THE UPPER BOUND OF ABUTMENT SCOUR DEFINED BY SELECTED LABORATORY AND FIELD DATA

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Abstract The U.S. Geological Survey, in cooperation with the South Carolina Department of Transportation, conducted a field investigation of abutment scour in South Carolina and used that data to develop envelope curves defining the upper bound of abutment scour. To expand upon this previous work, an additional cooperative investigation was initiated to combine the South Carolina data with abutment-scour data from other sources and evaluate the upper bound of abutment scour with the larger data set. To facilitate this analysis, a literature review was conducted to identify potential sources of published data on abutment-scour, and selected data, consisting of 446 laboratory and 331 field measurements, were compiled for the analysis. These data encompassed a wide range of laboratory and field conditions and represent field data from six states within the United States. The data set was used to evaluate the South Carolina abutment-scour envelope curves. Additionally, the data were used to evaluate a dimensionless abutment-scour envelope curve developed by Melville (1992), highlighting the distinct difference in the upper bound for laboratory and field data. The envelope curves evaluated in this investigation provide simple but useful tools for assessing the potential maximum abutment-scour depth in the field.

INTRODUCTION

> *Scant situations of hydraulic engineering are more complex than those associated with scour in the vicinity of a bridge abutment, especially one located in a compound channel. Accordingly, few situations of scour depth estimation are as difficult (Ettema and others, 2005).*

The complexity of abutment-scour processes has made it difficult to formulate prediction methods, and few would dispute the above assessment by Ettema and other (2005). Current scour-prediction equations largely consist of semi-empirical relations developed from simplified laboratory investigations (Sturm and others, 2011), and the performance of these equations can vary (Wagner and others, 2006; Benedict and others, 2007; Lombard and Hodgkins, 2008). While overprediction occurs frequently (and at times excessively), underprediction also is of concern. Because of the uncertainty in scour prediction, Hydraulic Engineering Circular No. 18 (HEC-18; Arneson and others, 2012) recommends that computed scour be evaluated for reasonableness by comparing with available historical data at or near the site of interest. Based on such an evaluation, the predicted scour can be modified if deemed appropriate. The wisdom and benefit of using historical flow and scour data to evaluate predicted scour is unquestionable. However, such data are frequently unavailable making the evaluation recommended in HEC-18 difficult, if not impossible. One way to address this issue of limited historical data is through the use of upper-bound envelope curves derived from laboratory and field measurements of abutment scour. While such envelope curves are not site (or near site) specific, they display the general trends for the upper bound of abutment scour over a wide range of conditions, providing a tool to help assess the maximum potential for scour. Envelope curves for abutment scour have been previously developed for laboratory and field data. With respect to laboratory data, Melville (1992) developed envelope curves using dimensionless variables associated with

selected laboratory data (96 measurements). With respect to field data, the U.S. Geological Survey (USGS), in cooperation with the South Carolina Department of Transportation (SCDOT), developed envelope curves for selected field data (209 measurements) in South Carolina (Benedict, 2003). These previous investigations demonstrate how envelope curves can be developed and used for assessing the maximum abutment-scour potential. To expand upon the previous work by Benedict (2003), the USGS and SCDOT initiated another cooperative investigation to compile additional laboratory and field data from other existing sources, and evaluate the upper-bound trends of abutment scour within this larger data set. A literature review was conducted to identify potential sources of abutment-scour data, and selected data were compiled into a digital database consisting of 329 field and 446 laboratory measurements. These data significantly extended the range of the data previously used by Benedict (2003) and Melville (1992), providing a means to evaluate the previously developed envelope curves. This paper presents preliminary findings providing a brief description of (1) the field and laboratory data used in the investigation, (2) the comparison of the field data with the Melville (1992) dimensionless envelope curve, (3) the evaluation of selected South Carolina abutment-scour envelope curves with additional field data, and (4) conclusions.

FIELD AND LABORATORY DATA

All of the field data, compiled from the previously noted literature review, were collected by the USGS and included 15 measurements from the USGS National Bridge Scour Database (NBSD; USGS, 2001), 92 measurements from the moderate-gradient streams of the South Carolina Piedmont with cohesive sediments (Benedict, 2003), 106 measurements from the low-gradient streams of the South Carolina Coastal Plain (none are tidally influenced) generally with sandy, non-cohesive sediments (Benedict, 2003), 93 measurements from the small, steep-gradient streams of Maine with coarse sediments (Lombard and Hodgkins, 2008), and 23 measurements from the low-gradient streams of the Alabama Black Prairie Belt with cohesive sediments (Lee and Hedgecock, 2008). Most of these data are historical scour measurements, similar to post-flood measurements, and are assumed to represent the maximum abutment-scour depth that has occurred at the bridge since construction. The field data are largely associated with clear-water scour conditions where sediments do not refill the scour holes as flood waters recede, providing justification for this assumption. Because the scour measurements were made during low-flow conditions, one-dimensional flow models were used to estimate the hydraulic properties. The post-flood nature of the scour measurements, in conjunction with the estimated hydraulics, makes these data less than ideal. These limitations should be kept in mind when using the USGS field data in any analysis. While the limitations of the USGS abutment-scour field data are acknowledged, this is currently (2015) the best available set of field data, and the large number of measurements (329) should be sufficient to gain insights into the general trends of abutment scour in the field. In addition to the USGS field data, two abutment-scour measurements at Interstate 70 crossing the Missouri River (Parola and others, 1998), associated with the 1993 flood also were included. The Missouri River data are perhaps the largest measured riverine abutment-scour depths in the United States (30 feet (ft) at the bridge and 56 ft upstream from the bridge) and were strongly influenced by a levee breach located approximately 350 ft upstream from the abutment. Additionally, the site has a drainage area of 500,000 square miles (mi^2). In contrast, the maximum drainage area for the South Carolina data is 8,830 mi^2 with a median value of approximately 100 mi^2. The adverse flow conditions and substantially larger drainage

area of the Missouri River site contribute to the larger scour depths than those of the South Carolina data. While the Missouri River data do not represent typical abutment scour, they were included in the analysis for perspective.

In addition to field data, 446 laboratory measurements of abutment scour reported by selected authors, including 96 measurements from Melville (1992), 191 measurements from Palaviccini (1993), 80 measurements from Sturm (2004), 17 measurements from Briaud and others (2009), and 62 measurements from Ettema and others (2010), were incorporated into the database. The data from Melville (1992) and Palaviccini (1993) were compiled from multiple authors of previous investigations, and are not listed here for brevity. The laboratory data are largely associated with non-cohesive sediments, with the exception of the Briaud and others (2009) investigation, which used cohesive sediments. Additionally, the data primarily represent clear-water scour conditions with the exception of 28 measurements from Ettema and others (2010) that represent live-bed scour conditions.

THE MELVILLE (1992) UPPER-BOUND ENVELOPE CURVE COMPARED WITH LABORATORY AND FIELD DATA

Melville (1992) used 96 laboratory measurements collected in rectangular flumes at threshold clear-water scour conditions to develop an envelope curve of abutment-scour depth (figure 1). The curve is based on the relation of relative scour depth (D_{sadj}/y) to relative abutment length (L/y), where D_{sadj} is the measured abutment-scour depth adjusted for the effect of abutment shape [see Melville (1992) for details on this adjustment], L is the abutment (also called embankment) length blocking flow, and y is the approach-flow depth. Melville (1992) noted that the upper bound of D_{sadj}/y generally increased with increasing L/y, and identified three abutment-length categories where the rate at which scour increased varied. These categories, identified in figure 1, included short abutments ($L/y \leq 1$) with the smallest scour potential, long abutments ($L/y \geq 25$) with the largest scour potential, and intermediate abutments between these values. The selected laboratory data from Palaviccini (1993), Sturm (2004), Briaud and others (2009), and Ettema and others (2010) also are shown in figure 1. All of the laboratory data falls within or close to the Melville (1992) envelope curve, indicating that the envelope curve is a reasonable representation of the approximate upper bound of abutment scour for laboratory data.

Figure 2 shows the previously described field data plotted with the Melville (1992) laboratory data and envelope curve. While the upper bound of the field data (4.25y) is significantly smaller than the laboratory data (11y), it is notable that this upper bound conforms well to the general shape and breakpoints associated with the Melville (1992) envelope curve. Based on this pattern, an envelope curve of the field data was drawn parallel to the laboratory envelope curve using the same breakpoint at the transition from intermediate to long abutments. The field data encompass the range of the three abutment-length categories; however, they are heavily weighted toward the long-abutment category where the potential for scour is greatest. The one Maine measurement that significantly exceeds the field-data envelope curve was collected using ground-penetrating radar (GPR), which is a useful tool for measuring scour. However, the interpretive nature of this method introduces uncertainty into the scour measurement which can lead to overestimates of scour (Benedict and Caldwell, 2009). The Missouri River data, the largest scour depths

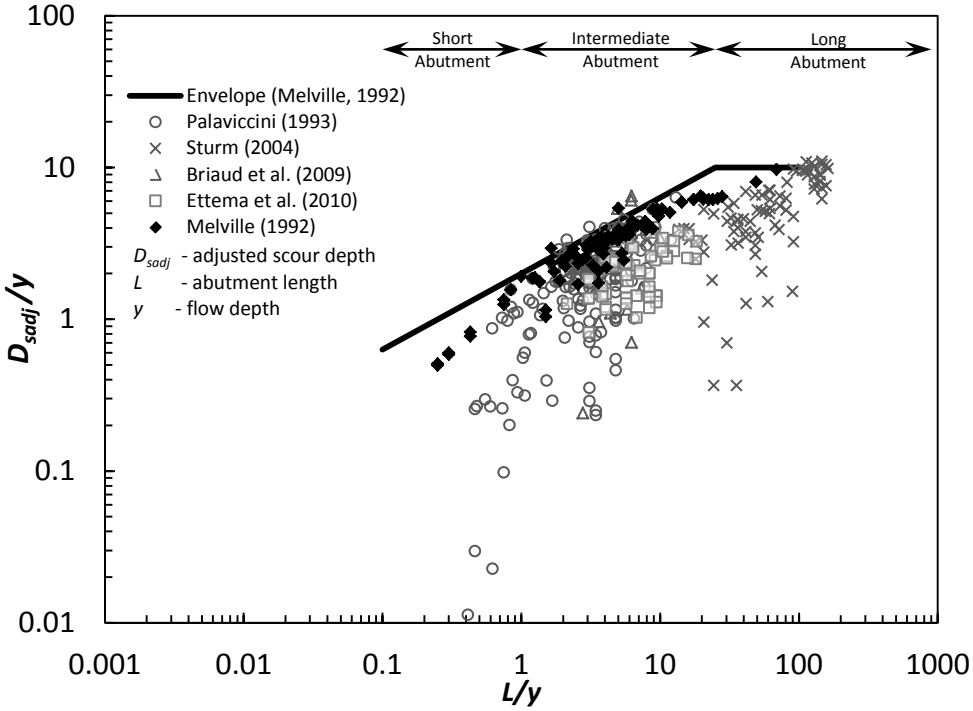

Figure 1 Relation of the relative scour depth (D_{sadj}/y) to relative abutment length (L/y), for selected laboratory data.

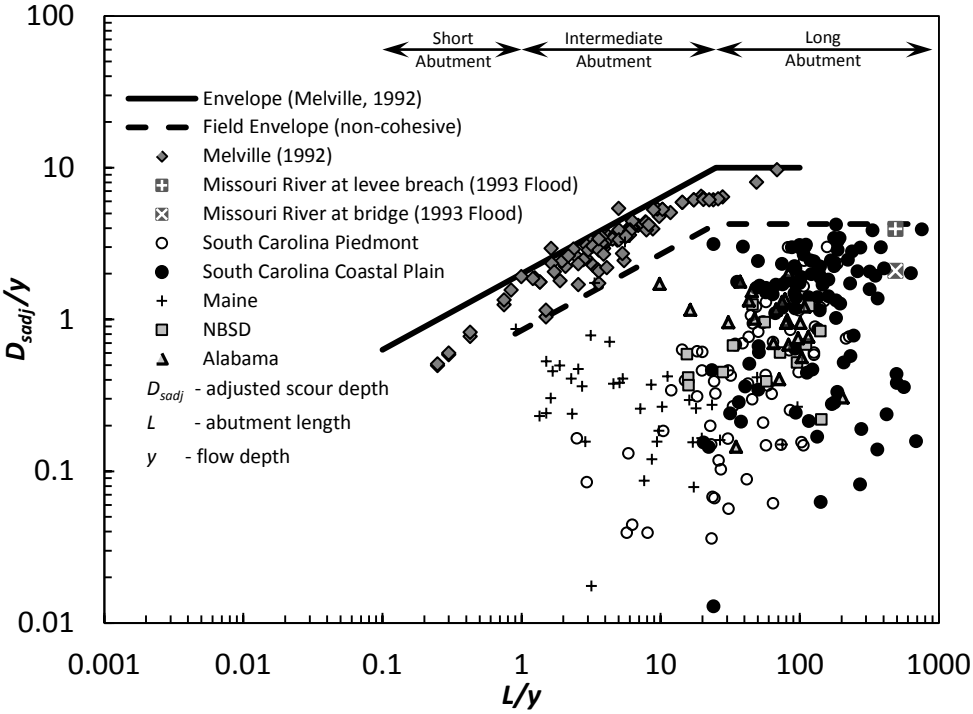

Figure 2 Relation of the relative scour depth (D_{sadj}/y) to relative abutment length (L/y), for selected laboratory and field data.

in this investigation, fall within the field envelope curve, providing a measure of confidence that the field envelope curve is reasonable. The significant difference in the upper bound of relative scour for the laboratory and field data, as shown in figure 2, is likely caused by multiple factors. The primary reasons for the discrepancy are thought to be short flow durations insufficient to produce equilibrium scour; approach-flow velocities significantly below threshold conditions for sediment motion that produce smaller scour depths than velocities at threshold conditions; and non-uniform sediments more resistant to scour.

VERIFICATION OF SELECTED SOUTH CAROLINA ABUTMENT-SCOUR ENVELOPE CURVES

Benedict (2003) used 209 field measurements of clear-water abutment scour to develop envelope curves for the Piedmont and Coastal Plain of South Carolina to be used as supplementary tools for evaluating the potential for abutment scour at bridges in South Carolina. Two envelope curves were developed for each region with one envelope curve using the geometric contraction ratio as the primary explanatory variable and the other curve using the abutment (or embankment) length blocking flow. Both variables are known to be strong explanatory variables for abutment-scour depth (Melville and Coleman, 2000; Benedict, 2003), thus providing justification for their use as explanatory variables. The geometric contraction ratio is a dimensionless variable that represents the severity of the contraction created by the bridge, with 0.0 being no contraction and 1.0 being 100-percent blockage. Larger geometric contraction ratios will tend to produce larger abutment-scour depths. The embankment length, measured from the edge of the floodplain to the abutment toe, is a relative measure of the blocked flow passing by the abutment with longer embankment lengths tending to block more flow, producing larger abutment-scour depths. As an example of these curves, figure 3 shows the South Carolina abutment-scour envelope curves with respect to the geometric contraction ratio for the Piedmont and Coastal Plain.

All of the previously noted field data are shown on this figure, with the exception of the largest Missouri River measurement, which was excluded for the purpose of the figure scale. With the exception of two data points, all of the field data falls within the Piedmont envelope curve with most of the data falling within the Coastal Plain envelope curve, providing a measure of validation for these curves. The one Maine data point that exceeds the envelope curve, as noted previously, was measured using GPR, giving some explanation for its exceedance. The exceedance of the Missouri River data can be attributed, in part, to the levee breach and the much larger drainage area, and highlights the importance of limiting the application of the South Carolina bridge-scour envelope curves to site characteristics similar to the South Carolina data used to develop them. Current guidance and limitations for using the South Carolina abutment-scour envelope curves can be found in Benedict (2003).

CONCLUSIONS

Current methods for predicting scour have some uncertainty, and therefore, should be assessed for reasonableness. One way to make such assessments is by comparing predicted scour to field measurements of historical scour. The recent investigations of scour in South Carolina

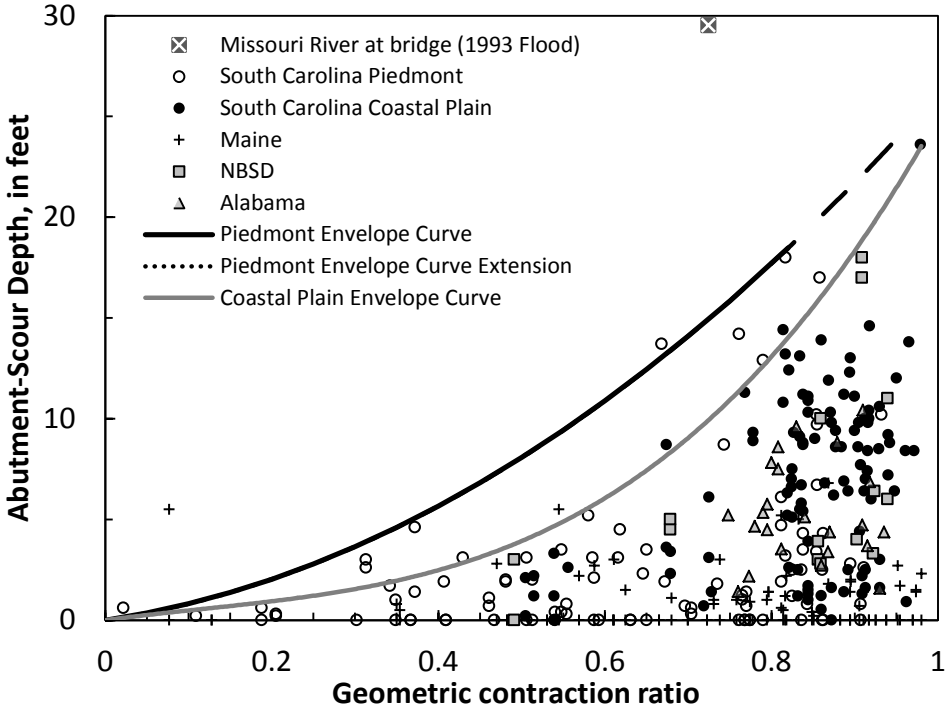

Figure 3 The South Carolina abutment-scour envelope curves with respect to the geometric contraction ratio compared with selected field data.

demonstrate how a strategic sample of historical field data can be used to develop regional bridge-scour envelope curves for assessing scour potential. The verification of these envelope curves with field data from other sources indicates that the South Carolina bridge-scour envelope curves are reflecting the upper bound of scour under field conditions in South Carolina. However, the exceedance of the Missouri River data highlights the importance of limiting the application of the South Carolina bridge-scour envelope curves to site characteristics similar to the South Carolina data used to develop the curves. A comparison of the field data with the laboratory data indicates that the upper bound of relative-scour depth in the field is significantly lower than the laboratory data, which likely is caused by the differing flow and sediment characteristics between these two environments. Because of the complexity of scour, caution and judgment are needed in the application of the envelope curves presented in this paper, and they should not be relied upon as the only tool for assessing abutment-scour potential. One can best assess anticipated scour by compiling and studying the available information for a given site, bringing sound engineering principals to bear on the final estimate of anticipated abutment-scour depth. Current guidance and limitations for using the South Carolina abutment-scour envelope curves can be found in Benedict (2003).

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