BRIDGE SCOUR EVALUATION IN THE UNITED STATES

by

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ABSTRACT

In September 1988, the U.S. Federal Highway Administration (FHWA) issued Technical Advisory T514023 entitled "Scour at Bridges" to State Highway Departments or Departments of Transportation which recommended that each State evaluate every bridge over a stream as to its vulnerability to scour of its foundations. Accompanying the advisory was a document entitled "Interim Procedures for Evaluating Scour at Bridges." This was the first U.S. publication which gave specific recommendations and equations for evaluating scour. Subsequently, FHWA issued Hydraulic Engineering Circulars (HEC's) 18, 20, and 23 which gave state-of-practice for evaluating bridge scour for bridges over riverine and tidal waterways, stream stability at highway structures and bridge scour and stream instability countermeasures. This paper presents the FHWA’s recommendations for bridge scour and stream instability evaluation.

INTRODUCTION

In September 1988, the U.S. Federal Highway Administration (FHWA) issued Technical Advisory T514023 entitled "Scour at Bridges" to State Highway Departments or Departments of Transportation which recommended that each State evaluate every bridge over a stream as to its vulnerability to scour of its foundations. The Advisory stated: "Most waterways can be expected to experience scour over a bridge's service life (which is now approaching 100 years). Exceptions might include waterways in massive, competent rock formations where scour and erosion occur on a scale that is measured in centuries.... The added cost of making a bridge less vulnerable to scour is small when compared to the total cost of a failure which can easily be two or three times the original cost of the bridge itself. Moreover, the need to ensure public safety and to minimize the adverse effects stemming from bridge closures requires our best effort to improve the state-of-practice of designing and maintaining bridge foundations to resist the effects of scour."

Accompanying the advisory was a document entitled "Interim Procedures for Evaluating Scour at Bridges". This was the first U.S. publication which gave specific recommendations and equations for evaluating scour. Subsequently, in 1991, this document was revised and issued as Hydraulic Engineering Circular 18 (HEC-18) entitled "Evaluating Scour at Bridges." Also, in 1991 a companion document (HEC-20) entitled "Stream Stability at Highway Structures was issued."

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As new knowledge was obtained the two documents were revised. HEC-18 in 1993 and 1995 (Richardson and Davis, 1995) and HEC-20 in 1995 (Lagasse et al., 1995). Also in 1997 HEC-23 entitled "Bridge Scour and Stream Instability Countermeasures-Experience, Selection and Design Guidance" was issued (Lagasse et al., 1997). These three documents, which have been endorsed by the American Association of State Highway and Transportation Officials (AASHTO, 1992), represent the present state of practice in the United States for evaluating and design for stream stability and scour at highway bridges. Presently (2000) all three documents are being revised.

HEC-18 presents methods and equations for evaluating and inspecting scour at bridges over riverine and tidal waterways. HEC-20 presents methods for evaluating stream stability and HEC-23 provides methods and equations for the design of countermeasures for stream instability and scour at highway bridges.

BACKGROUND

Bridge failures cost millions of dollars each year as a result of both direct cost necessary to replace and restore bridges, and indirect costs related to disruption of transportation facilities. However, of even greater consequence is loss of life from bridge failures. In the United States there are over 575,000 bridges in the National Bridge Inventory. These numbers include federal highway system, state, county and city bridges. Approximately 84 percent of these bridges are over water. Erosion of the foundations of the bridges resulting from stream instability, long-term degradation, contraction scour and local scour cause 60 percent of bridge failures. There has been 25 fatalities from bridge failures in the United States since 1987 (Richardson and Lagasse, 1999).

Rhodes and Trent (1993, Richardson and Lagasse, 1999, p. 1013) document that $1.2 billion was expended in the U.S. for restoration of flood damaged highway facilities during the 1980s. They state that this amount is conservative because they (1) only include the amount funded by the U.S. Government which ranges from 75 to 100 percent of the total restoration costs, and (2) the funds were only for disaster that are very large and do not include the hundreds of smaller events that occur every year. These costs do not include the additional indirect costs to highway users for fuel and operating costs resulting from temporary closure and detours and to the public for costs associated with higher tariffs, freight rates, additional labor costs and time. Rhodes and Trent also demonstrate that the indirect cost (operating a vehicle over a detour and time lost traveling when a bridge failed) can exceed by several times the direct cost of bridge replacement or repair.

Bridge scour research in the U.S. started in the early 1950s through Carl Izzard's efforts to have the U.S. Bureau of Public Roads (predecessor agency to the Federal Highway Administration) and Iowa State Highway Department fund Laursen's research on bridge scour (Laursen and Toch, 1956; Laursen, 1958, 1960, and 1963). However, only recently has extensive data of field measurements of scour at bridges become available (Landers and Mueller, 1996 and Richardson and Lagasse, 1999, p. 585). Also, many analytical techniques are recommended for use simply because they are the best currently available and are overly
conservative. For example, many equations for determining local scour depths at bridge abutments use abutment and roadway approach length as a variable instead of the flow they intercept (Richardson and Richardson, 1992, 1993 and Richardson and Davis, 1995). In the field case, this is a spurious correlation.

All material on the stream bed and banks at a bridge crossing will erode. It is just a matter of time. Some material, such as granite may take hundreds of years. Whereas, sand bed streams will erode to the maximum depth of scour in hours. Sandstones, shales, and other sedimentary bed rock material, do not erode in hours or days but will over time erode to the extent that a bridge will be in danger unless the substructure are founded deep enough. Cohesive bed and bank material such as clays, silty clays, silts and silty sand or material such as glacial tills, which are cemented by chemical action or compression, will erode. The erosion of these materials is slower than sand bed material but their ultimate scour will be as deep as the scour depth in a non-cohesive sand bed material (Jackson et al., 1991, Richardson and Lagasse, 1999, p. 578, and Briaud et al., 1999). Briaud et al. (1999) describes a procedure for determining the scour rate in cohesive soils. The procedure uses a special laboratory flume named the Erosion Function Apparatus (EFA). Shelby tube samples of the subsurface cohesive soils are extruded into the EFA and subjected to flows of varying velocity to determine a plot of erosion rate vs velocity. From the flood history and hydraulic characteristics of the river at the bridge site and the results from the EFA tests, a time-dependent scour rate can be developed. If the assumption is made that the future flow conditions of the river will be similar to the historic conditions, a time rate of scour can be projected into the future for a period equal to the anticipated service life of the bridge to determine a depth of scour. The method assumes that the depth of scour is a function of time and that scour will continue to occur until the scour depth is equal to the ultimate scour depth similar to what would occur in a sand bed. The depth obtained from the EFT tests can be compared to the ultimate scour depth from an existing equation to aid in the analysis.

Scour at bridge crossings is a sediment transport process. Long term degradation, contraction scour and local scour at piers and abutments result from the fact that more sediment is removed from these areas than is transported into them. If there is no transport of bed material into the bridge crossing, clear-water scour exists. Transport of appreciable bed material into the crossing results in live-bed scour. In this latter case the transport of the bed material may limit scour depth. Whereas, with clear-water scour the scour depths are limited by the critical velocity or critical shear stress of a dominant size in the bed material at the crossing.

Typical clear-water scour situations include (1) coarse bed material streams, (2) flat gradient streams during low flow, (3) local deposits of larger bed materials that are larger than the biggest fraction being transported by the flow (rock riprap is a special case of this situation), (4) armored stream beds where the only locations that tractive forces are adequate to penetrate the armor layer are at piers and/or abutments, and (5) vegetated channels where, again, the only locations that the cover is penetrated is at piers and/or abutments. During a flood event, bridges over streams with coarse bed material are often subjected to clear-water scour at low discharges, live-bed scour at the higher discharges and then clear-water scour on the falling
stages. Clear-water scour reaches its maximum over a longer period of time than live-bed scour (See Figure 1). In fact, local clear-water scour may not reach a maximum until after several floods.

Floods tend to scour the material at a bridge crossing during the rising limb of the flood and refill these scour holes during the recession limb. Often, the redeposited material in the scour hole is more easily eroded by subsequent floods. Post-flood inspection of the bridge crossing may indicate the material around the foundations are adequate, when in fact, the bridge is in jeopardy of failing during the next flood. This infilling also, makes it difficult to obtain field measurement of scour depths because the measurements have to be made during a flood.

Figure 1. Pier Scour Depth in a Sand-Bed Stream as a Function of Time (not to scale) (Richardson and Davis, 1995).

The magnitude of the scour depth depends on the flow variables of the stream (discharge, flow velocity and depth, angle of the flow to the bridge, etc.), bed and bank material characteristics (bed rock, alluvial or non-alluvial, cohesive or non-cohesive, size distribution, etc.) and bridge characteristics (size and shape of the pier and abutments, width of opening, elevation of the deck, etc).

Design Discharge

The magnitude of the flow variable depends on the selection of a design discharge. The selected design discharge for a bridge is based on the design life of the bridge, bridge importance, consequence of failure, etc. The design discharge for a divided highway with large average daily traffic (ADT) (interstate highway, autobahns, etc.) would be larger than for a farm to market or logging road. Some engineers advocate a maximum possible flood for important bridges (Laursen, 1998) others recommend risk analysis. Important bridges are those with large ADT, Interstate highways, school bus and ambulance routes, and etc.

The Federal Highway Administration (FHWA) in HEC-18 (Richardson and Davis, 1995) recommends that bridges should be designed to resist the flood event(s) that are expected to
produce the most severe scour conditions. HEC-18 recommends the 100-year flood or the overtopping flood when it is less than the 100-year flood. Overtopping refers to flow over the approach embankment(s), the bridge itself or both. Also, investigate other flood events if there is evidence that such events would create deeper scour than the 100-year or overtopping floods. In addition HEC-18 states, "Bridges should be designed to withstand the effects of scour from a super-flood (a flood exceeding the 100-year flood) with little risk of failing. This requires careful evaluation of the hydraulic, structural, and geotechnical aspects of bridge foundation design. It is recommended that this super-flood or check flood be on the order of a 500-year event." The bridge design for the 100 year or overtopping flood should be designed with the normal safety factors but checking the design for the super flood is made with safety factors of 1.0. Also, "The foundation should be designed by an interdisciplinary team of engineers with expertise in hydraulic, geotechnical, and structural design."

**TOTAL SCOUR**

Total scour at a highway crossing is composed of long-term degradation, general scour (contraction and other general scour), and local scour. The components are assumed additive. In addition, lateral shifting of a stream can cause or increase the scour of bridge foundations. Each of the three types of scour and stream instability are introduced separately below.

**Long-Term Aggradation and Degradation**

Aggradation is the deposition of sediment in the bridge reach of a stream. Whereas, degradation is the erosion of the sediment in the bridge reach. The former causes the bed elevation to increase and the later causes the bed elevation to decrease. These riverbed elevation changes are over long lengths and time due to natural or man made changes. Long term degradation is defined as long-term scour and is added to the other scour components to obtain total scour but long term aggradation is not usually considered because over time it could stop or change to degradation.

Long-term bed elevation changes (aggradation or degradation) may be the natural trend of the stream or may be the result of some modification to the stream of watershed condition. The streambed may be aggrading, degrading, or not changing in the bridge crossing reach. When the bed of the stream is neither aggrading or degrading, it is considered to be in equilibrium with the sediment discharge supplied to the bridge reach. It is the long-term trends, not the cutting and filling of the bed of the stream that might occur with contraction scour, that must be determined. The engineer must assess the present state of the stream and watershed and determine future changes in the river system, and from this, determine the long-term stream bed elevation changes.

Factors that affect long-term bed elevation changes are dams and reservoirs upstream and downstream of the bridge, changes in watershed land use (urbanization, deforestation, etc.), channelization, cutoff of meander bends (natural or man-made), changes in the downstream base level (control) of the bridge reach, gravel mining from the streambed, diversion of water into or out of the stream, natural lowering of the total system, movement of a bend, bridge location in
reference to stream planform and stream movement in relation to the crossing (Keefer et al., 1980). Richardson et al. (1990) provide examples of long-term bed elevation changes.

Analysis of long-term stream bed elevation changes must be made using the principles of river mechanics in the context of a fluvial system analysis. Such analysis of a fluvial system requires the consideration of all influences upon the bridge crossing, i.e., runoff from the watershed to the channel (hydrology), the sediment delivery to the channel (erosion), the sediment transport capacity of the channel (hydraulics), and the response of the channel to these factors (geomorphology and river mechanics). Many of the largest impacts are from man's activities, either in the past, present, or future. Analysis requires a study of the past history of the river and man's activities on it; a study of present water and land use and stream control activities; and finally contacting all agencies involved with the river to determine future changes to the river system.

A method to organize such an analysis is to use a three-level fluvial system approach. This method provides three levels of detail in an analysis (1) a qualitative determination based on general geomorphic and river mechanics relationships, (2) engineering geomorphic analysis using established qualitative and quantitative relationships to establish the probable behavior of the stream system to various scenarios of future conditions, and (3) quantifying the changes in bed elevation using available physical process mathematical models such as BRI-STARS (Molinas, 1993) or HEC-6 (U.S. Army Corps of Engineers, 1993). The approach is extrapolation of present trends, and using engineering judgment to assess the result of the changes in the stream and watershed. Recent FHWA reports, such as "Stream Channel Degradation and Aggradation: Analysis of Impacts to Highway Crossings" (Brown et al., 1980), "Stream Stability at Highway Structures" (Lagasse et al., 1995) and "Highways in the River Environment" (Richardson et al., 1990) discuss methodologies to determine long term elevation trends. The discussion of degradation, aggradation and sediment transport in Vanoni (1975) is very useful in understanding and determining long term degradation.

**General Scour**

General scour is a uniform or non-uniform lowering of the waterway bed as the result of the passage of high flow. It may result from contraction of the flow (contraction scour) or the flow around a bend (other general scour). General scour is different from long term degradation in that it may be cyclic and/or related to the passage of a flood.

**Contraction Scour** Contraction scour occurs when the flow area of a stream at flood stage is reduced, either by a natural contraction or by a bridge and/or its approach embankments. From continuity, a decrease in flow area results in an increase in average velocity and bed shear stress through the contraction. Hence, there is an increase in erosive forces in the contraction and more bed material is removed from the contracted reach than is transported into the reach. This increase in transport of bed material from the reach lowers the bed elevation. As the bed elevation is lowered, the flow area increases and, in the riverine situation, the velocity and shear stress decrease until relative equilibrium is reached. That is, either the quantity of bed material that is transported into the contraction is equal to that removed from the reach, **live-bed scour** or
the mean velocity (V) or average shear stress (τ₀) in the contraction is less than the critical velocity (Vc) or critical (τc) of the median diameter (D50) of the bed material, clear-water scour. Clear-water contraction scour occurs when (1) there is no significant bed material transport in the upstream reach into the downstream bridge reach or (2) the material being transported in the upstream reach is transported through the downstream bridge reach mostly in suspension.

In coastal streams which are affected by tides, as the cross-section area increases the discharge from the ocean may increase and thus the velocity and shear stress may not decrease. Consequently, equilibrium may not be reached. Thus, at tidal inlets which experience clear-water or live-bed scour, contraction scour may result in a continual lowering of the bed (long-term degradation) (Richardson et al., 1993, 1995 and Richardson and Davis, 1995).

Live-bed contraction scour is typically cyclic. That is, the bed scours during the rising stage of a runoff event, and fills on the falling stage. The contraction of flow due to a bridge can be caused by either a natural decrease in flow area of the stream channel or by abutments projecting into the channel and/or the piers blocking a large portion of the flow area. Contraction can also be caused by the approaches to a bridge cutting off floodplain flow. This can cause clear water scour on a setback portion of a bridge section and/or a relief bridge because the floodplain flow does not normally transport significant concentrations of bed material sediments. Other factors that can cause contraction scour are (1) ice formation or jams, (2) natural berms along the banks due to sediment deposits, (3) island or bar formations upstream or downstream of the bridge opening, (4) debris, (5) the growth of vegetation in the channel or floodplain, and (6) pressure flow.

Other General Scour In a natural channel, the depth of flow and velocity are always greater on the outside of a bend. In fact there may well be deposition on the inner portion of the bend at the point bar. Other General Scour at a bridge located on or close to a bend will be concentrated on the outer part of the bend. Also, in bends the thalweg (the part of the stream where the flow is deepest and, typically, the velocity is the greatest) may shift toward the center of the stream as the flow increases. This can increase scour and the nonuniform distribution of the scour in the bridge opening (chute channel).

Local Scour

Erosion of the stream bed around a pier or abutment as the result of the pier or abutment obstructing the flow is local scour. These obstructions accelerate the flow and create vortexes that remove bed material around them.

Lateral Shifting of the Stream

In addition to the above, lateral shifting of a stream (stream instability) may erode the approach roadway and abutments of a bridge and/or change the angle of the flow to the piers and abutments (angle of attack). This later can increase local scour at the piers or abutments.

CONTRACTION SCOUR EQUATIONS
Contraction scour equations are based on the principle of conservation of sediment transport. In the case of live-bed scour, this simply means that the fully developed scour in the bridge cross-section reaches equilibrium when sediment transported into the contracted section equals sediment transported out and the conditions for sediment continuity are in balance. For clear-water scour, the transport into the contracted section is essentially zero and maximum scour occurs when the shear stress reduces to the critical shear stress of the bed material.

To determine if the contraction scour at a bridge is clear-water or live-bed determine if the critical velocity \( V_c \) or critical shear stress \( \tau_c \) of the median diameter \( D_{50} \) of the bed material in the channel upstream from the bridge opening is larger than the average velocity or shear stress (clear-water scour) or smaller (live-bed scour). **Or calculate the contraction scour depths using both equations and take the smaller scour depth** (Richardson and Davis, 1995).

**Live-Bed Contraction Scour Equation**

Richardson and Davis (1995) in HEC-18 recommend a modified Laursen (1960) equation for live-bed contraction scour. It is based on a simplified transport function (Laursen, 1956) to obtain equilibrium sediment transport in a long contraction. In short contractions such as at a bridge it over estimates the scour depth (Richardson and Davis, 1995). The equation is: