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Research Report

EVALUATING AND UNDERSTANDING OF BRIDGE SCOUR CALCULATION

Prepared by

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16. Abstract

Channel scour and channel instability at bridges are the major causes of bridge collapses caused by flooding. Currently, Departments of Transportation (DOTs) in USA use the HEC-18 procedure and associated software, which were developed for the scour depth calculation of non-cohesive soil, for scour calculation of any soil. HEC-18 provides a deterministic procedure to calculate the scour depth near a bridge site, but the procedure and the input parameter determination have various uncertainty; therefore, the calculated scour depth could be different or quite different in some cases. The type of uncertainty in HEC-18 is dealt with in this study for scour depth calculations. In order to study the soil property based uncertainty of HEC-18, the critical shear stress and critical velocities for six clay soil samples are compared to the critical shear stress and critical velocity previously obtained from the Erosion Function Apparatus (EFA). The multilayer method was proposed and tested to determine the total potential scour depth calculated using a layer-by-layer D_{50} along depth. This multilayer method can give more reasonable prediction of scour depth but requires D_{50} values up to or below the estimated scour depth. HEC-18 lacks clear instructions in determining hydraulic parameters for scour calculation in different parts of the channel cross section. Various one-dimensional models such as WSPRO and HEC-RAS can be used to determine the hydraulics of bridges. Although these models use the standard step method to solve the energy equation for gradually varied flow, these models have their own processes to solve the energy equation that are different from each other in many ways. The HEC-RAS models for four bridge sites in Alabama were developed by using the input data of the WSPRO models to calculate the hydraulic parameters needed for HEC-18 to calculate the scour depth. The differences in the hydraulic parameters and eventual scour depths were discussed and analyzed for understanding and evaluating the uncertainty of hydraulic parameters. The uncertainty of predicting and estimating the scour depth comes from various sources such as soil properties (D_{50}, critical velocity and scour rate) and hydraulic parameters. EFA testing results could help to reduce uncertainty of scour calculations.

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Channel scour and channel instability at bridges are the major causes of bridge collapses caused by flooding. Currently, Departments of Transportation (DOTs) in USA use the HEC-18 procedure and associated software, which was were developed for the scour depth calculation of non-cohesive soil, for scour calculation of any soil. HEC-18 provides a deterministic procedure to calculate the scour depth near a bridge site, but the procedure and the input parameter determination have various uncertainty; therefore, the calculated scour depth could be different or quite different in some cases. This The type of uncertainty of in HEC-18 is dealt with in this study for scour depth calculations. In order to study the soil property based uncertainty of HEC-18, theHEC-18 critical shear stress and critical velocities of for six clay soil samples are compared to the critical shear stress and critical velocity previously obtained from the Erosion Function Apparatus (EFA) to study the uncertainty of HEC-18 due to the soil property. The A multilayer method was proposed and tested to determine the total feasible potential scour depth calculated using a layer-by-layer D50 along depth. This multilayer method can give more reasonable prediction of scour depth but requires D50 values up to or below the estimated scour depth. HEC-18 lacks clear instructions in determining hydraulic parameters for the scour calculation in different parts of the channel cross sections. Various one-dimensional models such as WSPRO and HEC-RAS can be used to determine the hydraulics of bridges. Although these models use the standard step method to solve the energy equation for gradually varied flow, these models have their own processes to solve the energy equation that are different from each other in many ways. The HEC-RAS models for four bridge sites in Alabama were developed by using the input data of the WSPRO models to calculate the hydraulic parameters needed for HEC-18 to calculate the scour depth. The differences in the hydraulic parameters and eventual scour depths were discussed and analyzed for understanding and evaluating the uncertainty of hydraulic parameters. The uncertainty of predicting and estimating the scour depth comes from various sources such as soil properties (D50, critical velocity and scour rate) and hydraulic parameters. EFA testing results could help to reduce uncertainty of scour calculations.

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Chapter 1 INTRODUCTION

1.1 BACKGROUND

A bridge is a structure that is built over a railroad, water body, or road so that people or vehicles can cross from one side to the other. In the context of civil engineering, a bridge is defined as a structure built to span physical obstacles without closing the way underneath for providing passage over the obstacle. Hydraulics is a branch of science that deals with practical application (such as the transmission of energy or the effects of flow) of liquid such as water in motion (https://www.merriam-webster.com/dictionary/hydraulics). At many locations, either a bridge or a culvert will fulfill both the structural and hydraulic requirements for a stream crossing. A hydrologic and hydraulic analysis is required for designing all new bridges over waterways, bridge widenings, bridge replacements, and roadway profile modifications that may adversely affect the floodplain, even if no structural modifications are necessary.

According to the Federal Highway Administration (FHWA), in 2009, there are approximately 603,000 bridges in the national bridge inventory. Out of 603,000 bridges, roughly 83 percent are over water (Lagasse 2007). The result of water overflowing its path is, of course, flooding. Flooding can be defined as an overflowing of a large amount of water beyond its normal confines, especially over what is normally dry land. Flooding is the most common natural disaster. The Federal Emergency Management Agency (FEMA) states that about 90 percent of presidential disaster declarations involve flooding as a major component (FEMA, 1996). Scour is a phenomenon that is caused due to the high flow of water. Scour can be defined as removal of sediments such as sand and rock from around bridge abutments or piers. With 83 percent of the bridges crossing over water, scour is a major concern with high flow velocities. More than half of all bridge failures were caused by hydraulic factors (Shirole and Holt 1991). Hydraulic factors include scour, channel movement, debris or ice jam buildup, and embankment erosion due to overtopping. There does not appear to be a central database in the United States that can provide comprehensive information about bridge failure. The New York Department of Transportation (NYSDOT) compiled a nationwide list of bridge failures and reported them by categories since 1950 for a time period of 41 years (Shirole and Holt 1991) as shown in Table 1.1. In this study, scour around bridges was evaluated.

Table 1.1 Bridge failure modes.

Failure Type	Number of failures	Percentages (%)
Hydraulics	494	60
Collision	108	13
Overload	84	10
Fire	24	3
Earthquake	14	2
Other	99	12
Total	823	100

History shows that there were many bridge failures due to scour. One example is, the bridge in Schoharie Creek (Figure 1.1) which was in Albany, New York. The bridge was constructed in 1954 and collapsed in 1987 due to scour underneath pier 3. This bridge failure caused 10 fatalities with the loss of property. A bridge located in Covington, Tennessee over the Hatchie River was constructed in 1936. It collapsed in 1989 due to scour (Figure 1.2). There were 8 fatalities.

Figure 1.1 Bridge failure in Schoharie Creek

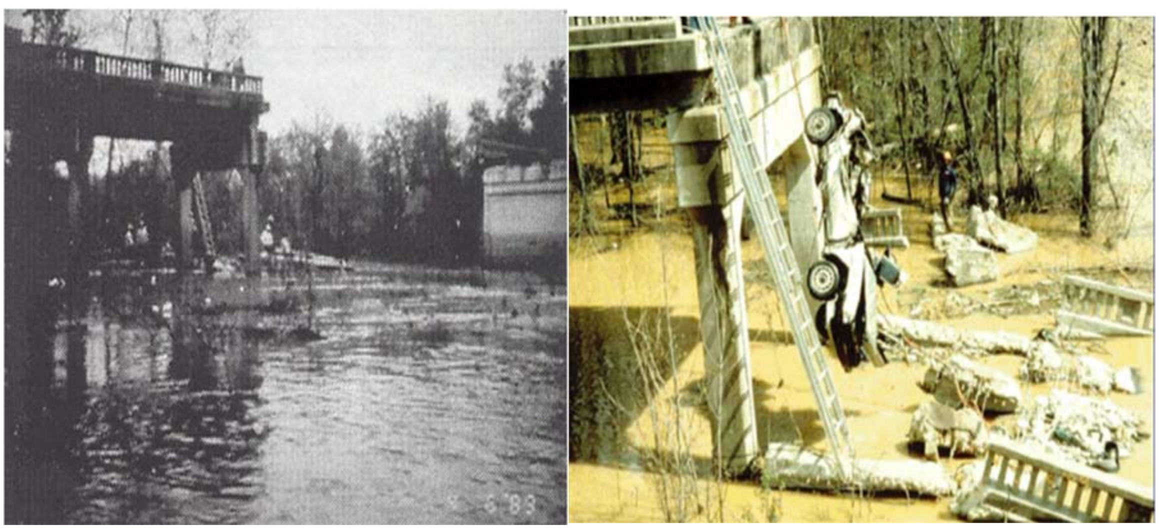

Figure 1.2 Bridge failure in Hatchie River[1]

Currently, DOTs are using the procedures presented in Hydraulic Engineering Circular 18 or HEC-18 (Arneson et al. 2012) and Hydraulic Engineering Circular 20 or HEC-20 (Lagasse et al. 2012) to calculate bridge scour. These reports recommend the scour depth be estimated based on four primary variables: channel configuration, stream velocity, soil grain size, and underlying bed material. The FHWA developed a Hydraulic Toolbox (FHWA 2014) for DOT engineers to perform various hydraulic calculations. The Hydraulic Toolbox has scour calculators that follow the HEC-18 procedures. In this thesis, the FHWA scour calculators were used to estimate the scour depth. Since the scour calculators just mathematically implement the HEC-18 procedures, in this study they are simply called HEC-18. In professional practice, DOT engineers use HEC-18 in reference

[1] The above figures and data were taken from Ms. Alacyia Hall, ALDOT, who presented the information at the 53rd annual transportation conference on February 23, 2010

to the HEC-18 procedure, report, and associated software (scour calculators). Hydraulic parameters required for HEC-18 were calculated or modeled using either the Water Surface Profile (WSPRO) (Arneson and Shearman 1998) or the Hydrologic Engineering Center-River Analysis System (HEC-RAS) (Brunner 2001) computer programs and then manually input to HEC-18 for calculating the scour depth. From version 3.0.1 (current version is 5.03) of HEC-RAS, the HEC-18 procedures were also implemented in HEC-RAS as one of the Hydraulic Design Functions – "Bridge Scour," which automatically utilizes hydraulic parameters modeled by HEC-RAS for calculating the scour depth.

1.2 BRIDGE SCOUR

There are two major components of bridge scour. One is general scour, and the other is local scour. General scour is the aggradation (accumulation) or degradation (removal) of the riverbed material and is not related to the bridge or the presence of the local obstacles. Aggradation can be defined as the gradual accumulation of the sediments on the river bed. In contrast, degradation is the gradual removal of the sediments from the riverbed. Local scour is the erosion of soil around obstacles to the water flow, such as those imposed by a bridge (Akan 2011). Local scour can be divided into three components as shown in Figure 1.3

- Contraction scour
- Pier scour
- Abutment scour

Contraction scour can be defined as the removal of sediment from the riverbed due to the contraction of the stream channel either naturally or created by the bridge approach embankment and bridge piers. Pier scour is the removal of the soil around the foundation of a pier. Abutment scour is the removal of soil around an abutment at the junction between a bridge and embankment.

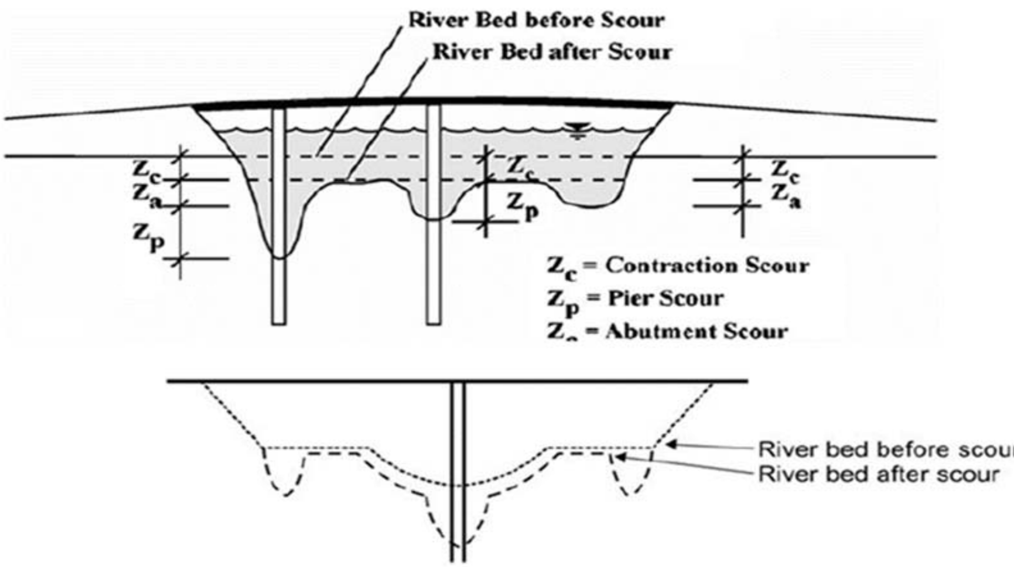

Figure 1.3 Sketch of different scour types (Briaud et al. 2009)

Only contraction scour is investigated here. There are two types of contraction scour: clear-water and live-bed. When there is no movement of bed materials in the flow upstream of the bridge or when the upstream flow velocity is less than the critical velocity, clear-water scour occurs. In contrast, when there is movement of bed materials from the upstream reach to the bridge section at a significant rate and the flow velocity is greater than critical velocity, live-bed scour occurs (Arneson et al. 2012). Critical velocity is defined as the velocity above which the bed material of a specified size and smaller will be transported. Critical velocity is one of the criteria used to determine whether the scour is live-bed or clear-water type. Equation (1.1) is used to calculate the critical velocity in HEC-18.

$$V_c = K_u y^{1/6} D_{50}{}^{1/3} \tag{1.1}$$

where y = average depth upstream of the bridge
D_{50} = mean particle size
K_u = correction factor = 6.19 $m^{1/2}/s$ or11.17 $ft^{1/2}/s$

Most of the current literature has focused on local scour. The literature presents various methods for estimating contraction scour including regime equations, hydraulic-geometry equations, numerical sediment-transport models, and contraction scour equations (Zhang et al. 2013).

Regime and hydraulic-geometry equations are empirical relationships that are used to define changes in channel geometry for given hydraulic conditions. Numerical sediment-transport models combine various sediment-transport equations with numerical hydraulic models to simulate scour processes in streams. The literature shows that the various sediment-transport equations provide significantly different estimates of sediments discharge for the same site. To assure that the results from the numerical models are reasonable, the model should be calibrated and verified with observed field data. However, sediment transport models are rarely used to estimate the contraction scour because of the time and cost associated with data collection necessary to construct, calibrate and verify these models. Also, the literature describes a number of semi-empirical contraction scour equations that were developed using laboratory tests (Zhang et al. 2013).

Similarly, many analytical equations have been primarily derived for pier and abutment scour from observations obtained from small-scale physical model studies conducted in laboratory flumes (Zhang et al. 2013). The empirical equations were developed from envelope curves or a regression analysis of dimensionless variables obtained from laboratory investigations. Several other equations were derived from field observations which were not valid or may not be applicable to other sites.

Different methods exist which were developed to predict the scour depth (Zhang et al. 2013). Significant effort and resources were devoted to study bridge scour by FHWA, state DOTs and academic institutions. Significant research has been conducted to estimate the scour at bridges, but all DOTs are not using the same design method for determining the scour depth. Scour depths at bridge cross sections are the function of stream hydraulic conditions, sediment transport by flowing water, streambed sediment properties, bridge structure dimensions and time. Numerous models and equations have been developed, but none of the equations/models developed can accurately predict the scour depth without the aid of engineering judgment.

The most widely used model is HEC-18 recommended by FHWA for calculation of the scour depth. HEC-18 was developed by assuming a uniform, unstratified, non-cohesive sediments that are representative of the most severe scour condition. However, the soils found at bridge sites could be the combination of stratified soils with varying degrees of cohesiveness.

The HEC-18 method uses the peak discharge during a flood event to calculate the hydraulic parameters needed to calculate scour. Mainly, the 100-year discharge is used, but the 500-year discharge can also be used with a factor of safety. The discharge data can be obtained from the US Geological Survey (USGS) or calculated using regression equations developed by USGS. Hydraulic analysis is performed using USGS or FHWA' s WSPRO computer program or U.S Army Corps of Engineer (USACE) HEC-RAS program utilizing the flood discharge data. The equations that are used in HEC-18 were primarily developed based on laboratory small-scale flume studies on a uniform non-cohesive soil. Thus, it can be said that the HEC-18 method tends to overestimate the scour depth as there is stratified soil with varying cohesion at actual bridge sites. This uncertainty of HEC-18 is discussed later.

Contraction scour as described earlier can be a live-bed or clear-water. The live-bed contraction scour occurs when the bed material is being transported from the upstream section of the bridge (Laursen 1962). In Figure 1.4, BU and BD are the automatically created cross-sections inside the bridge by HEC-RAS after running a simulation. BU is the cross-section passing through the upstream edge of the bridge deck but below cross-section 3. BD is the cross-section passing through the downstream edge of the bridge deck but just above cross-section 2.

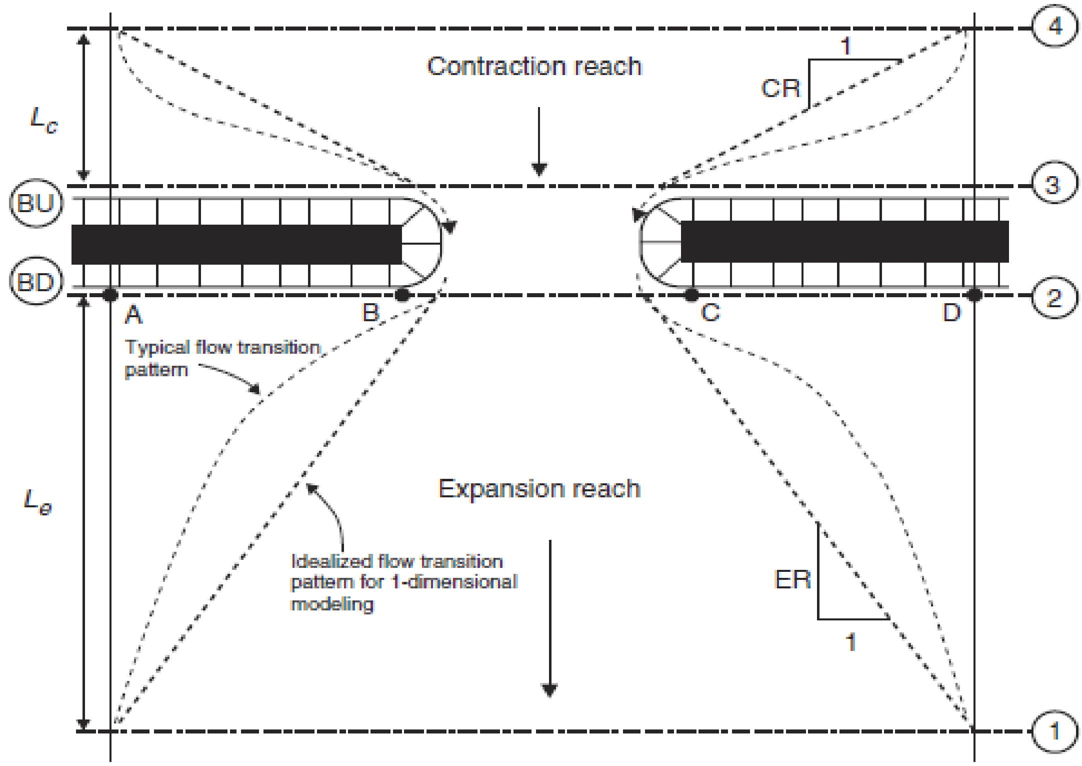

Figure 1.4 Layout of cross-section for modeling bridges using HEC-RAS (after US Army Corps of Engineers, 2002)

Equation (1.2) is used by HEC-18 to calculate the live-bed contraction scour.

$$y_s = y_4 \left(\frac{Q_{BU}}{Q_4}\right)^{6/7} \left(\frac{W_4}{W_{BU}}\right)^{k1} - y_{BU} \quad \textbf{(1.2)}$$

where

y_s = Scour depth
y_4 = Average depth upstream of the bridge (at the approach section 4 in Figure 1.4)
Q_{BU} = Discharge at contraction section (section BU in Figure 1.4)
Q_4 = Discharge at the upstream section
W_4 = Width upstream of the bridge
W_{BU} = Width at the contraction section
y_{BU} = Average depth prior to scour at the contraction section
K_1 = exponential coefficient (Table 1.2)

The value of K_1 depends upon the ratio of shear velocity (V_*) to the sediment settling velocity also known as the fall velocity (w). The shear velocity, calculated as $(gY_4 s_{f4})^{1/2}$, where g is the acceleration due to gravity, depends upon the slope of energy grade line (S_{f4}). The fall velocity depends on the D_{50} value of the bed material and the water temperature.

Table 1.2 Value of K_1 (after Richardson and Davis, 2001)

$\frac{V_*}{w}$	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

The clear-water scour equation (1.3) used in HEC-18 was derived from the bed shear stress concept by Laursen (1962).

$$y_s = \left(\frac{{Q_{BU}}^2}{C_u {D_m}^{2/3} {W_{BU}}^2}\right)^{3/7} - y_{BU} \quad \textbf{(1.3)}$$

where

y_s = Scour depth
Q_{BU} = Discharge at the contraction section (bridge crossing, i.e., BU and BD)
W_{BU} = Width at the contraction section
y_{BU} = Average depth prior to scour at the contraction section
D_m = 1.25D_{50}
C_u = 40 m/s^2 or 130 ft/s^2

Figure 1.5 shows the step by step procedure for calculating the contraction scour in HEC-18. In the flow chart, V_4 is the upstream cross-section velocity. The upstream velocity (V_4) is compared with the critical velocity (V_c) to determine the scour as either live-bed or clear-water contraction scour.

1.3 OBJECTIVE AND SCOPE

The goal of this study was to understand, evaluate, and confirm some uncertainties in the HEC-18 procedures and recommend a better method to determine the scour depth at bridge sites. The Alabama Department of Transportation (ALDOT) is using HEC-18 to calculate the scour depth for both cohesive and non-cohesive soils. ALDOT provided four bridge cases for the study. For all the bridge cases, the scour depth was calculated using HEC-18 that uses average D_{50} to determine the scour type. Also, ALDOT provided the input and output files of WSPRO models for these bridge sites. To calculate the scour depth from HEC-18 different hydraulic parameters were needed. The input and output files of WSPRO were used to build HEC-RAS models for the four bridge sites. The hydraulic parameters were calculated compared and evaluated using two computer models, WSPRO and HEC-RAS.

There are currently several hydraulic tools available for use in bridge hydraulic modeling. Each of the various methods provides its own set of guidelines and assumptions for operation. Each of the methods may give a different output depending upon the method of calculation and the set of guidelines. The objective of the study was to suggest and assist bridge engineers to use the best method among many methods available by illustrating the uncertainties in HEC-18. Since RAS is the newest, and seemingly popular, tool available for hydraulic modeling, the RAS model was used for most of the calculations in this study. RAS provides six different methods to calculate water surface profiles through a bridge reach. Some of these methods are compared as they are directly related to calculating the hydraulic parameters that in last can influence the scour depth calculation. Also, to get the same output as provided by ALDOT, WSPRO is also used in this study.

HEC-18 provides a deterministic (not stochastic) procedure to calculate the scour depth near a bridge site. Therefore, one should expect the same prediction on the scour depth at the same bridge site by different designers and engineers. If the procedure and the determination of input parameters have uncertainties, the calculated scour depth could be variable. This is the uncertainty that this study deals with. This is not a sensitivity analysis on model inputs even though the study does examine impacts of input parameters on the scour depth prediction/estimation. If there has not been the scour after the bridge is constructed, scour depth for bridge design is unknown so that it is impossible to quantify uncertainty since no observed scour depth is available to compare with calculated scour depth. For 25 Alabama bridge sites studied by Lee and Hedgecock (2008) in USGS, both observed and theoretically calculated scour depths are included, but the information cannot be directly used to compare with scour depths in this study (six soil samples collected in the field presented in Chapter 3 and four bridge study sites presented in Chapters 4 and 5).

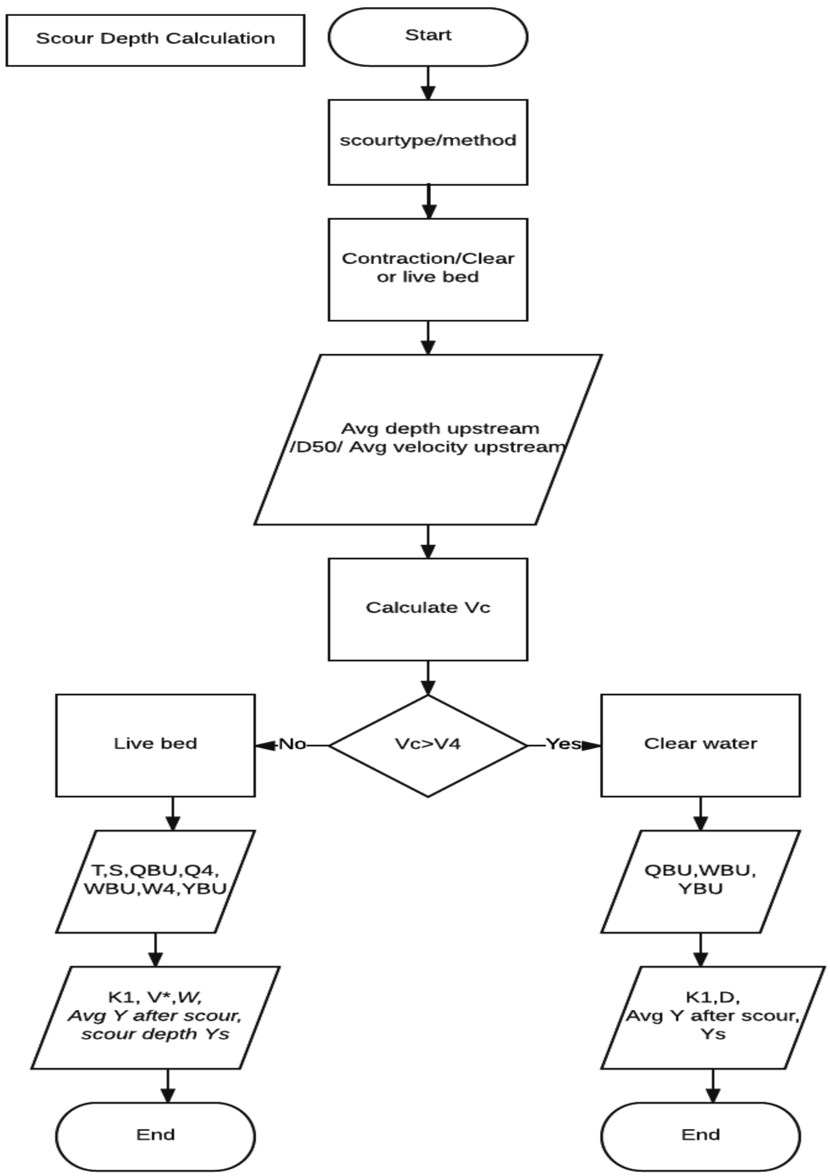

Figure 1.5 Step by step procedure of calculation of contraction scour in HEC-18.

The specific objectives of this study were:

1. To understand and evaluate uncertainties in HEC-18 using the median particle size (D_{50}) for calculation of scour depth (contraction scour only).

2. To propose and test a multilayer method for determining the total feasible scour depth and compare with the scour depths determined from HEC-18 (using average D_{50}).
3. To understand the process of calculation of water surface profiles and associated hydraulic parameters using WSPRO and HEC-RAS and to develop HEC-RAS models for the four bridge sites in this study.
4. To compare the different hydraulic parameters obtained from WSPRO and HEC-RAS models and corresponding scour depths using HEC-18 to evaluate the uncertainty of HEC-18 in scour calculation from hydraulic parameters

To accomplish the objective 1, the following tasks were completed:

1. Critical shear stresses determined from HEC-18 and EFA tests for six soil samples near bridge sites in Alabama were compared.
2. Critical velocities were calculated from the critical shear stresses determined from the EFA tests and then compared with the critical velocities from HEC-18.

To accomplish the objective 2, the following tasks were completed:

1. Mean particle sizes at different layers within the soil profiles at four bridge sites were determined and tabulated
2. HEC-18 simulations were performed, and scour depth was calculated using D_{50} for each layer.
3. A multilayer method was proposed and comparisons of scour depths were made between HEC-18 (using average D_{50} value) and the proposed multilayer method (using D_{50} values layer by layer).

To accomplish the objective 3, the following work was performed:

1. An in-depth literature review was conducted for both WSPRO and HEC-RAS model (Pokharel 2017).
2. The necessary input data were prepared, such as geometry data, reach lengths, contraction and expansion coefficients, and bridge geometry from the WSPRO input to develop HEC-RAS models for each bridge site
3. The flow distribution and water surface profile were simulated to obtain hydraulic parameters needed to calculate scour depth

To accomplish the objective 4, the following tasks were completed:

1. Hydraulic simulations at bridge sites were carried out using WSPRO and HEC-RAS
2. Different hydraulic parameters needed for scour depth calculation were extracted and compared
3. Scour depths from the hydraulic parameters of WSPRO and RAS were calculated using HEC-18 procedure and compared.

1.4 REPORT ORGANIZATION

This report is divided into six chapters. Chapter 1 covers background, scope, objectives, and overall thesis organization. Chapter 2 covers literature review on bridge scour. Chapter 3 describes the study of the uncertainty in bridge scour that could result from the HEC-18 methods when the median particle size D_{50} is used. Chapter 4 presents the proposed multilayer method for determining the scour depth considering characteristics of the soil with depth. The scour depth obtained using the average D_{50} value (traditional HEC-18 method) and the multilayer method are compared. Chapter 5 presents the comparisons of the hydraulic parameters from both WSPRO and HEC-RAS models. In addition, the differences in corresponding scour depths are also tabulated and discussed to understand and evaluate the uncertainty due to hydraulic parameters. Chapter 6 includes the overall summary, conclusions and scope for future studies.

Pokharel (2017) documented the procedure involved in WSPRO and HEC-RAS models, the use of USGS envelope curves to quantify/estimate the scour depth at a bridge site (Pintalla Creek), and the use/procedure of pug mill (Pugger Mixer) to prepare soil samples and test them in the EFA for future study. Above information associated with this study is not given in the report here but available through a Master thesis at Auburn University.

Chapter 2 LITERATURE REVIEW

2.1 LITERATURE REVIEW

An extensive literature review was conducted to study bridge scour, scour types, and issues related to bridge scour, including the concepts of bridge scour, underlying theories, and current design methods recommended by FHWA, and other agencies. The 1950's had a boom in federal transportation funding with the beginning of the United States interstate system. The research carried over into all the areas of highway design including bridge hydraulics. The FHWA is one of the organizations that is heavily involved in bridge and hydraulic research. The WSPRO computer program was developed by the FHWA in contract with USGS (Arneson and Shearman 1998).

Various methods were developed over the years to predict bridge scour. The FHWA has developed design manuals, including HEC-18, HEC-20, and HEC-23 for the state DOTs to evaluate the scour potential of existing bridges and estimate the scour depths for new bridges. The Florida Department of Transportation developed a new method based on the HEC-20 method. The Maryland State Highway Administration developed the ABSCOUR program based on research by Chang and Davis (1998), which differs slightly from the HEC-18 method. The Texas Department of Transportation also developed a scour rate based method. Texas A&M University developed the SRICOS-EFA method that focuses on pier and contraction scour in cohesive soils. Many states use the HEC-18 procedure (Arneson et al. 2012) to quantify bridge scour. The HEC-18 manual was extensively reviewed for this project.

The U.S Army Corps of Engineers is responsible for flood control in most watersheds throughout the United States. The Corps has conducted an abundance of research in the area of flood control and flood plain management. This led to the development of HEC-2, HEC-RAS, and several other related hydraulics programs. The HEC-2 and HEC-RAS programs have been used extensively to gather the data needed to perform scour depth calculations.

Since 1950, the FHWA and the U.S Army Corps of Engineers have been the major sponsors of hydraulic research. The final output of the research by both the agencies, which are used for hydraulic modeling, are used and accepted by engineers throughout the country. The programs used in this study are WSPRO by the FHWA and HEC-RAS by the U.S Army Corps of Engineers.

For the calculation of scour depth by HEC-18, a number of hydraulic input parameters are needed. These hydraulic parameters or variables can be calculated by using either the FHWA program or U.S Army Corps program. Many documents concerning the theories and equations used by RAS are available. The HEC-RAS user's manual (Brunner 2001) and hydraulic reference manual (Brunner 1995) are available for complete knowledge of RAS. The user's manual for WSPRO (Arneson and Shearman 1998) is a great help to understand and prepare the input data in a proper format. Without that manual, it would be difficult for a user to know the exact meaning of data in different columns of the text input file. Several researchers (Shearman et al. 1986; Angel and Huff 1997) have discussed the WSPRO methodology in detail. Shearman et al. (1986) provide theoretical background and data requirements for using the WSPRO method for bridge analysis. Also, they provide charts and tables for calculating the coefficient of discharge, which is one of the important parameters in WSPRO for the calculation of the hydraulic parameters and, eventually, scour depth.

Several studies were carried out to compare the outputs of HEC-RAS, WSPRO, and HEC-2. Brunner and Hunt (1995) compared the one-dimensional bridge hydraulics routines from the HEC-RAS, HEC-2 and WSPRO models for the same bridge sites. Their report discusses the similarities and differences of the fundamental computational methods of each of these models. Also, this report compares the observed water surface elevation with the computed water surface elevation from HEC-RAS, HEC-2, and WSPRO. Out of 22 bridge sites obtained from the USGS, 13 were used for the study. Also, some of them were omitted because of sparse water surface measurements near the bridge. A few sites were omitted due to inadequate bridge geometry and layout information. Almost all the events were the class A low flow (i.e., open channel, subcritical flow through the bridge opening), while three of the events had water surfaces higher than the bridge low cord on the upstream side of the bridge.

Bridge reach, transition length, cross-section spacing, and contraction and expansion coefficients (Brunner and Hunt 1995) are discussed in the literature. For one-dimensional hydraulic modeling using HEC-RAS, a bridge reach is a river segment defined by a minimum of four cross sections (Figure 1.4). The most downstream cross section (the section 1 in Figure 1.4) is located at the point where the active flow area has expanded to the full, unconstructed floodplain width, which is called the exit section in WSPRO. The most upstream cross section is located at the point where the active flow just begins to contract from the full floodplain width, i.e., section 4 in Figure 1.4, and it is called the approach section in WSPRO. It is suggested to use one cross section just upstream and downstream of the bridge, i.e., sections 2 and 3 (Figure 1.4) used in HEC-RAS, so that all the influences on the local water surface elevation are included. There are many conflicting recommendations about placing exit and approach sections in relation to the bridge. Different models use a different convention in selecting the exit and approach sections. Chow (1959) recommends the approach section be located at the upstream end point of the backwater curve, but he did not provide specific guidance as to where the point is. Matthai (1967) and Shearman et. al (1986) recommend locating the approach section one bridge length above the upstream bridge face. Shearman et al. (1986) suggest having the exit section one-bridge length below the downstream face while Matthai did not require an exit section in his procedure.

HEC-2 provides recommendations for locating the approach section and the exit section. The approach section should be located at a distance upstream equal to the obstruction length, and the exit section should be located downstream at a distance four times the obstruction length (the average of the distances A to B and C to D from Figure 1.4). The average obstruction length is half of the total reduction in floodplain width caused by the two bridge approach embankments. A more recent study discards this approach and declares this method to be inaccurate. The cross-section spacing is also an issue in hydraulic modeling. Both FHWA and HEC recommend that the cross section should be placed where there is a significant change in the channel like certain contraction or expansion. Some researchers have discussed the cross-section spacing. Brunner and Hunt (1995) determined that the location of the cross-section is more important than the type of model used. However, they do not provide guidance for this. Gates et al. (1998) provided guidance for this issue. HEC-RAS has the ability to interpolate the cross-section.

Soil exists naturally in layers or strata. Layers often have different particle sizes, due to the nature of deposition. The mean particle size is one of the important factors to determine the scour depth. Also, the scour depth at different flood events would be different. Briaud et al. (2001) proposed the SRICOS method. Their document shows the importance of considering multi-layer soil and multi-flood events. This method is limited to cylindrical piers and water depths larger than two times the pier width.

One thousand bridges have collapsed over the last 30 years in the United States and 60% of these failures are due to scour (Shirole and Holt 1991). Therefore, scour is considered as one of the major causes of bridge failure. Chang (1998) reported 25 percent of 383 bridge failures due to catastrophic floods involving pier damage, while 72 percent involved abutment damage. During the 1993 flood in the upper Mississippi and lower Missouri river basin, at least 22 of the 28 bridges that failed were due to scour at an estimated cost of more than $8,000,000. In 1994, flooding from the storm Alberto in Georgia (GA) damaged over 500 bridges. Thirty-one state-owned bridges experienced 15–20 ft. of scour and thus had to be replaced. The total damage to the Georgia Department of Transportation (GADOT) highway system was approximate $130 million (Zhang et al. 2013).

Since bridge scour is a major cause of bridge failure, bridge and hydraulic engineers are trying to design and maintain bridge foundations that are safe from scour. Bridge scour is a major factor that contributes to the total construction and maintenance cost of the bridge in the United States. Scour depth predicted using adapted methods by DOTs are crucial. Underprediction of the bridge scour depth can cause bridge failure and result in loss of lives and property. Over prediction of the bridge scour depth can cause loss of millions of dollars on a single bridge. From this viewpoint, we can say that bridge scour evaluation should be done as accurately as possible and consider a reasonable safety factor.

Different methods over the past years (Johnson et al. 2015) were developed to predict the scour depth. Although various methods have been developed to predict the scour depth, most of the DOTs in the USA are using the equations and methods given in FHWA HEC-18, which were developed for non-cohesive soils. In some laboratories, the EFA (further discussed in section 2.3) has been built/purchased and tested to measure the erosion rate of the cohesive soil. This method can be used to predict the erosion rate of the non-cohesive soil.

It is well-known that significant uncertainty exists in the use of HEC-18 equations (Johnson et al. 2015). These equations were developed based on flume tests performed on fine sand and later compared with field measurement. Those equations used in HEC-18 do not include soil parameters except the mean particle size D_{50} and make the basic assumption that all soils behave like a fine sand (Yao et al. 2014). Many research studies (Johnson et al. 2015) were carried out in the past to understand and quantify/determine the uncertainty of the HEC-18 for calculation of the scour depth. Many researchers (Breusers et al. 1977; Melville and Coleman 2000; Sturm et al. 2011) have acknowledged the uncertainty of the laboratory-derived equations. Several studies have been performed to highlight the uncertainty of HEC-18 equations by various field investigation of bridge scour. Mueller and Wagner (2005) checked the performance of 26 different pier-scour equations using 266 field measurements and concluded that none have accurately and conservatively predicted the scour observed in the field. Benedict and Caldwell (2006) assessed the performance of the HEC-18 clear-water contraction scour equation using 174 field measurements and concluded that the equation was conservative with frequent over prediction and significant numbers of under predictions. Benedict et al. (2006) assessed the performance of 6 abutment-scour equations using 209 field measurements and concluded that most of those equations were conservative with several under prediction.

Richardson and Davis (2001) notes that engineers must, "Evaluate whether the computed scour depths are reasonable and consistent with the design engineer's previous experience and engineering judgment." If the scour depth calculated is unreasonable design engineer can modify the obtained value by giving the sound engineering judgment.

2.2 SOIL TYPES

The soil is a mixture of sand, gravel, silts, clay, water, and air. Different types of soil layer are present in earth surface with different D_{50} values (Table 2.1). Depending upon the amount of these ingredients we can determine the cohesiveness of the soil. Cohesiveness can be defined as how well the soil holds together. Cohesive soil doesn't crumble. It can be molded easily when it is wet and becomes hard when it is dry. Clay is an example of cohesive soil and is a fine-grained soil. Sand and gravel are coarse-grained soil and has little cohesion or bonding, so it is often called as non-cohesive soil.

Table 2.1 Different soil types with D_{50} value.

Soil Types	D_{50} (mm)
Clay	< 0.002
Silt	0.002-0.06
Sand	0.06-2
Gravel	2-60
Cobbles and Boulders	60-200

One of the parameters involved in the erodibility of a soil is the critical shear stress (τ_c) that is the threshold shear stress at which erosion is initiated. It is assumed that if the shear stress exceeds τ_c, the soil will experience an erosion. In this framework, τ_c is considered as a soil property, which can be compared between cohesive and non-cohesive soil. The eroding mechanism of soil is different for cohesive and non-cohesive soil. In sands and gravels, which are non-cohesive, the main soil parameter influencing τ_c is the particle grain size D_{50}. In fact, in this case, gravity forces applied on soil is related to the particle size and then links or correlates to τ_c based on experimental studies of non-cohesive soils. But in the fine grained soil which is cohesive, the size of the particle only is not the good predictor of τ_c (Briaud et al. 2001a). The reason for this is that the gravity force will no longer be the only control of the soil behavior and electromagnetic and electrostatic forces become significant. Electrostatic force, also called as Coulomb force, can be defined as the attraction or repulsion of particles because of their electric charges. Electromagnetic force is a type of physical interaction that occurs between electrically charged particles. In fine-grained soil, many other factors can influence the critical shear stress τ_c. Briaud et al. (1999a) notifies some of the influencing factors including soil water content, the soil unit weight, soil plasticity, the soil mean grain size, the soil percent passing the no. 200 sieve, the soil clay mineral, the soil temperature, the water temperature, the soil cation exchange capacity, the soil sodium absorption ratio, and the water chemical composition. At this point, we can say that many differences lie in between the cohesive and non-cohesive soil and using the same equations suggested by HEC-18, which were derived based on lab experiments of non-cohesive soil, for cohesive soil will not accurately predict the scour depth.

2.3 EROSION FUNCTION APPARATUS

Calculation of scour depth around a bridge pier is a major design consideration for bridge design. All the bridge foundation design is based upon the scour of soil caused by the flow of water. The deeper the foundation the more expensive the bridge. It is, therefore, necessary to predict the scour depth with high accuracy so that the foundation design could be done accurately and effectively.

Scour in the non-cohesive soil like sand and gravel is well-understood (Briaud et al. 2001a). It is easy to calculate the scour rate in the non-cohesive soil since a single flood event can cause maximum scour depth. Clean sands and gravels erode particle by particle (Briaud et al. 2001a). Non-cohesive soils can be eroded quickly and very evenly because the only force that resists erosion is the frictional force between the grains (Briaud et al. 2001a). Unlike non-cohesive soil, the scour in cohesive soil is difficult to predict because of the electromagnetic and electrostatic forces between the particles (Briaud et al. 1999b). These forces increase the scour resistance in cohesive soil. Due to these forces, the cohesive soil can be eroded very irregularly and its erosion is slower than non-cohesive soil. An apparatus measuring the scour rate of the cohesive soil was developed by Briaud et al. (1999a) in the early 1990s called Erosion Function Apparatus (EFA).

The EFA is a closed rectangular conduit (pipe) equipped with a pump and a stepping motor. A circular opening at the bottom of the conduit is for testing the soil samples collected using the Shelby tube. The cross-section of the conduit is 101.6 mm × 50.8 mm with a total length of 1.22 meters. The tube is placed into the device and one millimeter of soil is protruded into the pipe (Figure 2.1). The velocity of the water for the test typically ranges between 0.1 to 6 m/s. The velocity is increased incrementally for testing soil sample’s erodibility at different velocities.

2.3.1 METHODS

The first step in performing an EFA test is to place the soil sample in the bottom of the conduit. The conduit is filled with water. After one hour, the flow velocity is set to 0.3 m/s and the sample is protruded 1 mm into the conduit. There is a viewing glass in EFA from which technician will view the erosion rate with respect to time. After 1 mm of soil sample eroded, or after one hour of testing whichever comes first, the sample is trimmed off and again 1 mm of the soil sample is advanced. The velocity is increased to 0.6 m/s. The erosion of the soil sample is again recorded and this process is repeated with an increase in velocity of 1 m/s, 1.5 m/s, 2 m/s, 3m/s, 4.5m/s, and 6 m/s (Briaud et al. 2001a).

2.3.2 EFA RESULTS

The test result consists of erosion rate (mm/hr) and shear stress (Pa). The erosion rate is obtained by simply dividing the length of the soil sample eroded by the time required to do so for each velocity.

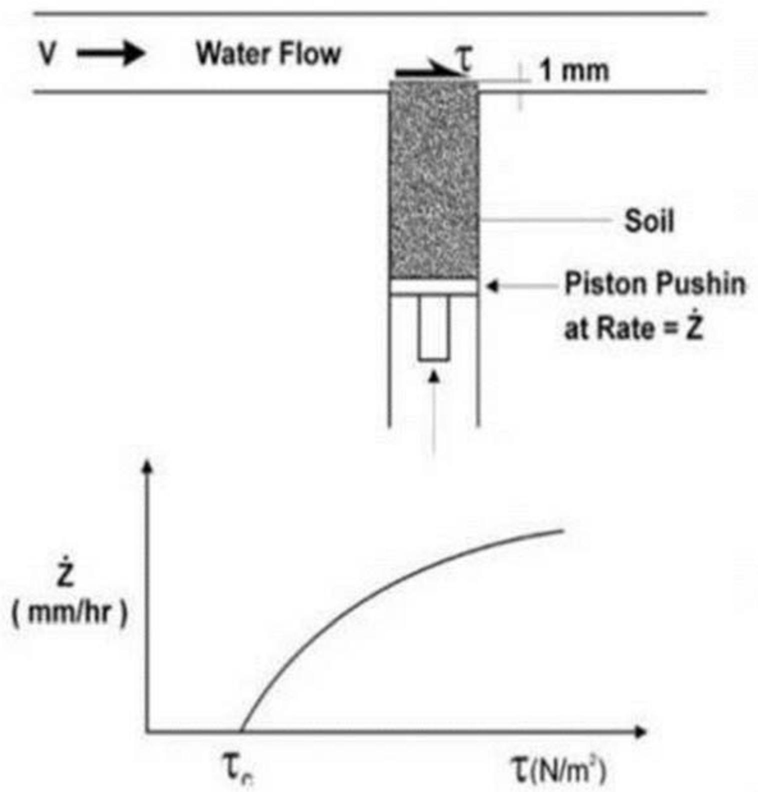

Figure 2.1 Erosion Function Apparatus to measure erodibility (Briaud et al. 1999a)

$$z = \frac{h}{t} \quad \textbf{(2.1)}$$

where *h* is the length of the sample eroded in time *t*. A different method was used for the calculation of the shear stress. After several attempts at measuring the shear stress, it was found that the best way to calculate shear stress τ for the EFA was by using the Moody's diagram (Briaud et al. 2001a).

$$\tau = \frac{1}{8} f \rho v^2 \quad \textbf{(2.2)}$$

where τ is the shear stress on the wall of the pipe, *f* is the friction factor obtained from the Moody diagram, ρ is the mass density of the water (1,000 kg/m^3), and v is the mean flow velocity in the pipe. The friction factor f is the function of the Reynolds number R and relative roughness $\mathcal{E}/\mathrm{D}$. The Reynolds number is a dimensionless value that measure the ratio of inertial force to viscous force and describe the degree of laminar or turbulent flow. The relative roughness is the ratio of the average height of the roughness elements on the pipe surface over the pipe diameter D. The average height of the roughness element ε is taken equal to 0.5 D_{50}. It is used because it is assumed that the top half of the particle protrudes into the flow while the bottom half is buried into the soil mass (Briaud et al. 2001a).

2.4 CLEAR-WATER SCOUR IN 25 ALABAMA BRIDGES

The U.S Geological Survey, in cooperation with the ALDOT, made observation of clear-water contraction scour at 25 bridge sites in the Black Prairie Belt of the Coastal Plain of Alabama (Lee and Hedgecock 2008). The theoretical clear-water contraction scour depths calculated using HEC-18 were compared with the observed scour depths (Figure 2.2). The observed scour depths ranged from 1.4 to 10.4 ft. The bridge sites that were studied have a mixture of grassland and wooden areas in the floodplain. In the USGS study, two assumptions were made: (1) the data collected were reflective of unaltered, clear-water scour; (2) the measured scour hole has reached its maximum depth and is at equilibrium. The observed scour depths were neither measured during or directly after a flood event. The observed scour depths were measured using an electronic total station. At first, several representative ground shots of the unscoured floodplain on both the upstream and downstream sides of the bridge opening were taken. A regression technique was used to develop a best-fit ground line on either side of the bridge opening. The maximum scour depth for a particular site was determined by finding the maximum difference between the estimated unscoured ground line and ground points surveyed in the bottom of the scour hole. A common level rod was used to measure the maximum deepest areas of the scour hole. The theoretical clear-water contraction scours were computed for the 50-years recurrence interval flood with the assumption that every bridge site selected have once experienced a 50-year flood flow.

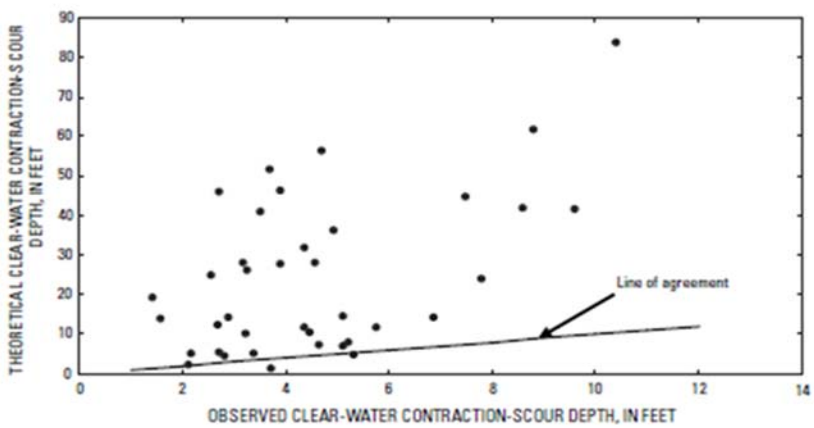

Figure 2.2 Comparison of observed and theoretical scour depth (Lee and Hedgecock 2008)

The comparison of the theoretical and observed scour depths showed the difference ranging from 73 ft to -2.5 ft with an average difference of ~20 ft. The comparison between theoretical and observed scour depths indicates that the theoretical clear-water scour depths were, on average, about 475 percent higher than the actual observed scour depths in the overbank areas.

Chapter 3 EVALUATING UNCERTAINTY IN BRIDGE SCOUR USING HEC-18 AND MEAN PARTICEL SIZE

3.1 INTRODUCTION

Uncertainty simple means lack of certainty, a state of limited knowledge where it is impossible to exactly describe the existing state, a future outcome, or more than one possible outcome. HEC-18 needs soil parameter D_{50} and hydraulic parameters for the calculation of the scour depth. The input variables for HEC-18 are not precisely known since they are not typically measured/observed or can be obtained/selected in various ways due to lack of guidance. There is usually an uncertainty in determining and specifying their values. The degree of uncertainty may vary from one variable to another. The HEC-18 equations were derived based on the lab experiments done on non-cohesive soils and is being used for calculation of scour depth for cohesive soils too. The soil parameter such as critical velocity for cohesive and non-cohesive soil is different and plays an important role in predicting the scour depth. However, HEC-18 equations only use D_{50} solely as the representation of the soil parameter. D_{50} is the grain diameter for which half the sample (by weight) is smaller and another half is larger.

This part of the study was carried out to identify and illustrate some uncertainties existing in HEC-18 by comparing the critical velocities and shear stresses obtained from HEC-18 (using D_{50}) and EFA. Even we got some basic soil data (e.g., D_{50}) for the four bridge sites from ALDOT where the scour depths were previously determined using HEC-18, the research team and ALDOT did not have specific funds to obtain soil samples from these four bridge sites for determining critical velocities and shear stresses using EFA. Therefore, an alternative approach was used in this study, i.e., using six soil samples obtained from a previous ALDOT project (Anderson et al. 2015), which were from or near Alabama bridge sites.

The EFA data were taken from a published report by Anderson et al. (2015). In that study, ten cohesive soil formations were sampled and tested in an updated EFA. Several geotechnical properties of the soil samples were determined experimentally and were correlated to measured scour rate determined using EFA. Velocity- and shear-based erosion functions were generated for the seven erodible soil samples (other three soil samples were classified as scour-resisted). Shear stress is related to velocity by using the geometry of the conduit, density of water, and friction factor obtained from the Moody diagram. The median grain particle size, critical velocity (V_c), and shear stress ($\tau_{c\text{-}EFA}$) obtained from EFA for six soil types are shown in Table 3.1.

3.2 COMPARISON OF CRITICAL VELOCITY AND SHEAR STRESS

In HEC-18, the critical velocity plays a vital role in determining the scour depth. If the flow velocity is above the critical velocity, then scour occurs. The critical velocity should be determined accurately otherwise, scour depth could be overestimated or underestimated. The critical velocity in the scour related studies is defined as the velocity above which the bed material of a specified size and smaller will be transported.

Table 3.1: Summary of data taken from EFA for six soils.

Soil Type	D_{50} (mm)	Critical velocity V_c (m/s)	EFA's Critical Shear Stress $\tau_{c\text{-}EFA}$ (N/m^2)
Naheola-Dark	0.016	0.59	1.15
Naheola-Yellow	0.028	0.65	0.41
Bucatunna	0.033	0.39	0.53
Nanafalia	0.080	0.42	0.63
Porter's Creek	0.082	0.20	0.16
Yazoo	0.088	0.47	0.79

In HEC-18 the critical velocity is determined from the equation developed by Laursen (1963). The derivation of the critical velocity equation is given below. The average bed shear stress on the channel bed is expressed as (Chow 1959)

$$\tau_0 = \gamma R S_f \tag{3.1}$$

where τ_0 is the average shear stress, R is the hydraulic radius, S_f is the friction slope, and γ is the specific weight of water (~62.4 lbf/ft^3 or 9.81 kN/m^3).

Using Manning's formula to evaluate the frictional slope and approximating the hydraulics radius by flow depth (e.g., wide rectangular channels), Equation (3.1) can be written as,

$$\tau_0 = \frac{\gamma n^2 V^2}{{k_n}^2 y^{1/3}} \tag{3.2}$$

where n is Manning's roughness coefficient, k_n is 1.0 m$^{1/3}$/s for SI units or 1.49 ft$^{1/3}$/s for engineering units, y is the flow depth and V is the mean velocity of the flow.

Shields (1936) conducted experiments of incipient motion to determine the relationship between the Reynolds number $\frac{VD_s}{\gamma}$ and $\frac{\tau_0}{(\gamma_{s-\gamma})D_s}$, known as the shield relation. The study has four parts of which the second part considers primary the conditions at the beginning of bed-load movement. The study considered the grains of uniform sizes and investigated: when the grain be dislodge from the bed and set in motion. From the Shield relation (Shields 1936), the critical bed shear stress can be expressed as,

$$\tau_c = k_s(\gamma_s - \gamma)D_s \tag{3.3}$$

where τ_c is critical shear stress, k_s is Shield's coefficient, D_s is particle size, γ_s is specific weight of the sediment particle. The motion of the sediment particle is initiated when $\tau_0 = \tau_c$, so that the critical velocity can be determined by equating right hand sides of both equations (3.2) and (3.3) and solving for $V = V_c$

$$V_c = \frac{k_n}{n}\sqrt{k_s(s-1)}\, y^{1/6} {D_s}^{1/2} \tag{3.4}$$

where s = γ_s / γ is specific gravity of the soil particles. Substituting D_{50} for D_s and using Strickler equation (Chow 1959) $n = 0.034(k_v D_{50})^{1/6}$ with k_v = 3.28 m^{-1} = 1.0ft^{-1}, one obtains

$$V_c = K_u y^{1/6} {D_{50}}^{1/3} \tag{3.5}$$

where $k_u = k_n\{k_s(s-1)\}^{1/2}/\left(0.034{k_v}^{1/6}\right)$ is a constant equal to 6.19 m$^{1/2}$/s or 11.17 ft$^{1/2}$/s when the Shield's coefficient of 0.039 is used (Akan 2011), the specific gravity is assumed as 2.65, D_{50} is the median particle size, and y is the average water depth upstream of the bridge contraction. Equation (3.5) is used in HEC-18 for the calculation of the critical velocity using necessary inputs: D_{50} and y.

In Table 3.2, the critical shear stress obtained from EFA (τ_{c2}) is compared to the critical shear stress obtained from the HEC-18 (τ_{c1}) using D_{50} as input. The ratio of τ_{c2}/τ_{c1} ranges from 3.2 to 115 with an average of 31.8 and standard deviation of 37.9; therefore, it means for these clay soils the critical shear stress from HEC-18 is significantly smaller than the critical shear stress determined using EFA tests. When the critical shear stress calculated from HEC-18 is used, the scour would start at lower upstream velocity and the scour depth could be overestimated.

The critical velocity for an EFA test is determined by changing the testing velocity in the conduit and then visually identifying whether the soil sample erosion starts or not. For modified EFA, the soil erosion was determined by distance measurement using ultrasonic sensors (Walker 2013). The critical velocity in HEC-18 is linked with D_{50} and water depth (y) in channel where the bridge locates. Therefore, comparing the critical velocity from EFA (flow velocity in the conduit) with

Table 3.2 Comparison of critical shear stress from EFA and HEC-18

Soil Type	D_{50} (mm)	Critical Shear Stress for HEC-18 (N/m^2) (τ_{c1})	EFA's Critical Shear Stress $\tau_{c\text{-}EFA}$ (N/m^2), (τ_{c2})	Ratio (τ_{c2}/τ_{c1})
Naheola-Dark	0.016	0.01	1.15	115
Naheola-Yellow	0.028	0.02	0.41	20.5
Bucatunna	0.033	0.02	0.53	26.5
Nanafalia	0.080	0.05	0.63	12.6
Porter's Creek	0.082	0.05	0.16	3.2
Yazoo	0.088	0.06	0.79	13.2

Note: critical shear stress from HEC-18: $\tau_c = k_s\, \gamma(s-1)\, D_{50}$ and $k_s = 0.039$, $s = 2.65$

the critical velocity obtained from the HEC-18 is not considered feasible. To compare the critical velocities obtained from EFA and HEC-18 equations, the above derivation was modified. Substituting the critical bed shear stress into Equation (3.4), one can get the relation of V_c and τ_c:

$$V_c = \frac{k_n}{n} * \sqrt{\frac{\tau_c}{\gamma}} * y^{\frac{1}{6}} \tag{3.6}$$

Manning's roughness factor n can be determined from Strickler's equation as function of D_{50} (Akan 2011). Equation (3.6) was used to calculate the critical velocity using the shear stress and D_{50} values obtained in EFA tests.

The critical velocity calculated from HEC-18 and the critical velocity using $\tau_{c\text{-}EFA}$ and D_{50} (Table 3.3) are compared when the upstream water depth (y) is taken as constant equal to 4 m (close to water depth in Spear Creek main channel, Table 3.4) and 1.5 m (close to water depths in Spear Creek overbank areas, Table 3.4) for all calculations. The ratio of V_{c2}/V_{c1} ranges from 1.7 to 10.4 with an average of 4.8 and standard deviation of 2.7. This means for the clay soil samples the critical velocities calculated from HEC-18 are significantly smaller than critical velocities calculated using τ_c determined using EFA and D_{50}. Table 3.3 shows that the critical velocities calculated from HEC-18 equation using same D_{50} value and different upstream average depths (4 m for channel and 1.5 m for overbank areas) are somewhat different since they are proportion to $y^{1/6}$. When the particle size D_{50} ranges from 0.016 to 0.088 mm, the critical velocity from HEC-18's equation (3.5) changes from 0.2 to 0.35 m/s (proportion to $D_{50}^{1/3}$) and shows an impact of D_{50} on calculating the critical velocity then the scour depth. For example, for the bridge site in Spear Creek, the velocity at the upstream approach section (V_1) calculated using WSPRO is 0.72 or 0.97 ft/s (0.22 or 0.29 m/s) in the overbank areas and 3.35 ft/s (1.02 m/s) in the main channel (Table 3.4).

Table 3.3 Critical velocities from EFA data and from HEC-18

Soil Type	D_{50} (mm)	V_{c1} (HEC-18) Eqn. (3.5) (m/s)	V_{c2} using $\tau_{c\text{-}EFA}$ and D_{50} Eqn. (3.6) (m/s)	Ratio V_{c2}/V_{c1}
Naheola-Dark	0.016	0.20 (0.17) [1]	2.07 (1.76)	10.4
Naheola-Yellow	0.028	0.24 (0.20)	1.13 (0.96)	4.7
Bucatunna	0.033	0.25 (0.21)	1.25 (1.06)	5.7
Nanafalia	0.080	0.34 (0.29)	1.17 (1.00)	3.4
Porter's Creek	0.082	0.34 (0.29)	0.59 (0.50)	1.7
Yazoo	0.088	0.35 (0.30)	1.29 (1.10)	3.7

Note: – [1] the water depth y in Equations (3.5) and (3.6) was assumed as 4.0 m for the comparison purpose. The critical velocity inside brackets was computed using y = 1.5 m.

Based on Table 3.3 **Error! Reference source not found.**for six soil samples, V_C from Equation (3.6) is always greater than the upstream approach-section velocity V_1 in overbank areas, but V_C from Equation (3.5) could be greater or less than V_1. When overbank areas are heavily vegetated, current DOT practices force or always use the clear-water scour to compute the scour depths in overbank areas. Therefore, the critical velocity linked to the particle size does not play a role to determine which type of the scours occurs in the overbank areas, but the particle size D_{50} directly affects the scour depth calculation based on Equation (1.3).

For the main channel, V_C obtained from HEC-18 Equation 3.5 is less than V_1 so that it would be a live-bed scour. Table 3.4 shows the scour depth of 7.74 ft calculated using default method from HEC-18, which allows HEC-18 to determine whether or not the clear-water or live-bed scour would occur. HEC-18 results show the live-bed scour would occur. However, V_C obtained from Equation 3.6 is greater than V_1 for same channel section so that it would be a clear-water scour. The particle size D_{50} has a direct impact on calculating the clear-water scour depth (Equation 1.3), i.e., proportion to $1/D_{50}^{2/7}$. The scour depth calculated using the clear-water scour would result in 47.76 ft of scour depth in the main channel. This is a huge difference in calculated scour depth. This example is to illustrate the uncertainty in HEC-18 equation.

Why is the scour depth calculated by the clear-water scour much different from the scour depth calculated by the live-bed scour? For the live-bed scour, hydraulic parameters at the upstream approach section and the contraction section (bridge crossing) play a role in calculating the scour depth at the bridge site. If $V_1 > V_c$ at the upstream approach section for the live-bed scour, V_2 is definitely greater than V_c at the bridge contraction section (Table 3.4); it means the scour occur at both approach and contraction sections, which is why both hydraulic parameters at both sections are used for the scour computation. The soil scoured from the approach section becomes the supply of soil for the contraction section; therefore, the total or overall scour at the bridge site is smaller, e.g., 7.74 ft at Spear Creek under the 100-year flood.

The ratio of hydraulic parameters between the contraction section (i.e., the cross section 2 used for the following discussion) and the approach section would be small such as Q_2/Q_1 = 1.59 and W_1/W_2 = 1.10, when these ratios are multiplied it will give a small value for determining water depth after the live-bed scour (Equation 1.2). Subtracting Y_0 the depth at the contraction section prior to scour would give the final scour depth of a live-bed scour; therefore, the scour depth for the live-bed scour is much smaller. For clear-water scour only the ratio of Q_2 and W_2 at the contraction section is used which gives greater value of the water depth after the scour (Equation 1.3). The ratio of the hydraulic parameter, i.e., $(Q_2^2/W_2^2)^{6/7}$ is greater and equals to 43.37 in Spear Creek. The ratio of other parameters, i.e., $(1/C_u{*}D_m^{2/3})^{3/7})$ is just 1.44. When this ratio is multiplied by the ratio of hydraulic parameters the result would be 62.04 which when deducted from Y_0 (14.28 ft) would give a scour depth of 47.76 ft. This calculation and comparison to the live-bed scour depth clearly shows the uncertainty of HEC-18 equations.

From the comparison in Table 3.4, a firm conclusion can be drawn regarding the use of the HEC-18 equation in calculating the scour depth of cohesive soil. The critical velocity and critical shear stress obtained from the HEC-18 for soils with small D_{50} is far less than those obtained from EFA. The critical velocity is used in HEC-18 to determine the types of contraction scour (live-bed and clear-water). The possible change in type of contraction scours would cause a change in scour depth estimate as the equation used in calculating the scour depth would be different (Arneson et al. 2012). The meaning of smaller critical velocity is that the scour will occur earlier than it should be which will overestimate the scour depth. The effect of the change in the type of equations used would have a huge effect in the scour depth. The difference in the scour depth using two different equations is 35.63 ft for the main channel in Spear Creek, which is a huge difference. It is well-known that determination of accurate scour depth is imperative to designing safe and economic bridge foundation. HEC-18 compared to EFA predicts higher scour depth that leads to extra cost and not economic bridge foundation. It can also be concluded that HEC-18 equations, which are developed based on the experiments done on non-cohesive soil, do not account well for cohesive soil. This information is very important in scour calculation because, if cohesive soils are encountered at a bridge site, scour will occur at a much lower rate than that is given by the HEC-18 equation.

Table 3.4 Hydraulic parameters in Spear Creek from WSPRO method

Hydraulic Parameters	LOB [3]	CH [3]	ROB [3]
Y_1 (ft) [1]	3.56	13.75	5.38
V_1 (ft/s)	0.72	3.35	0.97
Y_o (ft) [2]	4.02	14.28	5.14
Q_2 (cfs)	514.12	2357.13	948.75
W_2 (ft)	41.00	29.00	50.00
V2 (ft)	3.12	5.69	3.69
D_{50} (mm)	0.03	0.047	0.055
Scour Eqn.	Clear-water	Default	Clear-water
Q_1 (cfs)	1347.64	1473.89	998.48
W_1 (ft)	290.00	32.00	100.00
Scour (ft)	10.25	7.74 (47.76) [4]	11.97

Note: [1] – the subscript 1 for the upstream approach section, 2 for the contraction section at the bridge crossing, [2] - Y_0 is the average depth prior to scour at contraction section, i.e., Y_{BU} in Equations (1.2) and (1.3); [3] – LOB for the left overbank, CH for the main channel, and ROB for the right overbank area of a floodplain; and [4] – the number in the bracket is for the scour depth calculated using the clear-water scour equation (1.3).

3.3 DISCUSSION

The equations for the HEC-18 to calculate critical velocity were derived from the laboratory experiments using non-cohesive soil and only should be used for non-cohesive soil for the calculation of the scour depth. For the cohesive soil, other methods like using EFA data should be considered/used which give more reliable values. For the calculation of the scour depth, HEC-18 uses one median particle size D_{50} of the bed material. Only taking D_{50} of a bed material in the calculation of the scour depth could either underestimate or overestimate the scour depth.

Two different soil samples, which have different percentage of sand, clay, and silt, could have same D_{50} value as illustrated in Figure 3.1. The critical shear stress and velocity for initiating scour on those two samples could be different and could result in different scour depths under the same flood. The sample 2 has more fine-grained soil (30% clay, $D_{50} \leq 0.002$ mm) compared to the sample 1, which has less fine-grained soil as shown in Figure 3.1. Sample 2 having more clay would erode slowly compared to sample 1. However, if HEC-18 is used for the calculation of the scour depth it would only consider D_{50}, which is same for both soil samples, and give same prediction of the scour depth. This hypothetical example further illustrates the uncertainty of HEC-18 equations.

HEC-18 manual should give clear definition and instructions how to determine the hydraulic and soil parameters used. This could help the new engineers to correctly/accurately quantify the parameter data they should acquire to calculate the scour depth. EFA as one of the reliable methods could be used to determine critical velocities and shear stresses for both cohesive and non-cohesive soil. EFA results can be used to calculate the scour depth based on the relationship between the erosion rate and the hydraulic shear stress applied. EFA can be a very useful tool for designing bridges. It is used to determine the critical velocity and shear stress using a relatively undisturbed, site-specific soil sample. This apparatus should be part of a complete procedure to predict the scour depth.

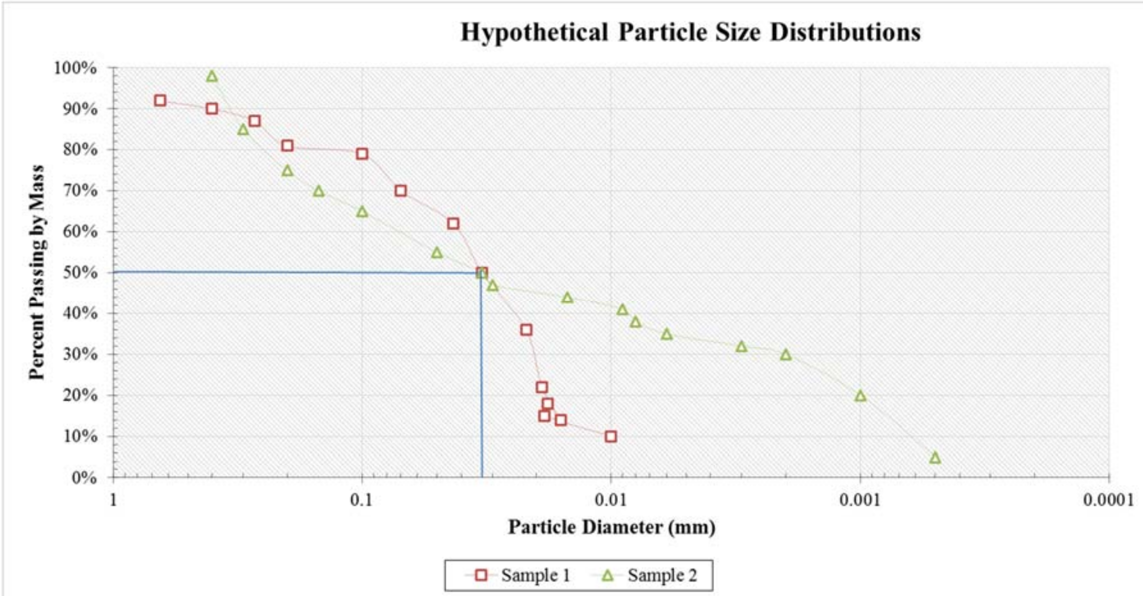

Figure 3.1 Hypothetical particle size distributions with same D_{50}.

Chapter 4 MULTILAYER METHOD AND COMPARISION OF SCOUR DEPTHS FROM HEC-18

4.1 INTRODUCTION

Scour is crucial in designing bridge foundation. The bridge foundation is the pillars where the heavy mass of bridge deck resists on. The bridge foundation is constructed on the earth surface and penetrated to a certain depth. There are different soil types in earth surface with different D_{50} values (Table 2.1). At a bridge site, different soil layers along depth may exist with different D_{50}.

D_{50} is one of the important parameters to calculate the scour depth using HEC-18. One of the reasons of bridge failure is the stratification of the river bed. Stratification of soils means the arrangement of soils in different layers with different D_{50} values at different depths. In the same zone (e.g., left or right overbank area or main channel) where the soil samples are taken, there are several D_{50} values from different sample sites. At the same sample site, there could be clay layers, which have smaller D_{50}, or sand or gravel layers having higher D_{50}. HEC-18 lacks specific instructions on whether average surface D_{50} or average D_{50} at certain depths to be used to calculate the scour depth. This uncertainty could result in either over prediction or under prediction of the scour depth.

From the literature analysis, it is known that either the top soil layer data or the average of the soil data in the river bed is considered while calculating the scour depth. In the complex geological structure of the river bed with different soil layers, calculated depth of scour may increase or decrease, depending on the thickness and sequence of the layer. Using the top layer D_{50} or the average of them along the layers could result in wrong scour depth and possible structures destruction. For example, the depth of scour is always greater when a fine sand layer is under a coarse-sand layer(s), compared with the depth of scour obtained with mean grain size diameter of the coarse-sand layer, which is on the top (Gjunsburgs et al. 2013). When a fine sand layer is under a coarse-sand layer, critical conditions can occur. When the coarse-sand layer is scoured, the depth of scour is rapidly developing in the next fine-sand layer. In this case, the dominant grain size for computing the depth of scour at foundations under stratified bed conditions is the mean diameter of the second layer or of the next one, where scour stops (Gjunsburgs et al. 2014). Thus, the calculation of scour depth taking only one-grain size diameter of the soil can lead to unbearable damage of the structure.

The aim of the following study is to elucidate the influence of the river bed stratification on the scour depth calculation by comparing the scour depth obtained from the HEC-18 model (using average D_{50} value) with the scour depth using a layer by layer D_{50} value, i.e., multilayer method proposed and tested through this study. The average D_{50} used for HEC-18 in this study was determined by doing the average of D_{50} in all layers provided in the bridge cases from ALDOT. For the ALDOT practice, average D_{50} is determined after removing some outliers from D_{50} in all layers based on engineer's experience. Due to not enough information on which D_{50} value ALDOT took as outliers, all the given D_{50} values were averaged and used for the calculation of scour depth. The comparison of scour depths calculated using with or without outliers was also made to illustrate the uncertainty of the scour depth calculation due to using the average D_{50}.

In this part of the study, soil data (D_{50}) at different depth layers collected by ALDOT from four bridge sites were used to test and evaluate the multilayer method proposed in this study. For bridge design projects, it typically does not have any observed scour depth from any previous flood for comparison. Therefore, scour depths obtained from the HEC-18 model and the multilayer method were compared each other, but it is impossible to conclude which scour depth is more accurate. However, this analysis and discussion can still infer which scour depth could be more reasonable or a better estimate.

4.2 STUDY AREA

In this study, reports and related information for four bridge sites that had scour estimations were provided by ALDOT along with the input and output files of the WSPRO model. The bridge site provided were of Spear Creek located in Choctaw County, Valley Creek located at Dallas County, Pintalla Creek located at Cantelous County, and Alamuchee Creek located at Sumter County, Alabama.

Spear Creek is a small perennial stream located in the city of Butler on SR-10, Choctaw County. Spear Creek has a narrow floodplain with a drainage area of 9.4 square miles upstream the bridge. The channel is roughly thirty feet wide and ten to twelve feet deep. There is thick tree undergrowth line in the channel banks. The channel is sinuous through this reach and appears entrenched. The channel boundaries are semi-alluvial with little or no natural levees through this reach of the stream (Figure 4.1).

Valley Creek is a small perennial stream with a narrow floodplain that is located in the city of Selma, Dallas County with a drainage area of 63.5 square miles. The channel is roughly eighty feet wide and six to eight feet deep. There are trees and thick undergrowth in the channel banks (Figure 4.2).

Pintalla Creek is a medium perennial creek with a wider floodplain that is located in the line of Montgomery and Lowndes County with a drainage area of 250 square miles at the bridge crossing. The channel is roughly ninety-one feet wide and eighteen to nineteen feet deep. The channel boundaries are alluvial. There is thick tree undergrowth line in the channel banks and cover the floodplain. The stream is highly meandering (Figure 4.3).

Alamuchee Creek is a small perennial stream with a wide floodplain with a drainage area of 62.3 square miles, which is located in Sumter County. The channel is approximately seventy feet wide and eight to ten feet deep. There is thick tree undergrowth line in the channel banks and cover the floodplain. The stream is meandering (Figure 4.4).

4.3 SITE AND SOIL INFORMATION OF SPEAR CREEK

As an example, detailed site and soil information provided by ALDOT for the bridge at Spear Creek is summarized below, and similar information for other three bridge sites is also used for the study but not presented here. ALDOT, on September 18, 2008, started a project to replace the existing bridge on SR-10 over Spear Creek. WSPRO was used to compute the water surface profile of Spear Creek by ALDOT. The input and output data files of the WSPRO model along with the detail of the bridge stationing and boring values at different sample sites around the bridge were used for this study. Figure 4.5 shows the cross section of the Spear Creek bridge: solid line is at the riverbed bottom elevation, short dashed line shows projected scour depth at 100-year flow; and long dashed line shows projected scour depth at 500-year flow. Those scour depths were calculated by ALDOT.

The cross-section of the bridge provides the information about the begin bridge station and end bridge station. Information about the spacing of the piers, abutments, the overbank and main channel was figured out from the station number provided in the cross section (Figure 4.5). The bridge starts at the station no STA. 903+45 and ends at station STA. 904+95. The total length of the bridge is 150 ft. The distance between the begin bridge and bent 2 (Figure 4.5) is 50 ft. Also, the spacing of bent 3 from bent 2 is 50 ft. Bent is a part of a bridge substructure, for example, bridge piers or piles.

Different boring locations with station number were provided in the ALDOT bridge report. Seven borings were done around the bridge site. All seven-boring stations around the bridge can be seen in the plan view of the bridge site (Figure 4.6).

Figure 4.1 Location of Spear Creek and bridge site characteristics.

Figure 4.2 Location of Valley Creek and bridge site characteristics.

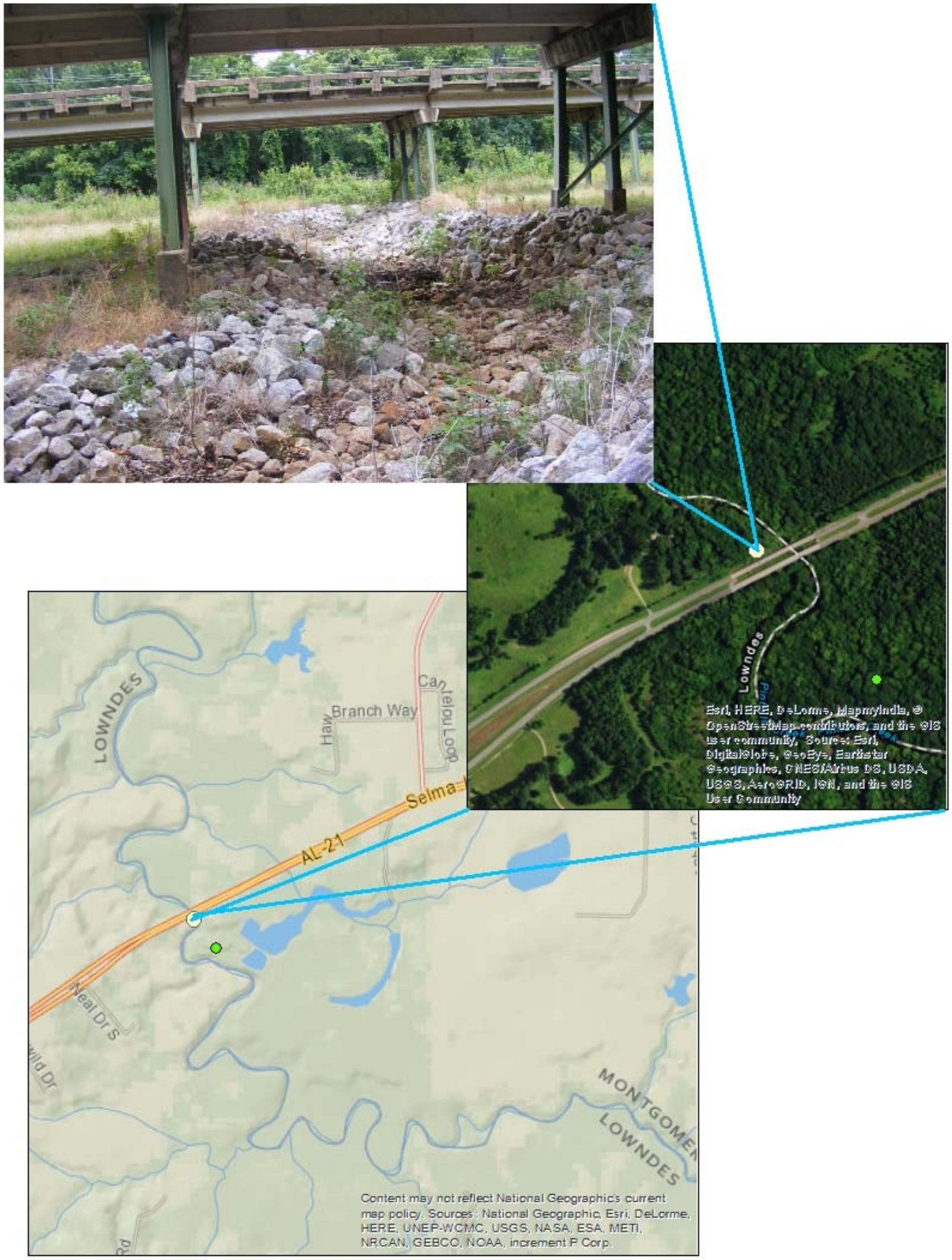

Figure 4.3 Location of Pintalla Creek and bridge site characteristics.

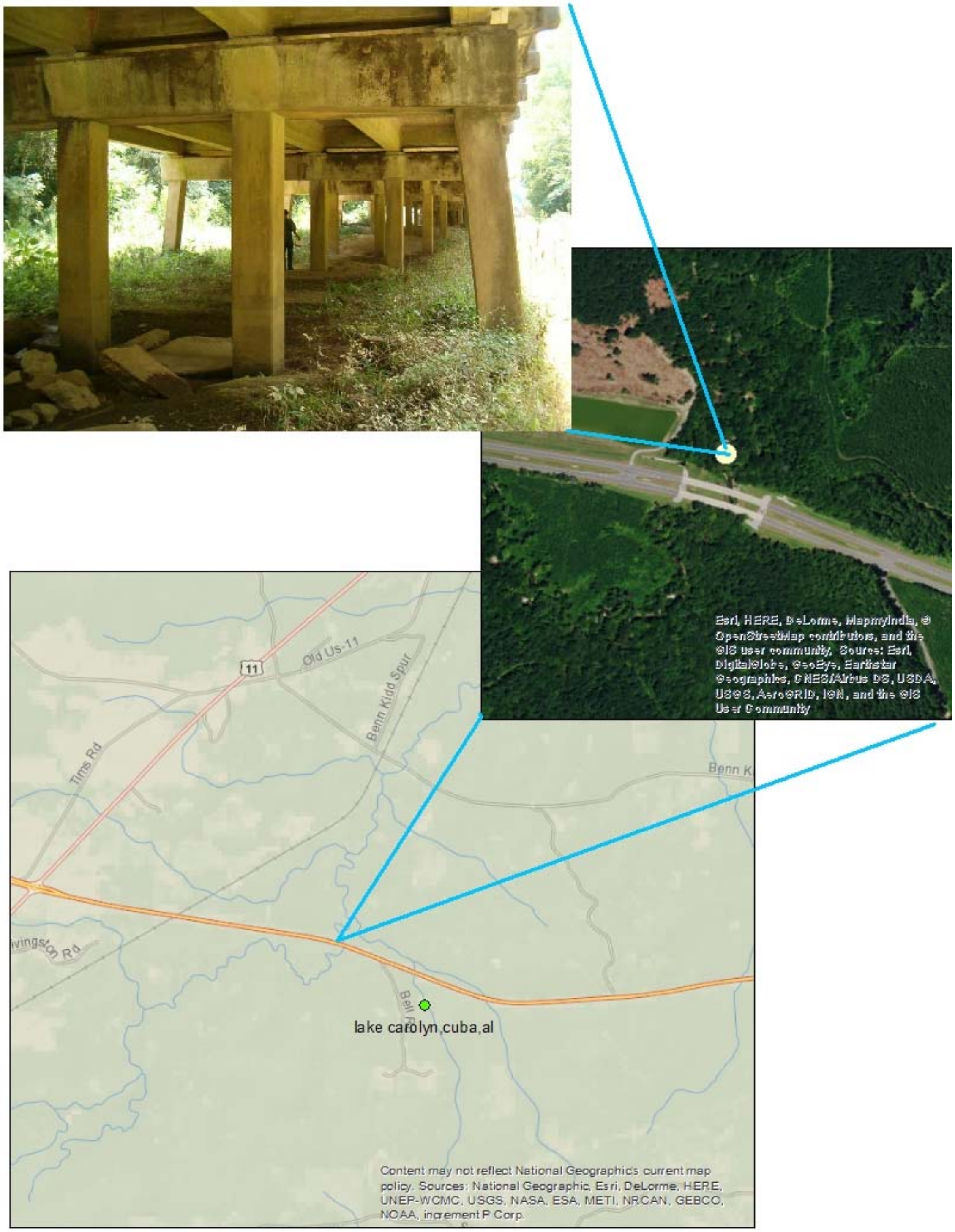

Figure 4.4 Location of Alamuchee Creek and bridge site characteristics.

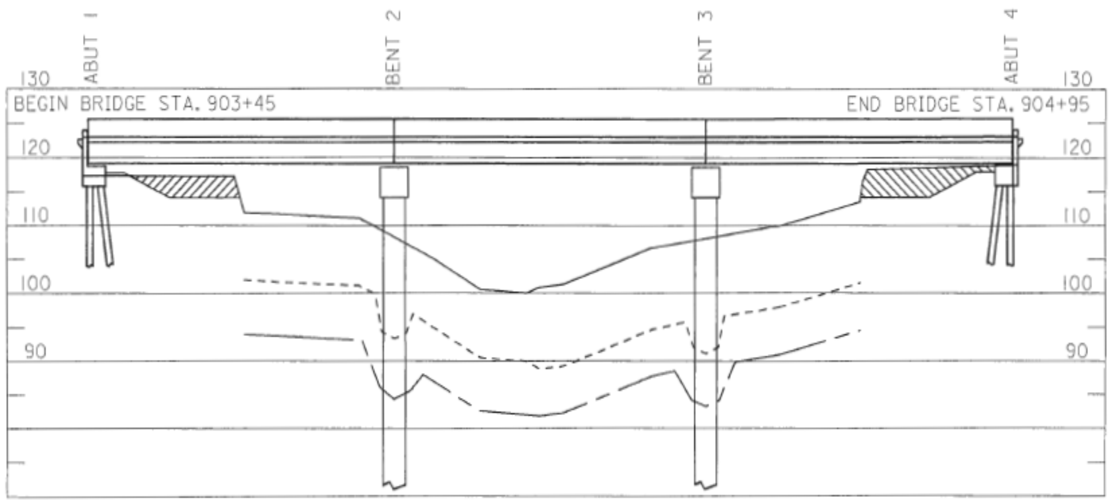

Figure 4.5 Cross-section of bridge at Spear Creek with station number and projected scour depths.

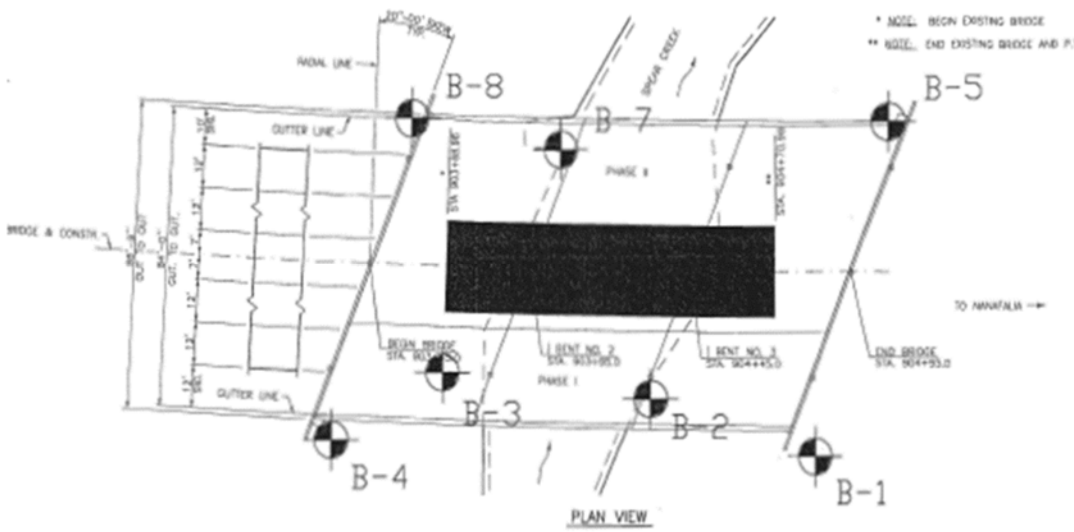

Figure 4.6 Plan view of the bridge site with boring location (Spear Creek).

To figure out the left overbank, main channel, and right overbank, a convention followed by HEC-RAS is applied. HEC-RAS reference manual (Brunner 1995) states; from the view looking downstream, if the bank is in right then that is called as right overbank and if the bank is in left then that is called as left overbank. Additionally, the ALDOT report provides the information about the boring station number with different D_{50} values (Figure 4.7), which helps in determining the location of the borings.

HEC-RAS convention and the station numbers provided in the report were used to determine the location of the borings as LOB, CH, and ROB (Table 4.1) where LOB stands for left overbank, CH stands for channel, and ROB stands for right over banks, which are abbreviations used in HEC-RAS.

Table 4.1 Boring locations with station number.

Boring NO	Station	Banks
B-01	STA 904+84	ROB
B-02	STA 904+34	CH/ROB
B-03	STA 903+69	LOB
B-04	STA 903+34	LOB
B-05	STA 905+06	ROB
B-07	STA 904+04	CH
B-08	STA 903+56	LOB

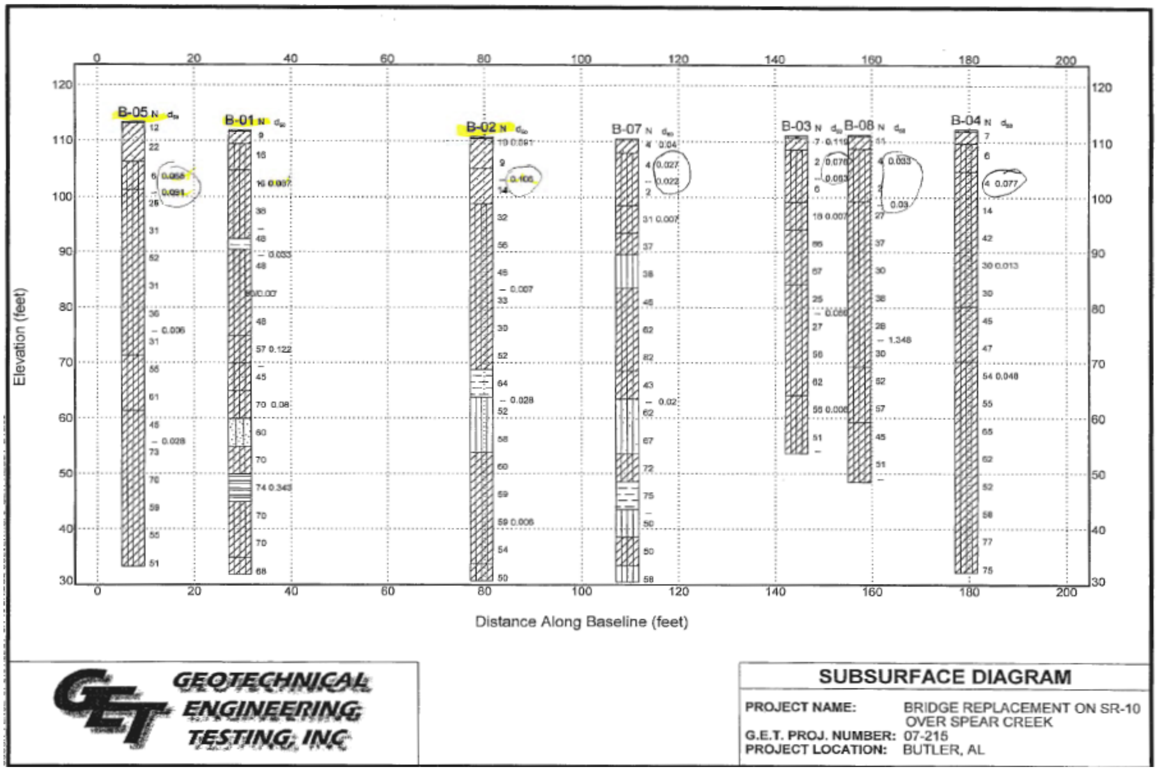

Figure 4.7 D_{50} values (Table 4.2) along depth of seven boring stations.

The peak discharge for 100-year recurrence interval was 3820 ft^3/s estimated by ALDOT from USGS regression equations. The borings that are near the bridge were taken for calculation purpose. Boring no B-5 and B-1 are taken for the right overbank calculation. Boring no B-2's D_{50} value is used for the main channel. Boring no B-3's D_{50} value is taken for left overbank. From the report provided by the ALDOT, D_{50} value along depth at four boring sites were extracted and D_{50} values were tabulated in Table 4.2.

Hydraulic parameters and scour depth for each soil layer were calculated using HEC-RAS developed for each bridge. Detailed information on the development of HEC-RAS model based on the WSPRO input data from ALDOT is presented and summarized by Pokharel (2017). For this part of the study, WSPRO method included in HEC-RAS was used to calculate the water surface profile. The data required for the calculation of scour depth are all automatically updated in the hydraulic design function windows of HEC-RAS after the hydraulic simulation is completed. Contraction scour can be computed in HEC-RAS by either Laursen's clear-water (Laursen 1963) or live-bed (Laursen 1962) contraction scour. To compute the contraction scour D_{50} value in mm and water temperature (°F) were entered to compute the K_1 factor (Table 1.2). Table 4.3 shows the example data of Spear Creek for the hydraulic design function windows of HEC-RAS.

Table 4.2 D_{50} values along depth of the boring B-1, B-2, B-3, and B-5

Depth (ft.)	Boring No	D_{50} (mm)	Average
0-1.2'	B-2	0.091	0.047
1.2'-8"		0.106	
8'-27.5'		0.007	
27.5'-47.5'		0.028	
47.5'-69.3'		0.006	
0-1'	B-3	0.119	0.055
1'-4.5'		0.076	
4.5'-7.5'		0.063	
7.5'-14.7		0.007	
14.7-32'		0.059	
32'-49'		0.006	
0-7.5	B-1	0.037	0.123
7.5-21		0.033	
21-29		0.122	
29-39		0.08	
39-54.5		0.343	
0-6.5	B-5	0.065	0.0475
6.5-9.7		0.091	
9.7-34.7		0.006	
34.7-54.2		0.028	

Table 4.3 Output from HEC-RAS

WSPRO method (HEC-RAS) with contraction and expansion as 0.0 and 0.5, respectively			
	LOB	**CH**	**ROB**
Y_1	4.02	14.67	5.77
V_1	0.65	2.7	0.87
Y_o	3.98	15.54	5.18
Q_2	379.87	2739.17	700.96
W_2	43.18	25.72	47.66
D_{50}	0.03	0.047	0.055
Q_1	1527.66	1255.99	1036.36
W_1	583.98	31.72	205.78
Scour depth	6.54	17.53	6.14

Note: Y_1 = Average depth at the approach section, Q_2 = Discharge in the main channel at the contracted section, Q_1 =Discharge in the main channel at channel section, W_2 = Bottom width of the main channel at section 2, W_1 = Bottom width of the main channel at channel section, Y_2 = Existing flow depth in the main channel at section 2 before scour, D_{50} = Mean particle size diameter in mm, and V_1 = Velocity upstream of the river section.

HEC-RAS has the capabilities to choose the equation as default, i.e., the model will itself calculate the critical velocity and compare with the upstream velocity and choose the governing equations either as live-bed or clear-water scour. Also, the user can force the model to calculate the scour on any conditions by changing the default value to either live-bed or clear-water scour.

4.4 MULTILAYER METHOD

Based on the knowledge of the multilayer scour, this study proposed/used the multilayer idea to calculate the total scour depth using D_{50} of each soil layer along the depth. As shown in Table 4.2 D_{50} values for several soil layers are available. The soil layer thickness Δz_i for the *i*-th layer can be determined, and the first or surface layer is the layer 1 (Δz_1 for its thickness). Using D_{50} in each layer as HEC-18 input, one can find corresponding scour depth layer by layer. The flood erodes the first layer at first and moves on to the second layer if Δz_1 is less than the scour depth obtained using D_{50} for the first layer, and the same procedure will be repeated for the next layer below until predicted scour depth is less than the layer thickness. A cumulative feasible scour depth is the sum of the scour depth for all layers. To perform this analysis layer by layer a simple IF clause is used in EXCEL and the cumulative feasible scour depth considering D_{50} values at multiple soil layers is then calculated. The clause used is as follows:

If (scour depth >Δz, Δz, scour depth)

where "scour depth" is the scour depth predicted by HEC-RAS using the WSPRO method and the D_{50} value of that layer as HEC-18 input, and Δz is the thickness of the soil layer. The flow chart for the calculation of scour depth is shown in Figure 4.8.

4.5 RESULTS FROM MULTILAYER METHOD

Table 4.4 shows the calculation of scour depth using the multilayer method for Spear Creek. It includes the layer thickness (*Δz*), depth range D_{50}, and computed scour depth from HEC-RAS for each layer in the channel, LOB, and ROB in Spear Creek, respectively. When the scour depth calculated using the HEC-18 procedure (which is integrated into HEC-RAS) for a layer is greater than the layer thickness (*Δz*), that layer is eroded. In the main channel of Spear Creek, the erosion stops at the third layer when the layer thickness is 19.5 ft that is greater than predicted scour depth 17.5 ft. Therefore, the cumulative feasible scour depth in the channel is 25.5 ft (Table 4.4) using the multilayer method. The scour depth calculated by HEC-RAS using average D_{50} value (0.0476 mm) in the channel is 17.5 ft. The difference in scour depth calculated by the two methods is 8 ft.

The scour depth calculated by HEC-RAS using average D_{50} value (0.055 mm) in LOB is 4.9 ft, whereas the scour depth calculated using the multilayer method is 10.9 ft when the erosion stops at the fourth layer. The difference in the calculated scour depth is 6 ft. Since two borings were done in ROB with layered particle size distribution, above multilayer method was applied to both stations first. At ROB1 station, the erosion (scour) stops in the first later but at ROB2 stops in the fourth layer. The average scour depth was then taken for the calculation for both cases. The average scour depth calculated by HEC-RAS using average D_{50} value in ROB is 7.65 ft whereas the average scour depth calculated using the multilayer method is 10.9 ft. The difference in the calculated scour depth is 3.25 ft. This means, in Spear Creek, using HEC-18 and average D_{50} underestimates the scour depths in the channel, LOB and ROB (Table 4.4) in comparison to the scour depth determined by the multilayer method. The consequences of this could be the failure of the bridge causing loss of life and property.

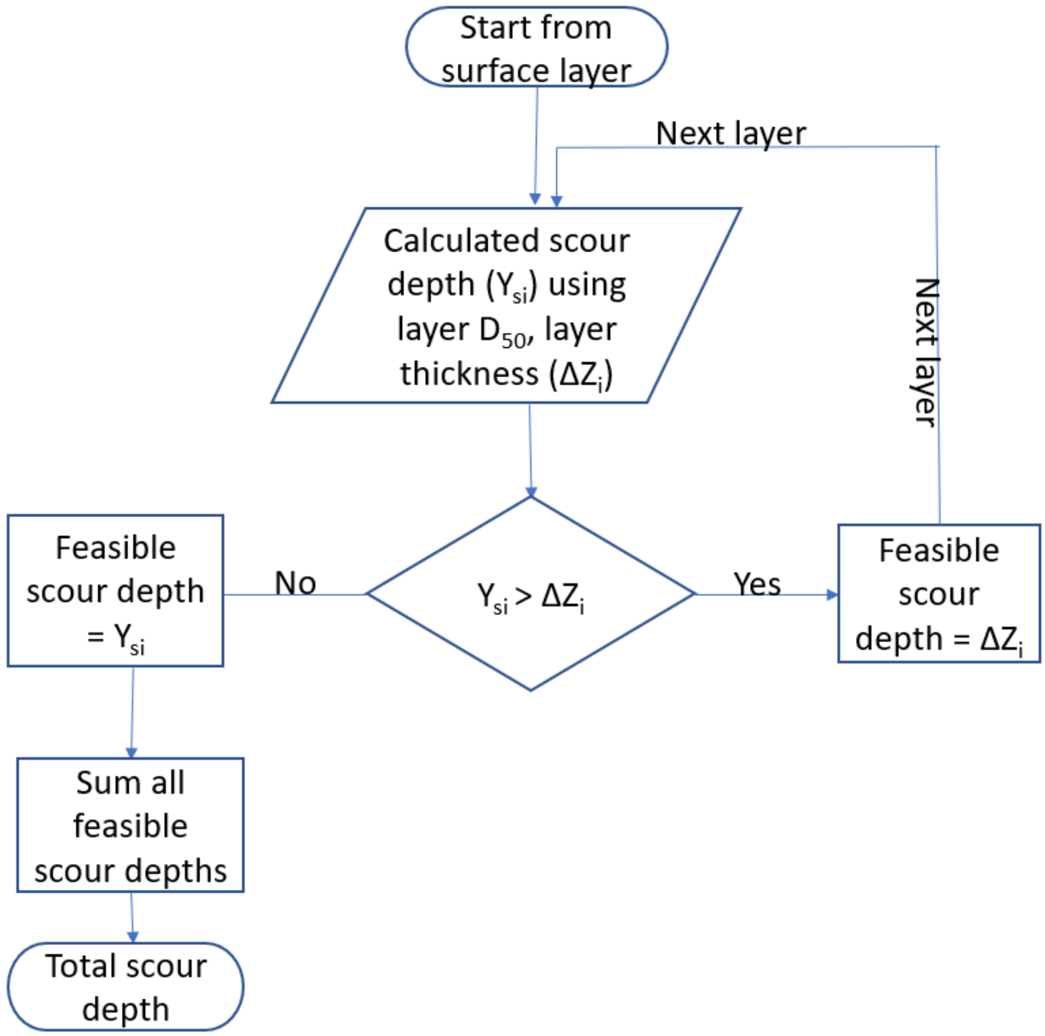

Figure 4.8 Flow chart for the multilayer method

Table 4.5 and Figure 4.9 present the differences in scour depths between the two methods in table and bar diagram, respectively. In the main channel, despite having different D_{50} values ranging from 0.007 to 0.028 mm, there is no change in the scour depth calculated from HEC-18 and D_{50} in each layer. Using these D_{50} values predicts the same scour depth of 17.5 ft. D_{50} value is first used to determine critical velocity in HEC-18. If the critical velocity determined is less than the average upstream velocity, then live-bed scour equation (1.2) is used to calculate the scour depth. There is no direct effect of D_{50} value in computing live-bed scour. Only the hydraulic parameters are used for calculating the scour depth in case of the live-bed scour condition. When computed critical velocity is greater than average upstream velocity then clear-water scour occurs. In the clear-water scour equation (1.3) D_{50} is one of the parameter used in calculating the scour depth. Therefore, in case of LOB and ROB where clear-water scour occurs, there is a change in computed scour depth with a change in D_{50} value. Based on the recommendation from ALDOT engineer, the scour depth in overbank areas is always calculated as the clear-water scour when the overbank areas have much more vegetation and other obstructions that create a larger roughness and slower velocity. For the main channel, depending on the critical velocity and upstream velocity, it could be the live-bed or clear-water scour.

Table 4.4 Calculation of scour depth using multilayer method (Spear Creek)

Main Channel				
Δz (ft)	Depth (ft)	D_{50} (mm) B-2 (pier no 3)	Scour depth (ft) (HEC-RAS) (Channel)	Scour depth (ft) (layer by layer) (Channel)
1.2	0–1.2	0.0910	17.5	1.2
6.8	1.2–8	0.1060	17.5	6.8
19.5	8–27.5	0.0070	17.5	17.5
20	27.5–47.5	0.0280	17.5	
	47.5–69.3	0.0060	17.5	
	Average	**0.0476**	**17.5 ft**	**Total scour = 25.5 ft**
Left Overbank (LOB)				
Δz (ft)	Depth (ft)	D_{50} (mm) B-3 (pier no 2)	Scour depth (ft) (HEC-RAS) (LOB)	Scour depth (ft) (layer by layer) (LOB)
1	0–1	0.1190	3.1	1.0
3.5	1–4.5	0.0760	4.1	3.5
3.0	4.5–7.5	0.0630	4.5	3.0
7.2	7.5–14.7	0.0070	3.4	3.4
	14.7–32	0.0590	4.7	
	32–49	0.0060	3.4	
	Average	**0.0550**	**4.9 ft**	**Total scour = 10.9 ft**
Right Overbank Station 1 (ROB1)				
Δz (ft)	Depth (ft)	D_{50} (mm) B-1	Scour depth (ft) (HEC-RAS) (ROB1)	Scour depth (ft) (layer by layer) (ROB1)
7.5	0–7.5	0.0370	6.1	6.1
13.5	7.5–21	0.0330	6.1	
8.0	21–29	0.1220	5.8	
10.0	29–39	0.0800	7.2	
15.5	39–54.5	0.3430	3.0	
	Average	**0.1230**	**5.7 ft**	**Total scour = 6.1 ft**
Right Overbank Station 2 (ROB2)				
Δz(ft)	Depth (ft)	D_{50}(mm) B-5	Scour depth (HEC-RAS)(ROB2)	Scour depth(ft)(layer by layer) (ROB2)
6.5	0–6.5	0.0650	7.9	6.5
3.2	6.5–9.7	0.0910	6.7	3.2
25.0	9.7–34.7	0.0060	6.1	6.1
19.5	34.7–54.2	0.0280	6.1	
	Average	**0.0475**	**9.6 ft**	**Total scour = 15.8 ft**
Average over two ROB stations			**7.65 ft [a]**	**10.99 ft [b]**

Note: [a]. Average scour depth at ROB1 and ROB2 (B-1 and B-5) from HEC-RAS = 7.65 ft. [b] Average scour depth at ROB1and ROB2 (B-1 and B-5) using the multilayer method = 10.99 ft.

Table 4.5 Differences in scour depth using average D_{50} and the multilayer method (Spear Creek)

Locations	Average D_{50} (mm)	Scour depth (ft)				
		Using average D_{50}	By layers	Difference [1]	% Error [2]	% Difference [3]
LOB	0.0550	4.9	10.9	-6.0	55.0	76.0
CH	0.0476	17.5	25.5	-7.9	31.2	37.0
ROB1	0.1230	5.7	6.1	-0.4	6.6	6.8
ROB2	0.0475	9.6	15.8	-6.2	39.2	48.8
Average of ROB1 and ROB2 (ROB)		7.6	10.9	-3.2	29.8	35.0

Note: [1] – Difference is the scour depth determined using average D_{50} value minus the scour depth by the multilayer method; [2] - % error is calculated by assuming the scour depth by the multilayer method as "exact or more accurate estimate"; [3] - % difference is calculated as absolute value of the difference dividing by the average scour depth by the two methods and converting that to a percentage value. For example, at LOB, ABS (-6.0)/ ((4.9+10.90)/2) *100% = 76.0 %.

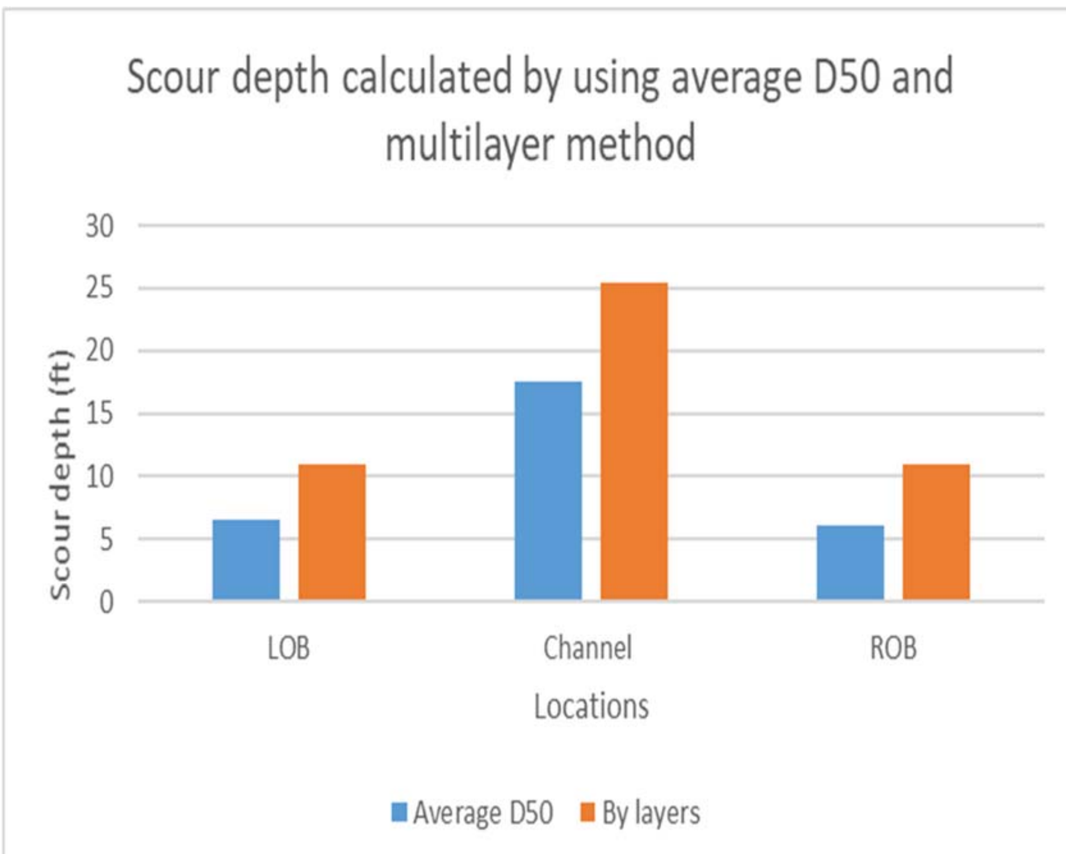

Figure 4.9 Bar diagram showing difference in scour depth using average D_{50} and the multilayer method

The same procedure and method were also applied for other three bridge cases (Valley Creek, Pintalla Creek, and Alamuchee Creek) to analyze the difference in scour depth using average D_{50} and the multilayer method (using different D_{50} layer by layer). For the bridge over Valley Creek, the D_{50} value of LOB and ROB were on the report provided by ALDOT. Some of the D_{50} values were in 200-** format, for example 200-56.9; this means 56.9 % of soil sample pass through the 200-sieve size. The maximum particle size that can pass through 200 sieve is 0.075 mm. According to Unified Soil Classification System, the percent passing the No 200 sieve is considered as fine-grained soil (clay and silt) which is considered as cohesive. For this kind of D_{50} format, the D_{50} value was assumed as 0.0750 mm. In Table 4.7, one depth layer (0–5 ft) at the surface was added and D_{50} value in the layer was assumed as D_{50} in the next layer below. This is because the multilayer method determines whether or not the erosion could be progressed layer by layer starting from the surface layer and requires continuous depth layers. Table 4.6 presents the calculation of scour depth using average D_{50} value and layer-by-layer D_{50} values (multilayer). The scour depth at LOB calculated using average D_{50} is equal to 11.0 ft and less than the scour depth (20.0 ft) calculated using layer-by-layer D_{50} values. The difference in scour depth calculated by the two methods is 9.0 ft (Table 4.6). The scour depth at ROB calculated using average D_{50} (12.0 ft) is also less than the scour depth calculated using layer-by-layer D_{50} values (20.0 ft). The difference in the calculated scour depth is 8.0 ft (Table 4.6). Figure 4.10 presents the differences in scour depth calculated from two methods in a bar diagram. In this case, HEC-18 underestimate the scour depth.

Table 4.6 Calculation of scour depth using multilayer method (Valley Creek)

Left Overbank (LOB)					
Δz (ft)	Depth (ft)	D_{50} information	D_{50} (mm)	Scour depth (ft) (HEC-RAS) (LOB)	Scour depth (ft) Layer by layer(LOB)
5	0–5		0.150 [1]	9.0	5
5	5–10		0.150	9.0	5
5	10–15	200–56.9	0.075	12.5	5
5	15–20	200–95.5	0.075	12.5	5
	Average		**0.100**	**11.0**	**Total scour depth = 20.0 ft**
Right Overbank (ROB)					
Δz (ft)	Depth (ft)	D_{50} information	D_{50} (mm)	Scour depth (ft) (HEC-RAS)	Scour depth (ft) Layer by layer
5	0–5		0.075 [1]	12.0	5
5	5–10	200–52.3	0.075	12.0	5
5	10–15		0.075	12.0	5
5	15–20	200–58.0	0.075	12.0	5
	Average		**0.075**	**12.0**	**Total scour depth = 20.0 ft**

Note: [1] – D_{50} was assumed as D_{50} from the layer below

The percent differences of scour depths at LOB and ROB determined using average D_{50} value and the multilayer method are 58.1 % and 50.0 %, respectively. The error percentage of scour depth assuming multilayer method as the exact value at LOB and ROB are 45 % and 40 % respectively.

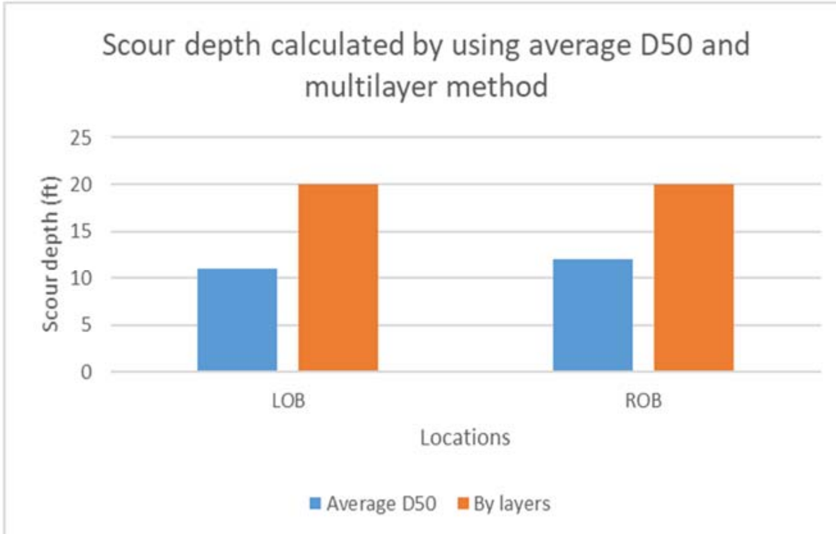

Figure 4.10 Bar diagram showing difference in scour depth from using average D_{50} and multilayer.

In the report provided by ALDOT for Alamuchee Creek, the D_{50} values were reported only for the LOB at four separate layers. It means depths with D_{50} data are not continuous, and this is different from the bridge site at Spear Creek (Table 4.4). In Table 4.7, three depth layers were added and D_{50} values in these layers were estimated as average of D_{50} for layers above and below. Table 4.7 presents the calculation of the scour depths using layer-by-layer D_{50} values (including three layers with estimated D_{50}) and average D_{50} value. The scour depth calculated using layer-by-layer D_{50} values is 15.0 ft and less than the scour depth (24.9 ft) calculated using average D_{50} value. The difference in scour depth calculated using two methods is 9.9 ft.

Table 4.7 Calculation of scour depth using multilayer method (Alamuchee Creek)

Δz (ft)	Depth (ft)	D_{50} (mm)	Scour Depth (ft) HEC-RAS (LOB)	Scour Depth (ft) Layer by layer (LOB)
1.5	0–1.5	0.0826	29.0	1.5
2.0	1.5–3.5	0.0803 [a]	29.3	2.0
1.5	3.5–5.0	0.0781	29.7	1.5
3.5	5.0–8.5	0.1479 [a]	23.4	3.5
1.5	8.5–10.0	0.2178	20.1	1.5
3.5	10.0–13.5	0.1700 [a]	22.2	3.5
1.5	13.5–15.0	0.1223	25.1	1.5
	Average	**0.1252**	**24.9 ft**	**15.0 ft** [b]

Note: [a] – D_{50} was estimated as average D_{50} from layers above and below, [b] - % difference of scour depths determined using average D_{50} value and the multilayer method is 49.6 %. The error percentage in scour depth using average D50 value and the multilayer method is 66.0%.

In the report provided by ALDOT for Pintalla Creek, the D_{50} value was reported only for the LOB. The D_{50} value were not continuous layer by layer. A continuous layer-by-layer D_{50} profile was created by averaging D_{50} values above and below the missing layer. At some depths two D_{50} values were reported (for example, 3.5–5.0 ft). The average of these two D_{50} values were taken for calculation. Table 4.8 presents the calculation of scour depth by using average D_{50} value and layer-by-layer D_{50} values. The scour depth calculated using average D_{50} value (HEC-18) is less than the scour depth calculated using layer-by-layer D_{50} values with a difference of 10.2 ft. For this case, HEC-18 underestimate the scour depth.

Table 4.8 Calculation of scour depth at LOB using multilayer method (Pintalla Creek)

Δz (ft)	Depth (ft)	D_{50} (mm)	D_{50} (mm)	Average D_{50} (mm)	Scour Depth (ft) HEC-RAS	Scour Depth (ft) Layer by layer
3.5	0–3.5			0.235 [a]	4.8	3.5
1.5	3.5–5	0.1300	0.3400	0.2350	4.6	1.5
3.5	5–8.5			0.1638 [b]	4.8	3.5
1.5	8.5–10	0.0750	0.1100	0.0925	4.8	1.5
3.5	10–13.5			0.0929 [b]	4.8	3.5
1.5	13.5-15	0.0750, 0.1300	0.0750	0.0934	4.8	1.5
	Average		**0.1336**		**4.8 ft**	**15 ft [c]**

Note: [a] – D_{50} was assumed as D_{50} from the layer below, [b] – D_{50} was estimated as average D_{50} from layers above and below, [c] - % difference of scour depths determined using average D_{50} value and the multilayer method is 103.0 %. The error percentage from these two methods is 68.0 %.

4.6 SCOUR DEPTHS USING AVERAGE D_{50} WITH AND WITHOUT OUTLIERS

In the report provided by ALDOT for four bridge cases (except Pintalla Creek), the scour depth is calculated using the average D_{50} after removing some outliers of D_{50}. The outliers are those D_{50} values that have large differences from the other D_{50} values. According to the ALDOT, the outliers are not used while doing the average of the D_{50}. In this section, the scour depths calculated from ALDOT (using average D_{50} without outliers) and using average D_{50} using all available D_{50} data are compared for three bridge cases. ALDOT used the envelope curve to calculate the scour depth for Pintalla Creek. The locations (LOB, CH, ROB) where the D_{50} information was provided in the report is used for the comparison.

From the cross section (Figure 4.5) and plan (Figure 4.6) view of Spear Creek the boring locations were selected for LOB, ROB, and Channel (Table 4.1). Table 4.4 presents the calculation done for the multilayer method and using average D_{50} from all available D_{50} data. The scour depths calculated from using average D_{50} without and with outliers are presented in Table 4.9. The scour depth calculated from the average D_{50} removing outliers for Spear Creek in LOB and ROB is greater than the scour depth calculated using all D_{50} data. In a channel where live-bed scours occur the scour depth calculated using all D_{50} data is greater than using average D_{50} removing outliers with a difference of 9.7 ft. The average D_{50} value for the channel was not found on the report provided by the ALDOT so it was left blank.

Table 4.9 Comparison of scour depths in Spear Creek determined from average D_{50} without and with outliers

Locations	Average D_{50} (mm)		Scour depth (ft)		Differences	
	Removing outliers	Using all data	Removing outliers	Using all data	Difference[1]	% Difference[2]
LOB	0.030	0.055	10.3	4.9	5.4	71.05
CH	-	0.0476	7.8	17.5	-9.7	76.68
ROB	0.055	0.1230 0.0475	12.1	7.65	4.45	45.06

Note: [1] - Difference is calculated as scour depth using D_{50} removing outliers minus the scour depth calculated using all D_{50} data, [2] - % difference is the absolute difference divided by the average of two values. For example, abs (5.4)/average (10.3, 4.9)*100% = 71.05 %

For Valley Creek, the D_{50} values in LOB and ROB were provided in a report by ALDOT. Table 4.6 presents the calculation of scour depth using multilayer D_{50}. Table 4.10 presents the comparison of the scour depth calculated from using average D_{50} removing outliers and using all D_{50} value. The difference in scour depth in LOB and ROB is 7 ft with a percentage difference of 48.3% and 6 ft with a percentage difference of 40.0%, respectively.

Table 4.10 Comparison of scour depth in Valley Creek determined from average D_{50} without and with outliers

Locations	Scour depth (ft)			
	Removing outliers (ft)	Using all data (ft)	Difference	% Difference
LOB	18	11	7	48.3
ROB	18	12	6	40.0

Table 4.11 presents the comparison of scour depth calculated using average D_{50} removing outliers and using all D_{50} data for Alamuchee Creek. The difference in scour depth is 7.9 ft with a percentage difference of 37.7 %.

Table 4.11 Comparison of scour depth in Alamuchee Creek determined from average D_{50} without and with outliers

Locations	Scour depth (ft)			
	Removing outliers (ft)	Using all data (ft)	Difference	% Difference
LOB	17	24.9	-7.9	37.7

4.7 DISCUSSION

In this part of the study, HEC-RAS model using only WSPRO method was used to calculate the hydraulic parameters required to calculate the scour depth. All the required data to run the HEC-RAS model were taken from the WSPRO input data file. Then the scour depths determined by three methods were discussed and compared. The first method used the average D_{50} from all available D_{50}, the second method considered/used D_{50} for all depth layers to compute the scour depths layer by layer and then determine the feasible cumulative scour depth, and the third method used the average D_{50} after removing outliers of D_{50}. The depth values and D_{50} taken for this study were obtained from the ALDOT reports provided. There was no information why ALDOT collected soil samples at those selected depths to determine D_{50} values. The ALDOT experienced engineer used the third method to determine the scour depth. If the calculated scour depth is unusual large (much larger than typical scour in the study region), the USGS envelope method was used by ALDOT to estimate the final scour depth. One could consider that the first method was implemented by a non-experienced engineer who has no engineering judgment to distinguish possible outliers of D_{50}.

D_{50} values along the different depths were used solely to calculate the scour depth in HEC-RAS and then “IF” clause was used to determine the feasible scour depth in each layer. The summation of all the feasible scour depth from each layer gives the total potential scour depth in the multilayer method. The multilayer method needs all layer D_{50} values to compute the scour depths. Since D_{50} values in all layers are used to calculate the scour depth, the multilayer method predicts the scour depth more accurate than other methods. However, if there is not a complete continuous layer D_{50} values it is required to assume or estimate D_{50} values based on engineering judgment (Table 4.6 and Table 4.7). This could create some uncertainty in the scour depth calculated. Also, if the layer thickness (Δz) with certain D_{50} value is not defined accurately it could affect the cumulative scour depth determined by the multilayer method. For example, if the layer thickness is 3 ft instead of 5 ft with a scour depth of 4 ft calculated from HEC-18, then according to the multilayer method it would erode first 3 ft and moves on to the second layer which would change the scour depth. The total potential (feasible) scour depth determined by the multilayer method is the sum of scour depths of all soil layers with D_{50} when predicted scour depth for each layer using its D_{50} is always larger than the layer thickness.

This study shows the real scenario of how the soil could erode layer by layers. Each soil layer's D_{50} has a role in determining the final scour depth. Taking only one average D_{50} value and using that to calculate the scour depth could either overestimate or underestimate the scour depth. If the scour depth is underestimated, it could lead to loss of lives and property. If the scour depth is overestimated, it could cause extra millions of dollars to design the bridge structure (piers). This study leads to the finding that using one average D_{50} value and not considering the nature (cohesive and non-cohesive) of soil could result in different scour depth. Also, this study suggests applying multilayer methods in calculating the scour depth so that the scour depth calculation could be more accurate.

From the analysis, it can be said that the scour depth calculated from HEC-18 using average D_{50} value could be less than (Spear, Valley, and Pintalla Creek) or greater (Alamuchee Creek) than the scour depth calculated from using the multilayer method (different layer D_{50}). It means that the top layer D_{50} value along with the thickness of the layer plays an important role in scour depth. Scour depth calculated from the average D_{50} value in HEC-18 is less than the scour depth obtained from using layer-by-layer D_{50} values in Spear Creek. There is a minimum scour depth difference of 4.36 ft in left overbank (LOB) to a maximum difference of 8.97 ft in the main channel (CH). This means that HEC-18, in this case, is underestimating the scour depth, which could result in bridge failure and loss of lives and properties. However, in case of Alamuchee Creek, the scour depth calculated from HEC-18 using average D_{50} value is 24.9 ft, which is greater than the scour depth (15 ft) calculated from using layer-by-layer D_{50} values. It means that in this case, HEC-18 overestimates the scour depth that results in loss of billions of dollars and mostly the valuable time.

From this study, it is now evident that using only average D_{50} value does not accurately predict the scour depth. The D_{50} values of all layers should be considered while calculating the scour depth. Using the layer-by-layer D_{50} values to calculate the scour depth and summing up all the feasible scour depths could give most accurate prediction of the total scour depth rather than using only average D_{50} value.

For this study only the average D_{50} value was simply arithmetic average of D_{50} values in all the layers and the scour depth was calculated. To determine a more accurate or representative D_{50} for HEC-18 application other techniques or methods could be applied. For example, the average could be done up to the layer where the scour would stop. In the case of Spear Creek in ROB1 the scour depth obtained using first layer D_{50} value is 6.1 ft which is less than the layer thickness 7.5 ft. This means scour would stop at first layer. The average D_{50} for this part should be only first layer D_{50} value. The first layer D_{50} value could be used to calculate the scour depth from HEC-18 and compare it to the multilayer method for more accurate results. Therefore, it requires an iterative method to compute average D_{50} using D_{50} data up to certain depth, calculate the scour depth, and then update average D_{50} using the scour depth for the next iteration of the calculation. Also, the weighted average D_{50} with layer thickness could be more accurate or representative D_{50}.

For using a multilayer method, the D_{50} value should be obtained lower than the total potential scour depth. There arises a question about how deep the boring should be done to obtain D_{50} in different layers for a more accurate prediction of scour depth. Where the boring should be stopped in earth surface? For example, in Alamuchee Creek, D_{50} was available in seven layers up to 15 ft (a few D_{50} between layers were estimated). The total scour depth determined by the multilayer method was 15 ft that is limited by the unavailability of lower layer D_{50} values. Using average D_{50} determined from 15 ft of the soil layers, HEC-18 predicted a scour depth of 24.9 ft (Table 4.7). Without knowing what type of soils below 15 ft, the prediction of 24.9 ft is also not reliable. Therefore, both the scour depths predicted from using average D_{50} and using multilayer D_{50} do not accurately represent the scour depth in Alamuchee Creek.

Chapter 5 COMPARISION OF HYDRAULIC PARAMETERS AND SCOUR DEPTH OBTAINED FROM WSPRO AND HEC-RAS MODEL

5.1 INTRODUCTION

Current practice to evaluate the scour depth is heavily influenced by FHWA's technical publications HEC-18 and HEC-20 (Arneson et al. 2012; Lagasse et al. 2012). HEC-18 methods need several hydraulic parameters to calculate the scour depth (Equations 1.2 and 1.3). There are different models that could be used to obtain hydraulic parameters of a stream with a bridge crossing. In current practice, WSPRO and HEC-RAS are two computer models that are often used to obtain the hydraulic parameters. These two methods solve the energy equation based on standard step methods and/or momentum equation for gradually varied flow. Both models have their own assumptions and procedures to calculate the water surface profiles.

WSPRO is a computer model that was developed in 30 years ago by FHWA. It works on DOS version. All the inputs are in text format. It uses a column-based input data that could be daunting if failed to enter the data in a correct format (Arneson and Shearman 1998). HEC-RAS is the newest model which has graphical user interface (GUI) and easy to operate. HEC-RAS integrates the WSPRO method as one of the methods to calculate the energy or momentum losses to determine water surface profile through the bridge. There are four methods included in HEC-RAS to calculate the water surface profiles. The user can select any one or all methods to calculate the losses through the bridge. If the user selects more than one methods, the program will give the greatest energy loss at section 3 through the bridge as the highest computed upstream energy (Brunner 1995). This function of HEC-RAS was used to compare the hydraulic parameters from several methods. For this study, the hydraulic parameters that are needed in HEC-18 to compute the scour depth are compared in different scenarios. In addition, water surface elevation obtained from both the models are also compared.

Hydraulic parameters are one of the important aspects that can influence the scour depth computation using HEC-18 equations (1.2) and (1.3). The critical velocity in HEC-18, i.e., equation (3.5) is first used to determine whether the live-bed scour or the clear-water scour occurs at the bridge site (Figure 1.5), therefore, the critical velocity plays a critical role in determining the scour depth. The equation (3.5) is used in HEC-18 to compute V_c as function of y, the average depth of flow upstream of the bridge contraction. The HEC-18 report (Arneson et al. 2012) lacks to provide a clear definition of the average depth y. For an open channel flow, average depth can be interpreted in two ways: flow depth or the hydraulic depth (Chow 1959). The flow depth can be considered as the average value of water depths along the channel cross-section, obtained by the differences between the water surface elevations and the bed elevations. The average depth of a channel can also be computed from average depths of the left and right overbank areas and main channel. Sometimes the flow depth can also be considered the maximum water depth over the cross-section. The hydraulic depth (D) is defined as the ratio of area (A) to the top width (T) of the flow: $D = A/T$.

The hydraulic depth can be computed for left and right overbank areas, main channel, and for the whole channel section. These definitions give different values on y for Equation (3.5). HEC-18 lacks clear instruction in noting down which average depth to be used for the calculation of the scour depth. The average depth y at the upstream section is an essential hydraulic parameter that is also used in the calculation of contraction scour and pier scour.

HEC-RAS (Brunner 2001) manual indicates that it follows the outline mentioned in HEC-18 for the calculation of the scour depth. HEC-RAS uses the hydraulic depth D in section 4 (Figure 1.4) as the average depth y in Equation (2.6) to perform the scour depth computation. Also, ALDOT engineers use hydraulic depth as the average depth. This is an essential knowledge that an entry-level engineer should possess which HEC-18 manual lacks to provide.

When HEC-18 is used, typically scour depths are calculated for overbank areas and main channel separately. Equations (1.2) and (1.3) for HEC-18 use average water depths, flows and widths at upstream approaching and bridge-crossing sections for determining the live-bed and clear-water scour depth. Even the same total flow rate over the cross section is given, different hydraulic models may distribute the total flow differently in left and right overbank areas and main channel, which could result in different scour depths in different parts of the channel. This part of the study is to evaluate and illustrate the uncertainty of the scour depth calculation due to hydraulic parameters calculated/simulated by two common hydraulic models (WSPRO and HEC-RAS).

5.2 METHODOLOGY

HEC-RAS was used to obtain the hydraulic parameters needed to calculate the scour depth. For the development of the HEC-RAS model, all the necessary data were taken from one of the report (Spear Creek) provided from ALDOT. Spear Creek data were used to develop the HEC-RAS model. For this part of the study, different sets of model parameters were changed and the differences in the hydraulic parameters and eventually differences in the scour were analyzed. Different sets of model parameters that were changed are as follows:

1. Methods to compute the water surface profile: HEC-RAS or WSPRO method
2. Change in expansion and contraction coefficients
3. Changing the expansion and contraction lengths based on HEC-RAS methodology
4. Including the ineffective flow areas in the model

This is not a sensitivity analysis since model coefficients/parameters were not changed or tested based on their natural variations. This part of the study demonstrated and examined the impact of the model configuration based on various technical guidance on the calculation of hydraulic parameters and then the scour depth near a bridge site, which is called uncertainty of hydraulic parameters here. This was not previously studied before by others.

1. Methods to compute the water surface profiles: HEC-RAS or WSPRO method

   HEC-RAS has the capabilities to run the model with different methods. As stated earlier there are four methods to calculate the low flow from HEC-RAS. Two methods: HEC-RAS's standard energy method and WSPRO method were used for this study to compare the data. In theory, WSPRO method also uses basic flow energy equation with certain special considerations and treatments. Various differences in applying energy equation between HEC-RAS and WSPRO were analyzed and summarized elsewhere by Pokharel (2017). Results from WSPRO method presented in Chapter 5 were derived from the text output from running the WSPRO DOS program with text input file. They are not from HEC-RAS using the WSPRO option for bridge simulation method.

2. Change in expansion and contraction coefficients

   The default values of expansion and contraction coefficients vary according to the model used. HEC-RAS has its own methodology for the use of contraction and expansion coefficients in the energy equation for the water surface profile computation. As per the HEC-RAS manual (Brunner 2001), the contraction and expansion coefficient far upstream and downstream the bridge should be 0.1 and 0.3, respectively, where there is no flow contraction and expansion due to the bridge. Whereas near the vicinity of the bridge the contraction and expansion coefficient are 0.3 and 0.5, respectively. WSPRO has its own default value of 0.0 and 0.5 for contraction and expansion coefficient, respectively. The contraction and expansion coefficients were changed accordingly and the change in the hydraulic parameters and ultimately the change in scour depth was analyzed.

3. Changing the expansion and contraction lengths based on HEC-RAS methodology

   WSPRO has its own method to select the expansion and contraction lengths. For the development of the HEC-RAS model, the lengths were first taken from the WSPRO model input data file. HEC-RAS has its own methodology to define expansion and contraction lengths. The change in the hydraulic parameters due to the change in the expansion and contraction length was analyzed.

4. Including the ineffective flow areas in the model

   When there is an obstruction to the flow by any inbuilt structure like bridge, the flow pattern is affected by the obstruction. The ineffective flow area is the area where there is water but there is no conveyance, i.e., the velocity is zero at that location in the direction of flow. In HEC-RAS, the user can quantitatively configure the ineffective flow areas. For Spear Creek HEC-RAS model, the ineffective flow area is set at stations 510 and 845 with elevation 118 ft. The model was run for the WSPRO method with coefficients of contraction and expansion as 0.0 and 0.5. This set of coefficients is used just to mimic the coefficient used in WSPRO program.

At the overbank areas, due to the presence of dense vegetation, it is assumed that these areas have high roughness values. Due to the high roughness on overbank areas the velocity upstream of the flow is typically less than the critical velocity, which means that there is always a clear-water contraction scour in the overbank areas. For the channel section, the default option in HEC-RAS was used, which lets the program to determine whether a clear-water or live-bed scour will occur. The equations (1.3) and (1.2) for the clear-water scour and the live-bed scour include some constant values such as C_u and D_m. These parameters are constants for all scenarios so for the comparisons only the discharges at upstream approach section (Q_1) and contraction section (Q_2) and width at approach (W_1) and contraction section (W_2) are taken. Average depth at approach section (Y_1 = Y_4 in Figure 1.4) and average depth prior to scour at contraction section (Y_0 = Y_{BU} in Figure 1.4) are found to be different by small percent so those values were not taken for the calculation purpose. For simplicity and comparison, the following ratios were calcualted

$$\left(\frac{{Q_2}^2}{{W_2}^2}\right)^{3/7} - Clear\ water\ scour \tag{5.1}$$

$$\left(\frac{Q_2}{Q_1}\right)^{6/7} * \left(\frac{W_1}{W_2}\right)^{K_1} - Live\ bed\ scour \tag{5.2}$$

On Figure 1.4 used for HEC-RAS, the upstream approach section is the section 4 (*i.e.*, Q_1 = Q_4), and the contraction section is the BU section (*i.e.*, Q_2 = Q_{BU}). The exponent K_1 has three values 0.59, 0.64, and 0.69 based on Table 1.2, which is affected by the ratio of shear velocity and fall velocity (a function of D_{50}).

5.3 WSPRO INPUTS FOR HEC-RAS MODEL DEVELOPMENT

WSPRO model works on DOS mode (Fortran 77 program). So, all the data inputs are coded in a certain fashion (ASCII character encoding format). Each column has its own meaning. Individual data items must be separated by either a comma or one or more blanks or any combination of a comma and one or more blanks. The row with * is skipped by the program and the user can provide other notes and information for the model in the * rows. The header of each input line, for example, XS, GR, etc. has its own meaning. The users should have a well-known background in surface water hydraulics to understand and write the input code in the required format. As the model runs on DOS version it is very difficult to debug the errors. It could be daunting for the non-experienced users to figure out the errors and resolve them. For more information on the header and the format, readers are encouraged to go through the WSPRO user's manual which is available in FHWA website (Arneson and Shearman 1998). In here, a short description of the header and the content in the header are described so that the reader get some knowledge on how the HEC-RAS model was developed from the input data of the WSPRO model. The following Figure 5.1 shows the input data of WSPRO for Spear Creek that were used to develop the HEC-RAS model. Understanding of WSPRO model parameters is given in WSPRO manual (Arneson and Shearman 1998) and also discussed/summarized by Pokharel (2017).

```
                                          PB10506.WSP
T1          BR-0010(506) SPEAR CK. BUTLER QUAD
T2          1/2 MI W BUTLER NE 1/4 SEC LINE 24/13
T3          CHOCTAW CO. DA=9.41 SQ MI PB10506.WSP
*
*             Q100  Q500
Q             3820  5820
SK          .0021 .0021
*
XS     EXIT 0 25 * * .0028
GR          000 120.0  030 114.6
GR          335 112.7  410 112.2  600 113.1  660 112.0  668 100.0
GR          688 100.0  695 111.4  770 108.9  805 109.3  840 112.2
GR          895 113.8  927 117.8  950 118.7  990 130
N           .18 .18 .08 .18 .18
SA          610 660 695 748
*
XS     FULL 160 25 * * .0028
*
*       3 @ 50' = 150' AASHTO GIRDER BRIDGE
*
BR     BRDG 160 117.7 25
GR          610 117.7  620 112.5  658 111.5  665 100.0  685 100  690 111.0
GR          730 110.0  748 117.8  610 117.7
CD          3 82 2 121
N           .05 .05 .05
SA          658 690
*
XR     ROAD 200 82 1 * 25
GR          -700 130.0  -200 121.3  000 121.0  800 121.0  950 128.9
*
AS     APRO 400 25 * * .0028
*
HP 1 BRDG 116.4 2 117.8
HP 1 APRO 117.5 2 119.5
*
HP 2 BRDG 116.4 * * 3820
HP 2 APRO 117.5 * * 3820
*
HP 2 BRDG 117.8 * * 5820
HP 2 APRO 119.5 * * 5820
*
EX
ER
```

Figure 5.1 Input data format of WSPRO

5.3.1 CROSS-SECTIONAL GEOMETRY

HEC-RAS needs at least four cross sections in a river to compute the hydraulic parameters of flow through a bridge, which were then used for the scour calculation. The cross section 1 is at far downstream, the section 4 at far upstream and the sections 2 and 3 just above and below the bridge structure (Figure 1.4). WSPRO input data file (Figure 5.1) provides detailed channel geometry (X and Y coordinates) at the downstream EXIT cross section and an energy gradient slope. The EXIT cross section data were used to project the cross-section geometry upstream from the EXIT section based on the slope. Four cross sections for HEC-RAS were then created. The cross-section just upstream and downstream of the bridge were assumed and created at 10 ft from the bridge. The cross-section data were adjusted with some adjustments in the elevation points. The reach lengths between two cross sections were set to what they were in the WSPRO model, i.e., 160 ft from the section 1 and 2 for HEC-RAS (Figure 1.4), 102 ft from the section 2 and 3 (82 ft for bridge deck plus 10 ft in each side), and 138 ft from the section 3 to 4 (400 – 102 – 160 = 138 ft).

5.3.2 MANNING'S N VALUES

HEC-RAS needs Manning's n values for the left overbank, main channel, and right overbank. WSPRO model provides the n values in the N row according to the sub-areas divided. By knowing the fact that the channel has lower roughness than the overbank areas, the Manning's values for HEC-RAS model could be specified as accurately as possible depending on the information in N row of WSPRO model. For Spear Creek, Manning's n was set as 0.18 for the left and right overbank areas and 0.08 for the main channel.

5.3.3 CHANNEL BANK STATIONS AND REACH LENGTHS

The cross-section data obtained from WSPRO were plotted and analyzed in Excel. The channel bank stations were decided by examining the cross-section plot. The channel reach lengths for the channel and overbank areas were determined from the input file of the WSPRO, which was discussed in section 5.3.2 for Spear Creek. It is necessary to mimic the same input reach length used in WSPRO when it is possible. Without additional information, the reach length is set to be the same for the overbank areas and the main channel.

5.3.4 INEFFECTIVE FLOW AREA

The ineffective flow area is the area where the flow velocity remains zero in the river flow direction. Any kind of obstruction (bridge in this case) to the flow of water will change the flow pattern. Due to the smaller opening of the bridge compared to the width of the full flow over the floodplain (including overbank areas), the flow must contract towards the bridge opening. Thus, floodplain areas immediately upstream of the bridge on either side of the bridge opening (Figure 1.4) do not convey flow, so these areas are called ineffective areas. The dotted line in (Figure 1.4) separates the ineffective and effective flow area in HEC-RAS. For the WSPRO model, its input data do not consider the ineffective flow area when the flow passes through a bridge. At first, we tried to mimic the WSPRO's no-ineffective-flow-area condition in HEC-RAS. At the next step, because of the less information about how to choose the ineffective flow area exactly, the ineffective flow areas were assumed at the left and right overbank areas, and the results for these different cases were analyzed and compared.

5.3.5 BRIDGE CROSSING GEOMETRY

Bridge data from the WSPRO input file were used to create a bridge geometry. Detailed information about the bridge (road embankment, bridge deck, and abutments) was well documented in each input file (Figure 5.1) provided. Due to the insufficient data for the bridge pier, some engineering judgement with some assumptions were made in the length, width, and angle of attack of the pier. Figure 5.2 shows the bridge geometry of Spear Creek in HEC-RAS.

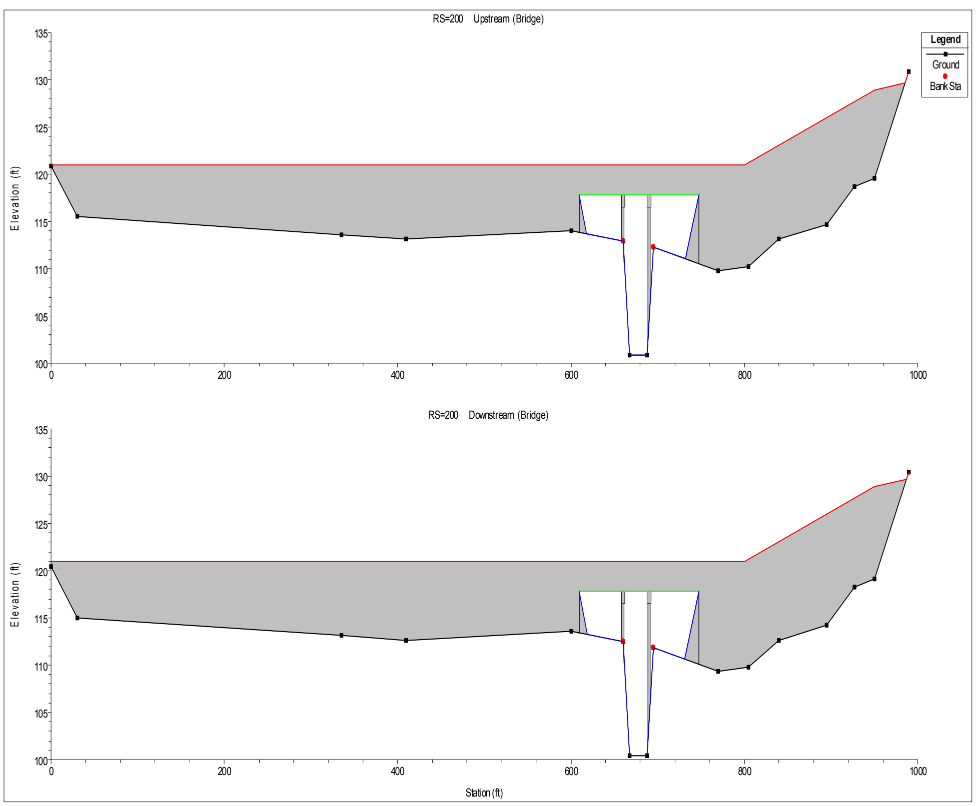

Figure 5.2 Bridge geometry of Spear Creek in HEC-RAS

5.3.6 CONTRACTION AND EXPANSION COEFFICIENTS

From the WSPRO input data (Figure 5.1), contraction and expansion coefficients were set to 0.0 and 0.5, respectively. Near the bridge, the coefficients, per HEC-RAS methodology, should be 0.3 and 0.5 for contraction and expansion coefficient (Sections 2 and 3 in Figure 1.4). Therefore, the coefficients were changed accordingly at the bridge site with different discreet settings (Table 5.1). In general, the changing of the contraction and expansion coefficients did not influence the results to any significant degree because the velocity head was low even at the bridge site.

Table 5.1 Expansion and contraction coefficients in WSPRO and HEC-RAS

Coefficients	WSPRO (Default value)	HEC-RAS (Near Bridge)	HEC-RAS (Far from bridge)
Expansion	0.5	0.5	0.3
Contraction	0.0	0.3	0.1

5.3.7 FINAL MODEL DEVELOPMENT

All the data required were obtained from the input of the WSPRO model. Next, the flow data and the boundary conditions were set up. The flow data used was the 100-yr return flow as in WSPRO model. For the calculation of subcritical water surface profile, the downstream boundary was set to normal depth by inputting a friction or river-bottom slope. The model was ran for the steady state condition.

5.4 OUTPUT OF WSPRO

WSPRO model generates detailed output describing the processing of the input data and the result of all profile computations. The model offers no option to suppress any output but users can edit out unwanted segments of the file before printing (Arneson and Shearman 1998). The HP records in WSPRO input are used to generate tables of cross-sectional properties and (or) velocity and conveyance distribution for any section(s). Cross-sectional properties can be obtained for the total cross-section, with or without a sub-area breakdown. Velocity and conveyance distribution can be obtained for one or more discharge(s) at one or more elevation(s) (HP row in Figure 5.1). For more information about the output of the WSPRO model readers are referred to read User's Manual for WSPRO (Arneson and Shearman 1998).

This section explains about the determination of the required parameters in HEC-18 for scour depth calculation from the output of WSPRO. The required parameters needed for scour depth calculation in HEC-18 are mentioned in section 1.2. These parameters needed are calculated using the data in the cross-sectional properties of WSPRO output as shown in Figure 5.3

```
1
 WSPRO          FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
 V082195            MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

         BR-0010(506) SPEAR CK. BUTLER QUAD

         1/2 MI W BUTLER NE 1/4 SEC LINE 24/13

         CHOCTAW CO. DA=9.41 SQ MI PB10506.WSP

            *** RUN DATE & TIME: 04-05-16  14:17
     CROSS-SECTION PROPERTIES:  ISEQ =  3;  SECID = BRDG ;  SRD =     160.

      WSEL  SA#      AREA        K   TOPW    WETP  ALPH    LEW    REW      QCR
              1       165    12160     41      42                         1869
              2       414    55751     29      43                         8883
              3       257    22440     50      51                         3313
    116.40            836    90351    120     137  1.18    613    745    11520

      WSEL  SA#      AREA        K   TOPW    WETP  ALPH    LEW    REW      QCR
              1       221    12096      0      88                            0
              2       453    45986      0      72                            0
              3       327    20549      0     107                            0
    117.80           1001    78632      0     267  1.22    610    748        0
1
   HP 1 APRO 117.5 2 119.5

1
 WSPRO          FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
 V082195            MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

         BR-0010(506) SPEAR CK. BUTLER QUAD

         1/2 MI W BUTLER NE 1/4 SEC LINE 24/13

         CHOCTAW CO. DA=9.41 SQ MI PB10506.WSP

            *** RUN DATE & TIME: 04-05-16  14:17
     CROSS-SECTION PROPERTIES:  ISEQ =  5;  SECID = APRO ;  SRD =     400.

      WSEL  SA#      AREA        K   TOPW    WETP  ALPH    LEW    REW      QCR
              1      1703    30500    535     535                        17242
              2       178     3658     45      45                         1997
              3       440    37354     32      45                         9297
              4       282     7577     48      48                         3870
              5       744    17731    152     152                         9342
    117.50           3346    96821    812     826  3.65     20    916    20167

      WSEL  SA#      AREA        K   TOPW    WETP  ALPH    LEW    REW      QCR
              1      2782    68263    545     545                        35676
              2       268     7270     45      45                         3705
              3       503    46758     32      45                        11378
```

Figure 5.3 Cross-sectional properties output from WSPRO (Spear Creek)

The required data to get the parameters needed for scour depth calculation in HEC-18 are SA (subarea), Area (A), K (conveyance), TOPW (top width), hydraulic depth (*y*) at the approach section and the bridge section. Discharges in three subsections (LOB, CH, and ROB) of a compound channel section were calculated using Manning's equation introduced in 1891 by Flamant (Henderson 1996).

$$Q = \frac{K_n}{n} AR^{2/3} {S_f}^{1/2} \quad \textbf{(5.3)}$$

Equation **(5.3**) can be rewritten as,

$$Q = K{S_f}^{1/2} \quad \textbf{(5.4)}$$

where K = conveyance, defined as

$$K = \frac{K_n}{n} AR^{2/3} \quad \textbf{(5.5)}$$

The conveyance of each subsection can be defined as,

$$K = \frac{K_n}{n_i} A_i {R_i}^{2/3} \quad \textbf{(5.6)}$$

where i = index referring to the i-th subsection. The total discharge Q_T in the compound section is equal to the sum of the subsection discharges, Q_i. Assuming the energy head doesn't vary across the compound section, i.e., S_f is the same for all subsections we can calculate the discharge of each subsection.

$$Q_T = K_T {S_f}^{1/2} \quad \textbf{(5.7)}$$

$$Q_i = K_i {S_f}^{1/2} \quad \textbf{(5.8)}$$

$$Q_i = \frac{K_i}{K_T} Q_T \quad \textbf{(5.9)}$$

where Q_T = total discharge, K_T = total conveyance, Q_i = discharge at the *i-th* subsection, K_i = conveyance at the i-th subsection. After calculation of each subsection discharge, velocity (V) for each subsection is calculated by ratio of discharge (Q) to area (A). Hydraulic depth (y) is calculated from the ratio of total area to top width.

5.5 RESULTS OF HYDRAULIC PARAMETERS AND SCOUR DPETHS

The hydraulic parameters obtained from the HEC-RAS model (using different methods) was compared with the hydraulic parameters obtained from the WSPRO model. The outputs from the WSPRO model using the default value for contraction and expansion coefficient (0.0 and 0.5) were compared with the outputs from the HEC-RAS methods selecting the energy method with default contraction and expansion coefficient, i.e., 0.1 and 0.3, respectively, far upstream and downstream and 0.3 and 0.5 near the bridge. The WSPRO model does not output the hydraulic parameters in sequence as HEC-RAS model. It outputs the velocity distribution and cross-sectional properties in a text format. Some calculations are needed to obtain the hydraulic parameters needed for scour depth calculation using HEC-18 (which is integrated into HEC-RAS). The data reduction process of the WSPRO method to get hydraulic parameters is described in section 5.4. All the hydraulic parameters obtained from both the models were similar but somewhat different, the discharge at upstream approach section Q_1, discharge at the contraction section Q_2, width at upstream approach section W_1 were different by a relatively large percent (Table 5.2).

Discharge at upstream section Q_1, width at upstream section W_1, discharge at contraction section Q_2, and width at contraction section W_2 are selected hydraulic parameters for the ratio comparison using Equations (5.1) and (5.2). Table 5.2 clearly shows the flow contraction from the section 1 to 2, for example, from WSPRO output, LOB contracts from 290 ft to 41 ft, and discharge changes from 1347.6 to 514.1 cfs at LOB and from 1473.9 to 2357.1 cfs at the main channel. In the main channel, discharge at the contraction section (bridge crossing) from WSPRO is 1.6 times larger than the discharge at the approach section, but it is 2.4 times larger from HEC-RAS (from

1332.12 to 3195.65 cfs). It means HEC-RAS lets much more flow in the main channel due to the contraction. At the contraction section, discharge at the main channel from HEC-RAS is 838.52 cfs more than the channel discharge from WSPRO.

Table 5.2 Comparison of the hydraulic parameters from WSPRO's and HEC-RAS's energy methods.

Hydraulic Parameters	WSPRO Output			HEC-RAS (Energy Method)		
	LOB	CH	ROB	LOB	CH	ROB
Y_1 (ft)	3.56	13.75	5.38	3.81	14.46	5.61
V_1 (ft/s)	0.72	3.35	0.97	0.67	2.90	0.87
Y_o (ft)	4.02	14.28	5.14	3.24	14.67	4.50
Q_2 (cfs)	514.12	2357.13	948.75	206.19	3195.65	418.16
W_2 (ft)	41.00	29.00	50.00	41.66	25.72	45.84
D_{50} (mm)	0.03	0.047	0.055	0.03	0.047	0.055
Scour Eqn.	Clear-water	Default	Clear-water	Clear-water	Default	Clear-water
Q_1 (cfs)	1347.64	1473.89	998.48	1494.37	1332.12	993.51
W_1 (ft)	290.00	32.00	100.00	582.91	31.72	204.25
Scour (ft)	10.25	7.74	11.97	3.19	20.70	4.63

Note: subscript 1 for the upstream approach section, 2 for the contraction section at the bridge crossing. Y_0 is the average depth prior to scour at contraction section, i.e., Y_{BU} in Equations (1.2) and (1.3).

The comparison of the hydraulic parameters and then the scour depth from both the models is shown in Table 5.3. The clear-water scour was selected for computing the scour depths in the overbank areas. The hydraulic design function windows in HEC-RAS used for the calculation of the scour need the value of D_{50} entered in millimeter (mm). For the main channel, HEC-18 determines that the live-bed scour could occur and D_{50} could affect the exponent K_1. The exponent K_1 is related to the ratio of shear velocity (V_*) to fall velocity (w). The fall velocity depends on the D_{50} value of the bed material. For Spear Creek study, the value of exponent K_1 was 0.69, when $V_*/w > 2.0$. Since K_1 becomes a constant, the calculated depth for the live-bed scour does not depend on D_{50}. Based on Equation (1.2), the ratio in Equation (5.2) times Y_1 (water depth at upstream approach section) minus Y_o or Y_{BU} (average depth prior to scour at the bridge) will be the scour depth; therefore, three factors (the ratio, Y_1, and Y_o) possibly affect the live-bed scour depth calculation.

For the overbank areas, Equation (5.1) was used to obtain the ratio of hydraulic parameters for the clear-water scour comparison. Based on Equation (1.3), the ratio in Equation (5.1) times the ratio $[1/(C_u D_m^{2/3})]^{3/7}$ minus Y_o will be the scour depth; therefore, three factors (two ratios and Y_o) possibly affect the clear-water scour depth calculation. Even though C_u is a constant depending on units, D_m = 1.25 D_{50} is a function the particle size D_{50} and directly affect the scour depth. The discharges in LOB and ROB at the contraction section (Q_2) calculated from WSPRO are 307.93 cfs and 530.59 cfs larger than corresponding discharges from HEC-RAS model, respectively. The absolute differences in the width at the contraction section (W_2) are 0.7 ft and 4.16 ft, respectively, at LOB and ROB (Table 5.2). For both the methods, the D_{50} value used is the same.

The ratio of selected hydraulic parameters (5.1) from both the methods for LOB and ROB is 2.22 and 1.87, respectively. Although the ratio of average depth prior to scour is close to 1.0 for both cases, it could affect the scour depth ratio if the selected parameters are changed. For example, the average depth prior to scour at contraction section for WSPRO and HEC-RAS is 4.02 and 4.5 ft, respectively. The ratio of hydraulic parameters (Equation (5.1)) is 8.74 for WSPRO and 3.94 for HEC-RAS at LOB. The ratio $[1/(C_u D_m^{2/3})]^{3/7}$ is 1.62 at LOB but 1.33 at ROB since D_{50} at LOB is 0.03 mm, half of 0.06 mm at ROB, but there is no change in the ratio for both the methods because of the same D_{50}. Based on Equation (1.3), calculated water depth after scour (Y_{AS} in Table 5.2) is the product of the ratio of hydraulic parameters (Equation 5.1) and $[1/(C_u D_m^{2/3})]^{3/7}$. The ratio of Y_{AS} values is the same as the ratio of hydraulic parameters between two methods (Table 5.2). The ratios of scour depths at LOB and ROB using hydraulic parameters from WSPRO and HEC-RAS are 3.21 and 2.59, respectively. Since the final scour depth is the difference of Y_{AS} and Y_o, the ratio and the percent difference of scour depths between the two methods are always different from the ratio and the percent difference of Y_{AS} and hydraulic parameters in Equation 5.1. When Y_o is close to Y_{AS}, above differences in the ratio and the percent difference become larger.

Based on Equation (1.3), the water depth after scour (Y_{AS}) is proportion to $[1/D_{50}]^{2/7}$. If D_{50} is 50% or 100% larger than the true D_{50}, it makes Y_{AS} 89% and 82% of the true Y_{AS} for the clear-water scour. For hydraulic parameters, the water depth after scour (Y_{AS}) is proportion to $[Q_2/W_2]^{6/7}$ since the exponent 6/7 is close to 1.0; the change in hydraulic parameters will have a similar impact on Y_{AS}, which means hydraulic parameters could have relatively large impacts on calculating the scour depth. Table 5.3 shows the ratio of hydraulic parameters (Equation 5.1) from WSPRO is 61% and 76% larger than the ratio from HEC-RAS at ROB and LOB, respectively. Figure 5.4 graphically presents the difference in scour depth predicted by the two methods.

Table 5.3 Comparison of ratios of the hydraulic parameters and scour depths from WSPRO and HEC-RAS's energy method at overbanks areas (LOB and ROB)

Hydraulic parameters	WSPRO		HEC-RAS (0.3,0.5)		Ratio[1]		%Difference[2]	
	LOB	ROB	LOB	ROB	LOB	ROB	LOB	ROB
$\left(\frac{Q_2^{\,2}}{W_2^{\,2}}\right)^{3/7}$	8.74	12.46	3.94	6.66	2.22	1.87	76	61
$\left(\frac{1}{C_u D_m^{2/3}}\right)^{3/7}$	1.62	1.33	1.62	1.33	1	1	0	0
Y_{AS} [3]	14.16	16.57	6.43	9.13	2.20	1.81	75	58
Y_0	4.02	5.14	3.24	4.5	1.24	1.14	21	13
Scour depth (Ys) ft	10.25	11.97	3.19	4.63	3.21	2.59	105	88

Note: [1] - Ratio is calculated from WSPRO method divided by the HEC-RAS method. For example, 10.25/3.19=3.21, [2] - % Difference is calculated as the difference divided by the average of WSPRO and HEC-RAS method. For example, (10.25 – 3.19)/(average (10.25,3.19)* 100 % = 105/ %, and [3] – water depth at the contraction section (bridge crossing) after scour.

For the main channel, Equation (5.2) is used to calculate the ratio of hydraulic parameters for the live-bed scour. The exponent K_1 used for the live-bed scour has three values (Table 1.2). There is a small change in calculated scour depth when K_1 is changed. This is because W_1/W_2 in the main channel is close to 1 (1.10 from WSPRO and 1.23 from HEC-RAS). The scour depth could be 7.73, 7.62, and 7.51 ft when K_1 used was 0.69, 0.64 and 0.59, respectively, when hydraulic parameters from WSPRO were used. The K_1 value remains same (analyzed for Table 5.2 Channel case) for large range of D_{50} values keeping hydraulic parameter Y_1 constant (used to calculate the shear velocity), the K_1 value remains as 0.69 for D_{50} changing from 0.005 mm to 0.74 mm and changes to 0.64 when D_{50} is from 0.75 to 7 mm. The K_1 value changes to 0.59 when D_{50} > 7.1 mm. When D_{50} changes but K_1 does not change, the difference in scour depth is due to the difference in the hydraulic parameters obtained from two methods.

The ratio of the hydraulic parameters between WSPRO and HEC-RAS method at channel is 0.66 but the ratio of the scour depth ratio is 0.37 (Table 5.4). This means the scour depth predicted from WSPRO model at channel is 37% of the scour depth predicted from HEC-RAS. The major cause for large scour depth from HEC-RAS is a large flow contraction: Q_2/Q_1 = 2.3 or $(Q_2/Q_1)^{6/7}$ = 2.1 but Q_2/Q_1 = 1.6 from WSPRO. The water depth Y_1 at the approach section is about 12% more from HEC-RAS, and calculated depth after scour (Y_{AS}) is 60.7 % from HEC-RAS, which is 13.37 ft more than Y_{AS} from WSPRO.

Table 5.4 Comparison of ratios of the hydraulic parameters and scour depths from WSPRO's and HEC-RAS's energy method at channel

Hydraulic Parameters	WSPRO	HEC-RAS	Ratio	% Difference
	CH	CH	CH	CH
$\left(\frac{Q_2}{Q_1}\right)^{6/7} * \left(\frac{W_1}{W_2}\right)^{0.69}$	1.60	2.44	0.66	41.6
Y_1	13.75	14.46	0.95	5.0
Y_{AS}	22.0	35.37	0.62	46.6
Y_0	14.28	14.67	0.97	2.7
Scour depth (Ys), ft	7.74	20.7	0.37	91.1

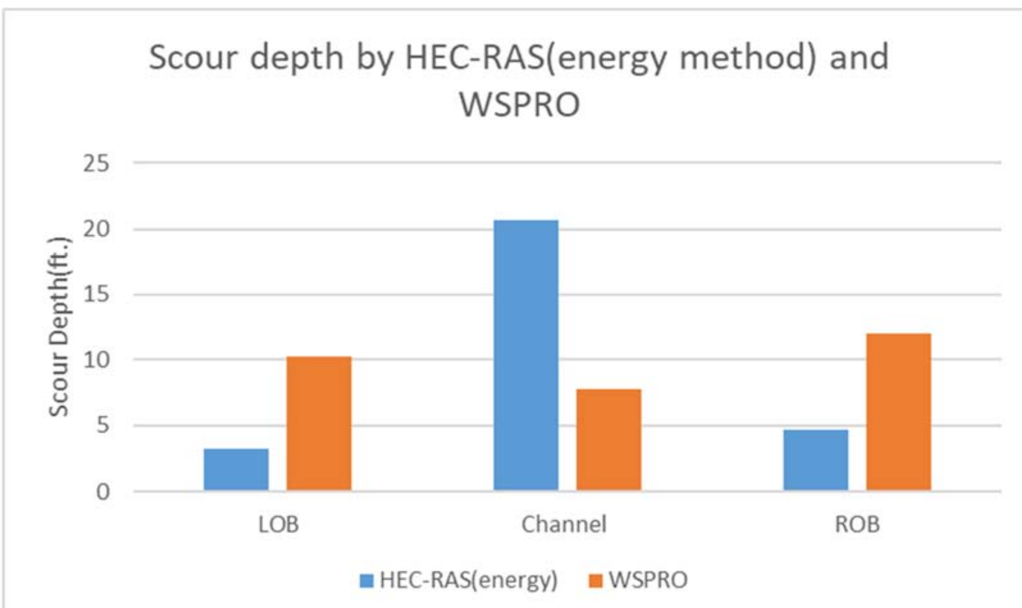

Figure 5.4 Comparison of scour depth from WSPRO and HEC-RAS (energy method)

For all other comparisons below, only the ratio of selected parameters, Equations (5.1) and (5.2), are shown in Tables 5.4 to 5.7. However, the scour depth is calculated using all the hydraulic parameters as in Equations (1.2) and (1.3). Also, to mimic the similar scenario the WSPRO method in HEC-RAS was used to compare to the output from the Energy method in HEC-RAS model by keeping the expansion and contraction coefficient same. These coefficients were set as HEC-RAS methodology (0.3 and 0.5) and comparison results are summarized in Table 5.5. Then WSPRO method in HEC-RAS model was compared by changing the expansion and contraction ratio from 0.3, 0.5 to 0.0, 0.5 respectively (Table 5.6). The HEC-RAS results for the scour depth for the first case is same to the results (Table 5.3 and Table 5.4) when only energy method was used. There is not much change in hydraulic parameters eventually giving very close scour depth value (Table 5.5). The ratio of selected hydraulic parameters (5.1) for the clear-water scour from both the methods for LOB and ROB are 1.0. The ratio of scour depth obtained from the two methods at LOB and ROB are 1.0 (Table 5.5). The ratio of selected parameters (Equation (5.2)) from both the methods at the channel is 1.02 with a scour depth ratio of 1.02 (Table 5.5). That means scour depth predicted from energy method from HEC-RAS model at the channel is 1.02 times less than the scour depth predicted from the HEC-RAS using WSPRO method.

For the second case, using WSPRO method in HEC-RAS with contraction and expansion coefficients as 0.0, 0.5; and 0.3, 0.5; there was a small change in the HEC-RAS results as obtained in the first case, i.e., using different contraction and expansion coefficient (Table 5.6). The discharge at contraction section differ (absolute) by 66.1, 63.76 and 2.35 cfs in LOB, CH and ROB, respectively. This difference in the discharge affects the scour depth mainly in channel with a difference of 2.01 ft. The scour depth at the main channel is 1.10 times the scour depth obtained using WSPRO method using expansion and contraction coefficients as 0.0 and 0.5 ft, respectively. For this case, there is a small difference; however, there could be large difference in cases where the difference in the velocity head between the sections is large.

Table 5.5 Comparison of the hydraulic parameters and scour depth from Energy method and WSPRO method of HEC-RAS model using same contraction and expansion coefficient as HEC-RAS methodology

Ratio	Energy method (HEC-RAS) (0.3, 0.5)			WSPRO method (HEC-RAS) (0.3, 0.5)			Ratio[1]		
	LOB	CH	ROB	LOB	CH	ROB	LOB	CH	ROB
$\left(\frac{{Q_2}^2}{{W_2}^2}\right)^{3/7}$	3.94	–	6.65	3.94	–	6.65	1.0	–	1.0
$\left(\frac{Q_2}{Q_1}\right)^{6/7} * \left(\frac{W_1}{W_2}\right)^{0.69}$	–	2.44	–	–	2.49	–	–	1.02	–
Scour depth (Ys) ft	3.19	20.7	4.63	3.18	21.4	4.63	1.0	1.03	1.0

Note: [1] - Ratio is calculated as WSPRO method divided by the energy method in HEC-RAS. For example, 3.94/3.94=1.

Table 5.6 Comparison of the hydraulic parameters and scour depth from HEC-RAS WSPRO method using different contraction and expansion coefficient

Ratio	WSPRO (HEC-RAS) method (0.3, 0.5)			WSPRO (HEC-RAS) method (0.0, 0.5)			Ratio[1]		
	LOB	CH	ROB	LOB	CH	ROB	LOB	CH	ROB
$\left(\frac{{Q_2}^2}{{W_2}^2}\right)^{3/7}$	3.94	–	6.65	3.87	–	6.6	1.02	–	1.01
$\left(\frac{Q_2}{Q_1}\right)^{6/7} * \left(\frac{W_1}{W_2}\right)^{0.69}$	–	2.44	–	–	2.40	–	–	1.02	–
Scour depth(Ys)	3.18	21.4	4.63	3.14	19.39	4.61	1.01	1.10	1.0

The effect of using different contraction and expansion lengths on scour depth calculation was also analyzed by changing them based on HEC-RAS methodology. The model was run for three times with different expansion and contraction lengths. The expansion and contraction lengths were taken based on one of the HEC-RAS methodology. The US Army Corps of Engineers (Brunner 1995) provides a table of ranges of expansion ratios that can be used as a guide to determine the expansion length. The average of distances A to B and C to D (Figure 1.4), i.e., an average of bridge embankment lengths into the floodplain) is multiplied by the expansion ratio obtained from (Table 5.7) to get the expansion length.

Table 5.7 Ranges of expansion ratio

		nob / nc = 1	nob / nc = 2	nob / nc = 4
b/B = 0.10	S = 1 ft/mile	1.4 – 3.6	1.3 – 3.0	1.2 – 2.1
	5 ft/mile	1.0 – 2.5	0.8 – 2.0	0.8 – 2.0
	10 ft/mile	1.0 – 2.2	0.8 – 2.0	0.8 – 2.0
b/B = 0.25	S = 1 ft/mile	1.6 – 3.0	1.4 – 2.5	1.2 – 2.0
	5 ft/mile	1.5 – 2.5	1.3 – 2.0	1.3 – 2.0
	10 ft/mile	1.5 – 2.0	1.3 – 2.0	1.3 – 2.0
b/B = 0.50	S = 1 ft/mile	1.4 – 2.6	1.3 – 1.9	1.2 – 1.4
	5 ft/mile	1.3 – 2.1	1.2 – 1.6	1.0 – 1.4
	10 ft/mile	1.3 – 2.0	1.2 – 1.5	1.0 – 1.4

Note: b/B is the ratio of bridge opening width to the total floodplain width, S is a longitudinal slope, and n_{ob}/n_c is the ratio of Manning's roughness coefficients in the overbank area and main channel.

In case of Spear Creek, the bride opening (b) is 138 ft and the total floodplain width (B) is 990 ft. The ratio of *b/B* is 0.13, which is near to 0.10. The Manning's coefficient for the overbank area is 0.18 and for the channel is 0.08. The ratio n_{ob}/n_c is 2.2, which is close to n_{ob}/n_c = 2. The longitudinal slope is ~5 ft/mile in Spear Creek. Based on above calculation, the expansion ratio is taken as 0.8 (minimum) and 2 (maximum), which lies in the range of 0.8 and 2.0. The contraction length is usually shorter than the expansion length. Therefore, the minimum and maximum expansion ratios of 1.0 and 2.0 were used and multiplied to 426 ft (the average of distances from A to B and C to D) to get the expansion length of 426 ft and 852 ft, respectively. HEC-RAS (Brunner 1995) recommends the contraction length in between 1 and 1.5 times the average of distance A to B and C to D (Figure 1.4). From this range,1 is chosen and multiplied to 426 to get 426 ft as the minimum contraction length and 1.5 is chosen and multiplied to 426 to get 639 as the maximum contraction length. WSPRO method in HEC-RAS was used for gathering the hydraulic parameters. There was a change in discharge value both upstream and at the contraction section with a change in the scour depth value when minimum expansion length as recommended by HEC-RAS is used. The absolute difference in discharge upstream (Q_1) at LOB, CH, and ROB were 314.1 cfs, 321.9 cfs, and 7.8 cfs, respectively, whereas the absolute difference in discharge at the contraction section (Q_2) were 43.06 cfs, 95.53 cfs, and 52.47 cfs respectively. The scour depth obtained using expansion and contraction length at 160 ft and 138 ft is 1.5, 1.5,and 1.4 times larger than the scour depth obtained using expansion and contraction length 426 ft and 426 ft at LOB, Channel and ROB, respectively.

Table 5.8 Change in scour depth with the change in minimum expansion and contraction length using HEC-RAS model.

Hydraulic parameters	Expansion length = 160 ft, contraction length = 138 ft			Expansion length = 426 ft, contraction length = 426 ft			Ratio[1]		
	LOB	CH	ROB	LOB	CH	ROB	LOB	CH	ROB
Y_1 *(ft)*	3.53	14.16	5.37	2.52	13.13	4.52	1. 4	1. 1	1. 2
V_1 *(ft/s)*	0.69	3.04	0.96	0.69	3.67	1.06	1.0	0.8	0.9
Y_0 *(ft/s)*	3.19	14.61	4.45	2.68	13.87	4.02	1.19	1. 0	1.1
Q_2 *(cfs)*	202.13	3204.69	413.18	159.07	3300.22	360.71	1.3	1.0	1.1
W_2 *(ft)*	41.56	25.72	47.72	46.07	29	50.46	0.9	0.9	0.9
D_{50} *(mm)*	0.03	0.047	0.055	0.03	0.047	0.055	–	–	–
Q_1 *(cfs)*	1414.20	1365.17	1040.63	1100.14	1687.06	1032.81	1.3	0.8	1
W_1 *(ft)*	581.42	31.72	202.11	635.76	35	214.69	0.9	0.9	0.9
Scour (y_s, ft)	3.14	19.39	4.61	2.04	12.70	3.39	1.5	1.5	1.4

Note: [1] - Ratio is calculated as 3.53/2.52=1.4

When the expansion and contraction lengths were changed from 426 and 426 ft to 639 and 426 ft, there was a change in discharge at contraction section (Q_2) (Table 5.8 and Table 5.9). The absolute difference in Q_2 is 31.3 cfs, 69.8 cfs in LOB and Channel, respectively. Due to the decrease in Q_2 value at channel, the scour depth decreases from 12.7 to 10.69 ft. This indicates that scour depth is affected by the change in the expansion and contraction lengths in the same model. Also, when the expansion and contraction lengths are changed to 852 and 639 ft from 639 and 426 ft, there is an increase in the discharge at contraction section in overbanks areas and decrease in main channel that makes the scour depth at overbanks areas to increase and decrease in main channel. The scour depth obtained from using WSPRO expansion and contraction lengths (160 and 138 ft) is 1.19, 2.28, and 1.25 times larger than the scour depth obtained from using maximum expansion and contraction length (852 and 639 ft) recommended by HEC-RAS. This indicates that using different expansion and contraction lengths could change the hydraulic parameters that eventually change the scour depth.

Table 5.9 Change in scour depth with the change in maximum expansion and contraction length using HEC-RAS model.

Hydraulic parameters	Expansion length = 639 ft, contraction length = 426 ft			Expansion length = 852 ft, contraction length = 639 ft			Ratio		
	LOB	CH	ROB	LOB	CH	ROB	LOB	CH	ROB
Y_1 *(ft)*	2.36	12.96	4.38	2.17	12.77	4.22	1. 1	1. 0	1. 0
V_1 *(ft/s)*	0.70	3.85	1.10	0.71	4.02	1.15	1	1	1
Y_0 *(ft/s)*	3.08	14.32	4.39	3.50	14.81	4.78	0.9	1. 0	0.9
Q_2 *(cfs)*	190.35	3230.41	399.24	224.17	3155.81	440.02	0.8	1.0	0.9
W_2 *(ft)*	46.94	29	51.49	47.88	29	52.63	1	1	1
D_{50} *(mm)*	0.03	0.047	0.055	0.03	0.047	0.055	–	–	–
Q_1 *(cfs)*	1042.67	1745.29	1032.05	972.12	1817.42	1030.46	1.1	1.0	1.0
W_1 *(ft)*	634.85	35	213.38	633.78	35	211.85	1.0	1.0	1.0
Scour (y_s, ft)	2.34	10.69	3.35	2.63	8.52	3.69	0.9	1.3	0.9

The HEC-RAS model for all above cases was configured without including the ineffective flow area. The HEC-RAS model was run using the ineffective flow areas as discussed in section 5.2 using WSPRO method with contraction and expansion coefficients as 0.0 and 0.5 (Table

5.10).The ratio of the selected hydraulic parameters (Equation (5.1)) for LOB and ROB were close to 1 for both. The scour depth ratio for a LOB and ROB were also close to 1. The scour depth ratio at channel was 0.95 (Table 5.10). That means the scour depth obtained without ineffective flow area is 0.95 times smaller than scour depth obtained with ineffective flow area at channel section.

When scour depths at LOB, CH, and ROB from HEC-RAS with ineffective areas are compared corresponding scour depths from WSPRO, one can see that the differences become larger at LOB and ROB but smaller in the main channel. It means ineffective areas reduce effective flow velocity in the overbank areas and channel that result in smaller scour depths. The ineffective flow areas were set for the sections immediately upstream and downstream of the bridge crossing in HEC-RAS.

Table 5.10 Change in scour depth with and without including ineffective flow area using HEC-RAS model with WSPRO method.

Ratio	WSPRO (without ineffective flow)			WSPRO (with ineffective flow)			Ratio[1]		
	LOB	CH	ROB	LOB	CH	ROB	LOB	CH	ROB
$\left(\frac{{Q_2}^2}{{W_2}^2}\right)^{3/7}$	3.87	–	6.6	3.98	–	6.69	0.97	–	0.99
$\left(\frac{Q_2}{Q_1}\right)^{6/7} * \left(\frac{W_1}{W_2}\right)^{0.69}$	–	2.4	–	–	2.44	–	–	1.0	–
Scour depth(y_s, ft)	3.14	19.39	4.61	3.21	20.32	4.65	0.98	0.95	0.99

Note: [1]- Ratio is calculated as WSPRO without ineffective flow divided by WSPRO with the ineffective flow.

The water surface elevations from both the models were also compared and tabulated in Table 5.11. Both models compute the water surface profiles within the tolerance. There was not much difference in the values obtained from both the models. The variation of the water surface elevations (WSEs) at any cross section for four bridge cases was in the order of 0.02 to 1.15 feet. Alamuchee Creek has the variation of the WSE in the range of 0.34 to 0.37 ft . The average absolute error for Alamuchee Creek is 0.36 ft. In case of Spear Creek at the approach section the WSE computed by HEC-RAS and WSPRO differs by 1.28 ft, which is the largest difference in WSE for all the bridge cases. The difference ranges from 0.34 to 1.15 with a average of 0.65 ft for the Pinatall Creek. The WSE computed for Spear Creek by WSPRO and HEC-RAS varies within a range of 0.21 to 1.2 ft with a average of 0.41 ft. For the case of Valley Creek the WSE computed by WSPRO and HEC-RAS varies within a range of 0.02 to 0.08 ft with an average of 0.054. Due to the unavalability of the observed WSE for all the bridge cases, these study could not accuartely point out the best method to compute the water surface elevation. In the report published by the US Army Corps of Engineers (Brunner and Hunt 1995) seventeen flood events were analyzed at 13 different bridge sites and the observed WSE was compared to the calculated WSE from HEC-RAS and WSPRO. There was a variation of 0.1 to 0.3 ft. In this case the variation is large at approach section of Pintalla Creek and Spear Creek. Other WSEs vary within a range of 0.02 to 0.46 ft, which are somewhat close to the variation in the different bridge site provided in the report.Therefore, it is believed that any of these models could be used to compute the water surface profiles at bridge location.

Table 5.11 Comparison of simulated water surface elevations between WSPRO and HEC-RAS models

	Cross Sections	HEC-RAS WSE (ft)	WSPRO WSE (ft)	Absolute error (ft)
Alamuchee Creek	Exit	181.42	181.79	0.37
	Full Valley	181.56	181.95	0.39
	Approach	183.66	183.32	0.34
	Average			**0.36**
Pintalla Creek	Exit	163.97	163.63	0.34
	Full Valley	164.19	163.73	0.46
	Approach	165.58	164.43	1.15
	Average			**0.65**
Spear Creek	Exit	115.92	115.90	0.02
	Full Valley	116.26	116.25	0.01
	Approach	118.09	116.81	1.28
	Average			**0.44**
Valley Creek	Exit	101.67	101.69	0.02
	Full Valley	101.85	101.91	0.06
	Approach	102.52	102.44	0.08
	Average			**0.05**

Chapter 6 SUMMARY AND CONCLUSIONS

6.1 SUMMARY

Scour is crucial in bridge designing. Bridge designing should be done with accuracy to minimize the future disasters. The ability to determine the hydraulic parameters and eventually scour depth is imperative to designing safe, economic, and efficient bridge foundations. Different types of soils either cohesive or non-cohesive soils are present in the Earth surface. Scour behavior for the non-cohesive soil is well understood. However, much research has been performed in an effort to understand scour behavior in cohesive soils. The cohesive soils act differently than the non-cohesive soils, which erode particle by particle. In the USA, currently, scour depths are calculated using HEC-18, which is used by many DOTs to calculate the scour depth around the bridge. HEC-18 provides different sets of equations to calculate the different types of scour depth, which are contraction scour, pier scour, and abutment scour. The HEC-18 equations are derived based on the lab experiments on non-cohesive soils. These equations are also used to calculate the scour depth in cohesive soils. Different sets of hydraulic parameters like discharge, width, and depth at different sections are needed by HEC-18 equations to calculate the different-type scour depths. The hydraulic parameters can be obtained from either WSPRO or HEC-RAS or other flow simulation programs. The HEC-RAS is the newest software package from HEC. This study was done to figure out and illustrate some uncertainties in HEC-18 equations that are being used for calculating the scour depth in cohesive soils. Different models that are used to obtain the hydraulic parameters were compared and the effect of the change in the hydraulic parameters to the scour depth were discussed.

Four bridge cases in which the scour depths were calculated using HEC-18 equations were provided by the ALDOT. These bridge cases were used to evaluate, understand, and illustrate the uncertainty in bridge scour calculation. The critical velocities and shear stresses of the six cohesive soils that were obtained from the EFA from the published report "Evaluation of cohesive soils-phase 2" were used to analyze the uncertainties of the HEC-18 equations. There are possible different types of soils in different layers (depths) with different D_{50} values.

Current DOTs typically use HEC-18 and the average D_{50} removing outliers to calculate the scour depth. The effect of using average D_{50} value and layer-by-layer D_{50} values was analyzed and discussed. Also, the effect of averaging D_{50} removing the outliers and without removing the outliers on scour depth was evaluated and discussed.

The HEC-18 equations for contraction scour (clear-water and live-bed) use several hydraulic parameters for the scour depth calculations. These hydraulic parameters were calculated in this study from two models: WSPRO and HEC-RAS. Both models were setup and different simulations using different model parameters/options were done using the same channel geometrical and flow data to obtain the hydraulic parameters. The differences in the hydraulic parameters obtained from WSPRO and HEC-RAS were analyzed and discussed. In addition, the scour depths resulting from respective hydraulic parameters were compared and analyzed.

There were various difficulties in past to obtain the soil samples to test the erosion rate in Alabama. The soil samples obtained were unusable for performing the soil erosion test due to cracks and fractures. A part of the initial plan for this study was to develop soil samples with different percentage of sand, clay, and silt using a pugger mixer and do the erosion testing on the EFA. However, due to the problem in the motor of the EFA, which is used to push the soil sample out of the Shelby tube, the EFA test could not be performed for more than two soil samples. The procedure of running the pugger mixer was figured out (Pokharel 2017). Two soil samples with different soil percentage were developed and tested in EFA using old methods (not using the ultrasonic sensor). The critical shear stress and the critical velocity from EFA and HEC-18 were compared and analyzed for two soil samples with different percentage of sand, clay, and silt.

6.2 CONCLUSIONS

It was concluded that certain uncertainties exist in HEC-18 equations and it is best and more suitable to be used to calculate the scour depth of non-cohesive soil as the equations were derived based on lab experiment on non-cohesive soils. The uncertainty of predicting and estimating the scour depth comes from various sources such as soil properties (D_{50}, critical velocity and scour rate) and hydraulic parameters. HEC-18 use only D_{50} value to calculate the critical velocity. Although, having same D_{50} value the percentage of cohesiveness could be different which would affect scour depth. For cohesive soils (e.g., clay) with small particle sizes (i.e., D_{50}), the HEC-18 method calculates smaller critical velocities and then make the scour occur earlier than it is supposed to occur. Calculated critical velocities and modeled velocity at the upstream approach section decide which equation to be used either as live-bed or clear-water scour. The critical shear stress obtained from EFA (τ_{c1}) was compared to the critical shear stress obtained from the HEC-18 (τ_{c2}) using D_{50} as input. The ratio of τ_{c1}/τ_{c2} ranges from 3.2 to 115 with an average of 31.8 and standard deviation of 37.9; therefore, it means for these clay soils (D_{50} < 0.09 mm) the critical shear stress from HEC-18 is significantly smaller than the critical shear stress determined using EFA tests.

The critical velocity calculated from HEC-18 (V_{c1}) and the critical velocity using τ_c from *EFA* and D_{50} (V_{c2}) were compared when the upstream water depth (y) is taken as 1.5 or 4 m for calculations. The ratio of V_{c2}/V_{c1} ranges from 1.7 to 10.4 with an average of 4.8 and standard deviation of 2.7. That means the HCE-18 predicts the scour earlier than it happens, which would overestimate the scour depth. For the main channel, V_c obtained from HEC-18 Equation 3.5 is less than V_1 (Table 3.4 for Spear Creek) which would make it a live-bed scour. Table 3.4 shows the scour depth of 7.74 ft calculated using default method from HEC-18, which allows HEC-18 to determine whether or not the clear-water or live-bed scour would occur. HEC-18 results show the live-bed scour would occur. However, V_c obtained from Equation 3.6 is greater than V_1 for same channel section which would make it as a clear-water scour. The particle size D_{50} has a direct impact on calculating the clear-water scour depth after the scour (Equation 1.3), *i.e.*, proportion to $1/D_{50}^{2/7}$. The scour depth calculated using the clear-water scour would result in 47.76 ft of scour in the main channel. This is a huge difference in calculated scour depth that explains the uncertainty in HEC-18 equation. Therefore, it was concluded that using HEC-18 with average D_{50} for cohesive soil has certain uncertainties and could overestimates the scour depth. Therefore, the USGS envelope curves developed for ALDOT (Lee and Hedgecock 2008) are used at the bridge sites where the scour depth predicted using HEC-18 is not reasonable. Two main variables influencing the clear-water scour were velocity index and channel contraction ratio. These two variables were used as independent variables to develop two envelope curves. The envelope curves developed for ALDOT can only be used to bridge sites that fall on the Black Prairie Belt. If the scour depth calculated from HEC-18 of any bridge site that falls on the Black Prairie Belt seems not reasonable then engineers are suggested to use those envelope curves to calculate the scour depth. Many DOTs do not have the envelope curves developed from observed scour depths as USGS did for ALDOT. DOTs may not have other additional tools to help designers estimate/predict the scour depth more accurately.

From the study of the multilayer method, it was concluded that using only average D_{50} value does not accurately predict the scour depth. The D_{50} value of all layers should be considered while calculating the scour depth. Using the layer-by-layer D_{50} values to calculate the scour depth from HEC-18 and summing up all the feasible scour depths in each layer could give more accurate scour depth rather than using only average D_{50} value. When recommending the multilayer method for predicting the scour depth, it is desired to have D_{50} for many layers up to deep depth; otherwise, limited data may affect the accuracy of the multilayer method. For obtaining better accuracy in the multilayer method, one can use the weighted average D_{50} with layer thickness or just take an average of D_{50} up to the layer where soil is eroded.

There is uncertainty to accurately determine representative D_{50} in the field in different depth layers and specify D_{50} for some depth layers where D_{50} was not determined. The variations of D_{50} could affect the scour depth calculation, for example, for the bridge site in Valley Creek, D_{50} is 0.15 mm in the first 10 ft and 0.075 mm in the next 10 ft, and using hydraulic parameters from HEC-RAS, HEC-18 predicts 9.0 ft and 12.5 ft of clear-water scour in the left overbank area. In above case, the particle size in deeper depth is half of D_{50} in the surface layers but the scour depth is about 39% more. For Spear Creek, D_{50} in the main channel ranged from 0.006 to 0.106 mm but it has no effect on the scour depth of the live-bed, and only hydraulic parameters dominantly control the scour depth calculation. The scour depth from all the D_{50} value of the layers was 17.5 ft. Since the water depth after live-bed scour is linked with D_{50} through an exponent K_1 in Equation (1.2), K_1 has three values (0.59, 0.64, and 0.69) as the ratio of shear velocity and fall velocity (depends on the D_{50} value of the bed material) falls into three ranges (<0.5, ≥0.5 but ≤2.0, and >2.0).

WSPRO and HEC-RAS models using the same geometry and flow input data output or predict similar but not exactly same magnitude of hydraulic parameters (e.g., discharges, width, and depths at the approach and contraction sections), although both use the standard step method to solve the one-dimensional energy equation. WSPRO model distributes more flow in the overbank areas than HEC-RAS does but HEC-RAS distributes more flow in the main channel for this case study. Therefore, HEC-RAS predicts much more scour in the main channel than WSPRO does. For example, HEC-RAS predicts 17.9 ft and WSPRO predicts 7.7 ft of live-bed scour in the main channel of Spear Creek under 100-year flood (the percent difference is 79.3%), but HEC-RAS predicts 6.6 and 8.6 ft and WSPRO predicts 10.3 and 12.0 ft of clear-water scour in overbank areas (the percent differences of 43.3% and 32.8%). Hydraulic parameters in Equations (1.2) and (1.3) play an important role in calculating the scour depth. Scour depths are typically calculated for overbank areas and main channel separately, and the clear-water scour is determined for heavily vegetated overbank areas. The effects of these hydraulic parameters on the scour depth were studied in Spear Creek as case study (Table 5.3). It is evident that predicted scour depth could be different according to the 1-D hydraulic model used for obtaining the hydraulic parameters. Results show there is not much change in the hydraulic parameters by changing the expansion and contraction lengths and the contraction and expansion coefficients for energy losses; therefore, they have not much impact on the scour depth also. However, in other studies (Brunner and Hunt 1995) these lengths and coefficients could play a much greater role in predicting the energy losses and water surface elevations near the bridge. This study also suggests considering the ineffective flow area while doing the simulation using HEC-RAS. Using ineffective flow areas could change the hydraulic parameters that will eventually change the scour depth. Given that a limited number of data sets were used in this study and due to the unavailability of observed data of hydraulic parameters, this study could not accurately point out which one-dimensional model to be the best one to calculate the hydraulic parameters for calculating scour depth.

The soil samples collected from the field when they were unusable for EFA tests could be made usable by using the pugger mixer. Different soil components that could be in or near the bridge site and are difficult to obtain can be engineered in the lab using the pugger mixture. The EFA test can be run with the soil samples developed by using pugger mixer. It would be easier and most reliable to use pugger mixer when the soil sample obtained from the site is not usable in EFA.

6.3 FUTURE STUDIES

The hydraulic parameters could be calculated from different models and using those hydraulic parameters to calculate scour depth could give different scour depths. A study can be carried out to figure out the best model for obtaining the hydraulic parameters by comparing them to the observed data, and this will lead to a more accurate scour depth prediction. Some of hydraulic parameters are also difficult to measure in the field, especially during the flood event; therefore, two- or three-dimensional computational fluid dynamics (CFD) models and laboratory experiments could be used/performed to determine how much flow should go to the main channel and overbank areas and which one-dimensional model is more accurate. Through the study it was still difficult to figure out the percentage effect of a change in the hydraulic parameters to scour depth. The more in-depth study could be carried out to create a relationship/trend of change in hydraulic parameters to scour depth.

EFA test is used to determine the critical velocity and the scour rate for both cohesive and non-cohesive soil. EFA test results should be used in the calculation and specifying the critical velocity and the erosion rate of cohesive soils for determining the scour depth. The soil samples with different percentage of soil components developed from the pugger mixer can be used in EFA to see difference in critical velocity and scour rate. The percentage of sand for the soil samples 1 and 2 that Pokharel developed for his study (Pokharel 2017) were relatively high, and corresponding D_{50} of the samples were 0.20 and 0.27 mm. For the future study, soil samples with high percentage of clay and silt than sand should be prepared to make it more cohesive. Soil samples with different moisture content can be made from the pugger mixer. The critical velocity and the scour rate for same soil samples with different soil moisture contents could be performed and analyzed in future so that the effect of moisture content in scour could be known. Another method called the scour rate in cohesive soil (SRICOS-EFA) (Briaud et al. 2005) could be used to calculate the scour depth of a fine-grained soil more accurately. SRICOS-EFA uses the data obtained from the EFA. The program needs the shear stress and scour rate in different layers for the calculation of the scour. SRICOS-EFA performs a site-specific scour calculation using soil properties (Briaud et al. 2005) and long-term discharge time-series data because it uses site specific soil samples and EFA to determine critical velocity and scour rate. Also, it includes the effect of a long-term hydrograph resulted from different rainfall events unlike using a peak flow rate of 100- or 500-year return flow rate as in HEC-18. In addition to that, the SRICOS-EFA method can handled layered soil system that could be much more beneficial in a site where there are different soil types or properties in different layers.

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