Conference Paper, Published Version

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Comprehensive Scour Analysis at Highway Bridges HEC-IS

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ABSTRACT

In 1988 The Federal Highway Administration issued FHWA Technical Advisory T5140.20 entitled "Scour at Bridges." It required the States to evaluate the scour risk at all bridges over water. Accompanying the Advisory was the publication "Interim Procedures for Evaluating Scour at Bridges." The "Interim Procedures" delineated the scour problem at highway encroachments and crossings as 1) stream instability and channel movement, 2) long term degradation or aggradation, 3) live-bed or clear-water contraction scour and 4) local scour at piers and abutments. The "Interim Procedures" provided guidance and equations for evaluating scour. This was the first time a manual was written that gave comprehensive methods and recommended equations for the hydraulic analysis to determine scour depths for design of foundations of new bridges or evaluation of existing bridges and to protect the river environment. Subsequently, the "Interim Procedures" were updated and issued as Hydraulic Engineering Circulars 18. The Fourth Edition of HEC-18 is summarized in this paper.

INTRODUCTION

In September 1988 The Federal Highway Administration issued FHWA Technical Advisory T5140.20 entitled "Scour at Bridges." It required the states to evaluate the scour risk at all bridges over water. Accompanying the Advisory was the publication "Interim Procedures for Evaluating Scour at Bridges." The "Interim Procedures" delineated the scour problem at highway encroachments and crossings as 1) stream instability and channel movement, 2) long term degradation or aggradation, 3) live-bed or clear-water contraction scour and 4) local scour at the piers and abutments. The "Interim Procedures" provided guidance for determining stream instability, channel movement, and long term elevation changes as well as methods to counteract them. It included equations to determine live-bed or clear-water contraction scour depths, based on the work of Emmett Laursen. To determine local pier scour depths, it recommended the "so called" Colorado State University Equation from FHWA's Publication "Highways in the River Environment." This pier scour equation was selected because a study of many pier scour equations by FHWA Research Engineer Sterling Jones (1983) showed this equation was the best fit. It enclosed all available scour depth research data and gave the smallest scour depths.

Recent studies indicate this is still the case (Mueller, 1996 and Mueller and Jones, 1999).

To determine local abutment scour depths, the "Interim Procedures" delineated seven abutment conditions (cases) such as abutment in the channel, at the bank, or set back and considering live-bed or clear-water scour. For each case it provided equations (Liu et al, 1961) or (Laursen, 1980) to determine scour depths and/or methods to protect the abutments.

The "Interim Procedures" (written by Everett V. Richardson and Stanley R. Davis) were the first comprehensive manual that gave detailed recommendations to determine stream instability, delineated the three components of scour at highway bridges (long term aggradations or degradation, contraction scour and local scour), and gave equations or methods to determine scour depths and/or countermeasures to protect highway bridges and encroachments from stream instability and scour.

The TA was written by Stanley Davis, Chief of FHWA's Hydraulics and Geotechnical Branch, with input by staff. Many drafts were prepared and reviewed by Stanley Gordon, Chief of the Bridge Division, FHWA legal staff and others before the TA was approved for dissemination. The TA was effective in implementing a national scour evaluation program that met the requirements of the Congress. While it presented policies and guidance for the program, it also permitted a degree of flexibility so that the states could carry out the program in a manner consistent with their existing organizations and procedures.

In 1991 FHWA updated and published the "Interim Procedures" as HEC-18, "Evaluating Scour at Bridges." (Richardson et al, 1991). The Fourth Edition was released May 2001 (Richardson and Davis, 2001) at which time FHWA also released two companion documents: HEC-20 entitled "Stream Stability at Highway Structures" (Lagasse et al, 2001) and HEC-23 entitled "Bridge Scour and Stream Instability Countermeasures" (Lagasse. et al, 2001, 2009). The three HECs provide guidance for bridge scour, stream stability analysis and the design of countermeasures. They contain the results of the latest research and form the basis of FHWA National Highway Institute's three short courses on scour (FHWA NHI, 2010). FHWA periodically updates these publications as new information becomes available. **The three HEC's are available from the National Technical Information Service, Springfield, VA 22161 (703) 487-4650.**

BACKGROUND

At 9:00 am on April 5, 1987 the Interstate (I-90) Highway Bridge over Schoharie Creek in Upstate New York collapsed killing 10 people. Four passenger cars and one truck fell 60 feet into the Creek. The failure received national television and newspaper coverage.

The National Transportation Safety Board investigated the accident and issued their findings in a highway accident report entitled "Collapse of New York

Thruway (I-90) over the Schoharie Creek near Amsterdam New York, April 5, 1987" (NTSB, 1988). Drs. Richardson and Lagasse were Consulting Engineers for the Safety Board's investigation, which included a physical model study made at Colorado State University. The Safety Board's findings were that scour of pier 3 caused the failure. All 5 piers were founded on spread footings without piles.

The U.S. Congress held hearings on the failure, where people such as Ralph Nader testified that the Federal Government should take over the design and construction of all highway roads and structures. FHWA officials and all State Highway Engineers and State political officials such as Governors opposed such move. But Congress instructed FHWA to strengthen its oversight of the design, construction and inspection of all bridges. In particular, Congress instructed FHWA to evaluate and determine the vulnerability of failure from scour of all bridges over water in the Federal bridge inventory and to periodically report back to Congress on the progress of the evaluation and condition of all bridges in the inventory as to their vulnerability to failure by scour. The FHWA was charged with the task of strengthening the National Bridge inspection program. FHWA responded by issuing Technical Advisory T5140.20 entitled "Scour at Bridges" and the accompanying "Interim Procedures for evaluating Scour at Bridges" requiring the States to evaluate the scour risk at all bridges over water.

HEC-18 EVALUATING SCOUR AT BRIDGES (FOUTH EDITION)

Design Philosophy (Chapter 2)

Bridge foundations should be designed to withstand the effects of scour without failing for the worst conditions resulting from floods equal to the 100-year flood or a smaller flood if it would cause scour depths deeper than the 100-year flood. Bridge foundations should be checked to ensure that they will not fail due to scour resulting from the occurrence of a superflood in the order of magnitude of a 500-year flood. Chapter 2 amplifies on the design philosophy and gives a general design procedure, concepts and a step by step detailed design procedure. Also, some miscellaneous hydraulic factors, such as drag forces on superstructures, ice forces and the design of spread footings placed on tremie seals or soils are described.

Basic Concepts and Definitions of Scour (Chapter 3)

The four components of a comprehensive scour analysis are defined and illustrated. These are: 1) Long term aggradation and degradation of the river bed. 2) General scour at the bridge (contraction scour or other general lowering of the bridge cross section. 3) Local scour at piers and abutments. 4) Lateral shifting of the stream. How sediment transport affects bridge foundations (that is the difference between clear-water and live-bed scour) is discussed in detail. Also, equations and methods of analysis are for non-cohesive soils. But are recommended for cohesive and cemented soils because the ultimate depth of scour is the same. Only time is the factor.

Long-term Aggradation and Degradation (Chapter 4)

The factors affecting long-term stream bed elevation changes, methods for evaluating these changes and the use of computer models are discussed. The role of geology, river mechanics, sediment transport, geomorphology and fluvial geomorphology are presented.

General Scour (Contraction Scour) (Chapter 5)

General scour is the general decrease in the elevation of the stream bed across the bridge opening. It does not include the local scour or the long term bed elevation changes. It can be cyclic, That is, there can be cutting and filling of the stream bed during the passage of a flood. Contraction scour is a main cause of general scour but other factors may cause general scour as well.

Contraction Scour Equations

Contraction scour occurs when the bridge and its approaches encroaches either on the stream channel or the stream's flood plain. This increases the stream velocity and sediment transport capacity. HEC-18 describes, with sketches, five cases of contraction scour at bridge crossings with two conditions of erosion (live-bed or clear-water). The cases are:

1. Bridge abutments project into the stream channel with or without overbank flow.
2. Bridge abutments at edge of the channel with overbank flow.
3. Bridge abutments setback from the channel and overbank flow.
4. Bridge crosses the stream at a narrow section.
5. Bridge piers significantly obstruct the flow (with or without debris) in the previous cases.

The "Interim Procedures" and HEC-18 give equations to determine contraction scour depth for each erosion condition. These are given below:

Live-bed contraction scour occurs at a bridge when the bridge opening contracts the flow and there is transport of bed material in the upstream reach into the bridge section. With live-bed contraction scour the area of the contracted section increases until, in the limit, the transport of sediment out of the contracted section equals the sediment transport in.

The equation, a modified version of Laursen's 1960 equation for live-bed scour in a long contraction, is;

$$y_2/y_1 = (Q_2/Q_1)^{6/7} (W_1/ W2)^k$$

Clear-water contraction scour occurs when (1) there is no bed material transport from the upstream reach into the bridge cross section, or (2) the material transported in the upstream reach is transported through the bridge section in suspension and at less than the capacity of the flow. With clear-water contraction scour the area of the contracted section increases until the velocity of the flow or the shear stress on the bed is equal to the critical velocity or critical shear stress of a representative particle size in the bed material.

The "Interim Procedures" and HEC-18 recommended equation, based on a development given by Laursen in 1963 is:

$$y_2 = ((K_u Q_2^2)/(D_m^{2/3} W^2))^{3/7}$$

$$y_s = y_2 - y_0 = \text{average contracted scour depth}$$

HEC-18 states that scour depths with live-bed contraction scour may be limited by coarse sediments in the bed material. Where coarse sediments are present HEC-18 recommends calculating contraction scour using both equations and taking the smaller scour depth.

Determination of Local Scour at Piers Chapter 6)

The "Interim Procedures," based on the study by Sterling Jones (1983) recommended the CSU equation for both live bed and clear-water conditions. The equation was developed for the FHWA Publication "Highways in the River Environment, Environmental and Hydraulic Considerations" (Richardson et al, 1975). The succeeding HECs recommended a modified CSU equation. The modifications were to add additional corrections factor (Ks) based of new research and field experience. The 4th HEC-18 Edition equation for local pier scour is:

$$y_s/a = 2.0\, K_1\, K_2\, K_3\, K_4\, K_w\, (y_1/a)^{0.35}\, Fr_1^{\,0.43}$$

The variables are defined in notation and values are given for the Ks in HEC-18. Also, HEC-18 places a limit on the maximum value of y_s/a.

Scour Depth Determination for Complex Piers

The 4th Edition of HEC-18 based on the research and papers of Jones (1989), Salim and Jones (1996, and 1999), Jones and Sheppard (2000), delineated a method for determining local scour depths for piers with complex geometry. Recent research supports the method and suggest a slight modification (Ataie-Ashtiani et al, 2010). Figure 1 illustrates the components of a complex pier and the methodology used. The reader is referred to the 4th Edition of HEC-18 for the development, an example problem and guidance in using the method.

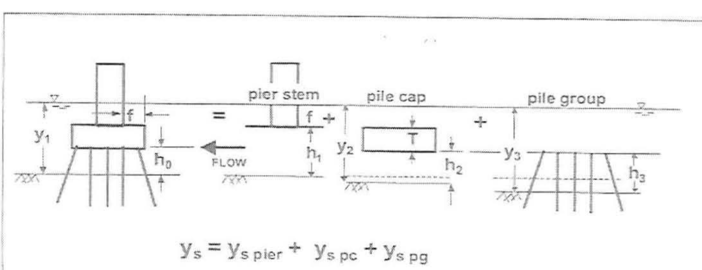

Figure 1. Definition sketch for scour at a complex pier (Jones and Sheppard, 2000).

Evaluating Local Scour at Abutments (Chapter 7)

The components of the local scour at abutments are illustrated in Figure 2. Note the horizontal vortex that produces scour depths at the upstream corner and side of the abutment. This is the scour depth determined by most abutment scour equations. But note also the wake vortex. This vortex erodes the downstream face of the abutment and approach embankment, causing abutment failure. Often this wake vortex causes a major scour problem. Erosion from the wake vortex can be easily controlled by recognizing the problem and placing riprap on the downstream face of the abutment and approach embankment.

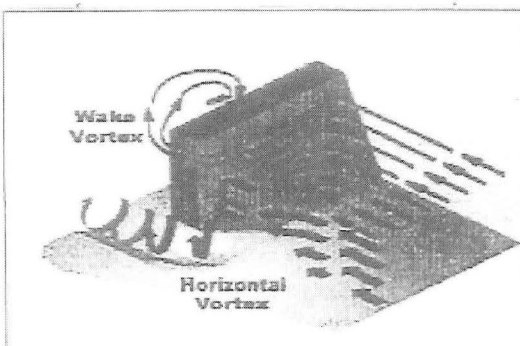

Figure 2. Schematic representation of abutment scour (HEC-18).

Equations for predicting local scour depths are mainly based on laboratory studies (Lieu et al (1961), Laursen (1980), Froehlich (1989) and Melville (1992). Little or no field data is available. The problem, as stated in HEC-18 is:

"The reason the equations in the literature predict excessive conservative abutment scour depths for the field situation is that, in the laboratory flume, the discharge intercepted by the abutment is directly related to abutment length; whereas, in the field, this is rarely the case."

The "Interim Procedures" and HEC-18 identified abutment site conditions, angle to the flow (skew), discharge intercepted by the abutment and approach embankment and abutment shape as scour depth factors. Researchers identified the same factors, but unfortunately used abutment and approach length as a substitute for discharge. Common abutment shapes are 1) vertical wall abutments, 2) vertical wall abutments with wing walls and spill-through abutments.

Abutments Local Scour depth Equations

HEC-18 recommends two equations for both live-bed and clear-water scour. They are Froehlich's (1989) and HIRE (Richardson et al, 2001). The latter is based of scour depths measure at the end of spurs in the Mississippi River and is applicable when the ratio of the projected abutment and embankment length to the flow depth is greater than 25.

Froehlich's (1989) live-bed abutments scour equation

$$y_s / y_1 = 2.27\, K_5\, K_6\, (L' / y_1)^{0.43}\, Fr^{0.61} + 1.0$$

HIRE live-bed abutment scour equation

$$y_s / y_1 = 4\ Fr^{0.33}\ (K_5 / 0.55)\ K_6$$

Comprehensive Example Scour Problem (Chapter 8)

A comprehensive hydraulic analysis from a paper by Arneson et al (1991) of scour at a bridge crossing using the procedure and equations given in HEC-18 is presented. The analysis uses SI units in Chapter 8. But in Appendix H uses English units. The hydraulic variables were obtained using FHWA's WSPRO computer program. WSPRO's input and output is given in Appendix G.

Chapters 9 to 13 and Appendixes

CHAPTER	BRIEF DISCRIPTION
9	SCOUR ANALYSIS FOR TIDAL WATERWAYS
	The special condition of scour analysis in tidal unsteady flow given.
10	NATIONAL SCOUR EVALUATION PROGAM
	National evaluation program is described, with progress as of 2000.
11	INSPECTION OF BRIDGES FOR SCOUR
	A FHWA recommended inspection program with procedures is given.
12	SPECIAL CONSIDERATIONS FOR SCOUR AND STREAM INSTABLITY
	This chapter discusses the development of plan of actions for scour critical bridges, scour in cohesive or rock bed materials countermeasures etc.
13	LITERATURE CITED
	107 publications are cited.
APPENDIX	
A	METRIC SYSTEM, CONVERSION FACTORS, WATER PROPERTIES
B	EXTREME EVENTS
C	CONTRACTION SCOUR AND CRITICAL VELOCITY EQUATIONS
D	INTERIM PROCEDURES FOR ESTIMATING PIER SCOUR WITH DEBRIS
E	STURM ABUTMENT SCOUR EQUATIONS
F	MARYLAND ABUTMENT SCOUR EVALUATION METHOD
G	WSPRO INPUT AND OUTPUT FOR EXAMPLE PROBLEMS
H	COMPREHENSIVE SCOUR PROBLEM, ENGLISH UNITS
I	FHWA TECHNICAL ADVISORY T 5140.23
J	FHWA 1995 CODING GUIDE FOR NATIONAL BRIDGES
K	UNKNOWN FOUNDATIONS
L	SCOUR IN COHESIVE SOILS
M	SCOUR COMPETENCE OF ROCK

NATIONAL HIGHWAY INSTITUE

The FHWA's National Highway Institute established a short course titled "Stream Stability and Scour at Highway Bridges in 1991 using the "Interim Procedures" as the course text. Subsequent courses used the current edition of HEC-18 as the course text. At first, bridge inspectors attended the 3 day course. But FHWA and NHI established a 1-day course for inspectors titled "Stream Stability and Scour at Highway Bridges for Inspectors" (FHWA NHI, 2009). This course concentrates on visual keys to detecting scour and stream instability problems and emphasizes guidelines to complete the hydraulic and scour-related coding requirements. With the increase in knowledge of scour and stream instability countermeasures NHI and FHWA established a new course entitled "Countermeasure Design for Bridge Scour and Stream Instability." It uses HEC-23 (Lagasse et al, 2001, 2009) as the course text. In the period 1991 to 2005 Ayres Associates, Inc. presented the scour courses to more than 5,700 students in 45 States. However, engineers and highway officials in all 50 States have attended the course.

CONCLUSION

In 1988 the U.S. Department of Transportation, Federal Highway Administration as part of Technical Advisory T5140.20 "Scour at Bridges" released a manual titled "Interim Procedures for Evaluating Scour at Bridges. " The "Interim Procedures" delineated the scour problem at highway encroachments and crossings as 1) stream instability and channel movement, 2) long term degradation or aggradation, 3) live-bed or clear-water contraction scour and 4) local scour at the piers and abutments. The "Interim Procedures" provided guidance for determining stream instability, channel movement, and long term elevation changes as well as methods to counteract them. This was the first time that a manual was written that gave a comprehensive method with recommended equations for the hydraulic analysis to determine scour depths for the design of foundations of new bridges or evaluation of existing bridge foundations. In succeeding years the "Interim Procedures" were updated and issued as Hydraulic Engineering Circulars HEC-18. The Fourth Edition was issued in May 2001.

FHWA (1991) updated the advisory to T51140.23 titled "Evaluating Scour at Bridges." In 1992 the American Association of State Highway and Transportation Officials (AASHTO, 1992) addressing the problem of stream stability and scour stated "The probable depth of scour shall be determined by subsurface exploration and hydraulic analysis. Refer to Article 1.3.2 and FHWA Engineering Circular (HEC) 18 for general guidance regarding hydraulic studies and design."

NOTATION

a = Pier width, m (ft)
f = Upstream projection of a footer from pier stem, m (ft)
Dm = Diameter of the smallest nontransportable particle in the bed material in the contracted section (taken as 1.25 D_{50}) m (ft)
D_{50} = Median diameter of the bed material, m (ft)
y_1 = Average depth in the upstream main channel, or directly upstream of the pier or abutment, m (ft).

y_2 = Average depth in the contracted section, m (ft)
y_s = Scour depth in the contracted section, m (ft)
y_0 = Existing depth in the contracted section before scour, m (ft)
Q_1 = Discharge in upstream channel TRANSPORTING SEDIMENT. m^3/s $(ft^3/s\}$
Q_2 = Discharge in the contracted channel or in the setback overbank area at the bridge. It is associated with the width W, m^3/s (ft^3/s)
W_1 = Bottom width of the upstream channel that is transporting bed material, m (ft)
W_2 = Bottom width of the contracted section less pier widths, m (ft)
k = Exponent determined below

V_*/w	k	Mode of Sediment Transport
<0.50	0.59	Mostly contact bed material transport.
0.50 to 2.0	0.64	Some suspended bed material transport.
>2.0	0.69	Mostly suspended bed material discharge

K_u = 0.025 SI units
K_u = 0.0077 English units
V_* = Shear velocity in the upstream section $(gy_1S_1)^{0.5}$ m/s (ft/s)
S_1 = Slope of the energy grade line in the upstream channel, m/m (ft/ft).
w = Fall velocity of the D_{50} of the upstream bed material, m (ft)
K_1 = Correction factor for pier shape, HEC-18
K_2 = Corection factor for angle of attack = $(\text{Cos. } 0 + L/a \text{ Sin. } 0)^{0.65}$
Maximum value of L/a is 12
K_3 = Correction factor for bed condition given in 4th Edition HEC-18
K_4 = Correction factor for armoring by bed material size 4th Edition HEC-18
K_5 = Coefficient for abutment shape = 1.0 for vertical wall abutment; 0.82 for vertical –wall with wing walls and 0.55 for spill-through.
K_6 = Coefficient for angle of embankment to flow. = $(0/90)^{0.13}$ (0<90 if embankment points downstream and 0>90 if embankment points upstream
K_w = Correction factor for pier width in shallow flows. HEC-18
L = Pier length, or abutment embankment length normal to the flow m (ft)
L' = Length of active flow obstructed by abutment and embankment m (ft)
A_e = Flow area obstructed by abutment and embankment m^2 (ft^2)
Q_e = Flow obstructed by abutment and embankment m^3/s (ft^3/s)
$V_e = Q_e / A_e$ m/s (ft/s)
Fr = Froude Number directly upstream of the pier or abutment

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