Division of Engineering Research on Call Agreement #34652

(Task #3 – Scour Prediction Tools)

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16. Abstract
The objective of this project is to compare the most recent ODOT procedures to currently recommended FHWA practices for predicting scour, and to develop a user-friendly spreadsheet solution for calculating/predicting scour at a structure based on the latest procedures. Examples of how to use the scour prediction tool are illustrated in the report

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

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* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Scope of Work

The Ohio Department of Transportation (ODOT) wishes to examine the current scour prediction methods available in different design manuals. With the current versions of the Location & Design Manual, Vol. 2 (LD2); Bridge Design Manual (BDM); and the future Geotechnical Design Manual (GDM), ODOT has substantially changed the process for predicting scour at structures. Given the number of scour models and their variability, it is important to understand how these models different from each other. The goals of the project are:

1. Thoroughly review the most recent procedures for determining scour, as outlined in the manuals listed above. Review and validate all equations, sample calculations, and logic. Note any discrepancies, errors, or technically illogical steps.
2. Compare the most recent ODOT procedures to currently recommended FHWA practices for predicting scour; thoroughly describe each and note any differences.
3. Describe the evolving change in streambed geometry that occurs over time at a structure and recommend how to best reflect this in the scour calculations.
4. Create a user-friendly spreadsheet solution for calculating/predicting scour at a structure based on the latest procedures. The spreadsheet must permit the number of bridge spans and location of substructures with respect to the stream cross section to be defined. ODOT has a spreadsheet, which was shared with the research team for review and use.
5. Create a white paper that clearly describes the process for calculating/predicting scour based on the latest procedures, complete with examples for cohesive and granular soils, bedrock, and varying layers at the same site.

1.2 Outline of the Report

Chapter 2 describes the scour methods used by ODOT, as well as those methods recommended by FHWA.

Chapter 3 illustrates the spreadsheet scour prediction tool. The input and output of the tool are explained.

Chapter 4 shows examples of the use of the scour prediction tool.

2. Scour Models

Scour is considered the primary cause of bridge failure and has the propensity to cause millions of dollars' worth of damage to bridges from a singular flood event. For instance, a 1994 assessment of damaged bridges in Georgia cost the state around $130 million to replace or restore (Arneson et al., 2012).The most current literature published by the FHWA regarding scour at bridges, HEC-18 5th edition, was published in April 2012. This document provides guidance on assessing and computing scour for primary bridge components. Scour must be evaluated where a bridge foundation may interface with a streambed or floodplain, more specifically at a bridge's abutments and piers. These two elements are the primary foundations for bridges and if undermined, may cause total catastrophic failure of the bridge. In addition to scour at the foundation of the structure, contraction scour must be evaluated for a given storm event. These three main components, abutment scour, pier scour, and contraction scour are dependent on physical stream characteristics such as the velocity of the water, resulting shear stresses at the streambed, and the composition of the streambed material. Total scour at a foundation structure is then considered as the sum of the local scour (e.g., pier or abutment) and contraction scour. In addition to the three primary scour factors, it is necessary to evaluate the long-term aggradation or degradation of a stream at bridge structures. Aggradation or degradation may occur at natural expansions or constrictions within a stream and may be the result of natural channel morphology or anthropogenic activity (Lagasse et al., 2012). Further evaluation of aggradation and degradation are not discussed at length in the remainder of this document as there is no universal standard to evaluate their effects and they must be evaluated on a per site basis. Lastly, further supplemental instances specific to evaluating velocities at abutments and providing scour countermeasures can be found in HEC-23. These supplemental methods may be used in lieu of two-dimensional (2D) hydraulic modeling, however, 2D modeling is highly encouraged to more accurately elucidate the principal scour related parameters for a given stream.

In both ODOT and FHWA literature, streambed materials are classified into four categories for scour evaluation; cohesive soils, granular (non-cohesive) soils, non-scour resistant rock, and scour resistant rock. Two supplementing reports, published in 2015 and 2016, have been provided to expand on information in HEC-18, with further discussion related to non-cohesive and cohesive soils.

Scour occurs when the shear forces in a stream reach or surpass the critical shear strength for a given substrate, causing the substrate particles to erode (Arneson et al., 2012). For cohesive soils, shear strength is a function of the plasticity index, water content, percent fines, and the unconfined compressive strength. For granular soils, with a mean particle diameter (D_{50}) greater than or equal to 0.2 mm, the shear strength is directly proportional to the soil's D_{50}. Finally, for non-scour resistant rock, the erodibility index, a function of the rock strength and its ability to resist fracture and erosion, dictates the rock's shear strength (ODOT, 2021).

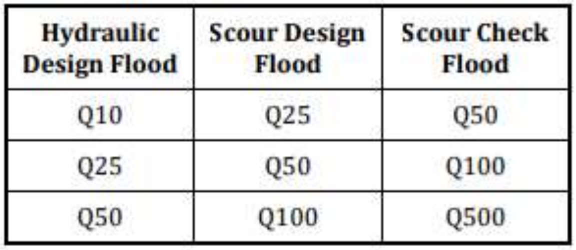
Computations of scour should first consider long-term aggradation or degradation of the stream at the structure being analyzed. This value should be added, when applicable, to contraction scour and local scour. However, the computations in Section 2.4 use the NCHRP scour equations for abutments, which includes contraction scour. Additionally, scour computations for three-sided culverts in Section 2.5 consider contraction scour in conjunction with local scour at the upstream portion of the culvert; however, if multiple open-bottom culverts are installed side-by-side pier scour must be computed for the common central leg.

2.1 Similarities and Variations in ODOT and FHWA Literature

Much of the content related to scour in the proposed GDM is either directly derived from HEC-18 and its supplementing updates or a conglomeration of the material. Examples of this can be seen in GDM Section 1302.3 wherein the critical shear stress for non-scour resistant rock is based on the stream power equations (7.38 and 7.39) in HEC-18. Additionally, the erodibility index for rock utilizes the same equations in both documents. When computing scour, GDM refers users to the appropriate sections in HEC-18 to calculate local and contraction scour depths.

However, some deviations between FHWA and ODOT practices are evident. For instance, Table 1 shows the ODOT (2021) recommended design flows for scour design and scour check based on the hydraulic design flow of a given structure.

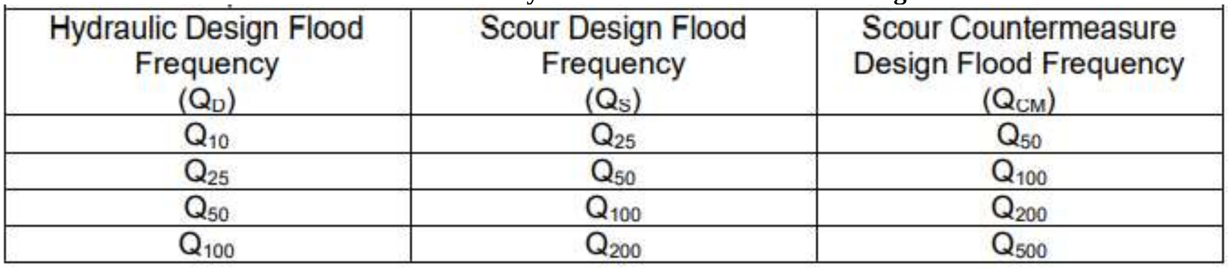
Table 1: ODOT Table 1008-1 Scour Design and Check Flood Return Periods



Hydraulic Design Flood	Scour Design Flood	Scour Check Flood
Q10	Q25	Q50
Q25	Q50	Q100
Q50	Q100	Q500

The primary difference between Table 1 and Table 2 lies in the scour check, or “scour countermeasure design flood frequency” as it is referred to in HEC-18, for the Q_{50} hydraulic design flood. This difference may be attributed to the proliferation of ready-to-use flow data in Ohio via USGS StreamStats web application.(https://streamstats.usgs.gov/ss/). A larger return period for the scour check flood also provides an extra factor of safety that errs on the conservative side for the implementation of scour countermeasures.

Table 2: HEC-18 Table 2.3 for Hydraulic and Scour Related Design



Hydraulic Design Flood Frequency (Q_D)	Scour Design Flood Frequency (Q_S)	Scour Countermeasure Design Flood Frequency (Q_{CM})
Q_{10}	Q_{25}	Q_{50}
Q_{25}	Q_{50}	Q_{100}
Q_{50}	Q_{100}	Q_{200}
Q_{100}	Q_{200}	Q_{500}

The remainder of Section 2.1 will focus on the differences between the FHWA (HEC-18) literature and ODOT literature.

2.1.1 Time rate of Scour

When scour is computed and found to be exceedingly large for a particular site or the calculated local and contraction scour depths are deeper than the bridge foundation (ODOT, 2022), a time-rate analysis may be used. HEC-18 gives the guidance that soil materials should be evaluated to determine scour as a function of time using equation 6.8. Expanding on this and utilizing research from Briaud (2008), a time rate of scour equation can be found in the L&D Vol. 2 Section 1008.10.4:

$$\dot{z} = 10^{\alpha \log(\tau)+\beta}$$

Where:

$\dot{z}$= Erosion rate (mm/hr)

τ= Bed shear stress (Pa)

$\alpha = \frac{13}{EC^{0.309}} - 7.1363$

$\beta = 7.377777 - \left[\left(1 - \frac{(EC-4.5)^2}{3.57^2}\right) 10.377777^2\right]^{0.5}$

EC= Erosion category = $4.5 - \frac{3}{1.07^{PI}}$ for cohesive soils ($1.5 \leq EC \leq 4.5$) and

EC= $1.2\ [1.83333 + \log(D_{50})]$ ($1 \leq EC \leq 6$) for granular soils

PI= Plasticity index

D_{50}= mean particle grain size in mm (≥ 0.1mm for granular)

Figure 1 shows the relationship of velocity and erosion rates for different materials and their corresponding erosion category (EC) subdivisions. Highly erodible materials, such as fine sands, are the most readily eroded materials with an EC=1 and scour-resistant, non-fractured bedrock is shown as the most erosion resistive material with an EC=6.

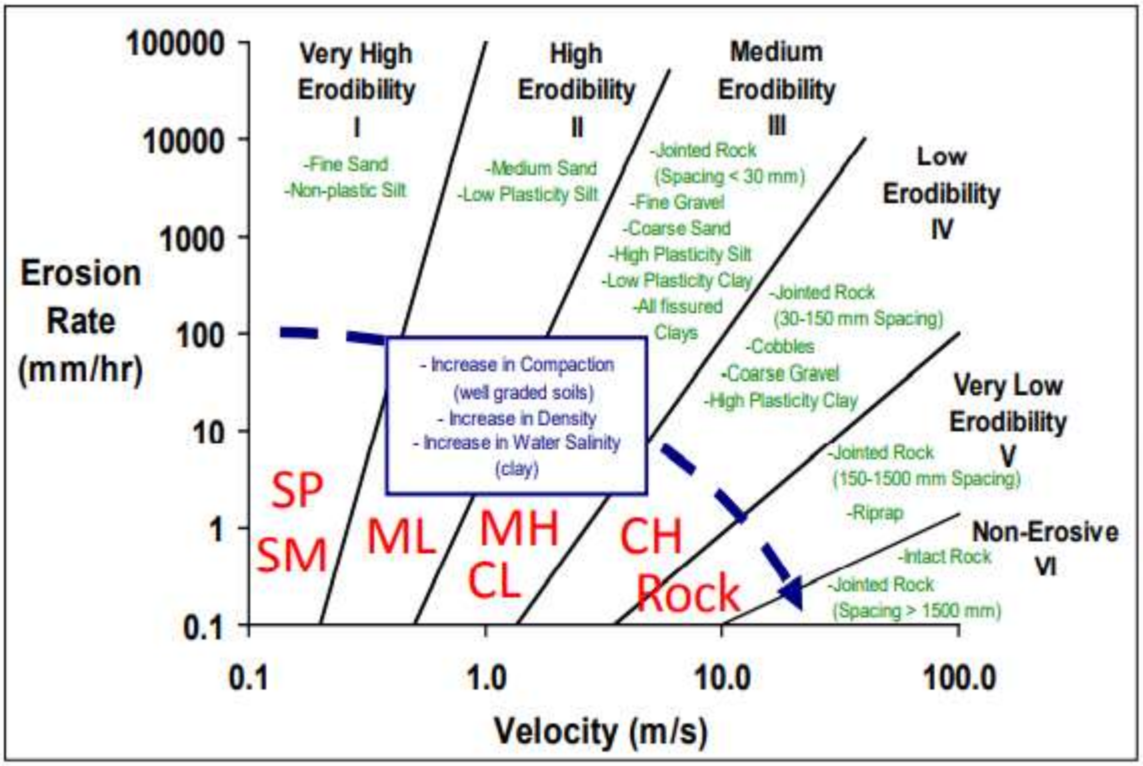


Figure 1: HEC-18 Figure 4.7 for Erosion Rate for a Given Velocity and Erodibility Category (Original Source: Briaud et al. 2011)

Time rate of scour should be evaluated for a design storm, with guidance in the L&D Vol. 2 suggesting a 24-hour duration for time rate analyses when the design storm hydrograph is not known. This tends to be a more conservative approach

Equation 6.8 in HEC-18 utilizes the initial rate of scour, computed ultimate scour, and the storm duration to determine scour as a function of time:

$$y_s(t) = \frac{t}{\frac{1}{\dot{z}} + \frac{t}{y_{s-ult}}}$$

Where:

$\dot{z}_i$= Initial scour rate (ft/hr)

t= Flow duration (hr)

y_{s-ult}= Ultimate scour depth (ft)

The method proposed in HEC-18 is still dependent on the ultimate scour, whereas the ODOT method utilizes parameters tied directly to the shear strength of a particular soil. However, the HEC-18 equation relates on the initial scour rate and does not consider decaying shear, whereas the ODOT method considers decaying shear and a dynamic scour rate.

2.1.2 Critical Shear Stress in Cohesive Soil

The equation for critical shear stress in cohesive soil in the ODOT GDM utilizes the equation in Figure 54 from FHWA-HRT-15-033:

$$\tau_c = \alpha \left(\frac{w}{F}\right)^{-2.0} PI^{1.3} q_u^{0.4}$$

Where:

τ_c= Critical shear stress $\left(\frac{lb}{ft^2}\right)$

w = Water content

F= Fraction of fines

PI= Plasticity index

q_u= Unconfined compressive strength $\left(\frac{lb}{ft^2}\right)$

α= Unit conversion factor (0.01 U.S. & 0.1 SI)

However, the proposed unit conversion factor of 0.01 (for U.S. customary units) listed in FHWA-HRT-15-033 is intended for evaluating existing structures. For the design of new structures, Shan (2015) suggests reducing the critical shear by a factor of 0.30 and using an α=0.007 for U.S. customary and α=0.07 for SI units. This reduction in critical shear errs cautiously towards more conservative estimates to provide a factor of safety against variability in soil parameters; this method is only included for discussion and will not be present in the final version of the scour prediction tool.

2.1.3 Variation Between Scour Prediction Tool and FHWA Hydraulic Toolbox Version 5.1 Scour Calculator

While both the scour prediction tool associated with this research and the FHWA Hydraulic Toolbox Version 5.1 Scour Calculator both aim to calculate scour at bridges, there are a few differences between the two described below.

Table 3: Variation between FHWA Hydraulic Toolbox Ver. 5.1 and the Newly Created Excel Scour Prediction Tool

Variations	FHWA	Excel Tool
Layered Analysis	No layered analysis.	Allows for layered analysis.
Decaying Shear	Does not account for decaying shear.	Recomputes shear stress if a layer is completely scoured or at the bottom of the scour hole within a layer. Note: A single soil layer can be divided into any number of layers to assess the shear at any desired interval
Abutment Scour	Includes multiple methods.	Only utilizes NCHRP 24-20 abutment scour calculations
Graphical User Interface	Allows for HEC-RAS geometry to be imported	No means for HEC-RAS geometry inclusion. Includes nomograph overlays for coefficient calculations.

2.2 Contraction Scour

Contraction scour at bridges is dependent on two primary conditions, live-bed and clear-water. HEC-18 defines live-bed contraction scour as the condition when sediments are being carried by the water and the amount of sediment that is carried into a control volume is equal to the amount of sediment being carried out of a control volume. Contrastingly, in clear-water contraction scour, it is presumed that little to no sediment material is being carried into the control volume from the upstream portion of the stream and if it is, it remains in suspension. A layered analysis can be considered for clear-water conditions where scour depth is dependent on the median particle diameter, however, live-bed conditions are not dependent on particle geometries. Furthermore, pressure flow analyses may be conducted to account for an increase in scour when a structure is overtopped, or downward forces are present.

Three-sided culverts are subject to both contraction scour and local scour that is calculated at the upstream corners. Because these structures are unique and require a varied evaluation approach, they are discussed independently in Section 2.5.

2.2.1 Live-Bed Contraction Scour

Live-bed contraction scour can be calculated using HEC-18 equation 6.2 and 6.3:

$$\frac{y_2}{y_1} = \left(\frac{Q_2}{Q_1}\right)^{\frac{6}{7}} \left(\frac{W_1}{W_2}\right)^{k_1}$$

$$y_s = y_2 - y_0$$

Where:

y_1= Average depth in the upstream main channel (ft)

y_2=Average depth in the contracted section (ft)

y_0= Existing depth in contracted section prior to scour (ft)

Q_1= Flow in the upstream channel transporting sediment (ft^3/s)

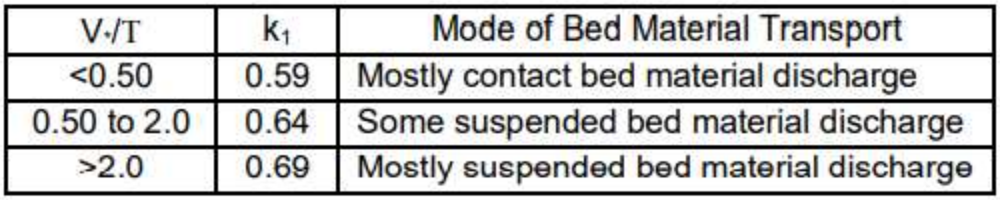
Q_2= Flow in the contracted channel (ft^3/s)

W_1= Bottom width of the upstream main channel that is transporting bed material (ft)

W_2= Bottom width of the main channel in contracted section minus pier width(s) (ft)

k_1= Exponent

Table 4: Determination of Live-Bed Contraction Scour Exponent Based on Particle Fall Velocity and Upstream Shear Velocity



V_*/T	k_1	Mode of Bed Material Transport
<0.50	0.59	Mostly contact bed material discharge
0.50 to 2.0	0.64	Some suspended bed material discharge
>2.0	0.69	Mostly suspended bed material discharge

V_*= shear velocity in the upstream section (ft/s)

T= fall velocity based on bed material D_{50} (ft/s)

HEC-18 provides a graphic to aid in the determination of particle fall velocity (Figure 2).

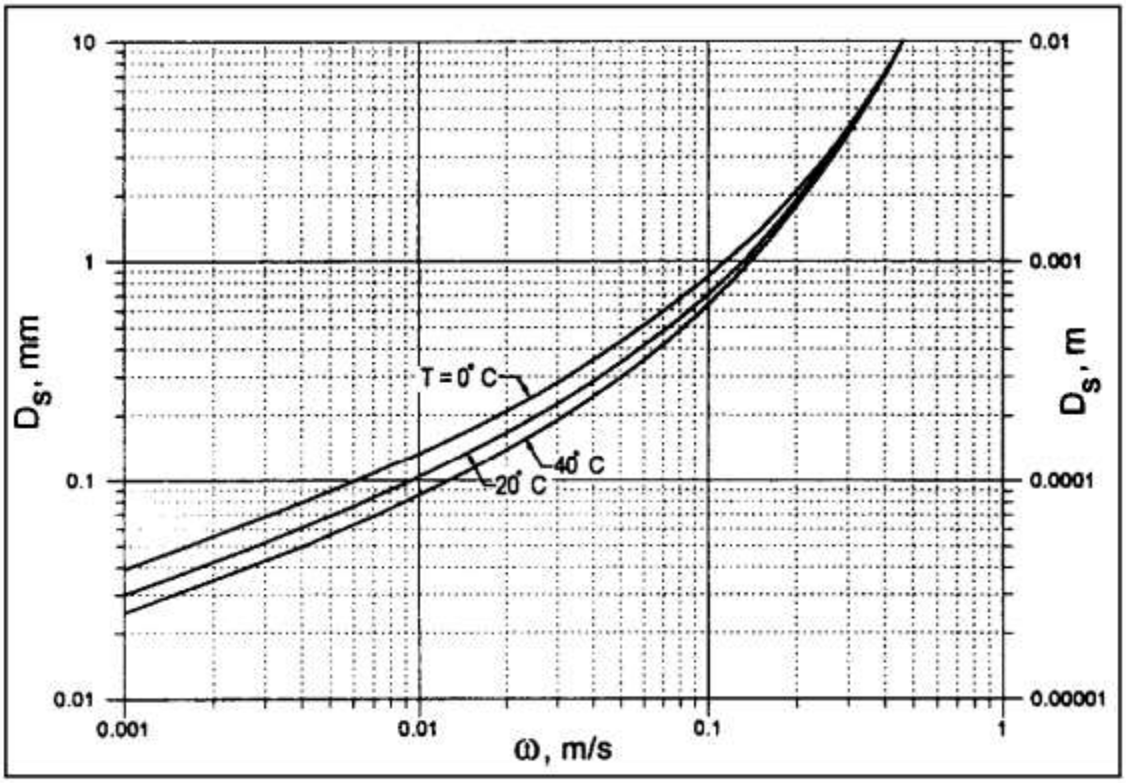


Figure 2: HEC-18 Figure 6.8- Fall Velocity for Sand Particles (Sg=2.65) at Various Temperatures

HEC-18 also notes that because of difficulties in evaluating bottom widths in cross sections, it is acceptable to use the top width so long as the top width is used for both the upstream and the constricted section. Further information can be found in HEC-18 section 6.3.

2.2.1.1 Live-Bed Contraction Scour Pressure Flow

Pressure flow analysis may be necessary if downward pressure results from a structure being overtopped or nearly overtopped. Pressure flow for live-bed conditions can be calculated using the equations 6.14 through 6.16 in HEC-18:

$$y_s = y_2 + t - h_b$$

Where:

t= Flow separation thickness (ft)

h_b= Vertical size of bridge opening prior to scour (ft)

y_s= Scour depth (ft)

$$Q_{ue} = Q_1 \left(\frac{h_{ue}}{h_u}\right)^{\frac{8}{7}}$$

Where:

Q_{ue}= Effective channel discharge for live-bed conditions and bridge overtopping flow (ft^3/s)

h_u= Upstream channel flow depth (ft)

h_{ue}= Effective upstream channel flow depth for live-bed conditions and overtopping (ft)

$$\frac{t}{h_b} = 0.5\left(\frac{h_b * h_t}{h_u^2}\right)^{0.2}\left(1 - \frac{h_w}{h_t}\right)^{-0.1}$$

Where:

h_t= Distance from the water surface to the lower face of the bridge girders (ft) [$h_t = h_u - h_b$]

h_w= Weir flow height (ft) [$h_w = h_t - T \ if \ h_t > T, h_w = 0 \ if \ h_t \leq T$]

T= Height of obstruction (ft) [girders, deck, parapet, debris, etc.]

The dimensions in the above equations can be visualized in Figure 3 shown below.

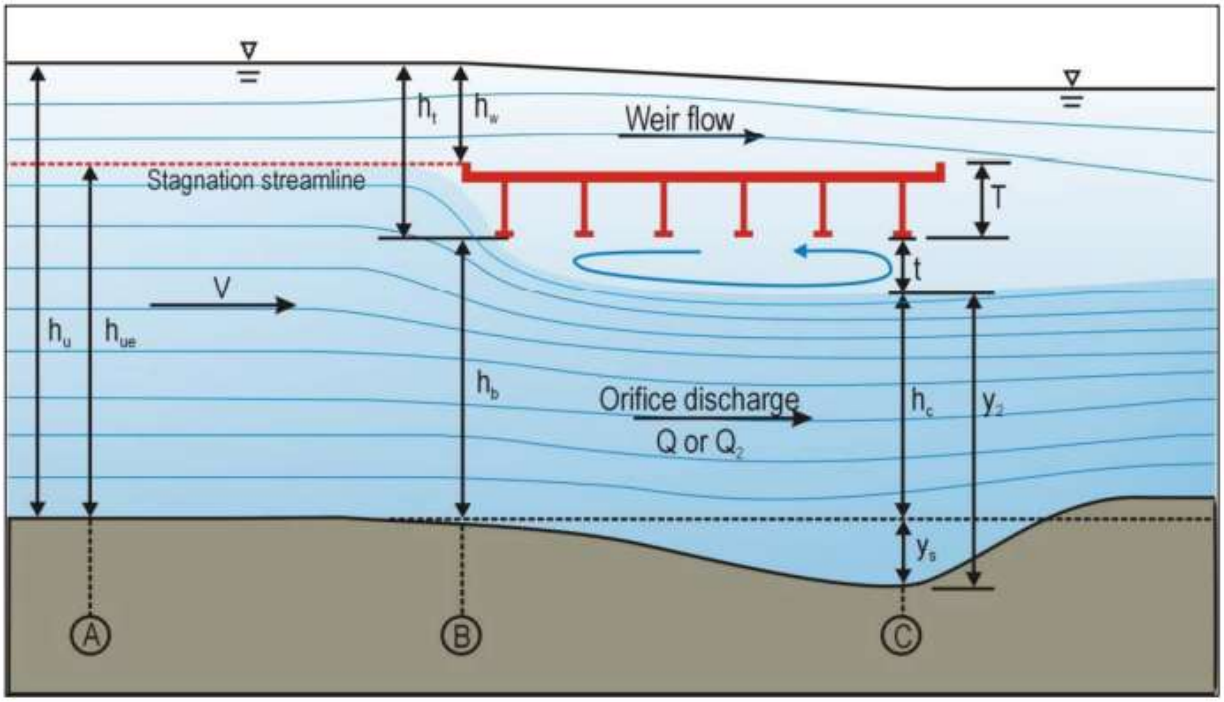


Figure 3: HEC-18 Figure 6.18 Geometric Parameters for Pressure Flow Equations

2.2.2 Clear-Water Contraction Scour

Clear-water conditions are dependent on the stream-bed material and flow characteristics of a given design storm. The following equations from HEC-18 are to be used when the critical velocity for the mean upstream bed particle is greater than the velocity of the stream.

$$y_2 = \left[\frac{K_u Q^2}{D_m^{\frac{2}{3}} W^2}\right]^{\frac{3}{7}}$$

Where:

y_2= Average equilibrium depth in the contracted section after contraction scour (ft)

Q = Discharge through the bridge or on the set-back overbank area at the bridge associated with the width W (ft^3/s)

D_m= Median diameter of bed material (ft) [= D_{50}*1.25]

W= Bottom width of contracted section minus pier widths (ft)

K_u= Constant (0.0077 U.S. Customary & 0.025 SI units)

$$y_s = y_2 - y_0$$

Where:

y_0= Average existing depth in contracted section (ft)

2.2.2.1 Clear-Water Contraction Scour Pressure Flow

Pressure flow analyses can be applied to clear-water conditions as well. However, no unique equation is required to calculate the effective flow through a structure, as is the case with live-bed applications. Pressure flow under clear-water conditions is calculated using the primary equation for y_2 in the previous section (2.2.2). However, the total scour depth is calculated in the same manner as in Section 2.2.1.1:

$$y_s = y_2 + t - h_b$$

$$\frac{t}{h_b} = 0.5\left(\frac{h_b * h_t}{h_u^2}\right)^{0.2}\left(1 - \frac{h_w}{h_t}\right)^{-0.1}$$

Further guidance on calculating pressure flow can be found in HEC-18 section 6.10.

2.3 Pier Scour

Pier scour comprises one of the two primary forms of foundation scour that must be evaluated at a bridge. There are two possible manners in which pier scour can be evaluated. The first, a simple evaluation in which the pile cap and pile group of a pier are not subject to scour (i.e., adequately buried below stream bed material). The second case is a complex evaluation which uses the superposition of pier elements: pier stem, pile cap, and pile group to determine the total scour when scour depths may exceed the top of the pile cap. Lastly, methods for evaluating piers with debris present and scour at wider piers are considered.

2.3.1 Simple Pier Scour

The fundamental aspect of pier scour can be seen in Figure 4. Pier scour applies to both live-bed and clear-water conditions. The simple pier scour equation given in HEC-18 is a function of pier width and shape, flow depth directly upstream of the pier, and the Froude Number of the point directly upstream of the pier.

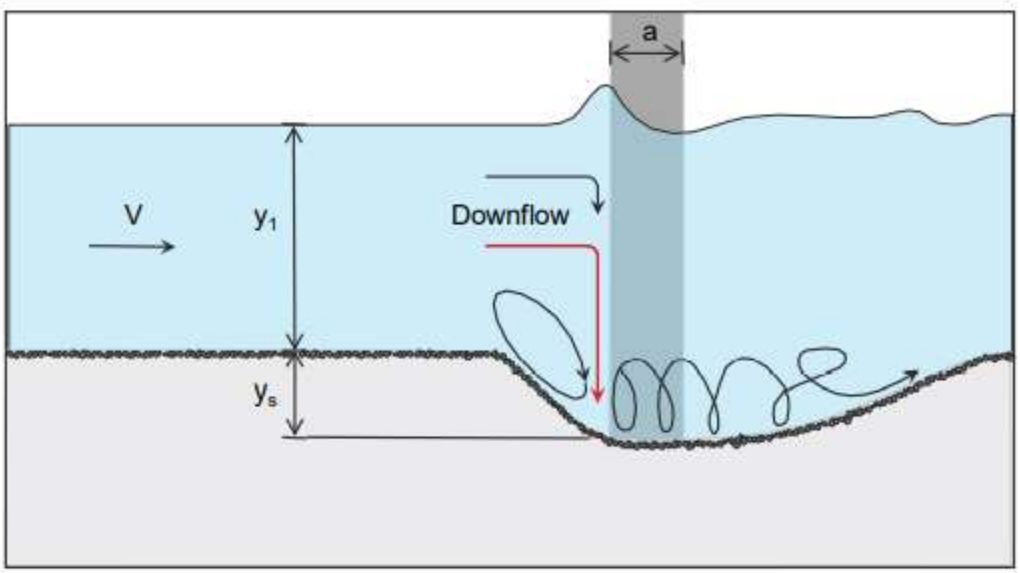


Figure 4: HEC-18 Figure 7.2: Pier Scour Graphic

Two HEC-18 equations are shown below:

$$\frac{y_s}{y_1} = 2.0 K_1 K_2 K_3 \left(\frac{a}{y_1}\right)^{0.65} Fr_1^{0.43}$$

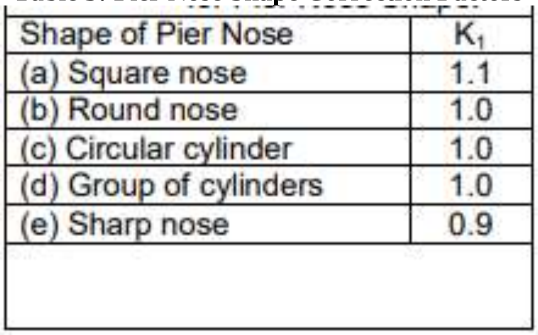
Or

$$\frac{y_s}{a} = 2.0\ K_1 K_2 K_3 \left(\frac{y_1}{a}\right)^{0.35} Fr_1^{0.43}$$

Where:
y_1= Flow depth directly upstream of pier (ft)
K_1= Pier nose shape correction factor
K_2= Angle of attack correction factor
K_3= Bed condition correction factor
a= Width of pier (ft)
L= Length of pier (ft)
Fr_1= Froude number directly upstream of pier

Correction factors for the pier nose shape are seen below in Table 5.

Table 5: Pier Nose Shape Correction Factors



Shape of Pier Nose	K_1
(a) Square nose	1.1
(b) Round nose	1.0
(c) Circular cylinder	1.0
(d) Group of cylinders	1.0
(e) Sharp nose	0.9

The correction factor for the angle of attack, K_2, can be calculated using equation 7.4 in HEC-18 shown below:

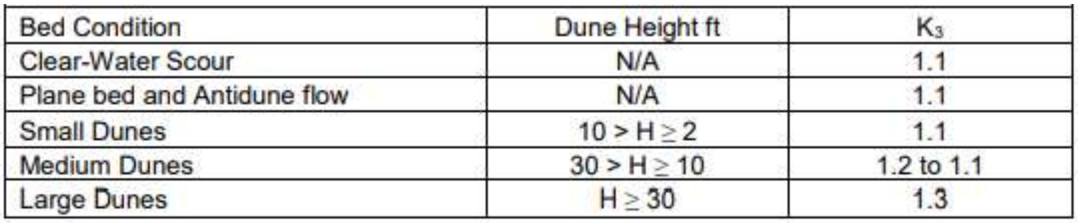
$$K_2 = \left(Cos\theta + \frac{L}{a} Sin\ \theta\right)^{0.65}$$

Where:

θ= skew angle of the flow in relation to the piers (degrees)

Lastly, the bed condition correction factor can be applied for simple pier scour computations. These values can be seen below in Table 6.

Table 6: HEC-18 Table 7.3: Bed Condition Correction Factors for Pier Scour



Bed Condition	Dune Height ft	K_3
Clear-Water Scour	N/A	1.1
Plane bed and Antidune flow	N/A	1.1
Small Dunes	$10 > H \geq 2$	1.1
Medium Dunes	$30 > H \geq 10$	1.2 to 1.1
Large Dunes	$H \geq 30$	1.3

Further guidance can be found in HEC-18 section 7.2.

2.3.2 Wide Pier Scour

Wide pier scour correction factors are calculated using the two conditional equations shown below. Further information on the application of the correction factor can be found in HEC-18 Section 7.4. This correction factor is designed to be used in the pier scour equations shown in the previous section (2.3.1). This factor is used as a coefficient in addition to the other K-factors already utilized.

$$K_w = 2.58\left(\frac{y}{a}\right)^{0.34} Fr_1^{0.65}\ for\ \frac{V}{V_c} < 1$$

$$K_w = 1.0\left(\frac{y}{a}\right)^{0.13} Fr_1^{0.25}\ for\ \frac{V}{V_c} \geq 1$$

Where:

K_w= Wide pier in shallow flow correction factor

V= Velocity at pier (ft/s)

V_c= Critical velocity of bed material at pier (ft/s)

According to Arneson et al. (2012, p. 7.10):

> *The correction factor should be applied when the ratio of depth of flow (y) to pier width (a) is less than 0.8 (y/a < 0.8); the ratio of pier width (a) to the median diameter of the bed material (D_{50}) is greater than 50 (a/D_{50} > 50); and the Froude Number of the flow is subcritical.*

2.3.3 Pier Scour with Debris

HEC-18 supplies guidance in section 7.7 for evaluating piers with debris present. The debris acts to increase the effective size of the pier and is evaluated as accumulating in either a rectangular or triangular shape. Once calculated, the effective pier width can be used in the simple pier scour equation in Section 2.3.1 above. The effective pier width with debris present is calculated using HEC-18 equation 7.32.

$$a_d^* = \frac{K_1(HW) + (y - K_1 H)a}{y}$$

Where:

a_d^*= Effective width of pier with debris (ft)

a= Pier width perpendicular to flow (ft)

K_1= 0.79 for rectangular debris and 0.21 for triangular

H= Height of debris on pier (ft)

W= Width of debris perpendicular to flow direction (ft)

Y= Approach flow depth (ft)

2.3.4 Pier Scour with Coarse Bed Materials

Coarse bed equations (applicable when $D_{50} \geq 20$ mm and $\frac{D_{84}}{D_{50}} \geq 1.5$) are supplied in HEC-18 section 7.11 to evaluate clear-water conditions that fit the aforementioned criteria. Computations are performed using equation 7.34 in HEC-18:

$$y_s = 1.1 K_1 K_2 a^{0.62} y_1^{0.38} \tanh\left(\frac{H^2}{1.97\sigma^{1.5}}\right)$$

Where:

H= Densiometric particle Froude number = $\frac{V_1}{\sqrt{g(S_g - 1)D_{50}}}$

v_1=Mean velocity of flow immediately upstream of pier (ft/s)

S_g= Specific gravity of sediment

σ= Sediment gradation coefficient $\frac{D_{84}}{D_{50}}$

2.3.5 Complex Pier Scour

Piers with complex foundations (i.e., pile groups and pile caps) should be evaluated if and only if the potential for scour to exceed the top of the pile cap is present. The basis of scour in a complex pier circumstance is shown in Figure 5. Where the scour potential at each component must be evaluated independently and then summed to determine the total scour. Further guidance can be found in HEC-18 Section 7.5.

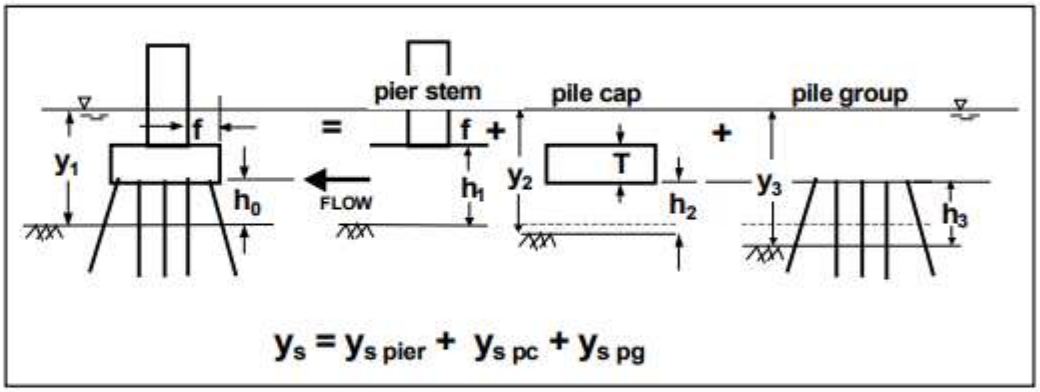


Figure 5: HEC-18 Figure 7.5: Superposition of Complex Pier Elements

Where the parameters given in the HEC-18 equation are defined as:

f= Distance between front edge of pile cap or footing and pier (ft)
h_0= Pile cap height at beginning of computation (ft) (**NOTE**: can be negative)
h_1= h_0 + T = height of pier stem above bed before scour (ft)
h_2= h_0 + $y_{s\,pier}$/2 = height of pile cap after pier stem scour component has been computed
$h_3 = h_0 + y_{s\,pier}/2 + y_{s\,pc}/2$ = height of pile group after the pier stem and pile cap scour components have been computed (ft)
S= Spacing between columns of piles (ft) [center to center spacing]
T= Thickness of pile cap (ft)
y_1= Depth of approach flow prior to scour (ft)
y_2= y_1+ $y_{s\,pier}$/2= adjusted flow depth for pile cap computations (ft)
y_3= $y_1 + y_{s\,pier}/2 + y_{s\,pc}/2$ = adjusted flow depth for pile group computations (ft)
V_1= Approach velocity before scour (ft/s)
V_2= $V_1\left(\frac{y_1}{y_2}\right)$= adjusted velocity for pile cap (ft/s)

V_3= $V_1\left(\frac{y_1}{y_3}\right)$= adjusted velocity for pile group (ft/s)

$y_{s\,pier}$= Scour component at pier stem (ft)

$y_{s\,pc}$= Scour component at pier cap (ft)

$y_{s\,pg}$= Scour at piles exposed to flow (ft)

For the pier stem scour component, HEC-18 equation 7.23 is seen below:

$$\frac{y_{s\,pier}}{y_1} = K_{hpier}[2.0K_1K_2K_3\left(\frac{a_{pier}}{y_1}\right)^{0.65}\left(\frac{V_1}{\sqrt{gy_1}}\right)^{0.43}$$

Where:

K_{hpier}= Coefficient for pier stem height above bed (Shown below in Figure 6)

g= Gravitational acceleration (32.2 ft/s^2)

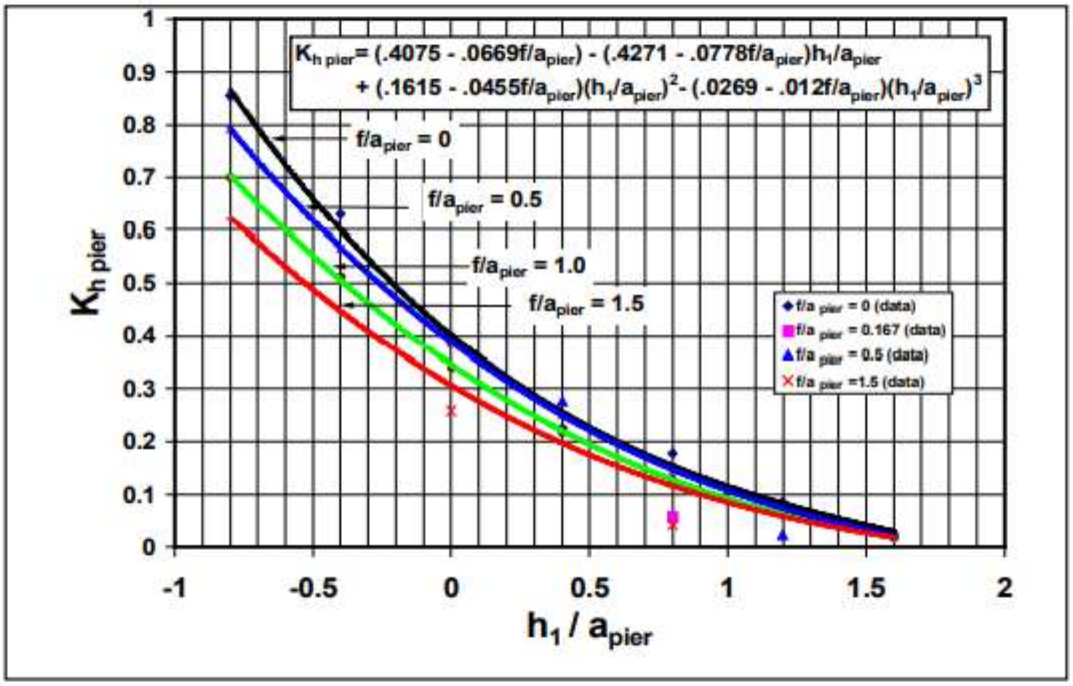


Figure 6: HEC-18 Figure 7.6: Suspended Pier Scour Ratio

Scour at the pile cap can be determined from HEC-18 equation 7.24 for Case 1 circumstances when the bottom of the footing in the flow is above the bed.

$$\frac{y_{s\,pc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

Where:

a_{pc}= Width of unadjusted pile cap (ft)

a_{pc}^{*}= Width of the equivalent pile cap (ft) [Determination seen in Figure 7]

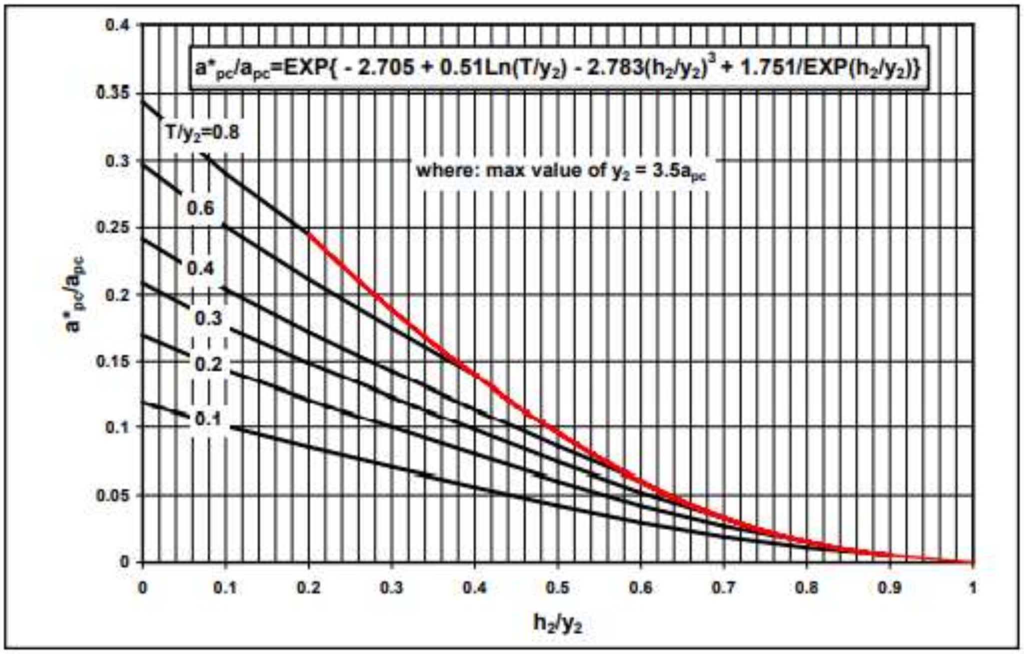


Figure 7: HEC-18 Figure 7.7 Pile Cap Equivalent Width

For Case 2 only, when the bottom of the footing is on or below the bed, the total scour can be computed using HEC-18 equation 7.27:

$$y_s = y_{s\,pier} + y_{s\,pc}$$

Under this condition, the scour component at the pile cap must be computed using HEC-18 equation 7.26:

$$\frac{y_{s\,pc}}{y_f} = 2.0\,K_1K_2K_3K_w\left(\frac{a_{pc}}{y_f}\right)^{0.65}\left(\frac{V_f}{\sqrt{gy_f}}\right)^{0.43}$$

Where V_f is calculated in HEC-18 equation 7.25 as:

$$\frac{V_f}{V_2} = \frac{\ln\left(10.93\left(\frac{y_f}{k_s}\right)+1\right)}{\left(\ln\left(10.93\left(\frac{y_2}{k_s}\right)+1\right)\right)}$$

And:

V_f= Average velocity in the flow zone below the top of the footing 9ft/s)

V_2= Average adjusted velocity in vertical of flow approaching the pier (ft/s)

$y_f = h_1 + y_{s\,pier}/2$= distance from the bed (after degradation, contraction scour, and pier stem scour) to the top of the footing (ft)

k_s= Grain roughness of the bed (ft)

y_2= Adjusted depth of the flow upstream of the pier (ft)

Figure 8 illustrates the constituent components of Case 2 pier cap scour, when the bottom of the footing is on or below the stream bed.

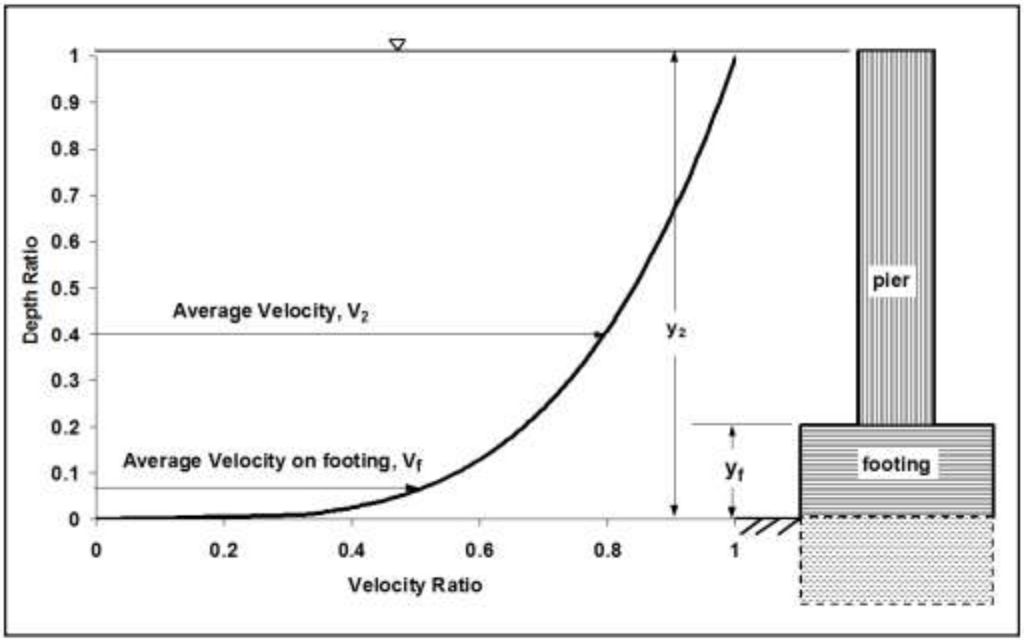


Figure 8: HEC-18 Figure 7.8: Schematic of Case 2 Pile Cap Scour Component

The final component of the complex pier scour that must be evaluated is the pile group, which is covered in-depth in HEC-18 section 7.5.5. To begin the computation of the pile group, the effective width of an equivalent pier at full depth needs to be calculated using HEC-18 equation 7.28:

$$a_{pg}^{*} = a_{proj} K_{sp} K_m$$

Where:

a_{pg}^{*}= Effective width of an equivalent full depth pier (ft)

a_{proj}= Sum of non-overlapping projected pile widths (ft) [see Figure 9 and Figure 10]

K_{sp}= Pile spacing coefficient [see Figure 11]

K_m=Aligned row coefficient [see Figure 12 NOTE: K_m=1.0 for skewed or staggered pile groups]

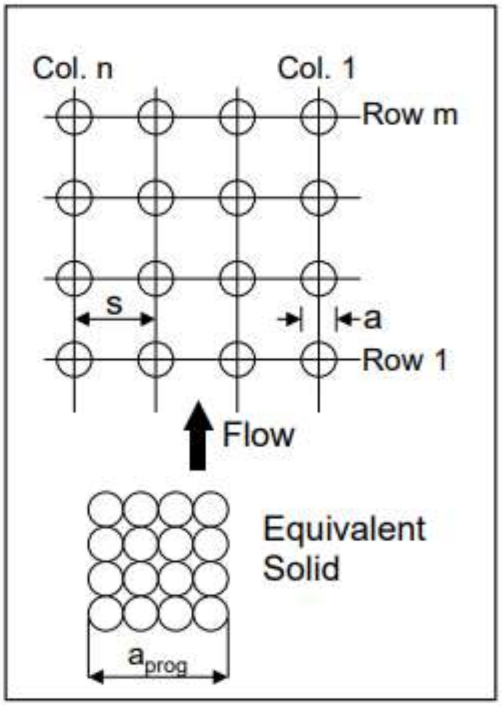


Figure 9: HEC-18 Figure 7.9: Projected Pile Width Aligned with Flow

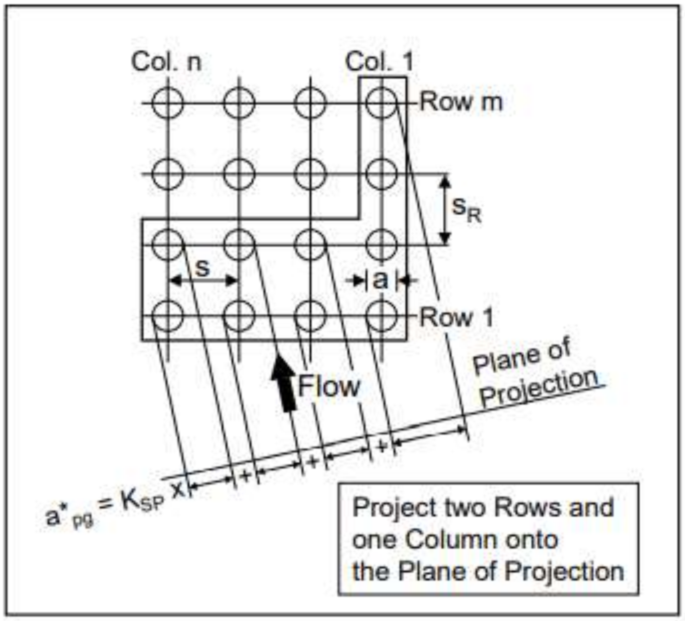


Figure 10:HEC-18 Figure 7.10: Projected Pile Width Skewed to Flow

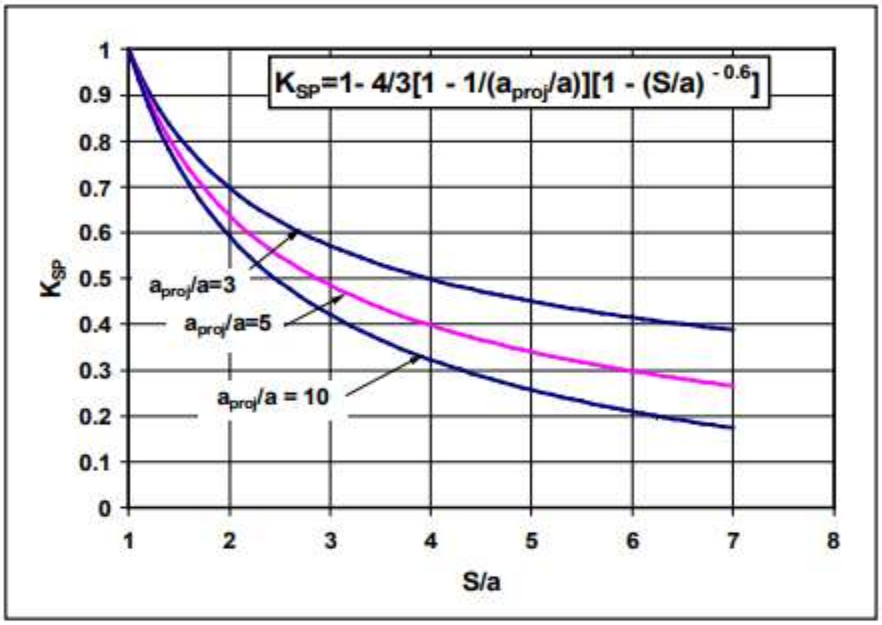


Figure 11: HEC-18 Figure 7.11: Pile Spacing Factor

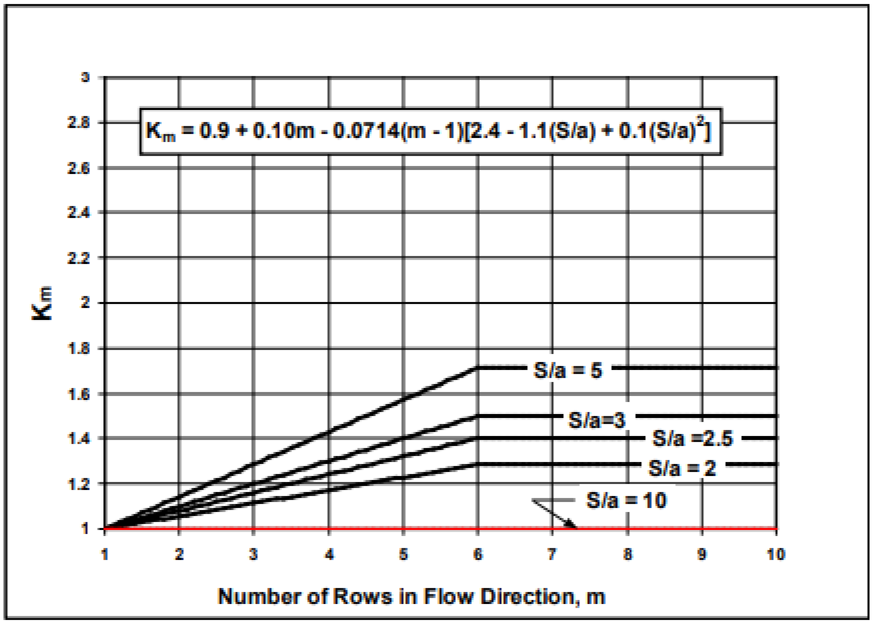


Figure 12: HEC-18 Figure 7.12: Aligned Row Adjustment Factor

Once the effective width of the pile group is computed, the pile group scour component can be evaluated using HEC-18 equation 7.31:

$$\frac{y_{s\,pg}}{y_3} = K_{h\,pg}\left[2.0\,K_1 K_3 \left(\frac{a^*_{pg}}{y_3}\right)\left(\frac{V_3}{\sqrt{g y_3}}\right)^{0.43}\right]$$

Where:

$K_{h\,pg}$= Pile group height factor [see Figure 13]

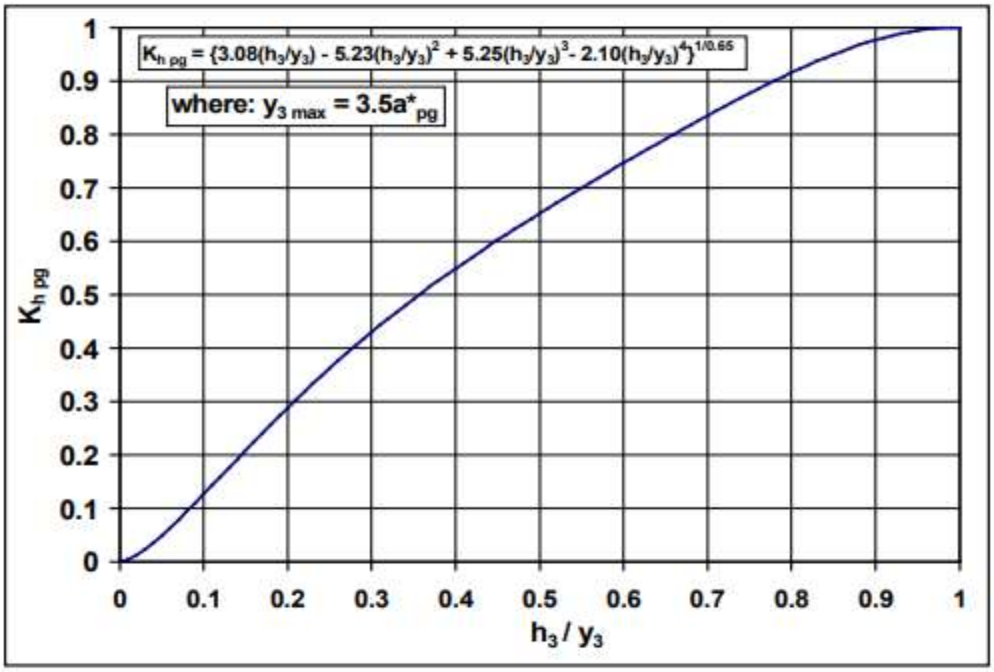


Figure 13: HEC- 18 Figure 7.13: Pile Group Height Adjustment Factor

Once the scour components for the pier stem, pile cap, and pile group are computed, they can be added together to obtain the total complex pier scour depth. The complex pier scour depth is then added to long-term degradation or aggradation and the contraction scour to find the total scour at each pier.

2.3.6 Pier Scour in Rock

For pier scour in non-scour resistant rock, a time rate scour analysis should be performed. Refer to section 7.13 in HEC-18 and Section 2.1.1 above for more information. Additionally, section 4.6 and 4.7 of HEC-18 provides guidance on determining rock strength parameters.

2.4 Abutment Scour

HEC-18 section 8 provides three possible options for computing abutment scour: Froehlich, HIRE, and NCHRP 24-20. After careful consideration, it was determined that the NCHRP 24-20 equation would be the most viable path forward for evaluating scour at abutments. This method uses an amplification factor, calculated independently for either live-bed or clear-water conditions, to determine the maximum flow depth. HEC-18 equation 8.3 illustrates this:

$$y_{max} = \alpha_A y_c \quad or \quad y_{max} = \alpha_B y_c$$

Where:

y_{max} = Maximum flow depth after scour (ft)

y_c= Flow depth resulting from live-bed or clear-water contraction scour (ft)

α_A= Amplification factor for live-bed conditions [see Figure 14 for spill-through abutments and Figure 15 for wing wall abutments]

α_B= Amplification factor for clear-water conditions [see Figure 16 for spill-through abutments and Figure 17 for wing wall abutments]

The scour depth is then computed using HEC-18 equation 8.4:

$$y_s = y_{max} - y_0$$

Where:

y_s= Abutment scour depth (ft)

y_0= Flow depth prior to scour (ft)

2.4.1 Abutment Scour: Live-bed Conditions

The flow depth resulting from contraction scour for live-bed conditions is computed using HEC-18 equation 8.5:

$$y_c = y_1 \left(\frac{q_{2c}}{q_1}\right)^{\frac{6}{7}}$$

Where:

y_1= Upstream flow depth (ft)

q_1= Upstream unit discharge (ft^2/s)

q_{2c}= Unit discharge in the constricted opening accounting for non-uniform flow (ft^2/s)

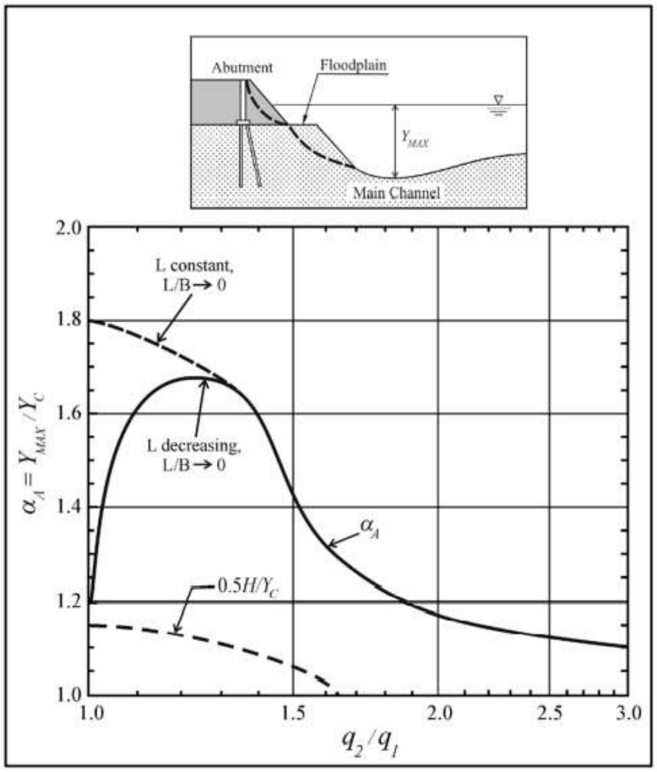


Figure 14: HEC-18 Figure 8.9: Amplification Factor for Spill-through Abutments with Live-bed Conditions

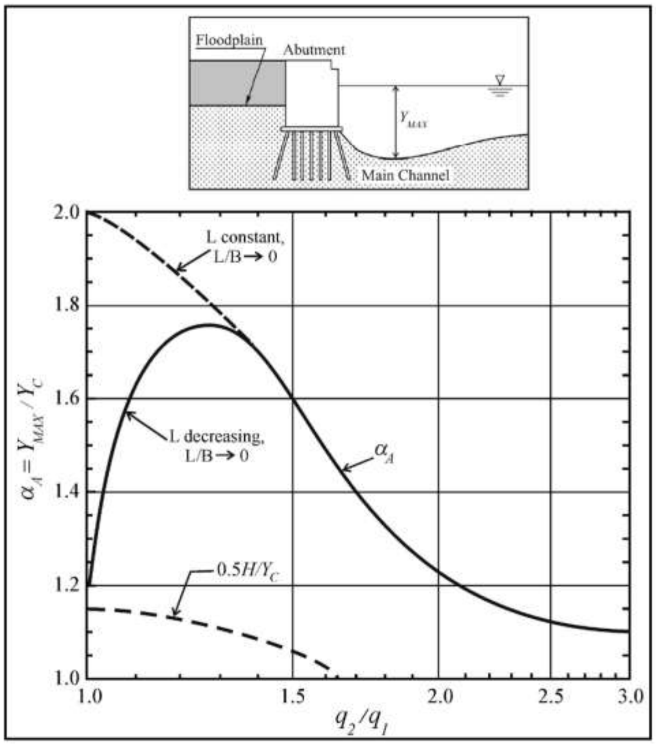


Figure 15: HEC-18 Figure 8.10: Amplification Factor for Wingwall Abutments with Live-Bed Conditions

2.4.2 Abutment Scour: Clear-water Conditions

The NCHRP 24-20 equations provide two methods for calculating the contraction flow depth in clear-bed conditions. One equation utilizes the stream bed material's D_{50} and the other uses the stream bed material's critical shear stress. This section will move forward focusing only on the equation related to critical shear stress due to fewer limitations associated with it. HEC-18 equation 8.7 is used to calculate the scour flow depth (y_c) below:

$$y_c = \left(\frac{\gamma}{\tau_c}\right)^{\frac{3}{7}} \left(\frac{nq_{2f}}{K_u}\right)^{\frac{6}{7}}$$

Where:

n= Manning's n for floodplain material at abutment of interest

τ_c= Critical shear stress of floodplain material (lb/ft^2)

γ= Unit weight of water (lb/ft^3)

K_u= 1.486 in U.S. customary or 1.0 SI

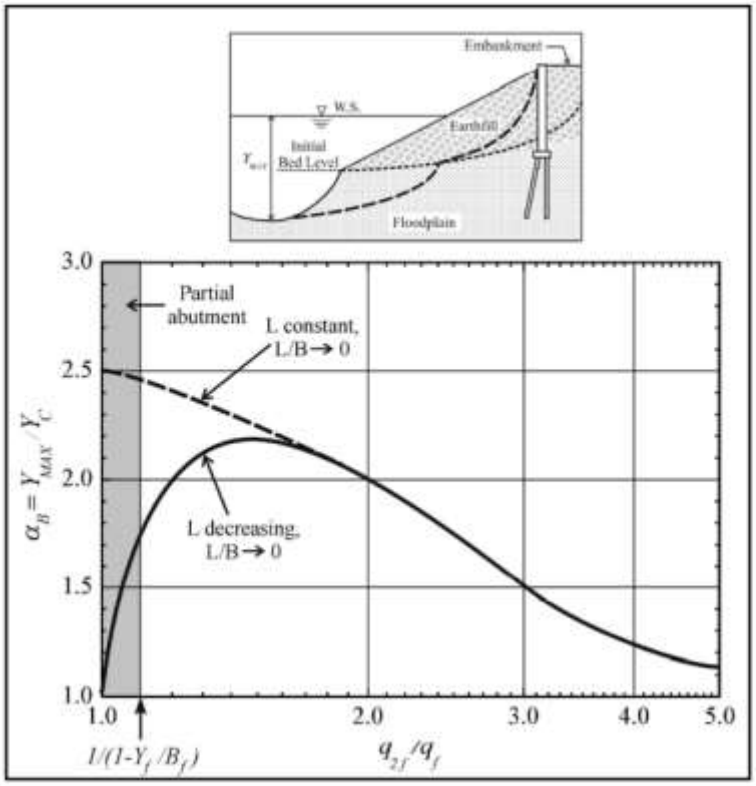


Figure 16: HEC-18 Figure 8.11: Amplification Factor for Spill-through Abutments with Clear-Water Conditions

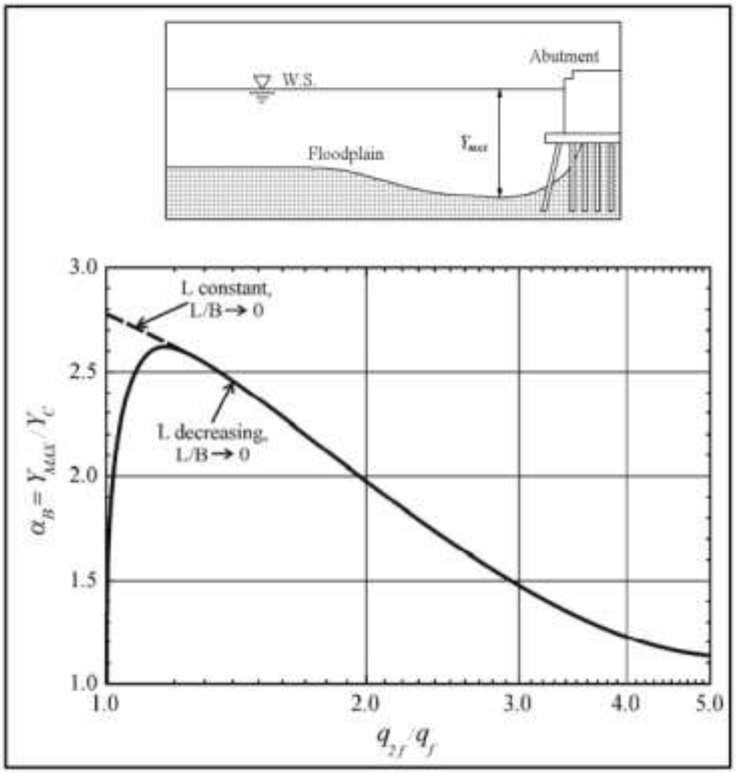


Figure 17: HEC-18 Figure 8.12: Amplification Factor for Wingwall Abutments with Clear-Water Conditions

It should be noted that the preferred method for evaluating velocities for abutment scour computations is through 2D hydraulic modeling. If 2D hydraulic modeling is not used, the next best method is to use 1D modeling and application of the set-back ratio (SBR) discussed in length in HEC-18 section 8.6.3.

2.5 Three-Sided Culverts

Scour at three-sided culverts can be considered as a special case of contraction scour. There are two main equations in HEC-18 for evaluating scour at three-sided culverts; one for culverts with wingwalls and one for culverts without wingwalls, both equations assume clear-water conditions. Unfortunately, no method for computing scour at three-sided culverts with live-bed conditions has been approved. For both cases, scour depth is computed using equation 6.11 or 6.13 from HEC-18:

$$y_s = y_{max} - y_0$$

2.5.1 Three-Sided Culvert with Wingwalls

For culverts with wingwalls, equation 6.10 in HEC-18 is used to evaluate the scour flow depth at the upstream corner of the culvert, which considers both local and contraction scour.

$$y_{max} = K_u Q_{BI}^{0.28} \left(\frac{Q}{W_c D_{50}^{\frac{1}{3}}} \right)^{0.26}$$

Where:

y_{max} = Flow depth at culvert entrance corner (ft)

Q_{BI} = Discharge blocked by road embankment on one side of culvert (ft^3/s)

Q = Discharge through culvert (ft^3/s)

W_c= Culvert width (ft)

D_{50}= Median diameter of bed material (ft)

y_0= Flow depth prior to scour (ft)

$K_u = 0.84$ for U.S. customary and 1.16 for SI units

2.5.2 Three-Sided Culvert without Wingwalls

For culverts without wingwalls, equation 6.12 in HEC-18 is used to assess the flow depth after scour, including contraction and local scour at the upstream corners of the culvert.

$$y_{max} = K_u Q_{BI}^{0.12} \left(\frac{Q}{W_c D_{50}^{\frac{1}{3}}} \right)^{0.60}$$

Where:

y_{max} = Flow depth at culvert entrance corner (ft)

Q_{BI} = Discharge blocked by road embankment on one side of culvert (ft^3/s)

Q = Discharge through culvert (ft^3/s)

W_c= Culvert width (ft)

D_{50}= Median diameter of bed material (ft)

y_0= Flow depth prior to scour (ft)

$K_u = 0.57$ for U.S. customary and 0.88 for SI units

2.6 Long-term Aggradation and Degradation

The propensity for long-term aggradation or degradation at a structure must be assessed in addition to local and contraction scour to determine the long term viability of a structure. Long-term aggradation or degradation should be explored by qualified personnel in accordance with HEC-18 section 5.3 and HEC-20. Hydraulic modeling software, such as HEC-RAS, may be used to aid in computations. These processes should be evaluated using qualitative and quantitative analyses (Arneson et al., 2012).

There are many potential causes of aggradation or degradation (referred to collectively from here on as degradation), however, none may be as impactful as anthropogenic activity. Potential for degradation may increase when dams or reservoirs are present, sediment is removed from the stream bed, land-use changes that reduce riparian buffers, or due to other natural changes such as channel migration during a storm event (Lagasse et al., 2012).

Section 4.5 of HEC-20 provides a more in-depth analysis in the qualitative and quantitative assessment of long-term degradation. In addition, section 4.6 of HEC-20 provides insight into basic engineering analyses, and section 4.7 provides discussion on mathematical modeling (Lagasse et al., 2012).

3. Scour Prediction Tool

3.1 Scour Prediction Tool Development

In order to streamline the process of scour calculation, an excel spreadsheet tool was developed using the methods discussed in Section 2. For all practical purposes, the built-in formatting options in excel have been used to indicate appropriate sections denoting user input (peach colored backgrounds), calculations (gray background with orange font), and output (gray with black font) when applicable. Users should enter information in the input formatted cells for each parameter. Some of the input options are restricted to predetermined options. An example of this would be the selection of clear-water or live-bed conditions for abutment or contraction scour. It is the users' responsibility to understand what conditions are applicable, however, design of the tool also allows users to run "what-if" scenarios with varying conditions. Calculation sheets have been included for main channel contraction scour, overbank contraction scour, local scour at piers, three-sided culvert scour, and abutment scour. Currently, only one sheet for pier scour is supplied. To analyze multiple piers, the pier scour sheet should be duplicated. Furthermore, as mentioned in Section 2.5, if two or more three-sided culverts are evaluated in succession (i.e., side by side) a pier analysis must be performed for the support between the culverts. Explanatory dialogue in the tool is programmed to auto populate based on input and guide the user throughout use of the tool. Lastly, nomograph overlays have been included to verify the calculation of coefficients, when applicable, throughout various sheets.

For each scour component (e.g., pier, abutment, etc.) there are input sections for bed material to perform a layered analysis. The inputs for the layered analysis are similar across all scour components with the exception of minute alterations where appropriate. When performing a layered analysis, users must choose from one of four soil-types: granular, cohesive, non-scour resistant rock, or scour resistant rock. Depending on the chosen soil-type, appropriate parameters should be input into the layer attribute sections for the determination of critical shear stress for that layer. Layer elevations should also be included to determine the corresponding layer thickness/depth. If the critical shear for a given layer is less than the streambed shear, the layer will be scoured. If needed, information for layers can be increased by simply dragging the entire row down to increase the number of fields where layer information is to be entered.

The layer depth analysis sections detail the amount of scour in a given layer, given its attributes when applicable, and compare the critical shear to the stream bed shear to determine if scour of the layer will occur. If a layer is not completely scoured, auto-populating dialogue will indicate that the layer is not completely eroded; in which case, the next layer down will indicate that the analysis has ended.

Example calculations with the prediction tool can be seen in the next section. Due to the complexity, amount of variation between sites, and differing methods of assessment, long-term aggradation and degradation is not included in the prediction tool but should be assessed in order to provide an accurate description of scour at the structure being analyzed.

3.2 Decaying Shear Stress in Layered Analysis

To increase analysis accuracy, a layered shear analysis is included in the scour prediction tool. It should be noted that layers can be included in any decimal or whole foot increment to capture the phenomenon of decaying shear on any interval desired. The first layer is evaluated using the initial bed shear stress, which is calculated in each tab in the accompanying scour tool. At the bottom of the layer or the bottom of the scour depth, whichever is less, shear stress is recomputed. Shear stress is computed using equation 4.5 from HEC-18:

$$\tau_{local} = \left(\frac{n * v_{local}}{1.486}\right)^2 \left(\frac{62.4}{y^{\frac{1}{3}}}\right)$$

Where:

τ_{local}= The local shear stress at any given point (lb/ft^2)

v_{local}= Velocity at a point (ft/s)

n= Manning’s roughness coefficient

y= Local flow depth at given point (ft)

Changes in the flow area are accounted for in the tool with rectangular sections for contraction and pier scour (e.g., channel width by increase in flow depth for contraction scour or rectangular scour area at pier). Abutment and three-sided culvert shear stresses are modeled as rectangular areas 3 inches wide, adjacent to the abutment.

4. Application of Scour Prediction Tool

In this section, scour examples completed using the scour prediction tool will be shown and discussed. These examples will be completed using the input data from the scour example computations in HEC-18. Additionally, scour examples using layered analysis from E.L. Robinson’s *MAD/PIC-71-4.56/0.00 structure foundation exploration report* are used for main channel contraction, pier, and abutment computations. These examples will accompany the non-layer dependent HEC-18 examples. One of the benefits of performing a layered analysis is a more accurate depiction of scour in the bed material. For instance, if a layer with greater critical shear resistance underlies a layer of lesser shear resistance, the layer with the greater shear resistance may not be scoured once the decaying shear stress due to the increase in flow depth of an above scoured layer is accounted for.

The HEC-18 example parameters are used to verify the accuracy of the scour prediction tool against an already completed computation; whereas, the layered analysis allows for an investigation to utilize decaying shear stress, as layers are scoured, and layer properties to more accurately determine scour effects. It should be noted that layers may be divided into any increment that a user determines appropriate for analysis to better capture the effects of decaying shear stress with depth. This is discussed in Section 3.2 in more detail.

An overview of the MAD-71-4.56 structure used in the analysis and its basic geometry can be seen in Figure 18 and Figure 19. Grain size analysis for non-cohesive soil layers is shown in Table 7 below.

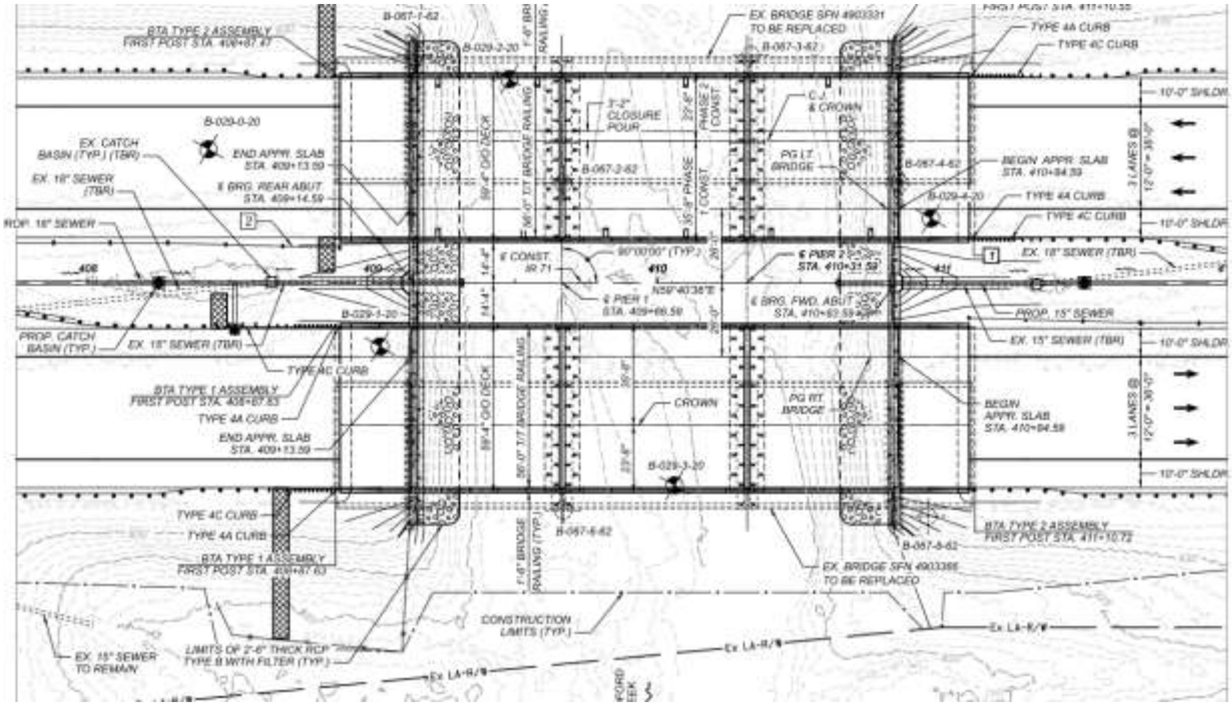


Figure 18: MAD-71-4.56 Bridge Overview- Source: E.L. Robinson

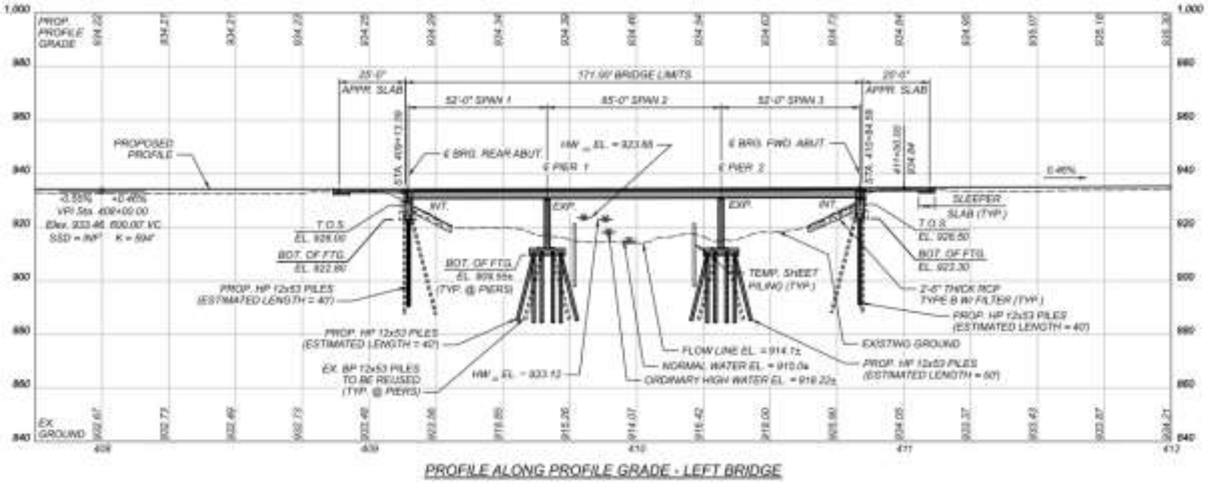
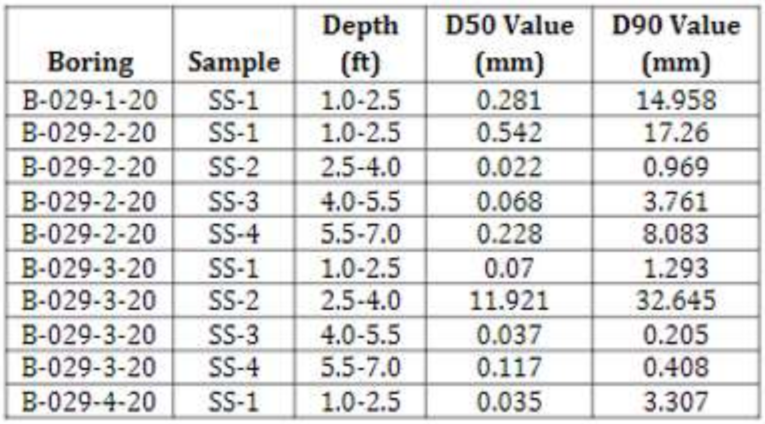


Figure 19: MAD-71-4.56 Bridge Overview (Continued)-Source: E.L. Robinson

Table 7: MAD-71-4.56 Soil Layer D50s and Depths



Boring	Sample	Depth (ft)	D50 Value (mm)	D90 Value (mm)
B-029-1-20	SS-1	1.0-2.5	0.281	14.958
B-029-2-20	SS-1	1.0-2.5	0.542	17.26
B-029-2-20	SS-2	2.5-4.0	0.022	0.969
B-029-2-20	SS-3	4.0-5.5	0.068	3.761
B-029-2-20	SS-4	5.5-7.0	0.228	8.083
B-029-3-20	SS-1	1.0-2.5	0.07	1.293
B-029-3-20	SS-2	2.5-4.0	11.921	32.645
B-029-3-20	SS-3	4.0-5.5	0.037	0.205
B-029-3-20	SS-4	5.5-7.0	0.117	0.408
B-029-4-20	SS-1	1.0-2.5	0.035	3.307

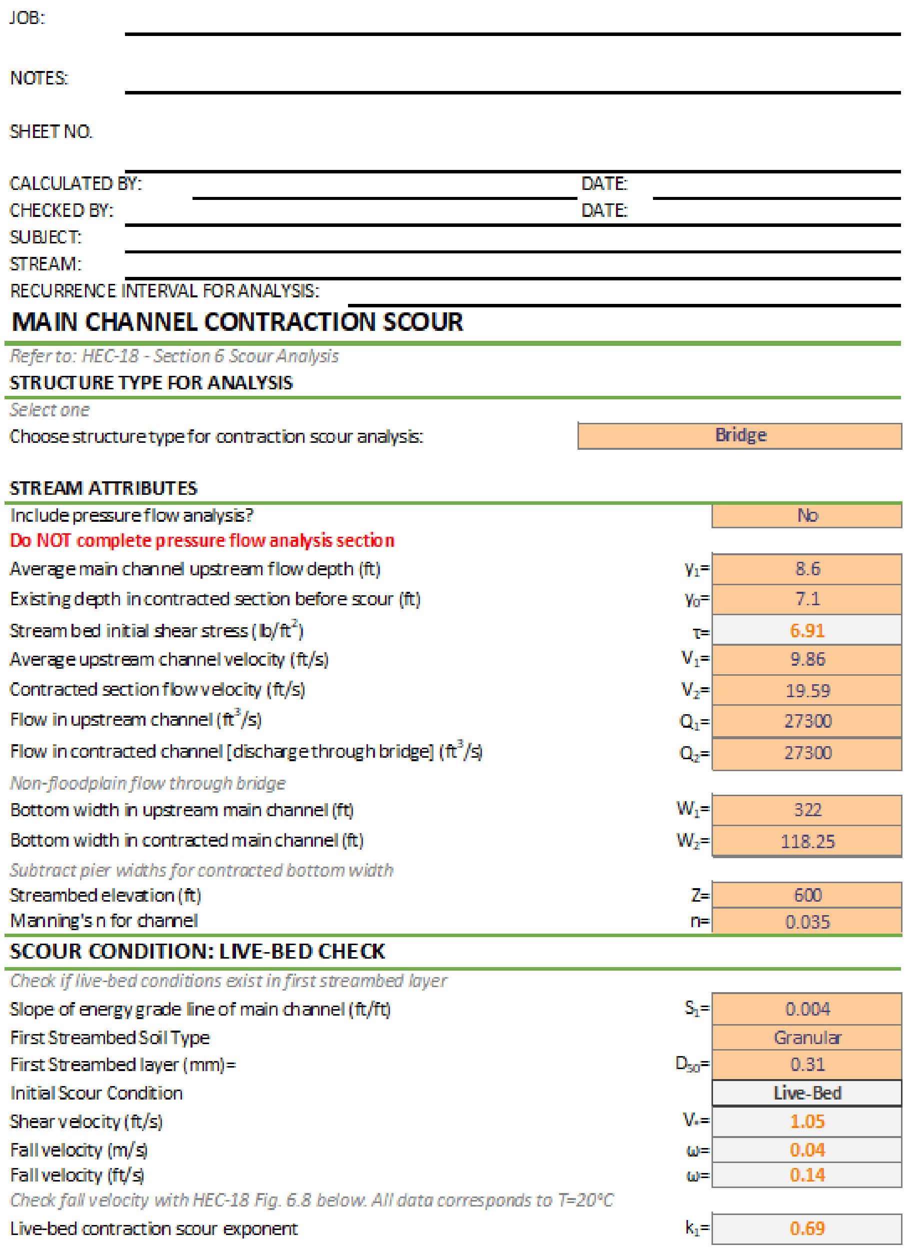
4.1 Main Channel Contraction Scour Example

The following examples are completed using example data from HEC-18 section 6.6 and E.L. Robinson’s MAD/PIC-71-4.56/0.00 Exploration Report. Parameter values for HEC-18 data have been inferred for data that is not present in the HEC-18 examples such as bed elevation or other parameters that are not pertinent to scour computation. Examples using E.L. Robinson’s MAD/PIC-71-4.56/0.00 Exploration Report obtained data from the accompanying HEC-RAS files.

4.1.1 Main Channel Contraction Scour: Live-Bed Conditions

Using data from HEC-18 example problem 1 (section 6.6.1) the parameters in the tool were completed. Since no pressure flow analysis was to be completed for this section, the remainder of the sheet showing pressure flow and overtopping data is not included in Figure 20. It should be noted that the fall velocity is found using HEC-18 Figure 6.8, which is included in the tool and seen in Figure 2 of Section 2.2.1 of this report, but must be converted to ft/s prior to entering its value in the scour condition check section. Once the exponent is determined, data for the streambed material should be entered in the layer attribute section, shown in Figure 21 on the next page. It should be noted that only the data necessary need be inserted based on the soil-type selection. Additionally, elevation data for the layers should be input into the appropriate columns. Once this data is entered, the critical shear stress of the material is automatically calculated. Finally, the scour output is given in the scour depth analysis section of the tool, seen in Figure 22. In this instance the total depth reported in HEC-18 was 10.1 feet which is verified by scour depth calculation.

Additionally, Figure 22 shows that layer 2 was not completely scoured and an automatically populated “END” statement will appear in the next layer down, indicating that layer 3 is not subject to scour. A clear-water analysis is performed in the same manner, in which case the “Scour Condition Live-Bed Check” “Initial Scour Condition” row should indicate that clear-water conditions exist.



JOB:

NOTES:

SHEET NO.

CALCULATED BY: DATE:

CHECKED BY: DATE:

SUBJECT:

STREAM:

RECURRENCE INTERVAL FOR ANALYSIS:

MAIN CHANNEL CONTRACTION SCOUR

Refer to: HEC-18 - Section 6 Scour Analysis

STRUCTURE TYPE FOR ANALYSIS

Select one

Choose structure type for contraction scour analysis: Bridge

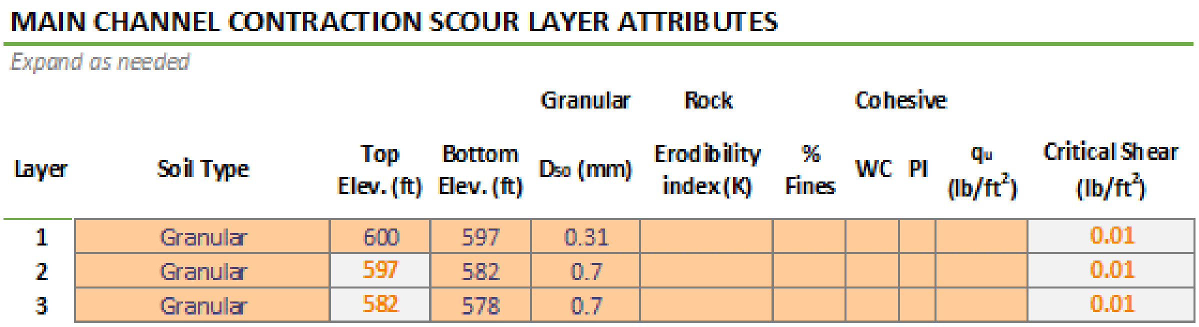
STREAM ATTRIBUTES

Include pressure flow analysis?		No
Do NOT complete pressure flow analysis section		
Average main channel upstream flow depth (ft)	y_1=	8.6
Existing depth in contracted section before scour (ft)	y_0=	7.1
Stream bed initial shear stress (lb/ft^2)	τ=	6.91
Average upstream channel velocity (ft/s)	V_1=	9.86
Contracted section flow velocity (ft/s)	V_2=	19.59
Flow in upstream channel (ft^3/s)	Q_1=	27300
Flow in contracted channel [discharge through bridge] (ft^3/s)	Q_2=	27300
Non-floodplain flow through bridge		
Bottom width in upstream main channel (ft)	W_1=	322
Bottom width in contracted main channel (ft)	W_2=	118.25
Subtract pier widths for contracted bottom width		
Streambed elevation (ft)	Z=	600
Manning's n for channel	n=	0.035

SCOUR CONDITION: LIVE-BED CHECK

Check if live-bed conditions exist in first streambed layer		
Slope of energy grade line of main channel (ft/ft)	S_1=	0.004
First Streambed Soil Type		Granular
First Streambed layer (mm)=	D_{50}=	0.31
Initial Scour Condition		Live-Bed
Shear velocity (ft/s)	V_*=	1.05
Fall velocity (m/s)	ω=	0.04
Fall velocity (ft/s)	ω=	0.14
Check fall velocity with HEC-18 Fig. 6.8 below. All data corresponds to T=20°C		
Live-bed contraction scour exponent	k_1=	0.69

Figure 20: Main Channel Contraction Scour Example Using HEC-18 Example 6.6.1 Data

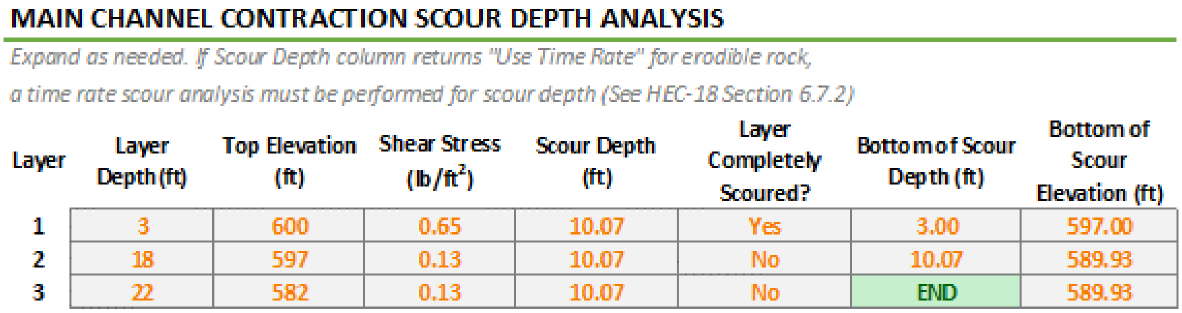


MAIN CHANNEL CONTRACTION SCOUR LAYER ATTRIBUTES

Expand as needed

				Granular	Rock		Cohesive			
Layer	Soil Type	Top Elev. (ft)	Bottom Elev. (ft)	D_{50} (mm)	Erodibility index (K)	% Fines	WC	PI	q_u (lb/ft^2)	Critical Shear (lb/ft^2)
1	Granular	600	597	0.31						0.01
2	Granular	597	582	0.7						0.01
3	Granular	582	578	0.7						0.01

Figure 21: Layer Attribute Data for Streambed Material Using HEC-18 Example 6.6.1



MAIN CHANNEL CONTRACTION SCOUR DEPTH ANALYSIS

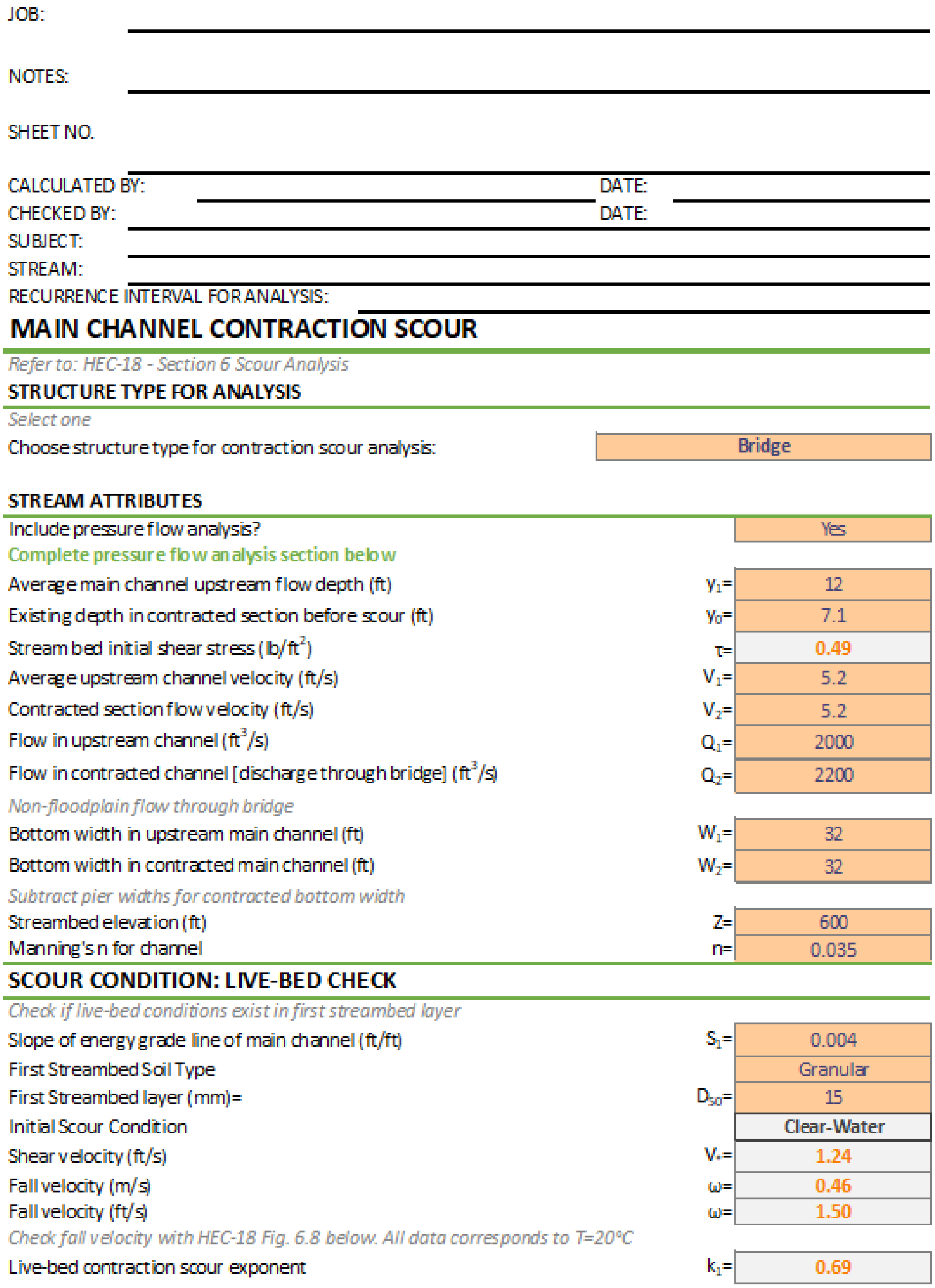
Expand as needed. If Scour Depth column returns "Use Time Rate" for erodible rock,
a time rate scour analysis must be performed for scour depth (See HEC-18 Section 6.7.2)

Layer	Layer Depth (ft)	Top Elevation (ft)	Shear Stress (lb/ft^2)	Scour Depth (ft)	Layer Completely Scoured?	Bottom of Scour Depth (ft)	Bottom of Scour Elevation (ft)
1	3	600	0.65	10.07	Yes	3.00	597.00
2	18	597	0.13	10.07	No	10.07	589.93
3	22	582	0.13	10.07	No	END	589.93

Figure 22: Scour Depth Analysis Data for HEC-18 Example 6.6.1

4.1.2 Main Channel Contraction Scour: Clear-Water with Pressure Flow and Overtopping

Using data from HEC-18 section 6.10.2 example 4, main channel contraction scour with pressure flow and overtopping is evaluated with the scour analysis tool. All applicable parameters are discussed in Sections 2.2 and 2.2.2.1. The input data in this example can be seen in Figure 23 and Figure 24. Input and output for the layers can be seen in Figure 25 and Figure 26 , respectively.



JOB:

NOTES:

SHEET NO.

CALCULATED BY: DATE:

CHECKED BY: DATE:

SUBJECT:

STREAM:

RECURRENCE INTERVAL FOR ANALYSIS:

MAIN CHANNEL CONTRACTION SCOUR

Refer to: HEC-18 - Section 6 Scour Analysis

STRUCTURE TYPE FOR ANALYSIS

Select one

Choose structure type for contraction scour analysis:	Bridge

STREAM ATTRIBUTES

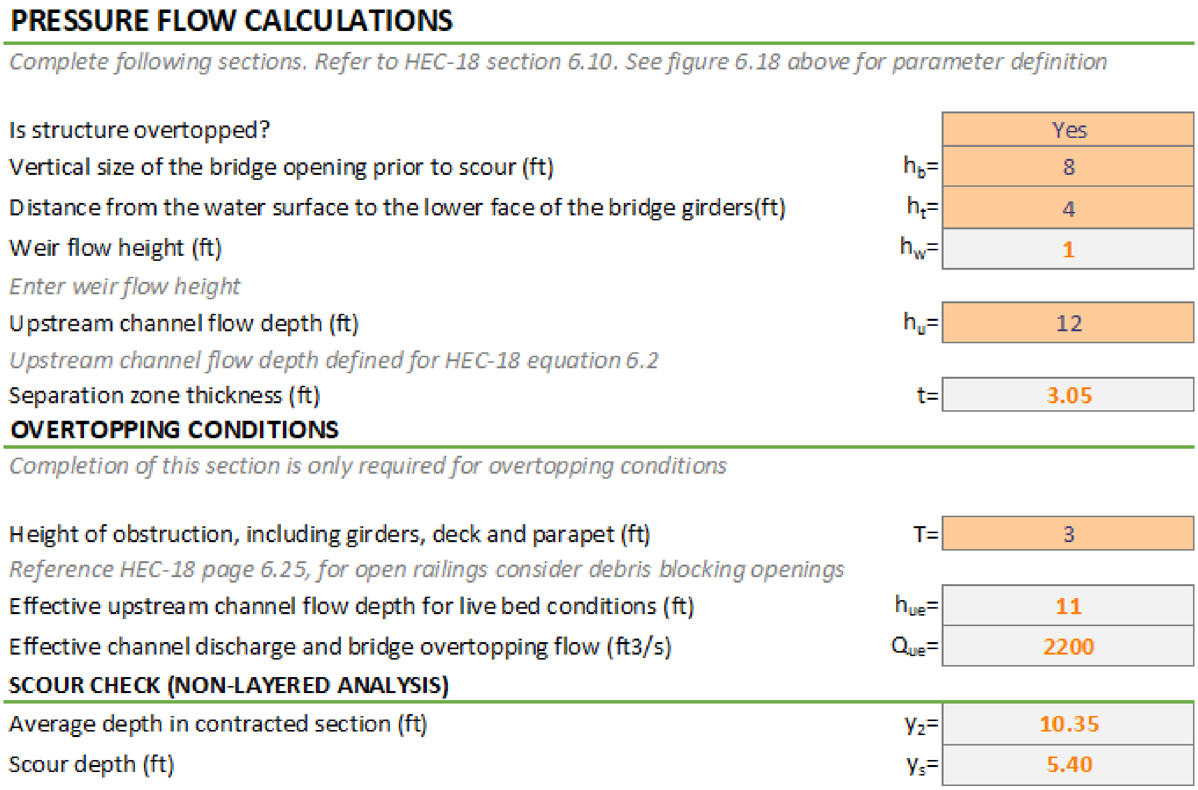
Include pressure flow analysis?		Yes
Complete pressure flow analysis section below		
Average main channel upstream flow depth (ft)	y_1=	12
Existing depth in contracted section before scour (ft)	y_0=	7.1
Stream bed initial shear stress (lb/ft^2)	τ=	0.49
Average upstream channel velocity (ft/s)	V_1=	5.2
Contracted section flow velocity (ft/s)	V_2=	5.2
Flow in upstream channel (ft^3/s)	Q_1=	2000
Flow in contracted channel [discharge through bridge] (ft^3/s)	Q_2=	2200
Non-floodplain flow through bridge		
Bottom width in upstream main channel (ft)	W_1=	32
Bottom width in contracted main channel (ft)	W_2=	32
Subtract pier widths for contracted bottom width		
Streambed elevation (ft)	Z=	600
Manning's n for channel	n=	0.035

SCOUR CONDITION: LIVE-BED CHECK

Check if live-bed conditions exist in first streambed layer

Slope of energy grade line of main channel (ft/ft)	S_1=	0.004
First Streambed Soil Type		Granular
First Streambed layer (mm)=	D_{50}=	15
Initial Scour Condition		Clear-Water
Shear velocity (ft/s)	V_*=	1.24
Fall velocity (m/s)	ω=	0.46
Fall velocity (ft/s)	ω=	1.50
Check fall velocity with HEC-18 Fig. 6.8 below. All data corresponds to T=20°C		
Live-bed contraction scour exponent	k_1=	0.69

Figure 23: Clear-Water Main Channel Contraction Scour with Pressure Flow and Overtopping



PRESSURE FLOW CALCULATIONS

Complete following sections. Refer to HEC-18 section 6.10. See figure 6.18 above for parameter definition

Is structure overtopped? Yes

Vertical size of the bridge opening prior to scour (ft) h_b= 8

Distance from the water surface to the lower face of the bridge girders(ft) h_t= 4

Weir flow height (ft) h_w= 1

Enter weir flow height

Upstream channel flow depth (ft) h_u= 12

Upstream channel flow depth defined for HEC-18 equation 6.2

Separation zone thickness (ft) t= 3.05

OVERTOPPING CONDITIONS

Completion of this section is only required for overtopping conditions

Height of obstruction, including girders, deck and parapet (ft) T= 3

Reference HEC-18 page 6.25, for open railings consider debris blocking openings

Effective upstream channel flow depth for live bed conditions (ft) h_{ue}= 11

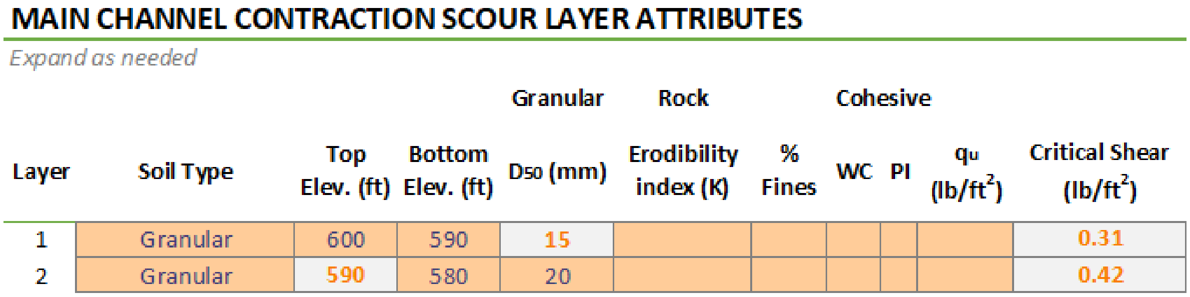
Effective channel discharge and bridge overtopping flow (ft3/s) Q_{ue}= 2200

SCOUR CHECK (NON-LAYERED ANALYSIS)

Average depth in contracted section (ft) y_2= 10.35

Scour depth (ft) y_s= 5.40

Figure 24: Clear-Water Contraction Scour Example Continued. Computation of Pressure Flow.

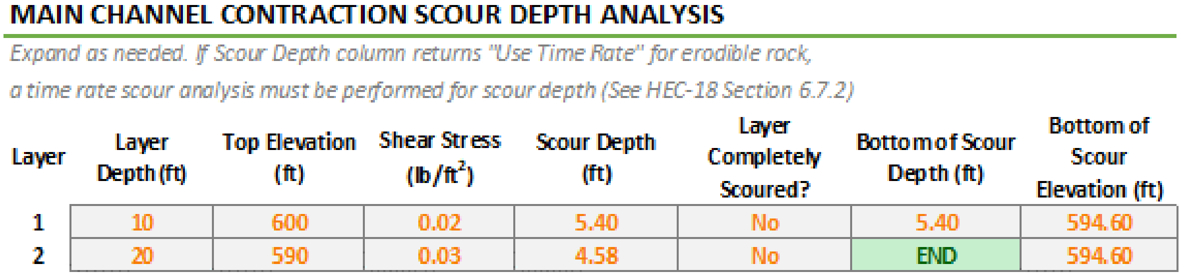


MAIN CHANNEL CONTRACTION SCOUR LAYER ATTRIBUTES

Expand as needed

				Granular	Rock		Cohesive			
Layer	Soil Type	Top Elev. (ft)	Bottom Elev. (ft)	D_{50} (mm)	Erodibility index (K)	% Fines	WC	PI	qu (lb/ft^2)	Critical Shear (lb/ft^2)
1	Granular	600	590	15						0.31
2	Granular	590	580	20						0.42

Figure 25: Layer Input for Clear-Water Pressure Flow Contraction Scour



MAIN CHANNEL CONTRACTION SCOUR DEPTH ANALYSIS

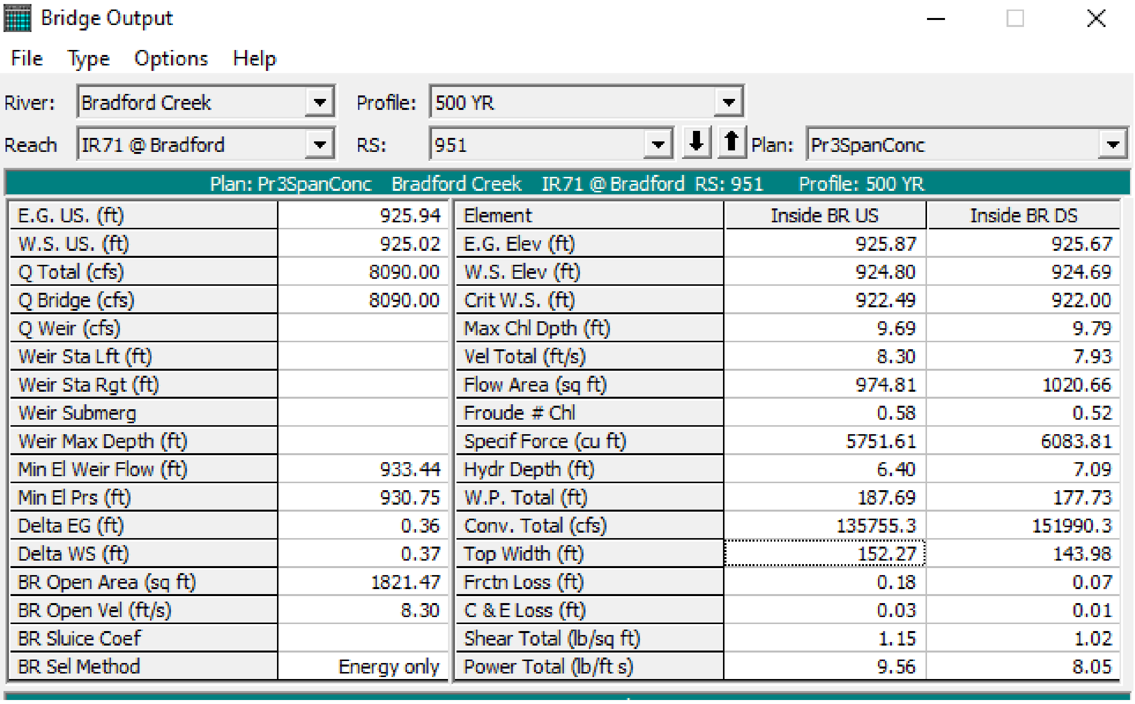
Expand as needed. If Scour Depth column returns "Use Time Rate" for erodible rock, a time rate scour analysis must be performed for scour depth (See HEC-18 Section 6.7.2)

Layer	Layer Depth (ft)	Top Elevation (ft)	Shear Stress (lb/ft^2)	Scour Depth (ft)	Layer Completely Scoured?	Bottom of Scour Depth (ft)	Bottom of Scour Elevation (ft)
1	10	600	0.02	5.40	No	5.40	594.60
2	20	590	0.03	4.58	No	END	594.60

Figure 26: Layer Output for Pressure Flow Scour

4.1.3 Main Channel Contraction Scour: Layered Analysis

Using soil layer data from E.L. Robinson's MAD/PIC-71-4.56/0.00 Exploration Report: Borehole Exploration ID B-029-3-20 and data from the accompanying HEC-RAS file a main channel contraction analysis was completed. For this analysis, a 500-year storm event for Bradford Creek was used to assess scour at the structure. Model output used in the analysis can be seen below in Figure 27 for the bridge and Figure 28 for the upstream cross-section.



River: Bradford Creek

Profile: 500 YR

Reach IR71 @ Bradford

RS: 951

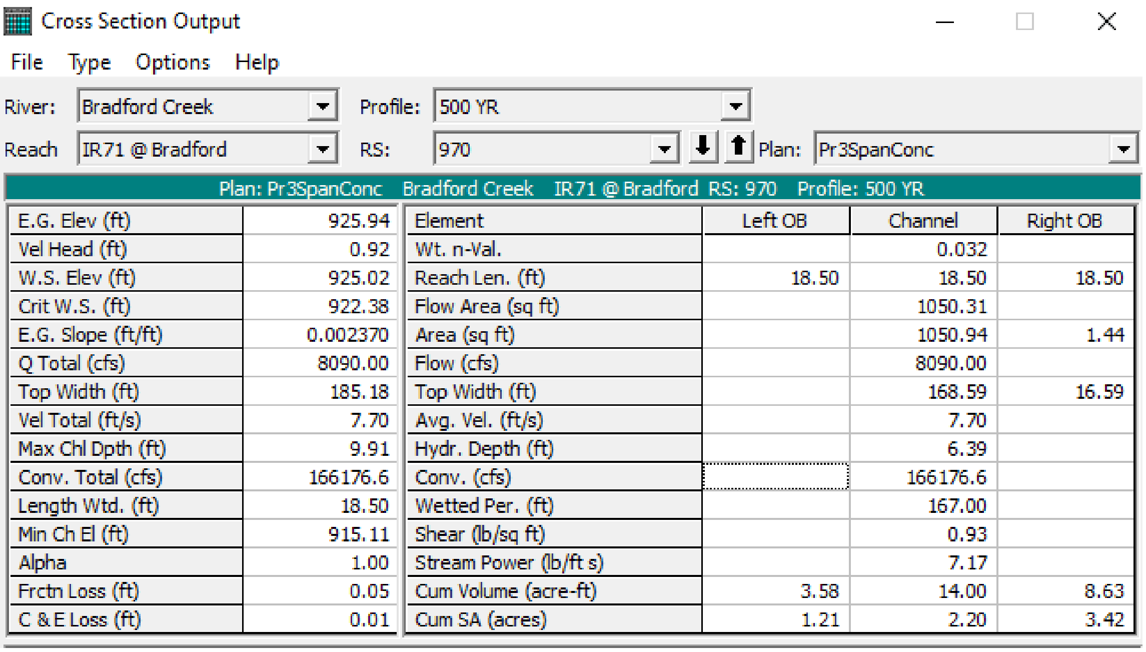
Plan: Pr3SpanConc

Plan: Pr3SpanConc Bradford Creek IR71 @ Bradford RS: 951 Profile: 500 YR

E.G. US. (ft)	925.94
W.S. US. (ft)	925.02
Q Total (cfs)	8090.00
Q Bridge (cfs)	8090.00
Q Weir (cfs)	
Weir Sta Lft (ft)	
Weir Sta Rgt (ft)	
Weir Submerg	
Weir Max Depth (ft)	
Min El Weir Flow (ft)	933.44
Min El Prs (ft)	930.75
Delta EG (ft)	0.36
Delta WS (ft)	0.37
BR Open Area (sq ft)	1821.47
BR Open Vel (ft/s)	8.30
BR Sluice Coef	
BR Sel Method	Energy only

Element	Inside BR US	Inside BR DS
E.G. Elev (ft)	925.87	925.67
W.S. Elev (ft)	924.80	924.69
Crit W.S. (ft)	922.49	922.00
Max Chl Dpth (ft)	9.69	9.79
Vel Total (ft/s)	8.30	7.93
Flow Area (sq ft)	974.81	1020.66
Froude # Chl	0.58	0.52
Specif Force (cu ft)	5751.61	6083.81
Hydr Depth (ft)	6.40	7.09
W.P. Total (ft)	187.69	177.73
Conv. Total (cfs)	135755.3	151990.3
Top Width (ft)	152.27	143.98
Frctn Loss (ft)	0.18	0.07
C & E Loss (ft)	0.03	0.01
Shear Total (lb/sq ft)	1.15	1.02
Power Total (lb/ft s)	9.56	8.05

Figure 27: HEC-RAS Bridge Output Data from Steady State Simulation



River: Bradford Creek
Profile: 500 YR
Reach IR71 @ Bradford
RS: 970
Plan: Pr3SpanConc

Plan: Pr3SpanConc Bradford Creek IR71 @ Bradford RS: 970 Profile: 500 YR

E.G. Elev (ft)	925.94
Vel Head (ft)	0.92
W.S. Elev (ft)	925.02
Crit W.S. (ft)	922.38
E.G. Slope (ft/ft)	0.002370
Q Total (cfs)	8090.00
Top Width (ft)	185.18
Vel Total (ft/s)	7.70
Max Chl Dpth (ft)	9.91
Conv. Total (cfs)	166176.6
Length Wtd. (ft)	18.50
Min Ch El (ft)	915.11
Alpha	1.00
Frctn Loss (ft)	0.05
C & E Loss (ft)	0.01

Element	Left OB	Channel	Right OB
Wt. n-Val.		0.032	
Reach Len. (ft)	18.50	18.50	18.50
Flow Area (sq ft)		1050.31	
Area (sq ft)		1050.94	1.44
Flow (cfs)		8090.00	
Top Width (ft)		168.59	16.59
Avg. Vel. (ft/s)		7.70	
Hydr. Depth (ft)		6.39	
Conv. (cfs)		166176.6	
Wetted Per. (ft)		167.00	
Shear (lb/sq ft)		0.93	
Stream Power (lb/ft s)		7.17	
Cum Volume (acre-ft)	3.58	14.00	8.63
Cum SA (acres)	1.21	2.20	3.42

Figure 28: HEC-RAS Upstream Cross-section Output

Geometric data for the bridge cross-section can be seen in Figure 29 soil bore hole data can be found in Figure 30. Finally, input and output from the scour prediction tool can be seen in Figure 31, Figure 32, and Figure 33. For this example, the initial computed scour depth exceeded the first layer. The initial scour depth was computed as 4.70 feet and the layer was only 2.5 feet thick. However, it was found that the critical shear stress of the second layer was greater than the bed shear once the bed shear was recomputed with the increase in depth after the first layer was scoured. Therefore, only the first 2.5 foot thick layer was scoured.

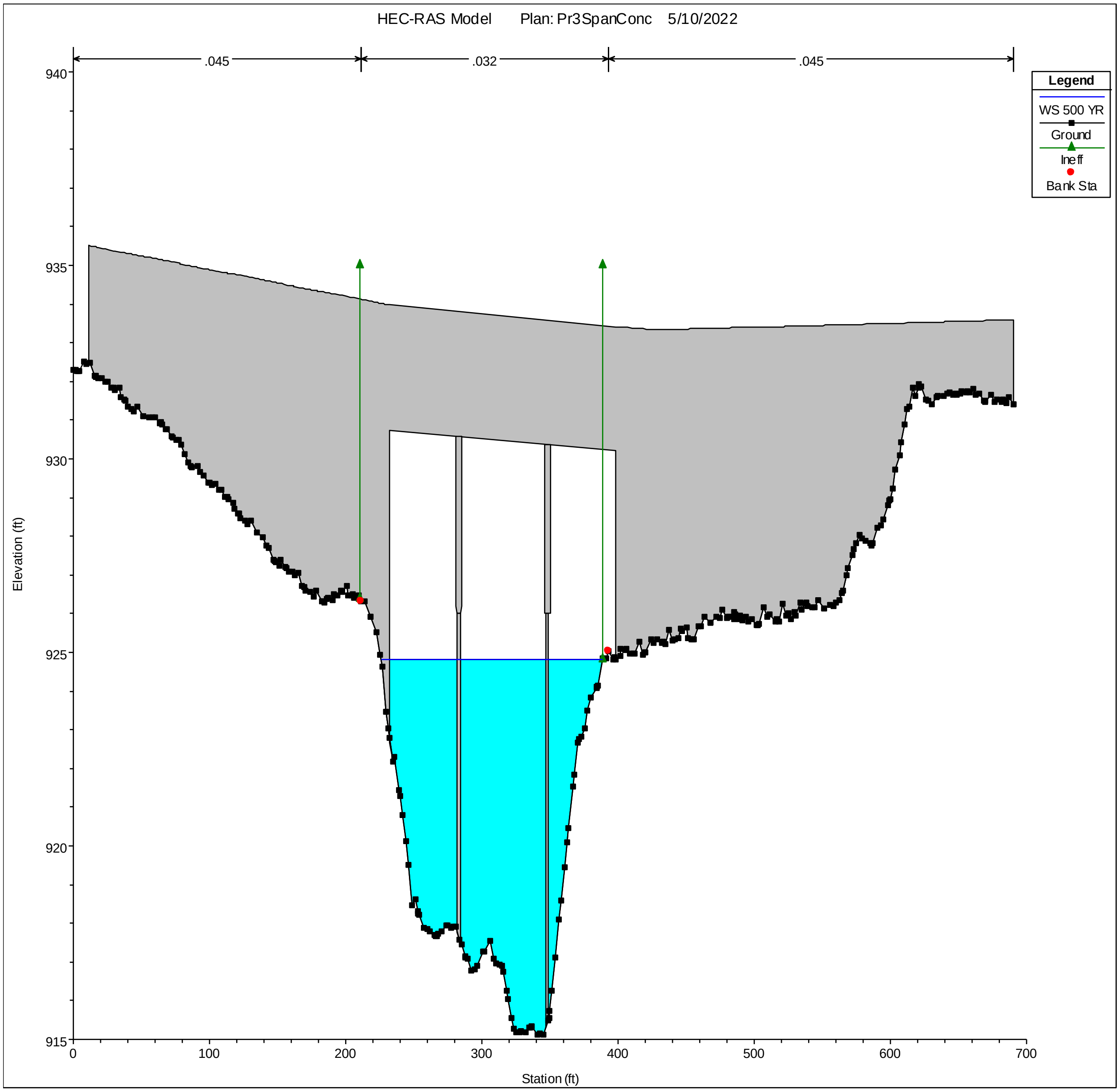
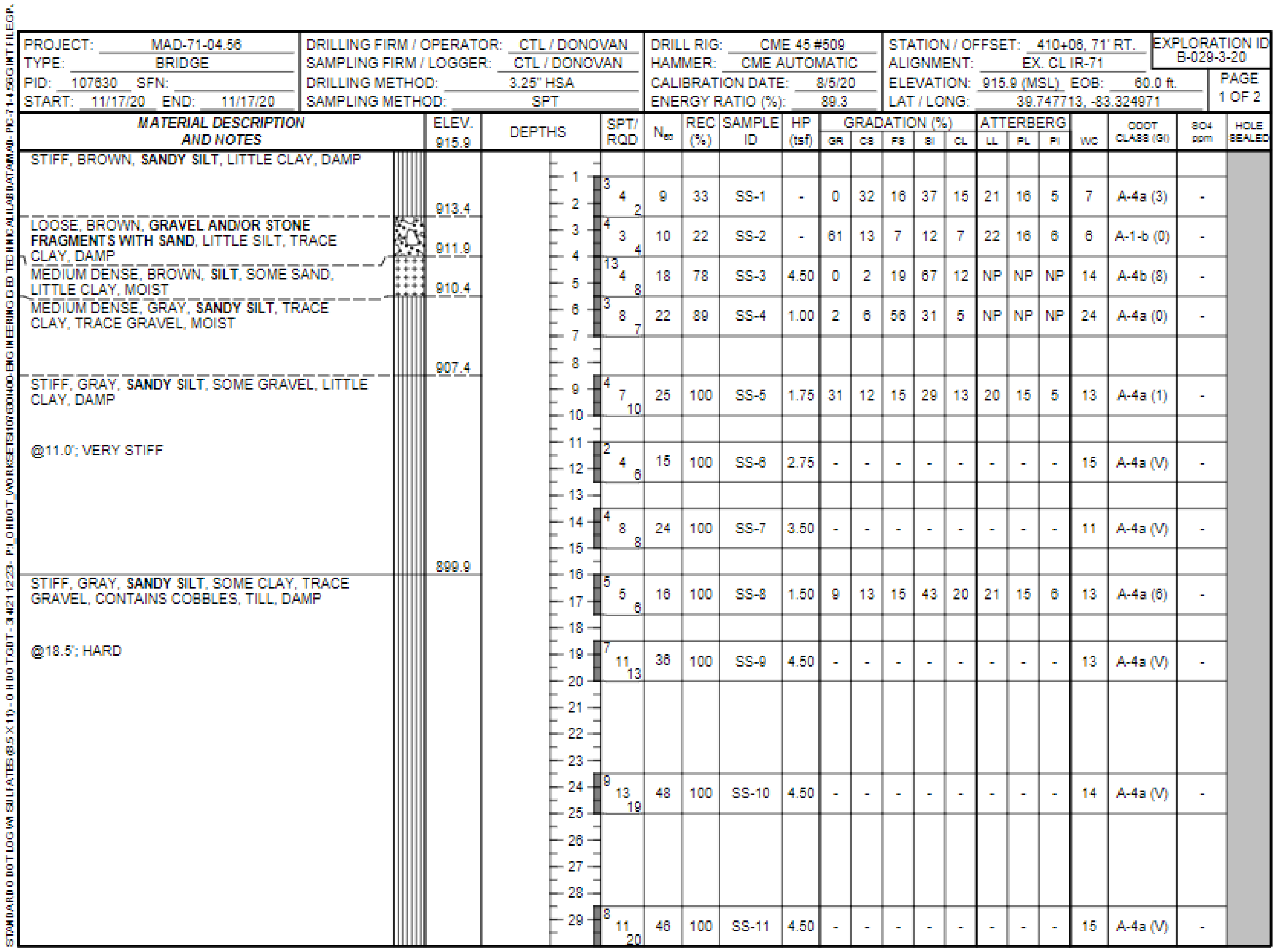


Figure 29: HEC-RAS Bridge Geometry for Scour Analysis at MAD-71-4.56

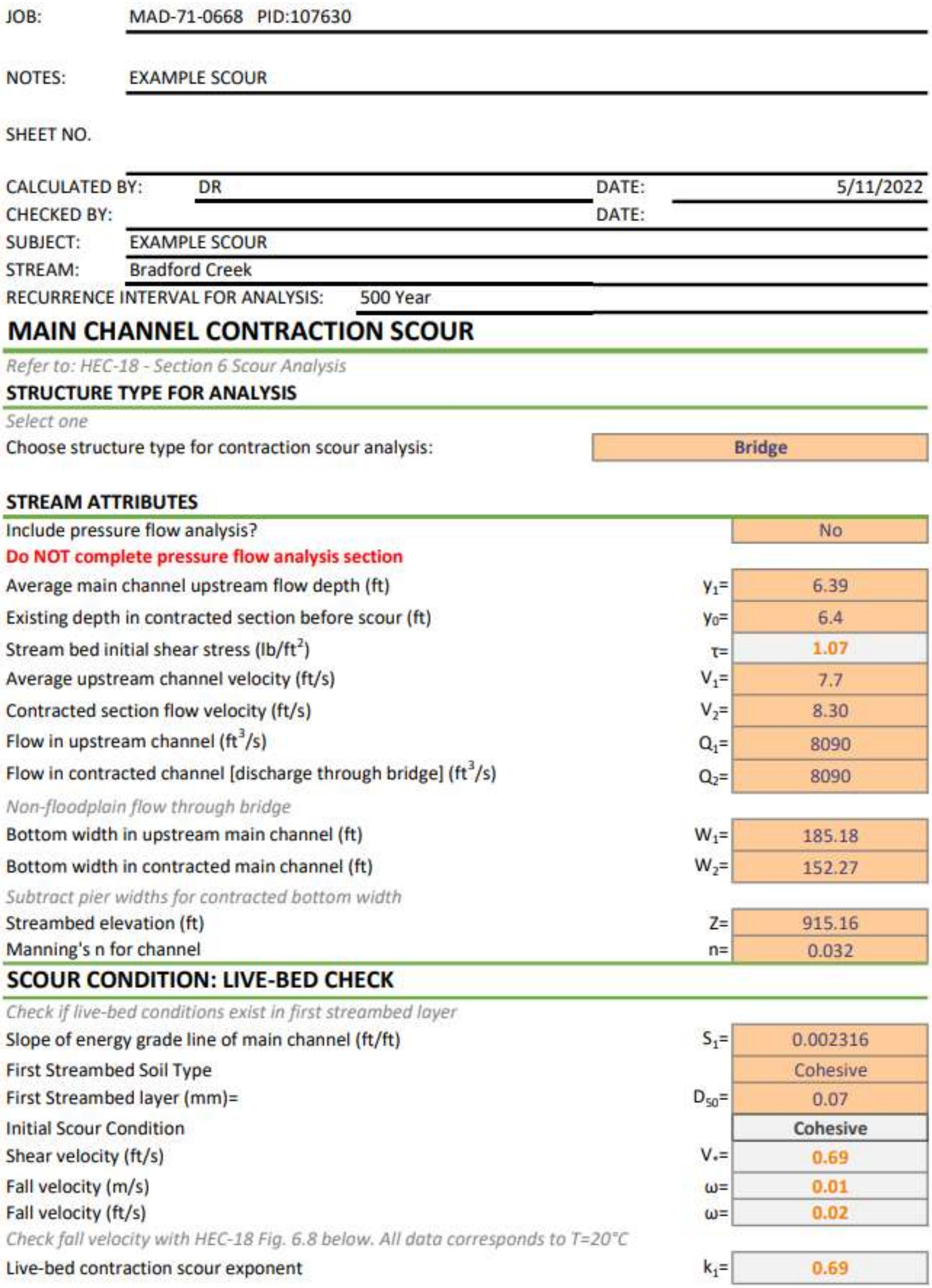


STANDARD ODOT LOG W/ SULFATES (8.5 X 11) - OH DOT.GDT - 3/4/21 12:23 - P:\OHDOT WORKSETS\107630\400-ENGINEERING\GEOTECHNICAL\LAB DATA\MAD-PC-71-4.56GINT FILE.GP.

PROJECT: MAD-71-04.56	DRILLING FIRM / OPERATOR: CTL / DONOVAN	DRILL RIG: CME 45 #509	STATION / OFFSET: 410+06, 71' RT.	EXPLORATION ID B-029-3-20
TYPE: BRIDGE	SAMPLING FIRM / LOGGER: CTL / DONOVAN	HAMMER: CME AUTOMATIC	ALIGNMENT: EX. CL IR-71	
PID: 107630 SFN:	DRILLING METHOD: 3.25" HSA	CALIBRATION DATE: 8/5/20	ELEVATION: 915.9 (MSL) EOB: 60.0 ft.	PAGE 1 OF 2
START: 11/17/20 END: 11/17/20	SAMPLING METHOD: SPT	ENERGY RATIO (%): 89.3	LAT / LONG: 39.747713, -83.324971	

MATERIAL DESCRIPTION AND NOTES	ELEV. 915.9	DEPTHS	SPT/ RQD	N_{60}	REC (%)	SAMPLE ID	HP (tsf)	GRADATION (%) GR	CS	FS	SI	CL	ATTERBERG LL	PL	PI	WC	ODOT CLASS (GI)	SO4 ppm	HOLE SEALED
STIFF, BROWN, **SANDY SILT**, LITTLE CLAY, DAMP	913.4	1 2	3 4 2	9	33	SS-1	-	0	32	16	37	15	21	16	5	7	A-4a (3)	-	
LOOSE, BROWN, **GRAVEL AND/OR STONE FRAGMENTS WITH SAND**, LITTLE SILT, TRACE CLAY, DAMP	911.9	3 4	4 3 4	10	22	SS-2	-	61	13	7	12	7	22	16	6	6	A-1-b (0)	-	
MEDIUM DENSE, BROWN, **SILT**, SOME SAND, LITTLE CLAY, MOIST	910.4	5	13 4 8	18	78	SS-3	4.50	0	2	19	67	12	NP	NP	NP	14	A-4b (8)	-	
MEDIUM DENSE, GRAY, **SANDY SILT**, TRACE CLAY, TRACE GRAVEL, MOIST	907.4	6 7 8	3 8 7	22	89	SS-4	1.00	2	6	56	31	5	NP	NP	NP	24	A-4a (0)	-	
STIFF, GRAY, **SANDY SILT**, SOME GRAVEL, LITTLE CLAY, DAMP		9 10	4 7 10	25	100	SS-5	1.75	31	12	15	29	13	20	15	5	13	A-4a (1)	-	
@11.0'; VERY STIFF		11 12 13	2 4 6	15	100	SS-6	2.75	-	-	-	-	-	-	-	-	15	A-4a (V)	-	
	899.9	14 15	4 8 8	24	100	SS-7	3.50	-	-	-	-	-	-	-	-	11	A-4a (V)	-	
STIFF, GRAY, **SANDY SILT**, SOME CLAY, TRACE GRAVEL, CONTAINS COBBLES, TILL, DAMP		16 17 18	5 5 6	16	100	SS-8	1.50	9	13	15	43	20	21	15	6	13	A-4a (6)	-	
@18.5'; HARD		19 20 21 22 23	7 11 13	36	100	SS-9	4.50	-	-	-	-	-	-	-	-	13	A-4a (V)	-	
		24 25 26 27 28	9 13 19	48	100	SS-10	4.50	-	-	-	-	-	-	-	-	14	A-4a (V)	-	
		29	8 11 20	46	100	SS-11	4.50	-	-	-	-	-	-	-	-	15	A-4a (V)	-	

Figure 30: MAD-71-4.56 Soil Boring Data for Scour Analysis- Source: E.L. Robinson



JOB: MAD-71-0668 PID:107630

NOTES: EXAMPLE SCOUR

SHEET NO.

CALCULATED BY: DR DATE: 5/11/2022

CHECKED BY: DATE:

SUBJECT: EXAMPLE SCOUR

STREAM: Bradford Creek

RECURRENCE INTERVAL FOR ANALYSIS: 500 Year

MAIN CHANNEL CONTRACTION SCOUR

Refer to: HEC-18 - Section 6 Scour Analysis

STRUCTURE TYPE FOR ANALYSIS

Select one

Choose structure type for contraction scour analysis:	**Bridge**

STREAM ATTRIBUTES

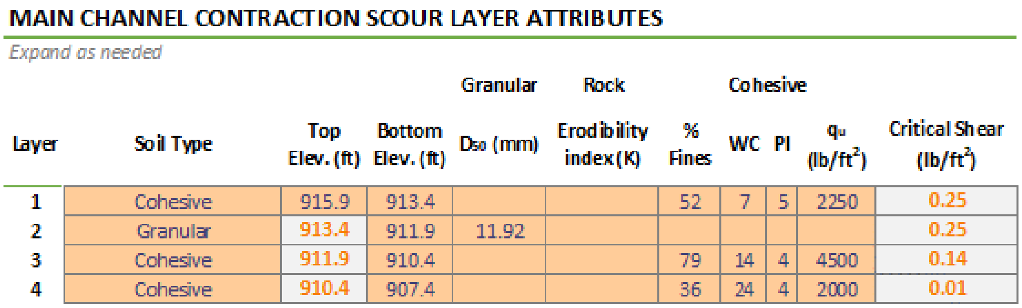
Include pressure flow analysis?		No
Do NOT complete pressure flow analysis section		
Average main channel upstream flow depth (ft)	y_1=	6.39
Existing depth in contracted section before scour (ft)	y_0=	6.4
Stream bed initial shear stress (lb/ft^2)	τ=	1.07
Average upstream channel velocity (ft/s)	V_1=	7.7
Contracted section flow velocity (ft/s)	V_2=	8.30
Flow in upstream channel (ft^3/s)	Q_1=	8090
Flow in contracted channel [discharge through bridge] (ft^3/s)	Q_2=	8090
Non-floodplain flow through bridge		
Bottom width in upstream main channel (ft)	W_1=	185.18
Bottom width in contracted main channel (ft)	W_2=	152.27
Subtract pier widths for contracted bottom width		
Streambed elevation (ft)	Z=	915.16
Manning's n for channel	n=	0.032

SCOUR CONDITION: LIVE-BED CHECK

Check if live-bed conditions exist in first streambed layer

Slope of energy grade line of main channel (ft/ft)	S_1=	0.002316
First Streambed Soil Type		Cohesive
First Streambed layer (mm)=	D_{50}=	0.07
Initial Scour Condition		**Cohesive**
Shear velocity (ft/s)	V_*=	0.69
Fall velocity (m/s)	ω=	0.01
Fall velocity (ft/s)	ω=	0.02
Check fall velocity with HEC-18 Fig. 6.8 below. All data corresponds to T=20°C		
Live-bed contraction scour exponent	k_1=	0.69

Figure 31: Scour Prediction Tool Layered Analysis Example

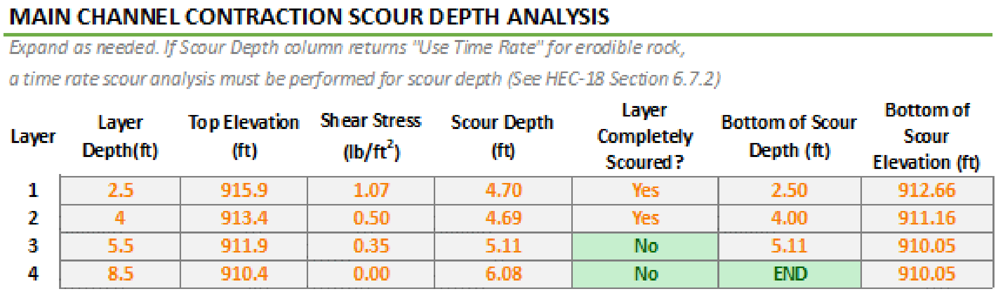


MAIN CHANNEL CONTRACTION SCOUR LAYER ATTRIBUTES

Expand as needed

				Granular	Rock	Cohesive				
Layer	Soil Type	Top Elev. (ft)	Bottom Elev. (ft)	D_{50} (mm)	Erodibility index (K)	% Fines	WC	PI	q_u (lb/ft^2)	Critical Shear (lb/ft^2)
1	Cohesive	915.9	913.4			52	7	5	2250	0.25
2	Granular	913.4	911.9	11.92						0.25
3	Cohesive	911.9	910.4			79	14	4	4500	0.14
4	Cohesive	910.4	907.4			36	24	4	2000	0.01

Figure 32: Scour Prediction Tool Soil Layer Input: Main Channel Contraction Scour



MAIN CHANNEL CONTRACTION SCOUR DEPTH ANALYSIS

Expand as needed. If Scour Depth column returns "Use Time Rate" for erodible rock, a time rate scour analysis must be performed for scour depth (See HEC-18 Section 6.7.2)

Layer	Layer Depth(ft)	Top Elevation (ft)	Shear Stress (lb/ft^2)	Scour Depth (ft)	Layer Completely Scoured?	Bottom of Scour Depth (ft)	Bottom of Scour Elevation (ft)
1	2.5	915.9	1.07	4.70	Yes	2.50	912.66
2	4	913.4	0.50	4.69	Yes	4.00	911.16
3	5.5	911.9	0.35	5.11	No	5.11	910.05
4	8.5	910.4	0.00	6.08	No	END	910.05

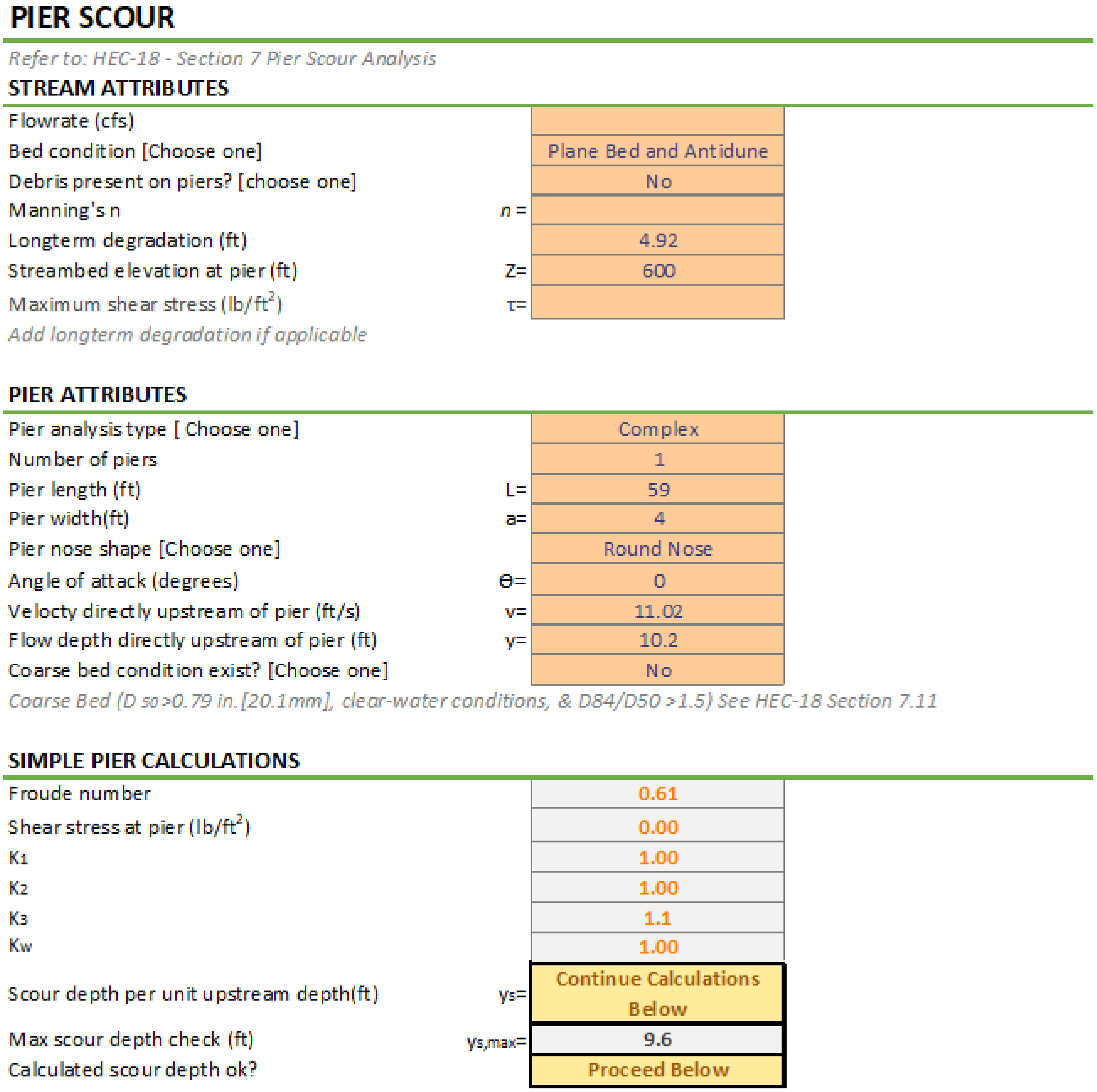
Figure 33: Scour Prediction Tool Output: Main Channel Contraction Scour

4.2 Pier Scour Example

Pier scour example data for this section is from HEC-18 section 7.10.3 “Example Problem 3-Scour at Complex Piers (Solid Pier on an Exposed Footing). These computations are considered as case 2, where the bottom of the pile cap is not exposed after assessing the initial pier stem scour. It should be noted that the HEC-18 example calculations contain an error for the pier nose shape coefficient, which inadvertently increases the pile cap scour component by 10% by increasing the pier nose shape coefficient (K_1) from 1.0 to 1.1. Input data can be seen in Figure 34 and Figure 35.

A layered analysis is performed in Section 4.2.2 using data from E.L. Robinson’s MAD/PIC-71-4.56/0.00 Exploration Report. This data is the same data as in Section 4.1.3 Figure 30.

4.2.1 Pier Scour: HEC-18 Example



PIER SCOUR

Refer to: HEC-18 - Section 7 Pier Scour Analysis

STREAM ATTRIBUTES

Flowrate (cfs)		
Bed condition [Choose one]		Plane Bed and Antidune
Debris present on piers? [choose one]		No
Manning's n	n =	
Longterm degradation (ft)		4.92
Streambed elevation at pier (ft)	Z=	600
Maximum shear stress (lb/ft^2)	τ=	

Add longterm degradation if applicable

PIER ATTRIBUTES

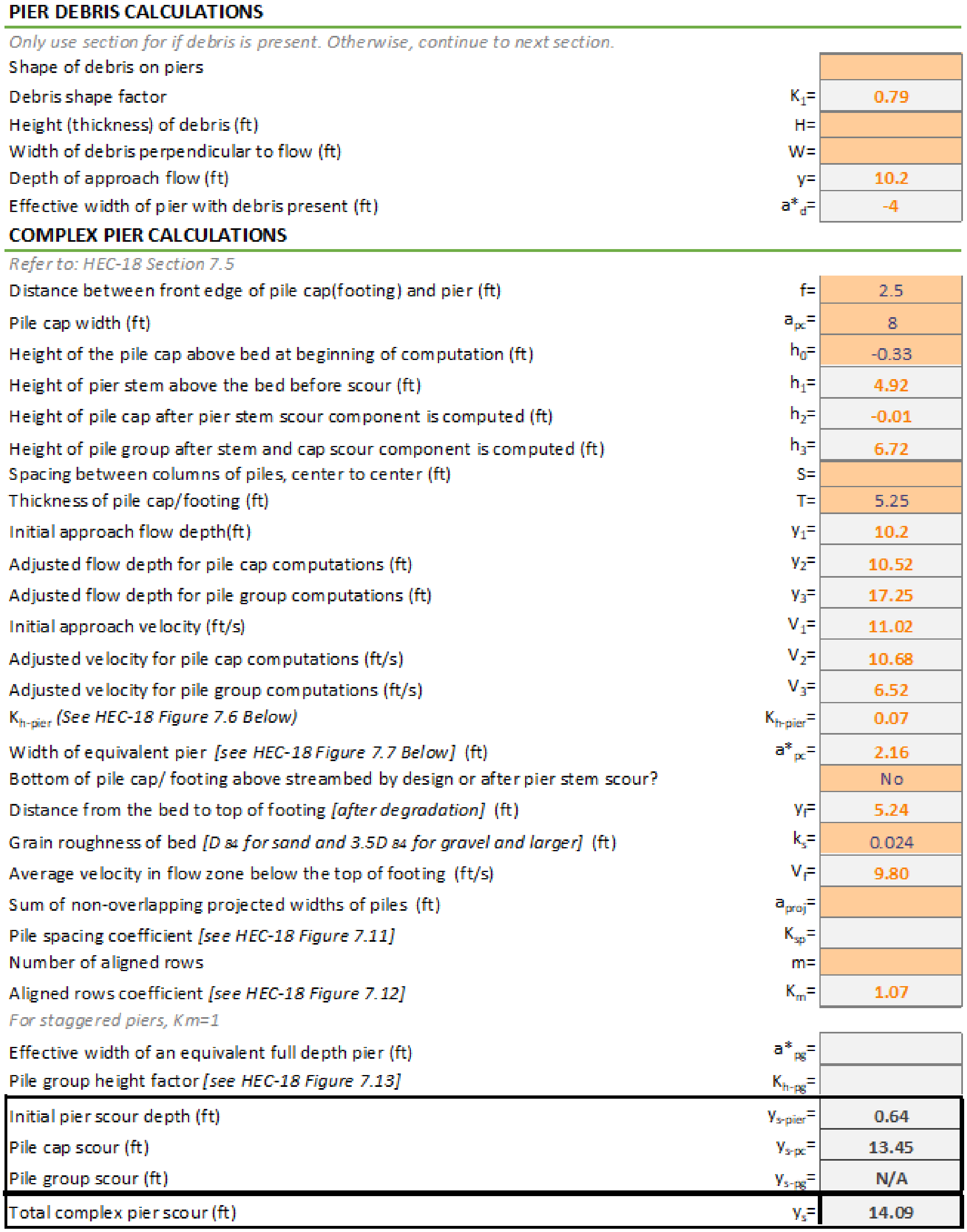
Pier analysis type [Choose one]		Complex
Number of piers		1
Pier length (ft)	L=	59
Pier width(ft)	a=	4
Pier nose shape [Choose one]		Round Nose
Angle of attack (degrees)	θ=	0
Velocty directly upstream of pier (ft/s)	v=	11.02
Flow depth directly upstream of pier (ft)	y=	10.2
Coarse bed condition exist? [Choose one]		No

Coarse Bed (D_{50}>0.79 in. [20.1mm], clear-water conditions, & D84/D50 >1.5) See HEC-18 Section 7.11

SIMPLE PIER CALCULATIONS

Froude number		0.61
Shear stress at pier (lb/ft^2)		0.00
K_1		1.00
K_2		1.00
K_3		1.1
K_w		1.00
Scour depth per unit upstream depth(ft)	y_s=	Continue Calculations Below
Max scour depth check (ft)	$y_{s,max}$=	9.6
Calculated scour depth ok?		Proceed Below

Figure 34: Complex Pier Scour Example with Exposed Footing in Flow



PIER DEBRIS CALCULATIONS

Only use section for if debris is present. Otherwise, continue to next section.

Shape of debris on piers		
Debris shape factor	K_1=	0.79
Height (thickness) of debris (ft)	H=	
Width of debris perpendicular to flow (ft)	W=	
Depth of approach flow (ft)	y=	10.2
Effective width of pier with debris present (ft)	a^*_d=	-4

COMPLEX PIER CALCULATIONS

Refer to: HEC-18 Section 7.5

Distance between front edge of pile cap(footing) and pier (ft)	f=	2.5
Pile cap width (ft)	a_{pc}=	8
Height of the pile cap above bed at beginning of computation (ft)	h_0=	-0.33
Height of pier stem above the bed before scour (ft)	h_1=	4.92
Height of pile cap after pier stem scour component is computed (ft)	h_2=	-0.01
Height of pile group after stem and cap scour component is computed (ft)	h_3=	6.72
Spacing between columns of piles, center to center (ft)	S=	
Thickness of pile cap/footing (ft)	T=	5.25
Initial approach flow depth(ft)	y_1=	10.2
Adjusted flow depth for pile cap computations (ft)	y_2=	10.52
Adjusted flow depth for pile group computations (ft)	y_3=	17.25
Initial approach velocity (ft/s)	V_1=	11.02
Adjusted velocity for pile cap computations (ft/s)	V_2=	10.68
Adjusted velocity for pile group computations (ft/s)	V_3=	6.52
$K_{h\text{-}pier}$ *(See HEC-18 Figure 7.6 Below)*	$K_{h\text{-}pier}$=	0.07
Width of equivalent pier *[see HEC-18 Figure 7.7 Below]* (ft)	a^*_{pc}=	2.16
Bottom of pile cap/ footing above streambed by design or after pier stem scour?		No
Distance from the bed to top of footing *[after degradation]* (ft)	y_f=	5.24
Grain roughness of bed *[D $_{84}$ for sand and 3.5D $_{84}$ for gravel and larger]* (ft)	k_s=	0.024
Average velocity in flow zone below the top of footing (ft/s)	V_f=	9.80
Sum of non-overlapping projected widths of piles (ft)	a_{proj}=	
Pile spacing coefficient *[see HEC-18 Figure 7.11]*	K_{sp}=	
Number of aligned rows	m=	
Aligned rows coefficient *[see HEC-18 Figure 7.12]*	K_m=	1.07

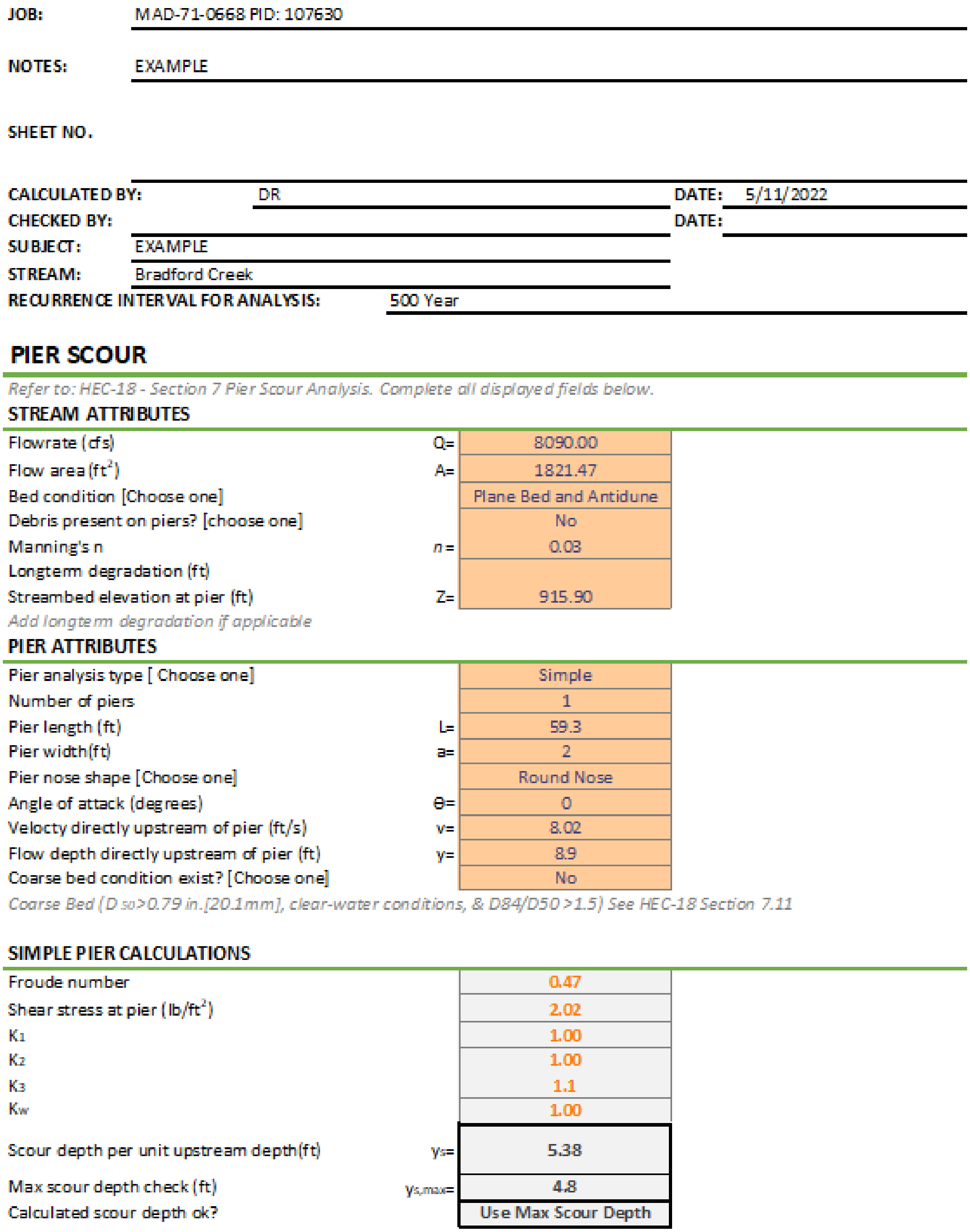
For staggered piers, Km=1

Effective width of an equivalent full depth pier (ft)	a^*_{pg}=	
Pile group height factor *[see HEC-18 Figure 7.13]*	$K_{h\text{-}pg}$=	
Initial pier scour depth (ft)	$y_{s\text{-}pier}$=	0.64
Pile cap scour (ft)	$y_{s\text{-}pc}$=	13.45
Pile group scour (ft)	$y_{s\text{-}pg}$=	N/A
Total complex pier scour (ft)	y_s=	14.09

Figure 35: Complex Pier Computations and Total Scour Output

4.2.2 Pier Scour: Layered Analysis Example

Using HEC-RAS data and soil boring data described in Section 4.1.3 above, an analysis of the right-most pier in Figure 29 is performed below. Flow depths and velocities were obtained from either RAS- Mapper output in HEC-RAS or the data in Figure 27 and Figure 28. Output from the scour prediction tool is seen in Figure 36 and Figure 38 The “maximum scour check” checks the scour computation against the upper limit defined in HEC-18: 2.4 times the pier width for Froude number less than or equal to 0.8 and no more than 3 times the pier width for Froude numbers larger than 0.8. If the computed scour depth is less than or equal to the maximum scour, the cell below “max scour depth check” will read “OK”. . In this instance, the layered analysis was needed as the computed scour depth was 5.38 feet; however, the max scour depth check gave a result of 4.80 feet. In this instance the maximum scour depth check was used. The first two layers were completely scoured, in this case, with the scour ending in the third layer.



JOB: MAD-71-0668 PID: 107630

NOTES: EXAMPLE

SHEET NO.

CALCULATED BY: DR **DATE:** 5/11/2022

CHECKED BY: **DATE:**

SUBJECT: EXAMPLE

STREAM: Bradford Creek

RECURRENCE INTERVAL FOR ANALYSIS: 500 Year

PIER SCOUR

Refer to: HEC-18 - Section 7 Pier Scour Analysis. Complete all displayed fields below.

STREAM ATTRIBUTES

Flowrate (cfs)	Q=	8090.00
Flow area (ft^2)	A=	1821.47
Bed condition [Choose one]		Plane Bed and Antidune
Debris present on piers? [choose one]		No
Manning's n	*n* =	0.03
Longterm degradation (ft)		
Streambed elevation at pier (ft)	Z=	915.90

Add longterm degradation if applicable

PIER ATTRIBUTES

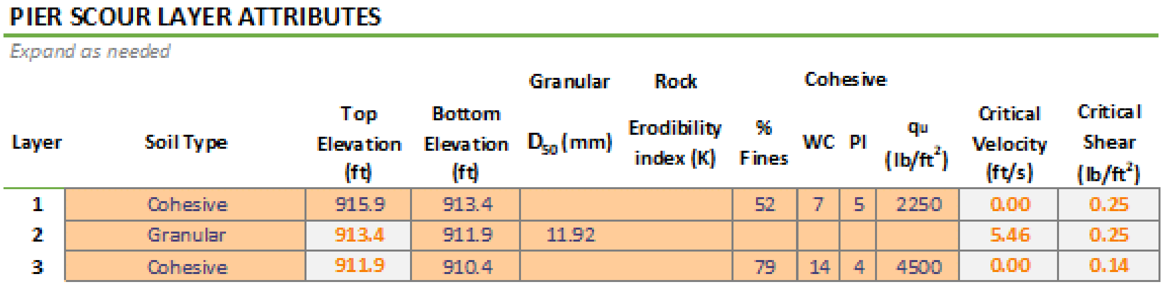
Pier analysis type [Choose one]		Simple
Number of piers		1
Pier length (ft)	L=	59.3
Pier width(ft)	a=	2
Pier nose shape [Choose one]		Round Nose
Angle of attack (degrees)	θ=	0
Velocty directly upstream of pier (ft/s)	v=	8.02
Flow depth directly upstream of pier (ft)	y=	8.9
Coarse bed condition exist? [Choose one]		No

Coarse Bed (D_{50}>0.79 in.[20.1mm], clear-water conditions, & D84/D50 >1.5) See HEC-18 Section 7.11

SIMPLE PIER CALCULATIONS

Froude number		0.47
Shear stress at pier (lb/ft^2)		2.02
K_1		1.00
K_2		1.00
K_3		1.1
K_w		1.00
Scour depth per unit upstream depth(ft)	y_s=	5.38
Max scour depth check (ft)	$y_{s,max}$=	4.8
Calculated scour depth ok?		Use Max Scour Depth

Figure 36: Layered Analysis Pier Scour Output

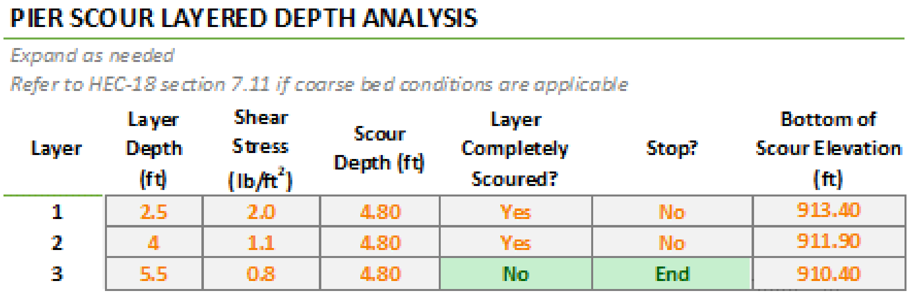


PIER SCOUR LAYER ATTRIBUTES

Expand as needed

Layer	Soil Type	Top Elevation (ft)	Bottom Elevation (ft)	Granular	Rock	Cohesive				Critical Velocity (ft/s)	Critical Shear (lb/ft^2)
				D_{50} (mm)	Erodibility index (K)	% Fines	WC	PI	qu (lb/ft^2)		
1	Cohesive	915.9	913.4			52	7	5	2250	0.00	0.25
2	Granular	913.4	911.9	11.92						5.46	0.25
3	Cohesive	911.9	910.4			79	14	4	4500	0.00	0.14

Figure 37: Pier Scour Soil Layer Input



PIER SCOUR LAYERED DEPTH ANALYSIS

Expand as needed

Refer to HEC-18 section 7.11 if coarse bed conditions are applicable

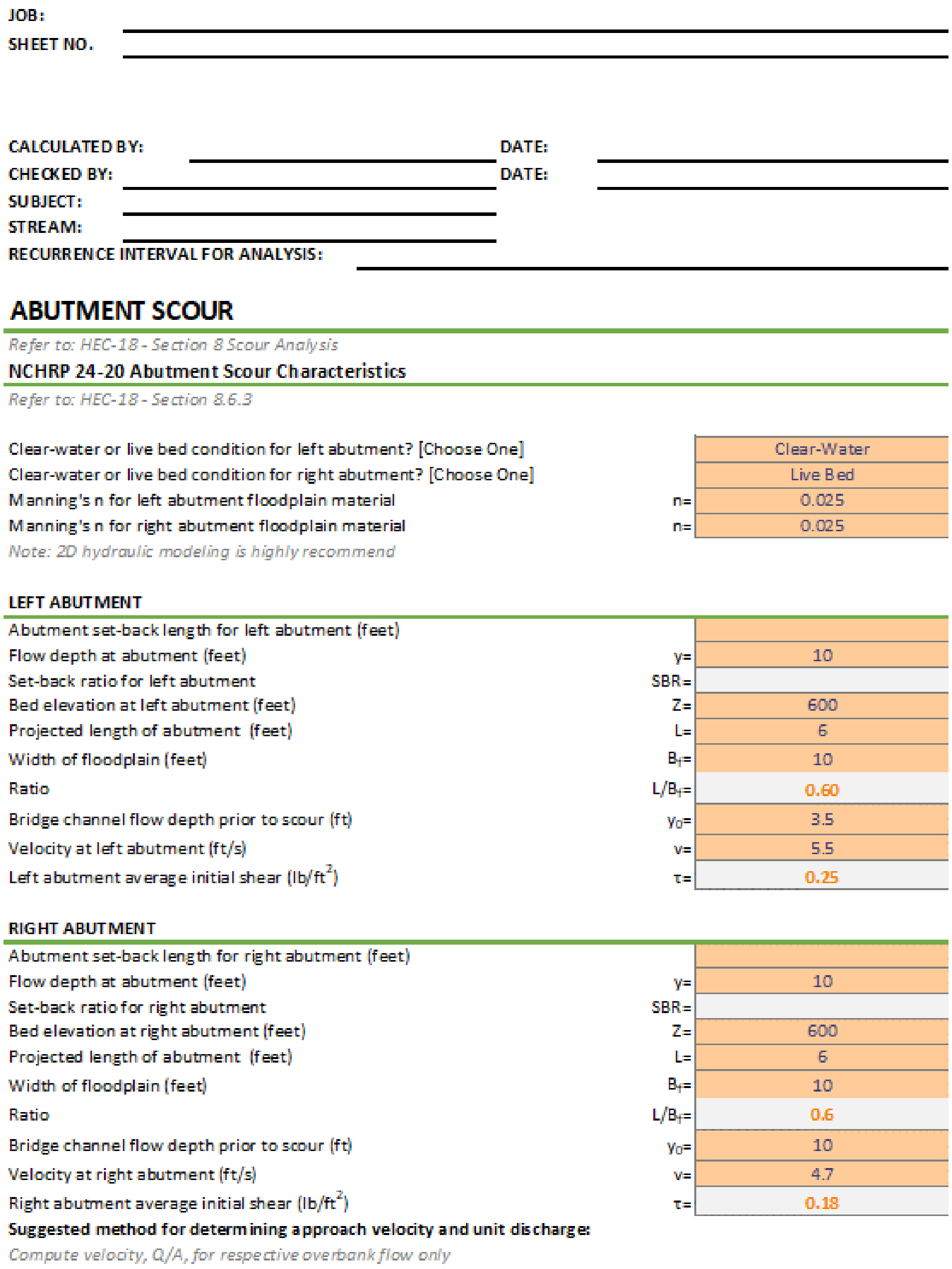
Layer	Layer Depth (ft)	Shear Stress (lb/ft^2)	Scour Depth (ft)	Layer Completely Scoured?	Stop?	Bottom of Scour Elevation (ft)
1	2.5	2.0	4.80	Yes	No	913.40
2	4	1.1	4.80	Yes	No	911.90
3	5.5	0.8	4.80	No	End	910.40

Figure 38: Pier Scour Layered Analysis Output

4.3 Abutment Scour Example

In this section we will evaluate example problems in HEC-18 (section 8.7.5 for the left abutment and section 8.7.3 for the right abutment). The left abutment is computed for clear-water conditions using the critical shear stress scour formula and the right abutment is computed with live-bed conditions. Small variations between values may be attributed to rounding errors. Additionally, a layered analysis was conducted using soil properties acquired from E.L. Robinson's MAD/PIC-71-4.56/0.00 Exploration Report: Exploration ID B-029-4-20 (Figure 46).

4.3.1 Abutment Scour: HEC-18 Examples



JOB: ____________________

SHEET NO. ____________________

CALCULATED BY: ____________________ **DATE:** ____________________

CHECKED BY: ____________________ **DATE:** ____________________

SUBJECT: ____________________

STREAM: ____________________

RECURRENCE INTERVAL FOR ANALYSIS: ____________________

ABUTMENT SCOUR

Refer to: HEC-18 - Section 8 Scour Analysis

NCHRP 24-20 Abutment Scour Characteristics

Refer to: HEC-18 - Section 8.6.3

Clear-water or live bed condition for left abutment? [Choose One]		Clear-Water
Clear-water or live bed condition for right abutment? [Choose One]		Live Bed
Manning's n for left abutment floodplain material	n=	0.025
Manning's n for right abutment floodplain material	n=	0.025

Note: 2D hydraulic modeling is highly recommend

LEFT ABUTMENT

Abutment set-back length for left abutment (feet)		
Flow depth at abutment (feet)	y=	10
Set-back ratio for left abutment	SBR=	
Bed elevation at left abutment (feet)	Z=	600
Projected length of abutment (feet)	L=	6
Width of floodplain (feet)	B_f=	10
Ratio	L/B_f=	0.60
Bridge channel flow depth prior to scour (ft)	y_0=	3.5
Velocity at left abutment (ft/s)	v=	5.5
Left abutment average initial shear (lb/ft^2)	τ=	0.25

RIGHT ABUTMENT

Abutment set-back length for right abutment (feet)		
Flow depth at abutment (feet)	y=	10
Set-back ratio for right abutment	SBR=	
Bed elevation at right abutment (feet)	Z=	600
Projected length of abutment (feet)	L=	6
Width of floodplain (feet)	B_f=	10
Ratio	L/B_f=	0.6
Bridge channel flow depth prior to scour (ft)	y_0=	10
Velocity at right abutment (ft/s)	v=	4.7
Right abutment average initial shear (lb/ft^2)	τ=	0.18

Suggested method for determining approach velocity and unit discharge:

Compute velocity, Q/A, for respective overbank flow only

Figure 39: Abutment Scour Using NCHRP Equations

LIVE BED SCOUR CONDITION RIGHT ABUTMENT- AMPLIFICATION FACTOR

Complete for live bed conditions

Right abutment type [choose one]		Wing Wall
Upstream flow depth [y1] (feet)	y1=	10
Upstream unit discharge [q1] (ft2/s)	q1=	57
Unit discharge in the constricted opening [q2c] (ft2/s)	q2c=	78.6

Note: account for non-uniform flow distribution for q2

Discharge ratio for ampification factor (q2/q1)	q2/q1=	1.38
Calculated amplifaction factor [αA]	αA=	1.71

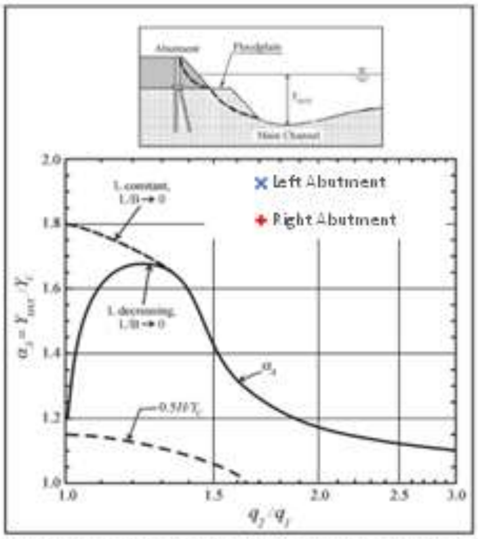


Figure 8.9. Scour amplification factor for spill-through abutments and live-bed conditions (NCHRP 2010b).

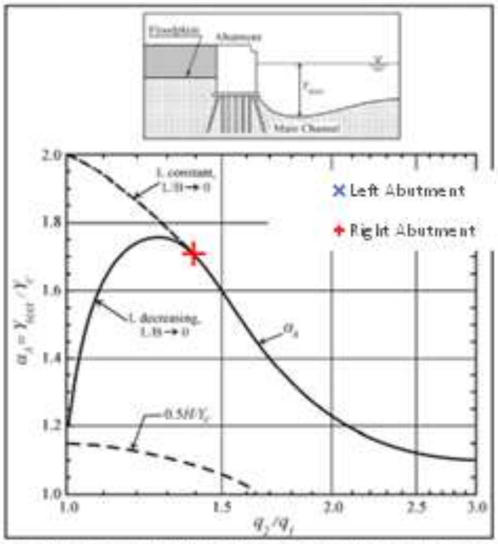
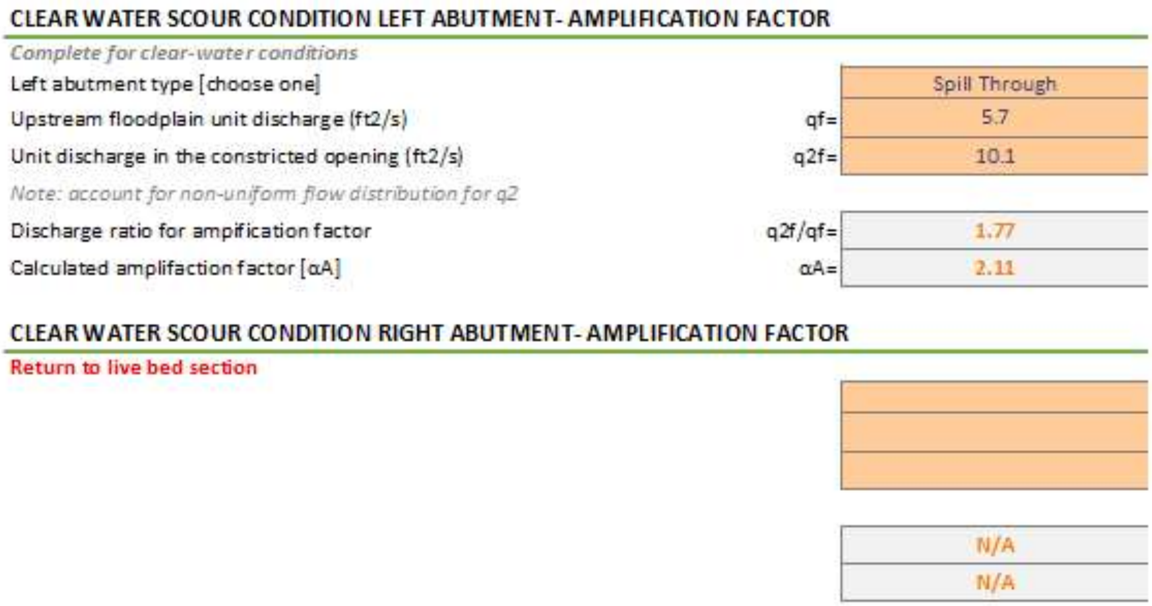


Figure 8.10. Scour amplification factor for wingwall abutments and live-bed conditions (NCHRP 2010b).

Figure 40: Scour Tool Input and Calculations for Right Abutment Scour Factors



CLEAR WATER SCOUR CONDITION LEFT ABUTMENT- AMPLIFICATION FACTOR

Complete for clear-water conditions

Left abutment type [choose one]		Spill Through
Upstream floodplain unit discharge (ft2/s)	qf=	5.7
Unit discharge in the constricted opening (ft2/s)	q2f=	10.1
Note: account for non-uniform flow distribution for q2		
Discharge ratio for ampification factor	q2f/qf=	1.77
Calculated amplifaction factor [αA]	αA=	2.11

CLEAR WATER SCOUR CONDITION RIGHT ABUTMENT- AMPLIFICATION FACTOR

Return to live bed section

N/A
N/A

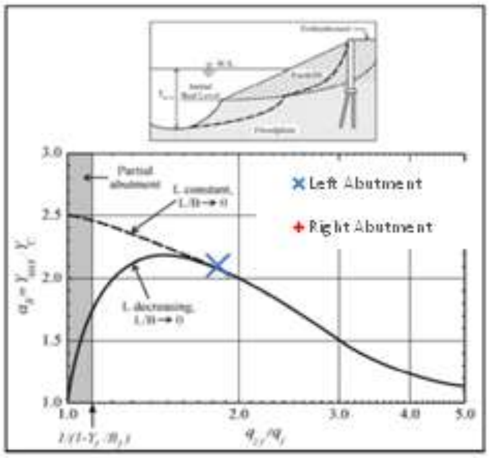


Figure 8.11. Scour amplification factor for spill-through abutments and clear-water conditions (NCHRP 2010b).

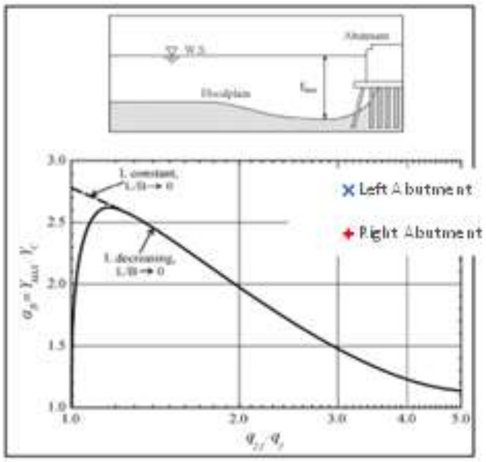
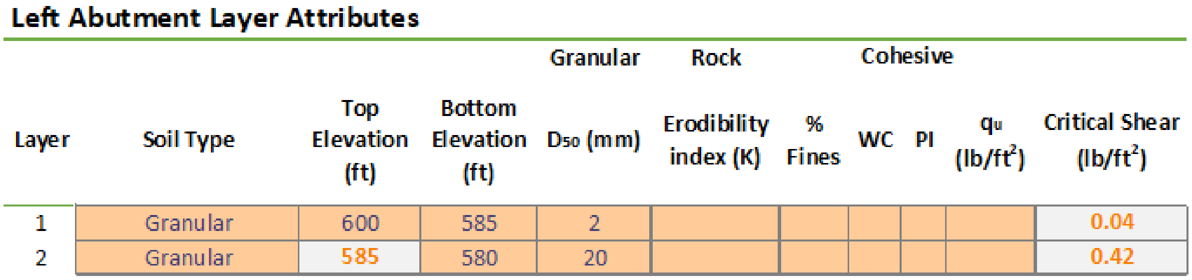


Figure 8.12. Scour amplification factor for wingwall abutments and clear-water conditions (NCHRP 2010b).

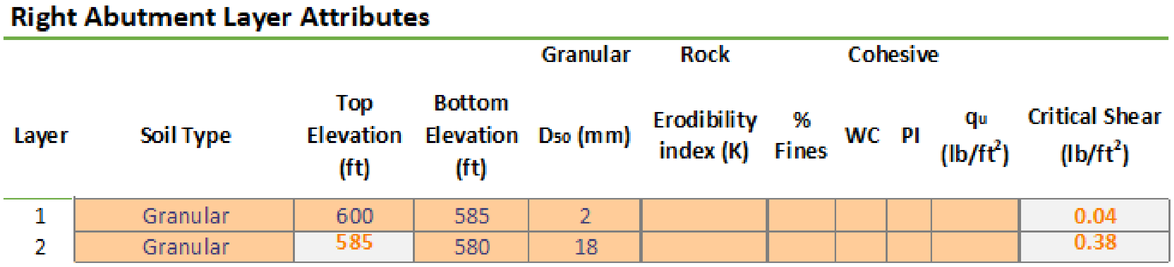
Figure 41: Left Abutment Scour Factors



Left Abutment Layer Attributes

				Granular	Rock	Cohesive				
Layer	Soil Type	Top Elevation (ft)	Bottom Elevation (ft)	D_{50} (mm)	Erodibility index (K)	% Fines	WC	PI	q_u (lb/ft^2)	Critical Shear (lb/ft^2)
1	Granular	600	585	2						0.04
2	Granular	585	580	20						0.42

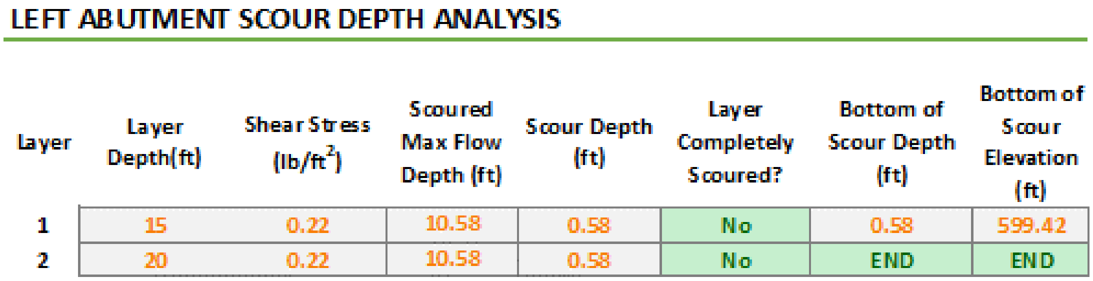
Figure 42: Streambed Material Attributes for Left Abutment with Clear-Water Conditions



Right Abutment Layer Attributes

				Granular	Rock	Cohesive				
Layer	Soil Type	Top Elevation (ft)	Bottom Elevation (ft)	D_{50} (mm)	Erodibility index (K)	% Fines	WC	PI	q_u (lb/ft^2)	Critical Shear (lb/ft^2)
1	Granular	600	585	2						0.04
2	Granular	585	580	18						0.38

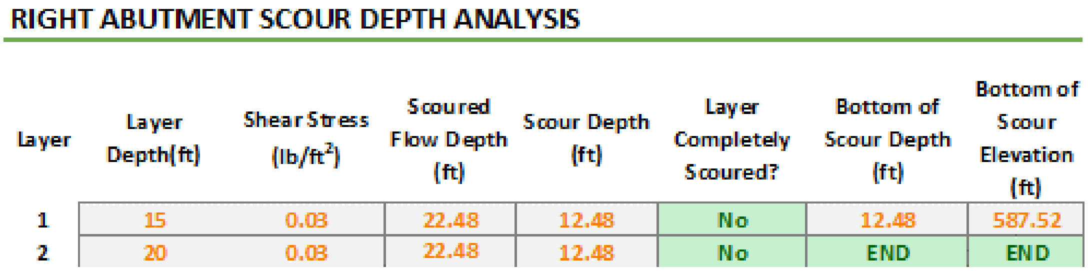
Figure 43: Streambed Material Attributes for Right Abutment with Live-Bed Conditions



LEFT ABUTMENT SCOUR DEPTH ANALYSIS

Layer	Layer Depth(ft)	Shear Stress (lb/ft^2)	Scoured Max Flow Depth (ft)	Scour Depth (ft)	Layer Completely Scoured?	Bottom of Scour Depth (ft)	Bottom of Scour Elevation (ft)
1	15	0.22	10.58	0.58	No	0.58	599.42
2	20	0.22	10.58	0.58	No	END	END

Figure 44: Left Abutment Scour Analysis



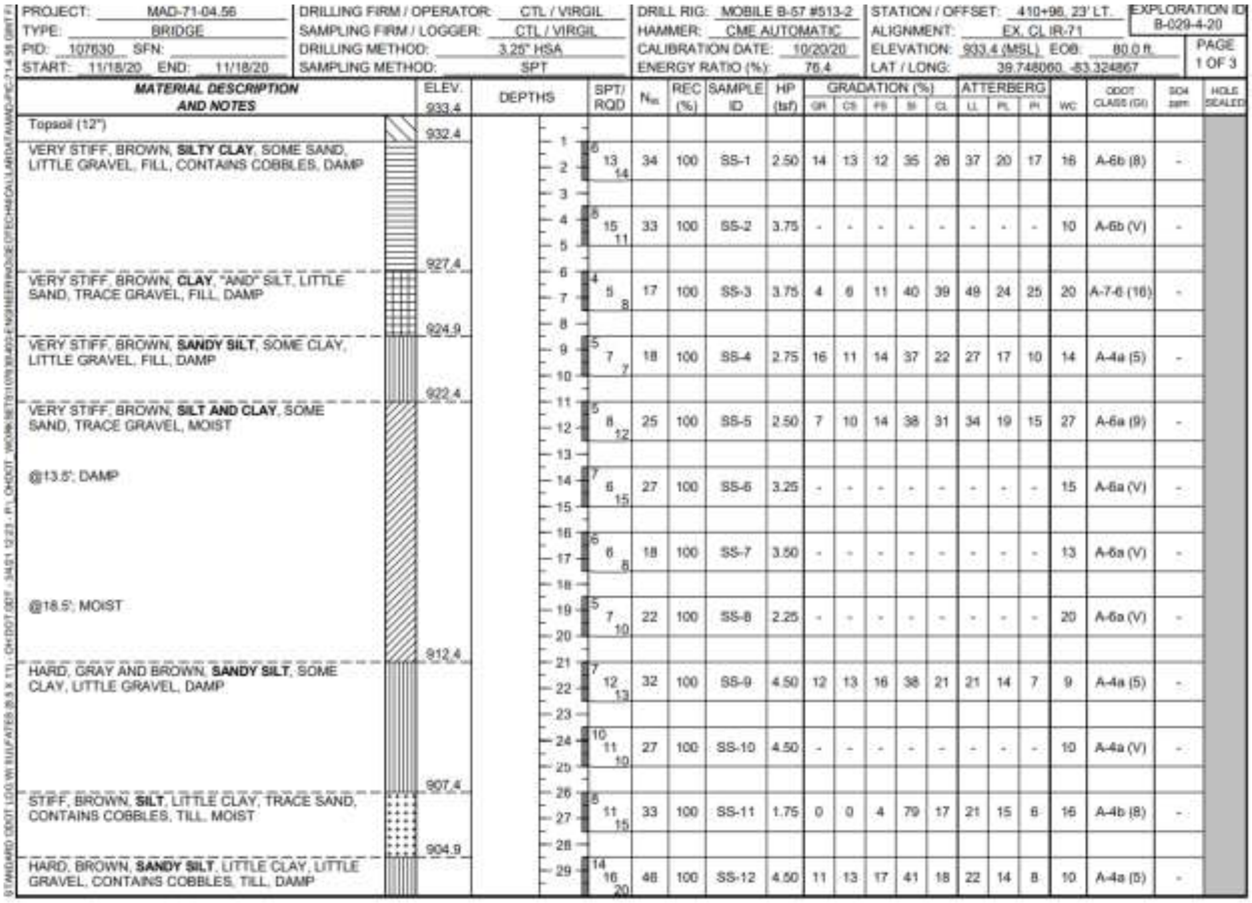
RIGHT ABUTMENT SCOUR DEPTH ANALYSIS

Layer	Layer Depth(ft)	Shear Stress (lb/ft^2)	Scoured Flow Depth (ft)	Scour Depth (ft)	Layer Completely Scoured?	Bottom of Scour Depth (ft)	Bottom of Scour Elevation (ft)
1	15	0.03	22.48	12.48	No	12.48	587.52
2	20	0.03	22.48	12.48	No	END	END

Figure 45: Right Abutment Scour Analysis

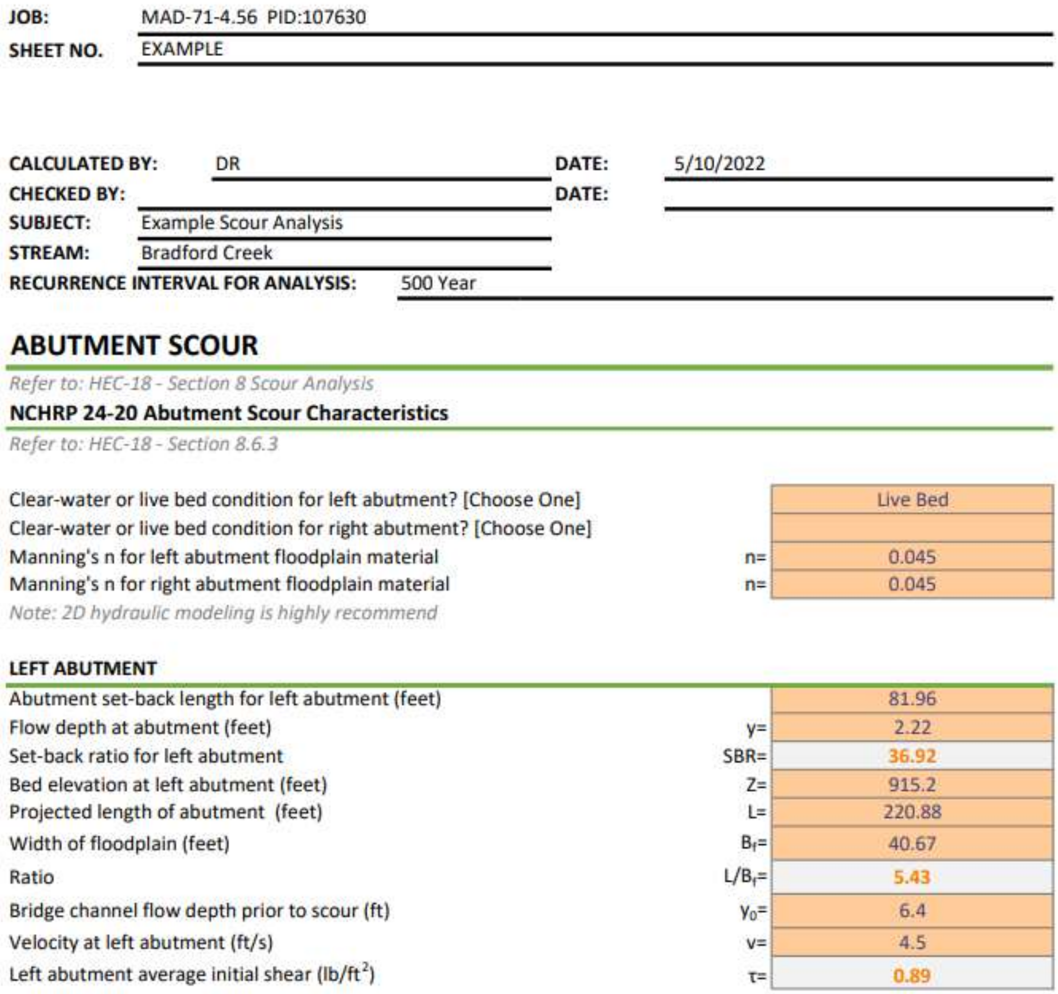
4.3.2 Abutment Scour: Layered Analysis Example

As seen in Figure 29, the flow depth at the right abutment is zero and is excluded from this analysis. Soil data from E.L. Robinson's MAD/PIC-71-4.56/0.00 Exploration Report: Exploration ID B-029-4-20, as seen in Figure 18, was used for this analysis. Soil data can be seen below in Figure 46. Results from the scour analysis are shown in Figure 50 below.


PROJECT: MAD-71-04.56
TYPE: BRIDGE
PID: 107630 SFN:
START: 11/18/20 END: 11/18/20
DRILLING FIRM / OPERATOR: CTL / VIRGIL
SAMPLING FIRM / LOGGER: CTL / VIRGIL
DRILLING METHOD: 3.25" HSA
SAMPLING METHOD: SPT
DRILL RIG: MOBILE B-57 #513-2
HAMMER: CME AUTOMATIC
CALIBRATION DATE: 10/20/20
ENERGY RATIO (%): 76.4
STATION / OFFSET: 410+96, 23' LT.
ALIGNMENT: EX. CL IR-71
ELEVATION: 933.4 (MSL) EOB: 80.0 ft.
LAT / LONG: 39.748060, -83.324867
EXPLORATION ID B-029-4-20
PAGE 1 OF 3

MATERIAL DESCRIPTION AND NOTES	ELEV. 933.4	DEPTHS	SPT/ RQD	N60	REC (%)	SAMPLE ID	HP (tsf)	GRADATION (%) GR	CS	FS	SI	CL	ATTERBERG LL	PL	PI	WC	ODOT CLASS (GI)	SO4 ppm	HOLE SEALED
Topsoil (12")	932.4																		
VERY STIFF, BROWN, **SILTY CLAY**, SOME SAND, LITTLE GRAVEL, FILL, CONTAINS COBBLES, DAMP		1 – 2	6 13 14	34	100	SS-1	2.50	14	13	12	35	26	37	20	17	16	A-6b (8)	-	
	927.4	4 – 5	5 15 11	33	100	SS-2	3.75	-	-	-	-	-	-	-	-	10	A-6b (V)	-	
VERY STIFF, BROWN, **CLAY**, "AND" SILT, LITTLE SAND, TRACE GRAVEL, FILL, DAMP	924.9	6 – 7	4 5 8	17	100	SS-3	3.75	4	6	11	40	39	49	24	25	20	A-7-6 (16)	-	
VERY STIFF, BROWN, **SANDY SILT**, SOME CLAY, LITTLE GRAVEL, FILL, DAMP	922.4	9 – 10	5 7 7	18	100	SS-4	2.75	16	11	14	37	22	27	17	10	14	A-4a (5)	-	
VERY STIFF, BROWN, **SILT AND CLAY**, SOME SAND, TRACE GRAVEL, MOIST		11 – 12	5 8 12	25	100	SS-5	2.50	7	10	14	38	31	34	19	15	27	A-6a (9)	-	
@13.5'; DAMP		14 – 15	7 6 15	27	100	SS-6	3.25	-	-	-	-	-	-	-	-	15	A-6a (V)	-	
		16 – 17	6 6 6	18	100	SS-7	3.50	-	-	-	-	-	-	-	-	13	A-6a (V)	-	
@18.5'; MOIST	912.4	19 – 20	5 7 10	22	100	SS-8	2.25	-	-	-	-	-	-	-	-	20	A-6a (V)	-	
HARD, GRAY AND BROWN, **SANDY SILT**, SOME CLAY, LITTLE GRAVEL, DAMP		21 – 22	7 12 13	32	100	SS-9	4.50	12	13	16	38	21	21	14	7	9	A-4a (5)	-	
	907.4	24 – 25	10 11 10	27	100	SS-10	4.50	-	-	-	-	-	-	-	-	10	A-4a (V)	-	
STIFF, BROWN, **SILT**, LITTLE CLAY, TRACE SAND, CONTAINS COBBLES, TILL, MOIST	904.9	26 – 27	5 11 15	33	100	SS-11	1.75	0	0	4	79	17	21	15	6	16	A-4b (8)	-	
HARD, BROWN, **SANDY SILT**, LITTLE CLAY, LITTLE GRAVEL, CONTAINS COBBLES, TILL, DAMP		29	14 16 20	48	100	SS-12	4.50	11	13	17	41	18	22	14	8	10	A-4a (5)	-	

Figure 46: MAD-71-4.56 Exploration ID B-029-4-20 Soil Data- Source: E.L. Robinson



JOB: MAD-71-4.56 PID:107630
SHEET NO. EXAMPLE

CALCULATED BY: DR **DATE:** 5/10/2022
CHECKED BY: **DATE:**
SUBJECT: Example Scour Analysis
STREAM: Bradford Creek
RECURRENCE INTERVAL FOR ANALYSIS: 500 Year

ABUTMENT SCOUR

Refer to: HEC-18 - Section 8 Scour Analysis

NCHRP 24-20 Abutment Scour Characteristics

Refer to: HEC-18 - Section 8.6.3

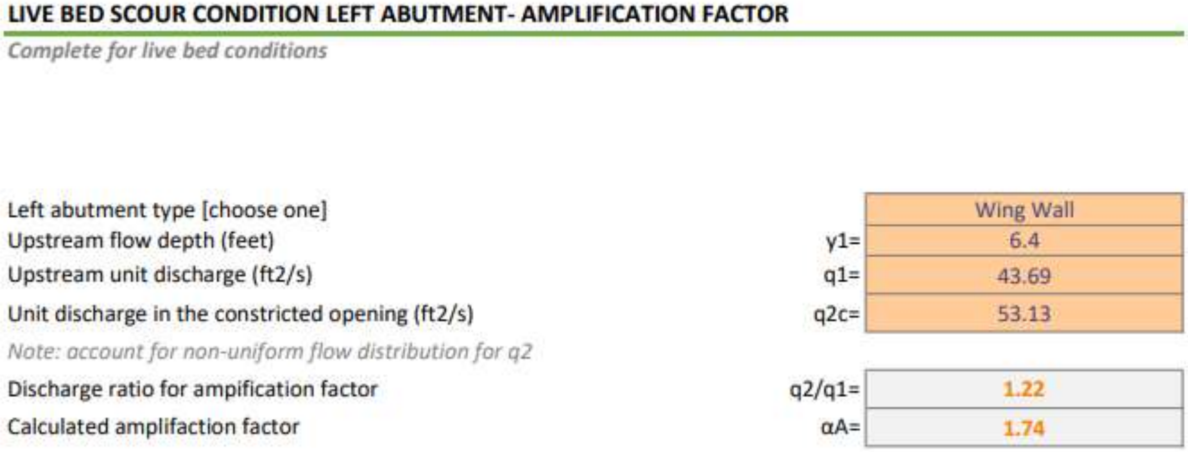
Clear-water or live bed condition for left abutment? [Choose One]		Live Bed
Clear-water or live bed condition for right abutment? [Choose One]		
Manning's n for left abutment floodplain material	n=	0.045
Manning's n for right abutment floodplain material	n=	0.045

Note: 2D hydraulic modeling is highly recommend

LEFT ABUTMENT

Abutment set-back length for left abutment (feet)		81.96
Flow depth at abutment (feet)	$y=$	2.22
Set-back ratio for left abutment	SBR=	36.92
Bed elevation at left abutment (feet)	$Z=$	915.2
Projected length of abutment (feet)	$L=$	220.88
Width of floodplain (feet)	$B_f=$	40.67
Ratio	$L/B_f=$	5.43
Bridge channel flow depth prior to scour (ft)	$y_0=$	6.4
Velocity at left abutment (ft/s)	$v=$	4.5
Left abutment average initial shear (lb/ft^2)	$\tau=$	0.89

Figure 47: Abutment Scour Layered Analysis Input



LIVE BED SCOUR CONDITION LEFT ABUTMENT- AMPLIFICATION FACTOR

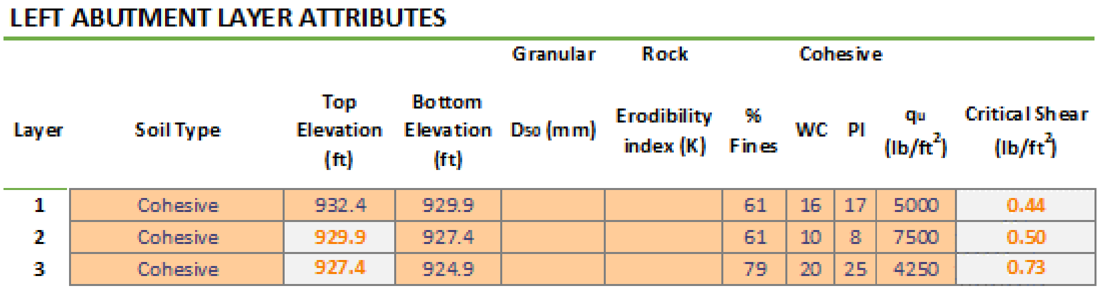
Complete for live bed conditions

Left abutment type [choose one]		Wing Wall
Upstream flow depth (feet)	y1=	6.4
Upstream unit discharge (ft2/s)	q1=	43.69
Unit discharge in the constricted opening (ft2/s)	q2c=	53.13

Note: account for non-uniform flow distribution for q2

Discharge ratio for ampification factor	q2/q1=	1.22
Calculated amplifaction factor	αA=	1.74

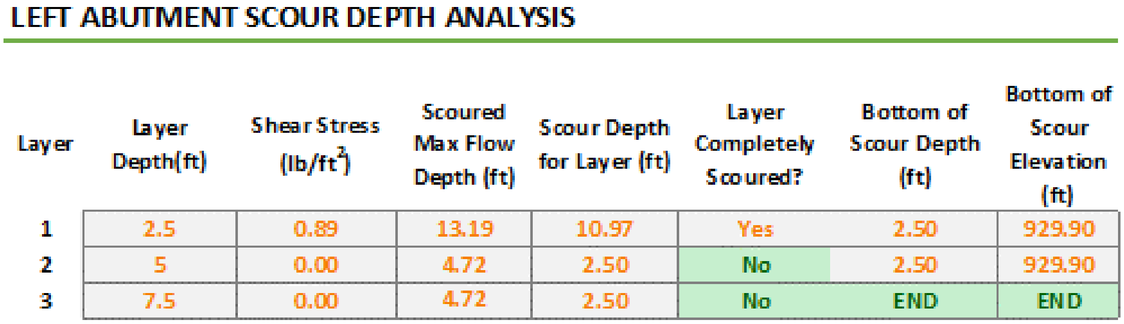
Figure 48: Abutment Scour Layered Analysis Input (Continued)



LEFT ABUTMENT LAYER ATTRIBUTES

				Granular	Rock	Cohesive				
Layer	Soil Type	Top Elevation (ft)	Bottom Elevation (ft)	D_{50} (mm)	Erodibility index (K)	% Fines	WC	PI	qu (lb/ft^2)	Critical Shear (lb/ft^2)
1	Cohesive	932.4	929.9			61	16	17	5000	0.44
2	Cohesive	929.9	927.4			61	10	8	7500	0.50
3	Cohesive	927.4	924.9			79	20	25	4250	0.73

Figure 49: Abutment Scour Layered Analysis Soil Data Input



LEFT ABUTMENT SCOUR DEPTH ANALYSIS

Layer	Layer Depth(ft)	Shear Stress (lb/ft^2)	Scoured Max Flow Depth (ft)	Scour Depth for Layer (ft)	Layer Completely Scoured?	Bottom of Scour Depth (ft)	Bottom of Scour Elevation (ft)
1	2.5	0.89	13.19	10.97	Yes	2.50	929.90
2	5	0.00	4.72	2.50	No	2.50	929.90
3	7.5	0.00	4.72	2.50	No	END	END

Figure 50: Abutment Scour Layered Analysis Output

Figure 50 above illustrates the benefit to using a layered analysis with a decaying shear stress. The initial scour depth was calculated as 10.97 feet, with the critical shear for the first layer, 0.44 psf (shown in Figure 49) was less than the stream bed shear stress, 0.89 psf (shown in Figure 47) indicating that scouring of the layer will occur. However, once the first layer was scoured, the critical shear of the next layer was greater (0.50 psf) than the recomputed shear (0.15 psf), which was recomputed with the initial flow depth at the abutment plus the depth of first layer using a control area 0.25 feet wide adjacent to the abutment (seen above as the corresponding shear stress for layer 1 in Figure 50). Because the critical shear of the second layer is greater than the shear calculated for layer 1 in Figure 50, incipient particle motion does not occur for the second layer, and the layer is not scoured.

5. References

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