

NUMERICAL MODEL EVALUATIONS OF CUMULATIVE CONTRACTION
SCOUR AT A BRIDGE SITE WITH COHESIVE SOILS

Except where reference is made to the work of others, the work described in this thesis is
my own or was done in collaboration with my advisory committee.

Dustin T. Harris

Certificate of Approval:

Oktay Güven
Professor
Civil Engineering

Joel Melville
Professor
Civil Engineering

Willie Harper
Assistant Professor
Civil Engineering

Stephen L. McFarland
Acting Dean
Graduate School

NUMERICAL MODEL EVALUATIONS OF CUMULATIVE CONTRACTION
SCOUR AT A BRIDGE SITE WITH COHESIVE SOILS

Dustin T. Harris

A Thesis

Submitted to

The Graduate Faculty of

Auburn University

In Partial Fulfillment for the

Degree of

Master of Science

Auburn, Alabama

August 8, 2005

NUMERICAL MODEL EVALUATIONS OF CUMULATIVE CONTRACTION
SCOUR AT A BRIDGE SITE WITH COHESIVE SOILS

Dustin T. Harris

Permission is granted to Auburn University to make copies of this thesis at its discretion, upon the request of individuals or institutions and at their expense. The author reserves all publication rights.

Signature of Author

Date

Copy sent to:

Name

Date

VITA

Dustin T. Harris, son of Thomas W. and Wanda H. Harris, was born January 31, 1981, in Fairhope, Alabama. He graduated from Fairhope High School, in Fairhope, Alabama in the Spring 1999. In the Fall of 1999 he entered undergraduate studies at Auburn University. December of 2003 he graduated magna cum laude from Auburn University with a Bachelor of Civil Engineering. He began his graduate studies at Auburn University with specialties in Hydraulics and Hydrology in pursuit of a Master of Science Degree in Civil Engineering.

THESIS ABSTRACT

NUMERICAL EVALUATION OF CUMULATIVE CONTRACTION SCOUR AT A
BRIDGE SITE WITH COHESIVE SOILS

Dustin T. Harris

Master of Science, Date

(B.C.E., Auburn University, 2001)

97 Typed Pages

Directed by Oktay Güven

The objective of this study was to perform 2-Dimensional numerical contraction scour calculations at an actual bridge site with cohesive soils. The 2-D model used in the analysis was the Finite Element Surface Water Modeling System (FESWMS) computer program provided within the Surface Water Modeling Software (SMS). The study presents the development of the model, the 2-D numerical transient contraction scour calculation method, and a comparison of the 2-D contraction scour calculation results from this study with 1-D numerical model results for the same bridge site presented in Curry et al. (2003). The 2-D calculations are performed using velocity distributions and water depths obtained from the FESWMS model along with the cohesive soil properties of the bridge site presented in Curry et al.(2003). The cohesive soil properties used in the calculations are the critical shear stress (τ_c), and the initial erodibility (S_i) that were

obtained from soil tests using the Erosion Function Apparatus described in Crim (2003). The model's output of water velocities and water depths that vary in two perpendicular horizontal planes provide the rest of the data needed for the calculations of the 2-D distribution of scour in the contraction at the bridge site. This allows for the creations of plan views of the predicted contraction scour, which is one of the primary advantages of the 2-D model. The outputs presented in this thesis include plan views, cross-sectional views, and longitudinal views of cumulative contraction scour for 5, 10, 50, and 100 days. The results are representative of how scour develops overtime using 2-dimensional calculations. The Choctawhatchee River bridge site near Newton, AL is the focused site of this study.

This study provides detailed information on how to set up a 2-dimensional numerical analysis of contraction scour using FESWMS within SMS. The process for calculating cumulative contraction scour at a bridge site with cohesive soil presented in this study is one possible way for predicting scour. The actual application of this method in the field of scour prevention and the development of new methods in bridge foundation designs is still to be seen. More research and experimentation needs to be done along with publications that promote these methods to the engineering field. This is a continuation of ongoing research in the field of scour prediction in cohesive beds, and presents methods and data that can be used for future research .

ACKNOWLEDGEMENTS

The author of this study would like to dedicate this thesis in the memory Dr. Güven for his support and guidance throughout the author's studies at Auburn University. Dr. Güven inspired the author's studies in hydraulics and hydrology and allowed the author to continue his studies into graduate school. The author spent many hours of study and conversation with Dr. Güven. He developed a great respect and appreciation for the professor and he will not be forgotten.

The author would also like to thank Dr. Melville and Dr. Harper for their advice and extended efforts to help the author complete his master's degree. The project would not have been nearly as successful without the guidance and knowledge of Mr. John Curry of Hydro Engineering Solutions, LLC. The author is very grateful for the help provided by Jake McLean and Sam Crim also of Hydro Engineering Solutions, LLC. Everyone at Hydro Engineering Solutions, LLC were very generous with their time and support

The next group of people the author would like to thank is his friends and family. The past six years at Auburn University has been wonderful and that could not have been possible without the support of so many people. I could not be more grateful for their support.

I would also like to extend my gratitude towards Auburn University and the entire staff of the Department of Civil Engineering. Everyone has been very kind and helpful whenever I had any problems. Thanks again to everyone mentioned above.

Style manual or journal used _____

Computer Software used Microsoft Office XP Professional (Microsoft Word, Microsoft Excel), Jasc Paintshop Pro 8.0, Surface Modeling Software (SMS) 7.0, Wordpad

TABLE OF CONTENTS

LIST OF TABLES.....	xii
LIST OF FIGURES.....	xiii
I. INTRODUCTION.....	1
<u>Purpose</u>	1
<u>Site Introduction</u>	3
II. LITERATURE REVIEW AND PAST RESEARCH.....	8
III. 2-D NUMERICAL MODELING USING THE SMS V.7.0 SOFTWARE PACKAGE.....	11
<u>Introduction to 2-D Numerical Theory</u>	11
<u>Development of Elevations</u>	12
<u>Development of the Model's Mesh</u>	19
IV. MODEL SIMULATION.....	28
<u>Preparing Model for Simulation</u>	28
<u>Simulating the Model</u>	31
<u>Validating the Model</u>	32
<u>Scour Calculations and Formulas Used</u>	38

<u>Model Simulation Problems/Solutions</u>	47
V. RESULTS.....	53
<u>Cumulative Contraction Scour Results for Soil 4C</u>	53
<u>Cumulative Contraction Scour Results for Soil 4B</u>	60
<u>Cumulative Contraction Scour Comparisons (1-D Results vs 2-D Results)</u>	67
<u>Discussion of Results</u>	75
VI. CONCLUDING REMARKS AND OTHER SUGGESTIONS.....	77
VII. REFERENCES.....	81

LIST OF TABLES

Table 1. The numerical values used to generate the scour profile
in Figure 30. *The orange cell represents maximum
contraction scour for that day used to calculated
cumulative contraction scour.*.....71

LIST OF FIGURES

Figure 1.	Aerial Photograph of Choctawhatchee River and Surrounding floodplain.....	5
Figure 2.	Picture of bridge and right overbank looking north on the upstream side.....	6
Figure 3.	Picture of bridge from the downstream side looking southeast towards abutment.....	7
Figure 4.	Topographic map of Choctawhatchee River and surrounding area.....	17
Figure 5.	Choctawhatchee River Cross-Section Data Used in Model Development (Looking Downstream).....	18
Figure 6.	Final Mesh of model overlaying aerial photograph.....	24
Figure 7.	Land use and corresponding Manning n Values applied to the mesh.....	25
Figure 8.	Elevation of the mesh (interpolated elevations).....	26
Figure 9.	Choctawhatchee River Cross-Section under Bridge near Newton,AL obtained from mesh (Looking Downstream).....	28
Figure 10.	Actual Measured vs. Modeled Water Surface Elevation (WSE) (500 year Flood/Cross-Section Looking Downstream).....	36
Figure 11.	Measured Velocity vs. Modeled Velocity Profiles (500 Year Flood/Cross-Section Looking Downstream).....	37
Figure 12.	EFA data for soil sample 4C (represents soil from main channel).....	44
Figure 13.	EFA data for soil sample 4B (represents soil from the overbank) (Curry et al. 2003).....	45

Figure 14.	Plan view of the Scour that occurred during Day 1 of model simulation. Image is zoomed into bridge site. (500 year Flood/Soil 4C).....	46
Figure 15.	Velocity vectors used to determine stagnation point.....	50
Figure 16.	New Mesh (Mesh 2) created to model just the flow going underneath the bridge.....	51
Figure 17.	Velocity Profiles Comparison of Model 1 and Model 2 (500 year Flood/Cross-Section Looking Downstream).....	52
Figure 18.	Cumulative Scour after 5 Days (500 Year Flood/Soil 4C/Plan View).....	54
Figure 19.	Cumulative Scour after 10 Days (500 year Flood/Soil 4C/Plan View).....	55
Figure 20.	Cumulative Scour after 50 Days (500 year Flood/Soil 4C/Plan View).....	56
Figure 21.	Cumulative Scour after 100 Days (500 year Flood/Soil 4C/Plan View).....	57
Figure 22.	Change in elevation due to scour after 5, 10, 50, & 100 Days 500 year Flood/Soil 4C/Cross-Section Looking Downstream) *Profiles correlate to the Choctawhatchee Bridge line seen in the plan view*.....	58
Figure 23.	Change in elevation due to scour after 5, 10, 50 & 100 Days (500 year Flood/Soil 4C/Longitudinal Profile/River Flow Right→Left) *Profiles correlate to the longitudinal profile line seen in the plan view*.....	59
Figure 24.	Cumulative Scour after 5 Days (500 Year Flood/Soil 4B/Plan View).....	61
Figure 25.	Cumulative Scour after 10 Days (500 Year Flood/Soil 4B/Plan View).....	62
Figure 26.	Cumulative Scour after 50 Days (500 Year Flood/Soil 4B/Plan View).....	63

Figure 27.	Cumulative Scour after 100 Days (500 Year Flood/Soil 4B/Plan View).....	64
Figure 28.	Change in elevation due to scour after 5, 10, 50, & 100 Days (500 year Flood/Soil 4B/Cross-Section Looking Downstream) *Profiles correlate to the Choctawhatchee Bridge line seen in the plan view*.....	65
Figure 29.	Change in elevation due to scour after 5, 10, 50 & 100 Days (500 year Flood/Soil 4B/Longitudinal Profile/River Flow Right→Left).....	66
Figure 30.	Cumulative Contraction Scour Cross-Section Profile. (Day 1/Soil 4B).....	70
Figure 31.	Comparison of soils 4B and 4C cumulative contraction scour in the main channel.....	72
Figure 32.	Compares 2-D Cumulative Contraction Scour Results to 1-D Contraction Scour results in main channel and soil sample 4C. Z_{ult} and Z_{max} for this site are also illustrated.....	73
Figure 33.	Equivalent Flood Durations for soil samples 4B and 4C.....	74

I. INTRODUCTION

Purpose

Scour is the removal or erosion of soil from the bed or banks of a stream caused by flowing water. Scouring occurs because of the high applied shear stress that the water imposes on the soil during high flow periods. Scour at bridge sites due to extreme flow events is a major cause of structural failure and cost the United States millions of dollars in damages each year. Due to the problems that scour poses, a large amount of research has been done and is currently being funded on the study of predicting scour. This project is a continuation of ongoing research in the field of predicting possible scour around bridge sites and similar structures that are threatened from scour due to extreme flow events. Most bridge foundation designs accommodate for scour using formulas that have been developed for soils that are noncohesive. Noncohesive soils such as sands have small critical shear stresses that result in significant and rapid erosion development when exposed to extreme flow rates. Practicing engineers lack fundamental information to determine how much scour might occur in cohesive soils, which sometimes results in unnecessary or unsafe designs being constructed. Recently, new methods for predicting scour in cohesive soils have been developed and researched at many universities. The

Department of Civil Engineering at Auburn University along with Alabama's Department of Transportation has been involved in the development and study of new methods for calculating scour at bridge sites with cohesive soils. Most of the methods are dependent upon a soil function apparatus (EFA), which provides laboratory measurements of the critical shear stress (τ_c) and initial erodibility (S_i) of a soil sample as a function of the bed shear stress imposed by a flowing stream (Curry et al., 2003). Using the EFA determined soil properties along with developed numerical models one can predict scour that may occur over a period of time. Research in the past began with developing one-dimensional models, which have proven to be inadequate when modeling complex hydraulic conditions such as those existing at bridge sites (Curry et al., 2003). The one-dimensional models have since been extended to 2-dimensional models such as the study of a hypothetical bridge site presented in Mclean et al. (2003). Unlike the one-dimensional research presented in Güven et al. (2002) that assumes a uniform flow distribution in the contraction, the two dimensional modeling accounts for the nonuniform nature of flow in the horizontal plane (Curry et al., 2003)

The objective of this study is to determine the effects of clear-water contraction scour on an actual bridge site with cohesive soils using the 2-dimensional Finite Element Surface-Water Modeling System FESWMS provided in the Surface Water Modeling Software version 7.0 (SMS) developed at Brigham Young University. The study will also go into the detail of actually setting up the model, running simulations, and performing calculations using SMS v.7.0.

Contraction scour is a direct result of the flow area of a stream being reduced. Examples that can cause such contractions are bridges, road embankments that approach a bridge, or natural landscapes of a stream that produce contractions. Contraction scour usually occurs during flooding events when flow from the larger area of a floodplain is diverted into a smaller area due to a contraction (Curry et al., 2003). The contraction increases water velocity corresponding to an increase flow per unit width causing an increase in shear stress at the soil bed. These effects cause scouring to occur at the site.

The bridge site selected for the study is the Choctawhatchee River bridge site near Newton, AL located in Dale County. An approximate 500 year flood that occurred in March 1990 was chosen to be modeled as a worst case scenario event. 1-Dimensional calculations have already been performed for this bridge site using the E-SRICOS and DASICOS methods and are presented in Curry et al. (2003). These 1-D calculations will be the basis for comparison with the 2-D numerical model calculation results presented in this thesis.

Site Introduction

The chosen bridge site is located on State Route 123 at the Choctawhatchee River near Newton, AL and has a drainage area of approximately 686 square miles. The bridge is 584 feet long with 10 spans and 9 piers. The main channel is approximately 150 feet wide with banks 20 to 25 feet high (Curry et al., 2003). This bridge site was selected for previous studies because of the cohesive soil properties at the site and available flow/stage information collected by a gauge station since the construction of

the bridge in 1976 made available by the USGS. The river's floodplain is intersected by the elevated roadway of State Route 123. This roadway along with the guide bank causes water to be diverted back towards the main channel of the river underneath the bridge forming a contraction. The bridge experienced an approximate 500 year magnitude flood of 87,500 cfs (feet per cubic second) in 1990 that caused noticeable scour and concern. Riprap has since been placed along the river overbanks as a scour counter measurement and will not be taken into account during this study. 1-D calculations of contraction scour using the DASICOS and E-SRICOS methods have also been performed and are presented in Curry et al. (2003). These qualifications make this site ideal for applying a 2-D numerical model to the bridge site using the 500 year flood event and comparing the results of the two different models. An aerial photograph of the bridge site and surrounding floodplain can be viewed in Figure 1, while two photographs of the actual bridge site are also shown in Figure 2 and Figure 3. The aerial photograph was created from images downloaded off of the website www.terraserver-usa.com, which is sponsored by the USGS. After downloading the images they were pasted together to create the larger image using the computer software Jasc Paint Shop Pro version 8.0. The photos were taken during a study of the 18 bridge sites in Alabama that is presented in Curry et al. (2002).



Figure 1. Aerial Photograph of Choctawhatchee River and surrounding floodplain (www.terraserver-usa.com)



Figure 2. Picture of bridge and right overbank looking north on the upstream side (Curry et al., 2002)



Figure 3. Picture of bridge from the downstream side looking southeast towards abutment (Curry et al., 2002)

II. LITERATURE REVIEW AND PAST RESEARCH

A paper entitled “Scour Evaluations of Selected Bridges in Alabama” was prepared by Curry et al. (2002) and consisted of a large state wide study on 18 selected bridge sites. In each study scour evaluations were performed for known 100-year, 200-year, or 500-year flood events that occurred at these sites. During this study all hydrologic, hydraulic, structural, and geotechnical information was gathered. Scour calculations were done using the HEC-RAS computer program by methods described in HEC-18. The results of the calculations are presented in the report Curry et al. (2002). In the conclusion of the report it was found that scour evaluations performed on bridges with sand foundations experienced scour consistent with scour depths calculated from HEC-18 equations; however, scour evaluations performed on sites with cohesive soils showed that calculated scour depths were not consistent with observed scour at the sites (Curry et al., 2002). The conclusion also states that beyond the input of HEC-18 equations, additional site specific information and improved scour calculation methods are needed for design of new bridges and analysis of existing bridges (Curry et al., 2003). This conclusion is the same as many other researchers and has initiated further study into prediction of scour in cohesive soils, such as this thesis. The Choctawhatchee River Bridge site near Newton, AL

was one of the 18 sites studied. The data collected during the study, which is mainly presented in the appendices of the report, is also used in the development of the 2-D model constructed in this thesis.

A thesis called “Erosion Functions of Cohesive Soils” written by Crim (2003) describes the methods and difficulties of developing the EFA functions from actual soil samples using the Erosion Function Apparatus. The critical shear stress (τ_c) and initial erodibility (S_i) are two soil properties derived from the EFA function described in Crim (2003), and are needed for the 2-D numerical calculations of cumulative contraction scour in cohesive soils presented in this thesis.

Curry et al. (2002) concluded that current methods for calculating scour in cohesive soils were inadequate. In response to this conclusion the study, “Scour Evaluations of Two Bridge Sites in Alabama with Cohesive Soils” (Curry et al., 2003) was performed. In this report scour was evaluated at the Choctawhatchee River bridge site near Newton, AL along with the Pea River bridge site near Elba, AL. Contraction scour development along with pier scour was calculated using two different one-dimensional methods. One method used is the Extended SRICOS (E-SCRICOS) method; a modified version of Simple SRICOS (Scour Rate In Cohesive Soils) method, which are both presented in Briaud et al. (1999, 2001a, 2001b, 2003). Güven et al. (2001, 2002a, 2002b) describes the other method used for a one-dimensional approach for modeling time dependent clear-water contraction scour in cohesive soils called the “DASICOS” (Differential Analysis of Scour in Cohesive Soils) method (Curry et al., 2003). Both of these methods that are presented in Curry

et al. (2003) use the EFA function soil properties in their scour prediction formulas. The results of these two methods will be used in comparison with the two-dimensional results that will be presented in this thesis. Curry et al. (2003) also presents the EFA data needed for the Choctawhatchee River Bridge site near Newton, AL.

“A Two-Dimensional Numerical Model Study of Clear-Water Scour at a Bridge Contraction with a Cohesive Bed” is a report done by McLean et al. (2003) that uses the FESWMS modeling program in SMS v.7.0 to model a hypothetical bridge site with designated EFA functions to calculate contraction scour. The report by Mclean et al. (2003) presents the actual equations and procedures for calculating contraction scour using the FESWMS 2-dimensional model program within the SMS v.7.0 computer package. It is the same method that will be described in this thesis and is used to calculate the cumulative contraction scour for the Choctawhatchee Bridge site near Newton, AL. McLean et al. (2003) is a follow up report to McLean’s graduate thesis, “A Numerical Study of Flow and Scour in Open Channel Contractions” (Mclean, 2002). In his thesis McLean discusses the advantages and uses of 2-D numerical models; specifically, FESWMS along with much of the same information that in presented in McLean (2003). McLean also describes a method for developing and running a model using the SMS v.7.0 software package for a simplistic hypothetical bridge contraction in his thesis (Mclean 2002). Mclean et al (2003) and Mclean (2002) were critical in establishing a basis for the development and simulation of a model at an actual bridge site with a cohesive river bed.

III. 2-D NUMERICAL MODELING USING THE SMS v.7.0 SOFTWARE PACKAGE

The first suggestion the author of this study recommends is for the model developer to familiarize him or herself with the SMS computer package. The following sections contain terms and commands that may be difficult to understand if one is not familiar with the program. Reading the SMS v.7.0 user manual and working the SMS v.7.0 tutorials would be beneficial before reading the following sections. Chapter III of Mclean (2002) also presents instruction and tips for using SMS v.7.0 that could aid in model development and simulation. The following section will briefly discuss the theory behind 2-D numerical modeling of surface water flow in a horizontal plane.

Introduction to 2-D Numerical Theory

In this study the 2-D numerical calculations are performed in the FESWMS program available in the SMS software package. A detailed explanation of the equations and theories applied in the FESWMS program can be found in the FESWMS User's Manual (Froelich, 1996). The 2-Dimensional modeling in this program is based on the conservation of mass and momentum principles. By averaging the flow by depth using vertically integrated momentum equations one

simplifies the real world of varying flow in 3-dimensions to the varying of flow in only 2-dimensions. In other words the flow rates vary in two perpendicular horizontal planes, yet remain at an averaged constant value vertically. A set of boundary conditions are used to solve the equations using the numerical procedure known as the Galerkin finite element method (Mclean, 2002). In this project the boundary conditions will be the introductory flow rate, and exiting water surface elevation at the downstream boundary. More information explaining the two-dimensional model theory can be found in Chaudhry (1993). Mclean (2002) also re-lists the equations and parameters described in the FESWMS User's Manual (Froelich, 1996). These equations also help explain lateral shear stress caused by turbulence and the effects of eddy viscosity.

Development of Elevations

The model development included many steps. The first step is to gather all elevation information of the given site so one can develop the unique geometric features of the site. The floodplain topography was developed from a topographic map created from images downloaded from www.terraserver-usa.com and then pasted together in Jasc Paint Shop Pro v.8.0. The process is the same that was used to develop the aerial photograph. The final developed topographic map that is used can be seen in Figure 4. The greatest advantage of downloading the images from www.terraserver-usa.com is that this web site also gives you longitudinal and latitudinal coordinates corresponding to the four corners of your image. These coordinates are very important in being able to geo-reference the aerial photograph to

the topographic map. One should make sure of the units and coordinate system he or she is using before beginning this step. Geo-referencing can be done by using the Map Module in SMS under the Images menu. From the Images menu one can use the Register command to verify three separate points along with their corresponding longitudinal and latitudinal coordinates. When the user selects the Register command a Register Image window will open. In the Register Image window the user must identify three individual points with the red cross-hairs and then input the geographical coordinates. The user can also convert longitude/latitude coordinates to UTM (Universal Transverse Mercator) coordinates from this window. Geo-referencing needs to be done for both the aerial photograph and topographic map. After registering the three points geographically for an image one should save the file as a TIFF/JPEG world file. Once the aerial photograph and topographic map have been geo-referenced one should open both images together and make sure the two images overlap one another as close as possible. In this project the roadway and river were lined up to verify that the two images overlapped. Adjustment of the coordinates in order to get the two images to overlap more precisely may be required. This precision is critical because the topographic map will be used to establish elevations and the aerial photograph will be used to create the mesh of the model. After the mesh and elevations have each been developed they will be combined. So it is important that the correct elevation correspond to the correct location in the mesh. During development one should reference back and forth between the aerial photo and topographic map to make sure they are matching up correctly. This is a very

important step in the initial setup of the model. The next paragraph will describe establishing the elevations in SMS.

The elevations are defined in the Create Mesh module using the Create Nodes tool in SMS. Following the contours of the topographic map, nodes were placed and the z-coordinate was set corresponding with the elevation of the contour. This was done for the entire topographic map. The next task is actually defining the geometry of the roadway, guide bank, and actual river cross-section near the contraction with elevations. These elevations are the most important because they establish the contraction and are the focused areas of scour development. These elevations were obtained from the actual design drawings of the bridge and roadway that were used for its initial construction. This was a difficult process with the limited information that was available. From the design drawings one estimates distances and elevations. Since the roadway and bridge for this particular site are in a curve the distances were difficult to manipulate. User judgment had to be used in the placement of the roadway, guide bank, and river cross-sections. An actual sounding of the bridge cross-section can be seen in Figure 5. Figure 5 is only an image of the cross-section and immediate overbanks; the actual plans used in this project consisted of the river cross-section, overbanks, guide bank, 3000 ft of the roadway, along with the bridge deck elevations. The best recommendation for this procedure is to use the aerial photograph, topographic map, and the bridge design plans all together. Using measured distances and elevations from the design plans the user must locate the same position on the topographic map or aerial photograph. The user should establish

a starting point and measure distances from it to the next elevation nodes that need to be placed. For this purpose SMS shows the user the distance between any two elevation nodes that are both selected at the same time. This process should be continued throughout the establishment of these elevation nodes. The elevation nodes should be close to one another in these critical sections because one needs to accurately define the geometric features. During the development of elevations for the roadway, guide bank, and cross-section; distances should be checked both horizontally and vertically. This should be done as precisely as possible and match as close as possible to the aerial photograph, topographic map, and design drawings.

As stated previously, the river-cross section from the original design drawings was used during development of the elevations. However, a problem occurred during this process. The elevations for the river cross-section did not correlate closely enough with the elevations from the topographic map. User judgment had to be used again and the actual river cross-section from the design drawing was carried both down and upstream from the bridge. The cross-sections had to be altered slightly and tied into the elevations of the topographic map. Otherwise, an extreme contraction would have occurred at the bridge site that was not there in actuality. The user judgments that had to be made were due to the lack of site information available. If one had numerous river cross-sections, a high resolution DEM, or both; this process could possibly have been easier and more accurate. More information about this is discussed in the conclusion.

The next step is to triangulate all of the elevation points. Before doing this step remember to save the file with all the elevations defined. Most studies will involve making changes to the original elevations of the project in the future. Triangulation is done by selecting the Triangulate command from the Elements menu. This will create a mesh with many more nodes between the actual elevation nodes. Elevations will automatically be assigned to these new nodes by linear interpolation done within the computer program. This brings out the importance of defining all critical elevation changes in your model manually; otherwise, the linear interpolation will automatically define the elevations which may or may not represent the actual conditions. The final step is to convert the mesh to a scatterpoints file. This is done by using the Mesh→Scatterpoint command located under the Data menu. After selecting this command all of the nodes will be converted to scatterpoints. This is the final step in establishing the elevations for the site's geometric features that will later be interpolated into the final mesh of the model. The newly created scatterpoint file should now be saved for later use.

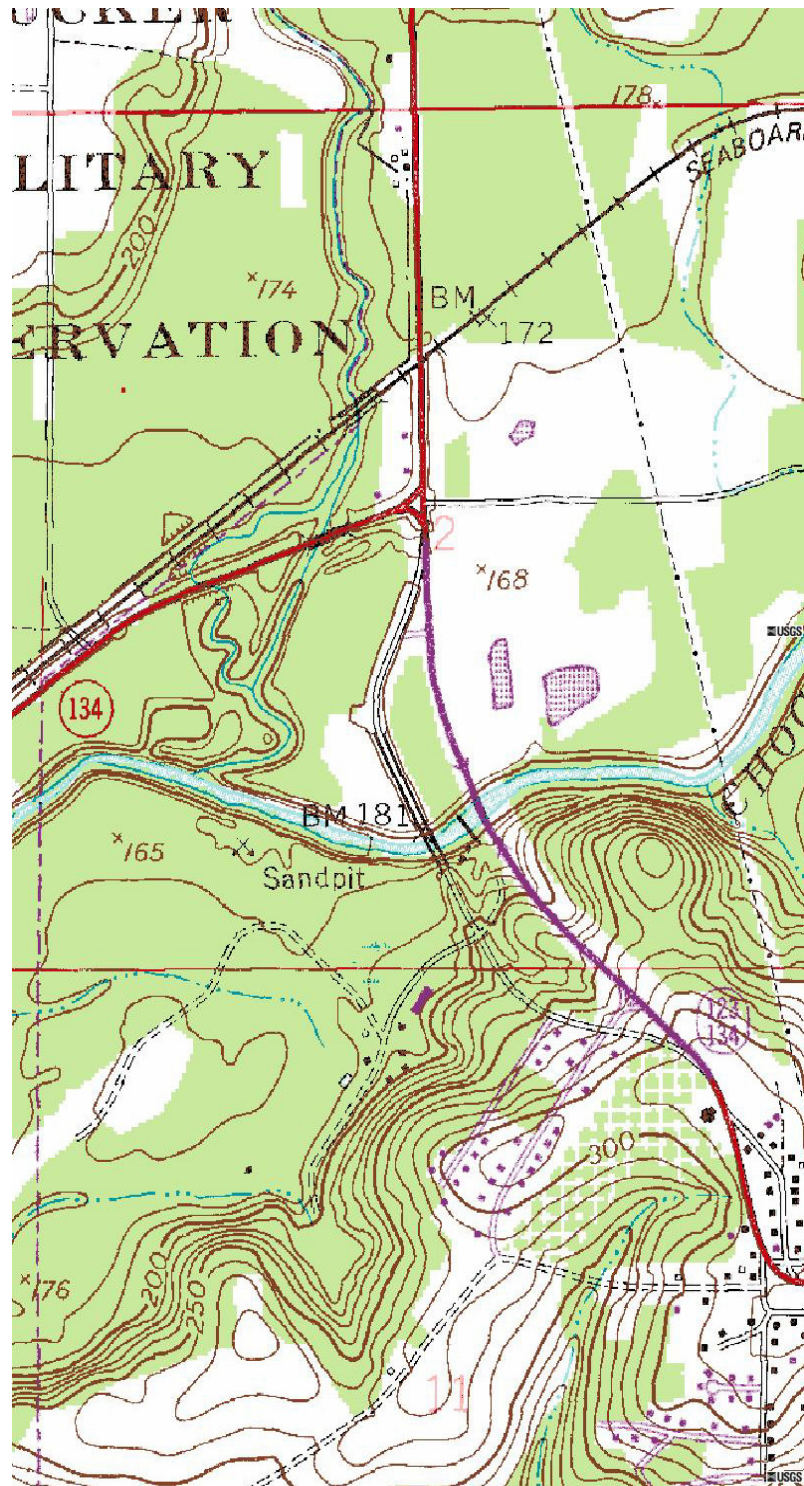


Figure 4. Topographic map of Choctawhatchee River and surrounding area (www.terraserver-usa.com)

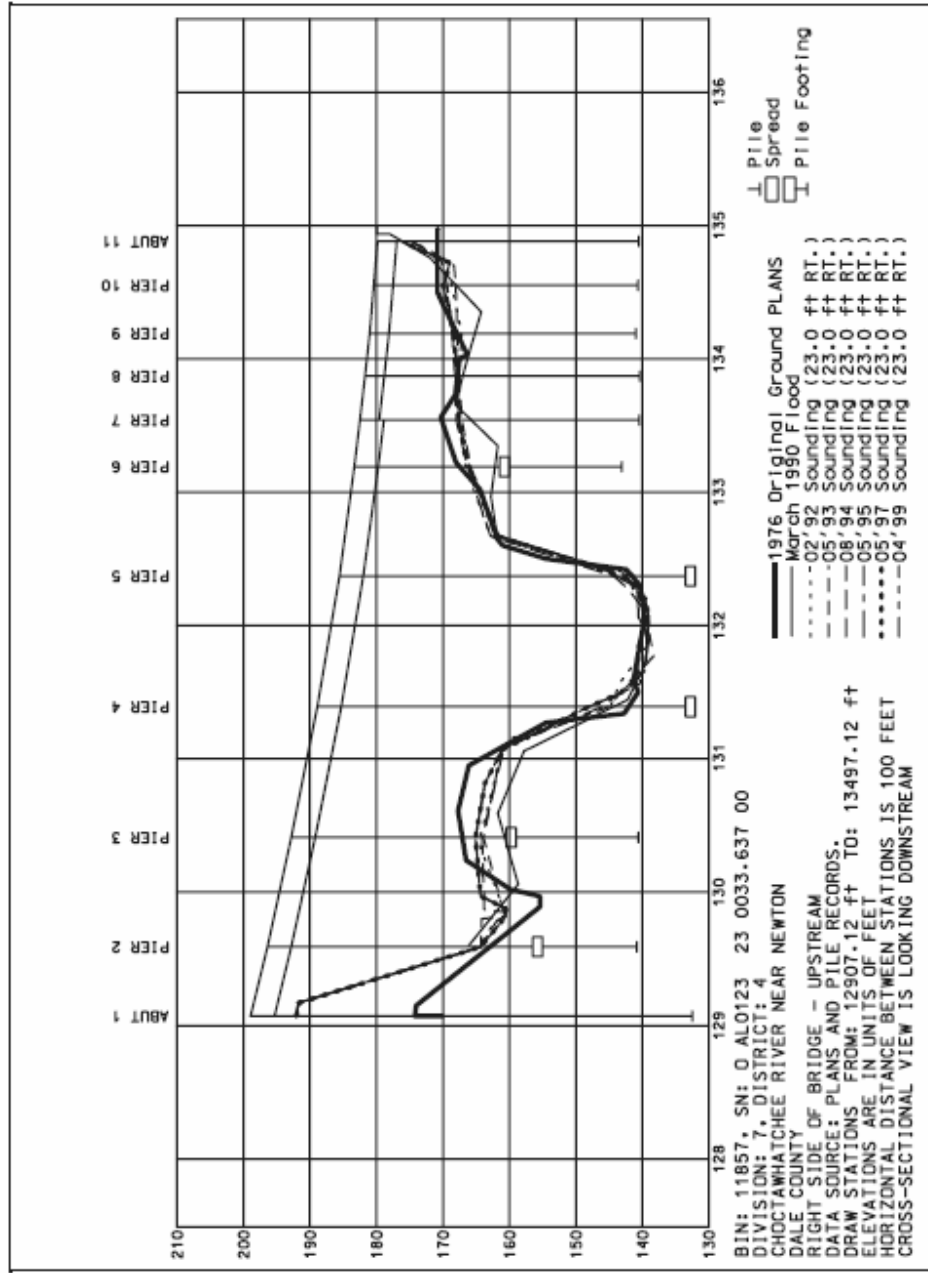


Figure 5. Choctawhatchee River Cross-Section Data Used in Model Development (Looking Downstream)

Development of the Model's Mesh

The following section describes the steps used by the author of this project to create the mesh of the final model. The first step is to create and establish the boundary of the mesh. The boundary of the floodplain was set as the model boundary using the Arc tool in the Map module. This is performed by using the topographic map, head water elevation of the flood to be modeled, and the user's judgment as to how far the floodplain will extend from both sides of the river. The Arc tool is simply used to connect a series of arcs into a large polygon that will represent the mesh boundary. Once the boundary is established one can use the aerial photograph to break up the entire area of the boundary into smaller areas. In this project the aerial photograph is used to break up the boundary area into smaller areas based on land use. For example; the river, road, heavily forested areas, etc. are blocked off using the Arc tool, establishing smaller polygons within the boundary polygon. Basically, one should create areas that contain an individual land use type and are as square in shape as possible for simplicity. This may include making a number of small squares from a large area of the same land use. After you have all of your sections blocked off with arcs, one must build the polygons. Polygons are built by selecting the Build Polygons command from the Feature Objects menu. Polygons consist of a set of arcs that join together to form an enclosed area. The user will now be able to select individual polygons for the purpose of editing unique attributes of the polygon using the Select Feature Polygon tool.

Assigning material properties for the different land uses is the step the author recommends should be done next. First, decide the land use types and then decide what Manning n value will correspond to each land use. Once the Manning n values have been decided one should switch to the Mesh module. It is important to be sure that the FESWMS model is selected at this point. This can be checked by performing the Switch Current Model command from the DATA menu and making sure that FESWMS is selected. Once the model has been switched to FESWMS one should go to the FESWMS menu and select the Material Properties command. A new window will open up where the user should select General Material Properties. This will open up a Materials Data window that allows the user to input land use type. Once all the land use types have been defined, the user should then assign the Manning n values to the corresponding land use type from within the Material Properties window.

The user should now switch back to the Map module from the Mesh module. In the Map module the user needs to setup the mesh from the polygons. This is an important step in the mesh development process. It is necessary to have more elements as the mesh approaches critical features of the model; such as river contractions, roadways, and guide banks. In order to have more elements the user must add more vertices to the arcs already created. During the generation of the mesh, efforts should be made to avoid adjacent elements with a size difference of more than two according to FESWMS literature (McClean, 2002). The developer of this project used the Patch command in the Select Feature Polygons tool for mesh development.

Using the Select Feature Polygon tool the user should select each polygon individually. Each polygon has a default mesh type set for Adaptive Tessellation. The user should change this to Patch. When changing the mesh type to patch the user may encounter some problems. In order for the Patch command to work properly the polygon must contain three or four arcs; too few or too many will result in errors. This can be fixed by adding nodes, removing nodes, or changing nodes to vertices. This can be done by using the Select Feature Node/Point Tool, or the Select Feature Vertex tool; and then selecting the node or vertex that needs to be changed. Once the node or vertex is selected the user should choose the Vertices↔ Node command from the Feature Objects menu. This will result in changing the point into the opposite feature. One can also split or change a node from within the Polygon Attribute window that appears when a polygon is selected. Each polygon should be selected individually and the Mesh type should be changed to Patch from within the Polygon Attribute window. The user should also define the material property/land use from within this window at this time.

Next, the user should begin to develop the elements within the polygons. As stated previously, the developer must keep in mind that more elements should be present in the critical areas to represent the data more accurately. The user should gradually increase the elements towards the critical areas. The author of this study started from the far boundaries and increased the number of elements as he approached the river contraction, guide bank, and roadway. The number of elements is increased by increasing the number of vertices on an arc. An arc is defined by a

line segment with a node on either end. The user should increase the vertices by using the Select Feature Arc tool to select the desired arc and then from the Feature Objects menu one should select the Redistribute Vertices command. This will open the Redistribute Vertices window where the user can define the number of arcs by selecting the number of subdivisions, or selecting the spacing of the vertices. After defining the vertices for each arc of a polygon, the user should preview the mesh created in that polygon. The Select Feature Polygon tool is used to select the intended polygon, which opens the Polygon Attribute window. Then by selecting the Preview command from the Polygon Attribute window the developer will be able to preview the mesh. The user should make sure that no elongated thin triangles exist in the previewed mesh because this can also cause problems within the model. The model has a hard time computing calculations in the thin triangles resulting in the model computing incorrect values and often causing the model simulation to crash. SMS will also let the user know if the mesh has any problems during the preview. The user should adjust the number of vertices in each arc of a polygon until the desired mesh is created. The user should change and alter vertices as needed to create a gradual increase in elements through the mesh. At this point the polygons should have been created with a Patch mesh type, the correct material property assigned, and have been previewed for the correct number of vertices and desired mesh. Now the user can actually develop this into his or her mesh. This can be done by selecting Map→2D Mesh command from the Feature Objects menu. From within the Mesh module the user can change elements shapes, delete elements, reassign material

properties, plus many more things to modify and edit the mesh. The instructions for these procedures can be found within the help options or from the SMS User Manual and Tutorials. The final mesh for this project is shown in Figure 6 and the material properties with their corresponding Manning n value can be viewed in Figure 7.

Another material property that must be defined is the eddy viscosity V_0 , which accounts for turbulence. In this project V_0 is set at the value $10 \text{ ft}^2/\text{s}$, which is in accordance to SMS software documentation that makes reference to a USACEWES table that suggest that values of $V_0=5\text{-}50 \text{ ft}^2/\text{s}$ for FESWMS (McLean, 2002).

Viscosity will be discussed more in the section titled, Simulating the Model, in Chapter IV of this study.

The final step in developing the mesh is interpolating the actual elevations to the mesh. First, open the scatterpoint file saved earlier that contains the elevation information. In the scatterpoint module the user should select the Interp to Mesh command from the Scatter menu. This will interpolate all of the elevation data to the final mesh. The user should now save the FESWMS file because this is the last step in creating the mesh. The elevations for the Choctawhatchee River and surrounding area that have been applied to the mesh can be viewed in Figure 8.0. This is the basis for the model and the elevations provide the initial ground elevation conditions for running the model. Figure 9.0 represents the river cross-section under the bridge that has been developed within the mesh. The next step will consist of setting up boundary conditions and actually performing a model simulation in FESWMS.

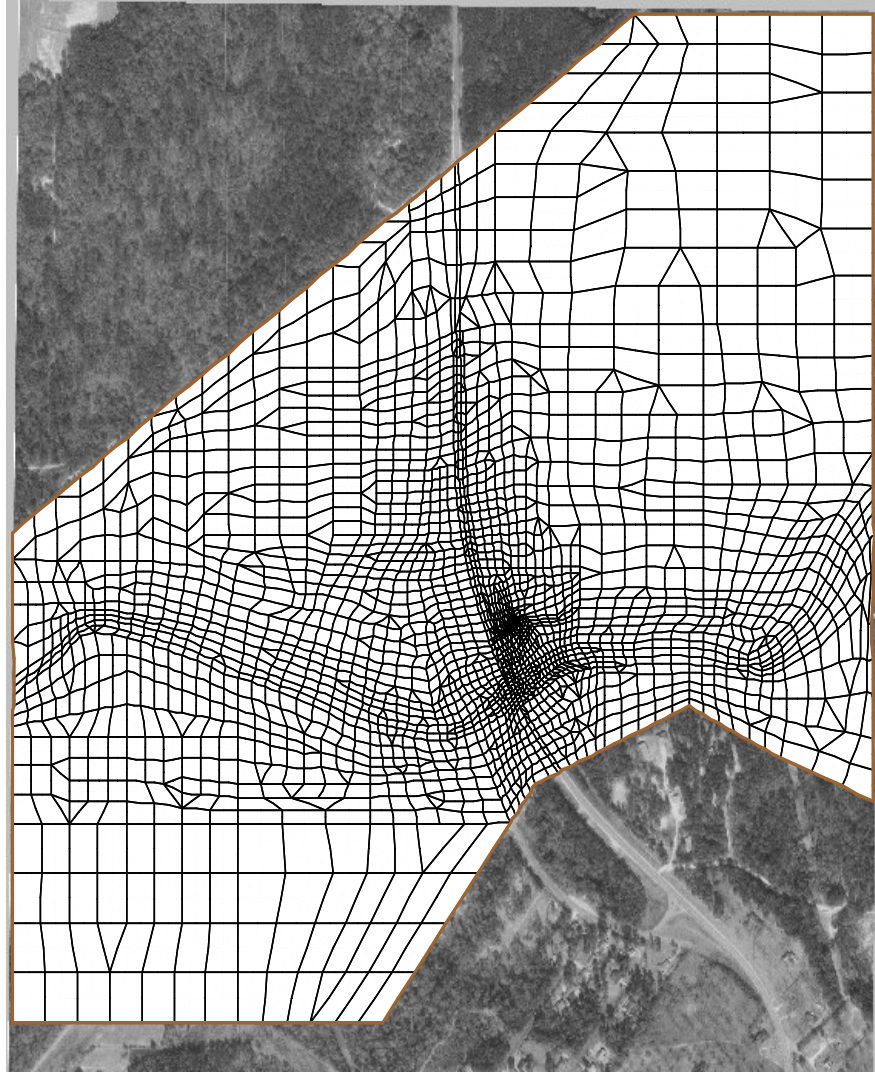


Figure 6. Final Mesh of model overlaying aerial photograph

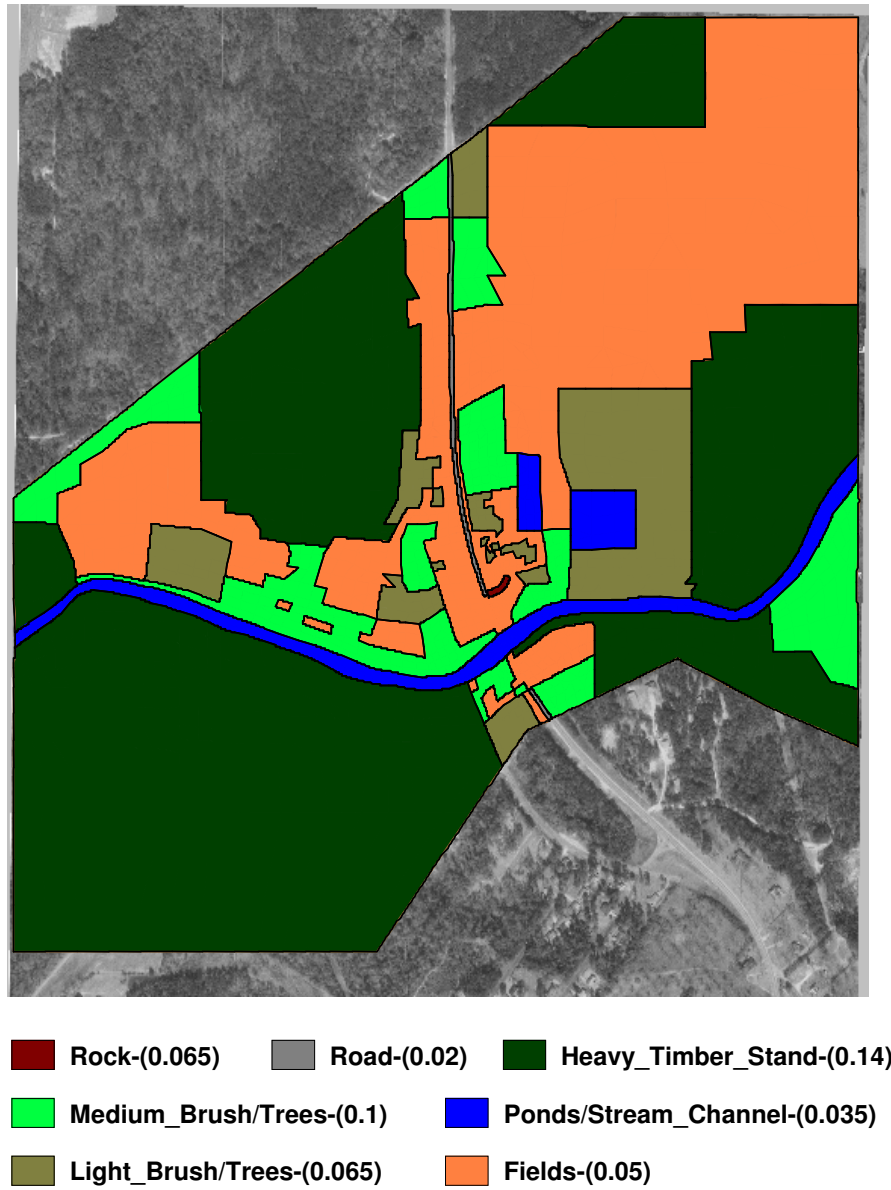


Figure 7. Land use and corresponding Manning n Values applied to the mesh.

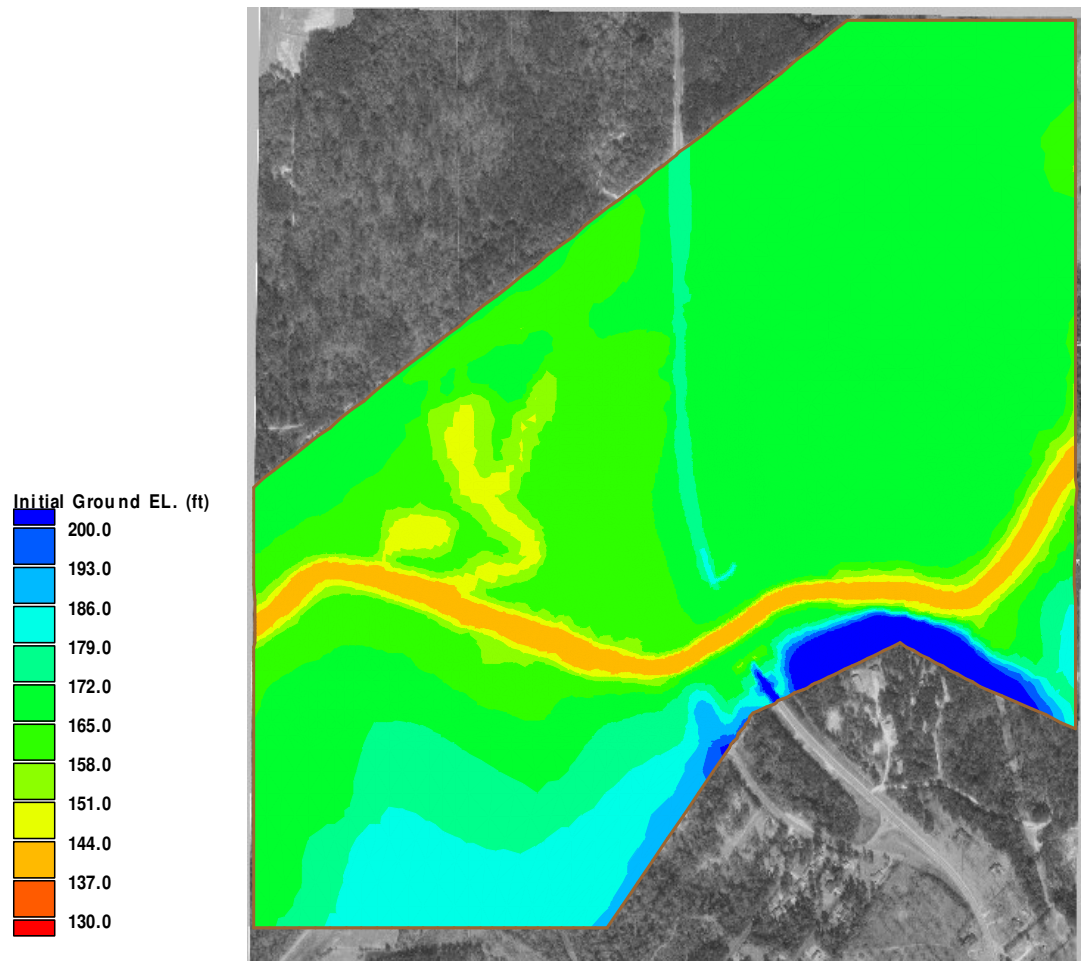


Figure 8. Elevation of the mesh (interpolated elevations)

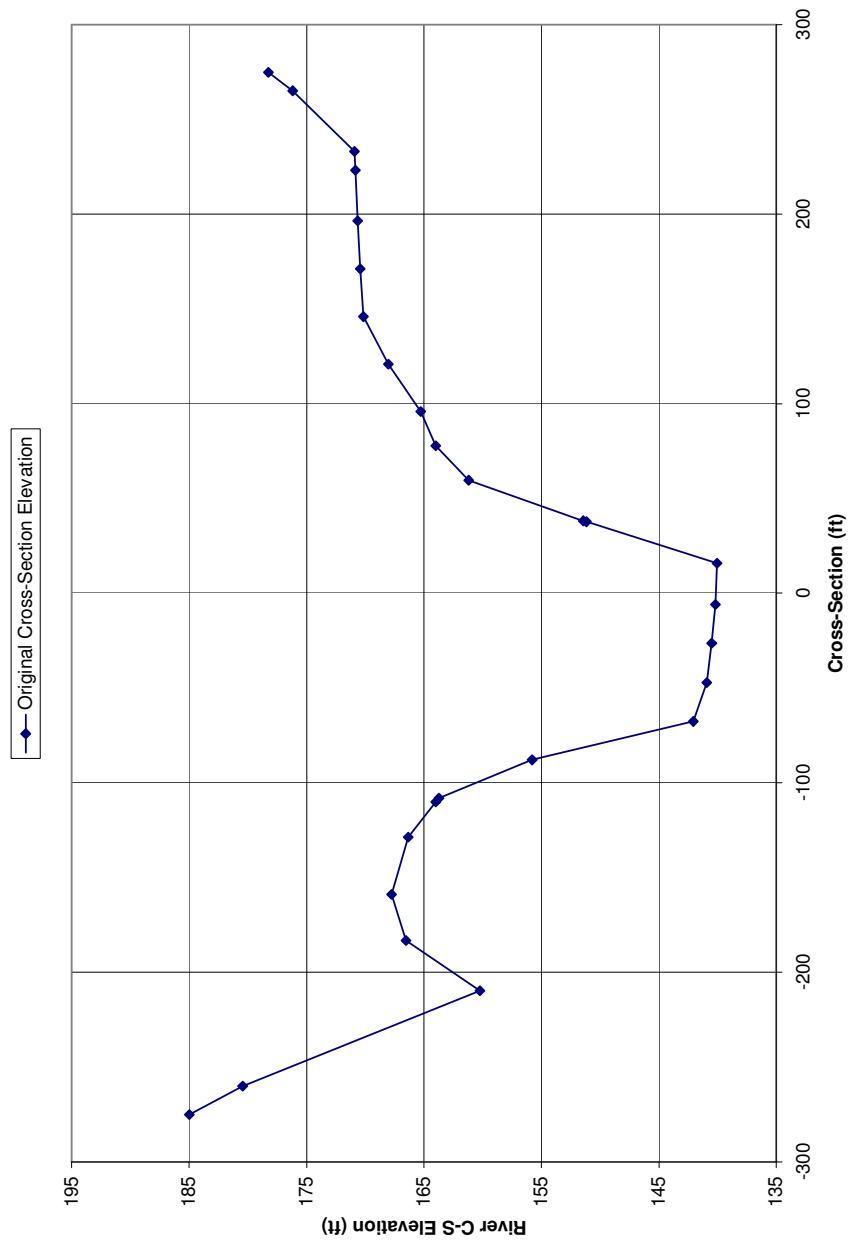


Figure 9. Choctawhatchee River Cross-Section under Bridge near Newton, AL obtained from mesh (Looking Downstream)

IV. MODEL SIMULATION

Preparing Model for Simulation

The predetermined flow rate the user chooses to run the model represents the first boundary condition. For this project the data was known for an approximate five hundred year flood. The flow rate of 87,500 cfs was introduced into the model. The next boundary condition is the stage of the water level at the exiting end of the model. For this project a stage of 178.86 feet was known to have occurred at the bridge site. The problem is that the model does not end at the bridge site; and therefore, the model must be calibrated. The calibration process involves setting the downstream water level to a certain stage elevation, running the model, and then checking the water level elevation at the bridge. The stage elevation downstream was set at 176 feet to get the correct stage elevation at the bridge in the original model. Both of these boundary conditions are kept constant throughout the scour development simulation in this project. It is possible to change the boundary conditions for each time step if desired. The process of setting up the boundary conditions will be described next.

In the Mesh module, the user should select the Create Nodestring tool. In this project the flow boundary condition was established first. Since the flow of the river

is moving east to west, the far right side of the mesh is where the flow boundary condition is introduced. The length of the flow introduction nodestring will be based on flood stages and ground elevations. Using the ground elevations and flood stages requires one to apply engineering judgment to decide how big of an area he or she will need to introduce the flow to. A nodestring should be created along the side of the mesh that the flow will be introduced. If the flow is moving from left to right the flow will be introduced on the left side and accordingly if the flow is moving in other directions. After the nodestring is created, the user should make sure that the arrows of the nodestring point in the direction of the flow. Next, the user should select the Select Nodestring tool and then select the boundary condition flow nodestring that was just created. After selecting the flow nodestring the user should then choose the Assign BC command from the FESWMS menu. This will open the FESWMS Nodestring Boundary Condition window. From this window the developer should first choose the Specified Flow/WSE elevation option under Boundary Definition. This is done because the boundary conditions are a specified flow and a water surface elevation (WSE) in this model. Under the title Specified Flow/WSE option the user should check Flow, Normal, Constant, and then type in the flow rate. This ends the process of setting up the flow rate boundary condition. The next step will involve setting up the water surface elevation (WSE) or stage boundary condition using the same process. The WSE boundary condition nodestring will be placed on the other side of the mesh where the flow is exiting the model. In the Nodestring Boundary Condition window the user will check Water Surface Elevation and then choose

Essential, Constant, and type in correct stage. While setting the stage elevation boundary conditions one should make sure the arrows of the nodestring are still pointing in the direction of the flow. The nodestring length will require the user to make an educated judgment. The water stage nodestring should incorporate all elements that the user believes will be able to receive flow from the set water stage elevation. For example, it would not be possible for the land elevation to be 180 feet and have a water elevation of 178.86 ft. This concludes the directions for setting up the model's boundary conditions.

A few more items must be set up in FESWMS before a model simulation can be performed. First, one should go to the Model Control command under the FESWMS menu. In this window one should make sure that NET file, Steady State below the Solutions option, Hydrodynamic as the Run type, Slip under the Slip Conditions options, and None under Higher Order Integration options are all selected. While still in this window one should select Parameters. One can alter these to their own conditions; however, in this case all were left at default, except, the Drying/Wetting option. The Drying/Wetting option was selected and the Depth Tolerance was set at 0.5 feet. This is an important step because it allows the user to be unconcerned about elements being dry causing the model to become unstable. The previous steps conclude the preparation needed for running a simulation. One should now save the project.

Simulating the Model

If everything has been done properly this should be the easiest part of the project; however, this is also where problems occur and errors in previous steps can cause the program to crash. To start the first model simulation, select the Run FLO2DH command under the FESWMS menu, which will begin the execution of the model simulation in FESWMS. This will open the FESWMS computation window. After the model has converged and completed its iterations it will prompt the user to press Enter, which will bring the user back to the SMS Mesh module window. A successful model simulation will create an output file (.flo) that will contain velocity, water surface elevation, and water depth for each node in the entire model.

A few suggestions in case errors occur while running the simulation are stated next. Sometimes one may want to start with a higher eddy viscosity (V_0) to make the model more stable. By increasing V_0 the user is making the water act more like oil or mud and this in return will make the model converge easier. Once the model is running correctly the user can use these runs and initial file (INI file) along with slowly decreasing V_0 to a level resembling water under the Model Parameters menu. Also, one should check the model very closely for any thin triangles or odd shape elements. Sometimes these elements are very small and hard to see. The author of this paper suggests zooming in very closely to the Mesh and examining it entirely for small thin triangles that may be causing the model to run improperly. Other problems may also occur and this is where one's engineering and trouble shooting skills may be

put to the test. Running Model Checks under the FESWMS menu along with checking output files created during a model simulation are some other suggestions.

Validating the Model

When selecting a bridge site to model the developer should be sure to have some actual data records to verify and validate his or her model. The model in this study is validated based on actual measurement taken at the bridge site during the flood event that occurred in March 1990. The measurements used to make validations for this model are the stage at the bridge site, the measured flow occurring underneath the bridge site and the velocity profile that occurred underneath the bridge cross-section. All of these measurements have been made available by the USGS and can also be found in the reports Curry et al. (2002, 2003). The first part of the validation process occurs by setting the stage boundary condition that produces the correct stage at the bridge site. The water surface elevation (WSE) measured at the site is 178.86 feet and the model's water surface elevation can be seen in Figure 10 over the entire bridge cross-section. It is best to compare the water surface elevation using Figure 10 because unlike the one measured WSE of 178.86 that is assumed constant; the model produces a water surface that varies slightly across the entire bridge cross-section.

The next parameter to be verified is the flow rate going underneath the bridge. The actual measured flow going under the bridge during the flood was 47,510 cfs and the amount measured in the model was 46,026 cfs. The modeled flow is 3.123% less than the actual flow; however, it was within 5% of the original flow and was considered acceptable for this project.

The next set of data used for validating the model is the velocity profiles that occurred under the Choctawhatchee River Bridge. A velocity profile comparison can be viewed in Figure 11. The velocity profile for the model is higher; however, the results are considered comparable and representative of the actual recorded velocity profile. One has to remember that this is just an idealized computer model and exact agreement would be very difficult to achieve; especially due to the lack of geometric data that is used for the creation of this model. Errors during the field data measurements are also likely to have occurred. The next paragraph will explain how the data is actually obtained from the model simulation.

Running a FESWMS model simulation produces the file, name_of_file.flo, which contains water surface elevations, water depth, and water velocity for every node in the entire model. First, the user must import this file. This is done by selecting the Data Browser command under the Data menu in the Create Mesh module. A window titled Data Browser will then open and the user should select Import, which will then open up the file manager and allow the user to select the correct file (.flo). Once the file is imported the user can select velocity mag, water depth, or water surface from the Scalar pull down menu on the original screen. By selecting one of these options the model will then display a plan view profile and legend of how that option varies in the model.

In order to get a cross-sectional profile one must draw a line exactly where he or she wishes to obtain cross-sectional data by using the Create Feature Arc tool in the Map module. Next, the user should return to the Mesh module and select the Plot

Options command under the Display menu. The Plot Option window will open and the user should select New, choose Observation Coverage under Plot Type, enter plot name, and then press OK. The next step will be to display the plot window, and this is done by selecting the Plot Window command under the Display menu. This will display a split screen with the cross-sectional plot on top and the plan view image on the bottom. The cross-section data can be exported from within the Plot Options window to form a file that can be reopened in other computer programs. This process is used to get both the water surface elevation data and velocity profile data files, which were then imported into the Microsoft Excel spreadsheet computer program to create Figures 10 and 11.

To obtain the flow of water moving underneath the bridge requires another process. The first step is to create a nodestring where the flow is to be measured. In this case a nodestring was placed across the length of the bridge. Next, the user must select the nodestring and then choose Flux string under the FESWMS menu. The program will then ask the user if he or she would like to set the Flux string to the total flow string and the user should select NO. The user should then run the model, which in return will create a .prt file that should be opened from one's File Manager using a computer program such as Wordpad. Once in Wordpad the user should perform a search for the words "flux string report" which will list the flows that occurred across the created nodestrings during the last iteration of the model's run (McLean 2002). One can then compare actual measured flows to the model's flow. Calibrating one's

model and validating the results is a very important part of doing research using computer generated numerical models.

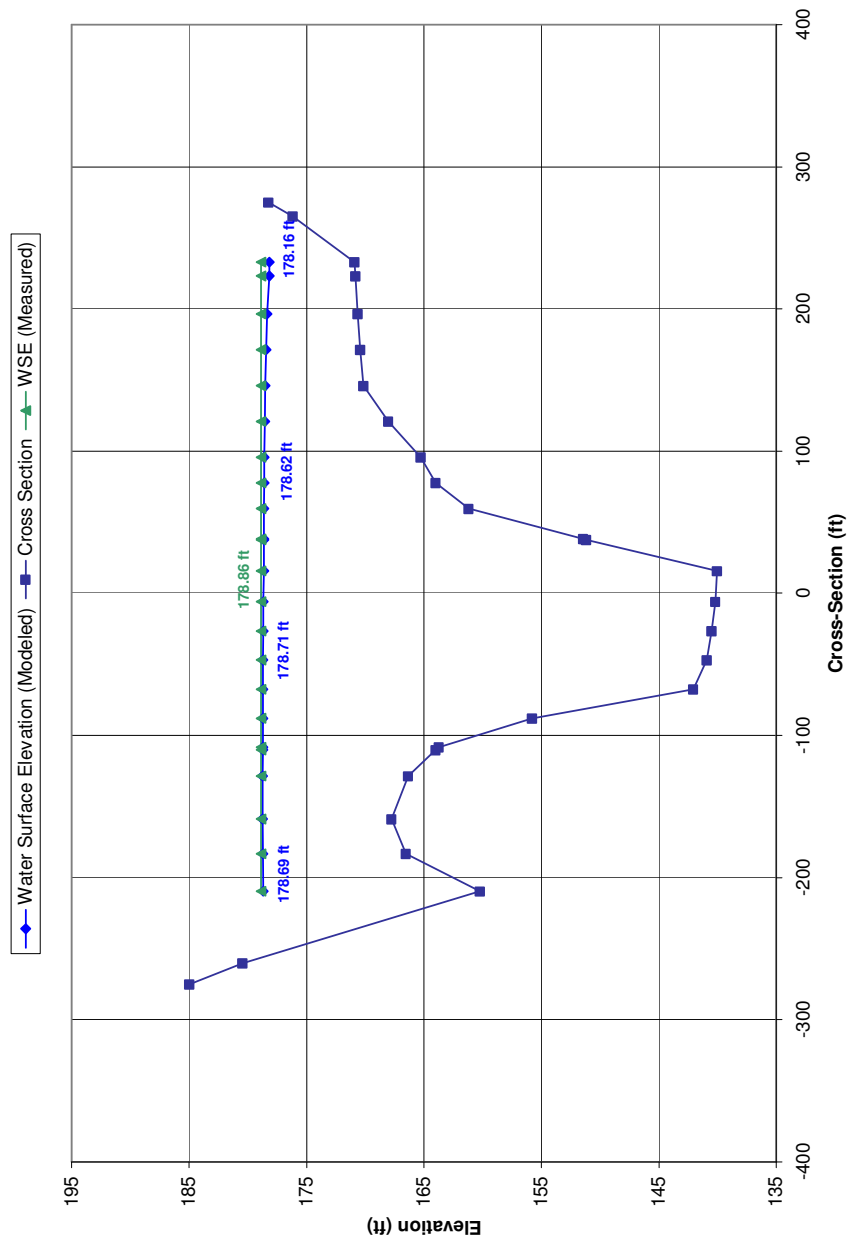


Figure 10. Actual Measured vs. Modeled Water Surface Elevation (WSE)
 (500 year Flood/Cross-Section Looking Downstream)

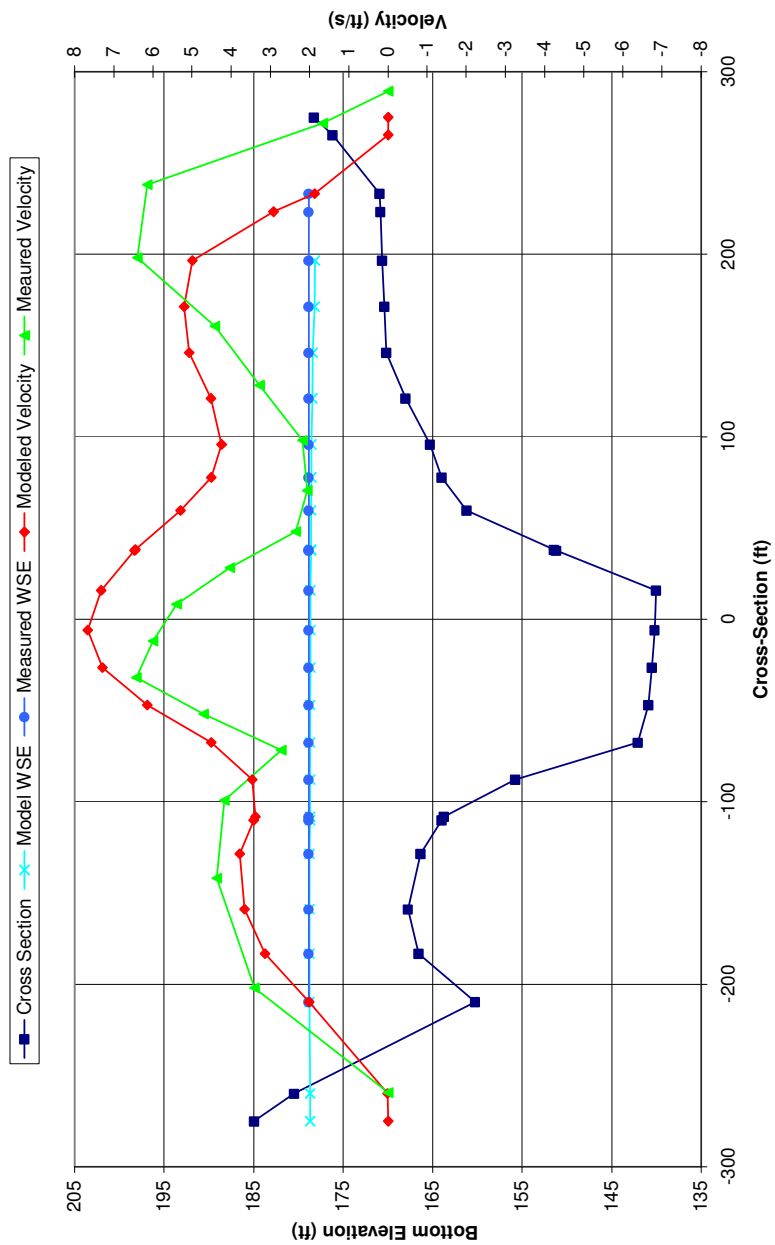


Figure 11. Measured Velocity vs. Modeled Velocity Profiles
(500 Year Flood/Cross-Section Looking Downstream)

Scour Calculations and Formulas Used

The methodology used in the calculation of the cumulative contraction scour is the same scour calculation methodology found in section 2.1 titled “Time Dependent Scour Calculation Method” of Mclean et al. (2003). This method is a 2-dimensional version of a one-dimensional approach for modeling time dependent clear-water contraction scour in cohesive soils presented in Güven et al. (2002), which is an extended version of the SRICOS method introduced by Briaud and his colleagues at Texas A&M. (Mclean et al. 2002). This method uses the three outputs of the FESWMS .flo output file: velocity (V), water depth (H), and water surface elevation at each node to compute the cumulative contraction scour. This process follows three basic steps. First, set up the model as described in this paper and run a successful simulation. This will represent the first day of running the model and its original conditions. The second step will include performing calculations to get the total scour that occurred during that day in the SMS calculator. The calculations include developing the flow per unit width (q), the Reynold’s number (Re), the friction factor (f), the shear stress (τ), the scour rate (R), and the total scour occurring during a day (ΔS). This process will also include subtracting the scour from the original elevation to form a new elevation. This new elevation will be saved as the Day 2 starting ground elevation. The third step is to run the model again with the new elevation. This process will be continued until the desired time frame has been reached. The following consist of the formulas and variables used in this method and are directly taken from Mclean et al. (2003.)

The Henderson implicit formula can be used to calculate the friction factor (f) in an iterative manner.

The formula is

$$f = \frac{0.25}{\left[\log\left(\frac{k_s}{12H} + \frac{2.5}{\text{Re}\sqrt{f}}\right) \right]^2} \quad (1)$$

f = friction factor

k_s = roughness height

H = flow depth

$$\text{Re} = \text{Reynolds number} = \frac{4q}{v} \quad (2)$$

q = unit flow rate = VH

V = velocity magnitude

v = kinematic viscosity of water = $1.06 \times 10^{-5} \text{ ft}^2/\text{s}$ at 70° F

To solve equation (1) for f , an initial estimate of f must be calculated first. The initial friction factor estimated value can be calculated using the Swamee-Jain explicit formula originally used for pipe flows. The Swamee-Jain formula is:

$$f = \frac{0.25}{\left[\log\left(\frac{k_r}{3.7} + \frac{5.74}{\text{Re}^{0.9}}\right) \right]^2} \quad (3)$$

$$k_r = \frac{k_s}{4H} \quad (4)$$

Note: $k_s = 0.0$ for smooth surfaces, which is assumed for this project

Once the initial friction factor is calculated the Henderson implicit formula is applied iteratively. Mclean et al. (2003) recommends five iterations due to the

finding that between the 2nd and 5th iteration the change was less than 1% for each node. For this particular model five iterations was considered appropriate.

The shear stress at each node can now be calculated using the determined friction factor in the following formula:

$$\tau = \frac{\rho V^2}{8} f = \frac{\rho q^2}{8H^2} f(\text{Re}, k_s, H) \quad (5)$$

τ = bed shear stress

ρ = density of water = 1.94 slugs/ft³ at 70°F

The next formula involves using information obtained from the results of the Erosion Function Apparatus (EFA) test of the soil samples. The parameters obtained from the soil samples are the slope of the erosion function/initial erodibility (S_i) and the critical shear stress (τ_c). The next step is to calculate the rate of scour (R), which can be done by using the following formula:

$$R = S_i * \max(0, (\tau - \tau_c)) \quad (6)$$

τ = bed shear stress

τ_c = critical shear stress

This equation uses the “max” function to choose the value from inside the parenthesis that is largest. If the calculated shear stress is less than the critical shear stress than no scour occurs, and this is represented by the zero that in effect causes the scour rate to be zero. The final scour for a given time step or incremental scour (ΔS) can be calculated from the following formula:

$$\Delta S = R * Time\ step \quad (8)$$

Note: For this project a time step of 1 day is used.

The new ground elevation can be determined by subtracting the incremental scour from the original ground elevation (McLean et al., 2002).

$$\text{New Ground Elevation} = \text{Original Ground Elevation} - \Delta S \quad (8)$$

The next part of the paper will describe the actual process of using these equations in the SMS calculator step-by-step to determine cumulative clear water contraction scour.

At this point in a project one should have had a successful model simulation and have imported a FESWMS (.flo) output file into SMS. All of the following steps will be done in the Mesh module and describe the process used to calculate the cumulative scour in this specific problem. The first step occurs by opening the beginning of day one project file (BDay1) and the corresponding FESWMS (.flo) output file. The next step consists of opening the SMS calculator under the Data menu. In the SMS calculator menu one should see the following list of variables under data sets:

- a. elevation**
- b. depth**
- c. velocity**
- d. water surface**
- e. x-coord**
- f. y-coord**

These are the current data sets available to the user. Each dataset consist of the numerical values assigned for each node in the model's mesh for the certain descriptors. The letters corresponding to the data set will be used in calculations to represent the

descriptor's value within the equations. The equations will also correspond to equations described previously. It is often easier to set up the equations beforehand in a word processor document so that one is able to copy and paste them into SMS calculator. This will make one's work much easier due to the repetitiveness of the equations throughout the entire project. The first calculation one makes is for flow per unit width (q). The equation that should be typed into the expression space is $(b \cdot c)$, and q should be inserted in the result space. One should then select the Compute command, which will result in the creation of the q dataset that corresponds to the letter g . The next equation to calculate is the Reynold's number. The formula that should be entered in the expression space is $(4 \cdot g) / (.000001)$, and Re should be entered in the result space and the Compute command executed accordingly. The Re dataset will correspond to the letter h .

Following the Re dataset one should now calculate the initial friction factor using the Swamee-Jain explicit formula. The expression entered is $.25 / ((\log(((k_s / (4 \cdot b)) / 3.7) + (5.74 / (h^{0.9}))))^2)$, and f_0 should be entered in for the result corresponding to the dataset i . After computing the f_0 data set one should begin the iterative process of calculating the friction factor using the Henderson implicit formula. For the first iteration of the friction factor the expression used will be $.25 / ((\log((0 / (12 \cdot b)) + (2.5 / (h \cdot (i^{1/2}))))))^2)$, and the result will be the f_1 dataset corresponding to the letter j . The second iteration's expression is $.25 / ((\log((0 / (12 \cdot b)) + (2.5 / (h \cdot (j^{1/2}))))))^2)$, resulting in f_2 dataset corresponding to the

letter **i**. The third iteration which results in the **f3** dataset corresponding to the letter **l** is calculated by the expression, $.25/((\log((0/(12*b)))+(2.5/(h*(k^{(1/2))}))))^2$. The fifth and final term in the friction factor iteration process is solved by the expression, $.25/((\log((0/(12*b)))+(2.5/(h*(l^{(1/2))}))))^2$, resulting in the **f4** dataset which corresponds to the letter **m**. The next resulting dataset will be shear stress and corresponds to the letter **n**. The expression used is $(m*1.94*c^2)/8$, and **shear stress** should be entered into the results space. The **scour rate** data set will be calculated next by using the expression $S_i*(\max(0, n-\tau_c))$, and correspond to the letter **o**. S_i and τ_c are obtained from EFA data. In this particular project two different datasets are used. Figure 12 and Figure 13 represent the EFA data from which S_i and τ_c are obtained. Once the rate is obtained the cumulative scour for the time step can be calculated. The expression used for calculating **scour** is $o*(24/12)*1$ which correspond to the letter **p**. The one in the scour expression represent the 1 day time interval used in this study. The final step is to calculate the end of day1's elevation. The expression will be **a-p** and the result will be **EDay1EL**, which corresponds to the letter **q**. This completes the calculation steps for the first day. One should now save the project file (EDay1). It is very important that one remembers to check units throughout the project. All of the equations used during this project are in English units and are for a time step of one day. All proper unit conversions were done previous to starting the calculations. Equations entered into the SMS calculator will require editing for other units. Be sure to start with original equations and then convert them into equations that will be used in the SMS calculator.

The next process of steps will involve setting up the project for Day 2's model simulation and calculations. First, choose the Map Elevation command under the Data menu. This will open a window that shows all of the datasets. Select the EDay1EL dataset and enter the name SDay2EL when prompted. This sets a new ground elevation that has had 1 day of scour subtracted from it. SDay2EL will be the new ground elevation condition when running the model in FESWMS. Next, the user should select the Data Browser command from the Data menu. This will open up the Data Browser window, which will have a list of solutions and a list the datasets corresponding to each solution (scalar datasets). The user should delete the FESWMS output file (.flo) from the solution list and then select Generic Data sets. Once the Generic Datasets solution is selected the user should delete all scalar data sets except the SDay2EL. SDay2EL should have [ELEVATION] next to it; indicating that it is the ground elevation that will be used in the model simulation. The program will not let you delete the dataset that has [ELEVATION] following it; so one does not have to worry about deleting this dataset by accident. Now the new model is ready to be run and the user should save the project file as SDay2 and begin the model running/calculation process over again following the steps described above. This process should be continued until the desired duration time in number of days is reached. Make sure to save the starting and ending project file for each day of model simulation. A plain view image of the cumulative contraction scour that occurred according to the above calculations during Day 1 of the simulation can be seen in Figure 14.

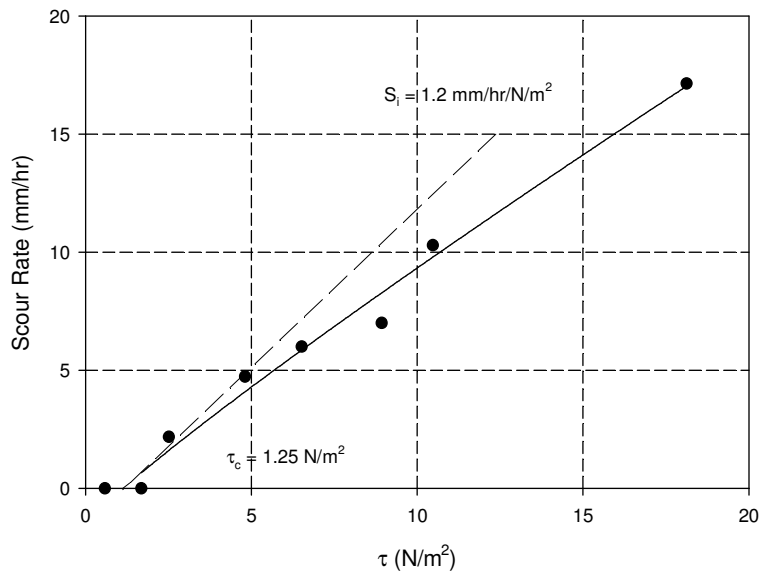


Figure 12. EFA data for soil sample 4C (represents soil from main channel) (Curry et al. 2003)

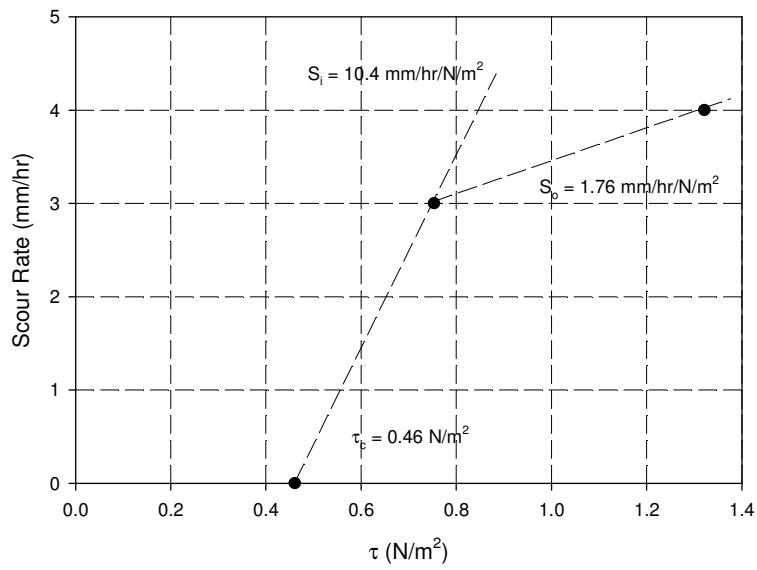


Figure 13. EFA data for soil sample 4B (represents soil from the overbank) (Curry et al. 2003)

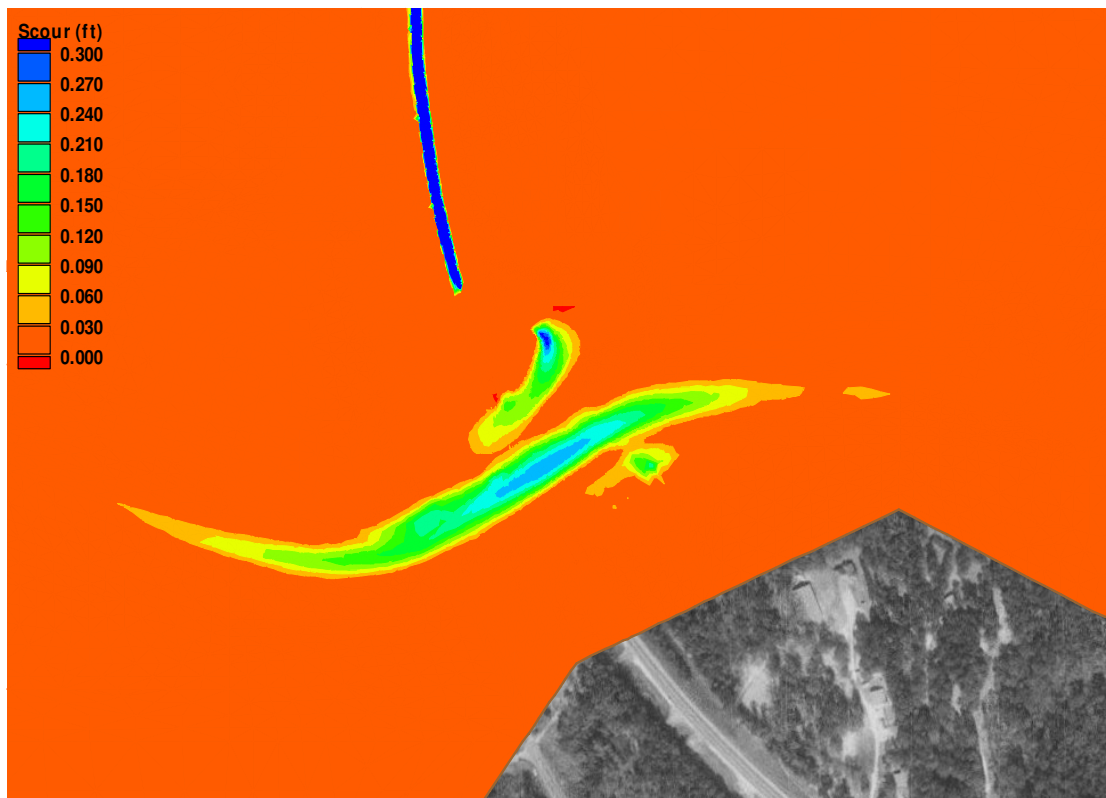


Figure 14. Plan view of the Scour that occurred during Day 1 of model simulation. Image is zoomed into bridge site.(500 year Flood/Soil 4C)

Model Simulation Problems/Solutions

One significant problem occurred during the execution of this project. As one can see from Figure 14, high areas of scour occurred over the roadway. Other parts of the model that are not visible from this image also developed high areas of scour. Another thing to consider is that the same EFA soil properties are used throughout the entire mesh even where they are not an accurate representation of the soil. The same scour calculations are also used for the entire mesh. This results in very large scour holes developing in the mesh at areas of high flow velocities. Water goes over the roadway at a relatively high velocity, the roadway is assigned the same EFA properties as the soil, and then scour calculations are performed resulting in large amounts of scour to occur on the roadway. In reality this would not occur, and the computer program does not allow you to assign different EFA soil properties to different parts of the model. The result of the high velocities over the roadway and similar areas in the model is that deep scour holes developed after several days of running that resulted in the model not converging and eventually crashing. This actually occurred after six days of running the model.

In order to fix this problem a large number of elements in the model had to be turned off or deleted in the original mesh. The mesh was also altered slightly where the flow was being introduced into the model to eliminate awkward shaped elements that produced high velocities. The solution involved solving for the flow that only went underneath the bridge. This means that all of the model that had flow that didn't go under the bridge could be eliminated. It is possible to do this because the total amount of

flow actually going underneath the bridge was known to be 47,510 cfs according to the information from the USGS gauge station.

The first step in developing a new mesh that models only the flow going underneath the bridge is to find the stagnation point in the original mesh of the total flood's flow. The stagnation point was determined by looking at the velocity vectors of the first day's simulation. The stagnation point is the place in the model where the flow either goes over the roadway or turns to go underneath the bridge. The stagnation point and velocity vectors for this model can be seen in Figure 15. This is where the beginning of creating the new mesh would begin. The rest of the new mesh would be created by deleting old elements of the original mesh. The new mesh was determined by using the old mesh, the velocity vectors, and user judgment to decide what elements were needed to represent the flow going underneath the bridge. The new mesh can be seen in Figure 16. The process of creating the new mesh for this particular model is not perfect and could have been approved upon. The appropriate method would have been to follow the velocity vectors and create a flow divide line. From this flow divide line a new mesh should have been created. If the author of this report would have had more time to fix the new model's mesh correctly it would have been done. However, the author believes the results of the new mesh are valid and accurately represent the conditions of the bridge site during the flood. This idea is supported by comparing the velocity profiles of the original model and new model, which can be seen in Figure 17. The velocities are almost a perfect match and therefore indicate that the model is valid.

After creating the new mesh, one should change the stage boundary conditions until the stage at the bridge is correct and change the flow rate boundary condition to the flow going only underneath the bridge (47,510 cfs). One should also check the flow underneath the bridge during the simulation. These processes are completed just as described in Chapter III of this paper. The new flow under the bridge was 47,822 cfs, which is only 0.656 % higher than the actual flow of 47,510 cfs that was introduced into the model. This shows some of the minor inaccuracies when determining the flow through a flux string. The new stage elevation or WSE can be seen in Figure 17 compared to the WSE of the original model at the bridge site.

A new model may not be needed for every site that is modeled using the methods described in this paper. The problems that occurred during the original model simulation were solved by creating the new mesh that will be referred to as Mesh 2 throughout the rest of the thesis. Using Mesh 2 the same procedure discussed in this paper was used to determine cumulative scour for two different soil samples with their corresponding EFA soil properties. The results will be presented in the next section.

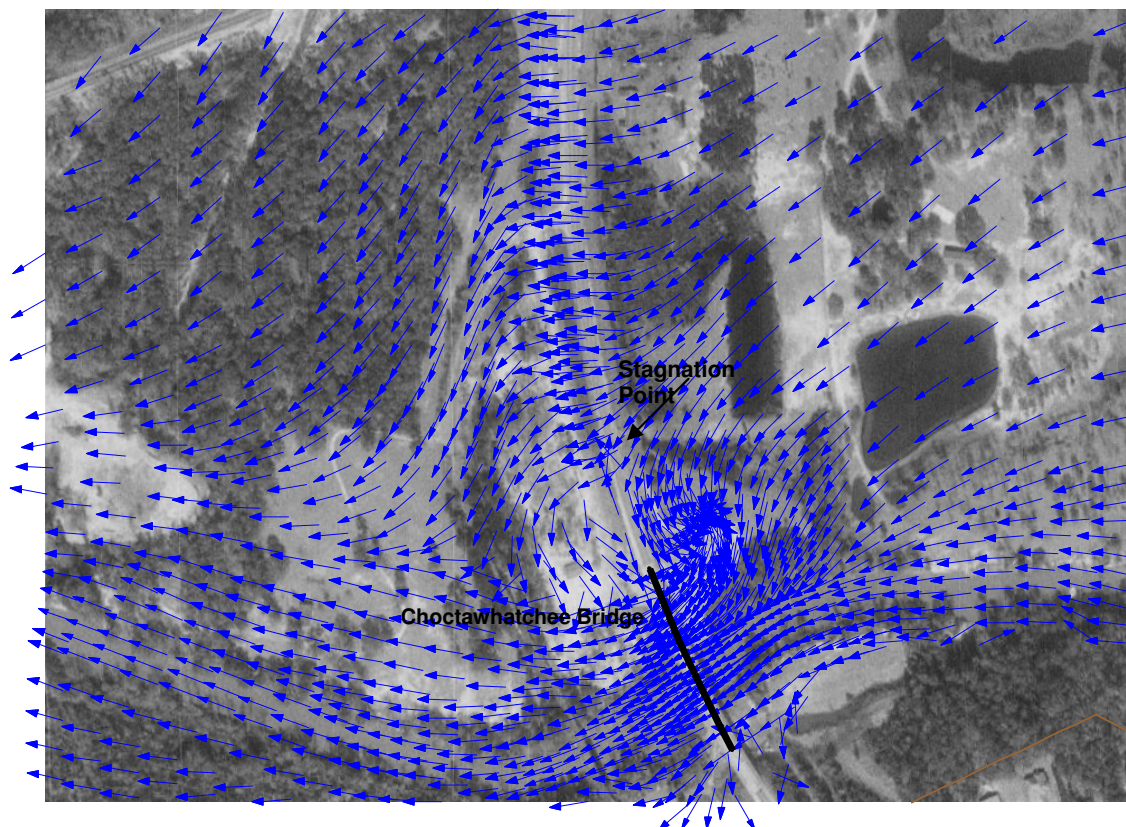


Figure 15. Velocity vectors used to determine stagnation point



Figure 16. New Mesh (Mesh 2) created to model just the flow going underneath the bridge.

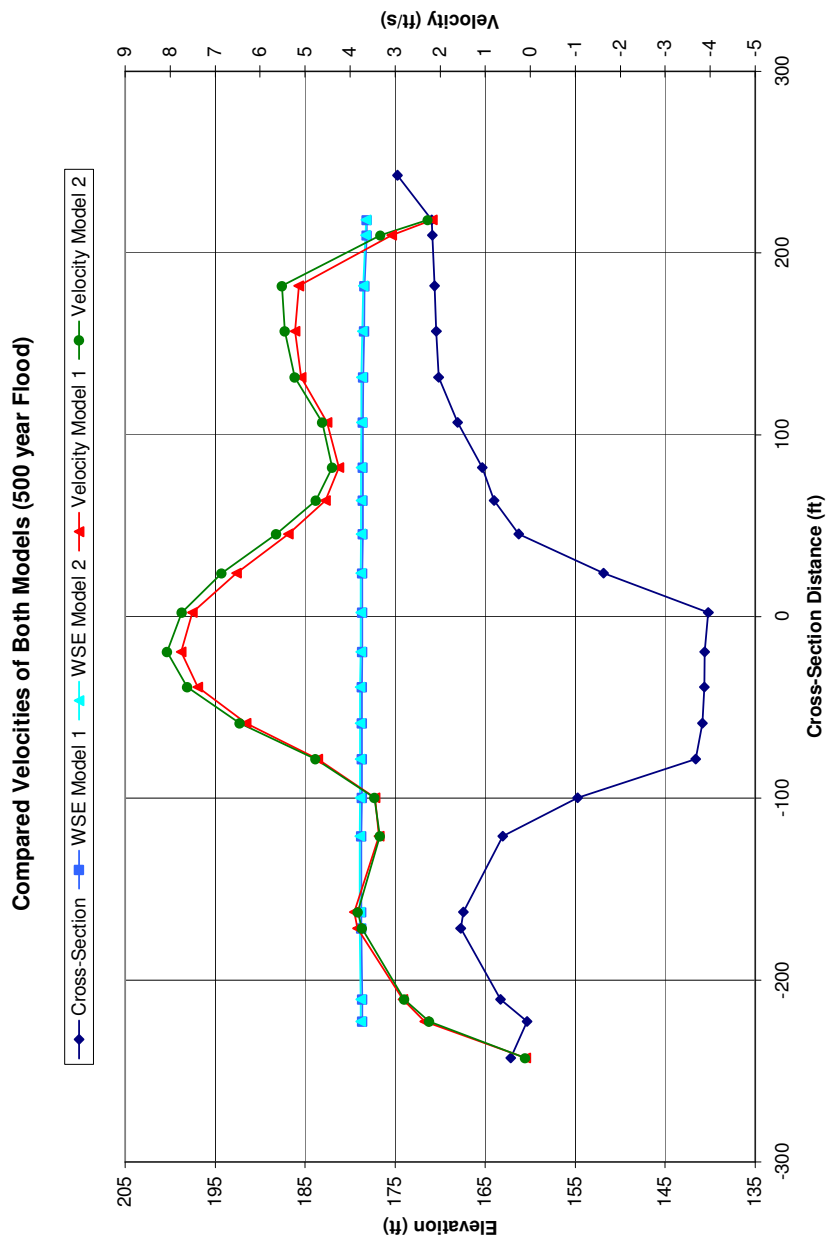


Figure 17. Velocity Profiles Comparison of Model 1 and Model 2 (500 year Flood/Cross-Section Looking Downstream)

V. RESULTS

This chapter contains the resulting figures and tables obtained from model simulations using Mesh 2. They include the results for soil samples 4C and 4B as well as comparisons to the 1-dimensional results. All figures and tables are labeled with a caption describing what the figure represents.

Cumulative Contraction Scour Results for Soil 4C

The first simulation was for a 500 year flood and the soil sample 4C. Soil sample 4C is a Shelby tube soil sample that represents soil from the main channel of the Choctawhatchee River underneath the bridge near Newton, AL. The EFA obtained data can be seen in Figure 12. The soil is described as hard silt with clay. The initial erodibility (S_i) converted to English units is 2.267 in/hr-PSF. The critical shear stress (τ_c) converted to English units is 0.026 PSF. By using these specifications the model was simulated for 200 days. The following are cumulative scour results consisting of plan views, cross-section views, and longitudinal views for 5 days, 10 days, 50 days, and 100 days.

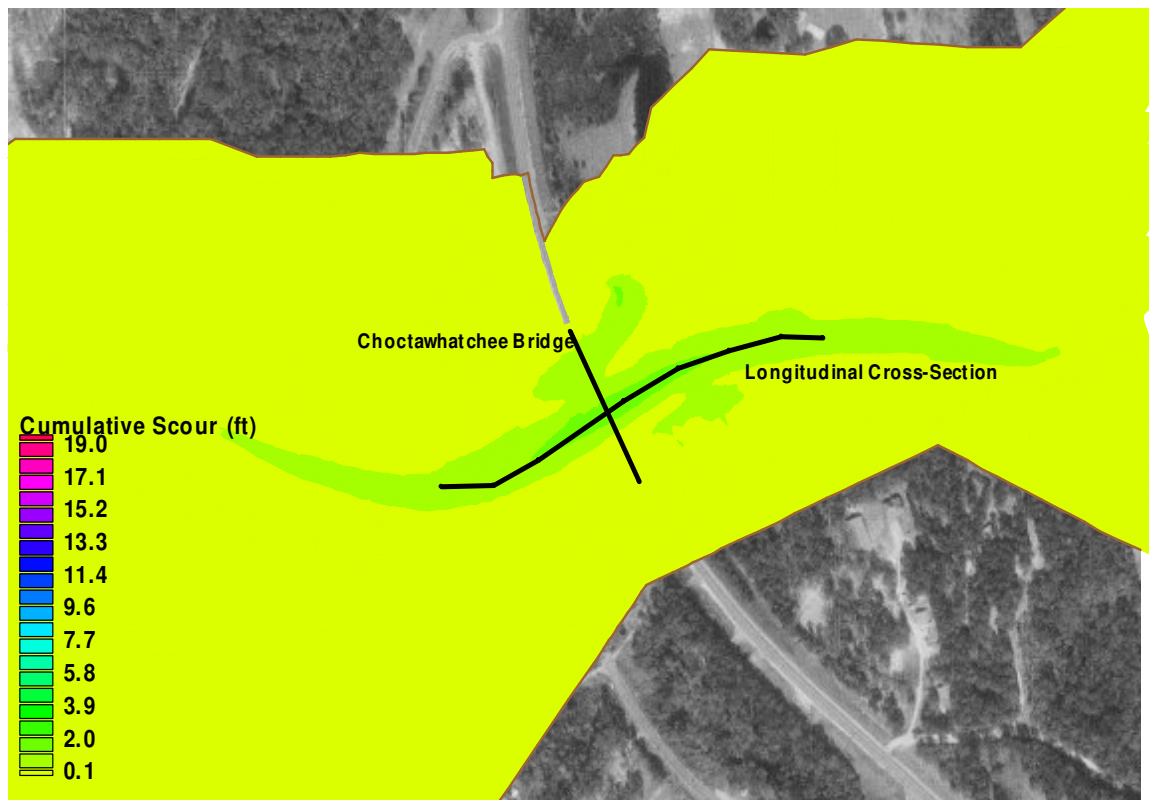


Figure 18. Cumulative Scour after 5 Days (500 Year Flood/Soil 4C/Plan View)

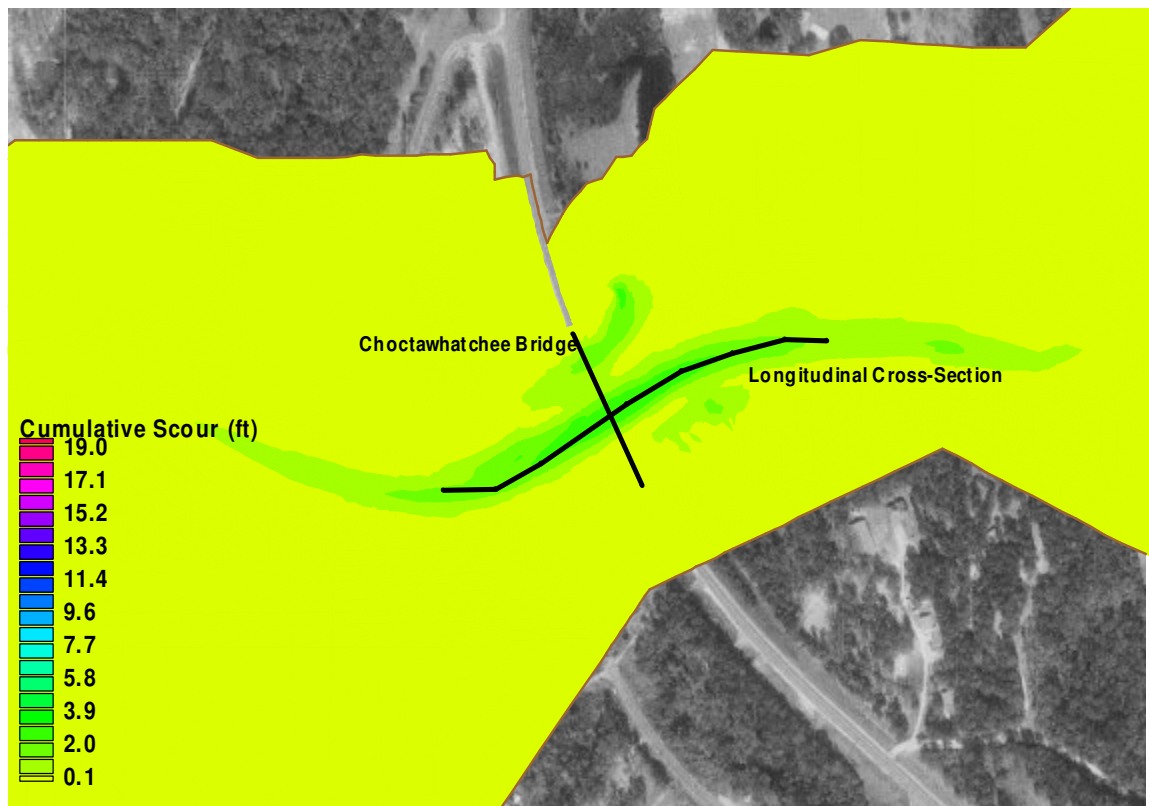


Figure 19. Cumulative Scour after 10 Days (500 year Flood/Soil 4C/Plan View)

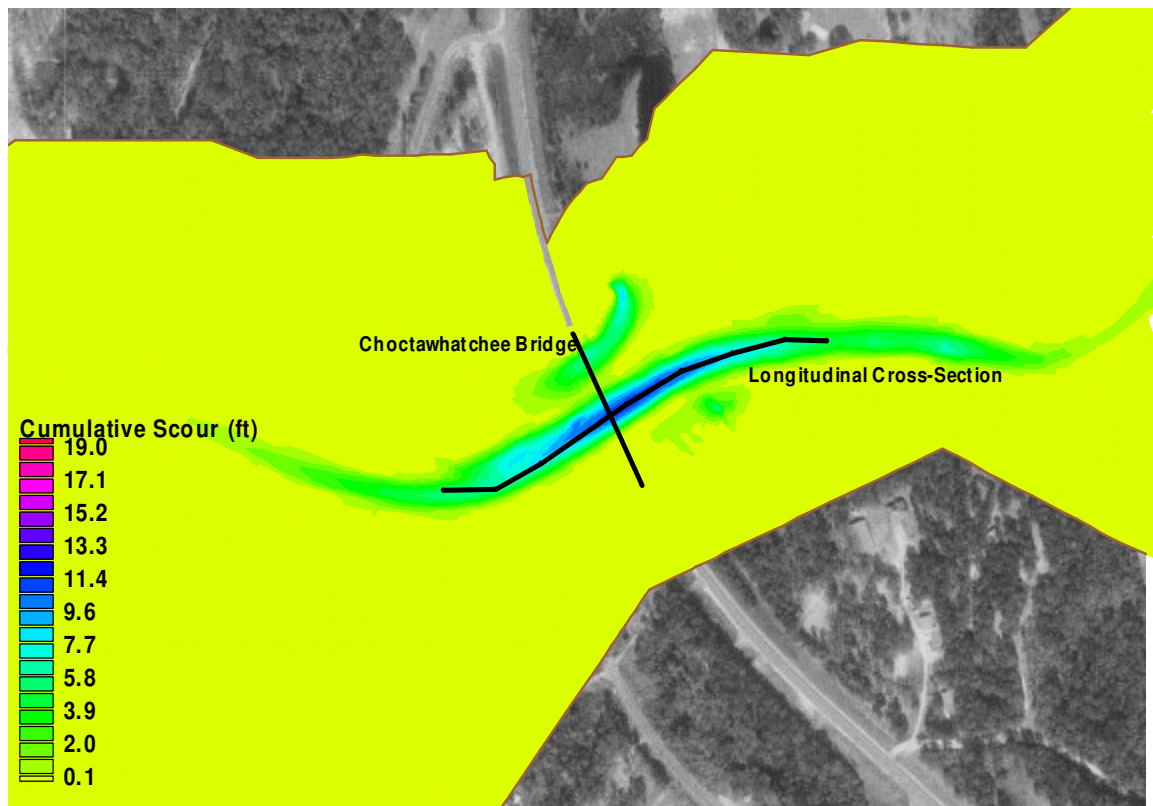


Figure 20. Cumulative Scour after 50 Days (500 year Flood/Soil 4C/Plan View)

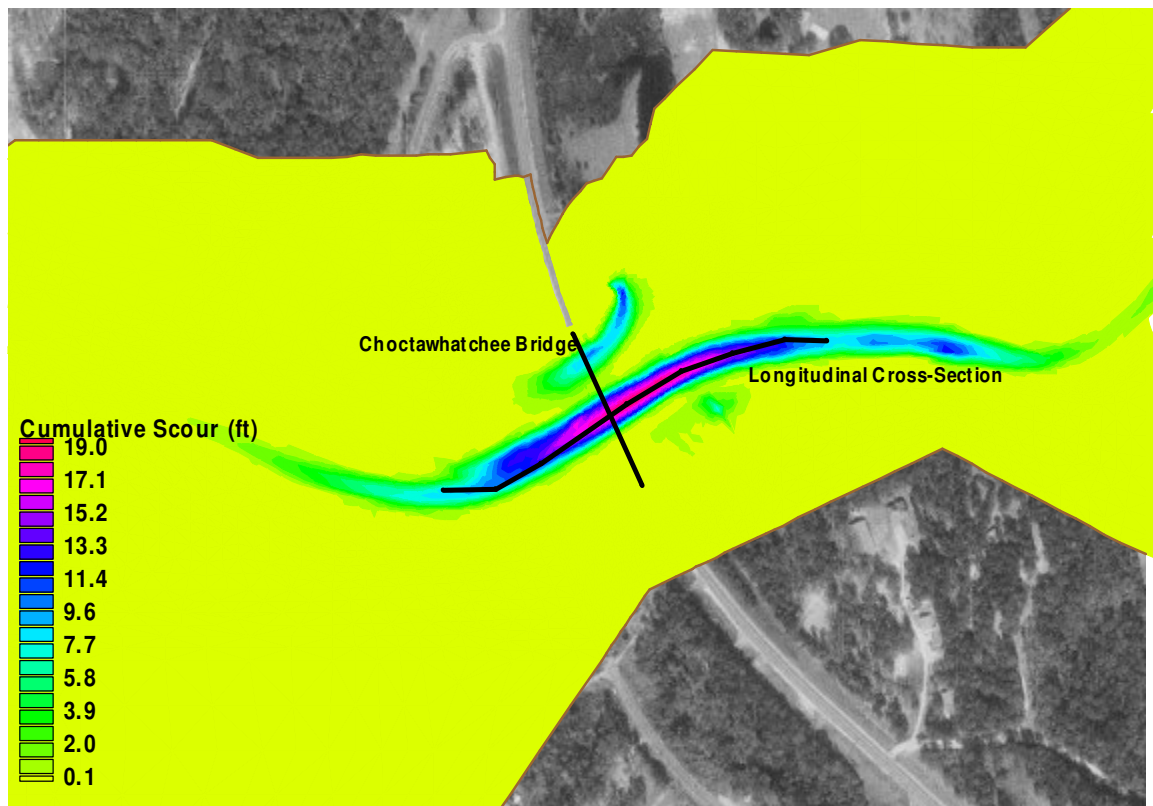


Figure 21. Cumulative Scour after 100 Days (500 year Flood/Soil 4C/Plan View)

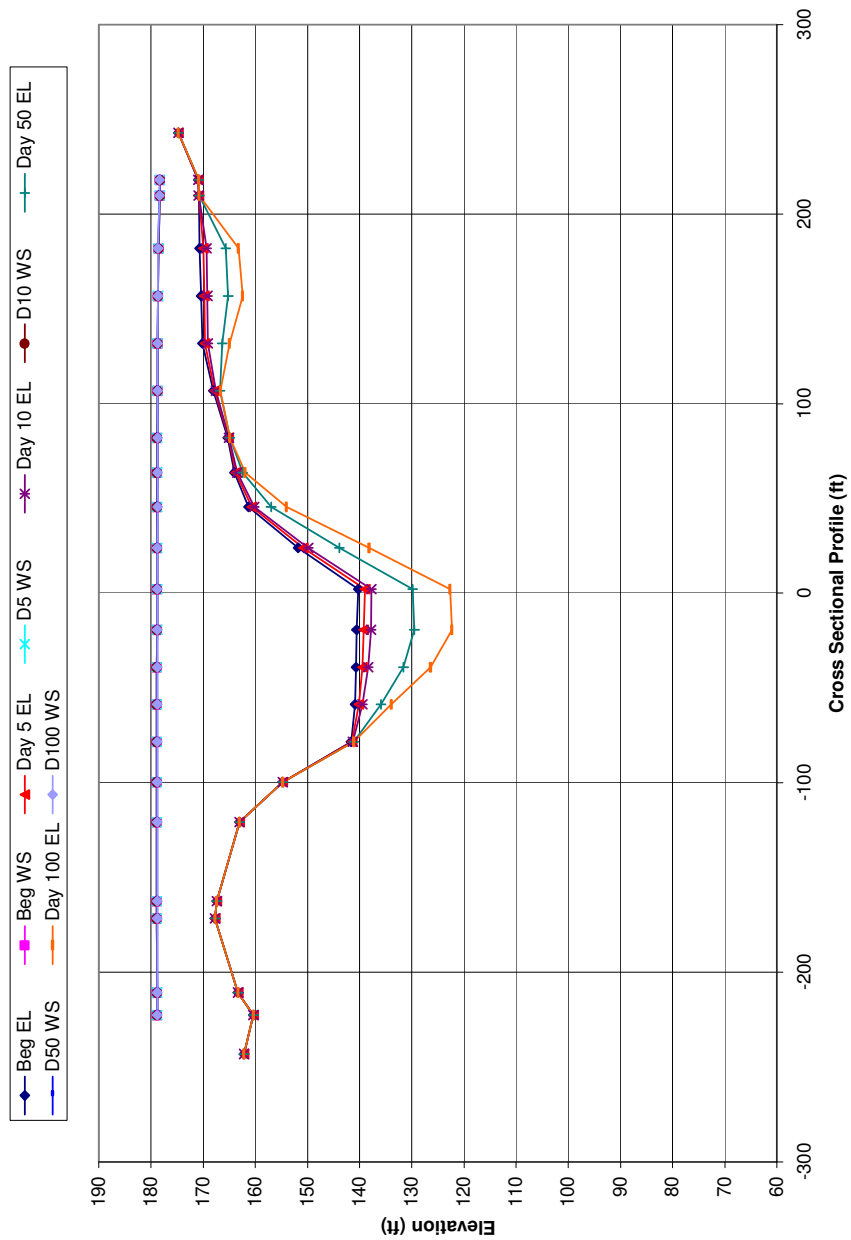


Figure 22.

Change in elevation due to scour after 5, 10, 50, & 100 Days
500 year Flood/Soil 4C/Cross-Section Looking Downstream)

Profiles correlate to the Choctawhatchee Bridge line seen in the plan view

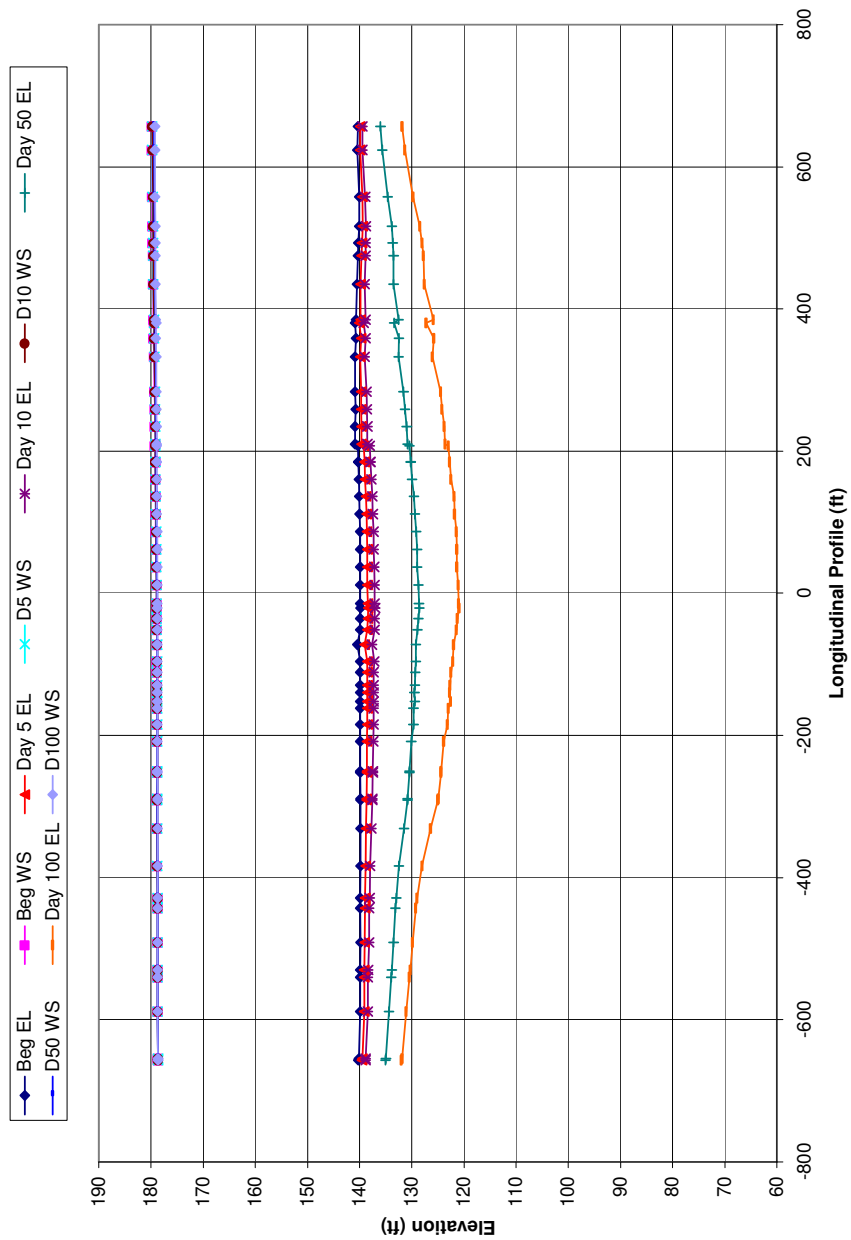


Figure 23. Change in elevation due to scour after 5, 10, 50 & 100 Days
(500 year Flood/Soil 4C/Longitudinal Profile/River Flow Right→Left)
Profiles correlate to the longitudinal profile line seen in the plan view

Cumulative Contraction Scour Results for Soil 4B

This section will have the results of the cumulative scour that occurred during model simulations using a five hundred year flood and the soil sample 4B. Soil sample 4B is a Shelby tube soil sample that came from the top layer of the left overbank of the Choctawhatchee River underneath the bridge near Newton, AL. The soil is described as loose sand with clay. The EFA data can be seen in Figure 13. The initial erodibility (S_i) converted to English units is 19.653 in/hr-PSF. The critical shear stress (τ_c) converted to English units is 0.00958 PSF. By examining the EFA properties one can predict that this soil will scour much more than soil sample 4C. Using these specifications the model was simulated for 100 days; it was not carried out for 200 days as soil sample 4C because it is really unnecessary to run a model for that long of a time period. The following cumulative scour results consist of plan views, cross-section views, and longitudinal views for 5 days, 10 days, 50 days, and 100 days. One should take notice that the legend on the plan view images is different for the two soil types to emphasize the scour development; however, the scales are the same for the other figures.

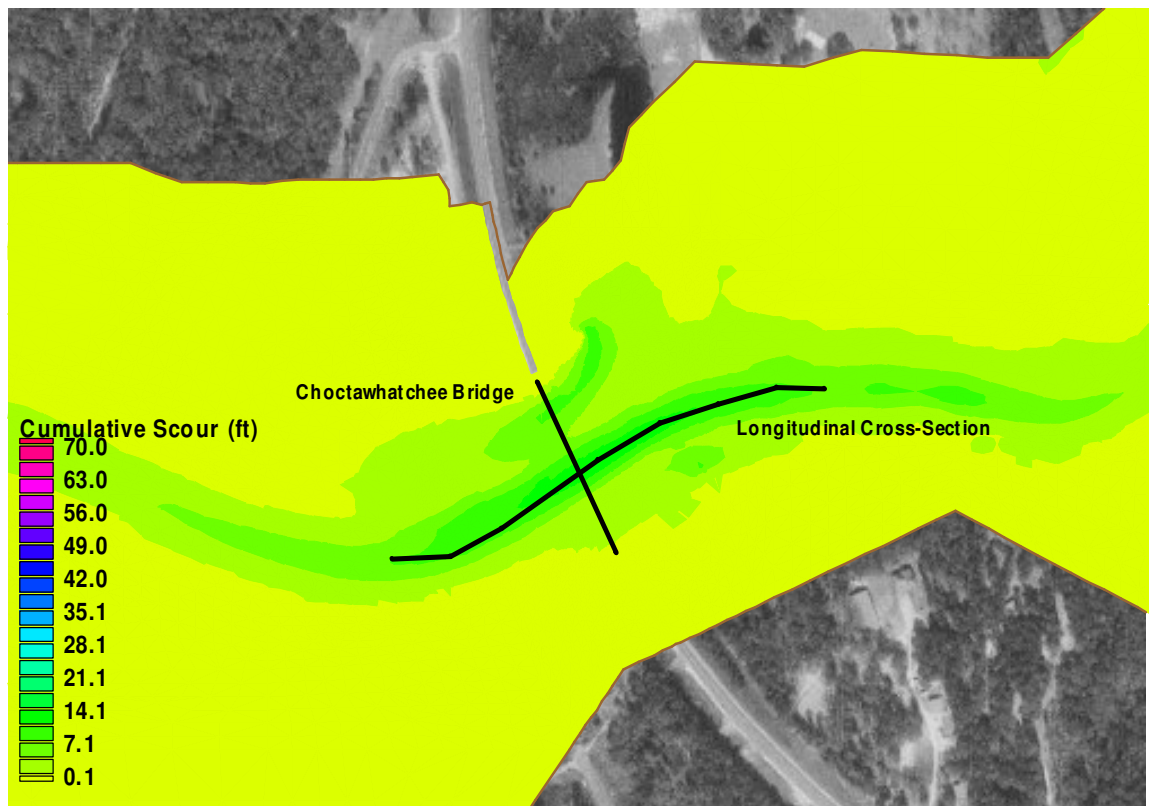


Figure 24. Cumulative Scour after 5 Days (500 Year Flood/Soil 4B/Plan View)

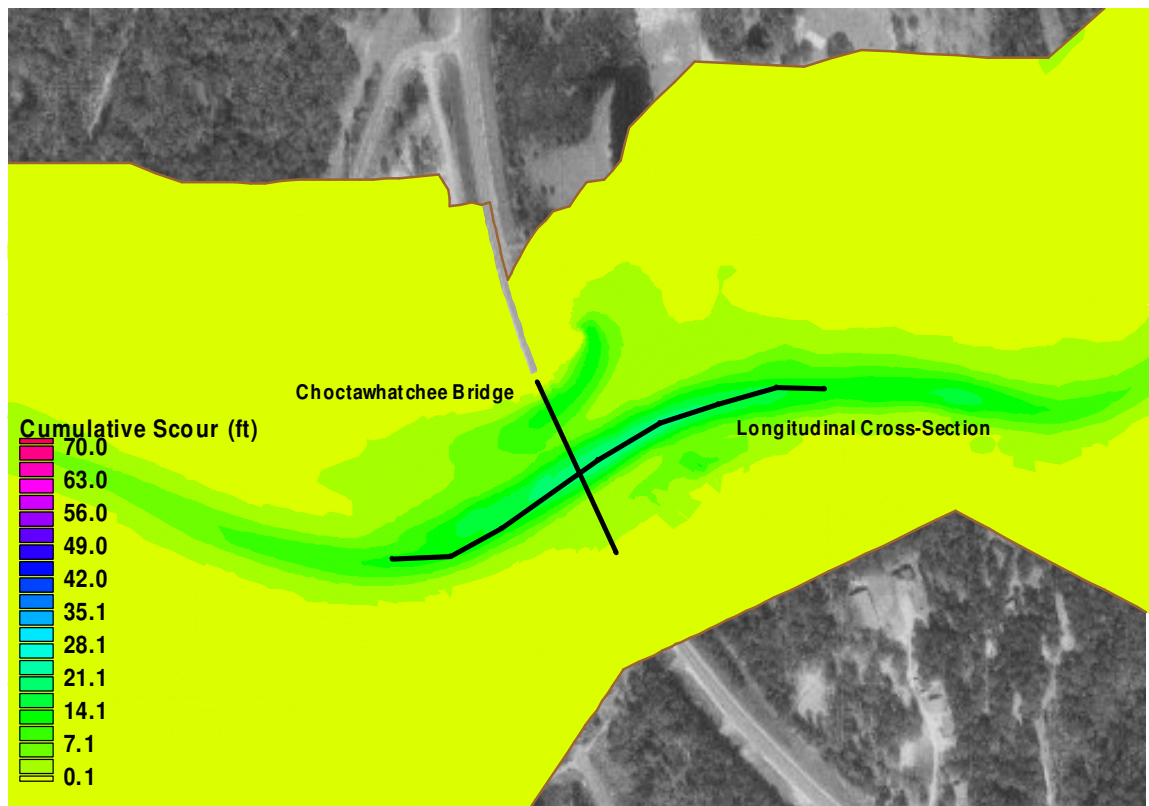


Figure 25. Cumulative Scour after 10 Days (500 year Flood/Soil 4B/Plan View)

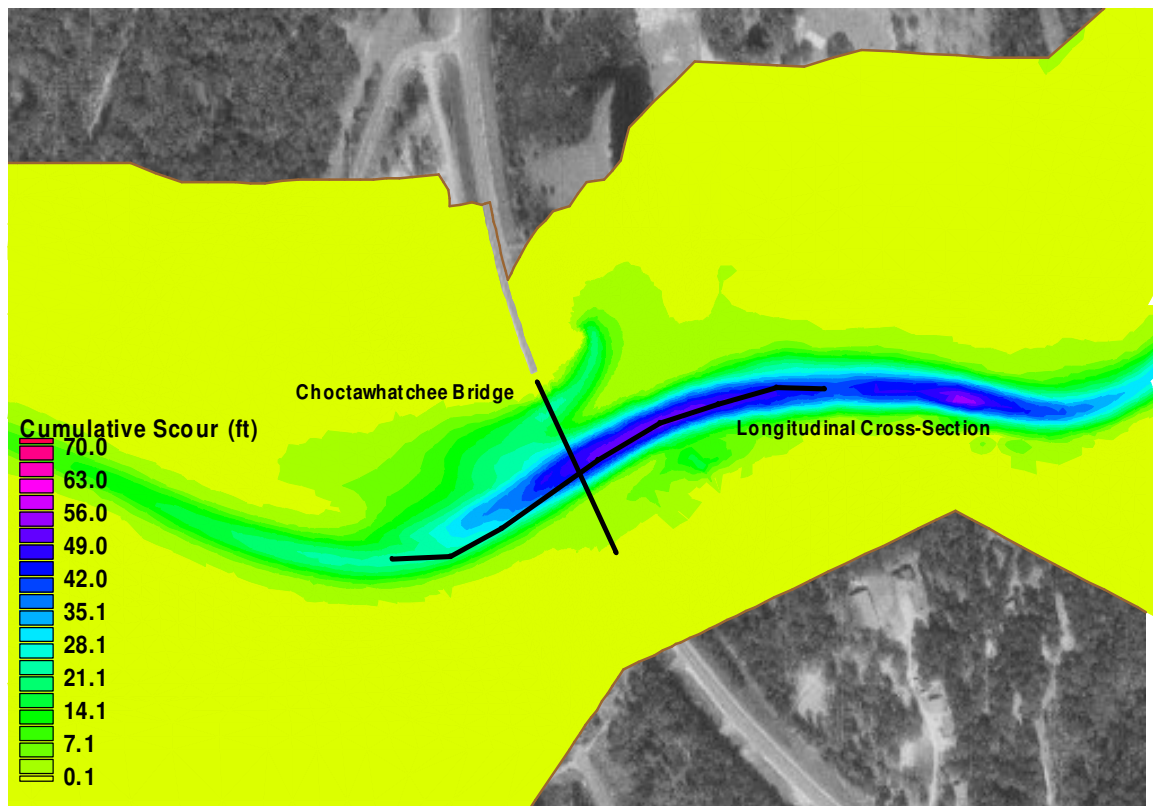


Figure 26. Cumulative Scour after 50 Days (500 year Flood/Soil 4B/Plan View)

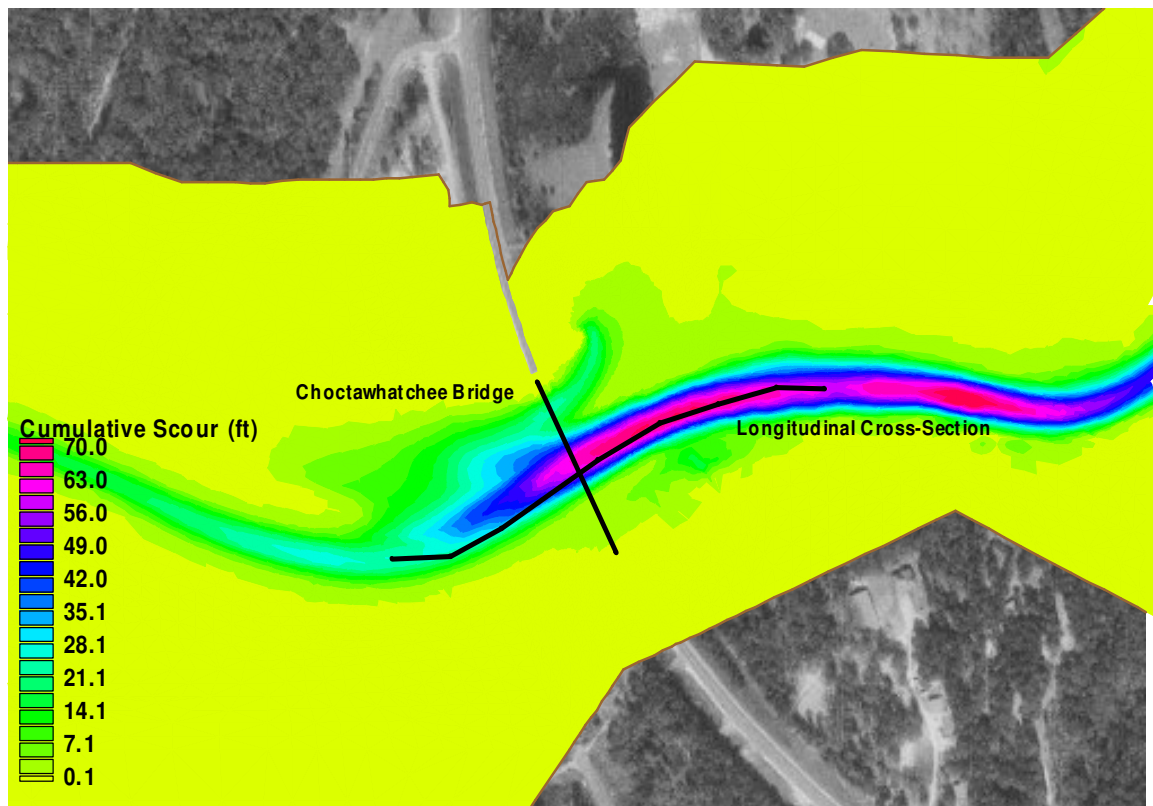


Figure 27. Cumulative Scour after 100 Days (500 year Flood/Soil 4B/Plan View)

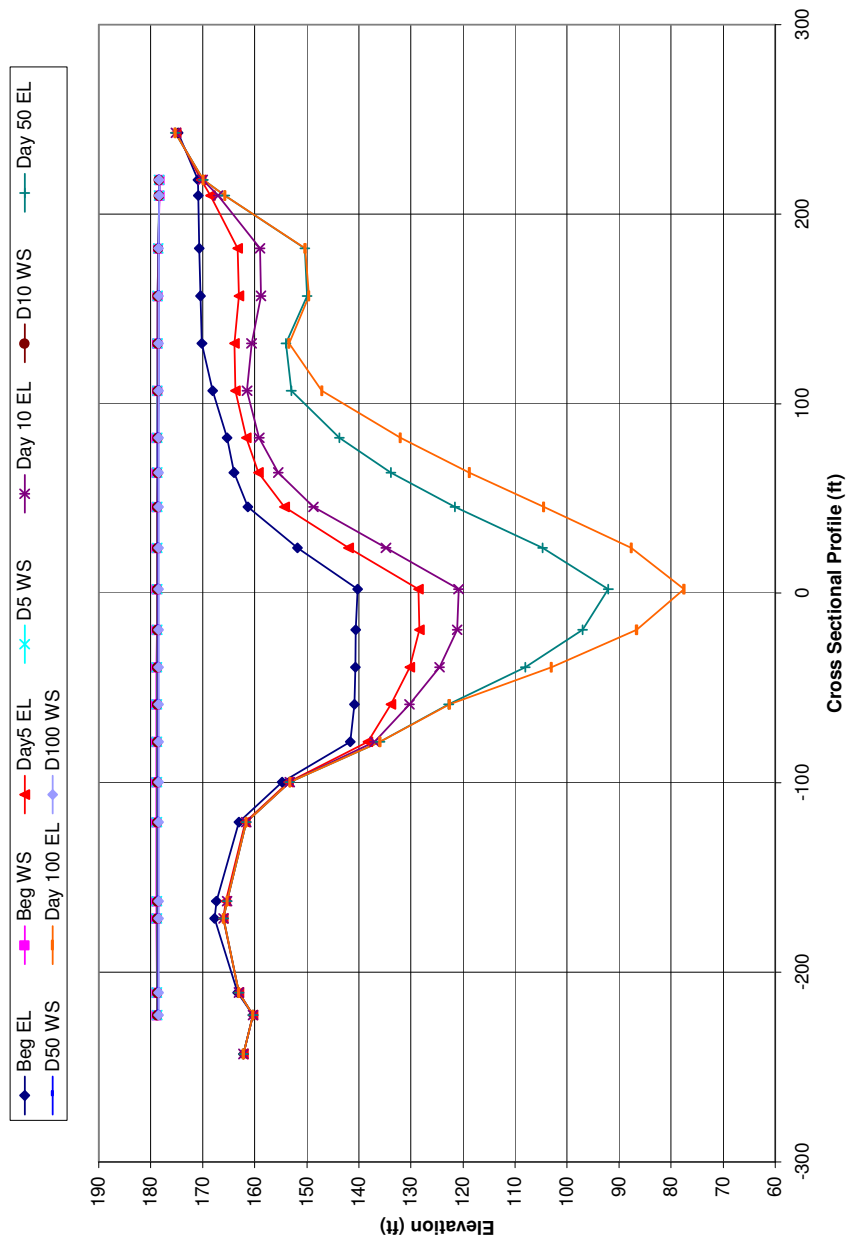


Figure 28. Change in elevation due to scour after 5, 10, 50, & 100 Days
(500 year Flood/Soil 4B/Cross-Section Looking Downstream)
Profiles correlate to the Choctawhatchee Bridge line seen in the plan view

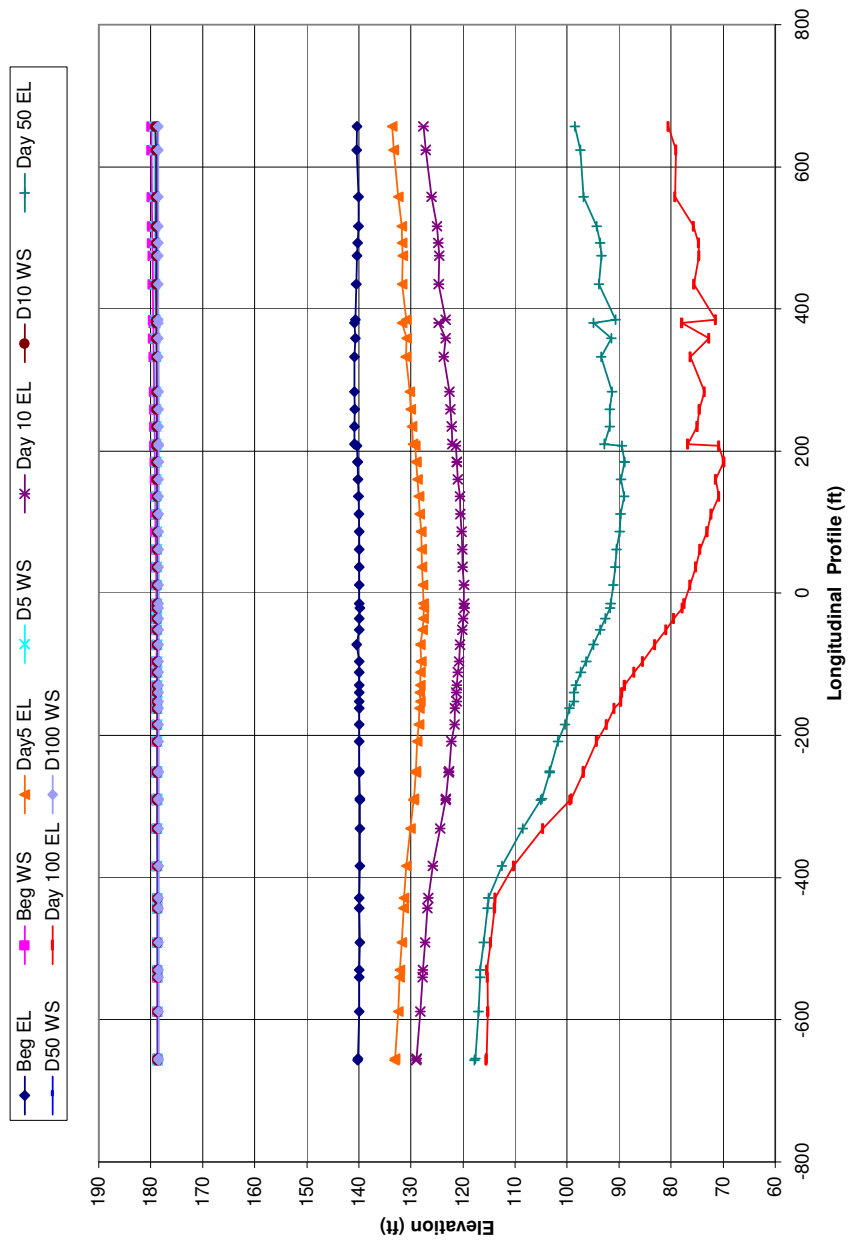


Figure 29. Change in elevation due to scour after 5, 10, 50 & 100 Days
(500 year Flood/Soil 4B/Longitudinal Profile/River Flow Right→Left)

Cumulative Contraction Scour Comparisons (1-D Results vs. 2-D Results)

This section of the report will show figures that compare the 1-dimensional results presented in Curry et al.(2003) with the 2-D time dependent cumulative scour results of this study. The 1-diminsional results are derived using the DASICOS and E-SRICOS methods for computing scour in cohesive soils. The 1-D DASICOS method uses the same approach as the 2-Dimensional calculations used during this project including the same EFA soil properties. Other examples of the DASICOS approach have been presented in previous studies by Güven et al. (2002a, b). The E-SRICOS or (Extended Sricos) method uses multiflood conditions in order to calculate cumulative contraction scour (Curry et al., 2003). The original SRICOS method (Scour Rate in Cohesive Soils) was introduced by Briaud et al.(1999) for a constant approach velocity and a circular pier. It was later extended in Briaud et al. (2001b) for multiflood and multilayer situations, which involves obtaining a Shelby tube sample to obtain with EFA soil properties for scour calculation purposes (Curry et al., 2003). In the report Curry et al. (2003) pier scour was also calculated; however, only contraction scour of the main channel is compared in this report. In order to perform these calculations stage-discharge rating curves; along with daily discharges dating back to the construction of the bridge were obtained from the USGS. 1-D time dependent cumulative contraction scour calculations for the main channel using both methods were preformed for everyday that had a discharge over 800 cfs. The critical shear stress was not reached until a discharge of 3000 cfs occurred and therefore in order to decrease calculation time an 800 cfs minimum flow limit was established. The calculations were also discontinued after the March 1990

flood (500 year flood event) due to riprap being placed at the sight for scour prevention. The results of these calculations represent the cumulative contraction scour occurring at this bridge from the time of its construction in 1976 up until the flood event in March 1990 (Curry et al., 2003). Matlab programs were developed to perform the calculations in both of these methods and can also be found in Curry et al.(2003).

Two other parameters that will be used for comparisons are Z_{max} and Z_{ult} . Z_{max} is the maximum scour depth that can occur in a contraction. The equation for Z_{max} presented in Curry et al.(2003) is:

$$Z_{max} = 1.90[1.49 * Fr_{hec} - Fr_c]^* y_h \quad (4.1)$$

Fr_{hec} is the Froude number corresponding to the velocity that is determined by the HEC-RAS computer program for the given model. Fr_c is the critical Froude number, while y_h is the water depth in the contraction. The equations for Fr_{hec} and Fr_c are the respective equations 21 and 22 in Curry et al.(2003). Z_{ult} is the ultimate scour depth for any flood over an infinite time period. The equation for Z_{ult} is:

$$Z_{ult} = y_{ult} - y_h \quad (4.2)$$

The variable y_{ult} is the ultimate water depth corresponding to the flood calculated by equation 32 in Curry et al.(2003) and y_h is the initial water depth of the flood.

Suggested readings for more background about the E-SRICOS, DASICOS and other scour calculation methods besides Curry et al. (2003) are Briaud et al. (1999, 2001a, 2002b, 2003), and Güven et al. (2001, 2002a, 2002b).

The 2-Dimensional results used for comparison are the maximum cumulative contraction scour that occurred in the main channel underneath the bridge. This data is

obtained from the daily scour cross-sectional data exported as an Excel spreadsheet file. This file contains the data of the modeled scour that occurs for a particular day for the entire given cross section. An example of this is shown in Figure 30 along with the corresponding numerical values in Table 1. A large Excel spreadsheet containing every day's scour profile was created. The maximum scour that occurred in the river's main channel was then added daily to form a cumulative maximum contraction scour versus time curve. Figure 31 shows the maximum cumulative contraction scour curves for both soil samples 4B, and 4C. Figure 32 shows all of the 1-D and 2-D cumulative clear-water contraction scour calculations results that have been performed for the Choctawhatchee River Bridge site near Newton, AL for the soil sample 4C. The 1-D results represent the maximum scour predicted by the calculations and do not vary with time such as the 2-D results. 1-D calculations were not performed for soil sample 4B in the previous study because it is not the type of soil actually found in the main channel at this site.

The last results figure depicts equivalent flood durations. The equivalent flood durations represented in this figure are the amount of time it takes for this 500 year flood to cause the same amount of contraction scour that the 1-Dimensional E-SRICOS model predicted over the life of the bridge site from 1976 to 1990 which is 1.8 feet or 0.55 meters.

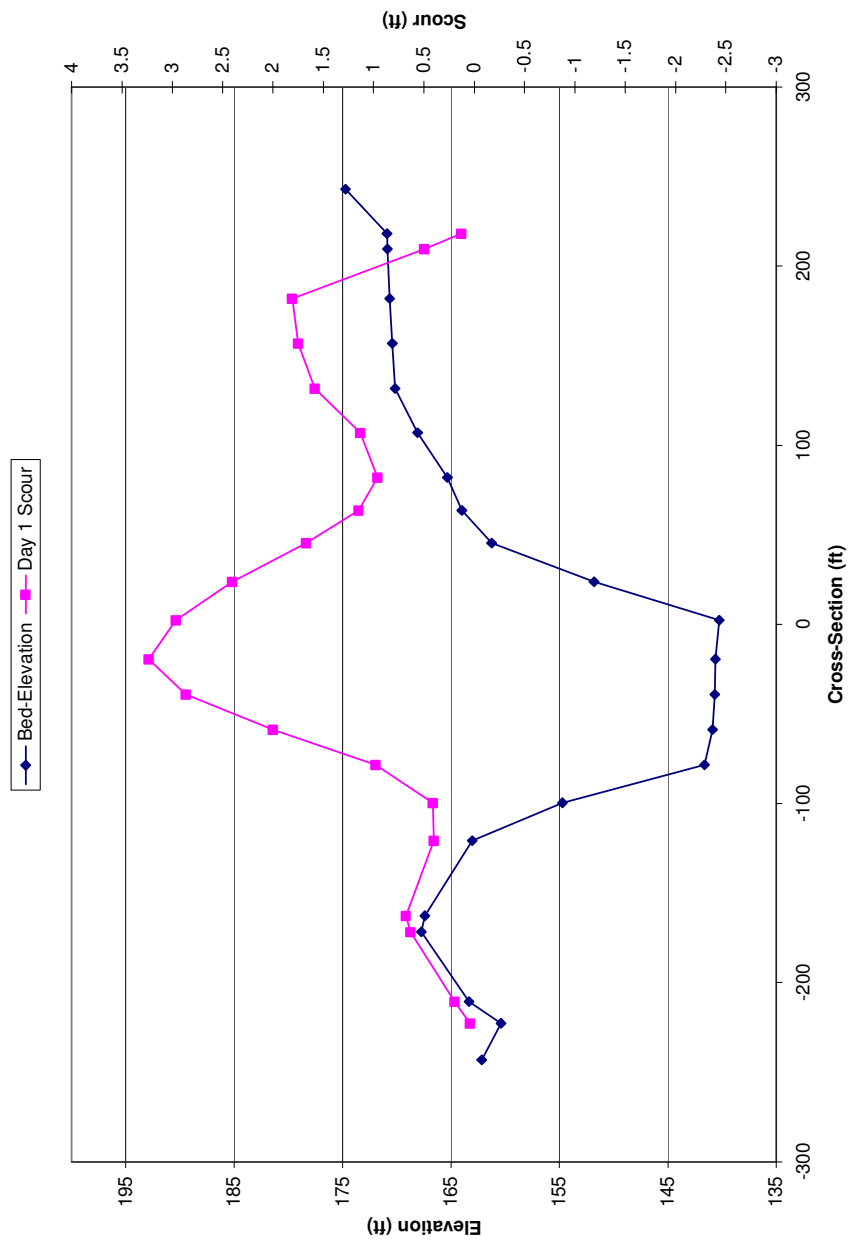


Figure 30. Cumulative Contraction Scour Cross-Section Profile.
(Day 1/Soil 4B)

x-Location	y-Scour
-222.603	0.045
-210.524	0.194
-171.622	0.635
-162.437	0.678
-120.807	0.402
-99.603	0.410
-78.352	0.979
-58.566	2.001
-38.876	2.866
-19.290	3.234
2.318	2.964
23.936	2.407
45.566	1.668
63.789	1.149
82.048	0.960
106.986	1.130
131.842	1.584
156.963	1.748
182.000	1.809
209.791	0.493
218.160	0.130

Table 1. The numerical values used to generate the scour profile in Figure 30.
 The orange cell represents maximum contraction scour for that day used to calculated cumulative contraction scour.

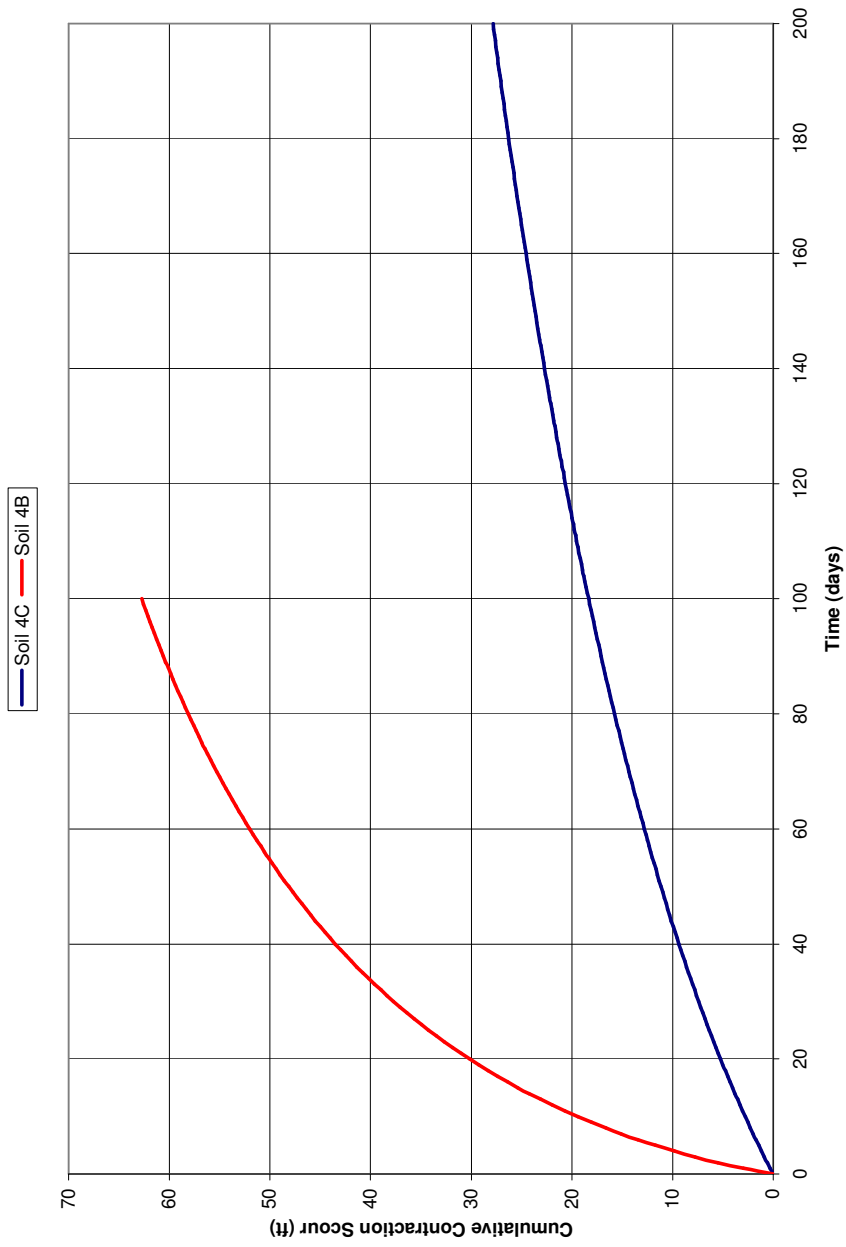


Figure 31. Comparison of soils 4B and 4C cumulative contraction scour in the main channel.

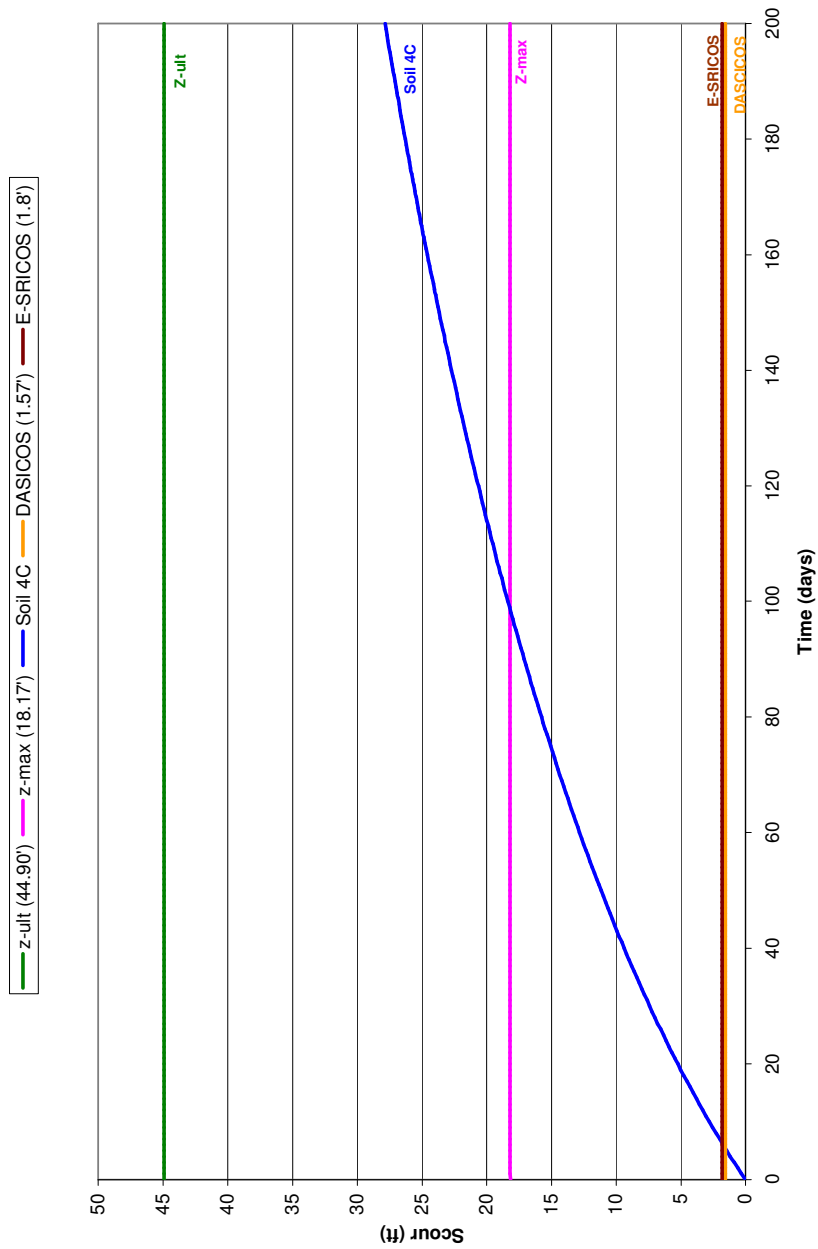


Figure 32. Compares 2-D Cumulative Contraction Scour Results to 1-D Contraction Scour results in main channel and soil sample 4C. Z_{ult} and Z_{max} for this site are also illustrated.

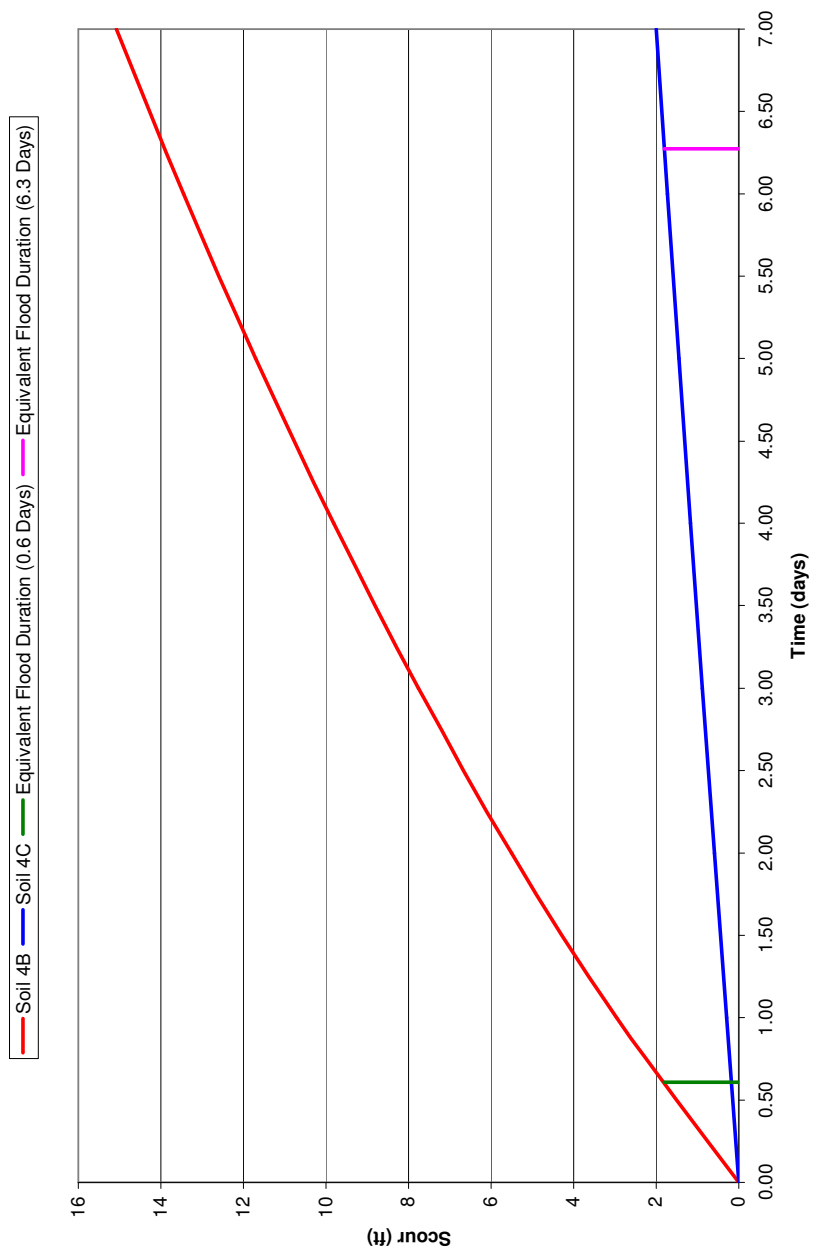


Figure 33. Equivalent Flood Durations for soil samples 4B and 4C

Discussion of Results

The results of these two model simulations reveal a lot about how scour will develop at this bridge site. By looking at the 2-D plan views one can predict where possible scouring may occur and proper precautionary measures could be taken. Also, by looking at Figures 23 and 29, which represent cumulative contraction scour over a longitudinal cross-section, one can see that the scouring occurs over a long span and has a very mild slope. In order to really picture this one needs to look at the scale of these figures and realize that in actuality they would be relatively flat. This coincides with the assumption of considering the river bed to act as smooth surface, which means the assumption is valid for the calculation performed in this model. The results also show considerable scouring around the contraction of the bridge site. The longitudinal profile along with the plan view profiles show that the scour holes develop gradually over a long distance in the contraction and are not an abrupt hole formed directly at the contraction. The main channel, over banks, and areas around the guide bank are all part of the river contraction that experienced scouring during the actual March 1990 flood that was modeled in this report. After the March 1990 flood, rip rap was placed in the scoured areas to prevent further scouring. The models show similar scouring in these areas and therefore similar models could be developed for other bridge sites to predict where scouring due to a flow contraction might occur.

Comparing the two soil types one can also see that soil 4B scours much more than soil 4C as expected. This is because soil 4C is much more cohesive and has a higher critical shear stress (τ_c) and lower initial erodibility (S_i). One may also notice that the

scouring of soil 4B upstream from the contraction is more severe and starts much further upstream than soil sample 4C. These models were also both run for a considerable amount of time. Running a model for 100 days allows one to see how scour develops over a long period of time. It is also evident that the amount of scour that occurs per day decreases over time. This decrease in daily scour can be determined by the decrease in the slope of the cumulative scour curve shown in Figure 33. The decrease in the slope is caused by the area of the channel increasing due to the increase in channel depth caused by scouring. This in return lowers the water velocity resulting in less shear stress applied to the soil. In actuality a 500 year flood would never last near 100 days. For most practical purposes one can look at the equivalent flood durations in Figure 33 and notice that running a model for 10-20 days could give one an idea of how much scour could be expected over the life of an actual bridge site.

VI. CONCLUDING REMARKS AND OTHER RESEARCH SUGGESTIONS

This study shows that 2-D numerical modeling using the SMS v.7.0 computer software package in correlation with EFA soil data are very useful in predicting where and how contraction scour may occur at an actual bridge site with cohesive soils. As predicted the bridge contraction caused flow to be diverted to the main channel resulting in higher water velocities and areas of high shear stress that resulted in scouring. The report shows examples of two different soil types from the Choctawhatchee River Bridge site near Newton, AL that were tested with the EFA and used to model clear water contraction scour as it developed as the result of a 500 year flood over a long period of time. Standard cross-sectional profiles and longitudinal profiles of elevations can be seen up to a 100 day time period. Plan views of the cumulative scour at the bridge contraction have also been developed for analysis. These are all benefits of using the 2-dimensional model FESWMS available in SMS v.7.0. The results have also been compared to the 1-D values that were calculated for the same bridge site and presented in Curry et al. (2003).

The author of this study also presents a detail description of the method he used to develop this model using the SMS v.7.0 software package. This report could be used as a

basis for developing similar models for other bridge sites. However, every bridge site is different and certain engineering judgment will have to be made for each site. The author also believes that the process of creating geometric and elevation data may be made easier by using high resolution DEMs (Digital Elevation Maps) of the bridge site and surrounding floodplain. Newer versions of the SMS software are also available; meaning improvements and possible changes in the method described in this study. An attempt was successful in importing a DEM and interpolating it to a mesh when the author obtained a low resolution DEM of the site from the USGS website, a trial version of SMS version 8.0, and an ArcGIS software package. The main problem the author noticed was the poor quality of the DEM. The author's attempt to import a DEM into SMS v.7.0 was unsuccessful. After mapping out the DEM contours and comparing them to the contours created from the topographic map in SMS v.7.0 during this study; the author believed the use of the topographic map to be more accurate. Therefore, the author stresses the use of high resolution DEM's that may cost extra money. The use of high detailed DEM's allows for the elevations of the entire floodplain to be much more accurate. The bridge cross-section and detailed river bed elevations would still have to be inputted manually using soundings and other available information from the bridge site.

The author also believes that the new mesh (Mesh 2) created from the original mesh in this study could have been developed more accurately so that it represented the actual flow divide line. The author believes that by using the velocity vectors from the original full scale model that the mesh should have been divided exactly, both up and downstream of the river based on the flow divide line. A new mesh should then have

been created from this divide. This represents a more professional engineering method besides the method described in this study. However, based on Figure 17, the author believes his model is valid and his results are very comparable to what the results would have been if Mesh 2 had been correctly created as described above.

The author believes that this method for predicting contraction scours at bridge sites is accurate and practical. For real world situations there is no need for running a model of this nature for more than 10-20 days. As shown for sample 4C, the amount of scour predicted by the 1-D model to have occurred over the life of the bridge site (approximately 15 years) occurred in 6.3 days of running the model with a 500 year flood. When studying scour around contractions it is also important to realize that pier and abutment scour also occurs at bridge sites, which is not taken into consideration during this study.

The actual flow and changing soil properties surrounding a bridge site make it impossible to make the perfect numerical model. This study represents a 2-D numerical study of contraction scour at an actual bridge site, which is definitely more revealing than the 1-D numerical models; however, there is still a level of uncertainty of the results. There are 3-D numerical models available that would possibly represent the real world actual flow conditions even more accurately, resulting in better scour prediction. More studies using 2-D numerical modeling to predict scour at actual bridge sites could be performed and compared to the actual scour that occurred at the bridge site. This should be done to make sure that these predictions are valid and accurate. The ultimate goal is to find a method that is reliable at predicting scour in cohesive soils and can be performed

with a reasonable amount of effort. The method in this report could definitely be improved upon with more information about the bridge site. The effort involved in the model development can be time consuming; however, an experienced modeler should be able set up the model in a reasonable amount of time. The EFA data may be the most difficult to get for a particular bridge site because an EFA is not that common, and operator interpretation of EFA data is not standardized. Development of a standard EFA index for certain soil descriptions, or certain geographic locations are perhaps other research ideas that could be beneficial to promoting this type of scour prediction.

Another research idea would be to build an actual physical model of a river contraction and compare it to numerical models. 1-D, 2-D, and 3-D numerical models could all be developed for comparison. This should be able to determine the most practical method of predicting scour in cohesive soil beds. However, this project would be very expensive and time consuming; a great deal of effort would be required in the development of such an experiment. However, the results could prove well worth the effort..

There are many benefits for this type of research. One example is to be able to predict the amount of scour that might occur at an old bridge so prevention measures could be taken. Another example is the development of a reliable method to predict an accurate amount of scour at future bridge sites with cohesive soils. The amount of money and possible lives that could possibly be saved by preventing structural failure and creating design improvements in bridge foundations is the very motive for the continuation of research in the area of scour around bridge sites with cohesive soils.

VII. REFERENCES

- Atkins, J.B., 1996. Magnitude and frequency of floods in Alabama: U.S. Geological Survey Water-Resources Investigations Report 95-4199, 234p.
- Briaud, J.L., F.C.K Ting, H.C. Chen, R. Gudavalli, S. Perugu, and G. Wei, 1999. SRICOS: Prediction of Scour Rate in Cohesive Soils at Bridge Piers. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 125, No. 4, April 1999, pp. 237-246, American Society of Civil Engineers, Reston, Virginia, U.S.A.
- Briaud, J.L., F.C.K Ting, H.C. Chen, Y. Cao, S.W. Han, and K.W. Kwak, 2001a. Erosion Function Apparatus for Scour Rate Predictions. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 2, February 2001, pp. 105-113, American Society of Civil Engineers, Reston, Virginia, U.S.A.
- Briaud, J.L., H.C. Chen, K.W. Kwak, S. W. Han, and F.C. Ting, 2001b. Multiflood and Multilayer Method for Scour Rate Prediction at Bridge Piers. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 2, February 2001, pp. 114-125, American Society of Civil Engineers, Reston, Virginia, U.S.A.
- Briaud, J.L., H.C. Chen, Y. Li, P. Nurtjahyo, J. Wang, 2003. "Complex Pier Scour and Contraction Scour in Cohesive Soils," NCHRP Report 24-15, Transportation Research Board National Research Council, National Cooperative Highway Research Program, January 2003.
- Chaudry, M. Hanif. Open Channel Flow. Prentice Hall, Englewood Cliffs, NJ, 1993.
- Crim Jr., S., 2003. "Erosion Functions of Cohesive Soils," Master Thesis, August 2003, Auburn University, Alabama.
- Curry, J.E., O. Güven, J.G. Melville, and S. H. Crim, 2002. "Scour Evaluations of Selected Bridges in Alabama," Highway Research Center 930-490, November 2002, Auburn University, Alabama.
- Curry, J.E., S.H. Crim, O. Güven, J.G. Melville, and S. Santamaria, 2003. "Scour Evaluations of Two Bridge Sites in Alabama with Cohesive Soils," Highway Research Center 930-490R, October 2003, Auburn University, AL

Froelich, David C. *Finite Element Surface-water Modeling System: Two-dimensional Flow in a Horizontal Plane Version 2 Draft User's Manual*. FHWA, U.S. Department of Transportation, 1996.

Güven, O., J.G. Melville, and J.E. Curry, 2001. Analysis of Clear-Water Scour at Bridge Contractions in Cohesive Soils, Highway Research Center IR-930-490, June 2001, Auburn, AL.

Güven, O., J.G. Melville, and J.E. Curry, 2002a. "Analysis of Clear-Water Scour at Bridge Contractions in Cohesive Soils", TRB Paper No. 02-2127, scheduled for publication in 2002 in the Transportation Research Record, National Research Council. Washington, D.C.

Güven, O., J.G. Melville, and J.E. Curry, 2002b. "Analysis of Clear-Water Scour at Bridge Contractions in Cohesive Soils", ICSF-1, pp. 14-33, Texas Transportation Institute, November 2002, College Station, Texas, USA.

McLean, J.P., 2002. "A Numerical Study of Flow and Scour in Open Channel Contractions," Masters Thesis, May 2002, Auburn University, Alabama.

McLean, J.P., O. Güven, J.G. Melville, and J.E. Curry, 2003. "A Two Dimensional Numerical Model Study of Clear-Water Scour at a Bridge Contraction with a Cohesive Bed," Highway Research Center 930-490, April 2003, Auburn University, Alabama.

Richardson, E.V., and Davis S.R., 1995. "Evaluating Scour at Bridges," 3rd Edition, Report FHWA-IP-90-017, *Hydraulic Engineering Circular No. 18 (HEC-18)*, Federal Highway Administration, Washington, D.C.

Aerial Photographs and Topographic Maps- USGS Sponsored Web Site
www.terraserver-usa.com