 103.82 | -0.01 |
| 53.96 | 295.95 | 103.95 | 103.96 | -0.01 | 103.95 | 0.00 |
| 54.14* | 289.55 | 104.07 | 104.08 | -0.01 | 104.08 | 0.00 |
| 54.32* | 289.55 | 104.20 | 104.21 | -0.01 | 104.21 | 0.00 |
| 54.5* | 289.55 | 104.33 | 104.34 | -0.01 | 104.34 | 0.00 |
| 54.68* | 289.55 | 104.47 | 104.47 | -0.01 | 104.47 | 0.00 |
| 54.86* | 289.55 | 104.59 | 104.60 | -0.01 | 104.60 | 0.00 |
| 55.04* | 289.55 | 104.72 | 104.73 | -0.01 | 104.72 | 0.00 |
| 55.22* | 289.55 | 104.85 | 104.85 | 0.00 | 104.85 | 0.00 |
| 55.4 | 289.55 | 104.97 | 104.98 | 0.00 | 104.97 | 0.00 |
| 55.5744* | 281.01 | 105.09 | 105.10 | 0.00 | 105.09 | 0.00 |
| 55.7488* | 281.01 | 105.22 | 105.23 | 0.00 | 105.22 | 0.00 |
| 55.9233* | 281.01 | 105.37 | 105.37 | 0.00 | 105.37 | 0.00 |
| 56.0977* | 281.01 | 105.51 | 105.51 | 0.00 | 105.51 | 0.00 |
| 56.2722* | 281.01 | 105.67 | 105.67 | 0.00 | 105.67 | 0.00 |
| 56.4466* | 281.01 | 105.82 | 105.82 | 0.00 | 105.82 | 0.00 |
| 56.6211* | 281.01 | 105.97 | 105.98 | 0.00 | 105.97 | 0.00 |
| 56.7955* | 281.01 | 106.13 | 106.13 | 0.00 | 106.13 | 0.00 |
| 56.97 | 281.01 | 106.28 | 106.28 | 0.00 | 106.28 | 0.00 |

Maximum Difference

Table 7a. Illustration of Error in HEC-RAS Scour Summary Table
(US Customary Units)

| Values in HEC-RAS Scour Report | | | Corrected Values | | |
|---|---|---|---|---|---|
| Pier No. | Station (ft) | Cont. + Pier Scour Depth (ft) | Pier Scour Depth (ft) | Contraction Scour Depth (ft) | Corrected Combined Scour Depths (ft) |
| 1 | 2466 | 2.99 | 2.09 | 0.91 | 3 |
| 2 | 2490 | 3 | 2.1 | 0.91 | 3.01 |
| 3 | 2514 | 3 | 2.09 | 0.91 | 3 |
| 4 | 2538 | 2.98 | 2.07 | 0.91 | 2.98 |
| 5 | 2562 | 3 | 2.1 | 0.91 | 3.01 |
| 6 | 2586 | 3.31 | 2.4 | 23.21 | 25.61 |
| 7 | 2610 | 3.31 | 2.4 | 23.21 | 25.61 |
| 8 | 2634 | 3.31 | 2.4 | 23.21 | 25.61 |
| 9 | 2658 | 3.31 | 2.4 | 23.21 | 25.61 |
| 10 | 2682 | 2.9 | 1.99 | 1.14 | 3.13 |
| 11 | 2703 | 2.88 | 1.98 | 1.14 | 3.12 |
| 12 | 2730 | 2.85 | 1.94 | 1.14 | 3.08 |
| 13 | 2754 | 2.86 | 1.95 | 1.14 | 3.09 |
| 14 | 2778 | 2.84 | 1.94 | 1.14 | 3.08 |
| 15 | 2802 | 2.86 | 1.95 | 1.14 | 3.09 |
| 16 | 2826 | 2.84 | 1.93 | 1.14 | 3.07 |
| 17 | 2850 | 2.76 | 1.85 | 1.14 | 2.99 |

Table 7b. Illustration of Error in HEC-RAS Scour Summary Table
(Metric Units)

| Values in HEC-RAS Scour Report | | | Corrected Values | | |
|---|---|---|---|---|---|
| Pier No. | Station (m) | Cont. + Pier Scour Depth (m) | Pier Scour Depth (m) | Contraction Scour Depth (m) | Corrected Combined Scour Depths (m) |
| 1 | 751.60 | 0.91 | 0.64 | 0.28 | 0.91 |
| 2 | 758.91 | 0.91 | 0.64 | 0.28 | 0.92 |
| 3 | 766.23 | 0.91 | 0.64 | 0.28 | 0.91 |
| 4 | 773.54 | 0.91 | 0.63 | 0.28 | 0.91 |
| 5 | 780.86 | 0.91 | 0.64 | 0.28 | 0.92 |
| 6 | 788.17 | 1.01 | 0.73 | 7.07 | 7.81 |
| 7 | 795.49 | 1.01 | 0.73 | 7.07 | 7.81 |
| 8 | 802.80 | 1.01 | 0.73 | 7.07 | 7.81 |
| 9 | 810.12 | 1.01 | 0.73 | 7.07 | 7.81 |
| 10 | 817.43 | 0.88 | 0.61 | 0.35 | 0.95 |
| 11 | 823.83 | 0.88 | 0.60 | 0.35 | 0.95 |
| 12 | 832.06 | 0.87 | 0.59 | 0.35 | 0.94 |
| 13 | 839.38 | 0.87 | 0.59 | 0.35 | 0.94 |
| 14 | 846.69 | 0.87 | 0.59 | 0.35 | 0.94 |
| 15 | 854.01 | 0.87 | 0.59 | 0.35 | 0.94 |
| 16 | 861.32 | 0.87 | 0.59 | 0.35 | 0.94 |
| 17 | 868.64 | 0.84 | 0.56 | 0.35 | 0.91 |

# CHAPTER 4

## Potential for Using the KDOT Scour Spreadsheets With HEC-RAS Output

The HR-WSPRO option of HEC-RAS uses the equal conveyance streamtubes of the regular DOS-WSPRO but the output does not provide the width, stations, velocity and area of each of the 20 streamtubes. This information as well as conveyance distributions for the over bank and main channel sections is computed in DOS-WSPRO using the HP1 and HP2 cards. The output from these cards is used in the KDOT scour spreadsheets. The execution of these cards in the program is not an integral part of the DOS-WSPRO program. Moreover, the cards are not used in HR-WSPRO. They are simply statements at the end of the DOS-WSPRO program. Steve Piper, one of the HEC-RAS developers, told us that the HP1 and HP2 cards were not used in the WSPRO bridge routine of HEC-RAS. Consequently, it will not be possible to use the KDOT spreadsheets with input from HEC-RAS output using the HR-WSPRO bridge analysis option. However, the same data that was used in the KDOT scour spreadsheets could be obtained from the approach section and the section just upstream from the bridge, in the HEC-RAS model, for any of the bridge modeling options – HR-WSPRO, energy or momentum. Given the computed water surface elevation, the cross section geometry and the n-values, a separate program or programs could be written in either spreadsheet form or in some program language to determine the 20 equal conveyance stream tubes at both the bridge and approach cross sections. The over bank and main channel conveyance distributions could be determined as well. It is doubtful that the HEC-RAS scour program will have all the options available in the KDOT spreadsheets any time soon, if ever. **At this point it is recommended that considerable caution be exercised in using the HEC-RAS Version 2.2 scour program.**

# CHAPTER 5

## Literature Review

### Definitions and Basic Equations of Bridge Scour

A review of several terms and fundamentals of scour processes, as well as accepted scour calculation techniques are presented. Obviously, if the reader is experienced in the field of bridge scour, this section will most likely prove unnecessary. Since the most widely used method of scour calculation is that developed in the Federal Highway Administration (FHWA) Hydraulic Engineering Circular No. 18 (HEC 18), it will serve as the standard to which all other methods in this report are compared. First, the term **scour** itself refers to the removal of bed material by erosion forces. **Bridge scour** refers to the special case of scour under bridge structures. Scour does occur in streams and rivers in areas other than bridges or other culvert locations, but it is usually on a slower, less dramatic scale. This streambed erosion can occur along a reach, starting at a confluence with a parent stream or river. Changes in the streambed slope can cause the streambed drop and is called degradation. When the streambed rises due to bed load deposition it is called aggradation. While aggradation and degradation occur at or near bridge structures, it is often the dramatic and rapid effects of contraction and local scour that present the greatest hazards to the structure, and thus to the public.

Scour effects exist in three categories: the long-term processes of aggradation and degradation, contraction scour, and local scour. **Contraction scour** is the removal of bed material across the entire channel width. Contraction scour usually results in a fairly uniform decrease in the bed level across the bed and banks. Several mechanisms can contribute to contraction scour. A reduction in flow area, mainly caused by contraction in the floodplain, is the most common mechanism, but increases in flow at the bridge or changes in the downstream control of the water surface can also contribute to contraction scour.

**Local scour** is the removal of bed material from around structures, such as piers, abutments, spurs, or embankments. It occurs as a result of acceleration of the flow around these obstructions, and the consequent vortices that develop. In bridge scour studies, and in this report, pier and abutment scour are the local scours that are relevant.

Therefore, the three principal types of bridge scour are contraction, pier, and abutment scour. They each have their own methods for calculation, but are all based on the same physical principles. Each type of scour is potentially dangerous on its own merit but in combination, which is often the case, the results can be catastrophic. Bridge scour is one of the greatest threats to the integrity of a bridge and to the safety of the traveling public and so, must be studied carefully. Moreover, scour analysis is required by the FHWA.

There is another distinction that is often made when describing scour, whether the scour is clear-water scour or live-bed scour. **Live-bed scour** occurs when the flow through the bridge transports bed load from upstream into the bridge section. **Clear-water scour** occurs when the flow does not carry bed load from the approach section into the bridge opening. There are several common examples of **clear-water scour**. For instance, streams with bed material that is fairly coarse often experience scour under clear-water conditions.  Streams with low slopes during low flows often show signs of clear-water scour.  Armored streambeds and vegetated channels or overbanks are also examples of situations where clear-water scour would occur.  Typically, clear water scour occurs in overbank locations under a bridge.

**Live-bed scour** can occur in almost any stream or river in high flows.  One interesting note about live-bed scour is that it tends to be cyclical.  This means that scour holes developed during the rise of floodwaters tend to be refilled with bed load during the falling stages.  While this may seem to be beneficial, this is a dangerous cycle that must be evaluated continually.  The streambed may look similar before and after a flood occurrence, but it is the in-between conditions that create the scour holes.  The scour may erode the bed to an extent that the footings of the bridge piers or banks become unstable.  Even if the bridge survives several flood occurrences, the scour holes that have been refilled often can progress to depths that put the bridge in danger when larger floods come.  The bed material that has been reworked and deposited is often very fine and more susceptible to scour in later floods.

The process of scour can be related to the flow mechanics as follows.  At the very lowest level, scour occurs because the bed shear stress is greater than the critical shear stress of the bed material.  Bed shear stress is created by the water flowing over the bed material, and can be related as:

$$t_0 = gyS_f = \frac{rgn^2V^2}{\sqrt[3]{y}} \qquad \text{Eq. 1}$$

Where:

$t_0$ = average bed shear stress (Pa)
? = unit weight of water (9810 N/m$^3$)

$y$ = average depth of water (m)
$S_f$ = friction slope
? = density of water (1000 kg/m$^3$)
g = acceleration of gravity (9.81 m/s$^2$)
n = Manning's n
V = average velocity (m/s)

Critical shear stress is the stress that the bed material sustains at incipient motion, and is a property of the bed material. Particles of any weight on the bottom of the channel resist the shear force of the flowing fluid by the friction force between the particle and surrounding particles on the bottom of the channel. This model and method of thinking does not account for cohesive materials that would resist movement due to forces other than grain-to-grain friction that would tend to keep the particles from moving. There are several methods for determining critical shear stress, but HEC-18 recommends the use of Shields relation:

$$t_c = K_S(r_S - r)gD \qquad \text{Eq. 2}$$

Where:

$t_c$ = Critical shear stress at incipient motion (Pa)
$K_S$ = Shield's coefficient
?$_S$ = Density of sediment (kg/m$^3$)
? = Density of water (1000 kg/m$^3$)
$g$ = acceleration of gravity (9.81 m/s$^2$)
$D$ = Diameter of smallest nontransportable particle in the bed material (m)

The bed material determines $K_S$. Typical values of $K_S$ are 0.047 for sand, 0.03 for median coarse-bed material, and 0.02 for coarse-bed material. The authors of HEC-18 recommend the use of the value $K_S$ = 0.039 for general problems.

The determining factor in the classification of scour as live-bed or clear-water conditions is the critical velocity of the bed material. **Critical velocity** is the minimum velocity of the water at which the bed material will go into motion and begin to be transported. If the velocity of the stream is greater than critical velocity, bed material will be suspended and transported, creating live-bed scour conditions. Velocities of the water below critical velocity will not transport bed material and clear-water scour conditions will exist. Critical velocity occurs when motion is incipient:

$$t_c = t_0$$

Equating Eq. 1 and Eq. 2 using the relationships from above gives:

$$K_S(r_S - r)gD = \frac{rgn^2V^2}{\sqrt[3]{y}}$$

Rearranging and solving for the critical velocity, $V_C$:

$$V_C = \frac{\left(y^{\frac{1}{6}}\right)\sqrt{K_S(S_S - 1)D}}{n} \qquad \text{Eq. 3}$$

Where: $S_S$ = Specific gravity of bed material

Now that the basic processes have been discussed, the core equations for computing contraction, pier, and abutment scour can be presented. It should be noted that these equations should be used with a great deal of engineering judgment and caution. The following procedure runs through the process of determining bridge scour and should not be considered complete. For a more complete explanation of the scour equations, consult HEC-18 chapter 4.

First, the magnitude of contraction scour should be determined. In order to properly assess the situation, it is necessary to know whether or not bed material is being transported. It is useful to use the critical velocity equation, Eq. 3, because there are different contraction scour equations are used for live-bed and clear-water conditions. It should be noted that the research used to develop the scour equations used a sand bed for the physical models. Therefore, noncohesive bed material was modeled. Although scour in cohesive soils is time dependent, the maximum scour depth will be the same for cohesive and noncohesive soils. The equation for clear-water scour is fairly simple and is:

$$y_2 = \left[\frac{n^2 Q^2}{K_S (S_S - 1) D_m W^2}\right]^{\frac{3}{7}} \qquad \text{Eq. 4}$$

The authors recommend using the following values; $n = 0.040 D_m^{1/6}$, $S_S = 2.65$, and $K_S = 0.039$, giving the relation:

$$y_2 = \left[\frac{0.025 Q^2}{(D_m)^{\frac{2}{3}} W^2}\right]^{\frac{3}{7}} \qquad \text{Eq. 5}$$

$y_S = y_2 - y_0$ = Average scour depth (m)

Where:

$y_2$ = Ave depth in the contracted section after the contraction scour (m)
Q = Discharge through the bridge or on the over bank at the bridge associated with the width W, ($m^3$/s)
$D_m$ = Diameter of the smallest nontransportable particle in the bed material (1.25 $D_{50}$) in the contracted section (m)
$D_{50}$ = Median diameter of bed material (m)
W = Bottom width of the contracted section less pier widths (m)
$y_0$ = Existing depth in the contracted section before scour (m)

The method for computing live-bed contraction scour is presented below. The live-bed contraction scour equation is:

$$\frac{y_1}{y_2} = \left[\frac{Q_2}{Q_1}\right]^{\frac{6}{7}} \left[\frac{W_1}{W_2}\right]^{k_1} \qquad \text{Eq. 6}$$

$$y_S = y_2 - y_0$$

Determine a $k_1$ value:

$k_1 = 0.59$ when $V_*$/? < 0.50

$k_1 = 0.64$ when $0.50 < V_*/? < 2.0$

$k_1 = 0.69$ when $V_*/? > 2.0$

Where the shear velocity, $V_*$, is given by:

$$V_* = \sqrt{\left(\frac{t_0}{r}\right)} = \sqrt{gy_1S_1} \qquad \text{Eq. 7}$$

and ? is the fall velocity of bed material based on the $D_s = D_{50}$ (see Figure 11).

Also:

$S_1$ = Slope of energy grade line of main channel
$V_*$ = Shear velocity in the upstream section (m/s)
$y_1$ = Average depth in the upstream main channel (m)
$y_2$ = Average depth in the contracted section (m)
$y_0$ = Existing depth in the contracted section before scour (m)
$Q_1$ = Flow in the upstream channel transporting sediment ($m^3/s$)
$Q_2$ = Flow in the contracted channel ($m^3/s$)
$W_1$ = Bottom width of the upstream main channel (m)
$W_2$ = Bottom width of the main channel in the contracted section less pier width(s) (m)

Pier scour is independent of live-bed or clear-water conditions. The pier scour equation is as follows:

$$\frac{y_S}{y_1} = 2.0K_1K_2K_3K_4\left[\frac{a}{y_1}\right]^{0.65} Fr_1^{0.43} \qquad \text{Eq. 8}$$

$$Fr_1 = \frac{V_1}{\sqrt{gy_1}}$$

Where:

$y_S$ = Scour depth (m)
$y_1$ = Flow depth directly upstream of the pier (m)
$K_1$ = Correction factor for pier nose shape from Table 8

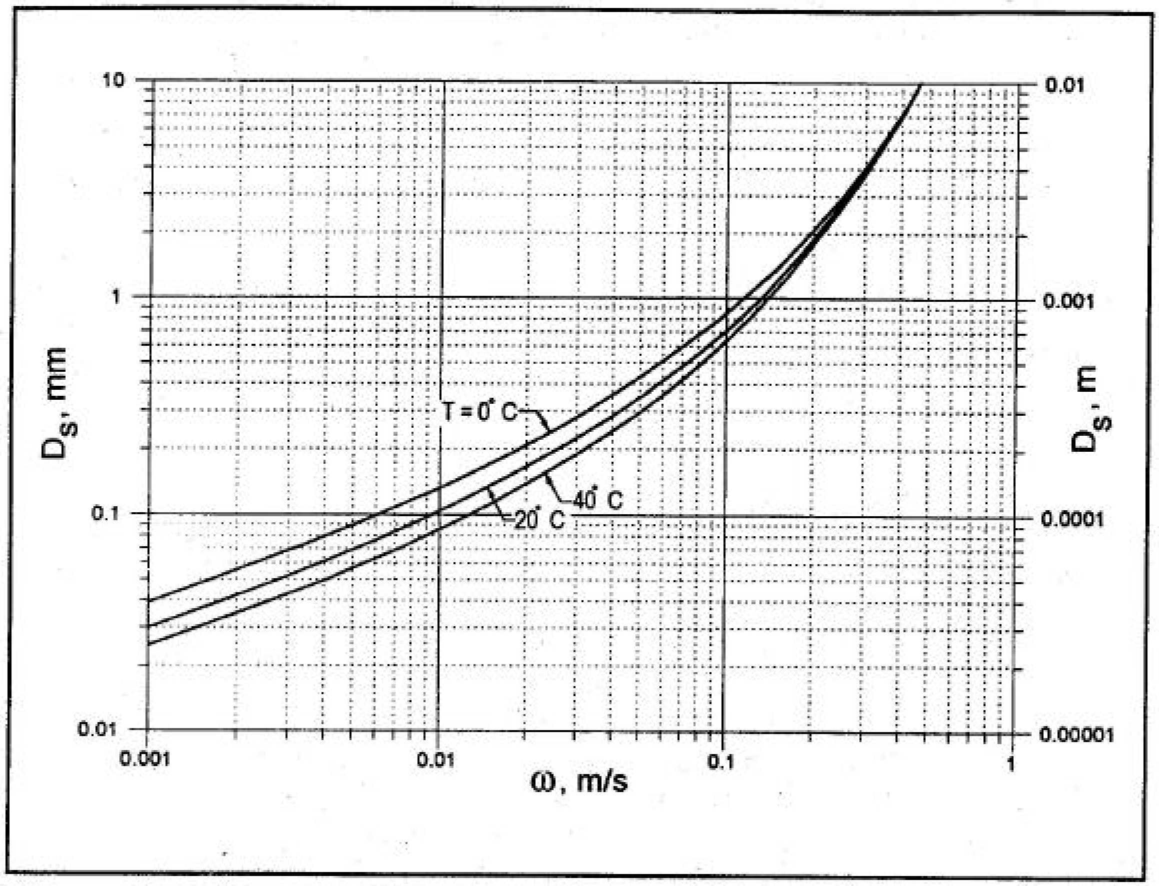



Figure 11. Fall velocity of Sand-Sized Particles

$K_2$ = Correction factor for angle of attack of flow
$K_3$ = Correction factor for bed condition from Table 9
$K_4$ = Correction factor for armoring by bed material size
a = Pier width (m)
L = Length of pier (m) normal to flow
$Fr_1$ = Froude Number directly upstream of the pier
$V_1$ = Mean velocity of flow directly upstream of the pier (m/s)

Table 8. Correction Factor for Pier Nose Shape

| Table 8 | |
|---|---|
| Shape of Pier Nose | $K_1$ |
| Square nose | 1.1 |
| Round nose | 1.0 |
| Circular cylinder | 1.0 |
| Group of cylinders | 1.0 |
| Sharp nose | 0.9 |

Table 9. Correction Factor for Bed Condition

| Table 9 | | |
|---|---|---|
| Bed Condition | Dune Height, m | $K_3$ |
| Clear-water Scour | N/A | 1.1 |
| Plane bed and Antidune flow | N/A | 1.1 |
| Small Dunes | 3>H=0.6 | 1.1 |
| Medium Dunes | 9>H=3 | 1.2 to 1.1 |
| Large Dunes | H=9 | 1.3 |

Where

$$K_2 = \left( Cos q + \frac{L}{a} Sin q \right)^{0.65} \qquad \text{Eq. 9}$$

and

$$K_4 = \left[ 1 - 0.89 (1 - V_R)^2 \right]^{0.5} \qquad \text{Eq. 10}$$

$$V_R = \left[\frac{V_1 - V_i}{V_{c90} - V_i}\right]$$

$$V_i = 0.645\left[\frac{D_{50}}{a}\right]^{0.053} V_{c50}$$

Eq. 11 and Eq. 12

$$V_C = 6.19 y^{\frac{1}{6}} D_C^{\frac{1}{3}}$$ (For $V_{c50}$ use $D_{50}$; for $V_{c90}$ use $D_{90}$) Eq. 13

Where:

$V_R$ = Velocity ratio
$V_1$ = Approach velocity (m/s)
$V_i$ = Approach velocity when particles at a pier begin to move (m/s)
$V_{c90}$ = Critical velocity for $D_{90}$ bed material size (m/s)
$V_{c50}$ = Critical velocity for $D_{50}$ bed material size (m/s)
a = Pier width (m)
$D_C$ = Critical particle size for the critical velocity $V_c$ (m)

Limiting $K_4$ values and bed material size are given as:

Table 10. Correction Factor for Armoring of Bed

| Limits for Bed Material Size and $K_4$ Values | | | |
|---|---|---|---|
| | | | |
| Factor | Minimum Bed Material Size | Minimum $K_4$ Value | $V_R$ > 1.0 |
| $K_4$ | D>0.06 m | 0.7 | 1 |

Abutment scour research has limited physical testing and assumes very controlled conditions. The range of values produced from the equation can vary greatly. Considerable engineering judgment should be used when estimating the scour at abutment toes. The basic abutment scour equation is:

$$\frac{y_s}{y_a} = 2.27 K_1 K_2 \left(\frac{L'}{y_a}\right)^{0.43} Fr^{0.61} + 1$$ Eq. 14

Where:

$K_1$ = Coefficient for abutment shape (see Table 11)
$K_2$ = Coefficient for angle of embankment to flow
L' = Length of abutment (embankment) projected normal to flow (m)
$A_e$ = Flow area of the approach cross section obstructed by the embankment ($m^2$)
Fr = Froude number of approach flow upstream of the abutment
$Q_e$ = Flow obstructed by the abutment and approach embankment ($m^3/s$)
$y_a$ = Average depth of flow on the floodplain (m)
$y_s$ = Scour depth (m)

Table 11. Abutment Shape Coefficients

| Abutment Shape Coefficients | |
|---|---|
| Descriptions | $K_1$ |
| Vertical-wall Abutment | 1 |
| Vertical-wall abutment with wing walls | 0.82 |
| Spill-through abutment | 0.55 |

$$Fr = \frac{V_e}{\sqrt{gy_a}}$$
$$V_e = \frac{Q_e}{A_e}$$
Eq. 15 and Eq. 16

$$K_2 = \left(\frac{q}{90}\right)^{0.13}$$
Eq. 17

?<90° if embankment points downstream

?>90° if embankment points upstream

This concludes this procedure and a review of the basic scour equations as presented by HEC-18. These should be considered the basis of the other works that are reviewed in chapter 2.

## New Findings in Bridge Scour

There have been many recent additions to the field of bridge scour research. Variations to the three categories of bridge scour (contraction, pier, and abutment) have been accentuated with research in the fields of scour countermeasures, pressure flow at bridges, and pier geometry effects, just to name a few. The research also ranges from scour prevention techniques to scour assessment methods. This study considers work done since the last version of HEC No. 18, Evaluating Scour at Bridges, Third Edition, 1995.

### Pier Scour

Pier Scour is an area of large concern to practicing engineers, and is consequently a topic that demands a large amount of research. One area that has drawn a great deal of consideration is that of pier shape and geometry. Melville has been a leading researcher in this area. Both of his articles featured on this topic (7), (10) are well-categorized manuals on pier shape and geometry. These articles focus more on non-uniform geometries and shapes, advancing upon previous knowledge. The practical applications of these papers are put into effect in a later article by Melville, which is reviewed later in this chapter. *See Melville's Integrated Approach for Pier and Abutment Scour*.

Sheppard and Jones (15) provide a somewhat involved methodology for computing scour at complex pier geometries. Their research involves combining the scour depth predictions for individual components of the complex structure to obtain a composite or superimposed value for the total scour. One drawback of the method is the use of empirically derived charts to determine effective diameters. On the other hand, the method allows for some estimation of exposed pile foundation effects on scour. Here is their method:

1. Compute the contraction scour at the bridge site using an accepted method, such as the one presented in HEC-18. Adjust the bed elevation to account for the contraction scour.

2. Divide the structure into three components: the pier, pile cap (footer), and the pile group (foundation). Starting with the upper-most component (the pier) compute the scour depths produced by each of the structural components.

3. Use the empirical curves in Figure 13a to obtain the effective diameter of the pier, $D_{*(p)}$. That is, obtain the diameter of the circular pile that would produce the same scour depth as the pier for the given pier width, pile cap width, and pier elevation above the (contraction) scoured bed.

4. Use the HEC 18 pier scour equation with an effective diameter, $D_{*(p)}$, and the given flow and sediment condition in the circular pile equation (the one used in formulating Figure 13) to obtain the equilibrium scour depth component due to the pier, $d_{s\ (p)}$.

5. Use the empirical curves in Figure 13b, to determine the effective diameter of the pile cap, $D_{*(pc)}$. That is, obtain the diameter of a circular pile that would produce the same scour depth as the pile cap for the given pile cap width, thickness and elevation above the (contraction and pier) scoured bed.

6. Use the effective diameter, $D_{*(pc)}$, and the given flow and sediment conditions in the circular pile equation to obtain the equilibrium scour depth component due to the pile cap, $d_{s\ (pc)}$. The HEC 18 pier scour equation is used to determine this scour depth.

7. Use the curves in Figure 2c, to determine the effective diameter of the pile group/foundation, $D_{*pg}$.

8. Use the effective diameter, $D_{*pg}$, and the given flow and sediment conditions in the circular pile equation to obtain the equilibrium scour depth component due to the pile group/foundation, $d_{s\ (pg)}$. The HEC 18 pier scour equation is used to determine this scour depth.

9. Finally, compute the total local scour depth for the complex geometry bridge pier by summing the scour depth components, i.e.
   $d_s$ = total local scour = $d_{s\ (p)} + d_{s(pc)} + d_{s\ (pg)}$.

The necessary charts and diagrams can be found on the following pages.

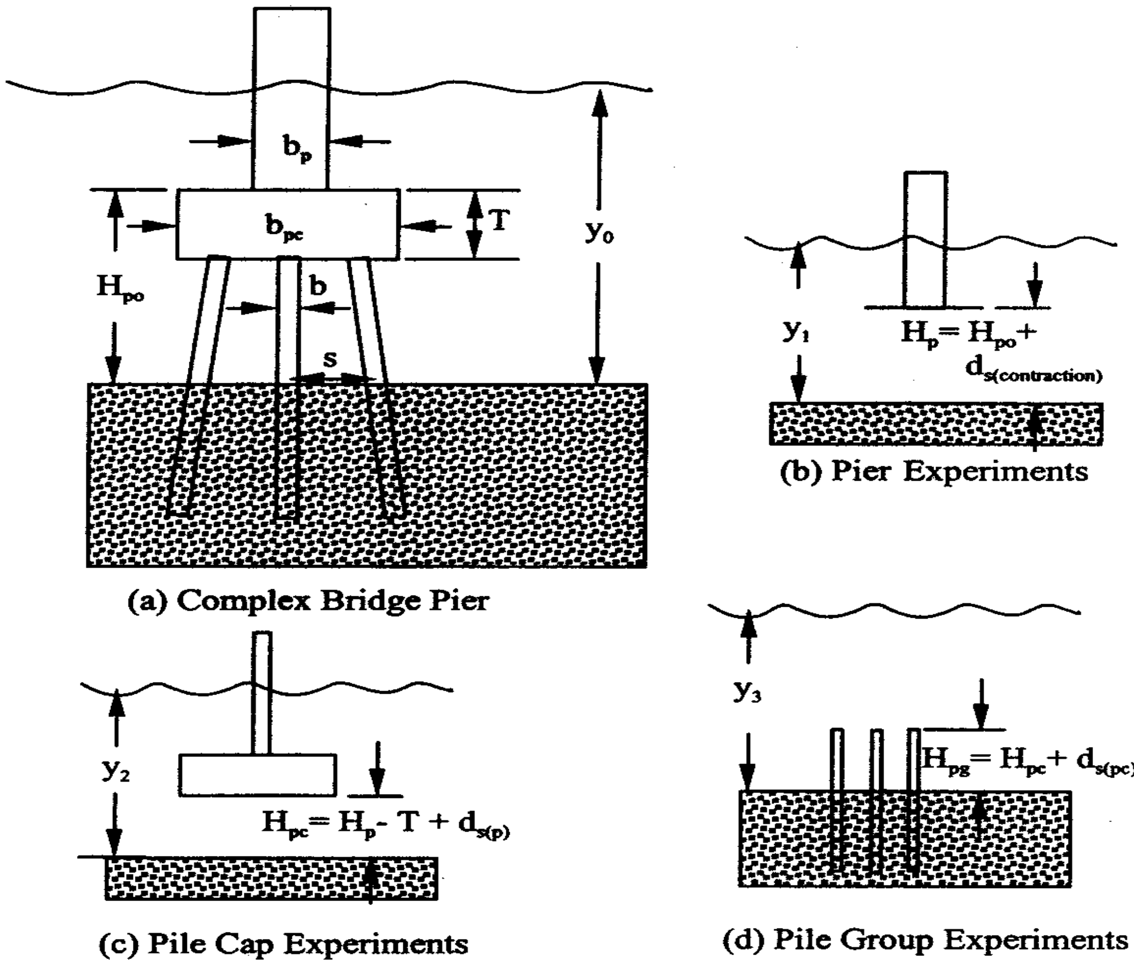



Figure 12. Pier Scour Variables (Sheppard and Jones (15))

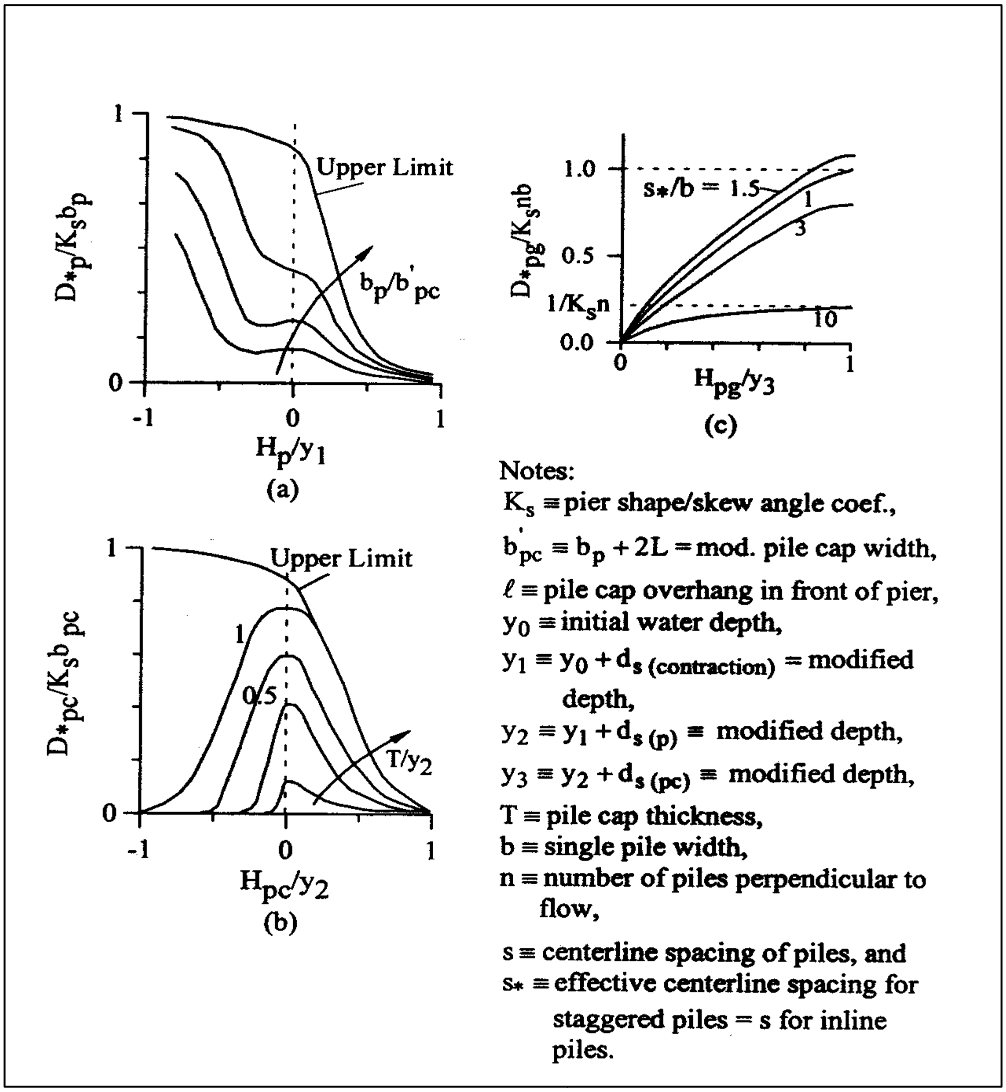



Figure 13. Effective Diameter Ratios for Bridge (a) Pier, (b) Pile cap, (c) Pile Group

Froehlich and Arneson (3) discuss pier scour with respect to bed characteristics. They discuss the effects of having coarse bed material as opposed to the common sand material. Their paper asserts that for live-bed scour, local scour depth increases as sediment size increases. They used recent on-site measurements of scour in coarse-bed channels to advocate the use of a reduction factor proposed by Hancu in 1971. Their basic formula is as follows:

$$\frac{d_s}{b} = 2.4 \times K_V K_y K_D \qquad \text{Eq. 18}$$

$$V_C = 1.167\sqrt{(S_S - 1)gD_{50}}\left(\frac{y}{D_{50}}\right)^{\frac{1}{6}} \qquad \text{Eq. 19}$$

The clear-water reduction factor is found by:

$$K_V = 0 \qquad \text{for } V \le \frac{1}{2}V_C$$

$$K_V = \frac{2V}{V_C} - 1 \qquad \text{for } \frac{1}{2}V_C < V < V_C$$

$$K_V = 1 \qquad \text{for } V \ge V_C$$

The relative depth factor is found by:

$$K_y = \left(0.2\frac{y}{b}\right)^{0.25} \qquad \text{for } \frac{y}{b} < 5$$

$$K_y = 1 \qquad \text{for } \frac{y}{b} \ge 5$$

The relative sediment size factor is found by:

$$K_D = \left(\frac{b}{D_{50}} - 12\right)^{-0.1} \qquad \text{for } \frac{b}{D_{50}} > 13$$

$$K_D = 1 \qquad \text{for } \frac{b}{D_{50}} \le 13$$

Where:

$d_S$ = local scour depth below the ambient bed level
$b$ = pier width
$V$ = depth-averaged approach flow velocity
$V_C$ = critical depth-averaged velocity at which live-bed scour begins
$S_S$ = specific gravity of bed material
$g$ = gravitational acceleration

$D_{50}$ = median diameter of substratum material
$y$ = approach flow depth

Pier alignment is also a topic of some importance that is explored in a paper by Ettema et al. (2). In this paper, the authors find that the currently accepted correction factor for pier skew does not take into account important parameters. The current correction factor is related only to the skew angle and pier aspect ratio. Here, the authors assert that such factors as shape, depth-averaged flow velocity, flow depth, and geometric standard deviation of the bed sediment also play significant roles in scour for skewed piers and should be accounted for in the skew factor.

**Contraction Scour**

With their article, E. V. and J. R. Richardson (13) present a concise and practical method for contraction scour calculations. E. V. Richardson is one of the authors of the HEC-18 manual (12), and in this small article the authors accomplish two tasks: one is to slightly modify the live-bed and clear-water contraction scour equations presented in HEC-18, and the other is to condense a rather lengthy discussion of theory and list of equations into a short and straightforward method. They accomplish this by substituting common values and situations into the general equations presented in HEC-18. For instance, the term $\left(\frac{n_1}{n_2}\right)^{k_2}$ is removed from the live-bed scour formula in HEC-18. This is done because the Manning's n values at the contracted section ($n_1$) and the upstream section ($n_2$) are typically the same, and this factor reduces to unity. They also present a simplified equation for clear-water contraction scour in English units, whereas the HEC-18 report presents the same equation in metric units. The modifications that the authors make to the original equations also come in the form of using the effective mean bed material size instead of the median diameter of bed material. It is simply more conservative to use this value. This article acts as a contraction scour summary preventing the practicing engineer from having to wade through the HEC-18 report presentation.

**Pressure Flow**

In their paper, Umbrell et al (16) examines contraction scour under bridges in pressure flow. As discussed in previous chapters, contraction flow occurs when flow area in the stream channel is reduced or constricted. Due to continuity, a reduction in flow area causes an increase in stream velocity. Factors that contribute to flow constriction and thus contraction scour include placing road embankment across a floodplain and constructing abutments, piers, and in the case of pressure flow, the bridge deck itself. There is an added component of constriction in pressure flow. It can be expected that the contraction scour in pressure flow situations would increase, as we will find it does. By further contracting the stream flow and further increasing the stream velocity, pressure flow situations result in an increase in tractive shear stress at the streambed and an increase in contraction scour. The resultant pressure flow contraction scour equation that their testing and regression yields is:

$$Y_s = y_a \left\{ 1.102 \left[ \left( 1 - \frac{w}{y_a} \right) \frac{V_a}{V_c} \right]^{0.603} \right\} - H_b \qquad \text{Eq. 20}$$

Where:

$Y_s$ = Pressure flow contraction scour
$y_a$ = depth of flow at the un-scoured upstream section
$w$ = depth of flow above the top of the bridge deck
$V_a$ = velocity of stream flow at un-scoured upstream section
$V_c$ = velocity of stream flow through contracted bridge section
$H_b$ = vertical distance from original streambed to low steel of the bridge

The paper recommends that this equation be used in place of the contraction scour equation presented by HEC-18, but that the procedure presented in HEC-18 be followed, which is to compute contraction scour and then add the local scour effects for abutments and piers. It should be noted that this equation and procedure was developed using clear water conditions only.

**Time Effects**

In the article by Cardoso and Bettess (1), the authors build upon the work of Ettema, Franzetti et al, and Whitehouse in the field of scour rate. Each of these three predecessors has advanced a theory on scour rate, and the researchers here watched to see which situations favored each method.

The equation that Ettema put forth in 1980 pertains to the local scour around a cylindrical pier. That equation is:

$$\frac{d_s}{b} = K_1 \cdot \log\left[\left(\frac{D_{50}}{b}\right)\left(\frac{u_* t}{b}\right)\left(\frac{v}{u_* b}\right)\right] + \log K_2 \qquad \text{Eq. 21}$$

Where:

$d_s$ = scour depth at time $t$
$b$ = pier diameter
$t$ = time
$D_{50}$ = average sediment size
$v$ = kinematic viscosity
$u_*$ = shear velocity

and K1 and K2 = coefficients determined for different values of $\frac{D_{50}}{b}$ and for values of $\frac{u_*}{u_{*c}}$ equal to 0.90 and 0.95. "$u_{*c}$" refers to the critical value of $u_*$ corresponding to the beginning of motion.

The equation put forth by Franzetti et al. studied the influence of test duration on the ultimate scour depth at cylindrical piers. Their equation is:

$$\frac{d_s}{d_{se}} = 1 - \exp\left[a_1\left(\frac{Ut}{L}\right)^{a_2}\right] \qquad \text{Eq. 22}$$

Where:

*U* = mean velocity of the undisturbed approach flow
$a_1$ *and* $a_2$ = constants
*L* = length scale

For cylindrical piers, Franzetti et al. suggested $a_1$ = -0.028 and $a_2$ = 1/3 and L = pier diameter.

The equation developed by Whitehouse in 1997 is the following:

$$\frac{d_s}{d_{se}} = 1 - \exp\left[-\left(\frac{t}{T}\right)^{p}\right] \qquad \text{Eq. 23}$$

The Whitehouse equation proves effective in Cardoso and Bettess' paper, however this equation was developed for marine applications. Also, the authors fail to explain the exponent "p," describing it simply as "coefficient of model used by Whitehouse." Thus, this particular approach can be passed over.

In Ettema's work, he describes three phases of scour with respect to time. They are the initial, the principal or erosion phase, and the equilibrium phase. They are each characterized by a distinct change in scour rate. In the initial phase, scour occurs very rapidly, but this phase does not last long. The principal phase consists of a longer, milder rate of erosion, and the equilibrium phase sees very low rates of scour. The phases are distinctly recognizable on a semi-log graph of scour depth versus time.

This study further confirmed the hypotheses of Ettema and Franzetti et al. by testing the rates of scour in the principal phase. Both equations matched the experimental data well. This study seems to fall a bit short in that it only dealt with the principal phase of scour, neglecting the initial phase.

Melville and Chiew develop a much more complete and useful method (8). They present an equilibrium time scale for local scour at bridge piers. Their findings are limited to clear water scour once again. However, the methodology is complete and functional for estimating the time to equilibrium and equilibrium depth. The procedure is presented herein:

Scour equilibrium depth is given by:

$$d_{se} = K_{yD} K_I K_d \qquad \text{Eq. 24}$$

Where:

$K_{yD} = 2.4D$ for $D/y < 0.7$

$K_{yD} = 2(yD)^{0.5}$ for $0.7 < D/y < 5$

$K_{yD} = 4.5y$ for $D/y > 5$

$K_I = \frac{V}{V_c}$ for $\frac{V}{V_c} < 1$ (clear-water scour situation)

$K_I = 1$ for $\frac{V}{V_c} > 1$ (live-bed scour situation)

$K_d = 0.57\log\left(2.24\frac{D}{d_{50}}\right)$ for $D/d_{50} < 25$

$K_d = 1$ for $D/d_{50} > 25$

Time to scour equilibrium is given by:

$$t_e(days) = 48.26\frac{D}{V}\left(\frac{V}{V_c} - 0.4\right) \qquad \text{for } y/D > 6 \qquad \text{Eq. 25}$$

$$t_e(days) = 30.89\frac{D}{V}\left(\frac{V}{V_c} - 0.4\right)\left(\frac{y}{D}\right)^{.25} \qquad \text{for } y/D \le 6 \qquad \text{Eq. 26}$$

Scour depth at any time can be found by:

$$\frac{d_s}{d_{se}} = \exp\left\{-0.03\left|\frac{V}{V_c}\ln\left(\frac{t}{t_e}\right)\right|^{1.6}\right\} \qquad \text{Eq. 27}$$

The term $V_c$ can be determined by the following relationships:

$$\frac{V_c}{u_{*c}} = 5.75\log\left(5.53\frac{y}{d_{50}}\right) \qquad \text{Eq. 28}$$

$$u_{*c} = 0.0115 + 0.0125 d_{50}^{1.4} \qquad \text{for } 0.1 \text{ mm} < d_{50} < 1 \text{ mm} \quad \text{and}$$
$$u_{*c} = 0.0305 d_{50}^{0.5} - 0.0065 d_{50}^{-1} \qquad \text{for } 1 \text{ mm} < d_{50} < 100 \text{ mm}$$

Where:

$u_{*c}$ = Critical shear velocity based on the $d_{50}$ size
$d_{50}$ = mean diameter of bed material
$y$ = mean approach flow depth
$V_c$ = mean approach flow velocity at threshold condition for sediment movement
$V$ = mean approach flow velocity
$T$ = time
$Te$ = time to equilibrium scour depth
$d_s$ = depth of scour at time $t$
$d_{se}$ = depth of equilibrium scour
$D$ = diameter of cylindrical pier

The scour at any time can be predicted using these formulas, as well as an estimate of the time to any scour depth less than equilibrium scour depth.

Briaud, et al. (18) have performed research on the time dependence of pier scour in cohesive soils. They have developed an experimental testing apparatus (called the Erosion Function Apparatus) to measure the erosion rate of different types of soils, ranging from clay to gravel and from soft soils to soft rocks. They developed the Extended SRICOS (Scour Rate In Cohesive Soils) Method for producing scour depth versus time relationships. They also developed the Simple SRICOS Method to estimate the scour depth at the end of the design life of the structure. Their work has a great deal of merit. Considerable money could be saved in the construction of bridges by incorporating construction methods that minimize the disturbance of natural cohesive channel beds. They have a publication coming out in February 2001 in the ASCE Journal of Geotechnical and Geoenvironmental Engineering describing additional research in time-dependence of abutment scour and multiple-column pier scour.

**Melville's Integrated Approach for Pier and Abutment Scour**

Melville (6) presents an approach to pier and abutment scour calculation that finds merit for many different reasons. First, it lends itself easily to computer programming, as this method is devoid of any complicated charts. This approach also allows for integrating debris flow effects into pier scour calculations by increasing the effective diameter of the piers. This method also allows the user to incorporate pier and abutment alignment factors into the calculations, although this does require the use of alignment tables to determine K factors.

The approach consists of four basic parts: input data collection, velocity calculations, estimation of K-factors, and finally the estimation of scour depth. The central scour equation is a local scour equation and is thus used for calculating both abutment and pier scour situations. That equation is:

$$d_s = K_{yW} K_I K_d K_S^* K_q^* K_G \qquad \text{Eq. 29}$$

Where: $K_{yW} = K_{yb}$ for piers and $K_{yW} = K_{yL}$ for abutments and $K_S^* = K_S$ and $K_\theta^* = K_\theta$ for piers.

The necessary input information needed consists of depth (y), mean channel velocity (V), Manning's n (n), median particle size ($d_{50}$), geometric standard deviation of the particle size distribution ($\sigma_g$), maximum particle size ($d_{max}$), pier size (width and length or diameter), shape and alignment, and flood channel characteristics (approach flow depth, width, and Manning's n) for compound channels. The calculations for the various K factors are:

$K_{yB}$ and $K_{yL}$ are depth size factors.

**For Circular and Cylindrical Piers:**

$$K_{yb} = 2.4D \quad \text{for} \quad \frac{D}{y} < 0.7 \qquad \text{Eq. 30}$$

$$K_{yb} = 2\sqrt{yb} \quad \text{for} \quad 0.7 < \frac{b}{y} < 5 \qquad \text{Eq. 31}$$

$$K_{yb} = 4.5y \quad \text{for} \quad \frac{b}{y} > 5 \qquad \text{Eq. 32}$$

for non-uniform pier shapes and debris flow, $D_e$ is used in place of $D$ for the above calculations. $D_e$ for non-uniform pier shapes is found as follows:

$$D_e = D\left(\frac{y - Z}{y + D^*}\right) + D^*\left(\frac{D^* + Z}{D^* + y}\right) \qquad \text{Eq. 33}$$

Where: $D^*$ = diameter of larger cylinder (or of footing) and

Z = the level of top of the footing (Z is negative if below the bed level)

$D_e$ for debris flow is found:

$$D_e = \frac{0.52 T_d D_d + (y - 0.52 T_d) D}{y} \qquad \text{Eq. 34}$$

Where: $T_d$ and $D_d$ are the thickness and diameter of the floating debris raft.

**For Abutments:**

$$K_{yL} = 2L \quad \text{for} \quad \frac{L}{y} < 1 \qquad \text{Eq. 35}$$

$$K_{yL} = 2\sqrt{yL} \quad \text{for } 1 < L/y < 25 \qquad \text{Eq. 36}$$

$$K_{yL} = 10y \quad \text{for} \quad \frac{L}{y} > 25 \qquad \text{Eq. 37}$$

For abutments that do not extend over the over bank region into the river channel, Melville suggests using

$$d_s = 1.93\sqrt{yL}$$ Eq. 38

To find the flow intensity factor, $K_I$, we must first complete some velocity computations.

The median armor size is equal to: $d_{50a} = \frac{d_{maz}}{1.8}$

$$V_a = 0.8V_{ca}$$ Eq. 39

$$\frac{V_c}{u_{*c}} = 5.75\log\left(5.53\frac{y}{d_{50}}\right)$$ Eq. 40

$$u_{*c} = 0.0115 + 0.0125d_{50}^{1.4}$$ for 0.1 mm < $d_{50}$ < 1 mm Eq. 41

and

$$u_{*c} = 0.0305d_{50}^{0.5} - 0.0065d_{50}^{-1}$$ for 1 mm < $d_{50}$ < 100 mm Eq. 42

In the above calculations, the relationships between $V_c$, $d_{50}$, *and* $u_{*c}$ pertain to the relationships between $V_{ca}$, $d_{50a}$, *and* $u_{*ca}$ as well. Thus:

$$\frac{V_{ca}}{u_{*ca}} = 5.75\log\left(5.53\frac{y}{d_{50a}}\right)$$ Eq. 43

$$u_{*ca} = 0.0115 + 0.0125d_{50a}^{1.4}$$ for 0.1 mm < $d_{50a}$ < 1 mm Eq. 44

and

$$u_{*ca} = 0.0305d_{50a}^{0.5} - 0.0065d_{50a}^{-1}$$ for 1 mm < $d_{50a}$ < 100 mm Eq. 45

Now, the $K_I$ calculations for both pier and abutment are simply:

$$K_I = \frac{V - (V_a - V_c)}{V_c}$$ for $\frac{V - (V_a - V_c)}{V_c} < 1$ Eq. 46

$K_I = 1$ for $\frac{V - (V_a - V_c)}{V_c} > 1$ Eq. 47

Note: if the geometric standard deviation of the particle size distribution ($\sigma_g$) is less than 1.3, the term $\frac{V-(V_a-V_c)}{V_c}$ is replaced with $\frac{V}{V_c}$.

The calculations for $K_d$, the sediment size, factor are

$$K_d = 0.57\log\left(2.24\frac{W}{d_{50}}\right) \quad \text{for } \frac{W}{d_{50}} \le 25 \qquad \text{Eq. 48}$$

$$K_d = 1.0 \quad \text{for } \frac{W}{d_{50}} > 25 \qquad \text{Eq. 49}$$

$W = D$ for piers and $W = L$ for abutments.

$K_s$ is the pier or abutment shape factor. The determination for $K_s$ for piers is fairly straightforward. Deciding upon the value of this factor for abutments involves a decision. One can either simply read values from a chart, or one can use an equation. The difference is that the equations take into account the fact that shape effects are unimportant at longer abutments. For shorter abutments, the table values are likely easier to use.

**For Piers:**

$K_s$ = 1.0 for Circular cylinder shapes
$K_s$ = 1.0 for Round nosed shapes
$K_s$ = 1.1 for Square nosed shapes
$K_s$ = 0.9 for Sharp nosed shapes

**For Abutments:**

The table values are:

$K_s$ = 1.0 for Vertical wall shapes
$K_s$ = 0.75 for Wing wall shapes
$K_s$ = 0.6 for Spill through shapes 0.5:1 (H:V)
$K_s$ = 0.5 for Spill through shapes 1:1
$K_s$ = 0.45 for Spill through shapes 1.5:1

The adjusted shape factors recommended by Melville are:

$$K_s^* = K_s \qquad \text{for } \frac{L}{y} \le 10 \qquad \text{Eq. 50}$$

$$K_s^* = K_s + 0.667(1 - K_s)\left(0.1\frac{L}{y} - 1\right) \qquad \text{for } 10 < \frac{L}{y} < 25 \qquad \text{Eq. 51}$$

$$K_s^* = 1.0 \qquad \text{for } \frac{L}{y} \ge 25 \qquad \text{Eq. 52}$$

The value for the flow alignment factor, $K_\theta$, is once again found in a table for piers. The value for $K_\theta$ for abutments is once again a decision as to whether to use the table or to use a formula. Abutment alignment has a fairly insignificant effect on scour depth though. The table is:

| | | θ=0 | θ=15 | θ=30 | θ=45 | θ=60 | θ=90 | θ=120 | θ=150 |
|---|---|---|---|---|---|---|---|---|---|
| Pier | l/b=4 | 1.0 | 1.5 | 2 | 2.3 | -------------- | 2.5 | -------------- | -------------- |
| | 8 | 1.0 | 2.0 | 2.75 | 3.3 | ------------- | 3.9 | -------------- | -------------- |
| | 12 | 1.0 | 2.5 | 3.5 | 4.3 | -------------- | 5.0 | -------------- | -------------- |
| Abutment | -------------- | -------------- | -------------- | 0.9 | -------------- | 0.97 | 1.0 | 1.06 | 1.06 |

The adjusted alignment factors for $K_\theta$ are:

$$K_q^* = K_q \qquad \text{for } \frac{L}{y} \ge 3 \qquad \text{Eq. 53}$$

$$K_q^* = K_q + (1 - K_q)\left(1.5 - 0.5\frac{L}{y}\right) \qquad \text{for } 1 < \frac{L}{y} < 3 \qquad \text{Eq. 54}$$

$$K_q^* = 1.0 \qquad \text{for } \frac{L}{y} \le 1 \qquad \text{Eq. 55}$$

The final factor in the equation is $K_G$, a channel geometry factor. The value of $K_G$ for piers is 1, as channel geometry is unimportant at bridge piers. The value for abutments is 1 unless the abutment spans the flood channel and extends into the main channel. Then the value is found by:

$$K_G = \sqrt{1 - \frac{L^*}{L}\left[1 - \left(\frac{y^*}{y}\right)^{\frac{5}{3}} \frac{n}{n^*}\right]} \qquad \text{Eq. 56}$$

Where:

> $L^*$ = width of the flood channel and is equivalent to the (projected) length of abutment spanning the flood channel.
> $y^*$ = Depth of flow in the flood channel
> $n^*$ = Manning's n for the flood channel

Finally, all the factors are combined to find the depth of scour at any pier or abutment within the channel cross-section. This method provides an alternative to the scour prediction equations found in HEC-18.

**Example Problem**

In order to show the differences in the HEC-18 method and Melville's method described above, the following example is presented.

> A stream is flowing under a bridge. The bridge has one round-nosed pier and two identical abutments, all in the main channel. Find the local scour at the pier and abutments using Melville's method and using the methods in HEC-18. The site characteristics are as follows:
>
> Pier width = 2.0 m
> Length of abutment = 12 m with vertical walls
> Velocity of the stream = 3.0 m/s
> Depth of flow = 8 m
> Manning's n = 0.020
> $D_{50}$ = 0.012 m
> $D_{90}$ = 0.08 m
> $D_{max}$ = .1 m
> Standard Deviation of bed particle size = 4
> Skew Angle ? = 30°
>
> First, using Melville's method on the pier;
> D/y = .25, therefore $K_{yb}$ = 2.4D = 4.8 so **$K_{yb}$ = 4.8**
> $D_{50}$ is greater than 1 mm, so:
>
> $u_{*c} = 0.0305 d_{50}^{0.5} - 0.0065 d_{50}^{-1}$ =. 105 note that $d_{50}$ is expressed in mm!!!!
>
> $\frac{V_c}{u_{*c}} = 5.75 \log\left(5.53 \frac{y}{d_{50}}\right)$ Thus $V_c$ = 2.156

$$d_{50a} = \frac{d_{maz}}{1.8}$$ = .0555 m

$$u_{*ca} = 0.0305 d_{50a}^{0.5} - 0.0065 d_{50a}^{-1}$$

$$\frac{V_{ca}}{u_{*ca}} = 5.75 \log\left(5.53 \frac{y}{d_{50a}}\right)$$ so $V_{ca}$ = 3.789

$$V_a = 0.8 V_{ca}$$ = 3.031

$$K_I = \frac{V - (V_a - V_c)}{V_c}$$ for $\frac{V - (V_a - V_c)}{V_c}$ <1 so **$K_I$ = .9856**

$$K_d = 1.0$$ for $\frac{b}{d_{50}} > 25$ so **$K_d$ = 1.0**

**$K_s$ = 1.0** for round-nosed piers
L/b = 4 and ? = 30° so **$K_?$ = 1.0**
**$K_G$ = 1.0** for piers

So combining with the equation $d_s = K_{yW} K_I K_d K_S^* K_q^* K_G$ ,

**$d_S$ = 9.46 m** **ANSWER**

Now let us run through with the pier scour method in HEC-18.

$$\frac{y_S}{y_1} = 2.0 K_1 K_2 K_3 K_4 \left[\frac{a}{y_1}\right]^{0.65} Fr_1^{0.43}$$

$$Fr_1 = \frac{V_1}{\sqrt{g y_1}}$$ = 0.339 so **$Fr_1$ = 0.339**

**$K_1$ = 1.0** for round-nosed piers.

$$K_2 = \left(Cosq + \frac{L}{a} Sinq\right)^{0.65}$$ = 1.98 so **$K_2$ = 1.98**

for plane-bed flow, **$K_3$ = 1.1**

$$V_{C90} = 6.19 y^{\frac{1}{6}} D_{C90}^{\frac{1}{3}}$$ = 3.772

$$V_{C50} = 6.19 y^{\frac{1}{6}} D_{C50}^{\frac{1}{3}}$$ = 2.00

$$V_i = 0.645 \left[\frac{D_{50}}{a}\right]^{0.053} V_{c50}$$ = .9857

$$V_R = \left[\frac{V_1 - V_i}{V_{c90} - V_i}\right]$$ = .7229

$$K_4 = \left[1 - 0.89 (1 - V_R)^2\right]^{0.5}$$ = .9652 so **$K_4$ = .9652**

**$y_s$ = 8.58 m** **ANSWER**

**Therefore the two results for the problem are 9.46 meters (Melville's method) and 8.58 meters (HEC-18 method).**

Now let us investigate the abutment scours. Using Melville's method;

Since L/y = 1.5, $K_{yL} = 2\sqrt{yL}$ = 19.59 so **$K_{yl}$ = 19.59**

**$K_I$ = 0.9856,** which is the same as the calculations above.

Since $\frac{L}{d_{50}} > 25$, **$K_d$ = 1.0**

**$K^*_S$ = 1.0** since the abutments are vertical,

$$K_q^* = K_q + (1 - K_q)\left(1.5 - 0.5\frac{L}{y}\right) = 0.975$$ So **$K^*_?$ = 0.975**

and finally, **$K_G$ = 1.0** since we assume that the abutment reaches the full depth of the stream.

Combining, we find that

**$d_S$ = 18.82 m** **ANSWER**

Now for the HEC-18 method:

$$\frac{y_s}{y_a} = 2.27 K_1 K_2 \left(\frac{L'}{y_a}\right)^{0.43} Fr^{0.61} + 1$$

**$Fr_1$ = 0.339**

**$K_1$ = 1.0** since vertical wall abutments are assumed

$$K_2 = \left(\frac{q}{90}\right)^{0.13}$$ = 0.8669 so **$K_2$ = 0.8669**

combining we get:

**$y_S$ = 17.69** **ANSWER**

**So the two results for the problem are 18.82 meters (Melville's method) and 17.69 meters (HEC-18 method).**

## Scour Countermeasures

There are many new ideas in the area of scour prevention. Most are concerned with mitigating pier scour, though some through their nature would help with contraction scour as well. Melville and Hadfield (9) explore the use of sacrificial piles in their article. Sacrificial piles were tested using clear-water and live-bed conditions, as well as in aligned and permanently skewed flow conditions. In this study, the piles were found to only have a substantial effect when used in clear-water conditions, and with moderate skew (ß<20 degrees). Using the piles in these conditions produced only moderate scour protection. Submerged piles were found to be slightly more effective than full depth piles in most cases tested.

Kumar et al (5) tested other flow-altering devices, namely rectangular slots in the column and collars around the pier itself. In their findings, the authors show that both devices help mitigate scour, with certain provisions. The rectangular slot in a column must be in good alignment with the flow to be effective, and the benefits of the slot improve if the slot extends below the streambed. The authors note that further study is needed to determine a design relationship for slot length and width. As for the use of collars around piers, a design relationship was derived, and it shows that larger collars at or near the streambed produce the best results. The relationship is as follows:

$$\left(\frac{ds_p - ds_c}{ds_p}\right) = 0.057\left(\frac{B}{b}\right)^{1.612}\left(\frac{H}{Y_O}\right)^{0.837}$$

Where:

$ds_p$ = depth of scour on pier without a collar

$ds_c$ = depth of scour on pier with a collar
$B$ = diameter of collar
$b$ = diameter of circular pier
$H$ = elevation difference between water surface and collar surface
$Y_O$ = depth of water above bed elevation

Parola et al (11) contributes to this discussion by suggesting a way to mitigate scour and that is to add an upstream foundation extension. This extension protects the downstream bed from the horseshoe vortex, and the effect of the extension becomes greater as the length of the foundation extension is increased. A serious flaw with this extension is that it actually increases scour at the upstream end and sides of the foundation if the extension top is above the streambed. The extension length of greatest benefit was found to be that of two times the pier width.

Vittal et al (17) discusses yet another approach to mitigating pier scour. Here they compare the effect of using pier groups as opposed to one large pier. They also discuss proper alignment and sizing considerations. They find that the scour due to a pier group in its best orientation is around 40% less than that produced by one pier of diameter equal to the circumscribing circle diameter of the pier group. It is important to note, however, that this study only took into account clear-water conditions.

Jones et al (4) provides a quick overview and review of the effectiveness of several different scour methods. The different methods were part of a FHWA research fellowship project by Lisa Fotherby. They tested the following techniques for pier scour protection: extended footings, grout bags, grout mats, tetrapods, cable-tied blocks, anchors, high density particles, and rock riprap with various apron sizes. They tested scour reduction methods at incipient motion and at higher velocities and they studied failure conditions for the countermeasures in unobstructed flow and around a bridge pier in obstructed flow. Most of their results have little bearing in practical engineering practice and are limited to the research realm. Here are some of their useful results:

- Interconnected mats such as cable-tied blocks and grout mats are prone to failure in two ways: overturning and rolling at the leading edge when the front edge is not properly anchored or toed in. The other failure mode of failure occurs at higher velocities when the inner portion of the mat lifts up. These mats must also be fitted around the pier and require a good seal between the mat and the pier to avoid being undermined by the diving currents along the upstream face of a pier.

- Extended footings can serve as scour arresters under favorable conditions, but they can become a major contributor rather than an arrestor to scour if they are located above the streambed.

**<u>Exposed Pile Foundations</u>**

In their paper, Salim and Jones (14) explore the differences and benefits of two approaches to exposed pile foundation scour. The two approaches that were matched and compared are the one presented in HEC-18 and one from the Summary of Pier Scour Equations used by the People's Republic of China. The report shows how different factors from each report were contrasted and tested in a flume. There were some difficulties (including translation questions from the Chinese report), but the researchers came up with a simplified method. This method deals with groups of piles in an exposed situation.

- Assume equivalent solid for pile group with piles touching one another.
- Calculate scour depth from the HEC-18 equation.
- Estimate scour depth for a full depth pile group using $K_s$ and $K_a$ correction factors from Figures 14 and 15.
- Determine pile group stub component factor, $K_p$ , from the equation:

$$K_P = \left(\frac{h_i}{y}\right)^{0.41} \quad \text{Eq. 57}$$

- ***Determine an equivalent pier width for the portions of the pier and pile cap that are obstructing the water column. A depth weighted average width is obtained by multiplying the pier width by the thickness of the water column it obstructs and the width of the pile cap by the thickness of the water column it obstructs and dividing the sum of those two values by the combined thickness of the water column obstructed. This is not as representative as we would like it to be, but is offered as an interim procedure.***

- Determine scour depth for pier/cap component using a depth weighted average pier width approach, assuming base of the pile cap level with the streambed. ***Since there is not an equation to estimate scour depth for a pier that does not extend below the stream bed, an interim recommendation is to use the HEC-18 pier scour equation to calculate $d_{s(e)}$ for this component.***

- Determine the pier/pile cap component factor, $K_c$, from Figure 16.

Use both components in the following equation to find total depth of scour:

$$d_s = K_P \times d_{s(pg)} + K_C \times d_{s(e)} \quad \text{Eq. 58}$$

Where:

*S* = center to center spacing of piles
*D* = diameter of a single pile
$d_{s(pg)}$ = scour depth around a skewed pile group
$d_s$ = total scour depth for the composite pile foundation
$d_{s(e)}$ = equivalent scour depth

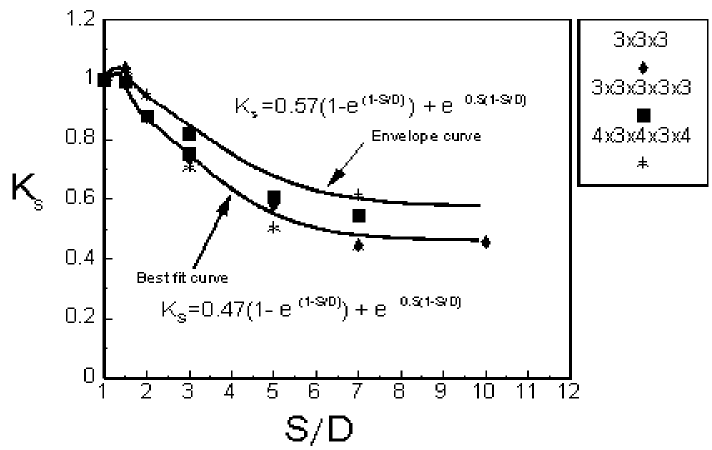



Figure 14. Adjustment Factor for Pile Spacing

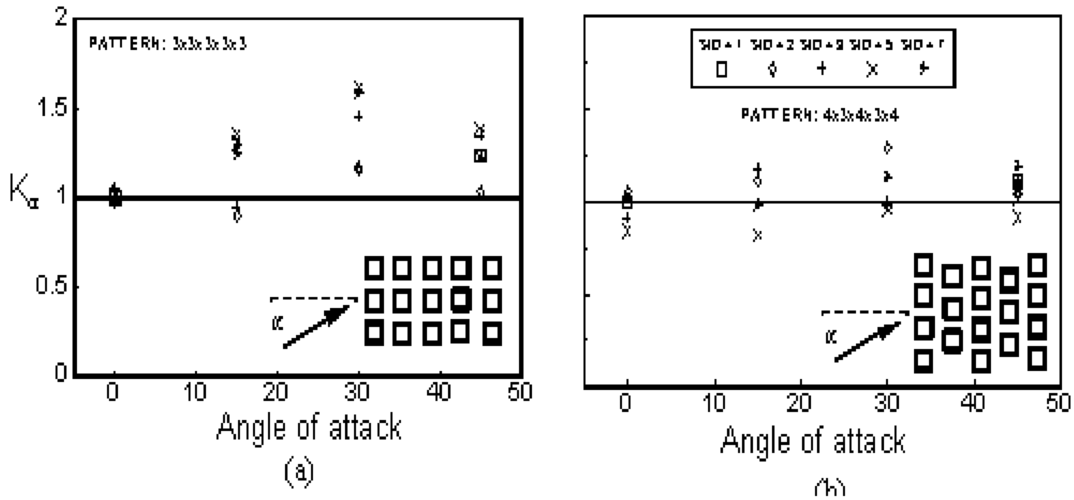



Figure 15.  Adjustment Factor for Angle of Attack

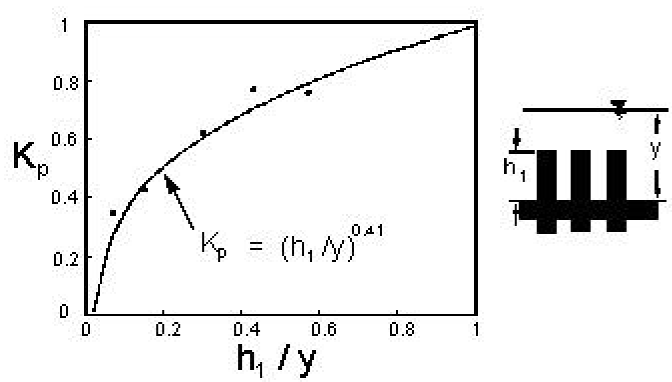



Figure 16.  Adjustment Factor for Pile Caps

# CHAPTER 6

# Summary and Conclusions

The study has found that the HEC-RAS 2.2 model is an excellent model for determining water surface profiles for various scenarios. It is easy to construct models in the Windows-based program and complicated situations such as multiple opening bridges, looped channels, etc. can be accurately modeled. The flow distribution option for cross sections allows the user to determine local transverse velocity and depth distributions at any cross section. This is precisely the information needed to perform bridge scour calculations. The scour option in HEC-RAS 2.2 does not, unfortunately, provide a very comprehensive or accurate scour analysis. Several errors were found in the model. It does not provide any estimates of angle of attack nor does it enable one to estimate scour for exposed footings and pilings. It also does not provide safeguards alerting the modeler to possible errors in input data or scour results. Comparisons of DOS-WSPRO and HR-WSPRO were made and it was found that the differences in computed water surface elevations were insignificant.

The many advantages of HEC-RAS 2.2 (metric capability, great hydraulic modeling capability, etc.) merit development of a scour analysis methodology based on the program. HEC-RAS 2.2 contains within the input and output files all the information required to perform a complete bridge scour analysis. It is doubtful that the scour program in HEC-RAS will be suitable for detailed, accurate bridge scour analysis in the near future. Moreover, since the HR-WSPRO bridge routine does not make use of the HP1 and HP2 cards it can not be used in conjunction with the existing KDOT scour spreadsheets. It is just a matter of deciding the best route to take in the development of the scour software that would extract the needed data files and perform bridge scour computations.

This completes the tasks for Phase I of K-TRAN Research Project KU-00-9. Software development along with a scour procedure manual and training is recommended under Phase II.

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# APPENDIX

# B8.DAT DOS-WSPRO INPUT FILE

```
T1         NATURAL CHANNEL WITHOUT CONTRACTION SCOUR
T2         B8.DAT PROBLEM
T3         50-YEAR CASE A
J1         0.5   0.01   0.001
Q          28200
SK         .0008
*            (Add 1000 Ft. to all Elevations)
XS   A-A      8500
*           STA.    ELEV    STA.   ELEV    STA.   ELEV    STA.   ELEV
GR          0       575     300    565     700    560     900    559
GR          1200    558     1250   556     1275   551     1300   550
GR          1400    551     1450   558     1600   561     1900   565
GR          2200    568     2500   575
N            .055     .045     .035     .045     .055
SA                 700     1200     1450     1900
*
XS   B-B        9400
*           STA.    ELEV    STA.   ELEV    STA.   ELEV    STA.   ELEV
GR            0     575     200    567     400    564     600    562
GR          800     561     1100   560.5   1200   560     1250   557
GR         1275     553     1300   552     1350   552.5   1400   553
GR         1425     556     1450   560     1650   563     1900   566
GR         2150     569     2500   575
SA               600     1250    1425    1650
*
XS   EXIT      10000
*           STA.    ELEV    STA.   ELEV    STA.   ELEV    STA.   ELEV
GR            00    575     200    568     300    566     450    564
GR           600    563     900    560     1000   559.5   1030   558
GR          1060    554     1100   553     1150   553     1250   554
GR          1275    556     1300   557     1450   559     1500   559
GR          1700    562     2000   566     2200   569     2500   575
SA               600     1060    1250   1450
*
XS   FULLV      10600   30
*           STA.    ELEV    STA.   ELEV    STA.   ELEV    STA.   ELEV
GR           00     575     200    567     400    564     600    563
GR          800     563     900    562     1000   562     1015   562
GR          1050    562     1100   560     1120   561     1140   560
GR          1170    555     1200   554     1250   555     1300   555
GR          1350    560     1400   561     1450   562     1480   563
GR          1503    563     1518   563     1700   563     1900   564
GR          2200    567     2500   575
SA          800    1140    1350    1700
*
BR   BRIDG     10600   569     30
*           STA.    ELEV    STA.   ELEV    STA.   ELEV    STA.   ELEV
GR          1000    569     1015   562     1050   562     1100   560
GR          1120    561     1140   560     1170   555     1200   554
GR          1250    555     1300   555     1350   560     1400   561
GR          1450    562     1480   563     1503   563     1518   569
GR          1000    569
N           .045    .035    .045
SA               1140    1350
PW        554.5  3  555    3   555    6    557.8  6   557.8  9   561    9
PW        561   15  562    15  562    18   562.7  18  562.7  21  564.5  21
PW        564.5  24.5  569  24.5
CD             3      44       3    572.8
```

```
KD        *,*,*,1006,1510
*
XR   ROAD     10622     44       *        *       30
*         ASSUMED ROAD DATA (ONLY 1000 FT OF WEIR FLOW)
GR          759   575     759   572.8   1759  572.8   1759  575
N            .03
*
AS   APPRO     11200
*           STA.  ELEV    STA.  ELEV    STA.  ELEV    STA.  ELEV    STA.  ELEV
GR           00   575     300   569     600   566     700   565     800   563
GR          850   562     900   561     950   560     1000  558     1050  556
GR          1100  555     1140  555     1200  556     1250  558     1300  560
GR          1350  561     1500  563     1518  563     1700  565     1900  567
GR          2200  569     2400  573     2500  575
SA                700     950      1300    1518
*
HP 2 BRIDG       565.98      0   565.98   28200
HP 2 APPRO       568.86      0   568.86   28200
HP 1 BRIDG       565.98      0   565.98
HP 1 APPRO       568.86      0   568.86
EX
ER
```

**EXTRACTED DATA FROM DOS-WSPRO OUTPUT FILE B8.OUT**
(USING POSTWSP.EXE POSTPROCESSOR TO CREATE B8.TXT)

```
 "03/07/00 10:52:01.39 file b8.txt: summarize DOS-WSPRO results file b8.out"
 "case P060188  03-07-00  10:51"



 "Velocity distribution:"
"iseq" "nsa" "secid"    "srd"   "skew"
    5    3 "BRIDG"   10600.0      30.0
"Section at bridge: (rows: coord. index, station, elevation)"
    1       2      15      16
  1000.0  1015.0  1503.0  1518.0
  569.00  562.00  563.00  569.00

 "       WSEL      LEW     REW    AREA        K        Q    VEL
        565.98  1006.5  1510.4  2989.8  472348.   28200.   9.43

 "j"     "x(j)"  "area(j)" "velo(j)" "depth(j)" "froude(j)"
  1      1006.5       0.0       0.00       0.00       0.00
  2      1088.2     292.5       4.82       3.58       0.45
  3      1135.4     224.9       6.27       4.76       0.51
  4      1160.5     159.9       8.82       6.37       0.62
  5      1173.7     119.2      11.83       9.03       0.69
  6      1184.9     109.9      12.83       9.81       0.72
  7      1195.7     108.9      12.95      10.08       0.72
  8      1206.2     108.3      13.01      10.31       0.71
  9      1216.7     107.1      13.17      10.20       0.73
 10      1227.9     111.5      12.64       9.96       0.71
 11      1239.1     109.4      12.89       9.77       0.73
 12      1250.8     112.2      12.57       9.59       0.72
 13      1262.5     111.2      12.68       9.50       0.73
 14      1274.3     112.5      12.53       9.53       0.72
 15      1286.0     111.6      12.63       9.54       0.72
 16      1298.0     113.8      12.39       9.48       0.71
 17      1310.6     114.7      12.30       9.10       0.72
 18      1327.1     130.0      10.85       7.88       0.68
 19      1357.0     177.4       7.95       5.93       0.58
 20      1408.7     238.2       5.92       4.61       0.49
 21      1510.4     316.6       4.45       3.11       0.44

 "Velocity distribution:"
"iseq" "nsa" "secid" "srd"
    7    5 "APPRO"   11200.0

 "       WSEL      LEW     REW    AREA        K        Q    VEL
        568.86   314.0  2179.0  9799.4 1425418.   28200.   2.88

 "j"     "x(j)"  "area(j)" "velo(j)" "depth(j)" "froude(j)"
  1       314.0       0.0       0.00       0.00       0.00
  2       794.8    1200.5       1.17       2.50       0.13
  3       887.7     620.9       2.27       6.68       0.15
  4       951.3     525.0       2.69       8.25       0.17
  5       990.6     381.7       3.69       9.71       0.21
  6      1021.0     336.6       4.19      11.07       0.22
  7      1046.7     314.1       4.49      12.22       0.23
  8      1070.0     303.7       4.64      13.03       0.23
  9      1092.2     298.8       4.72      13.46       0.23
 10      1113.3     292.6       4.82      13.87       0.23
 11      1134.5     293.2       4.81      13.83       0.23
 12      1155.7     291.4       4.84      13.75       0.23
 13      1178.2     302.2       4.67      13.43       0.22
```

```
 14     1201.1      298.3       4.73      13.03       0.23
 15     1227.1      320.4       4.40      12.32       0.22
 16     1256.8      331.1       4.26      11.15       0.22
 17     1295.8      383.3       3.68       9.83       0.21
 18     1356.5      506.5       2.78       8.34       0.17
 19     1436.9      581.3       2.43       7.23       0.16
 20     1550.7      687.6       2.05       6.04       0.15
 21     2179.0     1530.4       0.92       2.44       0.10


"FULLV:FV"     600.   247.    6329.   .66    .58  566.95    -999  28200.  566.29
     10600.   600.  2129.  695749.  2.15   .19     .00     .58    4.46


" XSID:CODE   SRDL    LEW     AREA   VHD    HF     EGL    CRWS       Q    WSEL
"       SRD   FLEN    REW        K  ALPH    HO     ERR     FR#     VEL
"BRIDG:BR"     600.  1006.    2990.  2.2   .86  568.19  564.94  28200.  565.98
     10600.   600.  1510.  472455.  1.60  1.15     .00     .80    9.43

"     TYPE PPCD FLOW      C    P/A    LSEL   BLEN   XLAB   XRAB
        3.   0.   1.   .791   .050  569.00   -999   -999   -999


" XSID:CODE   SRDL    LEW     AREA   VHD    HF     EGL    CRWS       Q    WSEL
"       SRD   FLEN    REW        K  ALPH    HO     ERR     FR#     VEL
"APPRO:AS"     556.   314.    9799.   .22    .69  569.08  562.99  28200.  568.86
     11200.   585.  2179. 1425366.  1.72   .20     .00     .29    2.88

"       M(G)   M(K)       KQ   XLKQ   XRKQ    OTEL
        .654   .289 1012714.  1006.  1510.   568.64


 "     CROSS-SECTION PROPERTIES:  ISEQ =  5;  SECID = BRIDG;  SRD =   10600.
 "      WSEL  SA#     AREA        K   TOPW   WETP  ALPH    LEW    REW     QCR
                1      541.   49760.   116.   117.                        6636.
                2     1858.  371438.   182.   183.                       33708.
                3      591.   51150.   139.   140.                        6910.
    565.98            2990.  472348.   436.   439.  1.33  1006.  1510.  38547.


 "     CROSS-SECTION PROPERTIES:  ISEQ =  7;  SECID = APPRO;  SRD =   11200.
 "      WSEL  SA#     AREA        K   TOPW   WETP  ALPH    LEW    REW     QCR
                1      745.   31284.   386.   386.                        5873.
                2     1590.  180696.   250.   250.                       22754.
                3     4196.  935371.   350.   350.                       82442.
                4     1552.  190260.   218.   218.                       23509.
                5     1716.   87808.   661.   661.                       15689.
    568.86            9799. 1425418.  1865.  1865.  1.72   314.  2179.  97113.
```

**ABUTMENT SCOUR SPREADSHEET**

```
ABUTMENT SCOUR SPREADSHEET, ABUT95.WK1
                            Alt E erases imported postprocessor stuff
 LIVE-BED SCOUR             Alt P prints the spreadsheet
                            Alt A print spreadsheet and preprocessor info
(Froehlich's Eq. 24)        Alt G imports postprocessor file POSTWSP.OUT
                            (Alt N imports postprocessor with a file name
                            to be specified by the user)

BRDG NO. B8.DAT                      DISCHARGE   28200 cfs
SER. NO.                             RET. INT.      50 Yrs.

                  (Input values from DOS-WSPRO output)

Left abutment                        Right abutment

WSEL =     565.98 (BRIDG section)   WSEL =     565.98 (BRIDG section)
Za =            562 (DOS-WSPRO input file)Za =            563 (DOS-WSPRO input
file)
LEW =         247 (FULLV section)   REW =        2129 (FULLV section)
LEW =        1006 (BRIDG section)   REW =        1510 (BRIDG section)
LEW =         314 (APPRO section)   REW =        2179 (APPRO section)
(LEW+a')@APPRO =     971.3          (REW-a')@APPRO =    1642.9
(Ae @ Qe are obtained by summing appropriate stream tube values.)
(See equations in ABUTMENT section of KDOT scour manual.)
Ae =       2540.8 (HP 2 APPRO)      Ae =       1114.1 (HP 2 APPRO)
Qe =       4943.5 (HP 2 APPRO)      Qe =       1024.9 (HP 2 APPRO)
theta =       120 deg - left abut   theta =        60 deg - right abut
Qtotal =    28200 (APPRO section)   Skewness=      30
Atotal =     9799 (HP 1 APPRO)      TOPW =       1865 (HP 1 APPRO)
V1 =         4.82 (HP 2 BRIDG)      V1 =         4.45 (HP 2 BRIDG)
                   1st streamtube                    20th streamtube

         (Input values for abutment scour calculations)

Left abutment                        Right abutment

Ya =         3.87 ft                Ya =         2.08 ft
a' =          657 ft                a' =          536 ft
Ae =       2540.8 sq ft             Ae =       1114.1 sq ft
Qe =       4943.5 cfs               Qe =       1024.9 cfs
K1 =         1.00                   K1 =         1.00
theta =       120 degree            theta =        60 degree
a'/Ya =       170                   a'/Ya =       258
```

**Ys = 32.44 ft** | **Ys = 14.93 ft**

```
Alternative answers from HIRE Eq. 25 in HEC No. 18, 2nd Ed.
      (applicable when a'/Ya > 25)
  Local depth Y1 = WSEL - Za, where Za = bed elev at abutment
  Local velocity V1 = vel. in 1st and 20th streamtube for lob & rob

Y1 =         3.98                   Y1 =         2.98
```

**Ys = 12.01 ft** | **Ys = 9.19 ft**

**CONTRACTION SCOUR SPREADSHEET**

```
CONTRACTION SCOUR SPREADSHEET, CONT95.WK1
                               Alt P prints the spreadsheet; /Alt E erases
       Br.No.B8.DAT            Alt A print spreadsheet and preprocessor info
                               Alt G imports postprocessor file POSTWSP.OUT
      Ser.No. N.A.             (Alt N imports postprocessor with a file name
                                 to be specified by the user)
    Case 1 --- Overbank flow on a flood plain being forced back to the
               main channel by the approaches to the bridge.

               (1a) -- Abutments project into main channel.
               (1b) -- Abutments set at the stream bank.
               (1c) -- Abutments set back from main channel.
    ____________________________________________________________________________
                   INPUT VALUES FROM DOS-WSPRO OUTPUT FILE
           No. of SA's for BRIDG (lob, mc, rob) =       1        1        1
           No. of SA's for APPRO (lob, mc, rob) =       2        1        2
                         LEFT      MAIN   RIGHT
                       OVERBANK  CHANNEL OVERBANK

             AREAa =      2335     4196     3268 (HP 1 APPRO)
             TOPWa =       636      350      879 (HP 1 APPRO)
             Ka    =    211980   935371   278068 (HP 1 APPRO)
             TOPWbr=       116      182      139 (HP 1 BRIDG)
             Wpier =         9        6        3 (Pier width)
             Kbr   =     49760   371438    51150 (HP 1 BRIDG)

             Katotal = 1425419 (APPRO)  Kbtotal =  472348 (BRIDG)
             Qatotal =   28200 (APPRO)  Qbtotal =   28200 (BRIDG)
             D50 (mm)=    1.00     1.00     1.00
             EGLappr =  569.08 (EGL of the APPRO section)
             EGLbr   =  568.19 (EGL of the BRIDG section)
             DISa-b =      600 (distance between BRIDG and APPRO)
    ___________________________________________________________________________
         INPUT VALUES FOR SCOUR EQUATIONS AND COMPUTED SCOUR DEPTHS
           [NOTE:  Scour calcs to the right on this spreadsheet]

      Eqs. 16 and 18, pp 33 and 35 of HEC No. 18, 2nd Ed., are used for
      live-bed and clear-water conditions, respectively.  Eq. 15 on page 31
      is used to determine the critical velocity, Vc, needed in classifying
      the flow as live-bed or clear-water.

     CASE 1a & 1b     Note: W1 limited to 3 x W2 and no overbank flow here.

        a) Main channel           NOT CASES 1a OR 1b!!!

             Y1 =         0.00 ft       D50 =        1.00 mm
             W1 =          350 ft       W2 =          176 ft
             Q1 =        18505 cfs      Q2 =        28200 cfs
             S1 =      0.00148 ft/ft    V/Vc =      N.A.



                        Live-bed Ys    =   N.A.  ft

                        Clear-water Ys =   N.A.  ft


      CASE 1c; Left Overbank, Main channel, and Right Overbank
```

```
         Main channel
Y1 =        11.99 ft       S1 =      0.00148 ft/ft
W1 =          350 ft       W2 =          176 ft
Q1 =        18505 cfs      Q2 =        22175 cfs
D50 =        1.00 mm       V/Vc =       1.79
```

**USE LIVE-BED!**

**Live-bed Ys = 10.31 ft**

Clear-water Ys = 24.62 ft

```
Left Overbank                                Right Overbank

 Y1   =    3.67 ft. S1  = 0.00148     Y1  =    3.72 ft. S1  = 0.00148
 W1   =     636 ft. W2  =     107 ft  W1  =     879 ft  W2  =     136 ft.
 Q1   =    4194 cfs Q2  =    2971 cfs Q1  =    5501 cfs Q2  =    3054 cfs
 D50  =    1.00 mm                    D50 =    1.00 mm
 V/Vc =    0.89                      V/Vc =    0.83
       W1 should not exceed 2 W2 by too much!
```

**USE CLEAR-WATER!** **USE CLEAR-WATER!**

Live-bed Ys = 4.79 ft Live-bed Ys = 3.62 ft

**Clear-water Ys= 7.00 ft** **Clear-water Ys= 5.18 ft**

NOTE: If vegetated overbanks are unlikely to be stripped even though the grain size is small, you may want to use the clear-water depth even though the grain size diameter indicates live-bed conditions.

**PIER SCOUR SPREADSHEET**

SUMMARY OF PIER SCOUR RESULTS

| PIER NO. | CSU Ys ft | SINGLE PIER LIMIT Ys ft | yf ft | FOOTING (W/O FLOW ANGLE) Ys ft | PILING (W/O FLOW ANGLE) Ys ft | FLOW ANGLE ADJSTMNT PIER SCOUR Actual a, Big K2 Ys ft | FLOW ANGLE ADJSTMNT PIER SCOUR K2=1, Eff a Ys ft |
|---|---|---|---|---|---|---|---|
| 1 | **5.07** | 6.90 | 0.00 | 0.00 | 0.00 | 21.74 | **10.36** |
| 2 | **5.90** | 6.90 | 0.00 | 0.00 | 0.00 | 19.01 | **12.06** |
| 3 | 8.92 | **6.90** | 5.27 | 17.81 | 14.72 | 20.99 | **18.23** |
| 4 | 8.77 | **6.90** | 4.60 | 17.26 | 14.27 | 13.28 | **14.36** |
| 5 | **6.74** | 6.90 | 0.48 | 9.42 | 0.00 | 11.46 | **12.37** |
| 6 | **5.73** | 6.90 | 0.00 | 0.00 | 0.00 | 14.57 | **11.71** |
| 7 | **4.81** | 6.90 | 0.00 | 0.00 | 0.00 | 18.56 | **9.82** |

PIER SCOUR SPREADSHEET, PIER95.WK1

Alt G imports postprocessor file POSTWSP.OUT
Alt N imports pstpr with different file name
Alt E erases old pstpr stuff        Alt. S prints summary only
BR. NO.  B8_P.DAT                   Alt. P prints all; Alt J erases junk
                                    Alt A prints spdsht & postprocessor
SER. NO. N.A.                          NO. OF PIERS  =       7 [max 10]

DISCHARGE   28200 cfs                  NO. OF COLS.  =       3 per pier

RET. INT.      50 yr                    COL. SPACING CL TO CL =   19.00 ft

PIER WIDTH OR DIA. OF COL. in ft =     3.00 ft.

K3 =     1.1      Water Surface Elev at Bridge =   565.98

(Input values from DOS-WSPRO output)
(............from HP 2 BRIDG...............) (from HP 2 APPRO)

| PIER NO. | STA(I) | PIER STA | STA(I+1) | A(I) | V(I) | STA(I) | STA(I+1) |
|---|---|---|---|---|---|---|---|
| 1 | 1006.5 | 1049.0 | 1088.2 | 292.5 | 4.82 | 314.0 | 794.8 |
| 2 | 1088.2 | 1117.0 | 1135.4 | 224.9 | 6.27 | 794.8 | 887.7 |
| 3 | 1184.9 | 1189.0 | 1195.7 | 108.9 | 12.95 | 1021.0 | 1046.7 |
| 4 | 1250.8 | 1259.0 | 1262.5 | 111.2 | 12.68 | 1155.7 | 1178.2 |
| 5 | 1327.1 | 1329.0 | 1357.0 | 177.4 | 7.95 | 1356.5 | 1436.9 |
| 6 | 1357.0 | 1399.0 | 1408.7 | 238.2 | 5.92 | 1436.9 | 1550.7 |
| 7 | 1408.7 | 1469.0 | 1510.4 | 316.6 | 4.45 | 1550.7 | 2179.0 |

Dist between Appro
and CL of Bridge       578 ft   b'= b*COS(Br.Skew)    Br Skew =      30 deg
Br Sec CL Sta Xb    1239.1 Refrnc Sta Xb,r =     1000 Ap CL Sta 1207.07
(NOTE: BR SKEW IS NEG WHEN RIGHT SIDE OF BRIDG IS CLOSEST TO APPRO)

CASE 1.  without flow angle adjustment

| PIER NO. | Y1 ft | V1 fps | a ft | K1 | K2 | CSU Eq. Ys ft | Limit Ys ft |
|---|---|---|---|---|---|---|---|
| 1 | 4.13 | 4.82 | 3.00 | 1.00 | 1.00 | 5.07 | 6.90 |
| 2 | 5.50 | 6.27 | 3.00 | 1.00 | 1.00 | 5.90 | 6.90 |
| 3 | 11.64 | 12.95 | 3.00 | 1.00 | 1.00 | 8.92 | 6.90 |
| 4 | 10.97 | 12.68 | 3.00 | 1.00 | 1.00 | 8.77 | 6.90 |
| 5 | 6.85 | 7.95 | 3.00 | 1.00 | 1.00 | 6.74 | 6.90 |
| 6 | 5.32 | 5.92 | 3.00 | 1.00 | 1.00 | 5.73 | 6.90 |
| 7 | 3.59 | 4.45 | 3.00 | 1.00 | 1.00 | 4.81 | 6.90 |

CASE 2. with flow angle adjustment !!(NOTE L/a ----->

| | [-----Flow angles to the piers---] | | | | For Opt. Angle =Zero Code.001 | [Eff. a limited to (n * dia. col.)] | | |
|---|---|---|---|---|---|---|---|---|
| PIER NO. | PIER STA | DIST to CL | APPRO STA | **FLOW ANGLE** | OPTIONAL ANGLE | **Eff a ft** | K2 | L/a |
| 1 | 1049.0 | 190.10 | 564.11 | 44.72 | 0.00 | 9.00 | 4.29 | 12.0 |
| 2 | 1117.0 | 122.10 | 851.48 | 25.79 | 0.00 | 9.00 | 3.22 | 12.0 |
| 3 | 1189.0 | 50.10 | 1030.76 | 13.52 | 0.00 | 9.00 | 2.35 | 12.0 |
| 4 | 1259.0 | 19.90 | 1171.47 | 5.13 | 0.00 | 6.40 | 1.51 | 12.0 |
| 5 | 1329.0 | 89.90 | 1361.61 | 7.02 | 0.00 | 7.64 | 1.70 | 12.0 |
| 6 | 1399.0 | 159.90 | 1529.35 | 15.61 | 0.00 | 9.00 | 2.54 | 12.0 |
| 7 | 1469.0 | 229.90 | 1923.23 | 36.73 | 0.00 | 9.00 | 3.86 | 12.0 |

INPUT FOR PIER SCOUR SHEET

| | | | | | Actual a, Big K2 | K2=1, Eff a |
|---|---|---|---|---|---|---|
| PIER NO. | Y1 ft | V1 fps | K1 | YTp ft | Ys ft | Ys ft |
| 1 | 4.13 | 4.82 | 1.00 | 16.68 | 21.74 | 10.36 |
| 2 | 5.50 | 6.27 | 1.00 | 16.68 | 19.01 | 12.06 |
| 3 | 11.64 | 12.95 | 1.00 | 16.68 | 20.99 | 18.23 |
| 4 | 10.97 | 12.68 | 1.00 | 16.68 | 13.28 | 14.36 |
| 5 | 6.85 | 7.95 | 1.00 | 16.68 | 11.46 | 12.37 |
| 6 | 5.32 | 5.92 | 1.00 | 16.68 | 14.57 | 11.71 |
| 7 | 3.59 | 4.45 | 1.00 | 16.68 | 18.56 | 9.82 |

INPUT FOR FOOTING AND PILING SCOUR
(NOTE: Cont Scour = 0 if it was already subtracted in DOS-WSPRO run.)

| | | | | | Assumed | Piling & Ftg | |
|---|---|---|---|---|---|---|---|
| PIER NO. | Cont Scour | Top of Ftg.Elev. | Ftg Width | Ftg Height | Piling Width | K1 | K2 |
| 1 | 7 | 549.30 | 10.8 | 4.5 | 8.06 | 1.00 | 1.00 |
| 2 | 7 | 549.30 | 10.8 | 4.5 | 8.06 | 1.00 | 1.00 |
| 3 | 10.31 | 549.30 | 10.8 | 4.5 | 8.06 | 1.00 | 1.00 |
| 4 | 10.31 | 549.30 | 10.8 | 4.5 | 8.06 | 1.00 | 1.00 |
| 5 | 10.31 | 549.30 | 10.8 | 4.5 | 8.06 | 1.00 | 1.00 |
| 6 | 5.18 | 549.30 | 10.8 | 4.5 | 8.06 | 1.00 | 1.00 |
| 7 | 5.18 | 549.30 | 10.8 | 4.5 | 8.06 | 1.00 | 1.00 |

OUTPUT FOR FOOTING AND PILING SCOUR

| | | | | | Footing | Piling |
|---|---|---|---|---|---|---|
| PIER NO. | D84 mm | YTp ft | Yf ft | Vf ft | Ys ft | Ys ft |
| 1 | 1.5 | 16.68 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | 1.5 | 16.68 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3 | 1.5 | 16.68 | 5.27 | 11.94 | 17.81 | 14.72 |
| 4 | 1.5 | 16.68 | 4.60 | 11.59 | 17.26 | 14.27 |
| 5 | 1.5 | 16.68 | 0.48 | 5.76 | 9.42 | 0.00 |
| 6 | 1.5 | 16.68 | 0.00 | 0.00 | 0.00 | 0.00 |
| 7 | 1.5 | 16.68 | 0.00 | 0.00 | 0.00 | 0.00 |

**SCOUR REPORT FROM HEC-RAS 2.2 WITH HR -WSPRO OPTION**

| | | | | |
|---|---|---|---|---|
| Hydraulic Design Data | | | | |
| Contraction Scour | | | | |
| | | Left | Channel | Right |
| Input Data | | | | |
| | Average Depth (ft): | 3.64 | 11.91 | 4.93 |
| | Approach Velocity (ft/s): | 1.86 | 4.4 | 1.9 |
| | Br Average Depth (ft): | 5.18 | 10.76 | 4.76 |
| | BR Opening Flow (cfs): | 3543.41 | 20864.67 | 3791.91 |
| | BR Top WD (ft): | 110.65 | 172.86 | 134.13 |
| | Grain Size D50 (ft): | 0.0033 | 0.0033 | 0.0033 |
| | Approach Flow (cfs): | 4244.97 | 18323.77 | 5631.26 |
| | Approach Top WD (ft): | 627.95 | 350 | 600 |
| | K1 Coefficient: | 0.59 | 0.59 | 0.59 |
| Results | | | | |
| | Scour Depth Ys (ft): | **6.9** | **9.42** | **6.09** |
| | Critical Velocity (ft/s): | 2.03 | 2.47 | 2.13 |
| | Equation: | Clear | Live | Clear |
| | | | | |
| Pier Scour | | | | |
| Pier: #1 (CL = 1042.43) | | | | |
| Input Data | | | | |
| | Pier Shape: | Group of Cylinders | | |
| | Pier Width (ft): | 3 | | |
| | Grain Size D50 (ft): | 0.00328 | | |
| | Depth Upstream (ft): | 5.09 | | |
| | Velocity Upstream (ft/s): | 5.09 | | |
| | K1 Nose Shape: | 1 | | |
| | Pier Angle: | 0 | | |
| | Pier Length (ft): | 44 | | |
| | K2 Angle Coef: | 1 | | |
| | K3 Bed Cond Coef: | 1.1 | | |
| | Grain Size D90 (ft): | 0.00491 | | |
| | K4 Armouring Coef: | 1 | | |
| Results | | | | |
| | Scour Depth Ys (ft): | **5.34** | | |
| | Froude #: | 0.4 | | |
| | Equation: | CSU equation | | |
| Pier: #2 (CL = 1101.32) | | | | |
| Input Data | | | | |
| | Pier Shape: | Group of Cylinders | | |
| | Pier Width (ft): | 3 | | |
| | Grain Size D50 (ft): | 0.00328 | | |
| | Depth Upstream (ft): | 6.24 | | |
| | Velocity Upstream (ft/s): | 5.09 | | |
| | K1 Nose Shape: | 1 | | |
| | Pier Angle: | 0 | | |
| | Pier Length (ft): | 44 | | |
| | K2 Angle Coef: | 1 | | |
| | K3 Bed Cond Coef: | 1.1 | | |
| | Grain Size D90 (ft): | 0.00491 | | |

| | | | | |
|---|---|---|---|---|
| | K4 Armouring Coef: | 1 | | |
| Results | | | | |
| | Scour Depth Ys (ft): | **5.49** | | |
| | Froude #: | 0.36 | | |
| | Equation: | CSU equation | | |
| Pier: #3 (CL = 1163.67) | | | | |
| Input Data | | | | |
| | Pier Shape: | Group of Cylinders | | |
| | Pier Width (ft): | 3 | | |
| | Grain Size D50 (ft): | 0.00328 | | |
| | Depth Upstream (ft): | 12.72 | | |
| | Velocity Upstream (ft/s): | 10.51 | | |
| | K1 Nose Shape: | 1 | | |
| | Pier Angle: | 0 | | |
| | Pier Length (ft): | 44 | | |
| | K2 Angle Coef: | 1 | | |
| | K3 Bed Cond Coef: | 1.1 | | |
| | Grain Size D90 (ft): | 0.00491 | | |
| | K4 Armouring Coef: | 1 | | |
| Results | | | | |
| | Scour Depth Ys (ft): | **8.26** | | |
| | Froude #: | 0.52 | | |
| | Equation: | CSU equation | | |
| Pier: #4 (CL = 1224.29) | | | | |
| Input Data | | | | |
| | Pier Shape: | Group of Cylinders | | |
| | Pier Width (ft): | 3 | | |
| | Grain Size D50 (ft): | 0.00328 | | |
| | Depth Upstream (ft): | 12.09 | | |
| | Velocity Upstream (ft/s): | 10.21 | | |
| | K1 Nose Shape: | 1 | | |
| | Pier Angle: | 0 | | |
| | Pier Length (ft): | 44 | | |
| | K2 Angle Coef: | 1 | | |
| | K3 Bed Cond Coef: | 1.1 | | |
| | Grain Size D90 (ft): | 0.00491 | | |
| | K4 Armouring Coef: | 1 | | |
| Results | | | | |
| | Scour Depth Ys (ft): | **8.1** | | |
| | Froude #: | 0.52 | | |
| | Equation: | CSU equation | | |
| Pier: #5 (CL = 1284.91) | | | | |
| Input Data | | | | |
| | Pier Shape: | Group of Cylinders | | |
| | Pier Width (ft): | 3 | | |
| | Grain Size D50 (ft): | 0.00328 | | |
| | Depth Upstream (ft): | 9.19 | | |
| | Velocity Upstream (ft/s): | 8.47 | | |
| | K1 Nose Shape: | 1 | | |
| | Pier Angle: | 0 | | |

| | | | | |
|---|---|---|---|---|
| | Pier Length (ft): | 44 | | |
| | K2 Angle Coef: | 1 | | |
| | K3 Bed Cond Coef: | 1.1 | | |
| | Grain Size D90 (ft): | 0.00491 | | |
| | K4 Armouring Coef: | 1 | | |
| Results | | | | |
| | Scour Depth Ys (ft): | **7.2** | | |
| | Froude #: | 0.49 | | |
| | Equation: | CSU equation | | |
| Pier: #6 (CL = 1345.53) | | | | |
| Input Data | | | | |
| | Pier Shape: | Group of Cylinders | | |
| | Pier Width (ft): | 3 | | |
| | Grain Size D50 (ft): | 0.00328 | | |
| | Depth Upstream (ft): | 6.11 | | |
| | Velocity Upstream (ft/s): | 5.02 | | |
| | K1 Nose Shape: | 1 | | |
| | Pier Angle: | 0 | | |
| | Pier Length (ft): | 44 | | |
| | K2 Angle Coef: | 1 | | |
| | K3 Bed Cond Coef: | 1.1 | | |
| | Grain Size D90 (ft): | 0.00491 | | |
| | K4 Armouring Coef: | 1 | | |
| Results | | | | |
| | Scour Depth Ys (ft): | **5.44** | | |
| | Froude #: | 0.36 | | |
| | Equation: | CSU equation | | |
| Pier: #7 (CL = 1406.15) | | | | |
| Input Data | | | | |
| | Pier Shape: | Group of Cylinders | | |
| | Pier Width (ft): | 3 | | |
| | Grain Size D50 (ft): | 0.00328 | | |
| | Depth Upstream (ft): | 4.46 | | |
| | Velocity Upstream (ft/s): | 3.96 | | |
| | K1 Nose Shape: | 1 | | |
| | Pier Angle: | 0 | | |
| | Pier Length (ft): | 44 | | |
| | K2 Angle Coef: | 1 | | |
| | K3 Bed Cond Coef: | 1.1 | | |
| | Grain Size D90 (ft): | 0.00491 | | |
| | K4 Armouring Coef: | 1 | | |
| Results | | | | |
| | Scour Depth Ys (ft): | **4.71** | | |
| | Froude #: | 0.33 | | |
| | Equation: | CSU equation | | |
| | | | | |
| Abutment Scour | | | | |
| | | Left | Right | |
| Input Data | | | | |
| | Station at Toe (ft): | 1012.99 | 1435.6 | |
| | Toe Sta at appr (ft): | 841.75 | 1432.5 | |
| | Abutment Length (ft): | 707.73 | 606.51 | |

| | | | | |
|---|---|---|---|---|
| | Depth at Toe (ft): | 5.09 | 4.09 | |
| | K1 Shape Coef: | 0.55 - Spill-through abutment | | |
| | Degree of Skew (degrees): | 120 | 60 | |
| | K2 Skew Coef: | 1.04 | 0.95 | |
| | Projected Length L' (ft): | 612.91 | 525.25 | |
| | Avg Depth Obstructed Ya (ft): | 2.63 | 4.18 | |
| | Flow Obstructed Qe (cfs): | 2172.98 | 3086.5 | |
| | Area Obstructed Ae (sq ft): | 1461.76 | 1954.28 | |
| Results | | | | |
| | Scour Depth Ys (ft): | **15.03** | **10.94** | |
| | Froude #: | 0.35 | 0.35 | |
| | Equation: | HIRE | HIRE | |
| | | | | |
| Combined Scour Depths | | | | |
| | | | | |
| Pier : #1 (CL = 1042.43) (Contr + Pier) (ft): | **12.24** | | | |
| Pier : #2 (CL = 1101.32) (Contr + Pier) (ft): | **12.39** | | | |
| Pier : #3 (CL = 1163.67) (Contr + Pier) (ft): | **15.16** | | | |
| Pier : #4 (CL = 1224.29) (Contr + Pier) (ft): | **15** | | | |
| Pier : #5 (CL = 1284.91) (Contr + Pier) (ft): | **14.1** | | | |
| Pier : #6 (CL = 1345.53) (Contr + Pier) (ft): | **12.34** | | | |
| Pier : #7 (CL = 1406.15) (Contr + Pier) (ft): | **11.61** | | | |
| | | | | |
| | Left abutment scour + contraction scour (ft): | **21.93** | | |
| | Right abutment scour + contraction scour (ft): | **17.03** | | |