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EVALUATION OF SCOUR POTENTIAL OF COHESIVE SOILS – PHASE 2

Submitted to

The Alabama Department of Transportation

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16 Abstract

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Abstract

Determination of erosion parameters in order to predict scour depth is imperative to designing safe, economic, and efficient bridge foundations. Scour behavior of granular soils is generally understood, and design criteria have been established by the Federal Highway Administration. The same is not true for cohesive soils, and because of their complexity, a universal scour prediction method has not been established by the industry. The Erosion Function Apparatus (EFA) was created to determine the rate of scour of cohesive soils under known shear stresses, which can then be used to predict scour depths under similar conditions.

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Chapter 1. Introduction

1.1 Background

In 2009, according to the Federal Highway Administration (FHWA), there were approximately 603,000 bridges in the National Bridge Inventory. Of these 603,000 bridges, roughly 83 percent span water (Lagasse et al. 2007). With such a high volume of bridges crossing water, scour can be a major concern with accelerated flow conditions such as flooding. Between 1961 and 1976, over 50 percent of the 86 major bridge failures were due to scour (Murillo 1987). More recently, from 1989 to 2000 just over fifteen percent of all bridge failures were due to scour (Wardhana and Hadipriono 2003). From these numbers it is evident that scour is a serious issue in bridge design and maintenance. When scour does occur, remediation measures are extremely costly, due to potential instabilities in the bridge and river bed, as shown in Figure 1-1. Estimates of scour are an important step in the bridge design process, as the estimated depth of scour is a driving force in the foundation system selection and penetration depth.

Figure 1-1. Example of Bridge Scour

Current scour predictions of highway bridges are made using techniques reported in Hydraulic Engineering Circular 18 (Richardson and Davis 2001), abbreviated as HEC-18, and Hydraulic Engineering Circular 20, or HEC-20 (Lagasse et al. 2001). These reports, published by the FHWA, estimate scour depth based on four major variables: channel configuration, stream velocity, soil grain size, and underlying bed material. It is important to note that the methods defined in HEC-18 and HEC-20 were based on predicting scour in cohesionless bed material. Alternatively, it is believed that the variables leading to scour in HEC-18, predominantly grain size, do not translate into accurately predicting scour in cohesive soils. Much work has been completed pertaining to predicting the rate and magnitude of scour of cohesive soils, most notably by Briaud et al. (1999, 2001a, 2001b, 2004). The Erosion Function Apparatus (EFA) was created by Briaud's research group, with the purpose of determining the rate of scour of cohesive soils.

The EFA uses a pump and a flume to create a constant flow, and corresponding shear stress, which is exposed to a one millimeter protrusion of soil. Determining the erosion rates of this one millimeter protrusion at different velocities, or bed stresses, creates an erosion function. This erosion function is then used in accordance with Briaud's Scour Rate in Cohesive Soils (SRICOS) method to predict the maximum depth of scour over flooding events (Briaud 1999). The erosion rates created from the EFA are determined using a viewing window in the flume of the EFA. An observer determines when the volume of the one millimeter protrusion has eroded and records a corresponding time stamp.

Accurate scour predictions are a major contributing factor to the economic foundation design of bridges crossing bodies of water. The depth of scour is a portion of the total depth of foundation needed to provide capacity to carry the bridge loads. If the depth of scour is overpredicted, the foundation length and construction costs of the bridge are unnecessarily increased. This principle is the driving idea for better predictions of scour depth in cohesive soils. This concept is directly tied to the SRICOS method as it is a relatively accepted method for predicting scour and is approved by the Federal Highway Administration.

1.2 Objectives

The objectives of the study were

- Conduct EFA tests on cohesive soil samples that were collected from locations below the fall line in the coastal plain of Alabama,
- Develop erosion functions for the soils tested, and
- Determine if measured scour parameters correlate with common geotechnical parameters such as shear strength, Atterberg Limits, grain size, or Standard Penetration Test N values.

1.3 Scope of Study

The scope of work included the following tasks:

- Update the Auburn University EFA with an ultrasonic sensor that can volumetrically measure the mass of eroded material at any point during testing. It is believed that this would add validity to current erosion testing practices,
- Create a testing regimen that incorporates the new updated EFA,
- Obtain samples from cohesive soil formations in the coastal plain of Alabama with the assistance of the Alabama Department of Transportation (ALDOT),
- Perform EFA tests to determine erosion functions,
- Developing means for incorporating swell rate of soils into scour evaluation, and
- Perform geotechnical index tests to determine geotechnical parameters.

1.4 Report Outline

Introduction of the study is given in Chapter 1. An in-depth literature review of bridge scour and determining scour rate of cohesive soils is presented in Appendix A. Chapter 2 provides more details of updated EFA at Auburn University featuring ultrasonic sensor consisting of 12 transducers. The verification of sensor operation and testing procedure (24 steps given in the section 2.4.2) are presented. It includes the information of sample procurement using the Central Mining Equipment's Continuous Sampling System. Based on previous work at Auburn

University, a testing regimen (system) was created to include six different testing velocities (0.3 m/s, 0.6 m/s, 1.0 m/s, 1.5 m/s, 2.0 m/s, and 3.0 m/s). Standard methods for geotechnical testing were presented in Chapter 2 also.

Chapter 3 presents summary of testing results with detailed information in Appendixes B and C. It first provides sampling overview, sampling observations, summary of nine soil formations tested (Table 3-1). The EFA testing observations indicate sample swelling prevalently observed throughout EFA testing. The data analysis of scour rates using detailed soil-column height change with time obtained from ultrasonic sensor is presented to consider both erosion and swelling of soil sample. Detailed results for each soil formation and each testing velocity are given in Appendix D. The EFA testing results first summarize three scour resistant chalk formations tested during the study, and erosion functions for other six clay formations are presented. The critical velocities and initial erodibility are summarized and analyzed. Finally, geotechnical and scour parameter correlations were discussed and presented at the end of Chapter 3. Chapter 4 provides summary, conclusions and recommendations of the study.

Appendix A provides more information on EFA originally created by Briaud's research group and the erosion function developed through EFA testing. The information of alternatives to EFA such as the Rotating Erosion Test Apparatus and the Sediment Erosion Rate Flume with the ultrasonic transducers developed by Sheppard's research group at the University of Florida is discussed in Appendix A. Previous scour research using EFA at Auburn University and by other researchers are summarized.

Appendixes B and C provide detailed information on sampling, EFA testing, and geotechnical testing of soil formations studied in Phase I (Appendix B) and Phase II (Appendix C) testing. These two appendixes provide information of location and depths of soil samples collected and any sampling difficulties encountered during sampling. Detailed observations and results of all EFA testing replicates at different velocities are provided.

Appendix D provides tables showing results of data analysis from EFA testing data of all scourable formations tested at different flow velocities. Each table includes total swelling and erosion (scour) depths (mm), overall or average sour rate (mm/min and mm/hr) considering both erosion and swelling, maximum and minimum scour and swelling rates (mm/hr) of the sample during each replicate test. The approach to determine overall scour rates considering both erosion and swelling at different testing velocities is discussed in the section 3.3.2.

Chapter 2. Testing Equipment and Procedure

2.1 Erosion Function Apparatus

Briaud (1999) constructed the first model of the EFA at Texas A&M University to determine quantitative data related to scour rate and magnitude of different soils. Incorporating the work of Sheppard et al. (2005), Auburn University retrofitted the device to include an ultrasonic sensor for measuring the change in specimen height. Figure 2-1 shows a picture of the updated EFA at Auburn University and its critical components.

Figure 2-1. Auburn University EFA and Critical Component Diagram.

Table 2-1 lists the critical components of Auburn University EFA and gives the primary purpose of these features. The ultrasonic sensor (shown in Figure 2-1A) will be explained in greater detail in the section 2.2.

The pump intake is located at the bottom of a water reservoir on the back side of the apparatus. This reservoir, shown in Figure 2-2, is filled prior to testing. During a test a water hose is constantly supplying water to the reservoir while a sump pump is constantly pumping water out of the system. This continuous water supply is needed to control the temperature of the water in the system as the constant use of the main pump causes an undesired increase in temperature over time.

Table 2-1. Critical Components of Auburn University EFA.

Label	Component Name(s)
A	Observation Window and Ultrasonic Sensor
B	Main Pump and Flow Control Valve
C	Machine Leveling Jack
D	Flow Meter and Temperature Sensor
E	System Control Board
F	Manual Crank Wheel, Automated Stepping Motor, Sample Piston

Figure 2-2. EFA Reservoir with Water Circulation to Control Water Temperature.

Despite these efforts for temperature regulation, the temperature of the water still increases in a few degrees. As will be explained later, the ultrasonic sensor measurements for specimen height are affected by changes in water temperature. Therefore, a thermistor, shown in Figure 2-1D, is used to record the temperature of the water so that a correction may be applied to the ultrasonic sensor readings.

Although the maximum flow velocity tested in this study was 3 meters per second (m/s), the main pump has the capacity to generate flow rates corresponding to velocities of about 6 m/s. The flow rate can be adjusted by turning the flow control valve counterclockwise to increase the flow and clockwise to decrease the flow. The flow velocity is determined by dividing the flow meter reading by the cross sectional area of the flume. Mobley (2009) calibrated the Auburn University EFA flow meter and concluded that there is up to 10% error in velocity measurements for a flow velocity below 1 m/s. The velocity is monitored at the EFA control station computer. This computer provides the current water temperature in the flume and also allows the technician to operate the stepping motor which forces the sample piston upwards in 0.5 mm increments. Figure 2-3 shows a photograph of this computer as well as a screenshot of the digital readout seen throughout testing.

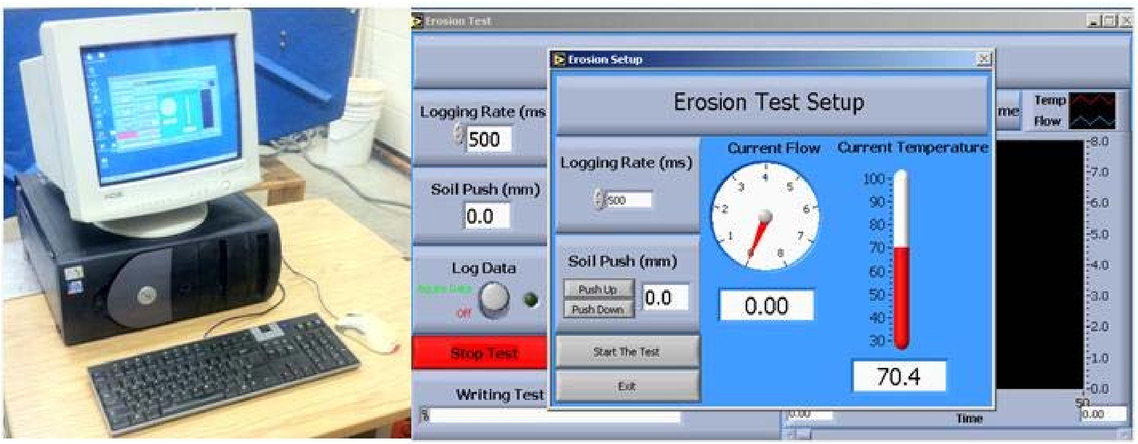

Figure 2-3. EFA Control Station for Advancing Sample and Monitoring Temperature and Velocity.

The stepping motor and sample piston are mounted on a platform which can be raised and lowered with the manual crank wheel. This wheel is used in setting and removing a soil sample before and after tests. In the case of extremely stiff soils (predominantly encountered in this study) the stepping motor was unable to resist the skin friction between the soil and tubing. Therefore, the manual crank wheel was used to advance the sample into the flume.

The system control board has four switches. From left to right, the first three switches are toggle switches to power on/off the entire system, the main pump, and the reservoir sump pump, respectively. The far right switch controls the stepping motor to advance the sample piston progressively rather than incrementally. After a test specimen has been advanced into the EFA flume the sample can be seen through the glass window to make visual observations throughout testing.

2.2 Ultrasonic Sensor

Similar to the work performed by Sheppard et al. (2005) at the University of Florida, an ultrasonic sensor was designed and installed on Briaud's Erosion Function Apparatus. The SERF created by Sheppard et al. (2005) was designed to not only assist in calculating erosion rates, but obtain a pattern of erosion. The ultrasonic sensor on the SERF consisted of 12 transducers. Eight of the transducers are used in measuring scour of a 73 mm sample, while all twelve transducers are used in measuring scour of a 95 mm sample. The design criteria for the EFA ultrasonic sensor was to create a similar array of transducers that will measure scour in cohesive soils, instead of rock, and consist of a tight grouping of transducers creating a clearly mapped soil surface. This ultrasonic sensor was designed and created with the help of Seatek and consists of 16 transducers mounted on a stainless steel housing. A schematic of the ultrasonic sensor designed by Seatek is shown below in Figure 2-4 and a photograph is included as Figure 2-5.

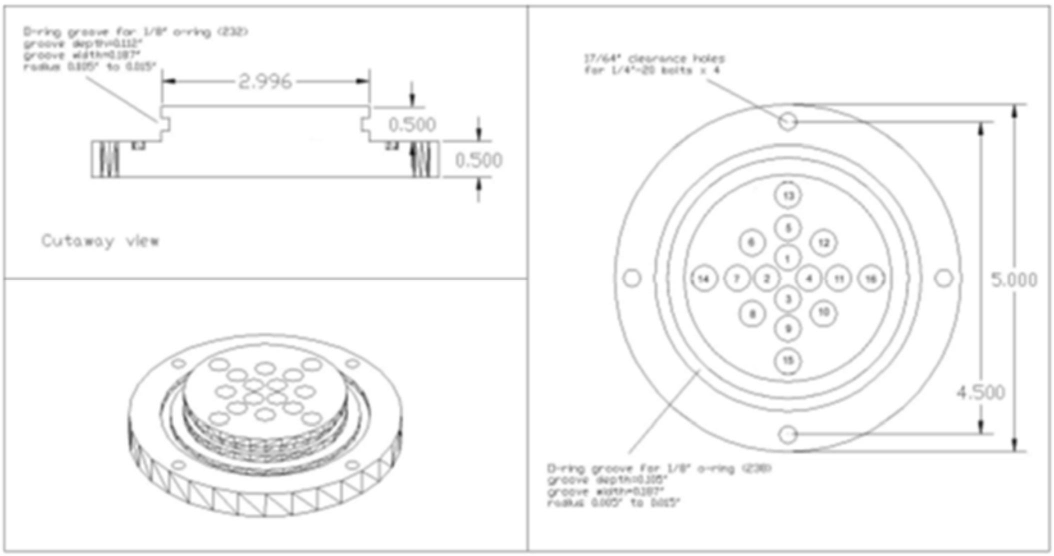

Figure 2-4. Auburn Ultrasonic Sensor Schematic.

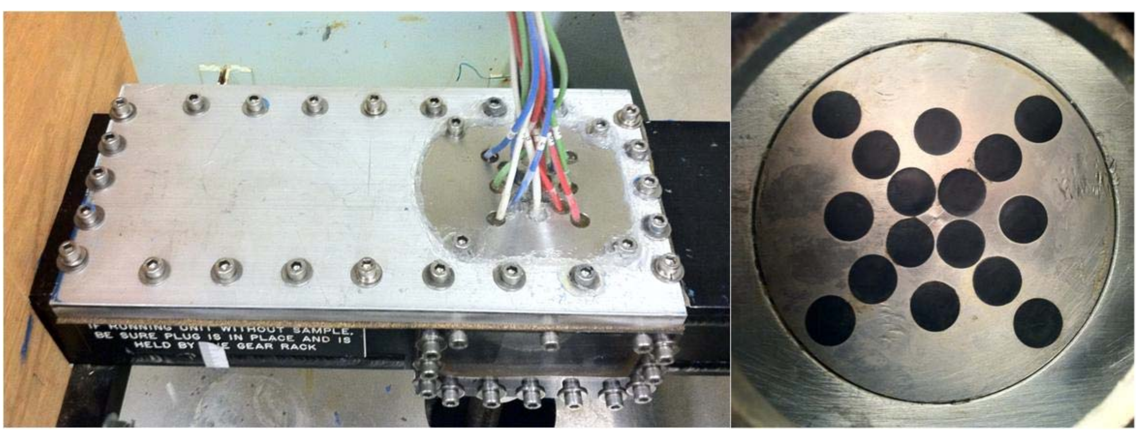

Figure 2-5. Auburn University Ultrasonic Sensor Photographs.

The transducers function at 5 MHz, with a physical diameter of 0.5 cm and an acoustic footprint of 0.8 cm at a distance of 5 cm (Jette 2010). The ultrasonic sensor was set into an aluminum cover, which replaced the original acrylic cover of the EFA. The ultrasonic sensor was sealed to the aluminum cover by using two O-rings. Careful considerations were made to ensure that the ultrasonic sensor was flush with the bottom on the EFA aluminum cover. The ultrasonic sensor could not protrude from the EFA cap, as this would result in irregular flow conditions. The ultrasonic sensor also could not be raised above the EFA cap, as the transducers must be submerged to function properly. The ultrasonic sensor is able to collect data from 16 different points across the area of a Shelby tube soil sample (71.12 mm). Also 12 data points can be obtained from standard rock coring soil samples which is convenient if a soil formation is too stiff to be sampled by pushing Shelby Tubes.

The data acquisition system used to accompany the ultrasonic sensor is capable of collecting data from all 16 transducers, along with the ability to sample up to 4 external analog channels. If any external analog channels are used, the output voltage must range between 0V and 4V. The electronics package is able to communicate via an RS232 (serial) connection. The software used to communicate with the data acquisition system was CrossTalk. CrossTalk is used to set the datalogging parameters for the system and produces an output ASCII text file from the data received that can easily be imported into a spreadsheet. The CrossTalk software and data acquisition system are set up on updated secondary computer that is separate from the computer that acquires the temperature and flow velocity from the EFA.

The ultrasonic sensor designed by Seatek for Auburn University was created with the idea of improving scour measurements taken using Briaud's EFA. However, the 16 transducer ultrasonic sensor did have a few constraints that were addressed before a cohesive soil testing regiment was adopted. As previously stated the bottom of the ultrasonic sensor, where the transducers contact the flow of water, could neither be elevated above the water or protruding into the flow of water. The ultrasonic sensor was originally designed to be mounted on top of the current acrylic cover of the EFA. This preliminary design left approximately a 13 millimeter hole above the flow of water allowing large air pockets to build up around the transducers. It was determined that the acoustic pulsing of the ultrasonic sensor was disturbed by these air pockets resulting in many blank readings. As a result a counter bore was machined into the acrylic cover of the EFA to recess the ultrasonic sensor flush with the bottom of the EFA cover. This design worked in theory, but the acrylic cover did not allow for a waterproof seal to be formed around the ultrasonic sensor. In an attempt to tighten the seal between the EFA cover and the ultrasonic sensor the acrylic in the ultrasonic sensor was cracked allowing more water to leak through the seal. A third EFA cover was designed counter boring the ultrasonic sensor into an aluminum stock plate. The aluminum plate was identical to the original acrylic cover, and strong enough to form a waterproof seal with the ultrasonic sensor.

The installed sensor measured distances using ultrasonic transducers, therefore, temperature effects were considered. The water temperature is an input in CrossTalk; however, the data acquisition system does not allow for any changes in water temperature throughout the duration of a test. This presents an issue as the data acquisition system assumes a certain water temperature in calculating the wave speed which dictates the scanned distance. A six hour continuous test showed that the water temperature in the EFA rose from 26 °C to 54 °C. This temperature change is related to the EFA's pump energy and flume friction. The EFA contains a water tank that is approximately 1.36 cubic meters. To reduce the magnitude of temperature change, water was continuously circulated through the EFA tank. Water was circulated into the EFA tank using a water hose from a spigot, while the water was pumped out by using the EFA's drain and sump pump. During a three hour test with water continuously circulated through the EFA the water temperature ranged from 19.2 °C to 21.3 °C. It is important to keep the water temperature in a reasonable range to mimic stream conditions as closely as possible. Due to the effects of temperature on wave speed, a temperature correction was necessary to overcome the variance in temperature. During a typical test the temperature was set at 20 °C, and a temperature correction was performed during data reduction.

As previously stated, the EFA contained a separate data acquisition system and software package intended to detect and record flow rate and water temperature. It was determined the thermistor installed on the EFA fits the voltage input for one of the analog channels on the ultrasonic sensor data acquisition package. The EFA thermistor readings were correlated as an analog input (voltage) for the ultrasonic sensor.

The thermistor readings were calibrated using a voltmeter and the digital readout from the EFA. The calibration data were then plotted and an equation relating temperature to voltage was derived. The temperature calibration can be viewed in equation 2-1, and an image of the temperature calibration can be viewed in Figure 2-6. The Auburn EFA flow meter was calibrated by Mobley (2009). This calibration was performed manually by measuring the amount of water coming out of the spout of the EFA and comparing it to the velocity shown in the EFA software. Mobley concluded there is up to 10 percent error in velocity readings less than 1.0 meter per second. At higher velocities there is not any appreciable error between the true flow velocity and the measured velocity by the EFA's flow meter.

$$Temp(^{o}F) = 0.1232 \cdot mV - 133.83 \qquad (2\text{-}1)$$

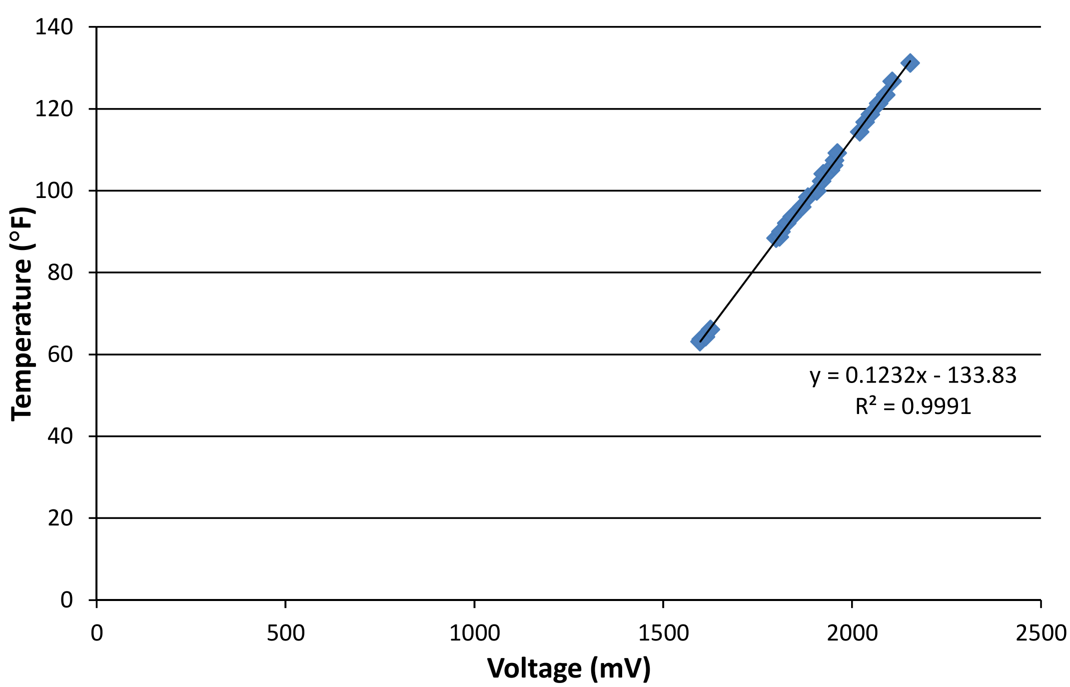

Figure 2-6. Temperature and Voltage Correlation for EFA Thermistor.

2.3 Verification of Sensor Operation

The accuracy of sensor measurements and data reduction was confirmed by testing a non-erodible dummy sample and comparing the results to direct measurements taken. A dummy specimen constructed for this sole purpose, consisted of a 6.35 cm diameter aluminum cylinder that is tested the same as an EFA soil sample. Because the extremely smooth aluminum surface caused erratic and inaccurate measurements from the sensors, a rugged sand surface was applied to the sample face. During this test the specimen is advanced by the motor, held constant for a period of time, advanced again, held steady again, and so on. Throughout the trial the height of the sample is measured directly and compared to height readings generated by the ultrasonic sensor. Figure 2-7 shows the results of a verification test run prior to EFA soil testing.

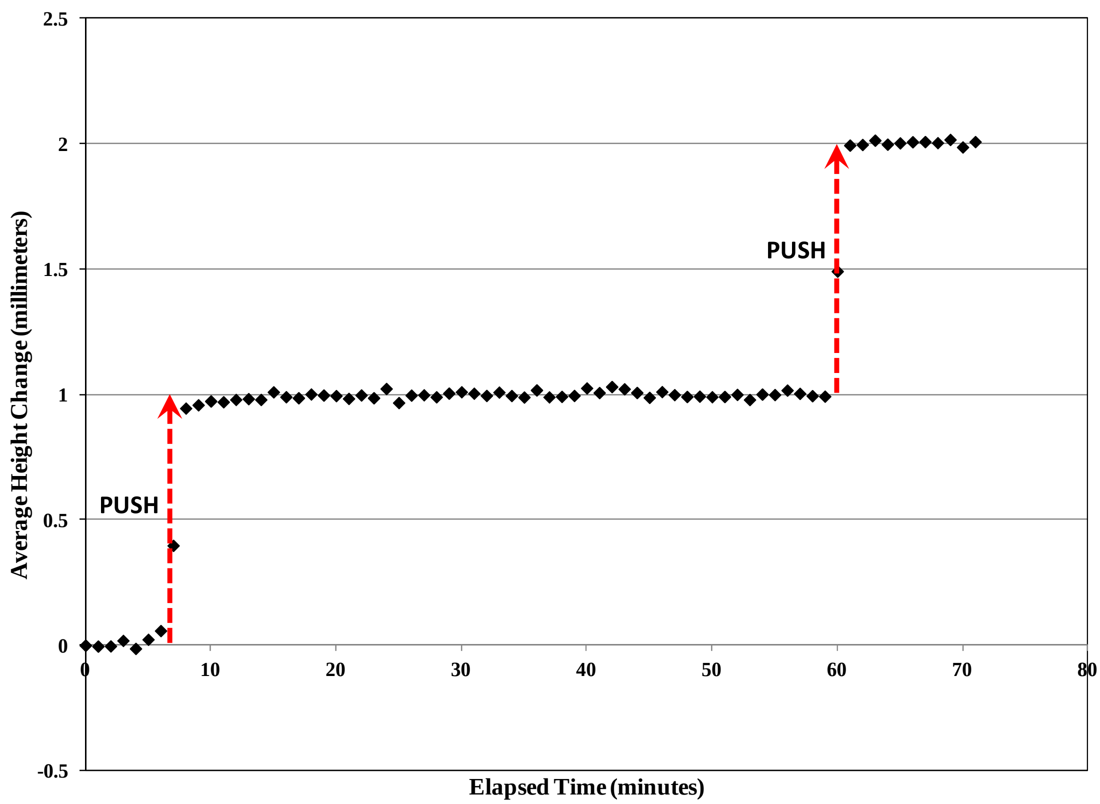

Figure 2-7. Verification of Sensor Operation.

As seen, the reduced data from the ultrasonic sensor is relatively precise and appears to be accurate. The specimen was advanced by the stepping motor on two separate occasions. Each push was exactly one millimeter and the accuracy of the ultrasonic sensor over time can be seen between consecutive advancements as the readings did not waiver far from the 1 and 2 mm gridlines. The very minor variations in height readings, which have a maximum departure from the target height of less than 0.06 mm, are negligible when considering the highly various nature of the soil.

2.4 Testing Procedure

2.4.1 Sample Procurement

Drilling operations were coordinated with ALDOT to acquire cohesive soil samples for testing. ALDOT stated that these hard cohesive soils and chalks would not be conducive to sampling via Shelby Tube. Since the materials to be sampled were so stiff, a typical ATV or truck drill rig would not be able to advance a Shelby tube sample without damaging the tube. Two sampling alternatives were derived to ensure that samples could both be acquired with relative ease and tested using the ultrasonic sensor at Auburn. Option one involved using either 44.5 mm or 47.6 mm rock core samples, while option two involved using 57.2 mm continuous samples, a new sampling method acquired by ALDOT. Preliminary tests were performed with the EFA using rock core samples, and it was determined that the rock core samples were not ideal and should be used as an alternative. This was decided as it was necessary for rock core samples to be completely vertical and plumb or else the samples would not fit into the previously created EFA testing tube. Also, it was determined that short segments could not be used with rock core samples as the flume created a "suction" like force pulling the loose sample towards the ultrasonic sensor. This sample movement upward could not be tolerated as any movement other than scour and planned sample advancements recorded would conflict with the results presented by the ultrasonic sensor.

Therefore, it was decided to sample with the new continuous sampling technique that ALDOT recently acquired. This sampler easily fits onto an ATV or truck mounted drill rig and can be used to acquire undisturbed soil samples in difficult to sample soil formations. The sampling technique involves first drilling down to the sample level with a hollow stem auger. The 1.52 m sampler is attached to either AW or NW threaded drill rod and lowered to the bottom of the hollow stem auger. Once connected the sampler is pneumatically advanced as the hollow stem auger cuts around the obtained soil sample. A sealed bearing assembly conveys the thrust from the drill rig to the tube and sampler shoe while isolating the sample tube from rotation of the auger (CME, 2012). An image of the Central Mining Equipment (CME) continuous sampling setup used is shown in Figure 2-8. A sampling shoe is used to contain the sample in the tubes for a maximum recovery. The sampler itself is a split spoon sampler that includes two acrylic 57.2 mm diameter tubes that are each 762 mm long. Once samples are gathered lids are placed on top and bottom of each sample allowing tubes to be tested and stored separately.

During a typical sampling trip ALDOT geologists located possible drilling sites containing the target formations. ALDOT geologists also determined the depth where the target formation was reached. Once the target formation was confirmed from drill cuttings and split spoon samples, a Standard Penetration Test (SPT) was performed to obtain the SPT N value for each formation. Typically 2–3 standard penetration tests were performed in each formation depending on the approximate depth of the formation provided by the ALDOT geologist. Once the SPT was completed, the AW rod was removed from the boring and a hollow stem auger was used to the depth of the previously drilled hole. Typically a Shelby Tube was pushed inside the hollow stem auger to ensure that any loose cuttings would not be sampled. Sampling was then performed as described above with the CME continuous sampling system. Typically 2–3 continuous samples were gathered in each formation resulting in 4–6 sample tubes. It was believed that obtaining 1.5–2.3 m of each formation would be sufficient for both EFA testing and geotechnical testing. After collection, sample tubes were capped and taped to maintain field moisture conditions. Since EFA and geotechnical testing could take place months after sampling, samples were stored in a curing room to preserve field moisture conditions. Sample tubes were also marked according to depth and formation prior to storage.

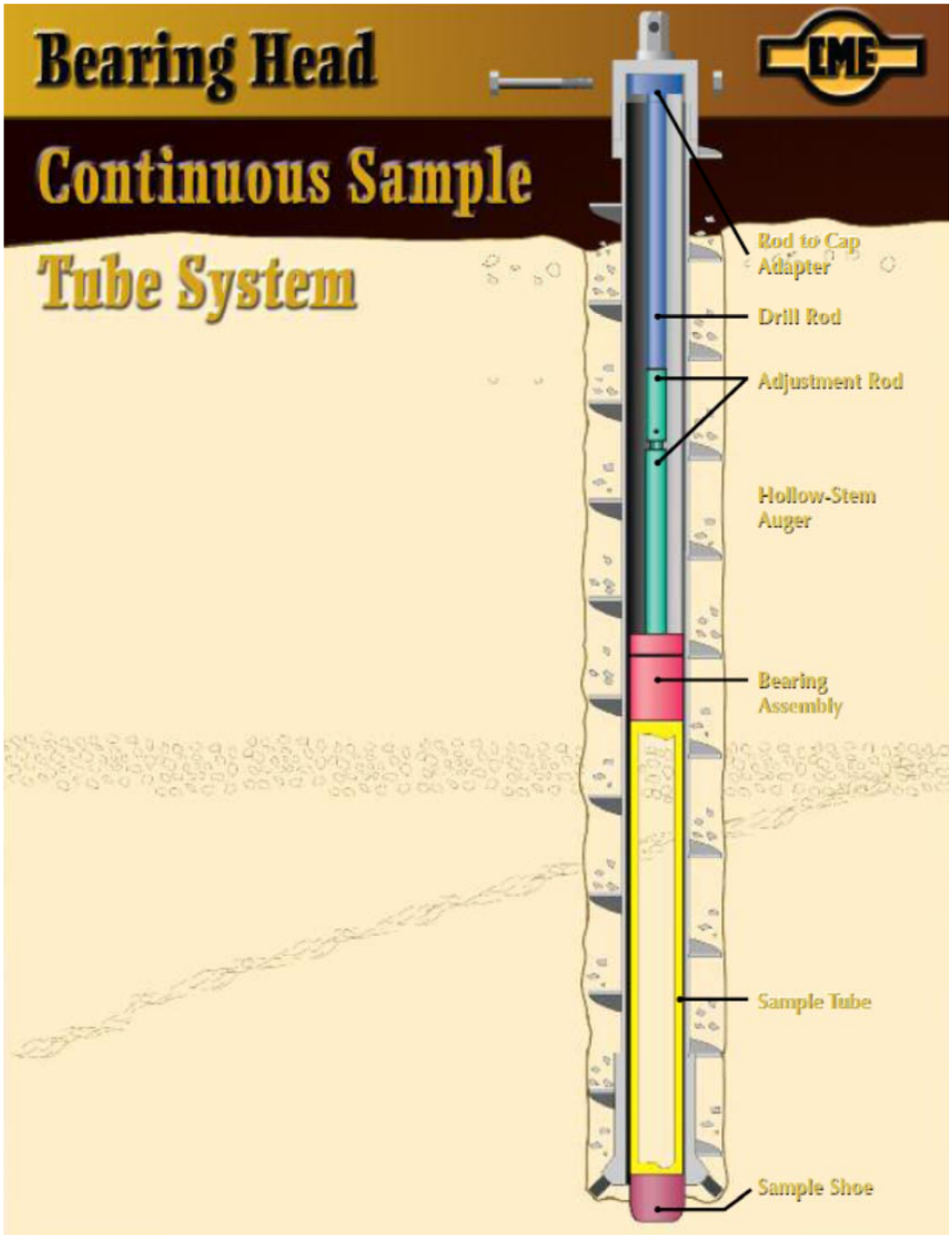

Figure 2-8. CME Continuous Sampling System.

2.4.2 EFA Testing Procedure

Once the EFA test sample was cut, extruded, and cleaned the procedure given below was followed for performing a typical EFA test.

1. The EFA tank was rinsed of any suspended material or debris to clean out the tank.
2. The EFA tank was filled with clean water, approximately 2/3 of the tank height.
3. The drainage valve at the bottom of the EFA was opened to allow water to drain from the EFA tank.
4. The sump pump on the EFA was turned on to assist the drainage valve in draining water from the tank.
5. Once the tank was full, drainage valve open, and sump pump on, clean water was added to the tank. This completed the continuous circulation of clean water in the EFA to control temperature levels.
6. The water level was monitored throughout the testing process to ensure that the water level did not drop below the pump intake or rise within 300 mm of the top of the tank.
7. The blank sample was loaded into EFA, and the pump was turned on. The flow velocity was adjusted to the target testing velocity. This step, suggested by Crim (2003), allowed for velocity to be adjusted between tests without exposing the soil sample to varying shear stresses.
8. Once the target velocity was reached the pump was turned off and the blank sample was removed from the EFA.
9. The prepared soil sample was then loaded into the EFA, assuring that the sample tube was flush with the lip of the base plate of the flume.
10. Using the stepping motor, the sample was advanced through the base plate until the sample is level with the base of the flume. Figure 2-9 shows the soil plunger being pushed against the base of the soil sample, and Figure 2-10 shows the sample pushed level with the base of the flume.
11. The CrossTalk program was started, connection settings entered, and the script dialog box was completed. It is important to note that this step occurred before the flume was started. Also it is important the CrossTalk script was simply set-up and not started, as blank scans at the beginning of a test would interfere with data reduction.
12. The EFA pump was started and the water velocity was allowed to accelerate until the target velocity was reached.
13. The CrossTalk script was quickly started by pressing “OK” on the Script Dialog Box and naming the data file according to the sample being tested. It is important that this step be started immediately after the flume fills with water, as any soil mass lost before the CrossTalk script was started would not be recorded.
14. Depending on the scour characteristics of the soil being tested, the Crosstalk script was usually allowed to run approximately three minutes with the soil sample level with the base of the flume. This step was essential is establishing a clear baseline before the sample was advanced and allowed to scour. However, when testing at high velocities that resulted in higher scour rates this amount of time was reduced to 1.5 minutes to ensure the soil mass did not scour prior to being advanced.
15. The sample was advanced 1mm into the flume using the EFA software. Figure 2-11 shows a sample advanced into the flume.

16. Throughout the entire test, scour behavior was visually monitored and recorded to verify the results provided by the ultrasonic sensor. Scour was also visually monitored to determine any trends in the scour mechanism of each formation tested.
17. Once the data acquisition system and EFA test were running smoothly, the real time data reduction Excel spreadsheet template was started. It is important to note that this step is not necessary as data reduction can be performed with the created data file after the test is completed. However, one of the benefits of CrossTalk software and data acquisition system is that data can be reduced in real time and scour results can be presented complimentary to visual confirmation. The Excel sheet was set to refresh the data from the text file every 2 minutes in order to monitor scour in real time.
18. Scour was monitored in the “Erosion Height Change” tab of the Excel template sheet. Typically the 1 mm push and subsequent scour was clearly visible. Once the “Erosion Height Change” tab showed erosion totaling 1 mm the test was ended. Again it was important to visually confirm that 1 mm of scour occurred before stopping the CrossTalk software or the EFA pump.
19. Once erosion occurred and the test was completed, the CrossTalk software was stopped by pressing “Control-C”. The EFA pump and the water supply were stopped once the test ended.
20. The water was allowed to drain from the flume before the sample was removed from the base plate of the EFA. The sample surface was cleaned similarly to the method described in the “Sample Preparation” section. This action was necessary to ensure that water did not percolate through the sample over time compromising future tests from being performed at field conditions.
21. Once the sample surface was cleaned and level with the sample tube the sample was capped, sealed with tape, and placed back into the curing room until the next EFA test was performed.
22. The EFA was drained and rinsed of any debris that resulted from erosion testing. It was important that the amount of suspended soil particles in the EFA were minimized as erosion could result by the collision of particles in future tests.
23. The erosion rate for each test was determined by dividing the height of erosion (1 mm) by the amount of time it took to achieve the height of erosion. This could be clearly mapped using the Excel data reduction spreadsheet.
24. The CrossTalk text file and the Excel data reduction spreadsheet were saved with the title of each test so that any additional post processing could be performed if necessary.

Figure 2-9. Soil Plunger Advancing Sample.

Figure 2-10. Soil Sample in EFA Level with Base of Flume.

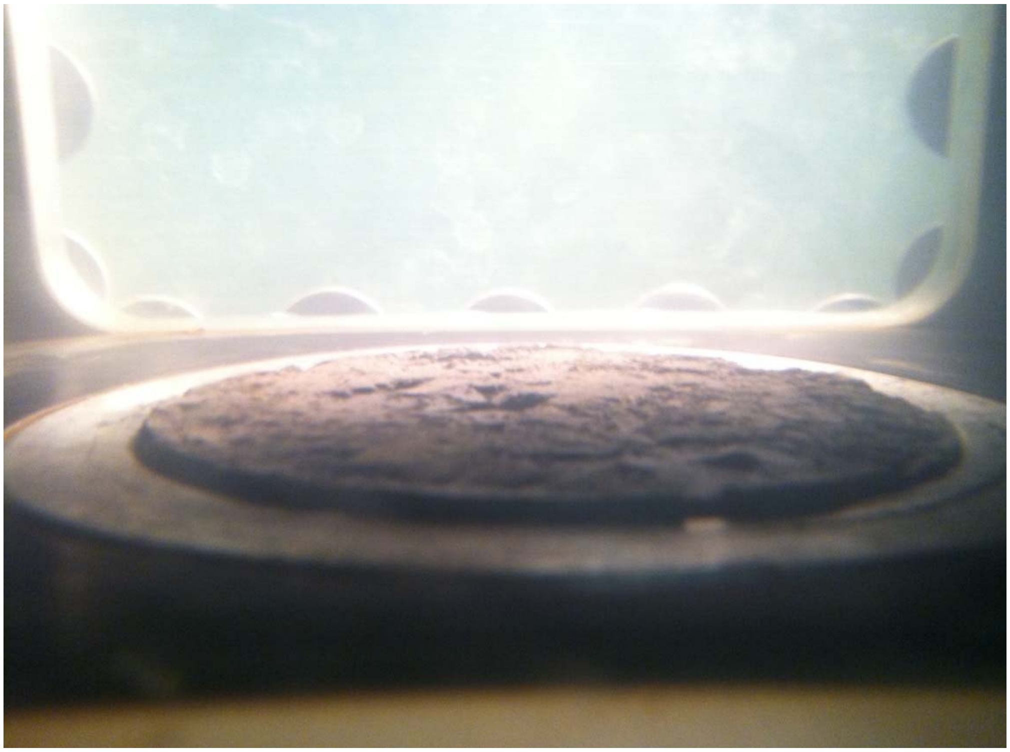

Figure 2-11. Soil Sample in EFA Advanced 1 mm.

2.5 Testing Regimen

Based on the original EFA reports by Briaud et al.(1999), previous work at Auburn University (Crim 2003, Mobley 2009), and the maximum stream velocity expected in Alabama rivers, a testing system was created to include six different testing velocities. These EFA testing velocities include 0.3 m/s, 0.6 m/s, 1.0 m/s, 1.5 m/s, 2.0 m/s, and 3.0 m/s. Typically a formation was first tested at 0.3 m/s and the velocity was gradually increased until scour occurred. A formation was considered to resist scour at a certain velocity if scour did not occur with one hour of testing. After it was determined that a given formation was scour resistant at a certain velocity, the velocity was increased to the next higher velocity. Once scour occurred at a given velocity, numerous tests were performed at each of the remaining testing velocities so that averages could be established. Typically a minimum of three EFA tests were performed at each velocity step greater than the threshold velocity related to the critical shear stress. The amount of tests performed at each velocity was dependent upon the amount of testable soil recovered during sampling.

After testing was completed across all of the testing velocities a threshold velocity test was performed to determine the velocity that correlates to the critical shear stress. This test was started by exposing the soil sample to the highest velocity that did not show any sign of erosion. The flow velocity was then steadily and carefully increased until scour started. Once scour started the velocity was recorded and used as the threshold velocity in the creation of erosion functions.

If a formation was determined to be resistant to scour at all of the listed EFA testing velocities, a multiple events test was performed. This test attempted to model the performance of a formation against changing shear stress cycles. For the purposes of this research, the multiple events test included running an EFA test on a sample for one hour at 3.0 m/s, reducing the velocity to 1.0 m/s for 30 minutes, and increasing the flow velocity to 3.0 m/s for another hour. The multiple events test was not performed on any formation with a threshold velocity less than 3.0 m/s. It was determined that adequate scour data could not be collected on a sample that had already scoured 1 mm and was simply advanced another millimeter. In previous work at Auburn University (Mobley, 2009) it was noted that scour in cohesive soils does not occur in a uniform fashion. Therefore advancing a sample 1mm after it has already eroded would not expose an even shear stress across the plane of the sample as some of the test specimen would be higher than the necessary 1 mm and parts of the specimen would be lower than the necessary 1 mm.

2.6 Geotechnical Testing

Several geotechnical tests were performed on each tested formation in order to derive correlations between scour and conventional geotechnical parameters. The geotechnical parameters determined included: SPT N-value, insitu moisture content, percent passing the No. 200 sieve (% 200), mean grain size diameter (d_{50}), liquid limit (LL), plastic limit (PL), and plasticity index (PI). Although it was planned that an unconfined compressive test be conducted on the samples there was insufficient material to run the test on any of the formations.

As previously mentioned, SPT N-values were determined from SPT tests conducted in the field by the ALDOT drilling crew. Prior to an EFA test a small portion of soil was taken from the sample to determine the insitu moisture content. The material remaining after EFA testing was used for grain size analyses (to determine % 200 and d_{50}) and Atterberg limit testing (to determine LL, PL, and PI).

The insitu moisture content was determined according to ASTM D2216 – 10 standards and all grain size analyses of the formations were determined according to the ASTM D422 – 63 standards (ASTM 2007b). Atterberg limit testing was performed according to the ASTM D4318 “Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils” (ASTM 2010b).

Chapter 3. Testing Results and Discussions of Different Formations

3.1 Sampling Overview

Since scour research commenced at Auburn around 2001, ALDOT has provided samples of various soils throughout the state of Alabama for scour analysis. With the exception of Talladega County, all samples were procured from sites south of the fall line where ALDOT is most concerned about bridge scour. Figure 3-1 shows the drilling locations for samples tested from 2001 to 2009 (Crim 2003 and Mobley 2009) and the current study.

Soils tested for this study were located in the southern and western portions of Alabama, specifically in the coastal plains and prairies. Borehole samples collected for this study are shown as red and black points in the Figure 3-1. Soil formations tested are listed in Table 3-1 including sampling date and county, geotechnical test results, related EFA testing information. This study included samples taken in the summer of 2012 (Bucatunna clay, Yazoo clay, Demopolis Chalk, Mooreville Chalk, Prairie Bluff Chalk, Porter's Creek clay, Nanafalia clay, Naheola clays, and Clayton clay), and the summer of 2013 (re-drilled Bucatunna clay, Naheola clay, and Porter's Creek clay). Re-drilled Bucatunna clay on 8/8/2013 in Choctaw County did not contained EFA testable samples, therefore, it is listed in Table 3-1.

EFA testing was conducted in two phases. Phase I included Bucatunna Clay, Yazoo Clay, Demopolis Chalk, Mooreville Chalk, Prairie Bluff Chalk, and Porter's Creek Clay. Nanafalia Clay, Naheola Clay, and Clayton Clay were tested in Phase II along with re-drills or verification tests of Bucatunna, Naheola, Porters's Creek, and Yazoo Clays. Detailed information of sampling each soil formation by the ALDOT drilling crew was presented in Appendix B for Phase I and Appendix C for Phase II.

3.2 Sampling Observations

As stated in Appendix B and Appendix C, nine clay and chalk formations from the coastal plains in southern Alabama were sampled using the Central Mining Equipment continuous sample tube system (Figure 2-10). The quality and consistency of the acquired samples varied between formations. Ideally the samples gathered would serve three purposes and be used for EFA testing, shear strength testing, and geotechnical index testing. All samples were successfully used for EFA testing in two testing phases.

The clay formations tested in the EFA were easier to test than three chalk formations. It appeared the very stiff chalk formations created a high amount of skin friction between the sample and the acrylic tube. At times this skin friction was too large for the sample to be automatically advanced using the stepping motor on the Erosion Function Apparatus. In these cases EFA testing was not ideal because the protrusion into the flume was not consistent with the calibrated one millimeter protrusion set forth in Briaud's (1999) procedure. The clay samples acquired, the Bucatunna Clay, Yazoo Clay, and Porter's Creek Clay formations, were able to be EFA tested without any difficulties.

The samples acquired, using the CME continuous sampler, were successfully used for geotechnical index testing. Samples were extruded from the sample tubes and processed for testing. However, the samples acquired were not conducive for shear strength testing. Given the cohesive material used for this study, the unconfined compression test is ideal for shear strength testing. With the diameter of the continuous sample being 57 mm, an acceptable unconfined compression sample would need to be at least 114 mm. Unfortunately the sampling method did not yield uncracked samples with a minimum length of 114 mm. Therefore, it was not possible for an unconfined compression test to be performed on any of the acquired samples.

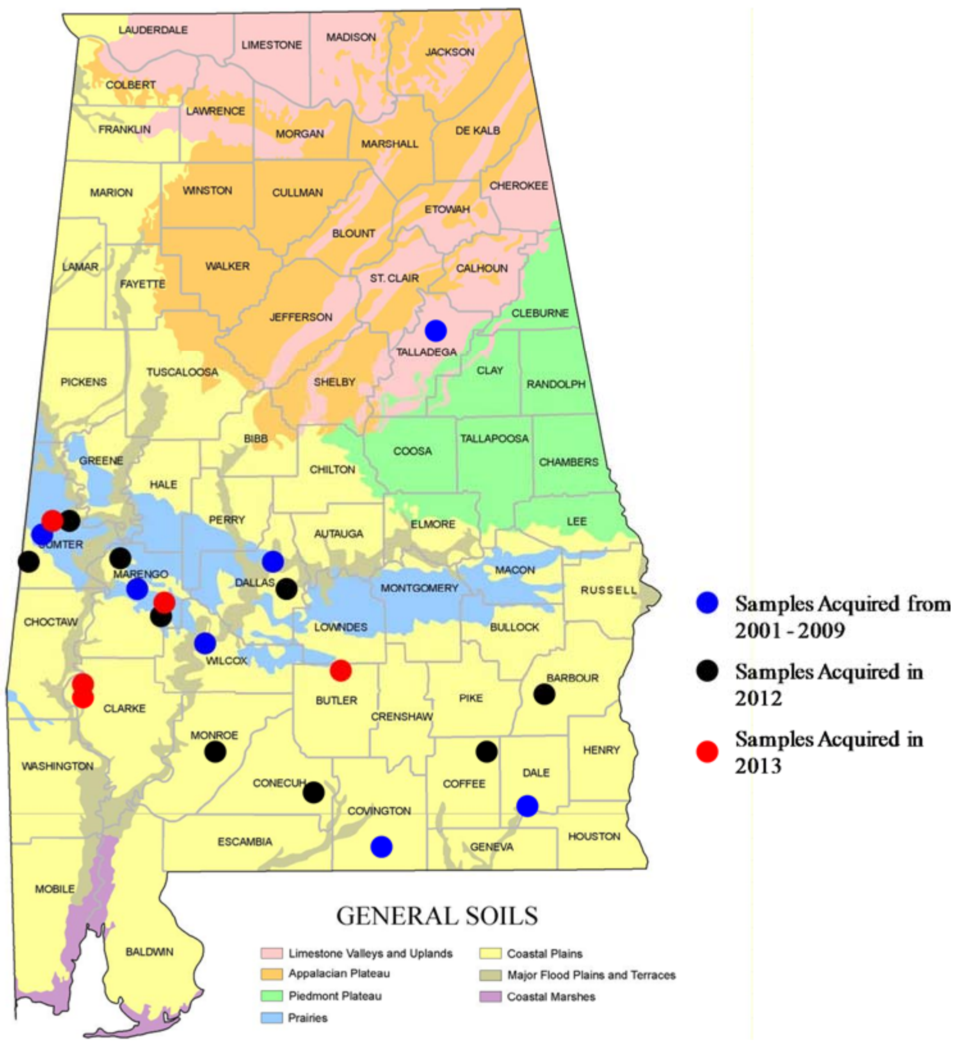

Figure 3-1. ALDOT Drilling Locations for Auburn University Scour Research.

Table 3-1 Nine Soil Formations Tested Using Updated EFA at Auburn Univeristy.

Formation	Sampling Date	County	Scourable	LL	PL	PI	D_{50} (mm)	% Passing #200	USCS Classification	AASHTO Classification	SPT N Value	Average Moisture	Pushable	Swelling Witnessed
Bucatunna Clay	4/15/2012	Monroe	Yes	68	39	29	0.0330	65	MH (Sandy Elastic Silt)	A-7-5(20)	9	47.9	Yes	Yes
Yazoo Clay	4/6/2012	Conecuh	Yes	57	NP	NP	0.0880	44	SM (Non-Plastic Silty Sand)	A-5(0)	15	59.9	Yes	No
Demopolis Chalk	5/5/2012	Sumter	No	37	27	10	0.0021	97	CL (Lean Clay)	A-4(11)	92	21.8	No	No
Mooreville Chalk	4/30/2012	Dallas	No	52	25	27	0.0024	92	CH (Fat Clay)	A-7-6(28)	60	23.4	Yes/No	No
Prairie Bluff Chalk	5/1/2012	Marengo	No	32	19	13	0.0028	82	CL (Lean Clay with Sand)	A-6(10)	86	17.7	No	No
Porter's Creek Clay	5/1/2012	Sumter	Yes	62	53	9	0.0082	90	MH (Elastic Silt)	A-5(16)	30	35.7	Yes	Yes
Porter's Creek Clay (Re-drilled)	8/5/2013	Marengo	Yes	114	40	74	0.0010	97	CH (Fat Clay)	A-7-5(88)	13	43.6	Yes	Yes
Clayton Clay	6/21/2012	Barbour	Yes	41	25	17	0.0230	76	CL (Lean Clay)	A-7-6(13)	23	51.4	Yes	Yes
Nanafalia Clay	6/6/2012	Coffee	Yes	42	25	18	0.0800	47	SC (Clayey-Sand)	A-7-6(5)	13	24	Yes	Yes
Naheola Clay (Yellow)	6/7/2012	Marengo	Yes	45	33	12	0.0280	91	ML (Silt)	A-7-5(14)	16	31	Yes	Yes
Naheola Clay(Dark)	6/7/2012	Marengo	Yes	61	25	35	0.0160	99	CH (Fat Clay)	A-7-6(41)	16	34	Yes	Yes
Naheola Clay (Re-drilled)	6/18/2013	Sumter	Yes	36	24	12	0.0440	61	ML (Silt)	A-6(6)	5	33	Yes	Yes

Note: Re-drilled soil samples in 2013 are listed separately, and Naheola Clay is listed separately for yellow and dark materials.

During sampling it was noted that most if not all of the uncracked sections acceptable for use in EFA testing were located in the bottom half of the acrylic sampling tubes. It is thought that this was due to friction being created between the cohesive surface of the sample and the acrylic sample tube as the sampler was advanced during sampling. It appeared that after a certain length the sampled material began to fail in friction and crack vertically within the sampling tube. This would explain the bottom of the samples being uncracked, as this segment of sample would be exposed to small or negligible frictional forces along the edges of the sample. This cracking was nominally improved by spraying a lubricant inside the sample tubes, although the effectiveness of the lubricant varied depending on the stiffness of the formation being sampled. Another issue associated with the cracking of sampled material is that the bearing assembly was not always successful in keeping the sample tube isolated from the rotation of the drill rig. This could expose the sample to torsional and shear forces during sample, which would be evident by the cracks in the recovered sample. This also could compromise the undisturbed state of the sample specimen. It is important to note this was not always the case and was only observed when sampling very stiff formations.

Another issue observed during sampling of the chalk formations was the bowing of the sample tube assembly. In these cases it appeared as if the acrylic sampling tubes were heated, due to the friction of material, allowing the tube to yield and expand radially. This too could question the undisturbed state of the obtained samples. Also the bowing of the sample tube made it difficult to test these samples in the EFA, as the opening in the flume of the EFA is equal to the diameter of the sample tube.

3.3 EFA Testing Observations

3.3.1 Sample Swelling

Ten formations were tested in the study including the Bucatunna Clay, Yazoo Clay, Demopolis Chalk, Mooreville Chalk, Prairie Bluff Chalk, Porters Creek Clay, Nanafialia Clay, Naheola Clay, and Clayton Clay. Detailed information of EFA testing for each soil formation is given in Appendix B for the Phase I testing and Appendix C for phase II testing, which include scour rates for each tested soil formation at different test replicates at different flow velocities summarized in separate tables (e.g., Tables B-1 and B-2 for Bucatunna Clay).

Swelling was prevalently observed throughout EFA testing. Frequently there was considerable scouring that occurred during a test but excessive swelling would result in the sample actually becoming taller over the test duration. In other words, the net change in specimen height measured by the ultrasonic sensor (i.e. initial specimen height – scour + swell) would be positive at the end of the test. In most cases the onset of swell would occur in phases, as would scour. The sample would begin to swell, then scour would occur while swelling subsided; scour would steadily come to a halt and swelling would pick up again. This was referred to in Appendixes B and C as the "scour-swell" pattern. When the samples were first exposed to water the top of the samples became saturated, causing the sample to swell. Eventually the increased specimen height resulted in excessive shear stress on specimen, causing the sample to scour. When the sample scoured, virgin or non-saturated soil was exposed, causing the sample to soak in additional water and swell again. Because this pattern was so commonly seen throughout testing, it was decided that erosion rates be determined from the events in which scour occurred, referred to as “scour events” in the results, rather than from the net change in specimen height over the test duration. This pattern is illustrated in Figure 3-2. Photographs corresponding to points 1 through 5 are shown in Figure 3-3.

The tested formations had relatively high plasticity indices. Swelling is known to be more significant in high plasticity clays. Of all the materials, the Porter’s Creek clay experienced the greatest magnitude of swell. As expected, the Porter’s Creek material also had the highest plasticity index. The liquid limit, however, appeared to be the determining factor on whether or not the clay would experience large amounts of swelling. It was observed that materials having a liquid limit of 45 or greater were highly susceptible to swell. The formations experiencing the most swelling were the Porter’s Creek, Yazoo, Dark Naheola, and Bucatunna clay, and those materials had liquid limits of 114, 57, 68, and 61, respectively.

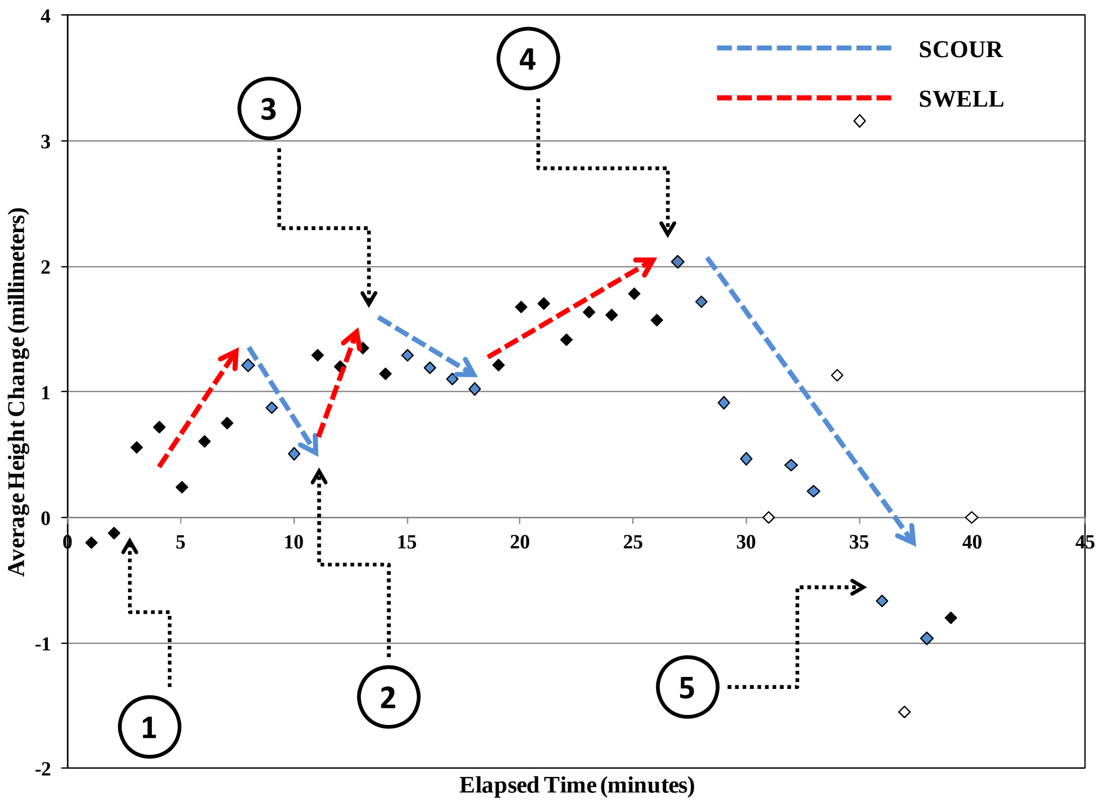

Figure 3-2. Scour-Swell Pattern from Porters Creek 24.5_1 EFA Test.

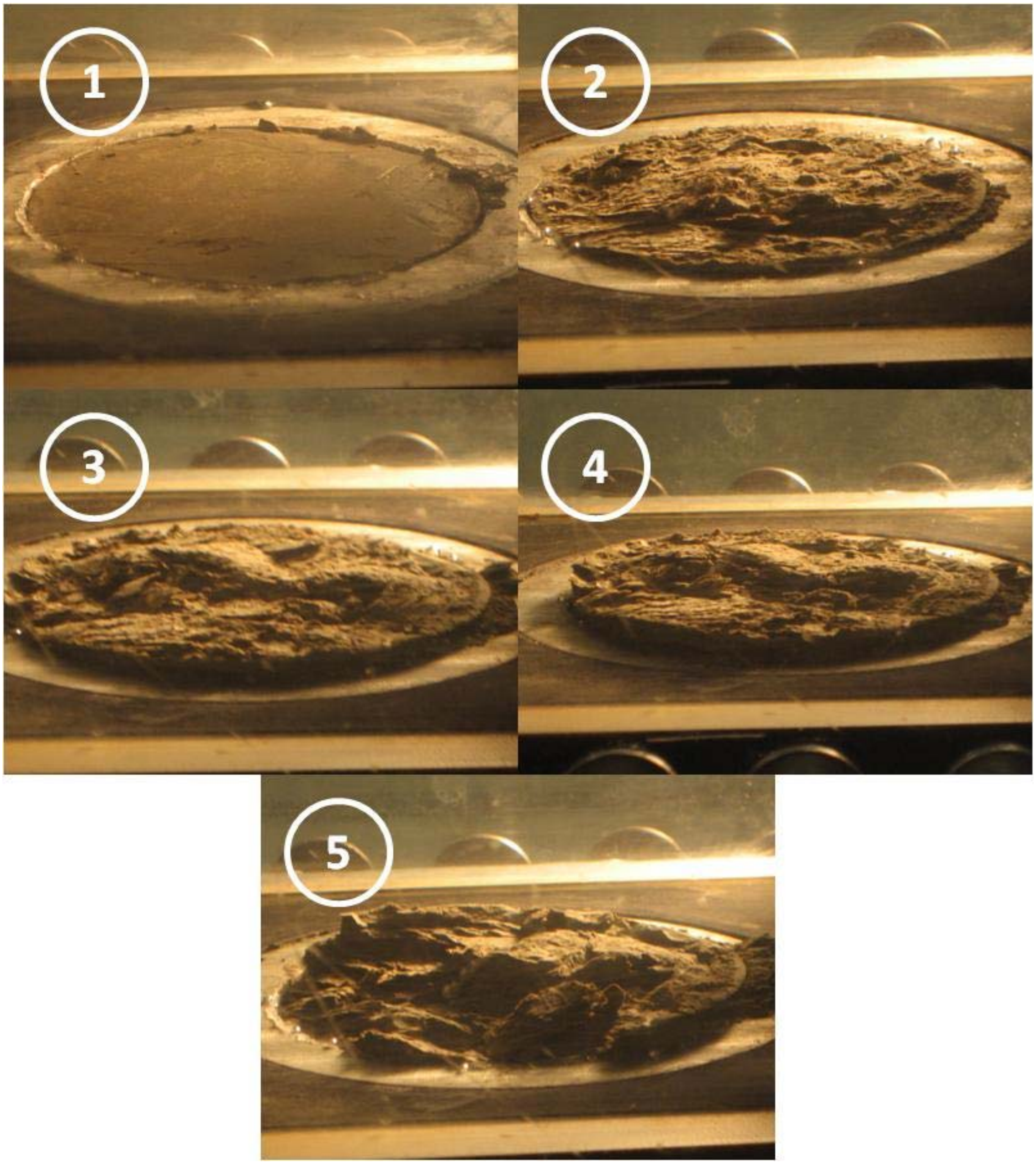

Figure 3-3. Photographs Taken at Critical Points During Porters Creek 24.5_1 EFA Test.

3.3.2 Data Analysis of Scour Rates

Using the ultrasonic sensor, average height changes from 16 transducers were recorded for every 15 seconds, and then average height changes per minute were derived to determine the scour rate for each EFA test. Two examples of average height changes per minute versus time are given in Figure 3-2 for Porters Creek clay and Figure 3-4 for Buccatunna clay. Figure 3-4 shows that the new sensor technology allowed us to detect the erosion (decreasing the soil-column height) and swelling (increasing the soil-column height) rates in each minute. During the Phase I of the study (Appendix B, (before September 2012; EFA tests were done by graduate student Mr. Melvin E. Walker), an erosion rate of 3.35 mm/hr (0.059 mm/min) was reported by Walker (2013) and shown as the black line on Figure 3-4.

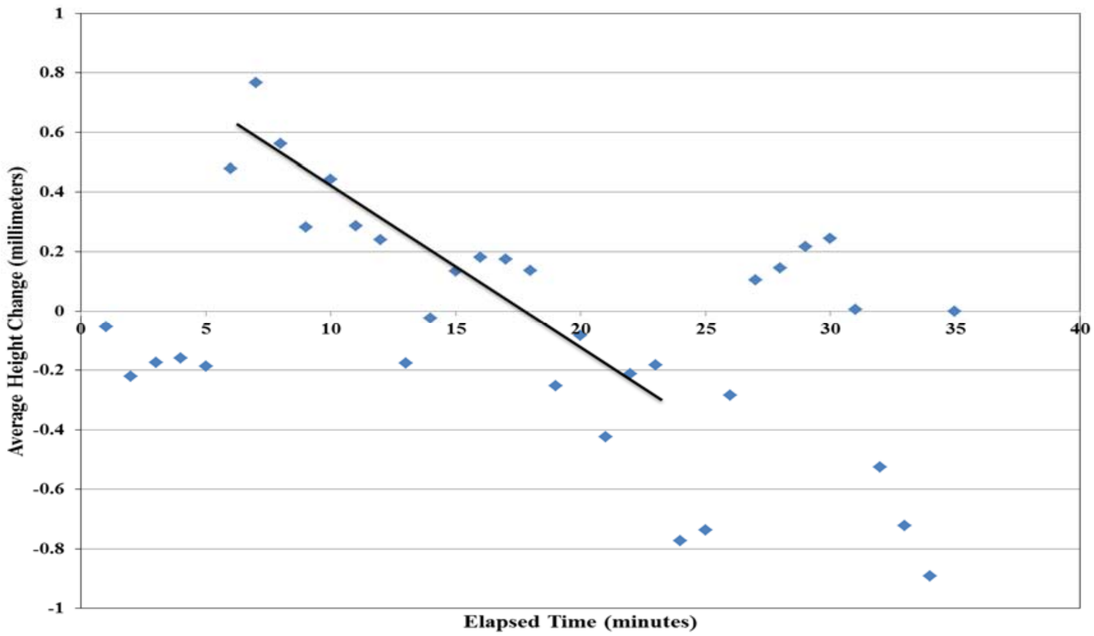

Figure 3-4. Buccatunna 27.0.4 Test Results at 0.6 m/s (Phase I Data Analysis).

We reexamined and reanalyzed the EFA test data for Bucatunna at 0.6 m/s (Fig. 3-4) and results of data analysis are shown on Figure 3-5. One may identify three erosion periods and can fit the data to determine three erosion rates, which are shown as three black dashed regression lines on Figure 3-5. These three estimated erosion rates are 0.1237, 0.0971, and 0.1996 mm/min, and the average erosion rate is 0.1734 mm/min or 10.4 mm/hr. Figure 3-5 also clearly shows there are time periods when the soil column had swelling (all data points with blue color), and the impact of swelling was not considered in above two types of data analysis.

In order to determine the overall erosion rate for the soil, we decided to compute the soil eroded or the soil swelling for each minute, and then we can find out the overall soil erosion rate by summing up the erosion and swelling rates in the one-minute interval. For Bucatunna 27.0.4 EFA test results, it was found that there was 3.85 mm soil erosion and 1.96 mm swelling over a 34-minute testing period (Figure 3-5). Therefore, the overall erosion rate, which considered the impact of swelling, was determined as 6.67 mm/hr (0.1112 mm/min) over the 17-minute erosion period that is indicated as red data points on Figure 3-5.

Table 3-2 shows example results of data analysis from EFA testing data for Buccatunna Clay at 0.6 m/s flow velocity. It includes total swelling and erosion (scour) depths (mm), overall sour rate (mm/min and mm/hr) considering both erosion and swelling, maximum and minimum scour and swelling rates (mm/hr) of the sample during the test. Maximum and minimum scour and swelling rates were based on scour and swelling rates each minute using average height changes per minute but presented as mm/hr (not mm/min). Results for all data analysis from EFA testing data for all scourable formations tested in this study are summarized in Appendix D.

Overall scour rates considering both erosion and swelling at different testing velocities were used to develop the erosion function in the next section.

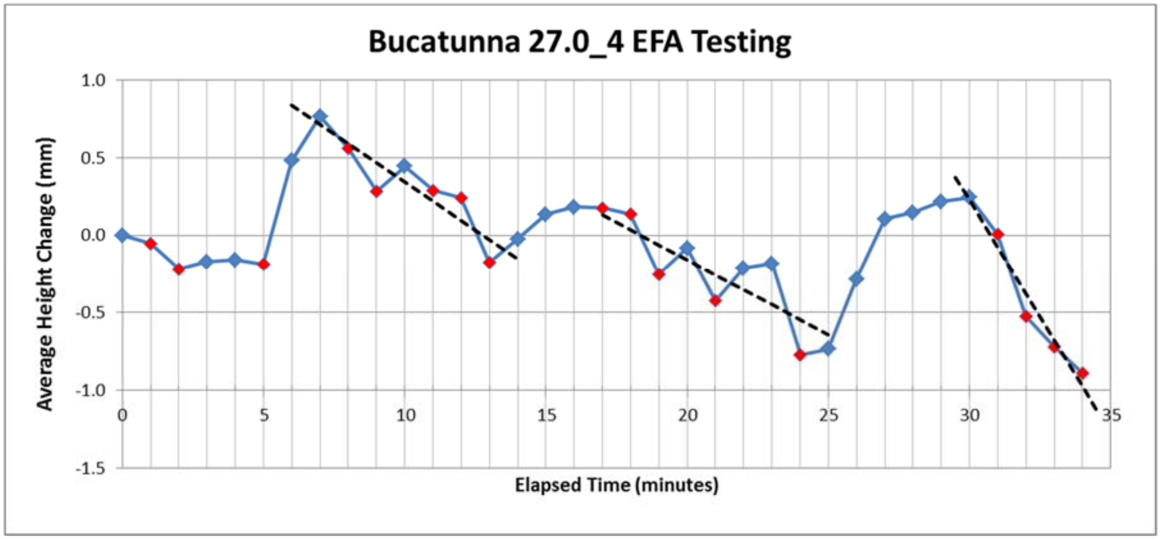

Figure 3-5. Reanalysis of Buccatunna 27.0.4 Test Results at 0.6 m/s.

Table 3-2. Results of Data Analysis from EFA Testing Data of Buccatunna Clay at 0.6 m/s.

Variables \ Test Sample	Buccatunna 27.0_3	Buccatunna 27.0_4	Buccatunna 27.0_5	Buccatunna 27.0_6	Buccatunna 27.0_7
Total swelling (mm)	19.27	1.96	-0.04	4.18	0.76
Total scour (mm)	-20.52	-3.85	-1.74	-4.25	-2.54
Average scour rate (mm/min)	0.04	0.11	0.12	0.00	0.14
Average scour rate (mm/hr)	2.19	6.67	7.10	0.28	8.22
Max. scour rate (mm/hr)	227.89	35.36	21.57	46.50	56.53
Min. scour rate (mm/hr)	0.31	0.40	0.36	0.22	1.77
Max. Swelling rate (mm/hr)	245.06	27.13	3.37	55.33	10.84
Min. Swelling rate (mm/hr)	0.02	1.58	3.37	1.25	1.07

3.4 EFA Testing Results

Figure 3-6 shows average scour rate versus velocity for all tested formations using updated EFA at Auburn University. Results for the same soil formation but tested in Phase I and Phase II were plotted separately using different symbols. The Porter’s Creek formation was without question the least scour resistant. This should be expected, however, as this material also had the lowest critical velocity. Porter’s Creek was the only material tested that scoured at 0.3 m/s and the average erosion rate for all scour events (Table C-27) at this velocity was determined to be 9.7 mm/hour, though rates as high as 21.3 mm/hr were observed. The dark Naheola formation (tested in Phase II) seemed to be the most scour resistant clay, as it was the only material not to scour at velocities below 1.5 m/s and had a scour rate of merely 2.4 mm/hr at this velocity. The largest scour rate observed was 79.8 mm/hr (Table C-16) and was determined from a single test of the re-drilled Naheola formation at a velocity of 3.0 m/s. Because this sample size was so small, this value may not be indicative of the true scour rate for the formation at this velocity. When compared to subsequent tests at 0.6, 1.0, and 2.0 m/s, this value appears to be a strong outlier. As noted in Appendix C (section C.4.2), the "Naheola Clay 19.5_5" sample (Table C-16) may be considered as a "chunk" scour, due to the sample being lost in large chunks over a very short period of time (2 minutes). With that said, the re-drilled Naheola material was considerably scour resistant when excluding this outlying value.

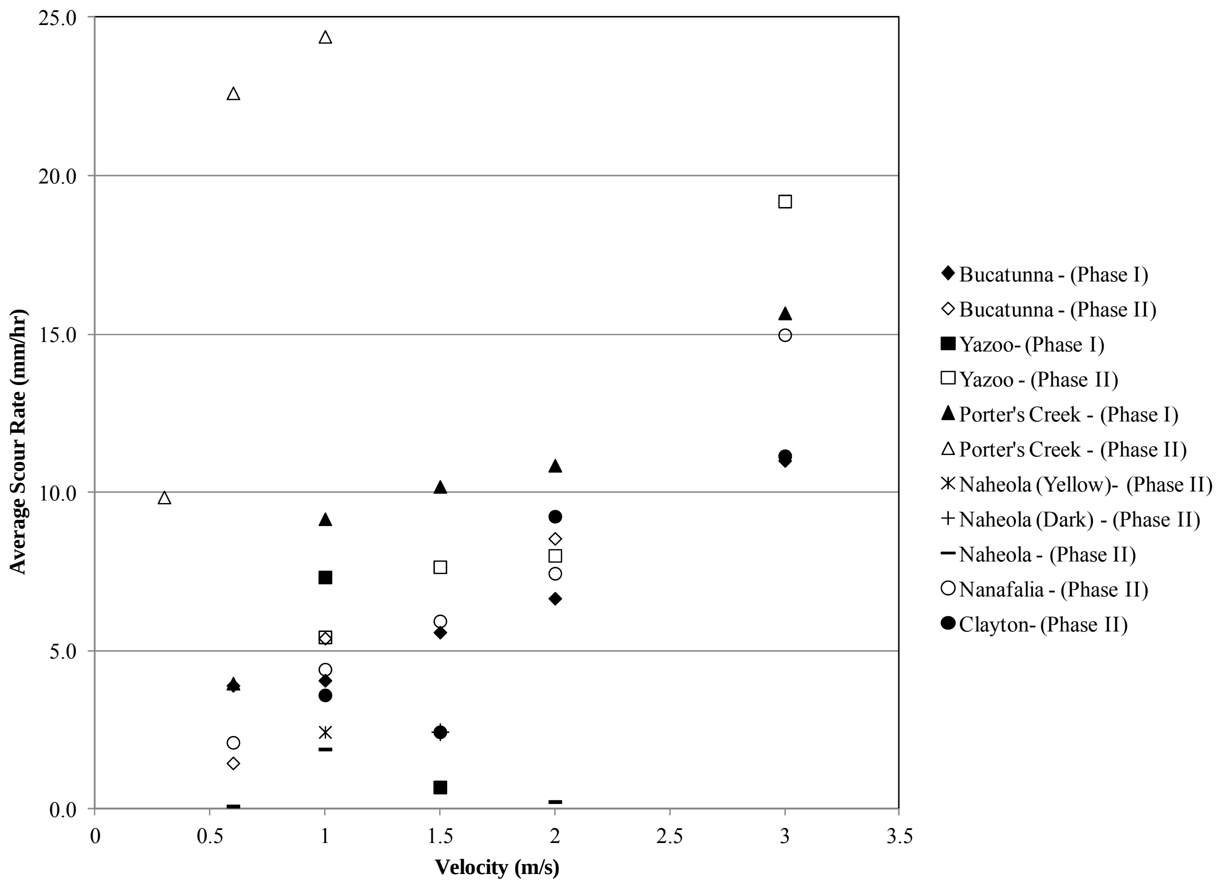

Figure 3-6. Average Scour Rate versus Velocity for all Tested Formations.

Tables 3-3 and Table 3-4 give summary of overall scour rates considering scour and swelling from EFA testing results for six soil formations that include the minimum and maximum overall scour rates, mean or average overall scour rates with standard deviations. These results were derived from data analysis of EFA testing results presented in Appendix D; and typically, several test runs or replicates were performed at the same flow velocity whenever enough soil sample material was available for tests. In some tests for some soil formations, the total swelling was more than total soil scour during the test, therefore, those tests resulted in overall negative scour rates (mm/hr), which are highlighted as red color numbers in Tables D-1 to D-7. The negative scour rates mean overall the soil sample had swelling for the test. Because of negative scour rates for some tests, there are four negative average scour rates for either Porter's Creek or Naheola Clay at certain velocities as shown in Tables 3-3 and 3-4.

3.4.1 Scour Resistant Formations

In this study, three chalk formations were sampled and tested using upgraded EFA with ultrasonic sensors in Phase I testing (Appendix B). They are Demopolis Chalk, Mooreville Chalk, and Prairie Bluff Chalk. Demopolis Chalk was tested at flow velocities of 1.0, 1.2, 2.0, and 3.0 m/s. Three EFA tests were performed at 3.0 m/s velocity and one test to mirror recurring storm events was performed at 3.0 m/s for one hour, and then 1.0 m/s for another 30 minutes, finally 3.0 m/s for the last one hour. All five tests for Demopolis Chalk did not show any signs of measurable scour (section B.3.2).

The scour behavior of the Mooreville Chalk formation varied, but it was recognized that the formation could be scour resistant. Testing was limited to the amount of testable sections recovered during sampling. Once the sample was able to be automatically advanced in the EFA, the formation showed minimal scour rates with no tests recording scour rates greater than 1.0 mm/hr. Finally, it was determined that the Mooreville Chalk formation did not scour uniformly in a particle by particle or even flake by flake fashion as observed in sands and earlier tested clays. The scour observed in the Mooreville Chalk formation consisted of large mass chunks of the material scouring at once. Three samples of Mooreville Chalk collected in Dallas County before 2009 were tested by Thomas J. Mobley in a previous study. All tests performed by Mobley (2009) were at the highest possible EFA velocity of 6.0 m/s, but the testes yielded no or minimal erosion. Mobley (2009) stated that Mooreville Chalk was extremely resistant to scour.

Seven EFA tests were performed on the Prairie Bluff Chalk formation to determine erosion rates. A large mass chuck scoured away at 1.0 m/s velocity but it was started form the loose area of the sample. There was no scour observed at the second test with 1.0 m/s velocity. The test at 1.5 m/s velocity had 1.76 mm/hr scour on dry loose areas also. One test at 2.0 m/s velocity and three tests at 3.0 m/s velocity did not have scour observed. Due to the lack of testable sample material, one test to mirror recurring storm events was not performed on the Prairie Bluff Chalk formation. Overall, it was recognized that the Prairie Bluff Chalk formation could be scour resistant.

Table 3-3. Summary of Overall Scour Rates Considering Scour and Swelling from EFA Testing Results for Bucatunna Clay, Yazoo Clay, and Porter's Creek Clay Formations.

Formation Tested	Testing Flow Velocity (m/s)	Minimum Scour Rate (mm/hr)	Maximum Scour Rate (mm/hr)	Average Scour Rate (mm/hr)	Standard Deviation (mm/hr)	No. of Replicates	Reference Table
Bucatunna Clay	0.6	-2.56	8.22	3.65	4.33	6	D-1
Bucatunna Clay	1.0	2.65	13.65	8.04	20.26	7	D-1
Bucatunna Clay	1.5	7.42	23.88	13.91	7.08	5	D-2
Bucatunna Clay	2.0	4.63	18.28	13.13	5.06	6	D-2
Bucatunna Clay	3.0	10.94	46.38	27.17	12.76	6	D-2
Yazoo Clay	1.0	-2.10	44.24	15.54	13.36	8	D-5
Yazoo Clay	1.5	-0.04	68.86	17.72	28.96	5	D-3
Yazoo Clay	2.0	4.96	99.43	46.85	77.14	5	D-3
Yazoo Clay	3.0	32.34	132.86	77.14	45.97	4	D-3
Porter's Creek Clay	0.3	-29.77	12.15	-9.20	21.18	4	D-4
Porter's Creek Clay	0.6	3.33	30.17	18.17	10.64	6	D-4
Porter's Creek Clay	1.0	19.12	23.00	20.28	1.83	4	D-4
Porter's Creek Clay	1.5	17.85	58.96	29.00	20.01	4	D-4
Porter's Creek Clay	2.0	14.50	31.13	22.50	8.33	3	D-4
Porter's Creek Clay	3.0	17.24	36.53	29.73	10.83	3	D-4

Table 3-4. Summary of Overal Scour Rates Considering Scour and Swelling from EFA Testing Results for Clayton Clay, Naheola, and Nanafali Clay Formations.

Formation Tested	Testing Flow Velocity (m/s)	Minimum Scour Rate (mm/hr)	Maximum Scour Rate (mm/hr)	Average Scour Rate (mm/hr)	Standard Deviation (mm/hr)	No. of Replicates	Reference Table
Clayton Clay	1.0	-0.52	29.45	14.46	21.19	2	D-5
Clayton Clay	1.5	2.22	15.09	9.04	6.47	3	D-5
Clayton Clay	2.0	7.49	89.72	35.02	47.37	3	D-5
Clayton Clay	3.0	30.29	99.57	53.46	39.93	3	D-5
Nanafalia Clay	0.6	-1.23	1.04	0.04	1.16	4	D-6
Nanafalia Clay	1.0	-2.34	16.74	7.18	10.32	4	D-6
Nanafalia Clay	1.5	1.47	20.00	11.02	9.28	3	D-6
Nanafalia Clay	2.0	4.55	18.49	12.63	7.23	3	D-6
Nanafalia Clay (Dark)	3.0	7.96	37.50	20.96	15.09	3	D-6
Naheola Clay (Dark)	0.6	-0.56	-0.56	-0.56	N/A	1	D-7
Naheola Clay (Dark)	1.0	-6.96	1.05	-2.96	5.66	2	D-7
Naheola Clay (Dark)	1.5	-2.27	22.79	7.55	13.38	3	D-7
Naheola Clay (Dark)	2.0	-0.65	-0.65	-0.65	N/A	1	D-7
Naheola Clay (Dark)	3.0	27.41	27.41	27.41	N/A	1	D-7

3.4.2 Erosion Functions

As previously stated, the scour rates that were determined compensated for swell occurring throughout testing. Consequently, the erosion functions based on the scour rates also accounted for sample swelling as summarized in Appendix D, Table 3-3 and Table 3-4. Analyses were performed on the EFA test results to produce erosion functions based on velocity and shear stress. Furthermore, the critical velocity, critical shear stress, and initial erosion rate were determined analytically. The shear stress (τ) included in the erosion functions was estimated using Equation (3-1):

$$\tau = \rho f V^2/8 \tag{3-1}$$

Where:

ρ = Density of water

V = Flow velocity

The fiction factor (f) was computed using Equation (3-2) presented by Crowe et al. (2009) [after Swamee and Jain (1976)].

$$f = \frac{0.25}{[log_{10}(\frac{k_S}{3.7D}+\frac{5.74}{Re^{0.9}})]^2} \tag{3-2}$$

Where:

k_s = Absolute roughness of the soil surface tested

D = Equivalent diameter of non-round conduits,

R_e = Reynolds's number = VD/v (v is the dynamic viscosity of water used in EFA)

The equivalent diameter is equal to four times cross-section area divided by wetted perimeter. Briaud et al. (2001b) suggest using the average height of the roughness elements, i.e. $D_{50}/2$ as absolute roughness k_s, where D_{50} is the mean particle diameter for the soil formation tested.

Figure 3-7 through Figure 3-20 are the erosion functions determined from the EFA testing data for seven soil formations (Bucatunna, Yazoo, Porter's Creek, Clayton, Nanafalia, yellow Naheola Clay, and dark Naheola Clay). For each soil formation, one graph of the erosion function shows scour rate (mm/hr) versus flow velocity (m/s), and another graph shows scour rate (mm/hr) versus shear stress (N/m^2). The regression equations shown in these figures contain variables for erosion rate (E_{rate}), velocity (Vel), and shear stress (τ). The average erosion rates that were derived from replicate EFA tests with the same flow velocity were plotted, with vertical lines of plus and minus one standard deviation, at each velocity tested. It should be noted that the re-drilled Naheola sample was included as a part of the dark Naheola samples in their analyses (Figures 3-19 and 3-20), but erosion function for the yellow Naheola samples (Figures 3-17 and 3-18) was plotted separately from one for the dark Naheola samples.

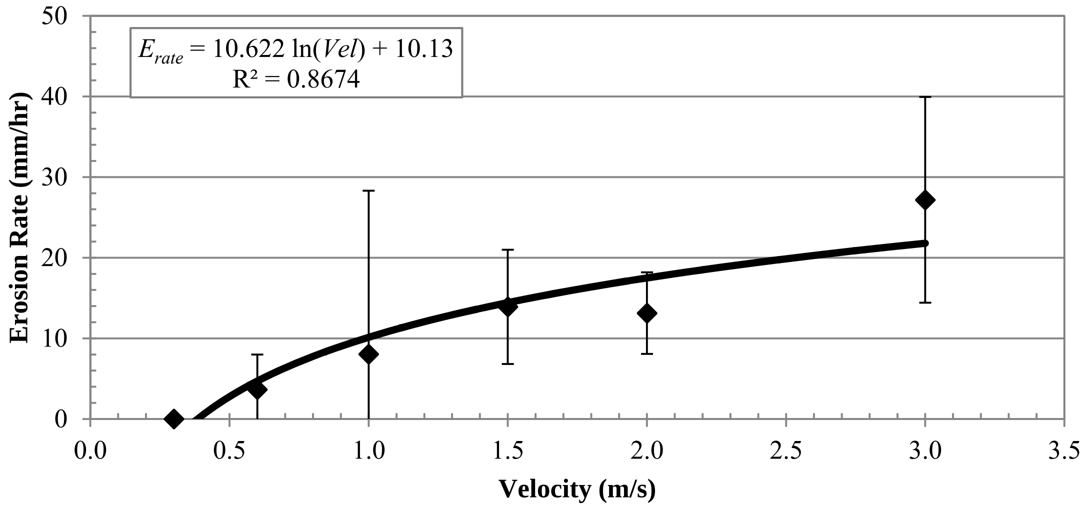

Figure 3-7. Velocity-based Erosion Function for Bucatunna Clay.

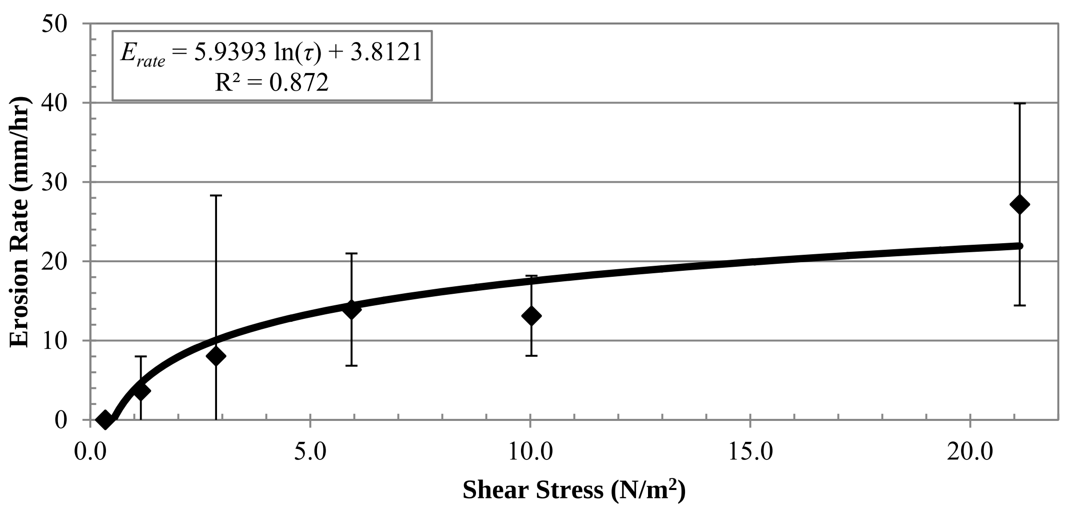

Figure 3-8. Shear Stress-based Erosion Function for Bucatunna Clay.

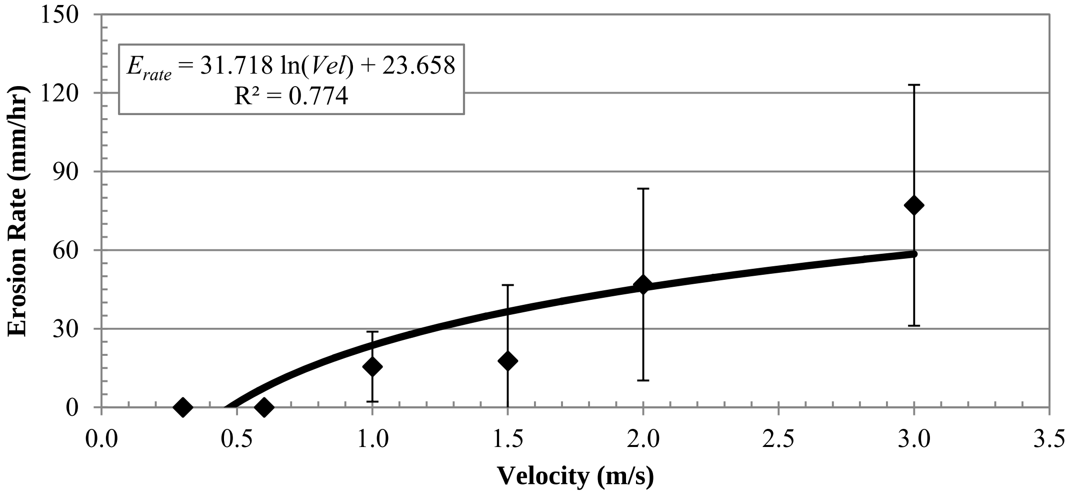

Figure 3-9. Velocity-based Erosion Function for Yazoo Clay.

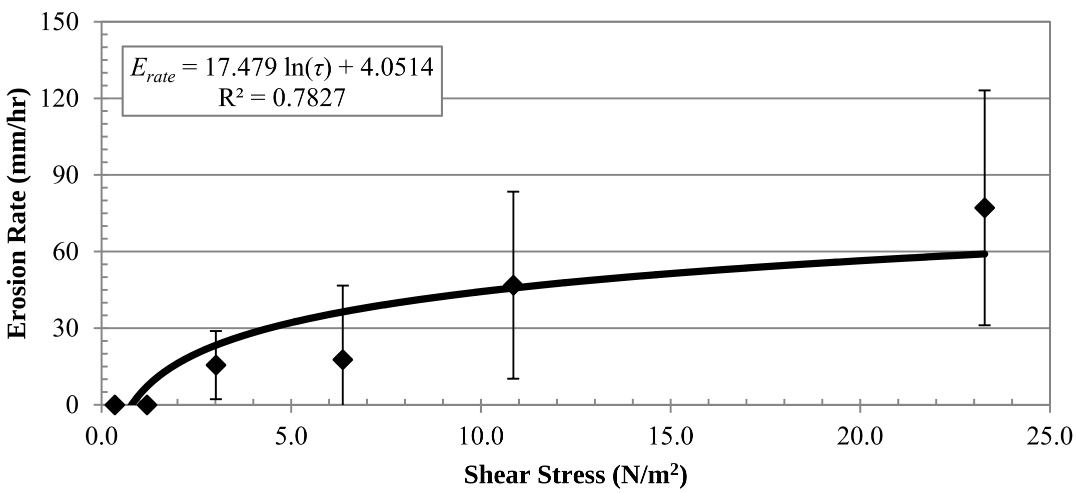

Figure 3-10. Shear Stress-based Erosion Function for Yazoo Clay.

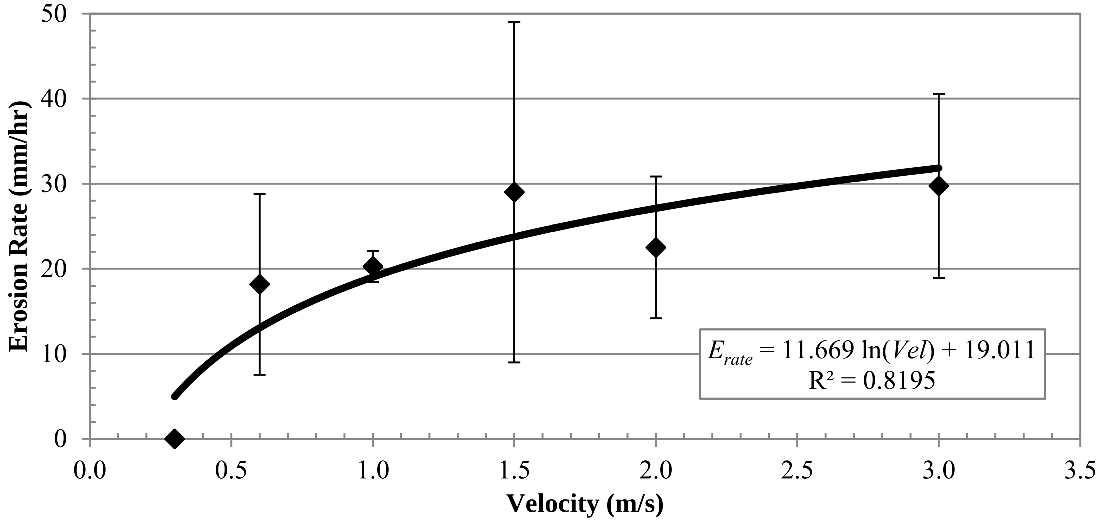

Figure 3-11. Velocity-based Erosion Function for Porter's Creek Clay.

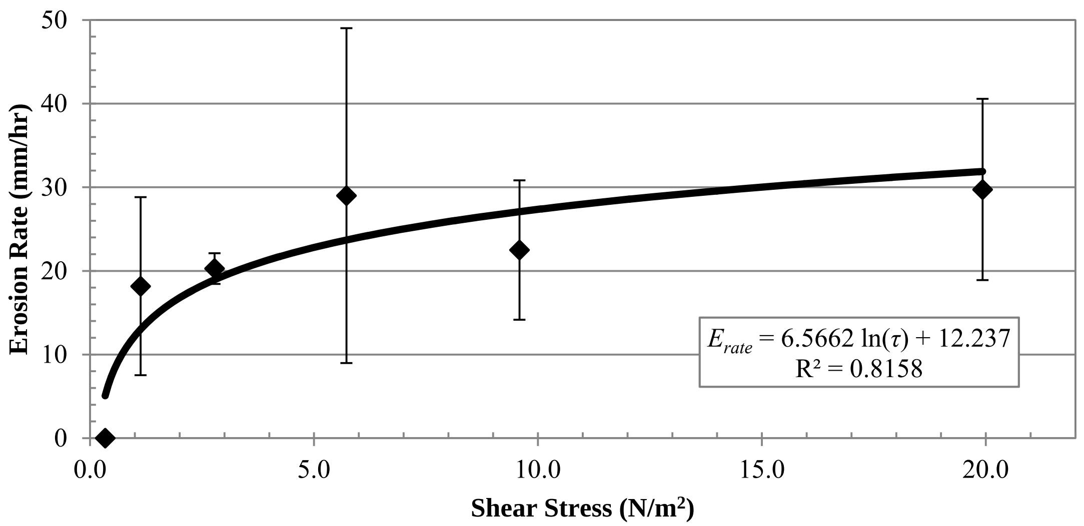

Figure 3-12. Shear Stress-based Erosion Function for Porter's Creek Clay.

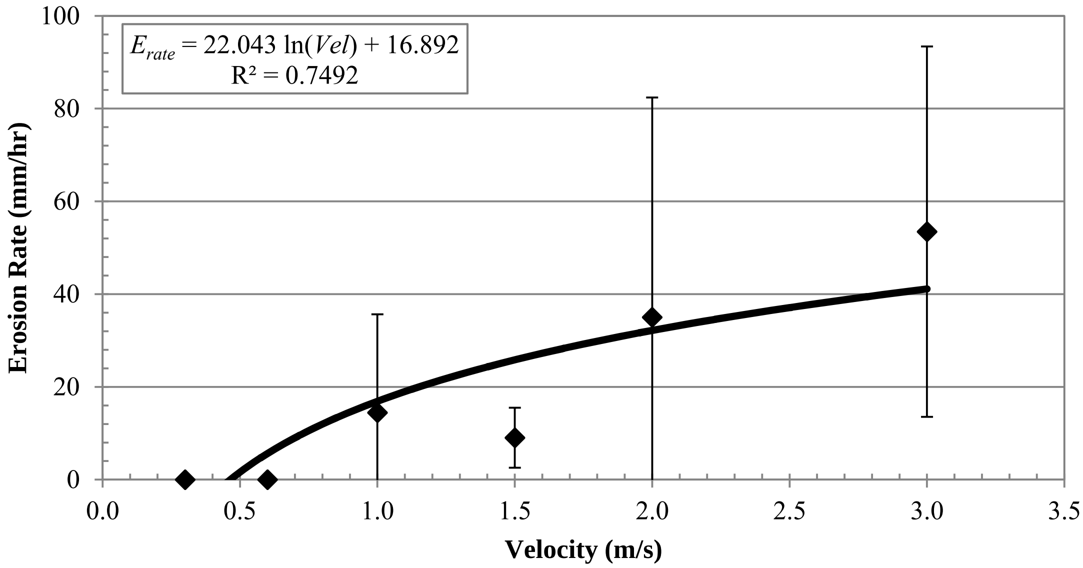

Figure 3-13. Velocity-based Erosion Function for Clayton Clay.

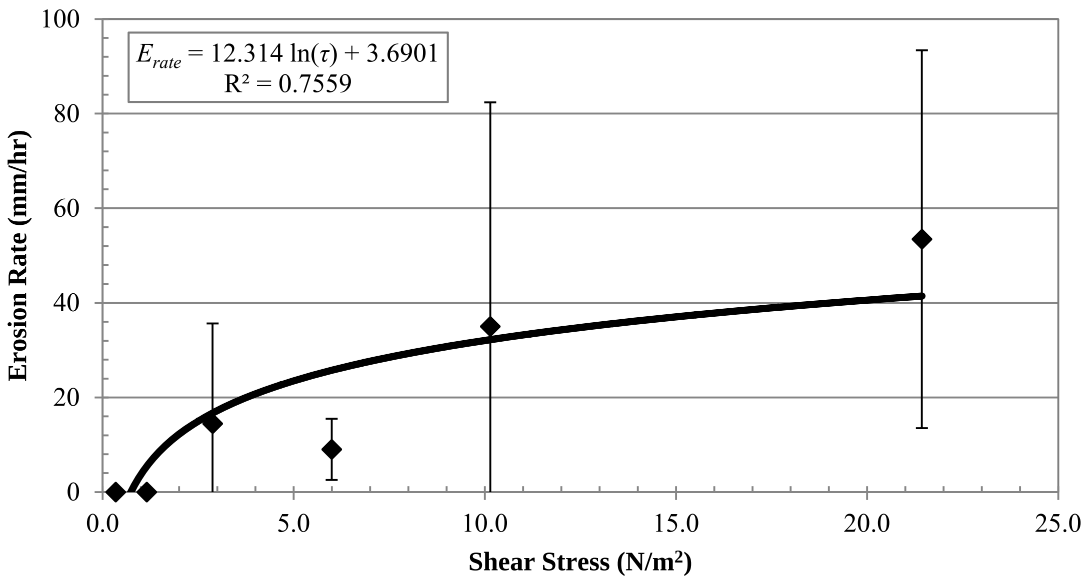

Figure 3-14. Shear Stress-based Erosion Function for Clayton Clay.

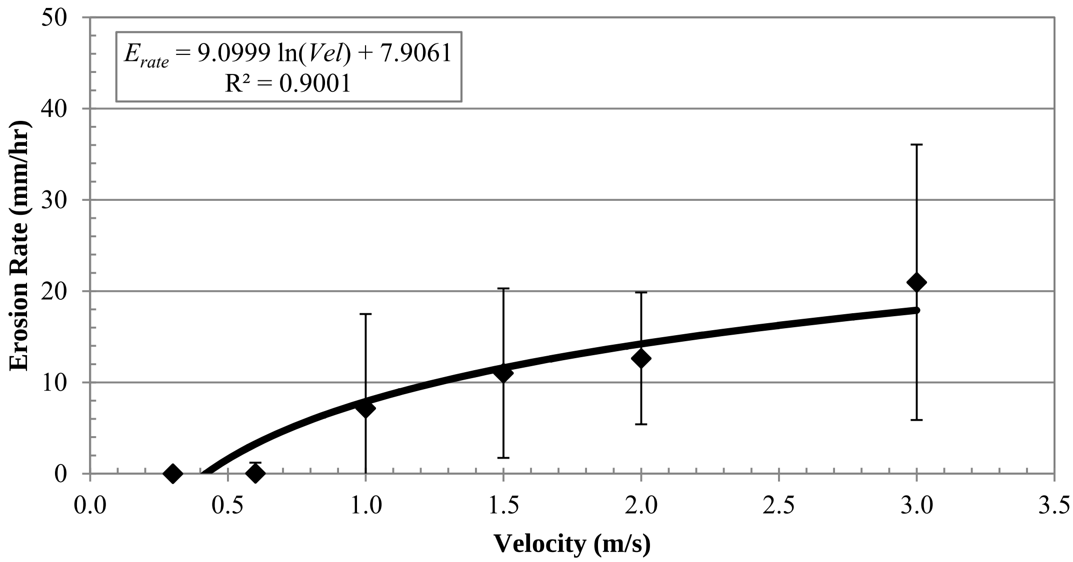

Figure 3-15. Velocity-based Erosion Function for Nanafalia Clay.

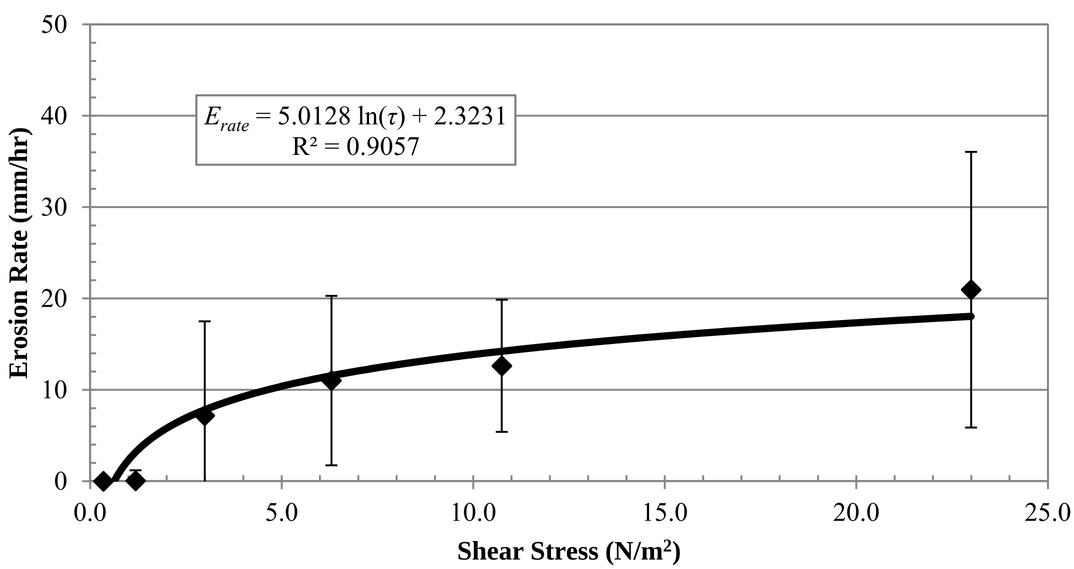

Figure 3-16. Shear Stress-based Erosion Function for Nanafalia Clay.

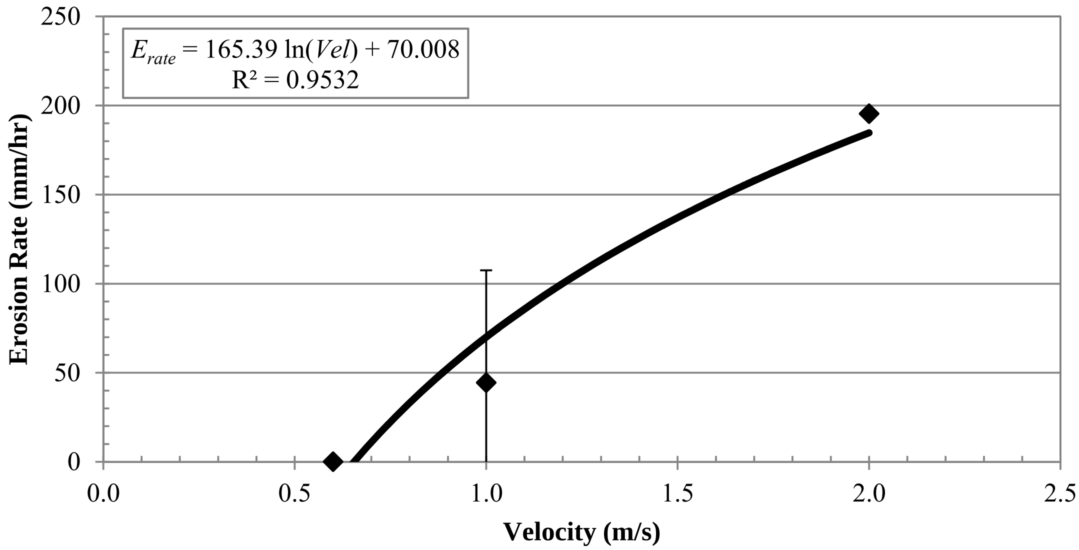

Figure 3-17. Velocity-based Erosion Function for **Yellow** Naheola Clay.

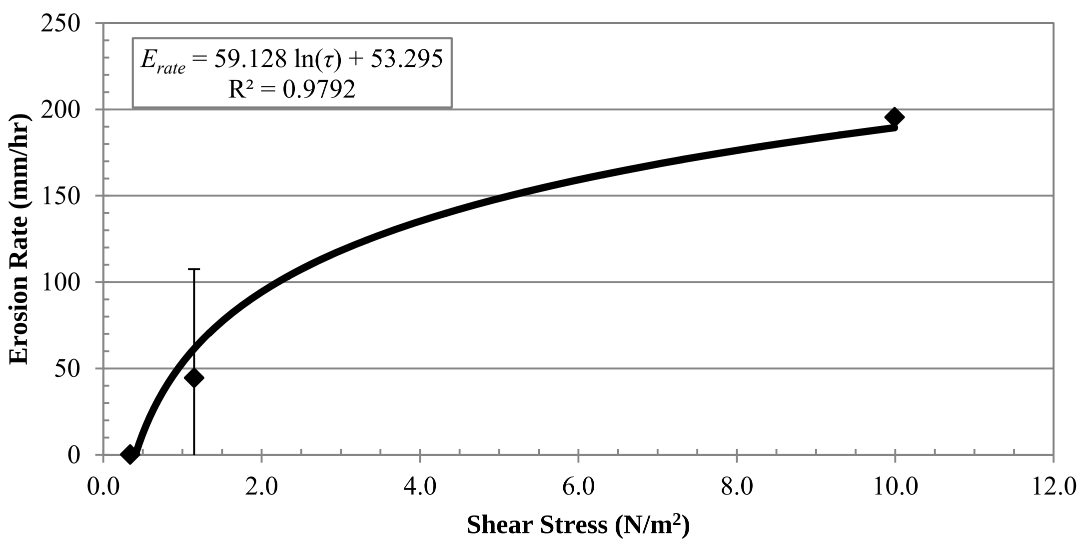

Figure 3-18. Shear Stress-based Erosion Function for **Yellow** Naheola Clay.

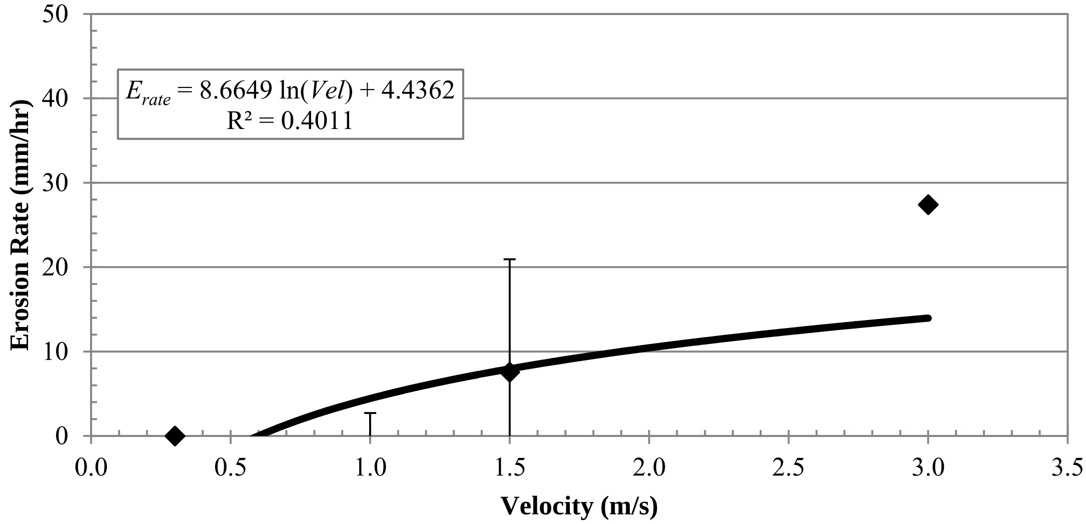

Figure 3-19. Velocity-based Erosion Function for **Dark** Naheola Clay.

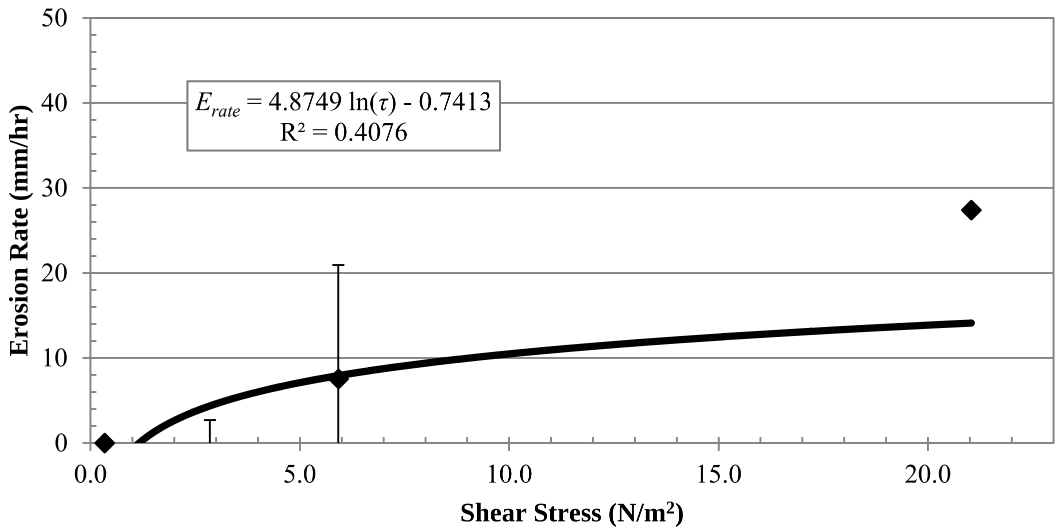

Figure 3-20. Shear Stress-based Erosion Function for **Dark** Naheola Clay.

3.4.3 Critical Velocity and Initial Erodibility

As presented in Appendixes B and C, the critical velocities of the various materials were determined visually during the EFA tests. The critical velocities, initial erodibility and critical shear stresses determined from the scour functions are shown in Table 3-5 for the respective materials (Figures 3-7 to 3-20). The critical velocity value represents the velocity at which scour begins to occur, while the critical shear stress is the value for shear stress at the critical velocity. The initial erodibility (S_i, Figure A-3) measures how fast scour occurs just after the critical shear stress is reached. The initial erodibility is calculated by drawing a line tangent to the erosion function through the critical shear stress (Crim 2003). Generally, the slope of the initial erodibility is higher in sands compared to cohesive soils (clays). The initial erodibility was estimated as the tangent slope of the fitted erosion function equation at the critical shear stress (Figures 3-7 to 3-20). Figure A-3 shows the initial erodibility can be estimated from data points of EFA testing results but may not be representative to the tangent slope. The initial erodibility as slope is the erosion rate (mm/hr) per unit velocity (m/s) or shear stress (N/m^2) change, and initial erodibility estimates in both units are given in Table 3-5.

Table 3-5. Summary of Critical Velocity, Critical Shear Stress, and Initial Erosion Rate Determined from Erosion Function.

Soil Type	Critical Velocity (m/s)	Critical Shear Stress (N/m^2)	Initial Erodibility	
			[mm/hr/(m/s)]	[mm/hr/(N/m^2)]
Bucatunna	0.39	0.53	27.57	11.29
Yazoo	0.47	0.79	66.87	22.04
Porter's Creek	0.20	0.16	59.51	42.33
Clayton	0.47	0.74	47.43	16.62
Nanafalia	0.42	0.63	21.69	7.97
Naheola – Yellow	0.65	0.41	252.55	145.63
Naheola – Dark	0.59	1.15	14.50	4.23

All clay formations scoured at a velocity of 1.5 m/s and greater based on EFA tests. The chalk formations did not show any tendency to scour. Average critical velocities for having minor scour ranged between 0.30 m/s and 1.60 m/s. The Porter's Creek formation produced the lowest observed critical velocity for minor scour, with an average value of 0.32 m/s from eight critical velocity test (Table C-26), while the largest critical velocity for minor scour was observed in the re-drilled Naheola clay material, having an average value of 1.55 m/s (Table C-12). The Nanafalia (Table C-1), Naheola – Dark (Table C-10), Clayton (Table C-17), Bucatunna, and Yazoo formations had very similar observed critical velocities, ranging between 0.63 and 0.71 m/s. The yellow Naheola formation had a relatively lower critical velocity of 0.46 m/s (Table C-7). The Yazoo clay critical velocities ranged from 0.4 m/s from initial tests (Phase I testing) to 0.67 m/s from the retest (Phase II testing, Table C-30). Likewise, the Bucatunna critical velocity was originally determined to be 0.45 m/s, and was 0.63 m/s during retesting (Table C-22). The respective values for the critical velocity of Porter's Creek clay matched reasonably well. The average critical velocity for this material was determined to be 0.40 m/s from Phase I testing and 0.32 m/s (Table C-26) from Phase II testing.

Figure 3-21 shows the calculated critical velocities (Table 3-5) from fitted erosion function equations compared to the average critical velocities observed during EFA testing. Theoretically, the respective values should be equal, representing a one-to-one linear relationship as shown by the black line. It is apparent that the average observed critical velocities, for the most part, are larger than those determined analytically. That being said, a conservative critical velocity estimate (i.e. one that is slightly larger than the true value) may be determined analytically using mean grain size diameter as the sole soil parameter.

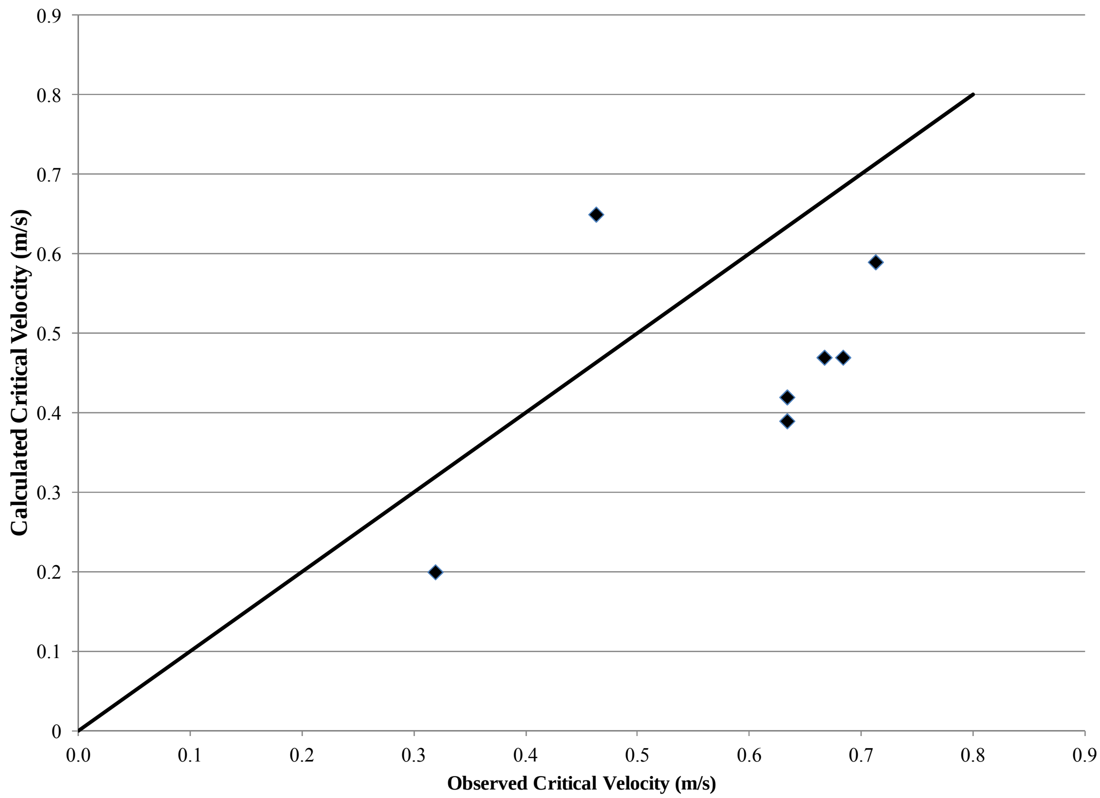

Figure 3-21. Comparison between Observed and Calculated Critical Velocity.

3.5 Geotechnical and Scour Parameter Correlations

Data from 14 soils, including this study, Mobley (2009), and Crim (2003), were analyzed for correlations between scour and geotechnical parameters. Three of these materials (, all of which were tested by Walker (2013), did not scour at velocities 3.0 m/s and lower. The 11 remaining soils (clay formation) were each scourable. Various trends and corrections were seen in the data as discussed below.

The SPT blow counts appeared to have a serious effect on scour resistance, as only N values 60 and above were scour resistant. Soils with moisture contents below 24 did not scour at velocities of 3.0 m/s and less. Figure 3-22 shows a plot of scourability as it relates to SPT N value and insitu moisture content. A general area with respect to soils that are not likely to exist or could not be evaluated using the EFA method is also shown in Figures 3-22, 3-23, and 3-24.

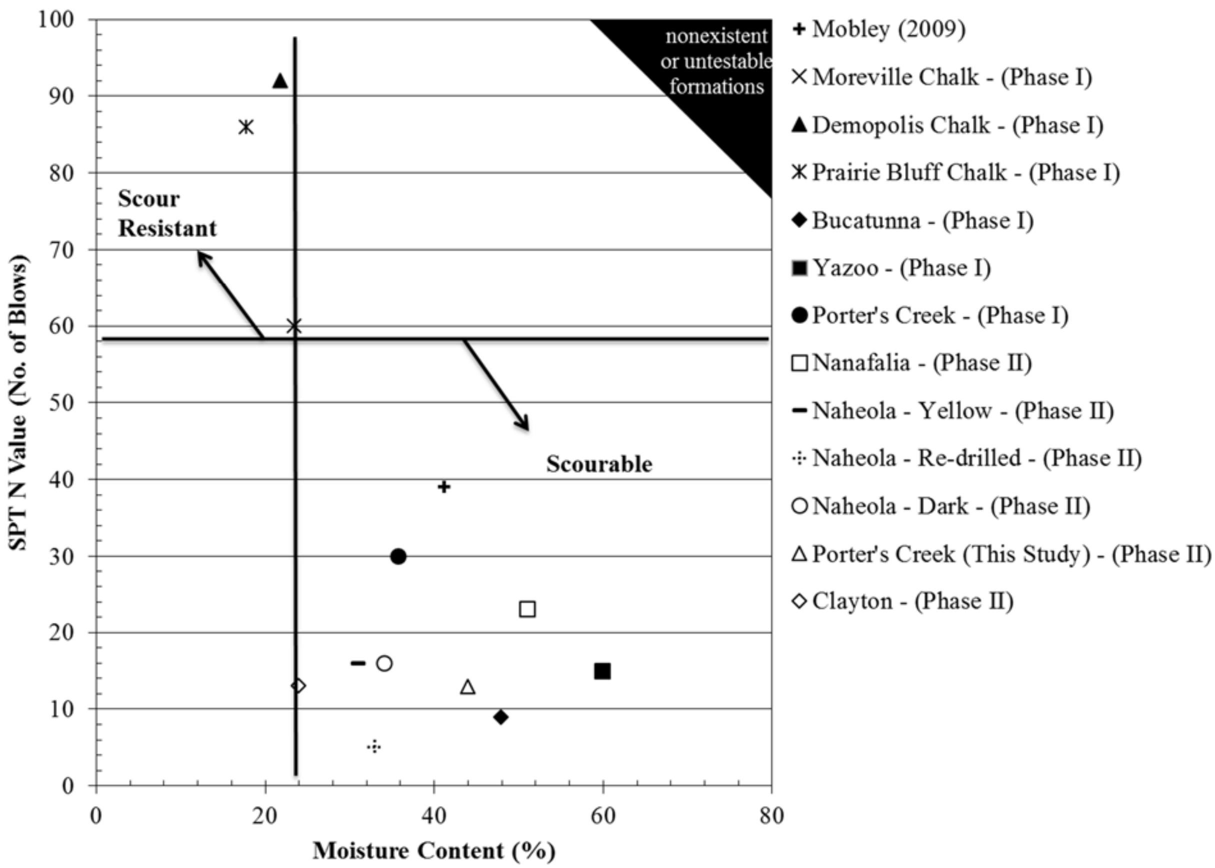

Figure 3-22. Scourability versus SPT N Value and Moisture Content.

The percentage of fined grained soil (i.e., the percent passing the No. 200 sieve) did not appear to have an effect on scourability. The scour resistant soils all had fines percentages greater than about 82%, though five of the scourable materials had a fines percentage falling above this value. Figure 3-23 shows a plot of scourability as it relates to SPT N value and fines percentage.

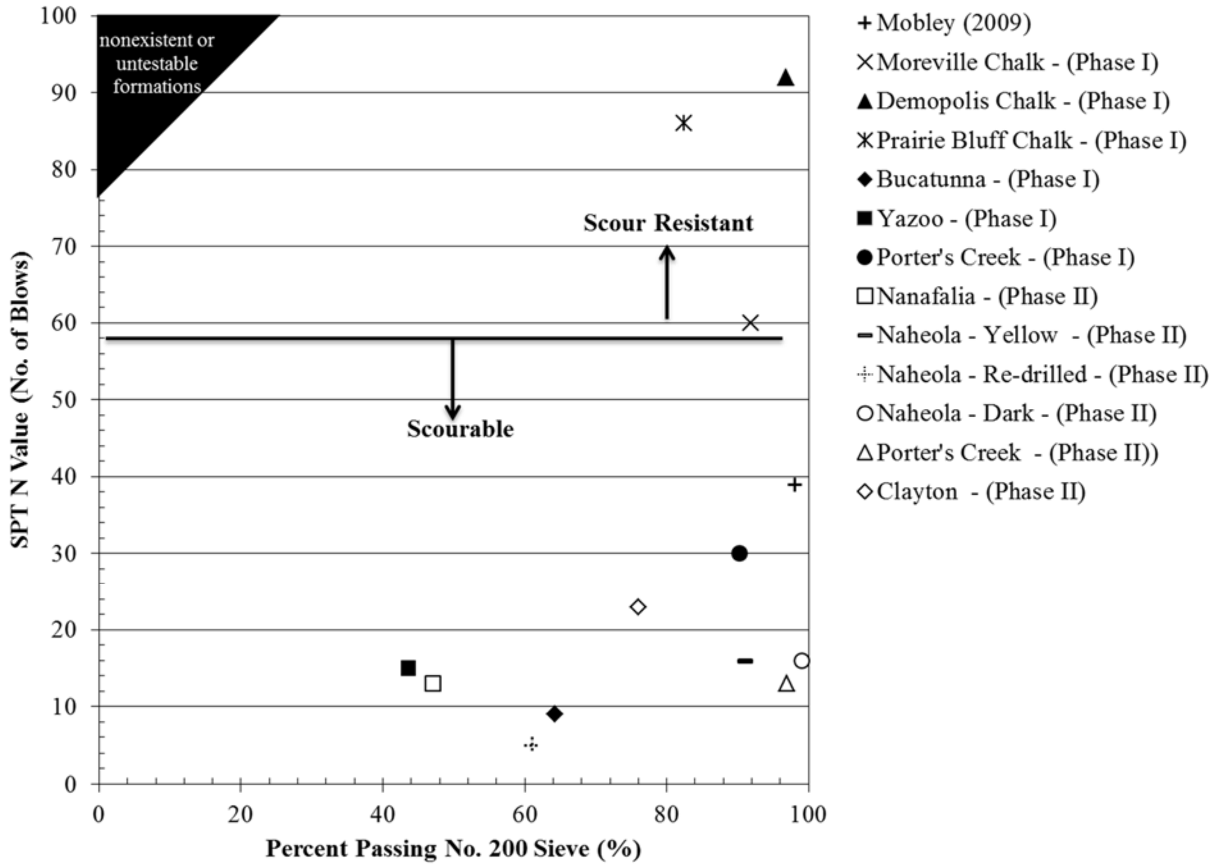

Figure 3-23. Scourability versus SPT N Value and Percent Passing the No. 200 Sieve.

Walker (2013) observed that soils were scour resistant when the material had a mean grain size diameter less than 0.0082 mm. This correlation was seen with the exception of the Porter's Creek sample. The Porter's Creek sample tested in this study was an extremely fine material. The mean grain size diameter of the Porter's Creek material tested by Walker was approximately 0.0082 mm. As previously stated, the mean grain size diameter of the re-sampled Porter's Creek material was not determined because a 48 hour hydrometer test was not sufficient for this very fine material. Because the mean grain size was certainly less than 0.001 mm, the correlation between scourability and mean grain size cannot be made. Figure 3-24 shows a plot of scourability as it relates to SPT N value and mean grain size diameter.

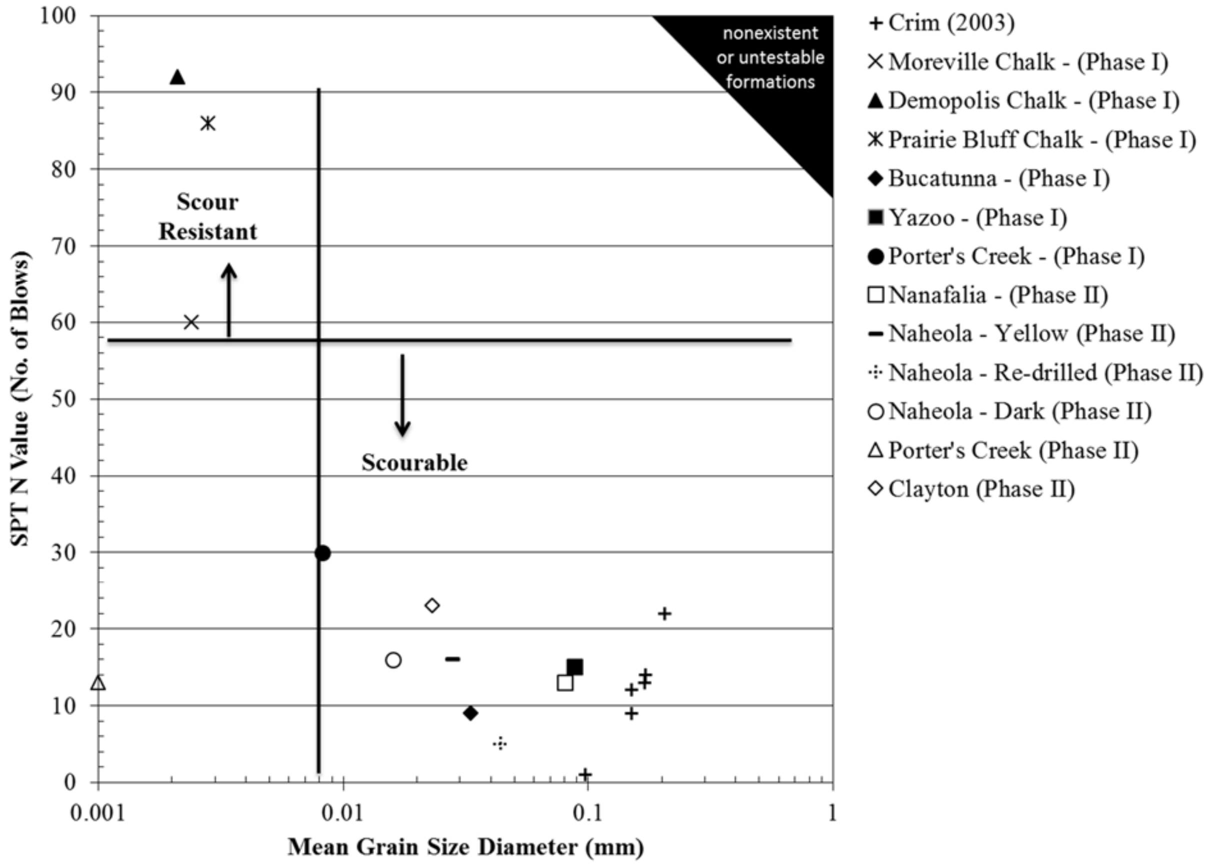

Figure 3-24. Scourability versus SPT N Value and Mean Grain Size.

Liquid limit, plastic limit, and plasticity index did not appear to have any effect on the scourability of the tested soils. The scour resistant chalk formations tended to have a lower plasticity index, with values ranging between 10 and 27, though other scourable materials had plasticity indices falling in this range. The material with the lowest critical velocity (the 2013 Porter's Creek formation) also had the highest critical velocity.

The vertical and horizontal lines dawn on the plots are representative of the boundaries for scourability. It should be considered, however, that scourability may be dependent upon both variables. For example, to determine whether or not a material is scour resistant, that may depend on the SPT N-value *and* insitu water together. Instead of two lines (one horizontal and one vertical) the relationship may better be described by one positively linear function.

Chapter 4. Conclusions and Recommendations

4.1 Summary

Determination of erosion parameters for different soil formations in order to predict scour depth is imperative to designing safe, economic, and efficient bridge foundations. Scour behavior of granular (non-cohesive) soils is generally understood, and design criteria have been established by the Federal Highway Administration. The same is not true for cohesive soils, and because of their complexity, a universal scour prediction method has not been established by the industry. The Erosion Function Apparatus, EFA was created to determine the rate of scour of cohesive soils under known testing flow velocities or shear stresses, which can then be used to predict scour depths under similar conditions.

During this study, ten cohesive soil formations were sampled with the assistance of the Alabama Department of Transportation. They are (1) Bucatunna Clay, (2) Yazoo Clay, (3) Demopolis Chalk, (4) Mooreville Chalk, (5) Prairie Bluff Chalk, (6) Porter's Creek Clay, (7) Nanafalia clay, (8) Naheola Dark Clay, (9) Naheola Yellow Clay, and (10) Clayton Clay. Specimens from these formations were scour tested under flow velocities of 0.6, 1, 1.5, 2, and 3.0 m/s in an updated EFA featuring an ultrasonic sensor for quantitative erosion measurements. EFA tests were performed to determine erosion rate (mm/hr) at different velocities for developing erosion functions (Figures 3-7 to 3-20) and whether any formations demonstrated scour resistance. Geotechnical index tests were also performed on these formations to possibly correlate scour to geotechnical properties. Geotechnical indexes determined for soils in this study include SPT N value (determined during sampling soils), insitu moisture content, percent of fine passing through the No. 200 sieve, particle size distribution, mean particle size (D_{50}), liquid limit, plastic limit, and plasticity index.

Results of testing verified the performance of the ultrasonic sensor and updated EFA. Three of the ten tested formations were scour resistant. Velocity and shear stress based erosion functions were generated for the scourable formations with scour rates upwards of 15 mm per hour. The scour behavior observed was unique among formations limiting the ability to establish correlations between tests.

4.2 Conclusions

The following conclusions were made from the study:

- Three chalk formations (Demopolis Chalk, Mooreville Chalk, and Prairie Bluff Chalk) sampled and tested in this study are recognized to be scour resistant. EFA tests on these chalk formations had no scour or minimal scour rates with no tests recording scour rates greater than 1.0 mm/hr.
- EFA tests on Mooreville Chalk performed in this study confirmed results of EFA tests on Mooreville Chalk performed by Mobley (2009) in a previous study. All tests performed by Mobley (2009) were at the highest possible EFA velocity of 6.0 m/s, but the testes

yielded no or minimal erosion. Mobley (2009) stated that Mooreville Chalk was extremely resistant to scour.

- Swelling was prevalently observed throughout EFA testing. The sample would begin to swell, then scour would occur while swelling subsided; scour would steadily come to a halt and swelling would pick up again. In some cases, there was considerable scouring that occurred during a test but excessive swelling would result in the sample actually becoming taller over the test duration.
- Updated EFA featuring ultrasonic sensor was able to quantify all scour and swelling events during each EFA test, which were not previously quantified before. Overall average scour rate considering both scour and swelling was proposed and determined from EFA data analysis for seven clay formation tested in this study (Appendix D, Tables 3-3 and 3-4).
- The Porter's Creek Clay formation was the least scour resistant in the ten formations tested in this study. The Porter's Creek formation produced the lowest critical velocity for minor scour, with an average value of 0.32 m/s, while the largest critical velocity for minor scour was observed in the re-drilled Naheola clay material, having an average value of 1.55 m/s.
- Erosion function curves for seven clay formations (erosion rate in mm/hr versus velocity in m/s or shear stress in N/m^2) were determined and presented in Figures 3-7 to 3-20. Calculated critical velocity, critical shear stress, and initial erodibility were determined from fitted erosion function equations and summarized in Table 3-5. The scour behavior observed was unique among formations limiting the ability to establish correlations between tests.
- The data analysis of scourbility and geotechnical parameters of soils was performed and revealed some weak correlations/connections. Scour resistant formations have SPT N value above 60 with moisture content less than 22% and mean grain size less than 0.008 mm (Figure 3-24).

4.3 Recommendations

Three chalk formations (Demopolis Chalk, Mooreville Chalk, and Prairie Bluff Chalk) are recognized to be scour resistant, but erosion function curves for six clay formations were based on limited EFA tests because limited soil samples were obtained. For example, dark Naheola Clay samples were tested with one or two replicate EFA test(s) for each flow velocity (see Table D-6). Because insufficient materials sampled for all formations, unconfined compressive test was not conducted for any soil formation in this study. Therefore, additional study with new soil samples in Alabama coastal counties will be necessary and benefit to ALDOT.

This is the first study using EFA featuring ultrasonic sensor to test Alabama soil formations. Data acquisition allows us to detect swelling and erosion events during each EFA test, which was not able to be done previously. Additional data analysis and additional EFA tests on the same and additional soil formations will be needed to help ALDOT to fully understand scour behavior of soils and risk/benefit of using average/minimum/maximum scour rates at different test velocities. Additional study will be helpful to develop implementable erosion functions using the updated equipment and procedures developed in this study.

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Appendix A Literature Review

A.1 Scour Background Information

Scour is defined as the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around the piers and abutments of bridges (Richardson and Davis 2001). More specifically scour at bridges can be related to the following factors: (Lagasse et al. 2001)

- Channel slope and alignment
- Channel shifting
- Bed sediment size distribution
- Antecedent floods and surging phenomena
- Accumulation of debris, logs, or ice
- Flow contraction, flow alignment, and flow depth
- Pier and abutment geometry and location
- Type of foundation
- Natural or man-induced modification of the stream
- Failure of a nearby structure

Scour is divided into three different classifications, aggradation and degradation, general scour, and local scour. Aggradation and degradation are based on long term streambed elevation changes (Richardson and Davis 2001). Aggradation is defined by the deposition of upstream material, resulting in the raising of a streambed. Degradation is defined by the lowering of a streambed due to a deficit in the deposits from upstream.

General scour is attributed to the lowering of a streambed across a stream at a bridge or large scale impingement in flow. General scour often refers to contraction scour which occurs when a streambed is narrowed, or contracted, by the addition of a bridge which increases flow velocities (Richardson and Davis 2001). Another type of general scour involves scour around a bend in a river, as velocities tend to vary with respect to distance from the bend. Typically contraction scour occurs across most of the streambed. However general scour and contraction scour are not uniform throughout a given cross section. General scour differs from aggradation and degradation in that general scour is cyclical and often reflects flood activity (Richardson and Davis 2001).

Local scour is defined as the removal of material around objects intercepting flow caused by the acceleration of flow around the objects. With acceleration in flow around a bridge pier comes an increase in shear stress on the stream bed resulting in removal of bed material. HEC 18 recommends calculating total scour at a bridge crossing by adding degradation, general scour, and local scour over the design life of the structure.

Scour occurs when the shear stress exerted on the bed material by the flow of water exceeds the critical shear stress (τ_c) for the bed material. As the shear stress increases beyond the critical shear stress of the bed material, a scour hole develops. Scour can develop around an object, as in local scour, or across a channel in general scour. As the scour increases and more particles are removed, the shear stress on the plane of the bed material decreases. Maximum scour depth is reached once enough material has been removed to reduce the shear stress at the bottom of the scour hole to a level below the critical shear stress (Briaud et al. 1999). This critical shear stress is proportional to the critical velocity (V_c) flowing through a channel. HEC-18 defines the critical shear velocity by equation A-1 below:

$$V_c = K_u \cdot y^{\frac{1}{16}} \cdot D^{\frac{1}{3}} \tag{A-1}$$

where:

V_c	=	Critical velocity above which bed material size D and smaller scours
y	=	Average depth of flow upstream of bridge
D	=	Particle size correlated to V_c
K_u	=	Curve fitting factor (6.19 for SI units and 11.17 for English units)

Equation A-1 states that the critical shear stress is directly proportional to two different properties, depth of flow and grain size. Grain size is also a variable in calculating the depth of contraction scour. In live-bed contraction scour, grain size is a variable used to determine the mode that bed material is being transported (Richardson and Davis, 2001). Similarly, in clear-water contraction scour the average depth of scour is proportional to an assumption based on the largest non-transportable particle in the bed material.

For calculating the scour depth around a pier HEC-18 suggests using equation A-2. This equation was created based on flume experiments in sand using different pier configurations and shapes.

$$\frac{y_s}{a} = 2.0 \cdot K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot \left[\frac{y_1}{a}\right]^{0.35} \cdot Fr_1^{0.43} \tag{A-2}$$

where:

y_s	=	Scour depth
y_1	=	Flow depth directly upstream of pier
K_1	=	Correction factor for pier nose shape
K_2	=	Correction factor for angle of attack of flow
K_3	=	Correction factor for bed condition
K_4	=	Correction factor for armoring by bed material size
a	=	Pier width
L	=	Length of pier
Fr_1	=	Froude Number directly upstream = $\frac{Velocity}{\sqrt{g \cdot y_1}}$
g	=	Acceleration due to gravity

In equation A-2 grain size is a variable in the constant K_4, a correction factor for armoring the pier by bed material. This correction factor reduces the amount of pier scour if the pier is considered protected by heavier coarse grain materials such as gravels. Throughout HEC-18, scour prediction equations are heavily influenced by grain size. This concept is based on the assumption that soils modeled in these scour predictions erode particle by particle. Erosion of coarse grained material such as sand and gravel occurs typically by rolling, sliding, or plucking of the particle. Close observations and slow motion cameras have determined that scour of these particles is typically a combination of these mechanisms (Briaud et al. 1999). Erosion of sands and gravels is mainly resisted by gravity forces from the weight of the particles. Using this logic, the larger the particle, the more shear stress it can resist. For example, it is understood that the shear stress needed to erode a grain of sand is much less than the shear stress needed to erode a boulder. However, HEC-18 uses these principles to predict the depth of scour of fine grained cohesive soils. HEC-18 does acknowledge that the rate, of scour may be much lower for cohesive soils, but states that the maximum scour depth should still be calculated by the equations above. In this regard, cohesive soils are considered to have a lower critical shear stress than sands using equation A-1. Also fine grained cohesive soils do not provide any protection against pier scour using the correction factor K_4 in equation A-2. In essence, the lack of understanding regarding scour of cohesive soils has resulted in a penalty using current design standards.

Until 2012, equation A-1 was the only means for calculating scour depth that HEC-18 had to offer. Although the model makes reference to cohesive soil parameters effecting erodibility, the equation itself does not incorporate any soil parameters and is based on the assumption that all soils behave like fine-grained sands (Briaud et al. 2013). In 2012 the HEC-18 (Arneson et al. 2012) model incorporated research by Briaud et al. (2011) which included the critical velocity as a variable in determining maximum scour depth. This is shown in equation A-3.

$$y_s = 2.2 * K_1 * K_2 * a^{0.65} * \left[\frac{2.6\, V_1 - V_c}{\sqrt{g}}\right]^{0.7} \qquad \text{(A-3)}$$

Where:

V_c = Critical velocity at which soil begins to erode, ft/s (m/s)
V_1 = Approach velocity, ft/s (m/s)

The critical velocity may be determined by conducting soil erosion tests or can be related to median grain size, D_{50} (Briaud et al. 2013). It is important to note, however, that median grain size is only included in the HEC-18 determination of maximum *contraction* scour depth. HEC-18 provides equation A-1 as a general means for determining critical velocity.

According to Briaud et al. (2013), because the critical velocity is incorporated into equation A-3 the soil parameters are also included. While critical velocity may inherently incorporate soil parameters when determined from soil erosion tests, it only includes particle size when calculated by means of Equation A-1. It should be considered that conducting soil erosion tests to determine the critical velocity of various materials is far from practical. With that said, representing critical velocity, or more broadly scour rate, as a function of conventional geotechnical parameters would be far more feasible.

A.2 Scour Rate in Cohesive Soils Method

Numerous studies have been performed to create a better understanding of scour of cohesive soils. Most of these studies involved channel or flume tests that simulated a flood event, and closely monitored scour. HEC-18 does acknowledge one study in particular as a method for predicting pier scour in cohesive soils. This research, performed at Texas A&M University, resulted in the SRICOS or Scour Rate in Cohesive Soils method, which started by determining the scour mechanisms in sands, clays, and rock (Briaud et al. 1999).

Water velocity ranges from 0.1 to 3.0 meters per second (m/s) in most rivers and streams. This velocity results in average bed shear stresses ranging from 1 to 50 N/m^2. Since the bed shear stresses resulting in scour are much less than the shear strength parameters typically found in clay, it is presumed that scour is a result of a cyclical failure (Briaud et al. 1999). Observations of scour in sands showed a quick immediate failure compared to the cyclical failure observed in cohesive soils. The different scouring methods of sand and clay suggest that the forces resisting scour are not similar. As previously stated the main force that resists scour in sand is gravity. Gravitational force is relatively small, depending on particle size. The resultant scour rates found in sand and resisted by gravitational forces, are represented in meters per hour. Research has shown Van der Walls forces, which hold clay particles together, can better resist the constant cyclical loading found in streams, resulting in scour rates in the order of millimeters per hour (Briaud et al. 1999). Similarly when scour occurs in clay, it does not occur particle by particle but in larger groups of particles or chunks.

The SRICOS method was created to predict the depth of pier scour with respect to time for a known flow velocity in a uniform cohesive soil. The SRICOS method involves testing a site specific soil sample in an EFA, or Erosion Function Apparatus, and recording scour rates for a range of velocities. The velocities tested in the EFA should encompass the expected shear stresses around the pier under flooding conditions. From EFA tests, an initial scour rate is established as the scour rate corresponding to the maximum shear stress expected during the flood event. A maximum scour depth is calculated based on site specific geometry and flow rates. Using the maximum scour depth, initial scour rate, and flood information, a flood specific scour depth is established.

The SRICOS method allows for an informed scour prediction to be made in cohesive soil. However, the SRICOS method makes certain assumptions that are not realistic in all streams. For instance the SRICOS method produces a depth of scour for one flood event, in a uniform soil layer (Briaud et al. 1999). This is not realistic as bridge piers will resist several floods with varying velocities over a design service period, and commonly are embedded into varying soil layers. To improve the accuracy of the SRICOS method Briaud et al. (2001a) expanded the SRICOS to encompass the full hydrograph throughout the design period. Also the Briaud et al. (2001a) expanded the SRICOS method to predict the maximum depth of scour in different soil layers. Since the combinations of varying soil layers and flood events can become very complex, a computer program was developed to calculate pier scour using the new Extended SRICOS (E-SRICOS) method. A Simple SRICOS (S-SRICOS) method was also created to accommodate scour predictions similar to the E-SRICOS method without the use of the SRICOS computer program (Briaud et al. 2001a)

The procedure for the E-SRICOS method is similar to the original SRICOS method. The maximum scour depth is still calculated using the mean flow velocity, diameter of the pier, and viscosity of the water. Samples are collected and tested in the same manner as the SRICOS method, and a velocity versus scour rate curve is created. The flow hydrograph is then created for the bridge, typically using a discharge hydrograph from the United States Geological Survey (USGS) near the bridge location (Briaud et al. 2001a). The flow hydrograph is then transformed into a velocity hydrograph using profile of the stream at the bridge crossing. Using the velocity hydrograph, the velocity versus scour rate curve created in the EFA, soil profiles, and general bridge properties the SRICOS program calculates the depth of pier scour throughout the entire design life of the bridge (Briaud et al. 2001a). Through several case studies Briaud et al. (2001a) found the maximum scour depth calculated, using HEC-18 standards, was not reached throughout the design life hydrograph

As previously stated the S-SRICOS method was created to produce similar results to the E-SRICOS method without the use of the SRICOS computer program. The maximum scour depth is calculated, usually related to the 100 year flood conditions. Site specific samples are collected and tested in the EFA to obtain erosion functions. It is important that samples are obtained and tested from all soil layers within the maximum scour depth (Briaud et al. 2001a). A single equivalent erosion function is then created by averaging the functions from all soils within the maximum scour depth. Using the flow hydrograph and bridge information, the maximum shear stress is calculated. The calculated maximum shear stress and combined erosion function are used to determine the scour rate corresponding to the maximum shear stress. An equivalent time factor is needed to reduce the number of iterations performed by the SRICOS computer program. The equivalent time is the time required for the maximum velocity in the hydrograph to create the same scour depth as the complete hydrograph (Briaud et al. 2001a). The equivalent time factor is a function of the design life of the bridge, the maximum velocity of the river, and the initial scour rate corresponding to the maximum shear stress. The total pier scour depth is then calculated using the equivalent time, initial scour rate, and maximum scour depth.

A.3 Erosion Function Apparatus

The quality of the SRICOS prediction is based on the results from the EFA test that is performed on site specific samples. The Erosion Function Apparatus is a closed channel flume-like machine equipped with a pump and a stepping motor. The bottom of the flume has a circular opening for testing a Shelby tube sample with a diameter of 76.2 mm. A watertight seal is created between the Shelby tube and the flume by an O-ring. The cross section of the rectangular flume is 101.6mm × 50.8 mm. The total length of the flume is 1.22 meters. The pump is regulated by a valve on the front of the EFA, and generates velocities ranging from 0.1 to 6 m/s. The Shelby tube is held flush at the bottom of the flume during testing. A piston attached to the stepping motor protrudes the sample from the Shelby tube into the flume in 1mm increments (Briaud et al. 2001b). The EFA can be viewed in Figure A-1 below. The EFA is instrumented with a thermistor and a paddle flowmeter to electronically monitor the temperature and flow rate on a computer.

Figure A-1. Erosion Function Apparatus

The first step in performing an EFA test proposed by Briaud is to place the sample in the EFA, fill the flume with water and wait an hour. Next the flow velocity is set to 0.3 m/s and the sample was advanced 1 mm into the flume. The EFA is equipped with a viewing glass so that a technician can observe the erosion of the sample. After the sample is advanced 1 mm it is the responsibility of the technician to record how much time it takes for the 1mm sample to erode. After 1 mm has eroded, or after one hour of testing, the sample is advanced to the 1 mm protrusion location and the velocity increased to 0.6 m/s. The erosion of the sample is again monitored and the time for the 1 mm protrusion to erode is recorded. The sample is advanced and the erosion timed for velocities of 1 m/s, 1.5 m/s, 2.0 m/s, 3/0 m/s, 4.5 m/s, and 6 m/s (Briaud et al. 2001b). A schematic of a prepared EFA test can be viewed in Figure A-2.

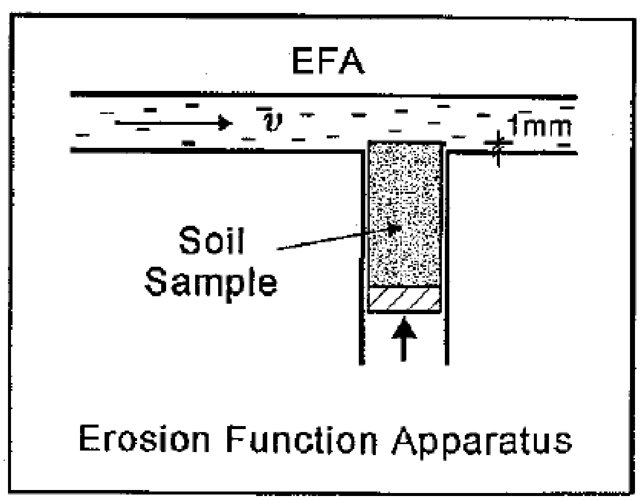

Figure A-2. Schematic of EFA Test

The results from the EFA are used to create an erosion function, which is used in the scour calculations of the SRICOS method. An example of an erosion function can be viewed in Figure 2-3. The erosion function is derived from a velocity versus erosion rate relationship that is created from the EFA data. An erosion function shows the relationship between erosion rate and shear stress for a given soil. Velocity is related to shear stress by using the geometry of the flume, density of water, and friction factor obtained from a Moody Chart. It is imperative the erosion function encompass all shear stresses expected in the stream bed during design flood conditions.

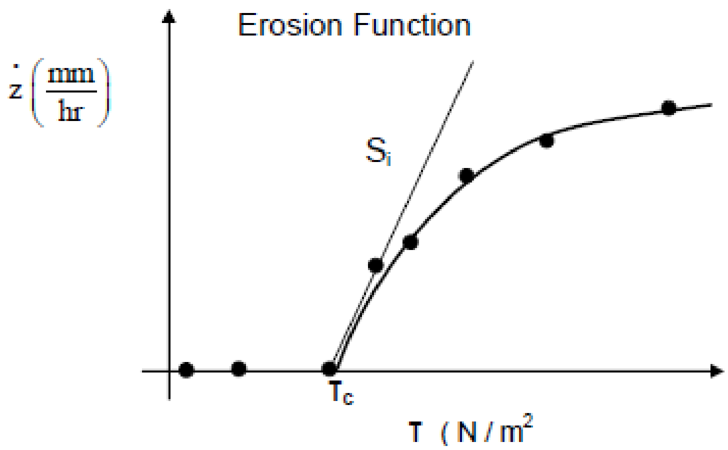

Figure A-3. Typical Erosion Function

Other than the relationship between shear stress and erosion rate, an erosion function provides two critical values that are used in scour predictions. The critical shear stress (τ_c) is the bed shear stress at which scour first occurs (Mobley 2009). The critical shear stress is found by observation while performing an EFA test. During erosion testing flow is gradually increased until erosion begins. This velocity is converted to a shear stress, recorded, and plotted on the erosion function. The initial erodibility (S_i) measures how fast scour occurs just after the critical shear stress is reached. The initial erodibility is calculated by drawing a line tangent to the erosion function through the critical shear stress (Crim 2003). Generally, the slope of the initial erodibility is higher in sands compared to cohesive soils.

Since the results of EFA tests are important to producing quality scour estimates using the SRICOS method, it is integral that scour rates are calculated with accuracy. The determination of scour rates can be a subjective process as erosion is typically not uniform in cohesive soils. Previous research suggested the technician performing an EFA test should estimate when one millimeter of scour has occurred by taking an average across the surface (Crim 2003). However, averaging is subjective and not consistent with different technicians. Several attempts have been made to reduce the subjectivity in erosion testing. The University of Florida created two different apparatuses to objectively measure scour of cohesive soil and soft rock.

A.4 Alternatives to the Erosion Function Apparatus

The Rotating Erosion Test Apparatus (RETA) was designed to determine the volume of erosion of stiff clay, sandstone, and limestone. A schematic of the RETA is shown in Figure A-4. The RETA performs an erosion test on a 102 mm long cylindrical soil sample with either a 61 mm inch or 102 mm diameter (Sheppard et al. 2005). A 6.4 mm diameter hole is drilled vertically through the sample and a support shaft that attaches to the RETA is inserted through the sample. The opposite end of the shaft is attached to a torque cell and clutch that is fixed to a surface (Sheppard et al. 2005). A larger diameter cylinder is placed over the sample, and water is added to fill the annulus between the sample and the outer cylinder. The outer cylinder is rotated using a motor and pulley system to create a shear stress on the surface of the sample. After a known duration of time the test is stopped and the test sample is measured radially and any eroded material is oven dried to determine the mass of the scoured soil. The shear stress is calculated by knowing the amount of torque applied to the sample along with the initial radius and length of the test specimen. The erosion rate is calculated using the change in radius, duration of the test, mass density of sample, and original sample geometry (Sheppard et al. 2005).

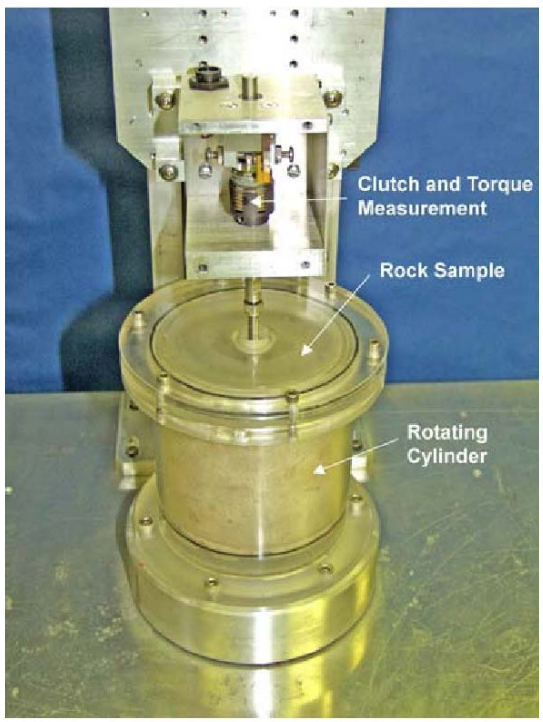

Figure A-4. Rotating Erosion Test Apparatus (RETA)

The RETA is an acceptable testing apparatus for determining erosion rate and shear stress relationship. The RETA is not ideal however since it does not test the appropriate failure plane. A soil specimen in a stream bed will be exposed to shear stress and eroded from the top down, where the RETA measures scour on a radial plane. Also, the sample preparation is difficult for the RETA specimen, as it can be difficult to create a consistent curvature around the entire outer diameter of the sample. If the radius of the sample is not consistent the shear stress will not be equally distributed throughout the sample causing irregular erosion.

The Sediment Erosion Rate Flume (SERF) is the second apparatus created at the University of Florida for the purpose of measuring relationships between erosion rate and shear stress. The SERF functions similar to the EFA. Like the EFA, the SERF uses a flume with a rectangular cross section, a water pump, a reservoir, and a stepping motor. The SERF does have a larger water capacity than the EFA, as it utilized two pumps and has an 1100 gallon reservoir. The SERF is much more automated than the EFA, using multiple instruments and a Labview program. Images of the SERF are shown in Figure A-5 and Figure A-6.

Figure A-5. Sediment Erosion Rate Flume (SERF)

The SERF utilizes a Multiple Transducer Array (MTA) created by SeaTek to scan across a Shelby tube sample (Sheppard et. al, 2005). This array consists of 12 ultrasonic transducers that are used to measure the distance from the top of the flume to the surface of the sample. A schematic of the ultrasonic sensor used in the SERF is shown in Figure A-7. The ultrasonic transducers are spaced so that both a 73 mm and 955 mm soil/rock sample can be scanned (Sheppard et. al, 2005). The data collected by the ultrasonic transducers are used in a Labview program to control the positioning of the sample being tested. Unlike the EFA the soil sample does not protrude from the bottom of the flume, but is kept level with the base of the flume. Once the sample averages a total scour of 0.5 millimeters, as detected by the ultrasonic sensor, the sample is automatically advanced by the stepping motor. After the test is completed the erosion rate is calculated by dividing the length of sample advanced by the stepping motor by the amount of time the test was performed. A video camera is used to verify the results from the SERF and to determine the method of erosion.

Figure A-6. SERF Sample Chamber and Stepping Motor

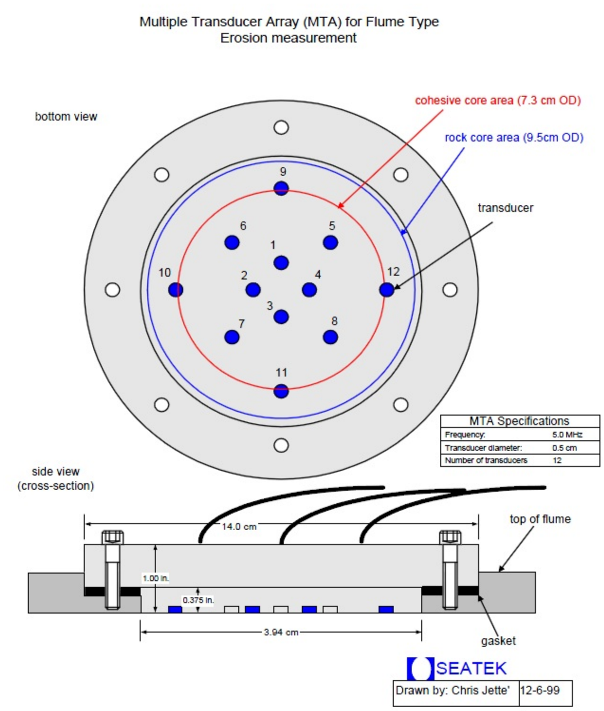

Figure A-7. Multiple Transducer Array Designed for SERF

Researchers at the Georgia Institute of Technology created and used another alternative to the Erosion Function Apparatus. A rectangular, tilting, recirculating flume was altered and utilized with the same general function of the EFA and SERF machines (Navarro 2004). The flume used was considerably larger than the ones used in the EFA and SERF with a length of 6.1 meters, width of 0.38 meters, and depth of 0.38 meters. Two variable-speed pumps generated flow to the flume. Adhered to the flume bed were gravel particles with a mean diameter of 3.3 millimeters (Navarro 2004). These gravel particles were used to assure fully developed and fully rough turbulent flow (Navarro 2004). The basin, which fed both pumps, had a holding capacity of approximately two cubic meters.

Shelby tube samples were collected using formations consisting of both cohesive and cohesionless materials. The Shelby tube was placed below a circular opening in the bottom of the flume, and the measurement of erosion was determined using a linear variable differential transformer (LVDT) attached to a piston which advanced the sample into the flume (Navarro 2004). An operator controlled the apparatus that advanced a piston during erosion testing, to ensure the sediment surface was level with the top of the gravel bed in the flume. This procedure is similar to the procedure for operating the SERF. These tests were run continuously at varying velocities throughout the entire length of a Shelby tube sample to mirror typical field stratification (Navarro 2004).

Erosion rates are calculated by converting the vertical displacement measured by the LVDT into mass eroded, using the dry density of the tested sample. The product of the vertical displacement and dry density of the sample is divided by the time interval over which the erosion occurs to determine the erosion rate at a given velocity or shear stress.

A.5 Scour Relationships with Geotechnical Parameters

Generally speaking the critical shear stress of fine grained soils increases when the soil unit weight increases, Plasticity Index increases, unconfined compressive strength increases, void ratio decreases, swell decreases, percent fines increases, and water temperature increases (Briaud et al. 1999). Erosion rates are influenced by the hydraulic shear stress applied, the clay content, the soil and water temperature, the soil and water chemical composition, the soil water content, the plasticity index, the soil unit weight, the soil undrained shear strength, and the mean grain size (Briaud et al. 1999). Briaud et al. (1999) found general qualitative relationships relating critical shear stress and initial erodibility to plasticity index, undrained shear strength, and percent fines (percent passing #200 sieve). Briaud et al. (1999) also plotted a correlation between critical shear stress and initial erodibility showing that as critical shear strength increases, initial erodibility decreases. Research hints that a correlation between scour parameters and geotechnical parameters is complex and involves a combination of many parameters. Research at the University of Florida developed a correlation between cohesive strength and erosion rates of limestone cores (Sheppard et al. 2006). This function relates erosion rate to applied hydraulic shear stress, unconfined compressive strength, and splitting tensile strength. Further research at the Georgia Institute of Technology suggests a correlation of critical shear stress with the percent fines and median particle diameter (Sturm et al. 2004). This relationship suggests the smaller the particle size of a given formation the greater the influence of interparticle forces on the erodibility of the formation. Although these relationships are relatively unproven it does show that a correlation is possible between cohesive materials and erosion rates.

A.6 Previous Scour Research at Auburn University

Auburn University has operated an Erosion Function Apparatus since 2001. Crim (2003) detailed work to develop a better understanding of the inner workings of the EFA, published a procedure, and created erosion functions as defined in the SRICOS method. With Shelby tube samples provided by ALDOT, Crim constructed erosion functions of five different Alabama cohesive soils. Crim tested samples from Goose Creek in Wilcox County, culverts on US 84 in Covington county, Linden Bypass in Marengo County, County Road 5 over Cheaha Creek in Talladega County, and Alabama State Road 123 over Choctawatchee River in Dale County.

The Goose Creek samples yielded critical shear stresses between 0.4 N/m^2 to 4.5 N/m^2, with an initial erodibility ranging from 0.18 $mm/hr/N/m^2$ to 5.6 $mm/hr/N/m^2$. The Covington County samples provided critical shear stresses between 1.1 N/m^2 to 3.1 N/m^2 with initial erodibilities between 1.72 $mm/hr/N/m^2$ to 6.06 $mm/hr/N/m^2$. The Marengo County samples had a critical shear stress between 0.85 N/m^2 to 4.7 N/m^2 and an initial erodibility of 0.38 $mm/hr/N/m^2$ to 11.42 $mm/hr/N/m^2$. A critical shear stress ranging between 0.6 N/m^2 to 2.82 N/m^2 and initial erodibility of 0.42 $mm/hr/N/m^2$ to 410$mm/hr/N/m^2$ was determined from the samples from Talladega County. Finally, Crim witnessed a critical shear stress between 1.25 N/m^2 to 2.5 N/m^2 and an initial erodibility between 0.96 $mm/hr/N/m^2$ and 1.2 $mm/hr/N/m^2$ for the Choctawhatchee River samples in Dale County. Overall Crim witnessed scour rates ranging from 0 mm/hour upwards of 100 mm/hour. Crim plotted the results from the erosion functions and geotechnical tests comparing critical shear stress and plasticity index between samples with varying Standard Penetration Test N Values. Crim also plotted results compatible with Briaud's relationship between initial erodibility and critical shear stress.

Mobley (2009) continued research with the EFA at Auburn. This work also showed erosion testing is highly variable and that few similarities exist in testing different formations. Mobley tested soils from Talladega County, Sumter County, and Dallas County. Mobley witnessed a high variability in erosion rates from the Talladega County soils, for example, the erosion rate during the first 10 minute test was much larger than the erosion rate during the last 60 minute test at the same velocity or shear stress. Generally, the critical shear stress of the Talladega County soils ranged from 0.61 N/m^2 to 4.5 N/m^2. Mobley tested rock core samples from Sumter County. Mobley was unable to generate an erosion function for the Sumter County samples due to difficulty in sample preparation. One test from Sumter County showed scour resistance with a flow velocity of 0.75 m/s. The Dallas County samples consisted of soil from the Mooreville Chalk formation. Mobley performed three EFA tests on the Dallas County samples at the highest velocity generated by the EFA, approximately 6 meters per second. None of these tests exhibited scour over a duration of two hours. Mobley stated the critical shear stress of the Mooreville Chalk was in excess of 45 N/m^2. Mobley also declared scour performance was highly variable between formations and was somewhat depended on sample preparation.

Due to limited soil samples, Mobley tested model soils with varying densities and clay content. Mobley determined that model soils with higher density and higher clay content resulted in higher critical stresses and lower erosion rates.

A.7 Previous Scour Research by Others

Sheppard et al. (2006) determined the critical shear stresses, using the SERF, for uniform sands ranging from 0.08 N/m^2 to 0.75 N/m^2. The critical shear stresses measured were increasing with mean grain size. Erosion rates for these tests exceeded 300 mm/hr.

Sheppard et al. (2006) also created erosion rates for natural limestone core samples. Eight of these cores were tested in the RETA with once core tested in the SERF. The SERF, limited by shorter test duration, observed no scour during testing. Erosion functions for the limestone cores were created using the RETA. These tests yielded a minimum critical shear stress of 20 N/m^2 ranging upwards of 35 N/m^2. The erosion rates calculated on the limestone were much lower than those observed in the uniform sands with a maximum erosion rate of 6 mm per year at a shear stress of 70 N/m^2.

In addition to the tests described above Sheppard et al. (2006) performed erosion tests on cemented sands in an effort to mimic the scour behavior of sands with cohesive materials. The results of these tests varied due to the difficulty of sample preparation. The critical shear stress of these samples ranged from 5 N/m^2 to 10 N/m^2. An estimate of erosion rate was created for these samples using the erosion function, splitting tensile strength, and unconfined compression strength.

Navarro (2004) performed erosion tests in a large scale flume, as described above, to produce critical shear stresses of soil samples obtained in Georgia. Samples obtained from Murray County in northern Georgia had critical shear stresses ranging from 3 N/m^2 to 21 N/m^2. These Shelby tube samples consisted of non-plastic silty sands. Samples acquired from Towns County consisted of sandy silt and had critical shear stresses ranging from 6.82 N/m^2 to upward of 21N/m^2. Sandy silt soil samples collected from Habersham County had a large range of critical shear stresses from 2.5 N/m^2 to upwards of 21 N/m^2. Samples collected from Haralson County were a silty sand with critical shear stresses ranging from 3 N/m^2 to 12 N/m^2. Bibb County samples varied from a poorly graded sand with silt having a critical shear stress of 3.32 N/m^2 to a lean clay with sand having a critical shear stress of 9.68 N/m^2. Samples collected from Wilkinson County consisted of a poorly graded sand with silt with a critical shear stress of 0.44N/m^2 and a fat clay with a critical shear stress greater than 21 N/m^2. Clayey sand collected from Effingham County also had a critical shear stress greater than 21 N/m^2. However a poorly graded sand in Effingham County had a critical shear stress of 3.24 N/m^2. Soils sampled from Decatur County were a clayey and silty sands with critical shear stresses ranging from 2.5 to 7.9 N/m^2. Clayey sand samples and fat clay samples collected from Berrien County had a critical shear stress greater than 21 N/m^2. Finally Navarro (2004) tested a clayey sand with gravel from McIntosh County finding a critical shear stress of 17.17 N/m^2. These critical shear stresses are compatible with common critical shear values ranging from 0.5 N/m^2 to 5.0 N/m^2 reported by Briaud et al. (1999).

Appendix B Phase I Testing

Appendix B summarizes detailed information on sampling, EFA testing, and geotechnical tests of six soil formations (Bucatunna clay, Tazoo clay, Demopolis chalk, Mooreville chalk, Prairie Bluff chalk, and Porter's Creek clay) during the phase I testing of the study. Sampling six formations was conducted by ALDOT drilling crew, and EFA testing and geotechnical tests were primarily performed by graduate student Mr. Walker at Auburn University. Additional information of phase I testing can be found from Walker's Master thesis.

Tables B-1 to B-13 report visual and ultrasonic elapsed times (in min) and scour rates (mm/hr) for each replicate test. The purpose to report visual elapsed time and scour rate is to independently verify ultrasonic elapsed time and scour rate because ultrasonic sensor implemented in Auburn EFA was first time used to test different soil formations in Alabama. Overall scour rates considering both swelling and erosion of the soil samples, which was discussed in the section 3.3.2 "Data Analysis of Scour Rates", are also reported in Tables B-1 and B-13.

B.1 Bucatunna Clay

The first formation tested using the updated EFA featuring the ultrasonic sensor was the Bucatunna Clay located in southern Alabama. The Bucatunna Clay formation was sampled using the CME continuous sample system.

B.1.1 Sampling

The Bucatunna Clay formation was sampled on April 5, 2012 in Monroe County, Alabama. An ALDOT geologist classified the Bucatunna Clay formation as a dark grey to brown clay. The formation was located with the assistance of an ALDOT geologist at a depth of 11 feet below the ground surface. A Standard Penetration Test was performed between 11.5 and 13 feet below the ground surface, yielding a SPT N value of 6. Three different continuous samples were taken from depths 13.5 to 18.5 feet, 18.5 to 23.5 feet, and 23.5 to 28.5 feet. Since this was the first sample procured using the CME continuous sample system and because the Bucatunna Clay was relatively soft, a Shelby Tube was advanced from 28.5 to 30.5 feet. The Shelby Tube sample was acquired as a back-up in case EFA testing could not be performed with the continuous samples. Lastly, another Standard Penetration Test was performed between 30.5 and 32 feet with a SPT N value of 9.

The continuous sample from 13.5 to 18.5 feet was determined to be unusable for EFA testing. The top of the sample was not usable as it had a plug missing from the Standard Penetration test taken above. The sample gathered from 13.5 to 18.5 feet meters was also smaller radially than the sample tube at the base of the sample as shown in Figure B-1.

Figure B-1. Bucatunna Clay Sample Smaller Radially than Sample Tube

The second sample of the Bucatunna Clay formation ranged from 18.5 to 23.5 feet and was mostly unusable. The entire top half of the sample was severely fractured in all directions and could not be used for EFA testing. However, the bottom third of the bottom half of the sample was mostly un-cracked and sections could be used for EFA testing. The third and final sample from 23.5 to 28.5 feet was wrinkled at the top with the bottom 20 to 30 mm un-cracked. It appeared in the second and third samples that the soil was failing in shear during sampling along the tube walls. This would be possible if the rotating head of the continuous sampler did not fully separate the sample from the rotation of the hollow stem auger and the sample was shoved and twisted into the tubes. This phenomenon was observed and monitored throughout the sampling of all formations and these disturbed and cracked regions were not tested in the EFA. These regions were however used in geotechnical testing where soil was processed prior to testing.

B.1.2 EFA Testing

The Bucatunna Clay was the first formation tested at Auburn University using the ultrasonic sensor and data acquisition system. In total 32 EFA tests were performed on the Bucatunna Clay formation with 27 tests providing results for determining a scour rate versus velocity relationship. The first sample used for EFA testing was located at approximately 27 feet below the ground surface. The first test titled “Bucatunna27.0_1” was performed to determine a starting velocity for testing. The data collected from “Bucatunna27.0_1” is shown below in Figure B-2.

The “Bucatunna 27.0_1” test specimen began at a starting velocity of 0.3 m/s, and was advanced 1 mm into the flume after approximately 5 minutes. This can be viewed in the jump at the five minute mark in Figure B-2, and further proves the validity of the ultrasonic sensor. The “Bucatunna 27.0_1” sample actually showed a net gain in height over the next hour while the velocity was held at 0.3 m/s. This seemed odd that the sample was actually rising into the flume as the shear stress was applied to the sample, but this movement was visually confirmed. After one hour, no scour was observed and the sample had raised an average of 2.5 mm. It was believed that this swelling was due to the Bucatunna Clay being a swelling clay formation, and this issue would be confirmed during geotechnical testing. As seen in Figure B-2, once the velocity was increased to 0.6 m/s the "Bucatunna27.0_1" sample scoured significantly. From the results of "Bucatunna 27.0_1" it was determined that the Bucatunna Clay formation did not scour at 0.3 m/s, the threshold velocity was between 0.3 and 0.6 m/s, and that further scour testing should start at a flow velocity of 0.6 m/s.

Five EFA tests were performed on the Bucatunna Clay formation at a flow velocity of 0.6 m/s. Table B-1 below shows the test results obtained by visual observation along with the ultrasonic sensor.

As shown in Table B-1, the elapsed time for erosion as determined by the EFA were similar to the elapsed time observed. The largest difference in the observed and measured elapsed time was two minutes as seen in test "Bucatunna 27.0_4". The scour rates for the five tests were similar with "Bucatunna 27.0_5" having a slightly higher scour rate of 5.0 mm/hour and "Bucatunna 27.0_6" having a slightly lower scour rate. The average scour rate at 0.6 m/s as calculated by the ultrasonic sensor was 3.91 millimeters per hour (mm/hr).

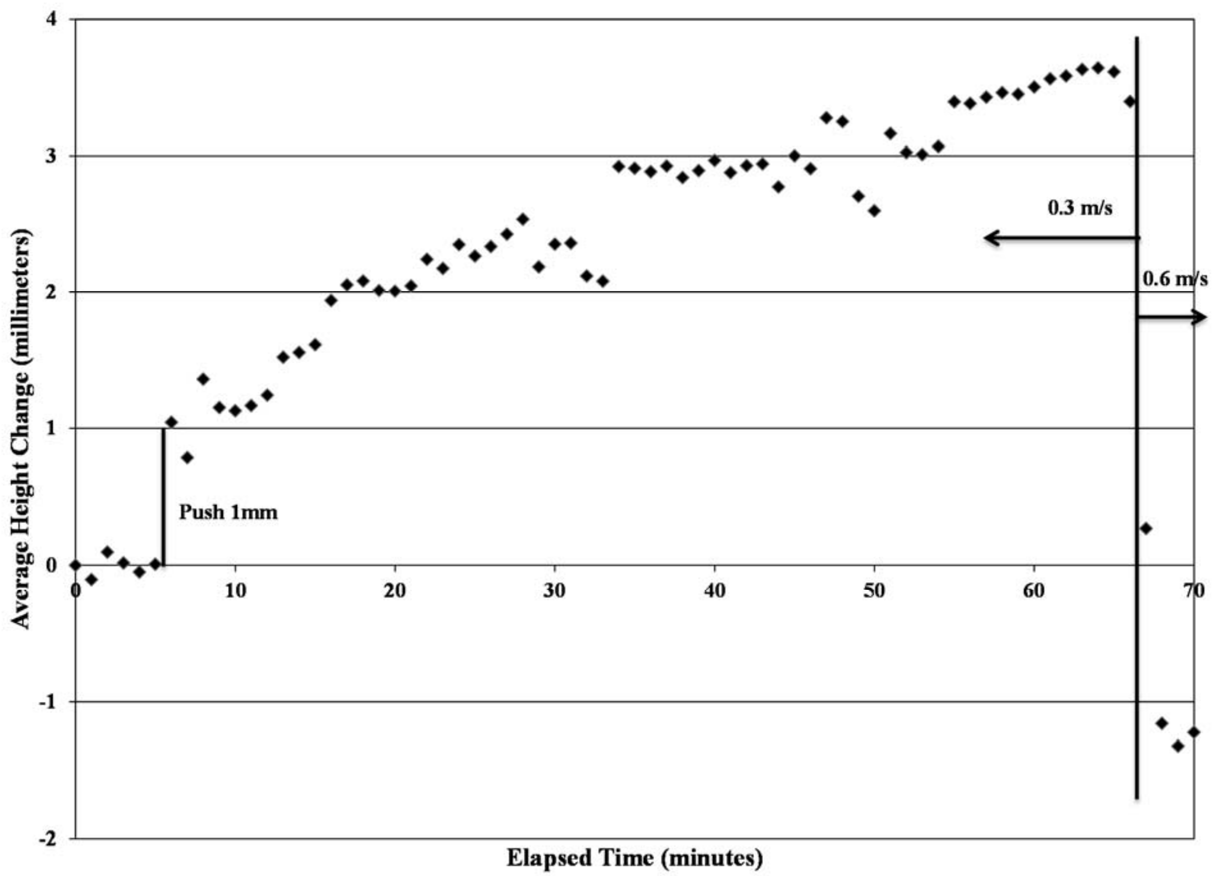

Figure B-2. Bucatunna 27.0_1 Results

Table B-1. Bucatunna Clay Results at 0.6 m/s

Sample:	Elapsed Time Ultrasonic (min)	Elapsed Time Visual (min)	Scour Rate Ultrasonic (mm/hr)	Scour Rate Visual (mm/hr)	Overall Scour Rate [1] (mm/hr)
Buccatunna 27.0_3	14	13	4.29	4.62	2.19
Buccatunna 27.0_4	17	15	3.53	4.00	6.67
Buccatunna 27.0_5	12	13	5.00	4.62	7.10
Buccatunna 27.0_6	22	22	2.73	2.73	0.28
Buccatunna 27.0_7	15	15	4.00	4.00	8.22

[1] See the section 3.3.2 "Data Analysis of Scour Rates".

Seven EFA tests were performed at a flow velocity of 1.0 m/s. Table B-2 shows the results obtained for the tests performed at 1.0 m/s. The elapsed time and subsequent scour rates observed at 1.0 m/s were more variable than those observed at 0.6 m/s. Seven tests were performed as two tests "Bucatunna 27.5_3" and "Bucatunna 27.5_4" were uncharacteristic of the rest of the data set with elapsed times measured at 7 and 38 minutes respectively. As seen in Table B-2, the "Bucatunna 27.5_3" test was unable to be visually observed, but visual observations were once again relatively close to ultrasonic sensor calculations. It was also observed that the "Bucatunna 27.5_3" test appeared to be softer than insitu conditions prior to testing, explaining the high scour rate. The average erosion rate for the 7 EFA tests performed on the Bucatunna Clay formation at a flow velocity of 1.0 ms/ was 4.07 mm/hr.

Table B-2. Bucatunna Clay Results at 1.0 m/s

Sample:	Elapsed Time Ultrasonic (min)	Elapsed Time Visual (min)	Scour Rate Ultrasonic (mm/hr)	Scour Rate Visual (mm/hr)	Overall Scour Rate (mm/hr)
Buccatunna27.5_2	13	14	4.62	4.29	6.20
Buccatunna27.5_3	7	N/A	8.57	N/A	13.65
Buccatunna27.5_4	38	24	1.58	2.50	2.65
Buccatunna27.5_5	15	16	4.00	3.75	6.85
Buccatunna27.5_6	17	17	3.53	3.53	5.56
Buccatunna27.5_7	18	18	3.33	3.33	8.77
Buccatunna27.5_8	21	17	2.86	3.53	12.62

Five tests were performed at a flow velocity of 1.5 m/s, and the results are shown in Table B-3. As expected the scour rates increased compared to those measured at lower velocities, with an average scour rate of 5.59 millimeters per hour. The data set acquired from this velocity had a low variability with the exception on the "Bucatunna 26.5_3" test that had a higher scour rate. It was encouraging that this data set was relatively close with respect to scour rates as it was the first data set tested using two different sample depths. It was noted during testing that a sand seam was located approximately 50 millimeters above the “Bucatunna 26.5_3” test sample. However, subsequent tests using this sample showed the same scour characteristics as previous test samples.

Table B-3. Bucatunna Clay Results at 1.5 m/s

Sample:	Elapsed Time Ultrasonic (min)	Elapsed Time Visual (min)	Scour Rate Ultrasonic (mm/hr)	Scour Rate Visual (mm/hr)	Overall Scour Rate (mm/hr)
Buccatunna27.5_9	14	11	4.29	5.45	7.70
Buccatunna26.5_2	12	11	5.00	5.45	23.88
Buccatunna26.5_3	7	8	8.57	7.50	18.14
Buccatunna26.5_4	13	14	4.62	4.29	7.42
Buccatunna26.5_5	11	11	5.45	5.45	12.39

Five EFA tests were performed on the Bucatunna Clay formation at a flow velocity of 2.0 m/s. The results from these tests can be viewed in Table B-4. The test titled “Bucatunna 26.5_7” was the lone outlier in this data set with an elapsed time of 22 minutes. However, there were not any oddities or special notes recorded with regards to this test, it just seemed as though this test was more scour resistant than other tests at this velocity. Overall the average scour rate at a flow velocity of 2.0 m/s was 6.67 mm/hr.

Table B-4. Bucatunna Clay Results at 2.0 m/s

Sample:	Elapsed Time Ultrasonic (min)	Elapsed Time Visual (min)	Scour Rate Ultrasonic (mm/hr)	Scour Rate Visual (mm/hr)	Overall Scour Rate (mm/hr)
Buccatunna26.5_6	10	10	6.00	6.00	12.63
Buccatunna26.5_7	22	20	2.73	3.00	4.63
Buccatunna26.5_8	10	10	6.00	6.00	11.52
Buccatunna26.5_9	7	8	8.57	7.50	13.42
Buccatunna26.5_10	6	8	10.00	7.50	18.28

The final velocity used in EFA testing of the Bucatunna Clay formation was at 3.0 m/s. Five EFA tests were performed at this velocity and two separate samples were used, similar to the tests performed at 1.5 m/s. The results from the tests performed at 3.0 m/s are included in Table B-5. At this high velocity, erosion occurred rather quickly averaging less than 6 minutes per test. Since the time for erosion was so brief, instead of advancing the sample after five minutes, the sample was advanced into the flume after only being exposed to flow for two minutes. This minimized the possibility of erosion prior to advancing the sample. The average scour rate at 3.0

m/s was 11.01 mm/hr, a jump of 5.0 mm/hr above the average scour rate at a flow velocity of 2.0 m/s.

Table B-5. Bucatunna Clay Results at 3.0 m/s

Sample:	Elapsed Time Ultrasonic (min)	Elapsed Time Visual (min)	Scour Rate Ultrasonic (mm/hr)	Scour Rate Visual (mm/hr)	Overall Scour Rate (mm/hr)
Buccatunna26.5_11	8	10	7.50	6.00	10.94
Buccatunna26.5_12	7	8	8.57	7.50	16.12
Buccatunna23.0_1	5	8	12.00	7.50	24.90
Buccatunna23.0_2	5	5	12.00	12.00	31.93
Buccatunna23.0_3	4	5	15.00	12.00	32.78

The final test performed on the Bucatunna Clay formation was aimed at determining the critical shear velocity of the formation. Since previous tests on the Bucatunna Clay formation was scour resistant, and actually swelled, at 0.3 m/s and scoured at 0.6 m/s, the critical shear velocity was located between the two velocities. The test titled "Bucatunna 23.0_4" was started with a flow velocity of 0.3 m/s and gradually increased until scour was observed. The flow velocity was held between 0.35 and 0.4 meters per second for approximately 15 minutes, and again swelling was observed instead of scour. Slowly the flow velocity was increased between 0.45 and 0.5 m/s. At this velocity a large chunk eroded from the sample. Figure B-3 shows the sample immediately after erosion occurred. This image agrees with the ultrasonic sensor, while portions of the sample are located above the base of the flume, the majority of the sample has eroded in deep pockets below the flume. From this test it was determined that the threshold velocity was 0.45 m/s.

Figure B-3. Bucatunna 23.0_4 After Erosion Occurred

B.1.3 Geotechnical Testing

As part of the scope of this research several common geotechnical index tests were performed on the Bucatunna Clay formation. Two initial moisture contents were taken to obtain the insitu moisture content of the formation prior to EFA testing. These tests yielded moisture contents of 49.5 and 46.2 percent, with an average of 47.9 percent. Using ASTM D421 – 85, several kilograms of the soil obtained during sampling was processed and oven dried. Using this processed soil, a full grain size distribution was performed on the formation following ASTM D422 – 63. The results of the grain size analysis are shown in Figure B-4. Since this research revolved around fine grained materials, a coarse sieve analysis was not performed as the maximum particle size diameter for this formation was approximately 0.43 millimeters. From the grain size analysis the mean particle diameter (D_{50}) was calculated to be 0.033 millimeters. Approximately 65 percent of the sample passed the number 200 sieve classifying the formation in the silt and clay family.

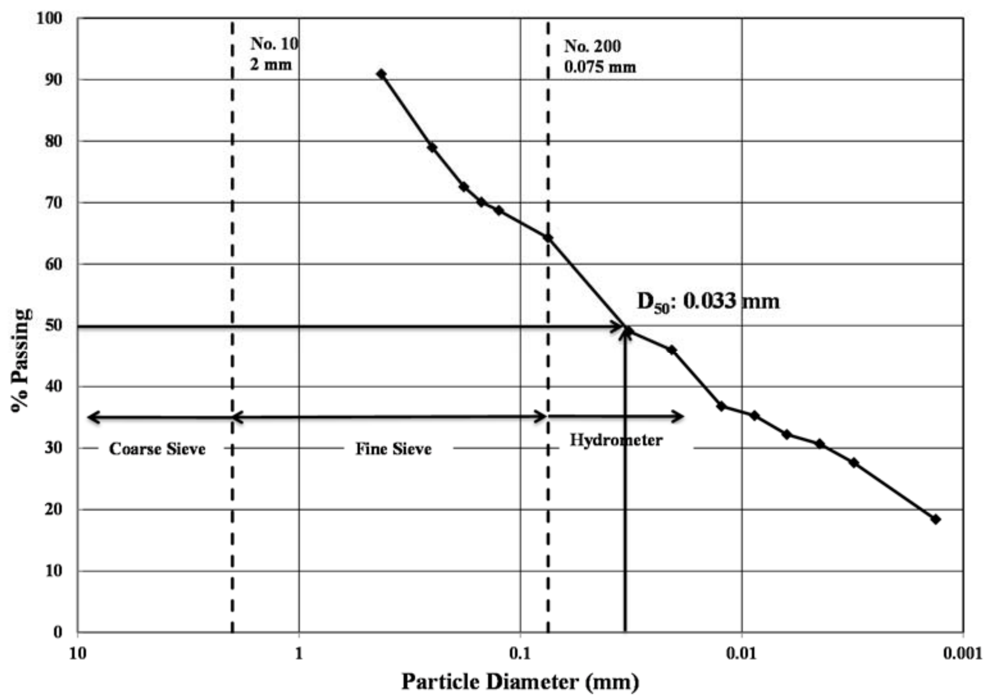

Figure B-4. Bucatunna Clay Grain Size Distribution

Atterberg limits were determined to complete the soil classification and geotechnical testing of the Bucatunna Clay formation. The procedure presented by ASTM D4318 was followed when determining these Atterberg limits. The liquid limit was determined to be approximately 68, while the plastic limit was found to be 39. Using the Atterberg limits, the plasticity index was 29. The high plasticity index of 29 is well above the threshold classifying this formation as a swelling clay. This explains the swelling phenomenon observed in a few tests at velocities below the critical shear velocity.

As previously stated, the recovered sample was not conducive to being used in an unconfined compression test as the sample was cracked at intervals tighter than the minimum test length of 115 millimeters.

B.2 Yazoo Clay

The second formation tested using the updated EFA featuring the ultrasonic sensor was the Yazoo Clay formation located in southern Alabama. The Yazoo Clay formation was sampled using the CME continuous sample system. EFA tests along with geotechnical index tests were also performed on the Yazoo Clay formation.

B.2.1 Sampling

The Yazoo Clay formation was sampled on April 6, 2012 in Conecuh County, Alabama. An ALDOT geologist classified the Yazoo Clay formation as a light colored stiff grey clay. The Yazoo Clay formation was sampled above a box culvert crossing a stream with a visible outcrop of the formation viewed in the streambed. An ALDOT geologist identified the formation in drill cuttings and split spoon samples at approximately 13.5 feet below the ground surface. A Standard Penetration Test was performed at the top of the formation yielding an N value of 15 blows. Three total CME continuous sample runs were performed on the Yazoo Clay formation with varying results.

The first run was taken from 14 to 19 feet below ground surface. The top half was disturbed and unusable for EFA testing due to the Standard Penetration Test which was terminated at 15 feet. The bottom half of the first run provided several sections that were testable in the EFA. The second continuous sample run was performed between 19 and 24 feet below the ground surface. The top tube of the run had many cracked sections that were not able to be used in the EFA, but could be used for classification and index testing. The bottom tube of the sample run from 21.5 to 24 feet had several EFA testable sections. The third and final sample run was performed between 24 and 29 feet below ground surface. After this continuous sample was obtained it was a sandy material that was noticed at a depth of 27 feet. The Yazoo clay material obtained in this third run was completely unusable as a transition into the sandy material below was apparent. Due to the change in material, another Standard Penetration Test was not performed after sampling.

B.2.2 EFA Testing

A total of twelve EFA tests were performed on the Yazoo Clay formation. After the samples were brought back to Auburn University and stored for testing, it was determined that much less of the formation was able to be tested in the EFA than originally thought. The best section for EFA testing was approximately one third of a meter long between 18 feet and 19 feet below the ground surface. It was noted during sample preparation that the Yazoo Clay formation was much tougher to cut and create a smooth sample surface. It was apparent that the sand content in the Yazoo Clay formation was much higher than the Bucatunna Clay formation.

The first test performed on the Yazoo Clay formation was used to help determine the starting test velocity and was titled “Yazoo Clay 18.5_1”. The “Yazoo Clay 18.5_1” test started with a flow velocity of 0.3 m/s, and scour was not observed. After one hour the flow velocity was increased to 0.45 m/s and immediately a wedge of the sample scoured away. This wedge developed shortly after the test was started and grew in size throughout the test, and image of this wedge can be viewed in Figure B-5. However, since this method of failure had not yet been observed a second test titled “Yazoo Clay 18.5_2” was performed starting at a flow velocity of 0.45 m/s.

Figure B-5. Yazoo Clay 18.5_1 Test Failure Wedge

The “Yazoo Clay 18.5_2” test did not perform similarly to the previous test but exhibited a swelling characteristic similar to that observed in the Bucatunna Clay formation. The test was started at a flow velocity of 0.45 m/s and did not scour after one hour. The flow velocity was then increased to 0.6 m/s for an hour in which scour was not observed. The flow velocity was then increased temporarily to 0.8 m/s for fifteen minutes before being increased once again to 1.0 m/s. During this time the test sample rose and had average height of 1.75 millimeters, and developed a large crack in the center of the sample as shown in Figure B-6. After the test sample was exposed for 25 minutes at a flow velocity of 1.0 m/s, the sample scoured well below the bottom of flume as shown in Figure B-7. The test was analyzed and it was determined that the testing regiment should be started at a flow velocity of 1.0 m/s.

Figure B-6. Yazoo Clay 18.5_2 Test Swelling and Cracking

Figure B-7. Yazoo Clay 18.5_2 Test After Failure

Five EFA tests were performed on the Yazoo Clay formation at a flow velocity of 1.0 m/s. The average scour rate among these five tests was 7.33 millimeters per hour, but included very high variability. Four of the five tests at this velocity resulted in scour times ranging from five to eight minutes. The fifth test titled "Yazoo Clay 18.5_7" did not scour after an hour at a flow velocity of 1.0 m/s. After an hour the flow velocity was increased to 1.2 m/s. Thin flakes began to scour immediately after the velocity was increased, but stopped when the flow velocity was increased to 1.5 m/s. After fifteen minutes at a flow velocity of 1.5 m/s, no significant scour was observed and the flow velocity was increased once again to 2.0 m/s. Five minutes later at a flow velocity of 2.0 m/s a large chunk of material scoured from the surface of the test. Once the "Yazoo

Clay 18.5_7" test was complete and results were analyzed, it was determined that the testing regiment should be continued at a flow velocity of 1.5 m/s. A summary table of the tests performed at a flow velocity of 1.0 m/s is shown below in Table B-6.

Table B-6. Yazoo Clay Results at 1.0 m/s

Sample:	**Elapsed Time Ultrasonic (min)**	**Elapsed Time Visual (min)**	**Scour Rate Ultrasonic (mm/hr)**	**Scour Rate Visual (mm/hr)**	**Overall Scour Rate (mm/hr)**
Yazoo Clay 18.5_3	5	5	12.00	12.00	17.84
Yazoo Clay 18.5_4	8	8	7.50	7.50	18.80
Yazoo Clay 18.5_5	7	7	8.57	8.57	13.49
Yazoo Clay 18.5_6	7	7	8.57	8.57	12.27
Yazoo Clay 18.5_7*	N/A	N/A	0.00	0.00	6.77
* Did Not Scour					

Two EFA tests were performed at a flow velocity of 1.5 m/s, and the results mirrored the "Yazoo Clay 18.5_7" test results. The first test performed at a flow velocity of 1.5 m/s showed minimum scour for the first 40 minutes of the test; however a huge chunk immediately scoured away after 43 minutes resulting in a scour rate of 1.40 mm/hr. The second EFA test performed at a flow velocity of 1.5 m/s had varying results mostly due to connection issues with the ultrasonic sensor. Once the second test, "Yazoo Clay 18.5_9", was started approximately one third of the sample scoured on the back half of the sample. This scour was not noticed much ultrasonically, due to high peaks in the scour surface being located directly under the transducers. Transducers 9 and 10 which were located directly above the location the scour occurred continued to record readings on par with the rest of the transducers. Transducers 11 and 12 showed very erratic readings during a fifteen minute stretch of the test. These erratic readings were most likely due to connection issues with the ultrasonic sensor and were rarely noted during testing. After one hour the "Yazoo Clay 18.5_7" test showed very little signs of scour other than the portion that eroded immediately. Images of this scoured section can be viewed below in Figure B-8 and Figure B-9. It is very plausible that the high readings observed in transducers 9 and 10 are directly associated with high peaks and steep valleys in the scoured area. Overall the average scour rate of the two tests performed at a flow velocity of 1.5 m/s was 0.70 millimeters per hour. A summary of these two tests is shown in Table B-7.

Figure B-8. Yazoo Clay 18.5_9 Test Scoured Area from Front

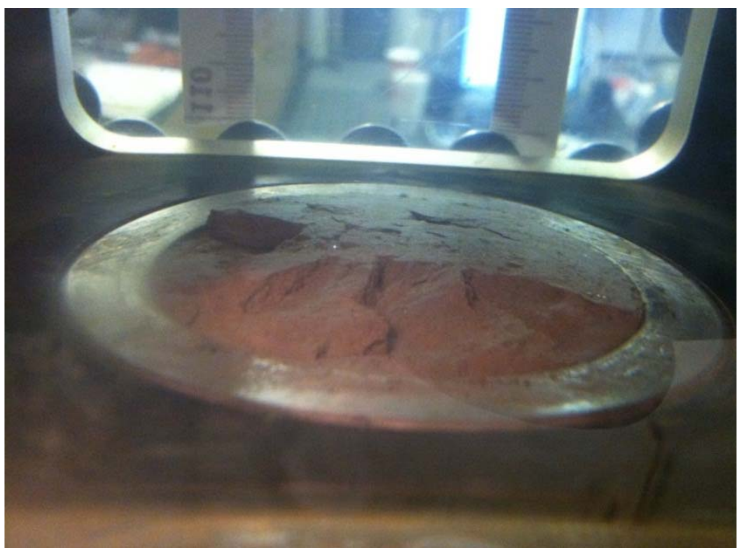

Figure B-9. Yazoo Clay 18.5_9 Test Scoured Area from Behind

Table B-7. Yazoo Clay Results at 1.5 m/s

Sample:	Elapsed Time Ultrasonic (min)	Elapsed Time Visual (min)	Scour Rate Ultrasonic (mm/hr)	Scour Rate Visual (mm/hr)	Overall Scour Rate (mm/hr)
Yazoo Clay 18.5_8	43	43	1.40	1.40	10.78
Yazoo Clay 18.5_9*	N/A	N/A	0.00	0.00	-0.04
* Did Not Scour					

Since the two specimens that were tested at a flow velocity of 1.5 m/s showed smaller amounts of scour than the tests at 1.0 m/s, the testing schedule was continued at a flow velocity of 2.0 m/s. Three tests were performed on the Yazoo Clay formation at a flow velocity of 2.0 m/s. The first test, titled "Yazoo Clay 18.5_10", had a resulting scour rate of 4.29 mm/hr. However, the test did not scour at a constant rate or even in small chunks as observed in previous Yazoo Clay EFA tests. The test showed minimum surface scouring for the first thirteen minutes of the test until a very large chunk scoured away. Using the ultrasonic sensor this chunk encompassed the entire sample and was approximately ten millimeters deep into the flume. Two additional tests were performed at a flow velocity of 2.0 m/s and both showed similar magnitudes of scour as the "Yazoo Clay 18.5_10" test but scoured immediately after the pump was started. Table B-8 below shows the three test results at a flow velocity of 2.0 m/s.

The sporadic scour behavior of the Yazoo Clay formation led to the pausing of the EFA testing schedule as most of the tests yielded inconsistent scour results. The only consistent results obtained from this formation were at a flow velocity of 1.0 m/s, which yielded an average scour rate of 7.33 mm/hr. The test performed at both 1.5 and 2.0 m/s were highly variable and inconsistent yielding no consistent results.

Table B-8. Yazoo Clay Results at 2.0 m/s

Sample:	Elapsed Time Ultrasonic (min)	Elapsed Time Visual (min)	Scour Rate Ultrasonic (mm/hr)	Scour Rate Visual (mm/hr)	Overall Scour Rate (mm/hr)
Yazoo Clay 18.5_10	14	11	4.29	5.45	64.39
Yazoo Clay 18.0_1**	0	0	N/A	N/A	N/A
Yazoo Clay 18.0_2**	0	0	N/A	N/A	N/A

B.2.3 Geotechnical Testing

Two initial moisture contents were taken to obtain the insitu moisture content of the formation prior to EFA testing. These tests yielded moisture contents of 62.2 and 57.6 percent, with an average of 59.9 percent. Using soil processed by following ASTM D421 – 85, a full grain size distribution was performed on the formation following ASTM D422 – 63 (ASTM 2007b). The results of the grain size analysis are shown in Figure B-10. Similar to the Bucatunna Clay formation one hundred percent of the formation passed through the number 10 sieve, thus neglecting the need for a coarse sieve analysis. From the grain size analysis the mean particle diameter was calculated as 0.088 millimeters. Approximately 44 percent of the sample tested passed the number 200 sieve classifying the sample as a sand.

Atterberg limits were performed to complete the soil classification and geotechnical testing of the Yazoo Clay formation. The liquid limit was determined to be approximately 57, and the formation was determined to be non-plastic.

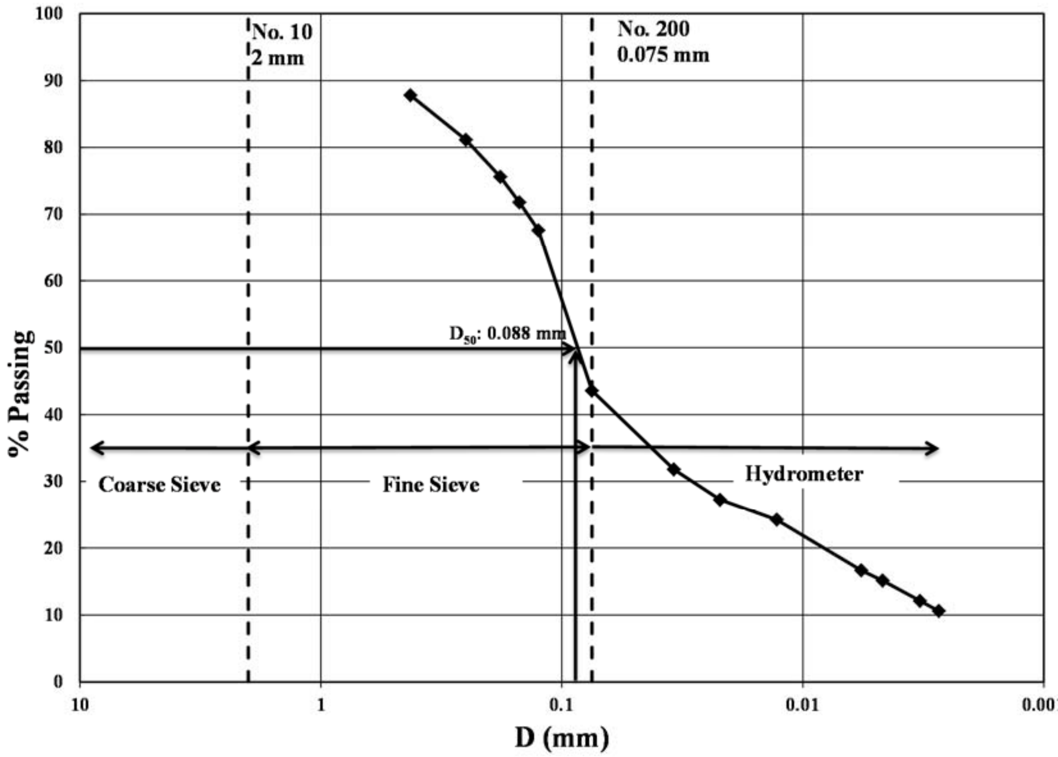

Figure B-10. Yazoo Clay Formation Grain Size Distribution

Due to the results of the geotechnical index tests along with the sporadic EFA test data, it was apparent that the sample acquired to represent the Yazoo Clay formation, was not purely Yazoo Clay, but had a high sand content. This sand content was not evenly distributed throughout the sample as several EFA test results show potential for scour resistance. Likewise, a high percentage of the sample was retained on the number 200 sieve and appeared to be a very fine silty sand. Since this layer of clay was sampled between two sandy layers it appears the sample tested was not a pure sample of the Yazoo Clay formation.

B.3 Demopolis Chalk

B.3.1 Sampling

The Demopolis Chalk formation was sampled on May 5, 2012 in Sumter County, Alabama. An ALDOT geologist classified the Demopolis Chalk formation as a very stiff light grey chalk. The Demopolis Chalk formation was sampled beside a bridge crossing the Tombigbee River. An outcrop of the formation could be viewed in the bluffs comprising the river bed. These bluffs were approximately 50 feet above the river, entirely comprised of the Demopolis Chalk formation. These bluffs are shown in Figure B-11.

Figure B-11. Demopolis Clay Formation Sampling Location

An ALDOT geologist identified the formation in drill cuttings and split spoon samples at approximately 14.0 feet below the ground surface. A Standard Penetration Test was performed at the top of the formation yielding a high N value of 92 blows. The ALDOT drill crew performed two CME continuous sample runs on the Demopolis Chalk formation.

The first run was taken from 15.0 to 20.0 feet below ground surface. The top half was disturbed and unusable for EFA testing due to the Standard Penetration Test which was terminated at approximately 15.3 feet. An EFA testable section was between 19.0 and 20.0 feet below ground surface. The middle portion of this top run was cracked in both the vertical and radial directions.

The second continuous sample run was performed from 20.0 to 25.0 feet below the ground surface. The top and middle portions of this sample were severely cracked in both the vertical and radial directions. The bottom third of the sample was uncracked, however, during sampling the sample tube was bowed and stretched. It was noted during sampling that the stiffness of the Demopolis Chalk formation made advancing the sample tubes increasingly difficult with depth. The torque necessary to advance the continuous sampler in the formation was great enough to distort the continuous sample tube and increase the outside diameter from 64 mm to approximately 74 mm. This increase in diameter of the sample tubes made this section of the Demopolis Chalk formation unable to be tested and advanced in the EFA. Due to the difficulty in sampling the stiff Demopolis Chalk formation only two continuous sample runs were performed, resulting in approximately 300 mm of EFA testable sample.

B.3.2 EFA Testing

Five EFA tests were performed on the Demopolis Chalk formation. The Demopolis Chalk Formation was unable to be automatically advanced into the EFA during testing due to the stiffness of the sample. Therefore, prior to each EFA test the sample was manually advanced approximately one millimeter using a hydraulic extruder, and then placed into the EFA at the testing height. The height of the test specimen protruding from the flume could be calculated by subtracting the know flume height from the corrected distances measured by the ultrasonic sensor. This changed the shape of the erosion rate versus elapsed time figures generated by the ultrasonic sensor and data acquisition system. Instead of a figure showing a starting location at 0, a push advancing the sample approximately one millimeter, and subsequent scour movement, the figure showed a starting location at 0 and subsequent scour movement from that datum.

The first test performed on the Demopolis Chalk formation was titled "DemopolisChalk19.0_1", and was started at a flow velocity of 1.2 m/s. Using scales attached to the outside of the EFA viewing window it appeared that the sample protruded from the flume approximately one millimeter. After 40 minutes of not witnessing any visually or by ultrasonic readings, the flow velocity was increased to 2.0 m/s. Another 20 minutes passed without any evidence of scour, and the velocity was increased to the maximum test velocity of 3.0 m/s. The test was allowed to run for one hour at the maximum velocity and no scour was witnessed. It was determined that three more tests should be performed at 3.0 m/s to determine if the Demopolis Chalk formation was scour resistant according to the parameters of this study.

The three tests mentioned above were titled "DemopolisChalk19.0_2", "DemopolisChalk19.0_3", and "DemopolisChalk19.0_4". These three tests averaged a protruded distance of 1.13 millimeters above the flume with values of 0.3, 1.5, and 1.6 millimeters respectively. All three of these tests were performed for at least on hour, and all three tests did not show any signs of significant scour resulting. The only scour witnessed was a very minor rounding of the sharp edges of the test samples. It is believed that this is due to stress concentrations that are not observed in the field with a continuous stream bed. This slight rounding of edges was visually observed and was not significant enough to be recorded by the ultrasonic sensor. The "DemopolisChalk19.0_3" and "DemopolisChalk19.0_4" tests both showed a slight raise in height in the ultrasonic output, averaging 0.2 millimeters over the duration of the tests, hinting that some minor swelling behavior is possible in the formation.

The final test performed on the Demopolis Chalk formation was titled "DemopolisChalk19.0_5". This test was intended to mirror recurring storm events on a small scale. The first hour of the test the flow velocity was 3.0 m/s, dropping to 1.0 m/s for the next 30 minutes, and then increased to 3.0 m/s for another hour. It was calculated that the test specimen started at an average height of 1.7 millimeters above the base of the flume. No significant scour was observed during the 2.5 hour test. Again only a slight rounding off of the front edge of the sample was noticed as shown in Figure B-12. In summary a total of five tests were performed on the Demopolis Chalk formation and all five tests did not show any signs of measurable scour.

This was the first sample tested in this study that did not exhibit any scour behavior with the set testing regiment. If future testing of the Demopolis Chalk formation is necessary the remaining testable section of the formation was sealed and placed into a curing chamber to preserve field moisture conditions.

Figure B-12. DemopolisChalk19.0_5 After Testing

B.3.3 Geotechnical Testing

Three initial moisture contents were taken to obtain the insitu moisture content of the Demopolis Chalk formation prior to EFA testing. These tests yielded moisture contents of 22.5, 21.5, and 21.4 percent, with an average of 21.8 percent. Using soil processed by following ASTM D421 – 85, a full grain size distribution was performed on the formation following ASTM D422 – 63. The results of the grain size analysis is depicted in Figure B-13. The grain size analysis on the Demopolis Chalk showed that the formation consisted of very fine grained particles with approximately 97 percent of the sample passing the number 200 sieve. From the grain size analysis the mean particle diameter was calculated to be 0.021 millimeters.

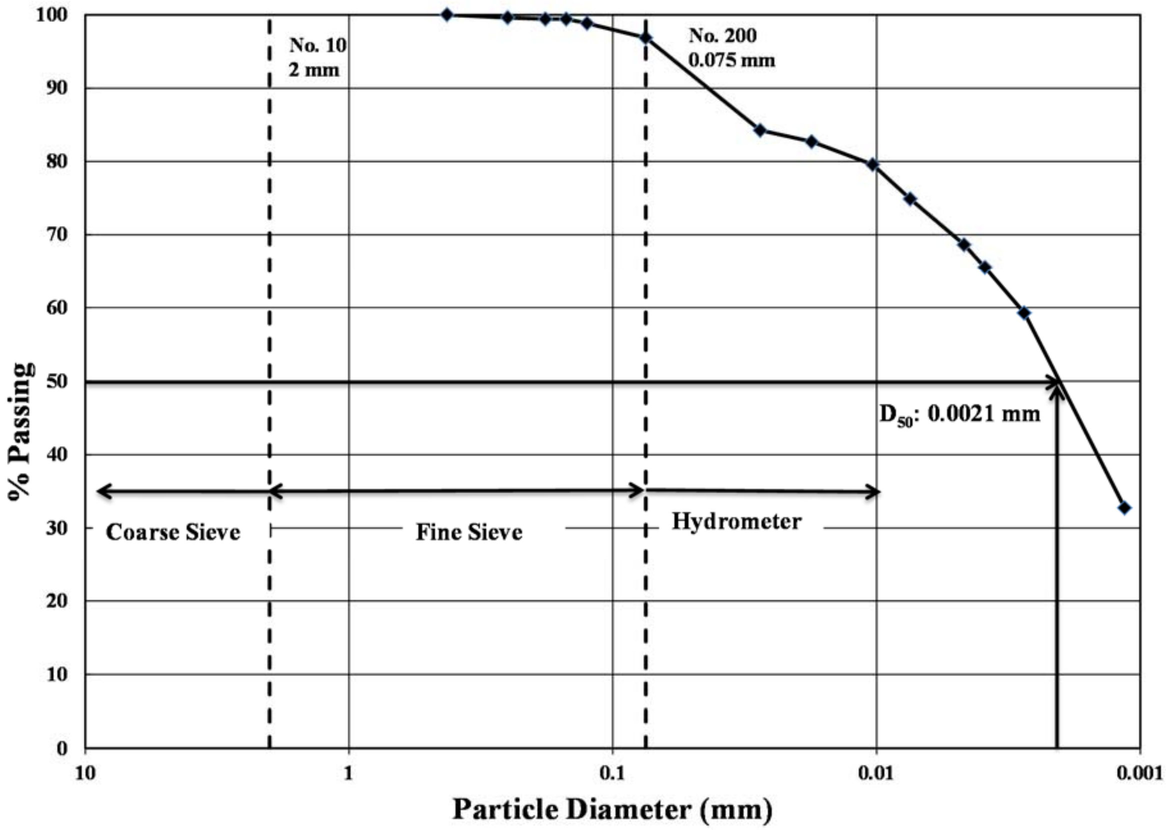

Figure B-13. Demopolis Chalk Formation Grain Size Distribution

Atterberg limits were performed to complete the soil classification and geotechnical testing of the Demopolis Chalk formation. The liquid limit was determined to be approximately 37, and the plastic limit was determined to be approximately 27, resulting in a plasticity index of 10. The calculated plasticity index proved the earlier observation during EFA testing, that this formation has minor swelling potential.

B.4 Mooreville Chalk

B.4.1 Sampling

The Mooreville Chalk formation was sampled on April 30, 2012 in Dallas County just west of Selma, Alabama. An ALDOT geologist classified the Mooreville Chalk formation as a stiff grey chalk. The ALDOT geologist identified the formation in drill cuttings and split spoon samples at approximately 16.4 feet below the ground surface. A Standard Penetration Test was performed at the top of the formation yielding an N value of 60 blows. The ALDOT drill crew performed three CME continuous sample runs on the Mooreville Chalk formation.

The sampling of the Mooreville Chalk formation occurred in two drill holes, the Standard Penetration Test and first sample run were performed in the first drill hole. The Standard

Penetration Test was taken from 20 to 21.5 feet. The CME continuous sample was taken from 22.5 to 27.5 feet below the ground surface. During sampling it was determined that a plug had developed in the drill hole and the continuous sampler had to be retracted. After the sample tubes were recovered, the sample tube from 25 to 27.5 feet showed approximately 300 mm of testable section. However, the sample tubes were extremely bowed approaching an outside diameter of 75 mm.

The second drill hole was located approximately 9.8 feet from the first, and the formation was encountered at a similar depth. Two continuous sample runs were performed in this hole. The first run was taken from 17.5 to 22.5 feet below the ground surface. A small testable section, approximately 15 centimeters long, was located in the top half of the sample. Another testable section with a similar length was located at the bottom of the sample. The rest of the sample was severely cracked in both the vertical and radial directions. The second CME continuous sample run was performed from 22.5 to 27.5 feet below the ground surface. The top half of the sample was severely cracked and unusable for EFA testing. A testable section with a length of approximately 300 mm was located at the base of the sample. However, 200 mm of this section was bowed out similar to the sample tube in the first sample hole. The Mooreville Chalk formation similar to the Demopolis Chalk formation proved difficult to sample with the CME continuous sampling system, but sufficient testable sections were recovered.

B.4.2 EFA Testing

Ten EFA tests were performed on the Mooreville Chalk formation resulting in varying results. The section used to test the Mooreville Chalk was from the second drill hole mentioned above at a depth of 22 feet. This section was the testable section with the least bowed sample tube. The sample tube was cut according the methods provided in Chapter 3, but also had to be sanded in order to fit into the flume of the EFA. Once the sample tube was altered to fit into the base of the flume it was determined that the automatic advancing motor on the EFA could not advance the sample. The sample was manually advanced in a similar manner that was done for the Demopolis Chalk formation.

The first test on the Mooreville Chalk formation was performed to determine the base velocity for testing the formation. The test titled "MoorevilleChalk22.0_2" was started at 1.0 m/s and quickly showed significant scour. It was determined that this test was not indicative of the scour parameters of the formation as it was calculated that the sample protruded from the base of the flume two millimeters which was double the distance specified by Briaud. The next test performed on the Mooreville Chalk formation was titled "MoorevilleChalk22.0_3", was started at a flow velocity of 0.3 m/s, and was able to be automatically advanced into the EFA flume. This test showed no signs of scour at 0.3 m/s. Some large masses of material scoured in chunks at 0.6 m/s, and scour continued once the flow velocity was increased to 1.0 m/s. From this test it was determined that testing should start at 0.6 m/s. It was noted that the sample section used to obtain the results from these two tests could have been exposed to varying stress states, not primarily associated to EFA testing. It appeared that the test sample could have been exposed to differing shear and torsional stress states, by being manually advanced with an extruder through a bowed sample tube.

Two EFA tests were performed at a flow velocity of 0.6 m/s. The first test titled "MoorevilleChalk22.0_4" resulted in a scour rate of 1.4 mm/hr. However, all the scour recorded was measured from two large mass scours in which a large chunk of material accounted for the measured scour. The second test performed at a flow velocity of 0.6 m/s did not show any signs of scour visually or ultrasonically. These two tests did not demonstrate the behavior as the previous two with regards to varying stress states, as both were easily automatically advanced. An additional test was performed at a flow velocity of 1.0 m/s on the Mooreville Chalk formation and no measurable scour was recorded.

Two EFA tests were performed at a flow velocity of 1.5 m/s on the Mooreville Chalk formation. The first of these two tests was titled "MoorevilleChalk22.0_7" and resulted in one third of the volume of the protrusion being scoured away by one large chunk in the upstream portion of the sample. Figure B-14 shows the final result of this test. The second test performed at a flow velocity of 1.5 m/s resulted in no measurable amount of scour. The only scour occurred during this test was witnessed visually and consisted of the rounding off of the front edges of the sample similar to that witnessed in testing the Demopolis Chalk formation.

Figure B-14. MoorevilleChalk22.0_7 After Testing

Since there was a limited amount of testable sample obtained from the Mooreville Chalk formation it was imperative that testing continued regardless of slightly varying results. The next EFA test performed on the Mooreville Chalk formation was performed at a flow velocity of 2.0 m/s and no scour was recorded. The flow velocity was increased to 3.0 m/s for the next EFA test and no scour was recorded. The final test performed on the Mooreville Chalk formation was titled "MoorevilleChalk22.0_11" and was a repeat even test similar to that performed on the Demopolis Chalk formation. This test was intended to be performed with a flow velocity of 3.0 m/s for one hour, 1.0 m/s for thirty minutes, and 3.0 m/s for another hour. This test showed no signs of scour through the first hour and a half of the test. However, soon after the velocity was increased from

1.0 m/s to 3.0 m/s two masses of material scoured from the sample. The smaller of the two masses came from the far side portion of the sample, while the larger mass scoured from the near side of the sample. After these two masses scoured away no other scour was noticed or measured throughout the remaining duration of the test. The volume of the scour measured from these two masses was approximately one third of the total protrusion.

In summary, the behavior of the Mooreville Chalk formation varied, but it was recognized that the formation could be scour resistant. Testing was limited to the amount of testable sections recovered during sampling. Once the sample was able to be automatically advanced in the EFA, the formation showed minimal scour rates with no tests recording scour rates greater than 1.0 mm/hr. Finally, it was determined that the Mooreville Chalk formation did not scour uniformly in a particle by particle or even flake by flake fashion as observed in sands and earlier tested clays. The scour observed in the Mooreville Chalk formation consisted of large mass chunks of the material scouring at once.

B.4.3 Geotechnical Testing

Two initial moisture contents were taken to obtain the insitu moisture content of the Mooreville Chalk formation. These tests yielded moisture contents of 21.9 and 24.9 percent, with an average of 23.4 percent. Using soil processed by following ASTM D421 – 85, a full grain size distribution was performed on the formation following ASTM D422 – 63. The results of the grain size analysis can be viewed below in Figure B-15. The grain size analysis on the Mooreville Chalk showed that the formation consisted of very fine grained particles with approximately 92 percent of the sample passing the number 200 sieve. From the grain size analysis the mean particle diameter (D_{50}) was calculated to be 0.024 millimeters. The mean particle diameter and percent of the Mooreville Chalk sample passing the number 200 sieve mirrored that of the Demopolis Chalk formation. Also after 24 hours in the Hyrdometer both formations had at least thirty percent of the sample still in solution.

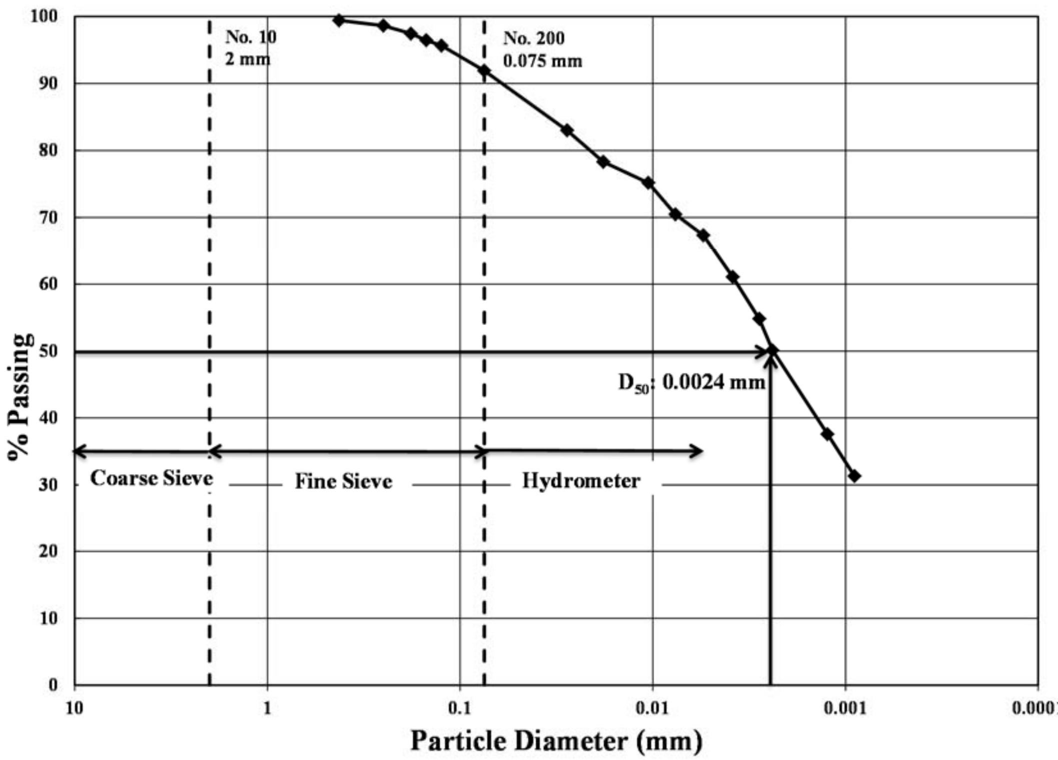

Figure B-15. Mooreville Chalk Formation Grain Size Distribution

Atterberg limits were performed to complete the soil classification and geotechnical testing of the Mooreville Chalk formation. The liquid limit was determined to be approximately 52, and the plastic limit was determined to be approximately 25, resulting in a plasticity index of 27. The calculated plasticity index is similar to that observed in the Bucatunna Clay formation.

B.5 Prairie Bluff Chalk

B.5.1 Sampling

The Prairie Bluff Chalk formation was sampled on May 1, 2012 in Marengo County west of Demopolis, Alabama. An ALDOT geologist classified the Prairie Bluff Chalk formation as a stiff grey chalk. Outcrops of the formation were viewed in a stream bed beside the drilling location. The ALDOT geologist identified the formation in drill cuttings and split spoon samples at approximately 11.5 feet below the ground surface. A Standard Penetration Test was performed at the top of the formation yielding an N value of 86 blows. The ALDOT drill crew performed three CME continuous sample runs on the Prairie Bluff Chalk formation.

The first sample run was taken from 15 to 20 feet below the ground surface. The top half of the sample consisted of a transitioning layer from the Standard Penetration Test. The bottom half of the sample was uncracked and acceptable for EFA testing. The second continuous sample run was taken from 22 to 25 feet below the ground surface. Similar to the previously sample chalk formations the Prairie Bluff Chalk was very stiff and difficult to sample. The second sample run was to be very difficult to advance, and upon recovery it was discovered that the acrylic sample tubes melted during sampling. The sections of the tubes that did not melt were severely cracked and could not be used for EFA testing. The third CME continuous sample run was taken from 25 to 30 feet below the ground surface. This run was also very difficult to advance as the sampler bowed out during drilling and became wedged the hollow stem auger. Once the sample was recovered, it was discovered that most of the sample tube was melted due to a plug that developed at the bottom of the drill hole. Upon recommendation from the ALDOT drill crew, sampling of the Prairie Bluff Chalk was abandoned due to difficult sampling conditions. A total of approximately 300 mm of the Prairie Bluff Chalk formation was collected for EFA testing.

B.5.2 EFA Testing

Seven EFA tests were performed on the Prairie Bluff Chalk formation to determine erosion rates. Once the samples were brought back to Auburn University it was discovered that the amount of testable sample was very limited due to bowed sample tubes. A 15 centimeter section of the sample was cut and prepared for testing. Similar to the Mooreville Chalk formation, the exterior of the sample tube had to be sanded down to fit into the flume of the EFA. Once the sample was prepared, it was determined that the automatic motor on the EFA could not advance the sample into the flume. Therefore, the sample was manually advanced using an extruder approximately 1 millimeter and placed into the EFA at the testing height. The height of each protrusion could be calculated by the values provided from the ultrasonic sensor.

The first test on the Prairie Bluff Chalk formation started at a flow velocity of 1.0 m/s. The protrusion into the flume was calculated to be 1.51 millimeters or fifty percent higher than the height specified by Briaud. After fifty minutes a large mass chunk scoured away, the volume of the scoured section was approximately equal to five times the volume of the protrusion. It was noted during testing that the sample seemed dry and loose in some areas, and that the large scoured volume started from the loose areas of the sample. Another EFA test was performed at a flow velocity of 1.0 m/s, with a total protrusion of 1.85 millimeters. No scour was observed during this test, suggesting that the flow velocity should be increased for future tests. The idea that the test samples that had altered tubes and been manually advanced were exposed to differing stress states than initially intended during EFA testing was confirmed during testing of the Prairie Bluff Chalk formation. It was thought that these samples were exposed to shear or torsional forces during extruding. This idea was reinforced by cracking on the edges of the advanced sample as viewed in Figure B-16 and Figure B-17. These shear and torsional forces could have been developed through an eccentricity between the bowed sample tube and the extruder advancing the sample. It is unknown if these forces negatively influenced EFA testing. It was noted that these cracks that developed in the EFA sample created shear planes for scouring to occur that would not naturally exist in a stream bed.

Figure B-16. Prairie Bluff Chalk Formation Cracking Example 1

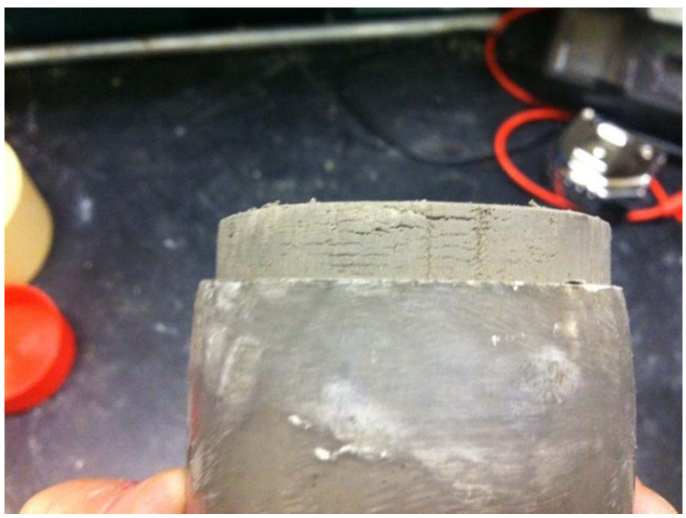

Figure B-17. Prairie Bluff Chalk Formation Cracking Example 2

An EFA test was performed at a flow velocity of 1.5 m/s, and a protrusion into the flume of 0.8 millimeters. This test showed one millimeter of erosion after thirty-four minutes resulting in a scour rate of 1.76 millimeters per hour. The scour started from dry loose areas noticed in the middle of the sample during sample preparation. The next EFA test performed on the Prairie Bluff formation was performed at a flow velocity of 2.0 m/s. The total protrusion into the flume from this test was calculated to be 1.33 millimeters. After eighty minutes no scour was observed visually or ultrasonically.

Three tests were performed at a flow velocity of 3.0 m/s, and all three tests showed no measurable scour. The protrusions from all three of these tests were greater than 1.0 millimeters and in one case the protrusion was double the specified height. It was noted that these samples did not seem to be as dry and loose as samples noted above. Also the cracks due to manually extruding these samples were smaller in size than those noticed during earlier tests that exhibited scour. Due to the lack of testable sample material, a repeat event test was not performed on the Prairie Bluff Chalk formation. It was also recognized that the samples tested that did not seem to be disturbed during sampling or extruding exhibited a resistance to scour at flume velocities up to 3.0 m/s.

B.5.3 Geotechnical Testing

Three initial moisture contents were taken to obtain the insitu moisture content of the Prairie Bluff Chalk formation. These tests provided moisture contents of 16, 17.1, and 20.1 percent with an average of 17.7 percent. As noted during EFA testing, these moisture contents were approximately five percent less than those observed from the other two chalk formations. Using soil processed by following ASTM D421 – 85, a full grain size distribution was performed on the formation following ASTM D422 – 63. The results of the grain size analysis can be viewed below in Figure B-18. The grain size analysis on the Prairie Bluff Chalk showed that the formation consisted of fine grained particles with approximately 82 percent of the sample passing the number 200 sieve. From the grain size analysis the mean particle diameter (D_{50}) was calculated to be 0.028 millimeters. The mean particle diameter and percent of the Prairie Bluff Chalk sample passing the number 200 sieve were similar to the other two chalk formations tested. The fine sand evident from the grain size distribution explains some of the difficulty in preparing the EFA test samples with some loose portions.

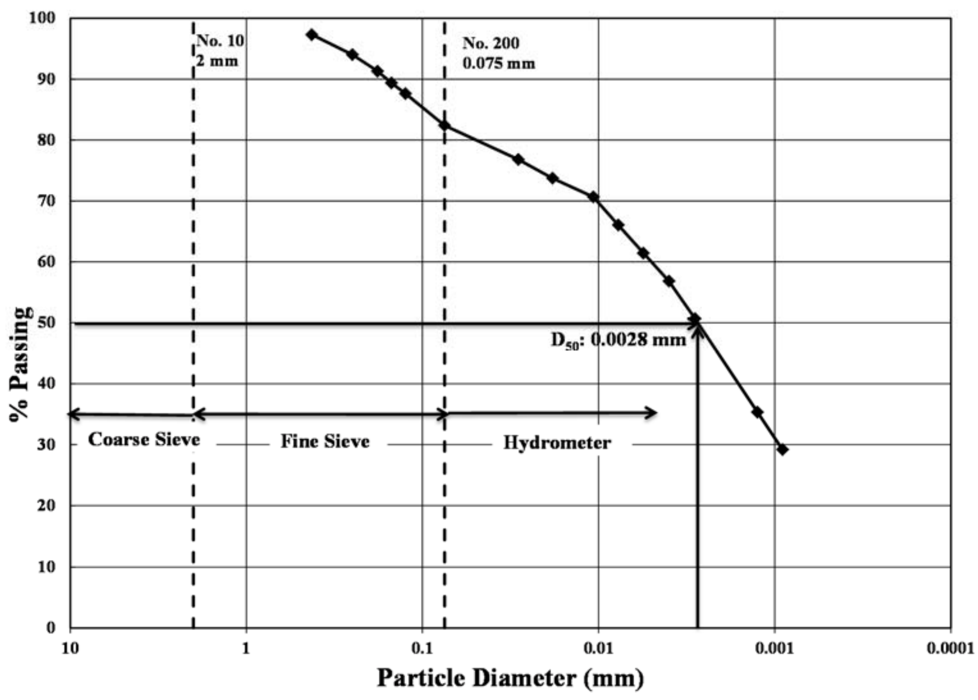

Figure B-18. Prairie Bluff Chalk Formation Grain Size Distribution

Atterberg limits were performed to complete the soil classification and geotechnical testing of the Prairie Bluff Chalk formation. The liquid limit was determined to be approximately 32, and the plastic limit was determined to be approximately 19, resulting in a plasticity index of 13.

B.6 Porter's Creek Clay

B.6.1 Sampling

The Porter's Creek Clay formation was sampled on May 1, 2012 in Sumter County, Alabama. An ALDOT geologist classified the Porter's Creek Clay formation as a stiff brown clay. The ALDOT geologist identified the formation in drill cuttings and split spoon samples at approximately 8.2 feet below the ground surface. A Standard Penetration Test was performed at the top of the formation yielding an N value of 30 blows. The ALDOT drill crew performed three CME continuous sample runs on the Porter's Creek Clay formation.

The first continuous sample run was performed between 10 and 15 feet below the ground surface. Unlike the previous chalk samples, the Porter's Creek Clay did not have any trouble advancing the sampler. Most of the sample run was unusable with cracks in the vertical and radial directions. A testable section was located in the bottom of this sample and was approximately 150 mm in length. The second continuous sample run was performed between 15 and 20 feet below the ground surface. A layer of sand was located in the top half of this run and was not used for EFA testing. The bottom half of the sample consisted of a 30 centimeter EFA testable section. It was noticed during sampling that some cracks due to weathering separated the testable sections. The third continuous sample run was performed between 20 and 25 feet below the ground surface. The top half of the sample was determined to be unusable for EFA testing due to heavy cracking and the presence of a wet seam. The bottom half of the sample was uncracked and could be used for EFA testing. The ALDOT geologist also noticed that the testable sections were divided by cracks representing weathered areas.

B.6.2 EFA Testing

A total of 20 EFA tests were performed on the Porter's Creek Clay formation. Three different test samples were cut and prepared for EFA testing ranging from 18.7 to 20 feet below the ground surface. The first test performed was started at a flow velocity of 0.3 m/s and did not scour after one hour, and swelling similar to that of the Bucatunna Clay was observed. The flow velocity was increased to 0.6 m/s for the next EFA test and the sample exhibited one millimeter of scour after 15 minutes, resulting in a scour rate of 4.0 mm/hr. Two more EFA tests were performed at 0.6 m/s flow velocity and resulted in scour rates of 3.33 and 4.62 mm/hr. The average scour rate for the three EFA tests performed at a flow velocity of 0.6 m/s was 3.98 mm/hr. The results of the EFA tests performed at a flow velocity of 0.6 m/s are shown in Table B-9 below.

Table B-9. Porter's Creek Clay Results at 0.6 m/s

Sample:	Elapsed Time Ultrasonic (min)	Elapsed Time Visual (min)	Scour Rate Ultrasonic (mm/hr)	Scour Rate Visual (mm/hr)	Overall Scour Rate (mm/hr)
Porter's Creek Clay 19.5_2	15	15	4.00	4.00	9.83
Porter's Creek Clay 19.5_3	18	18	3.33	3.33	3.33
Porter's Creek Clay 19.5_4	13	13	4.62	4.62	19.27

Three EFA tests were performed on the Porter's Creek Clay formation at velocity of 1.0 m/s. During these tests, the advancement of the sample occurred one minute after the flume and ultrasonic sensor was started. This time period was typically 3 to 5 minutes, allowing for a clear baseline to be created during testing. However, significant surface roughening had occurred before the sample was advanced. The ultrasonic sensor and data reduction software only required one minute to set an adequate base line for readings. The three tests performed at a flow velocity of 1.0 m/s resulted in an average scour rate of 9.17 mm/hr. Table B-10 below shows the results of these three tests.

Table B-10. Porter's Creek Clay Results at 1.0 m/s

Sample:	Elapsed Time Ultrasonic (min)	Elapsed Time Visual (min)	Scour Rate Ultrasonic (mm/hr)	Scour Rate Visual (mm/hr)	Overall Scour Rate (mm/hr)
Porter's Creek Clay 19.5_5	6	6	10.00	10.00	19.73
Porter's Creek Clay 19.5_7	6	6	10.00	10.00	19.28
Porter's Creek Clay 19.0_1	8	8	7.50	7.50	19.12

The Porter's Creek Clay formation was tested four times with a flow velocity of 1.5 m/s. However, one of these tests scoured immediately due to a weathered surface. The results of these tests are shown in Table B-11.

Table B-11. Porter's Creek Clay Results at 1.5 m/s

Sample:	Elapsed Time Ultrasonic (min)	Elapsed Time Visual (min)	Scour Rate Ultrasonic (mm/hr)	Scour Rate Visual (mm/hr)	Overall Scour Rate (mm/hr)
Porter's Creek Clay 19.0_2	5	5	12.00	12.00	20.83
Porter's Creek Clay 19.0_3	7	7	8.57	8.57	17.85
Porter's Creek Clay 19.0_5	6	6	10.00	10.00	18.37
*Porter's Creek Clay 19.0_4 Instant Scour (Weathered Sample)					

The average scour rate of these tests was calculated to be 10.19 mm/hr. The scour observed during these tests mirrored that of the Bucatunna Clay formation and not that of the three chalk formations previously tested. The scour did not typically involve large mass chunks, but small flakes that consistently scoured away the protrusion into the flume over time. This scour did occur rather quickly because elapsed times for scour at a flow velocity of 1.5 m/s was 5, 7, and 6 minutes, respectively.

Three EFA tests were also performed at a velocity of 2.0 m/s. The mechanism for scour was similar to those tests performed at a velocity of 1.5 m/s. The average scour rate for these three tests was 10.86 mm/hr. The results of these tests are shown below in Table B-12. The average scour rates for the EFA tests performed for flow velocities of 1.0, 1.5, and 2.0 m/s were similar with a difference of only 1.69 mm/hr.

Table B-12. Porter’s Creek Clay Results at 2.0 m/s

Sample:	**Elapsed Time Ultrasonic (min)**	**Elapsed Time Visual (min)**	**Scour Rate Ultrasonic (mm/hr)**	**Scour Rate Visual (mm/hr)**	**Overall Scour Rate (mm/hr)**
Porter's Creek Clay 19.0_6	5	5	12.00	12.00	31.13
Porter's Creek Clay 19.0_7	7	7	8.57	8.57	14.50
Porter's Creek Clay 19.0_8	5	5	12.00	12.00	21.88

The final set of EFA tests, used to determine scour rates, performed on the Porter’s Creek Clay formation were executed at a flow velocity of 3.0 m/s. The average scour rate on these three tests jumped to 15.67 mm/hr. The results of these tests are shown below in Table B-13.

Table B-13. Porter’s Creek Clay Results at 3.0 m/s

Sample:	**Elapsed Time Ultrasonic (min)**	**Elapsed Time Visual (min)**	**Scour Rate Ultrasonic (mm/hr)**	**Scour Rate Visual (mm/hr)**	**Overall Scour Rate (mm/hr)**
Porter's Creek Clay 19.0_9	5	5	12.00	12.00	17.24
Porter's Creek Clay 19.0_12	4	4	15.00	15.00	35.43
Porter's Creek Clay 19.0_14	3	3	20.00	20.00	36.53

During testing of the Porter’s Creek Clay formation it was noted that weathered planes existed within the tested samples. It was also noted that scour typically started on or around these weathered planes, which appeared to be planes of weakness with respect to scour resistance. As a result of these weathered lines and planes in the prepared sample four EFA tests were abandoned immediately following advancement into the flume. All four of these tests had large mass scouring occur at the location of the weathered planes immediately following the push. The volume of scour was not measured by the ultrasonic sensor as scour occurred very quickly before a scan from the sensor could be performed. Visually the volume of scour in these four instances was greater than the one millimeter protrusion into the flume. An image of these weathered lines and planes can be viewed below in Figure B-19. When the weathered lines were noticed in split spoon samples during sampling the ALDOT geologist confirmed that this weathering pattern was quite common in samples from the Porter's Creek Clay formation.

Figure B-19. Porter's Creek Clay Formation Scoured along Weathered Planes

The last test performed on the Porter's Creek Clay formation was intended to determine the threshold velocity, at which scour first occurs. From previous tests it was determined that the threshold velocity, or critical shear velocity, was between 0.3 and 0.6 m/s. The velocity during the first test performed on the Porter's Creek Clay formation typically ranged from 0.3 to 0.35 m/s. The velocity for the final test on the formation, titled "Porter's Creek Clay 18.75_1", was started at 0.4 m/s. At first surface scouring began to occur, at a reduced rate of that observed in the samples tested at 0.6 m/s. After about ten minutes small flakes began to scour away from the specimen, while the flow velocity ranged from 0.4 to 0.42 m/s. This scouring was substantial enough for the threshold velocity to be established at 0.4 m/s. It should be noted that the threshold velocity obtained is not an exact number. Previous work at Auburn University involved the calibration of the flow meter located in the EFA. This work showed at velocities less than 0.5 m/s the flow meter could have a margin of error of approximately ten percent (Mobley, 2009).

In summary, the Porter's Creek Clay formation behaved similarly to the Bucatunna Clay formation during EFA testing. The major concern in testing the Porter's Creek Clay formation was the scour behavior of the formation with respect to the weathered lines and planes within the formation. As stated above these weathered lines created planes of weakness during EFA testing increasing the observed scour rates.

B.6.3 Geotechnical Testing

Three initial moisture contents were taken to obtain the insitu moisture content of the Porter's Creek Clay formation. These tests provided moisture contents of 36.7, 33.6, and 36.9 percent with an average of 35.7 percent. Using soil processed by following ASTM D421, a full grain size distribution was performed on the formation following ASTM D422 – 63. The results of the grain size analysis can be viewed below in Figure B-20. The grain size analysis on the Porter's Creek Clay showed that the formation consisted of fine grained particles with approximately 90 percent of the sample passing the number 200 sieve. From the grain size analysis the mean particle diameter (D_{50}) was calculated to be 0.082 millimeters. The percent of the Porter's Creek Clay sample passing the number 200 sieve was similar to the three chalk formations that were tested.

Atterberg limits were performed to complete the soil classification and geotechnical testing of the Porter's Creek Clay formation. The liquid limit was determined to be approximately 62, and the plastic limit was determined to be approximately 53, resulting in a plasticity index of 9.

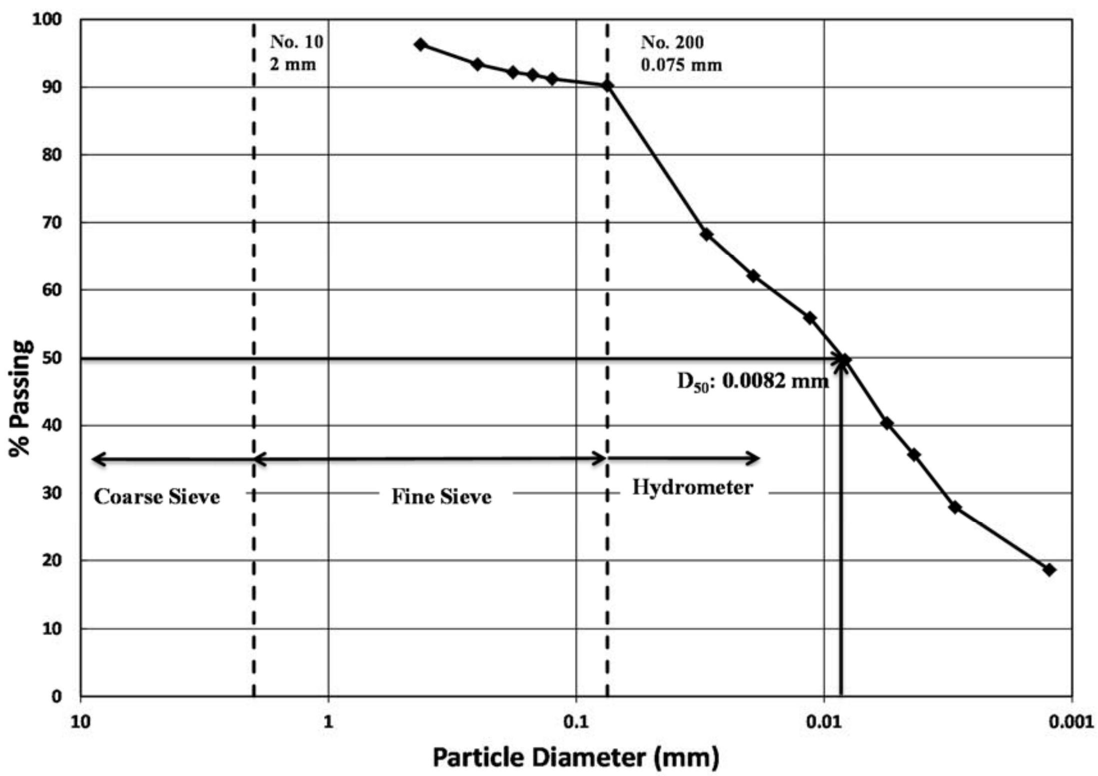

Figure B-20. Porter's Creek Clay Formation Grain Size Distribution

Appendix C Phase II Testing

Appendix C summarizes detailed information on sampling, EFA testing, and geotechnical tests of eight soil formations: Nanafalia clay, Naheola clay (Yellow material), Naheola clay (Dark material), Naheola clay (Re-drilled), Clayton clay, Bucatunna clay (Retest), Porter's Creek clay (Resampled), and Yazoo clay (Retest), during the Phase II EFA testing of the study. Sampling eight formations was conducted by ALDOT drilling crew, and EFA testing and geotechnical tests were primarily performed by graduate student William H. Wright at Auburn University. Additional information of the Phase II testing can be found from Wright's Master thesis (Wright 2014). For each formation tested, the first table typically summarizes results of tests for determining critical velocities of minor and major scour events. Other tables report ultrasonic elapsed times (in min), soil loss (eroded/scoured in mm), and scour rate (mm/hr) for each scour event during each replicate test, and also overall scour rates considering both swelling and erosion of the soil samples over each replicate test.

C.1 Nanafalia Clay

C.1.1 Sampling

The Nanafalia formation sample was drilled in Coffee County, AL on June 6, 2012. The geologist for ALDOT classified the formation as a plastic brown clay. An on-site geologist verified the formation with split spoon samples taken at approximately 8.2 feet below ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 13 blows. Two sections of the sampled material were used in EFA testing: a 6" section at a depth of 21.0 feet to 21.5 feet and another 6" section at a depth of 23.0 feet to 23.5 feet.

C.1.2 EFA Testing

Three separate critical velocity tests were performed on Nanafalia clay samples. During the first critical velocity test minor particle loss was observed at a velocity of 0.65 m/s and the entire sample eroded almost instantaneously at a velocity of 0.80 m/s. The second critical velocity test resulted in the same critical velocity of 0.60 m/s for minor scour. The sample showed very extensive soil loss at a velocity of around 2.90 m/s. The third and final critical velocity test resulted in a critical velocity of 0.60 m/s for minor scour and large chunks were being lost after 2.5 m/s. Table C-1 shows a summary of the critical velocity tests for Nanafalia clay. Critical velocities for minor scour that is the critical velocity used by Briaud et al. (2001b) were further summarized in the section 3.4.2.

Table C-1. Critical Velocity Summary for Nanafalia Clay.

Test No.	Critical Velocity (m/s)	
	Minor Scour	Major Scour
Critical Velocity Test 1	0.65	0.80
Critical Velocity Test 2	0.65	2.90
Critical Velocity Test 3	0.60	2.50

A total of 18 EFA tests were performed on the Nanafalia clay formation and the tests were further broken down to provide a total of 29 individual scour events. One test, titled "Nanafalia Clay 23.5_1", was conducted at the 0.3 m/s velocity. The test was run for a total of 66 minutes in which no scour was seen.

Four EFA tests were conducted at the 0.6 m/s velocity. The first test, titled "Nanafalia Clay 23.5_2", lasted 60 minutes in which a total of five scour events were witnessed. A lose chunk was lost approximately 4 minutes into the test and was seen in the sensor measurements. This loose chunk was most likely caused by the advancing of the specimen and therefore was not considered in the scour rate of the sample. Swelling of the sample was apparent and a scour-swell-scour-swell pattern was observed over the test duration. The second test run at 0.6 m/s, titled "Nanafalia Clay 23.5_3", lasted approximately 64 minutes in which two scour events were observed. The sample scoured on two separate occasions over the first 20 minutes of the test and no additional scour was seen afterwards. More than 0.3 mm of swell occurred over the test duration. The third test, titled "Nanafalia Clay 23.5_4", lasted approximately 69 minutes in which no scour was observed. More than 0.3 mm of swell was experienced during this test also. The fourth and final test, titled "Nanafalia Clay 21.0_1", also resulted in minimal to no scour. The plot showed that very minimal scour occurred however this was not corroborated visually. Table C-2 shows a summary of EFA testing results from the 0.6 m/s velocity. For tests with multiple scour events the value in parentheses represents the particular scour event number for the respective test.

Four EFA tests were performed at the 1.0 m/s velocity. The first test, titled "Nanafalia Clay 23.0_1", lasted 13 minutes before the entire sample scoured in one massive chunk. Scour was visually seen however very significant swelling counteracted measurement readings from the ultrasonic sensor. Approximately 8 minutes after advancing the specimen the entire top of the sample washed away. The second test run at 1.0 m/s, titled "Nanafalia Clay 23.0_2", lasted 60 minutes in which no scour was observed. Approximately 0.8 mm of swell occurred over the test duration. The third test, titled "Nanafalia Clay 23.0_3", lasted 6 minutes and scour was constant and extreme. In the last test at 1.0 m/s, titled "Nanafalia Clay 23.0_4", scour was constant but swelling compensated for it. Two scour events were observed over the test duration. Table C-3 shows a summary of EFA testing results from the 1.0 m/s velocity. The soil loss during an instantaneous scour event (i.e. losing a massive soil chunk) cannot be quantified visually or using the ultrasonic sensor. In such cases the value for "Soil Loss" in summary tables will be shown as "CHUNK" and the scour rate will be inapplicable, or "NA".

Table C-2. Nanafalia Clay Results at 0.6 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Nanafalia Clay 23.5_2 (1)	15	0.95	3.80	1.04
Nanafalia Clay 23.5_2 (2)	9	0.33	2.20	
Nanafalia Clay 23.5_2 (3)	7	0.28	2.40	
Nanafalia Clay 23.5_2 (4)	4	0.19	2.85	
Nanafalia Clay 23.5_2 (5)	7	0.50	4.29	
Nanafalia Clay 23.5_3 (1)	5	0.13	1.56	-1.23
Nanafalia Clay 23.5_3 (2)	6	0.19	1.90	
Nanafalia Clay 23.5_4	69	0.00	0.00	-0.66
Nanafalia Clay 21.0_1	47	0.00	0.00	1.02

Table C-3. Nanafalia Clay Results at 1.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Nanafalia Clay 23.0_1	13	CHUNK	NA	15.44
Nanafalia Clay 23.0_2	60	0.00	0.00	-2.34
Nanafalia Clay 23.0_3	6	1.11	11.10	16.74
Nanafalia Clay 23.0_4 (1)	7	0.33	2.83	-1.14
Nanafalia Clay 23.0_4 (2)	4	0.25	3.75	

Three EFA tests were conducted at the 1.5 m/s velocity. The first test, titled "Nanafalia Clay 21.5_1", lasted 7 minutes and scour was observed to be constant and relatively dramatic. The second test, titled "Nanafalia Clay 21.5_2", lasted a total of 65 minutes in which two scour events occurred. The scour-swell pattern was also seen during throughout this test. The third test, titled "Nanafalia Clay 21.5_3", lasted 6 minutes before the sample washed away in large chunks. Swelling was very extensive prior to scour. Table C- shows a summary of EFA testing results from the 1.5 m/s velocity.

Table C-4. Nanafalia Clay Results at 1.5 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Nanafalia Clay 21.5_1	7	1.12	9.60	11.58
Nanafalia Clay 21.5_2 (1)	7	0.59	5.06	1.47
Nanafalia Clay 21.5_2 (2)	7	0.37	3.17	
Nanafalia Clay 21.5_3	6	CHUNK	NA	20.00

Three EFA tests were performed at the 2.0 m/s velocity increment. The first test, titled "Nanafalia Clay 21.5_4", lasted 8 minutes in which extreme scour occurred at the beginning of the test. The scour rate show in Table C- for this test is indicative of this event. The second test, titled "Nanafalia Clay 21.5_5", lasted a total of 12 minutes in which two scour events were observed. Scour occurred in large chunks over each event. The third test, titled "Nanafalia Clay 21.5_6", lasted approximately 25 minutes and two separate scour events occurred. Scour was observed to be constant however significant swelling compensated values measured by the ultrasonic sensor. Table C- shows a summary of EFA testing results from the 2.0 m/s velocity.

Table C-5. Nanafalia Clay Results at 2.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Nanafalia Clay 21.5_4	8	0.60	4.50	4.55
Nanafalia Clay 21.5_5 (1)	4	0.61	9.15	14.85
Nanafalia Clay 21.5_5 (2)	3	0.66	13.20	
Nanafalia Clay 21.5_6 (1)	3	0.32	6.40	18.49
Nanafalia Clay 21.5_6 (2)	3	0.20	4.00	

Three EFA tests were conducted at the 3.0 m/s velocity. The first test, titled "Nanafalia Clay 21.5_7", lasted 5 minutes in which extreme scour occurred throughout the test. Scour appeared to be constant and continuous over the test duration. The second test at 3.0 m/s, titled "Nanafalia Clay 21.5_8", lasted about 25 minutes in which two scour events were observed. Initially scour was shown in the plot, representing the "Nanafalia Clay 21.5_8(1)" event, but swelling compensated for additional scour that was observed visually. Eventually the entire sample scoured in one large chunk about 25 minutes into the test. Photographs taken throughout the "Nanafalia Clay 21.5_8" test are shown in Figure C-1, Figure C-2, and Figure C-3. The third and final test, titled "Nanafalia Clay 21.5_9", lasted approximately 18 minutes in which two separate scour events occurred. Scour occurred at the beginning of the test and then stopped until the entire sample scour in one chunk. Table C-6 shows a summary of results from the 2.0 m/s velocity.

Table C-6. Nanafalia Clay Results at 3.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Nanafalia Clay 21.5_7	5	1.02	12.24	17.44
Nanafalia Clay 21.5_8 (1)	2	0.41	12.30	7.96
Nanafalia Clay 21.5_8 (2)	25	CHUNK	NA	
Nanafalia Clay 21.5_9 (1)	3	1.02	20.40	37.50
Nanafalia Clay 21.5_9 (2)	18	CHUNK	NA	

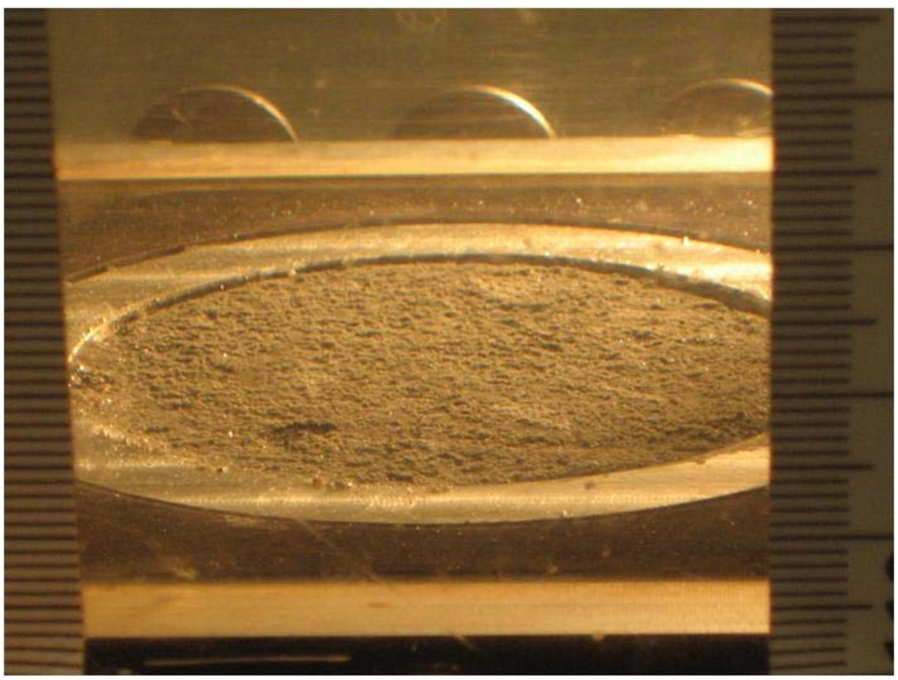

Figure C-1. Nanafalia Clay 21.5_8 Sample Prior to 3.0 m/s EFA Test.

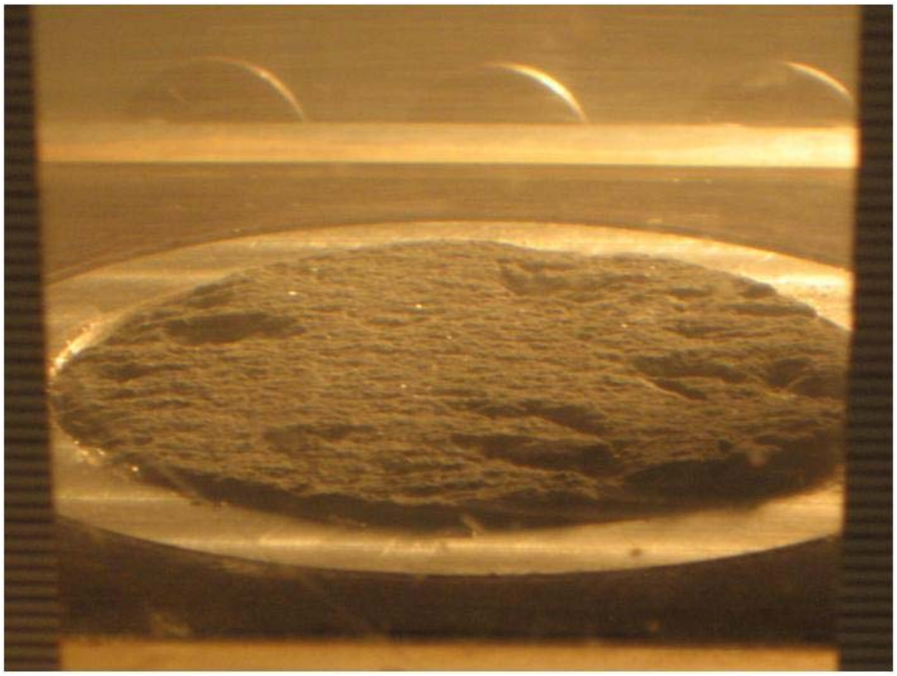

Figure C-2. Nanafalia Clay 21.5_8 Sample During the 3.0 m/s EFA Test.

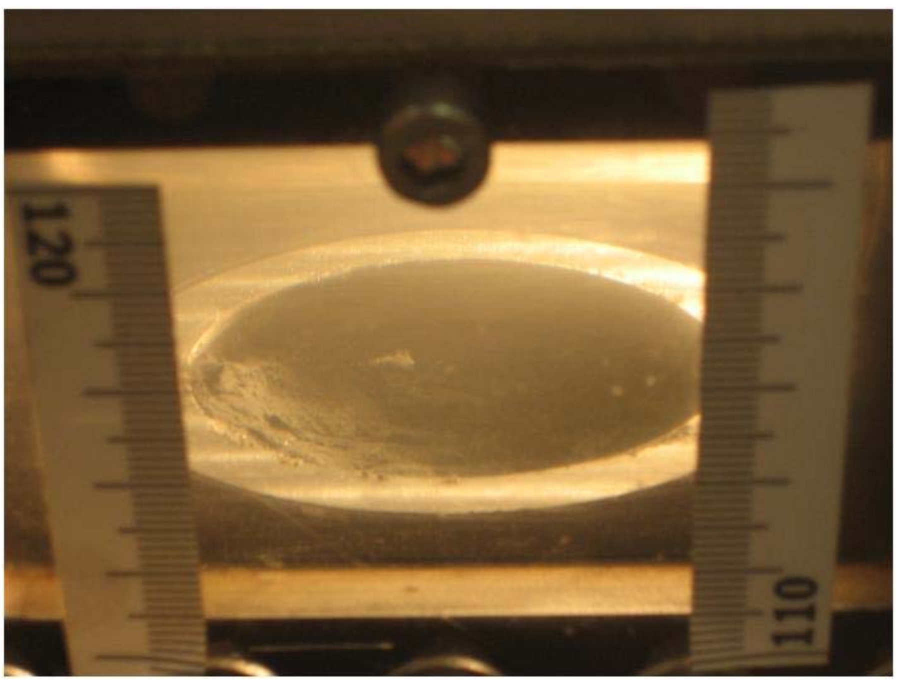

Figure C-3. Nanafalia Clay 21.5_8 Sample at the End of 3.0 m/s EFA Test.

C.1.3 Geotechnical Testing

An average insitu moisture content of 24.1% for the Nanafalia clay was determined according to ASTM D2216 – 10 standards (ASTM 2010a). A full grain size analysis, shown in Figure C-, was determined for the material using the ASTM D422 – 63 test method. Because none of the material was retained on the No. 10 sieve a coarse grain size analysis was not performed. The "fines percentage" (percent passing the No. 200 sieve) was determined to be 47 percent. The mean grain size diameter of the material was 0.080 mm. Atterberg limit testing was performed according to ASTM D4318 standards (ASTM, 2010b). The tests resulted in average values for liquid limit of 42, plastic limit of 25, and a plasticity index of 18. As previously stated, the SPT test performed by ALDOT resulted in an N value of 13 blows.

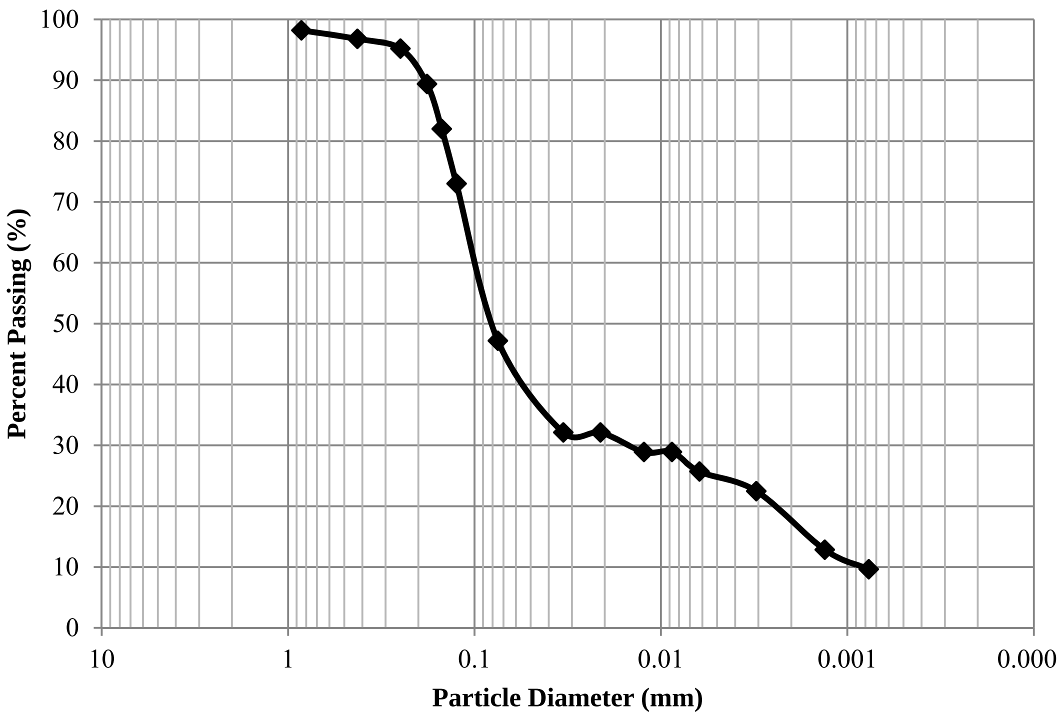

Figure C-4. Nanafalia Clay Grain Size Distribution.

C.2 Naheola Clay (Yellow Material)

The material was first sampled in 2012, and consisted of two different colored soils; one portion being a yellow-brownish material and the other having a dark grey color, as shown in Figure C-5. Because of this distinct difference in appearance the Naheola formation was divided and tested as two separate materials: Naheola (Yellow) and Naheola (Dark). The color change occurred at approximately 17 feet with the dark material overlying the yellow soil.

Figure C-5. Photograph of Naheola-Dark (left) and Naheola-Yellow (right) Formations.

C.2.1 Sampling

The Naheola formation sample was drilled in Marengo County, AL on June 7, 2012. The geologist for ALDOT classified the formation as a grey brown clay. An on-site geologist verified the formation with split spoon samples taken at approximately 12.8 feet below the ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 16 blows. There was very limited testable yellow material recovered from the 2012 Naheola drilling. The EFA tests were performed on the yellow material between depths of approximately 17.2 and 17.5 feet.

C.2.2 EFA Testing

Four critical velocity tests were performed on the yellow Naheola clay samples. Because the amount of yellow Naheola soil was so limited, only critical velocity tests for minor scours were performed. By testing for critical velocity of major scour too much soil would have been sacrificed and there would not be enough material available for the remaining EFA tests. Table C-7 shows a summary of the critical velocity tests for the yellow Naheola clay.

Table C-7. Critical Velocity Summary for Yellow Naheola Clay.

Test No.	Critical Velocity (m/s)	
	Minor Scour	**Major Scour**
Critical Velocity Test 1	0.40	Not Tested
Critical Velocity Test 2	0.45	Not Tested
Critical Velocity Test 3	0.60	Not Tested
Critical Velocity Test 4	0.40	Not Tested

A total of six EFA tests were performed on the yellow Naheola clay formation and the tests were further broken down to provide a total of seven individual scour events. The first test, titled "Naheola Clay 17.5_1", was conducted at the 0.3 m/s velocity. The test was run for a total of 70 minutes. A loose flake was lost with the velocity increase however no additional soil was lost afterwards. After considering that all critical velocities were above 0.3 m/s it was considered that the formation was scour resistant at a velocity of 0.3 m/s. Although the erosion plot showed otherwise, no scour was observed after the initial soil loss during velocity increase. Nearly 0.9 mm of swell was witnessed over the duration of the test.

A single test, titled "Naheola Clay 17.5_2", was performed at the 0.6 m/s velocity. In this test the plot showed very minimal soil loss however this was not visually corroborated. Although it was preferred that additional tests be conducted at this velocity, the amount of soil remaining for the following EFA tests was extremely limited.

Three EFA tests were conducted at the 1.0 m/s velocity. The first test, titled "Naheola Clay 17.5_3", lasted approximately 3 minutes. When the velocity reached 1.0 m/s the sample proceeded to scour in large chunks almost instantaneously. The second test run at 1.0 m/s, titled "Naheola Clay 17.5_4", was very similar to the prior test. The sample scoured very rapidly starting at a single point and extending outward. Although the total test lasted 3 minutes the scour event happened in a matter of seconds. The third and final test, titled "Naheola Clay 17.5_5", lasted approximately 67 minutes in which two scour events were witnessed. Scour was constant during the first occurrence and considerable swelling was observed following this event. Swelling continued throughout the second scour event. Some of the loose particles on the sample surface caused some erratic points on the erosion plot but the erosion rate slope was still easy to establish. Table C-8 presents a summary of results from the 1.0 m/s velocity.

Table C-8. Yellow Naheola Clay Results at 1.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Naheola Clay 17.5_3	3	CHUNK	NA	20.00 (Not used)
Naheola Clay 17.5_4	3	CHUNK	NA	90.35
Naheola Clay 17.5_5 (1)	4	0.19	2.85	1.26
Naheola Clay 17.5_5 (2)	16	0.54	2.03	

Because the amount of testable yellow Naheola material was so limited the 1.5 m/s test was not performed. Following the 1.0 m/s velocity increment there was only enough material remaining for one test. The last test conducted on the yellow Naheola formation was at 2.0 m/s. This test was titled "Naheola Clay 17.2_1". The test lasted 2 minutes and the majority of the sample was lost upon reaching a velocity of 2.0 m/s. Table C-9 shows the results for the single test performed at 2.0 m/s. Photographs taken at the beginning and end of the "Naheola Clay 17.2_1" test are shown in Figure C-6 and Figure C-7, respectively.

Table C-9. Yellow Naheola Clay Results at 2.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Naheola Clay 17.2_1	2	CHUNK	NA	195.45

As stated above, it was much preferred that additional EFA tests be conducted at the velocities tested as well as at 1.5 and 3.0 m/s. It should be noted, however, that supplementary tests were performed on the dark Naheola material as well as on a new Naheola sample drilled in 2013. The results of these tests are shown in sections **C.3 Naheola Clay (Dark Material)** and **C.4 Naheola Clay (Re-drilled)**.

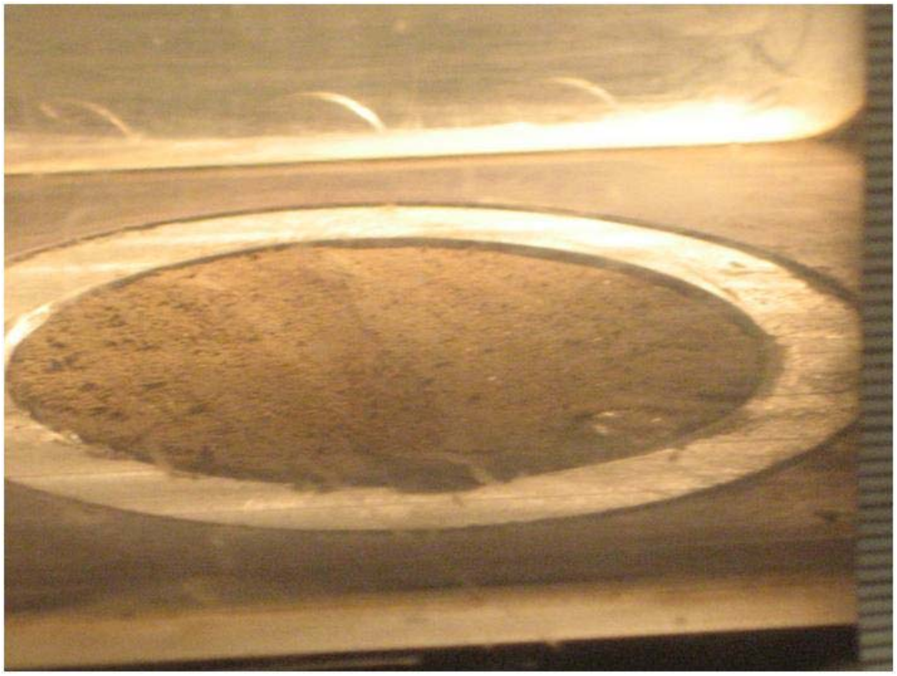

Figure C-6. Naheola Clay 17.2_1 Sample Prior to 2.0 m/s EFA Test.

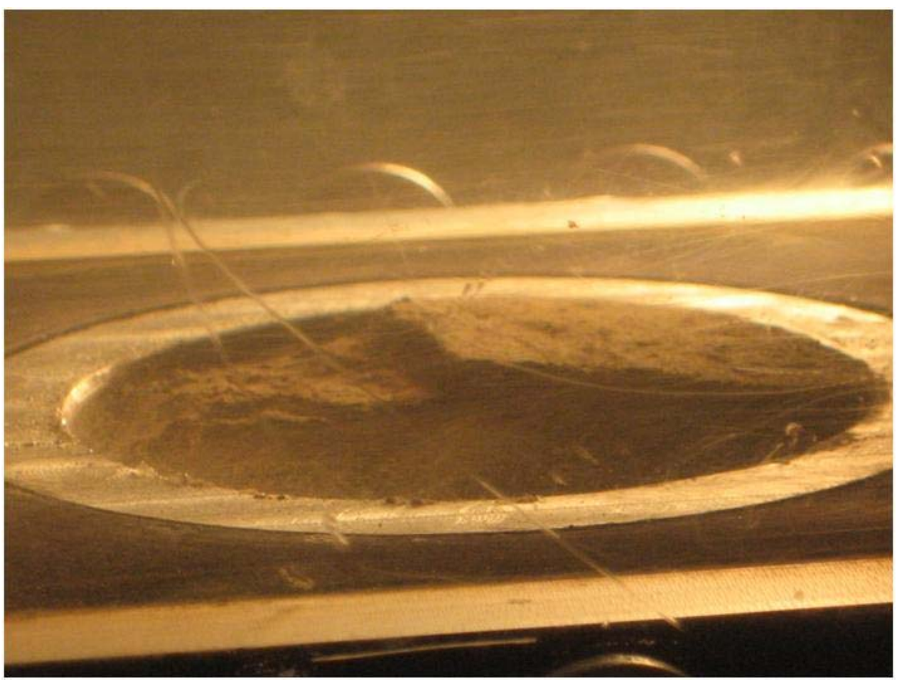

Figure C-7. Naheola Clay 17.2_1 Sample at the End of 2.0 m/s EFA Test.

C.2.3 Geotechnical Testing

An average in-situ moisture content of 31.4% for the yellow Naheola clay was determined according to ASTM D2216 – 10 standards (ASTM 2010a). A full grain size analysis, shown in Figure C-8, was determined for the material using the ASTM D422 – 63 test method. Because none of the material was retained on the No. 10 sieve a coarse grain size analysis was not performed. The "fines percentage" (percent passing the No. 200 sieve) was determined to be approximately 91 percent. The mean grain size diameter of the material was 0.028 mm. Atterberg limit testing was performed according to ASTM D4318 standards. The tests resulted in average values for liquid limit of 45, plastic limit of 33, and a plasticity index of 12. As previously stated, the SPT test performed by an ALDOT drill crew resulted in an N value of 16 blows.

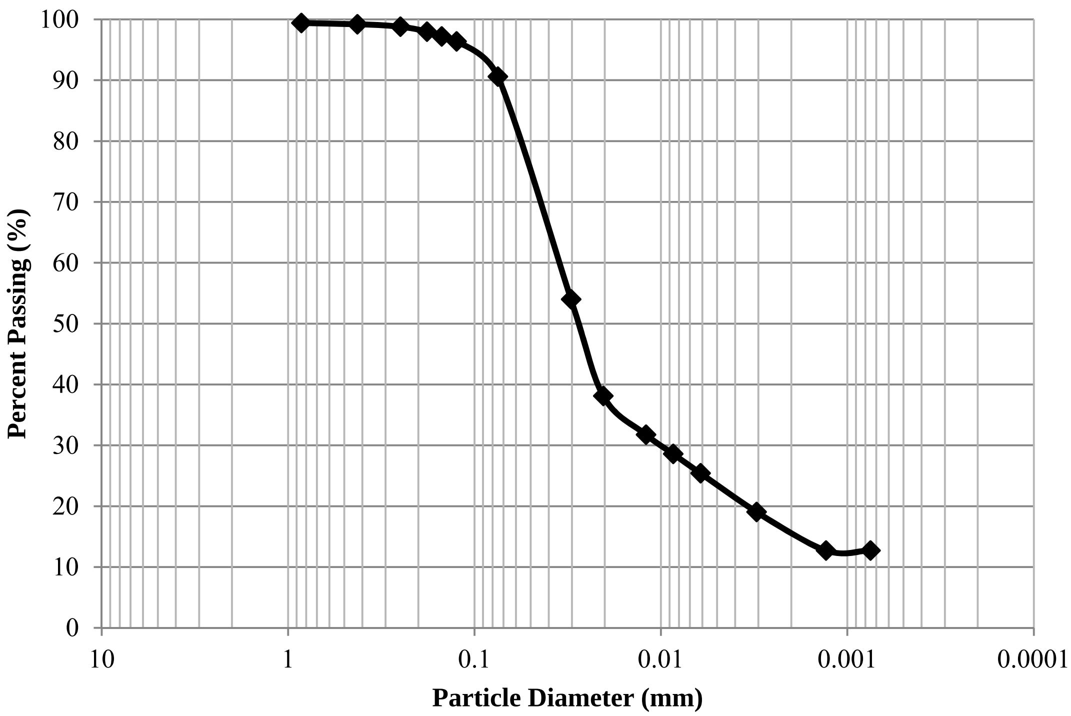

Figure C-8. Yellow Naheola Clay Grain Size Distribution.

C.3 Naheola Clay (Dark Material)

Because of the noticeable difference in color of the 2012 drilled sample (shown in Figure C-5), the Naheola formation was divided and tested as two separate materials: Naheola (Yellow) and Naheola (Dark). This section presents the EFA and geotechnical test results for the dark Naheola material.

C.3.1 Sampling

The Naheola formation sample was drilled in Marengo County, AL on June 7, 2012. The geologist for ALDOT classified the formation as a grey brown clay. An on-site geologist verified the formation with split spoon samples taken at approximately 12.8 feet below the ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 16 blows. As was the case for the yellow Naheola soil, there was very limited testable material for the dark Naheola clay. The EFA tests were performed on two 76 mm sections of the sample, one at a depth of approximately 17 feet and the other near 16 feet.

C.3.2 EFA Testing

Four critical velocity tests were performed on the dark Naheola formation. In the first critical velocity test scour began to occur at 0.7 m/s and extensive scour was seen once the velocity reached 2.1 m/s. In the second test minor scour occurred at a velocity of 1.0 m/s and increased dramatically at velocities greater than 1.0 m/s. At a velocity of 1.15 m/s the soil loss was very extreme. For the third test the critical velocity of minor scour was determined to be 0.65 m/s and major soil loss was witnessed moments later at this velocity. The final test was similar to the third test; producing equal critical velocities for minor and major scours of approximately 0.5 m/s. Table C-10 shows a summary of the critical velocity tests performed on the yellow Naheola clay.

Table C-10. Critical Velocity Summary for Dark Naheola Clay.

Test No.	Critical Velocity (m/s)	
	Minor Scour	Major Scour
Critical Velocity Test 1	0.70	2.10
Critical Velocity Test 2	1.00	1.15
Critical Velocity Test 3	0.65	0.65
Critical Velocity Test 4	0.50	0.50

A total of four EFA tests were performed on the dark Naheola clay material and the tests were further broken down to provide a total of seven individual scour events. Because all minor critical velocities were considerably larger than 0.3 m/s, the test at 0.3 m/s velocity was not performed. One test, titled “Naheola Clay 17.0_1”, was conducted at the 0.6 m/s velocity. The test was run for a total of 47 minutes. A few loose flakes were lost with the velocity increase but no significant scour was seen during the test.

One test, titled "Naheola Clay 17.0_2" was performed at the 1.0 m/s velocity. No scour was observed during the test however more than 1.5 mm of swell occurred over the 59 minute test duration. Although additional tests would like to have been performed at 1.0 m/s, there was too little testable material remaining. Therefore, EFA testing proceeded with the next velocity increment of 1.5 m/s.

Two EFA tests were performed at a velocity of 1.5 m/s. These tests produced a total of five scour events. The first test, titled "Naheola Clay 16.0_1", produced four individual scour events. Swelling was very extreme throughout this test which lasted approximately 62 minutes. It was seen that the sample would swell, crack, and the cracked pieces would be carried away over time. Although significant scour occurred during the test, the sample had a net height change of nearly 1 mm. Photographs taken prior to the test and near the end of the test are shown in Figure C-9 and Figure C-10, respectively. The second and final test at 1.5 m/s was titled "Naheola Clay 16.0_2". There was no scour or swell observed for the first 25 minutes of the test. After 25 minutes the sample began to swell quite dramatically. A total of 33 minutes into the test the sample washed away in one large chunk. Table C-11 presents the results of the 1.5 m/s EFA test.

Table C-11. Dark Naheola Clay Results at 1.5 m/s.

Sample:	**Elapsed Time (min)**	**Soil Loss (mm)**	**Scour Rate (mm/hr)**	**Overall Scour Rate (mm/hr)**
Naheola Clay 16.0_1 (1)	8	0.55	4.13	-2.27
Naheola Clay 16.0_1 (2)	3	0.10	2.00	
Naheola Clay 16.0_1 (3)	4	0.11	1.65	
Naheola Clay 16.0_1 (4)	3	0.10	2.00	
Naheola Clay 16.0_2	33	CHUNK	NA	22.79

Unfortunately, the entire dark Naheola inventory was depleted during the final 1.5 m/s EFA test. As previously stated, the Naheola formation was tested a third and final time using material procured in 2013. The results of those tests are presented in section **4.5 Naheola Clay (Re-drilled)**.

Figure C-9. Naheola Clay 16.0_1 Sample Prior to 1.5 m/s EFA Test.

Figure C-10. Naheola Clay 16.0_1 Sample at the End of 1.5 m/s EFA Test.

C.3.3 Geotechnical Testing

An average insitu moisture content of 34.3% for the dark Naheola clay was determined according to ASTM D2216 – 10 standards. A full grain size analysis, shown in Figure C-11, was determined for the material using the ASTM D422 – 63 test method. Because none of the material was retained on the No. 10 sieve a coarse grain size analysis was not performed. The "fines percentage" (percent passing the No. 200 sieve) was determined to be approximately 99 percent. The mean grain size diameter of the material was 0.016 mm. Atterberg limit testing was performed according to ASTM D4318 standards. The tests resulted in average values for liquid limit of 61, plastic limit of 25, and a plasticity index of 35. As previously stated, an SPT test performed by the ALDOT drill crew produced an N value of 16 blows.

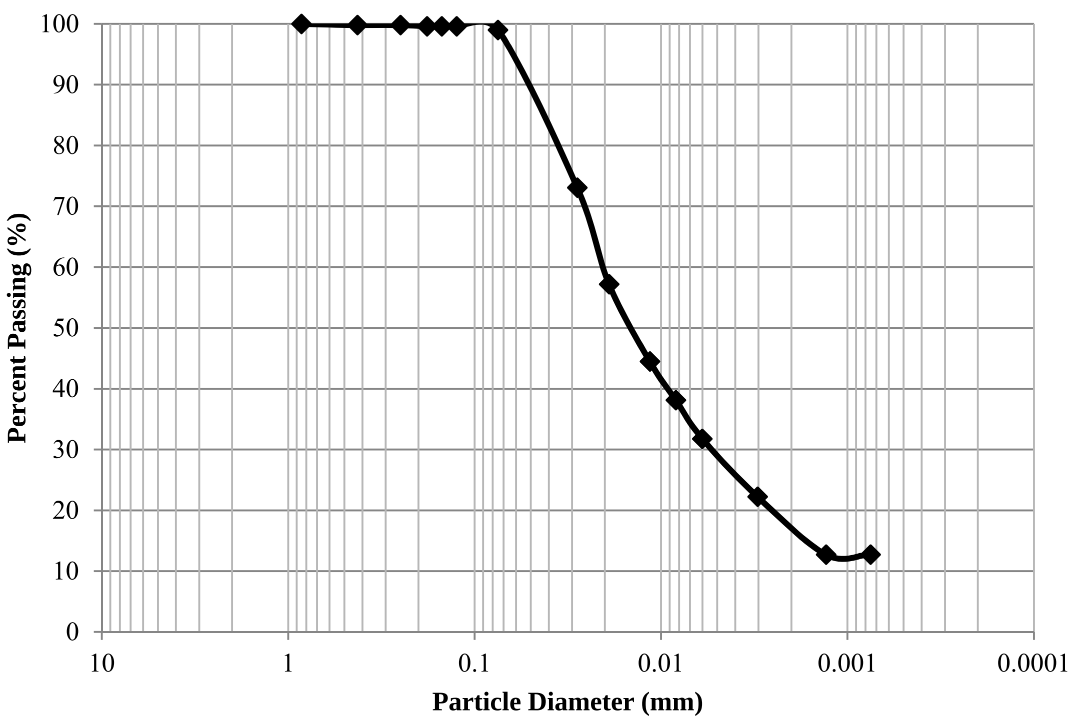

Figure C-11. Dark Naheola Clay Grain Size Distribution.

C.4 Naheola Clay (Re-drilled)

Due to the very limited testable Naheola material, it was suggested to ALDOT that additional samples of Naheola clay be drilled. This new sample of the Naheola formation was treated as a separate formation and complete EFA and geotechnical tests were performed on the material. This re-drilled sample was the third and final sample of the Naheola formation that was tested.

C.4.1 Sampling

The "re-drilled" Naheola sample was drilled on June 18, 2013 off of State Road 17 in Sumter County, AL. The geologist for ALDOT classified the formation as a plastic brown clay. An on-site geologist verified the formation with split spoon samples taken at approximately 17 feet below the ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 5 blows. The soil was very wet and only half a foot of the recovered sample was considered testable. One 152 mm section of the sampled material was used in EFA testing. The section was located at a depth of approximately 19.5 feet below the ground surface.

C.4.2 EFA Testing

Three critical velocity tests were performed on the re-drilled Naheola formation. In the first critical velocity test minor scour began to occur at 1.5 m/s. Because testable material was limited, no critical velocity test for major scour was conducted during this test. In the second test minor scour occurred at a velocity of 1.6 m/s and the major scour was once again not tested for. In the third and final test massive soil loss occurred at a velocity of approximately 3.0 m/s. In this test minimal to no scour was witnessed at velocities below 3.0 m/s and, therefore, no critical velocity for minor scour was determined. Table C-1 shows a summary of the critical velocity tests performed on the re-drilled Naheola clay.

Table C-12. Critical Velocity Summary for Re-drilled Naheola Clay.

Test No.	**Critical Velocity (m/s)**	
	Minor Scour	**Major Scour**
Critical Velocity Test 1	1.50	Not Tested
Critical Velocity Test 2	1.60	Not Tested
Critical Velocity Test 3	Not Determined	3.00

A total of five EFA tests were performed on the re-drilled Naheola clay material and the tests were further broken down to provide a total of six individual scour events. In order to conserve the limited testable material and considering the magnitude of the minor critical velocities shown in Table C-1, the re-drilled Naheola clay was not tested at the 0.3 m/s velocity.

One scour test, titled "Naheola Clay 19.5_1", was conducted at a velocity of 0.6 m/s. The test lasted a total of 52 minutes in which less than 0.1 mm of soil loss was measured by the sensors. Only one test was performed at this velocity in order to save testable material for subsequent velocity increments. Unfortunately there was not enough material remaining to test this velocity again. Table C-13 shows the results of the single test performed at 0.6 m/s.

Table C-13. Re-drilled Naheola Clay Results at 0.6 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Naheola Clay 19.5_1	52	0.09	0.10	-0.56

One test, titled "Naheola Clay 19.5_2", was performed at the 1.0 m/s velocity increment. Two separate scour events occurred throughout the test which lasted a total of 58 minutes. The scour started at a single point and extended outwards. A few erratic sensor measurements were seen towards the end of the test, most likely due to fluctuating temperature or interference from bubbles in the flume. Table C-14 presents the results from this test.

Table C-14. Re-drilled Naheola Clay Results at 1.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Naheola Clay_19.5_2(1)	3	0.10	2.00	1.05
Naheola Clay 19.5_2(2)	4	0.12	1.80	

A single test, titled "Naheola Clay 19.5_3", was conducted at a velocity of 1.5 m/s. The test lasted a total of 30 minutes in which very minimal to no scour was observed. As in the previous test, the sensor measurements were very erratic at certain points throughout the test. However these points were easily distinguished from the accurate measurements taken by the sensors.

There was one test, titled "Naheola Clay 19.5_4", performed at the 2.0 m/s velocity. The test lasted a total of 52 minutes in which constant scour on the upstream side of the sample occurred over a 35 minute span. Significant swelling was observed throughout the first ten minutes of the test. The plot showed that minimal scour occurred however appreciable scour was seen visually. The sample swelling could have counterbalanced measurements taken by the sensors. Figure C-12 and Figure C-13 are photographs taken at the start and end of the 2.0 m/s test, respectively. Table C-15 shows the results of the 2.0 m/s test.

Table C-15. Re-drilled Naheola Clay Results at 2.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Naheola Clay 19.5_4	35	0.14	0.24	-0.65

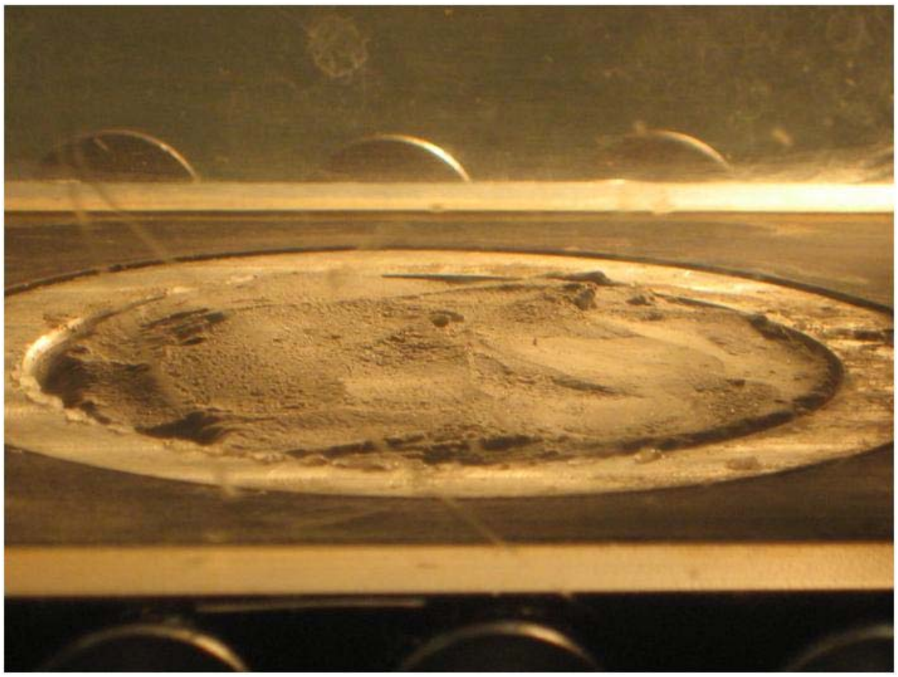

Figure C-12. Naheola Clay 19.5_4 Sample at the Start of 2.0 m/s EFA Test.

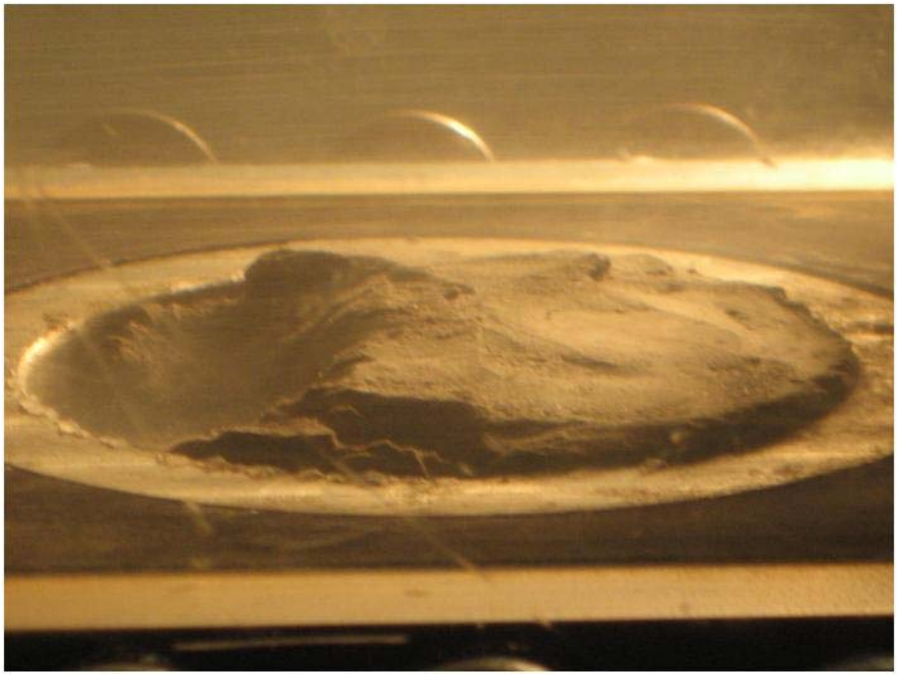

Figure C-13. Naheola Clay 19.5_4 Sample at the End of 2.0 m/s EFA Test.

One test, titled "Naheola Clay 19.5_5", was performed at the 3.0 m/s velocity. The single scour event lasted only 2 minutes and was extreme. A large chunk was lost when the velocity leveled off at 3.0 m/s and extensive scour continued until the test was stopped. This rapid scour may be considered to be "chunk" scour, as the sample was lost over a very short period of time. Table C-16 presents the results from this test.

Table C-16. Re-drilled Naheola Clay Results at 3.0 m/s.

Sample:	**Elapsed Time (min)**	**Soil Loss (mm)**	**Scour Rate (mm/hr)**	**Overall Scour Rate (mm/hr)**
Naheola Clay_19.5_5	2	2.66	79.80	27.41

C.4.3 Geotechnical Testing

An average insitu moisture content of 32.6% for the re-drilled Naheola clay was determined according to ASTM D2216 – 10 standards. A full grain size analysis, shown in Figure C-14, was determined for the material using the ASTM D422 – 63 test method. Because none of the material was retained on the No. 10 sieve a coarse grain size analysis was not performed. The "fines percentage" (percent passing the No. 200 sieve) was determined to be approximately 61 percent. The mean grain size diameter of the material was 0.044 mm. Atterberg limit testing was performed according to ASTM D4318 standards. The tests resulted in average values for liquid limit of 36, plastic limit of 24, and a plasticity index of 12. As previously stated, an SPT test performed by the ALDOT drill crew produced an N value of 5 blows.

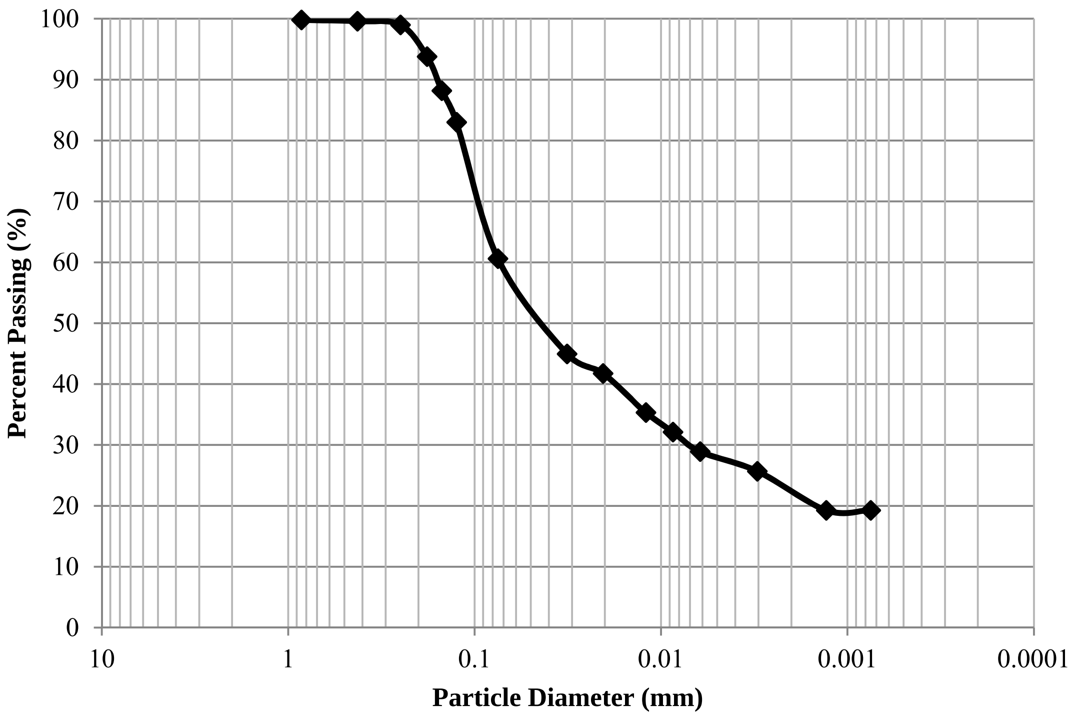

Figure C-14. Re-drilled Naheola Clay Grain Size Distribution.

C.5 Clayton Clay

The Clayton clay formation was sampled in 2012. EFA and geotechnical testing was performed in 2013.

C.5.1 Sampling

The Clayton formation sample was drilled in Barbour County, AL on June 21, 2012. The geologist for ALDOT classified the formation as a light brown clay. An on-site geologist verified the formation with split spoon samples taken at approximately 14 feet below the ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 23 blows. On August 8, 2013 ALDOT attempted to acquire additional Clayton material on Hwy 263 north of Greenville, AL. The drill team encountered large amounts of the Clayton formation, but as the geologic data suggested, it was marbled with layers of hard limestone. Although there seemed to be layers as thick as 6 to 8" of the Clayton soil, the broken rock was causing the tube to jam resulting in the soil to break apart. After drilling well over 40 feet the crew drilled into a thick layer of limestone that caused refusal. It was concluded that the limestone prevented the sampler from acquiring an adequate sample and drilling was discontinued. The EFA tests were performed on the 2012 Clayton sample ranging between depths of approximately 29 and 30 feet.

C.5.2 EFA Testing

Three critical velocity tests were performed on Clayton clay samples. During the first critical velocity test minor particle loss was observed at a velocity of 0.60 m/s and more significant erosion was experienced at 1.10 m/s. In the second critical velocity test very minor but constant soil loss was observed at a velocity of approximately 0.55 m/s. Much larger scour occurred near a velocity of about 1.5 m/s. The final critical velocity test resulted in a critical velocity of 0.90 m/s for minor scour and extensive soil was being lost at 2.5 m/s. Table C-17 shows a summary of critical velocity tests performed on the Clayton formation.

Table C-17. Critical Velocity Summary for Clayton Clay.

Test No.	**Critical Velocity (m/s)**	
	Minor Scour	**Major Scour**
Critical Velocity Test 1	0.60	1.10
Critical Velocity Test 2	0.55	1.50
Critical Velocity Test 3	0.90	1.20

Twelve EFA tests were performed on the Clayton clay formation and the tests were further broken down to provide a total of 23 individual scour events. Because the determined minor critical velocities were considerably large than 0.3 m/s, the test at 0.3 m/s velocity was not performed.

One test, titled "Clayton 29.5_3", was conducted at the 0.6 m/s velocity. The test was run for a total of 61 minutes in which no scour was seen. The sample experienced rapid swelling midway through the test duration. Figure C-15 shows a photograph of the sample prior to swelling while Figure C shows a photograph taken of the sample approximately 25 minutes later. As can be seen, the swelling experienced throughout the test was very significant, resulting in a change in specimen height of approximately 0.95 mm.

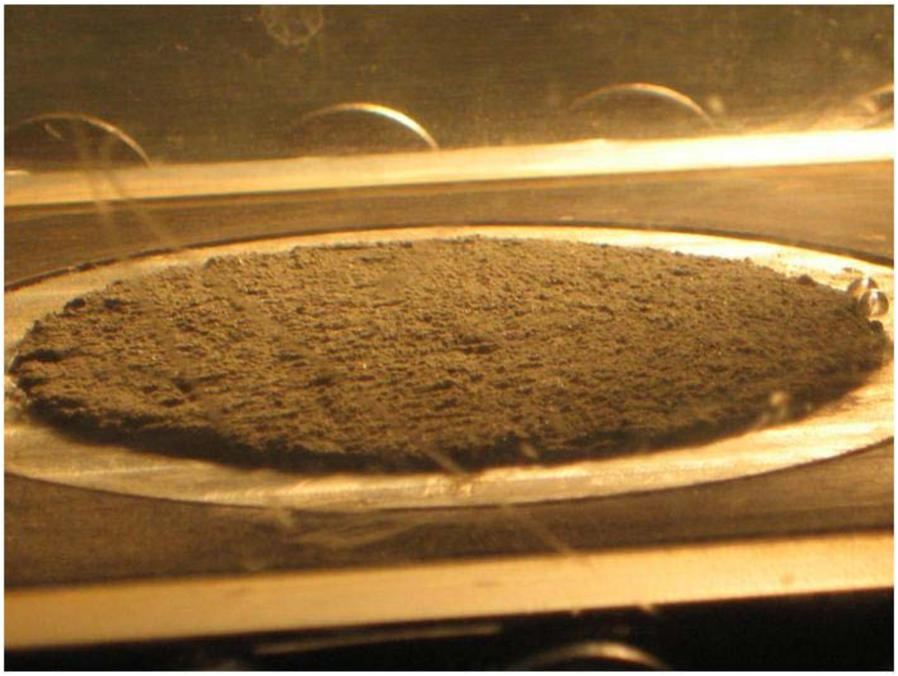

Figure C-15. Clayton 29.5_3 Approximately 20 Minutes into Test.

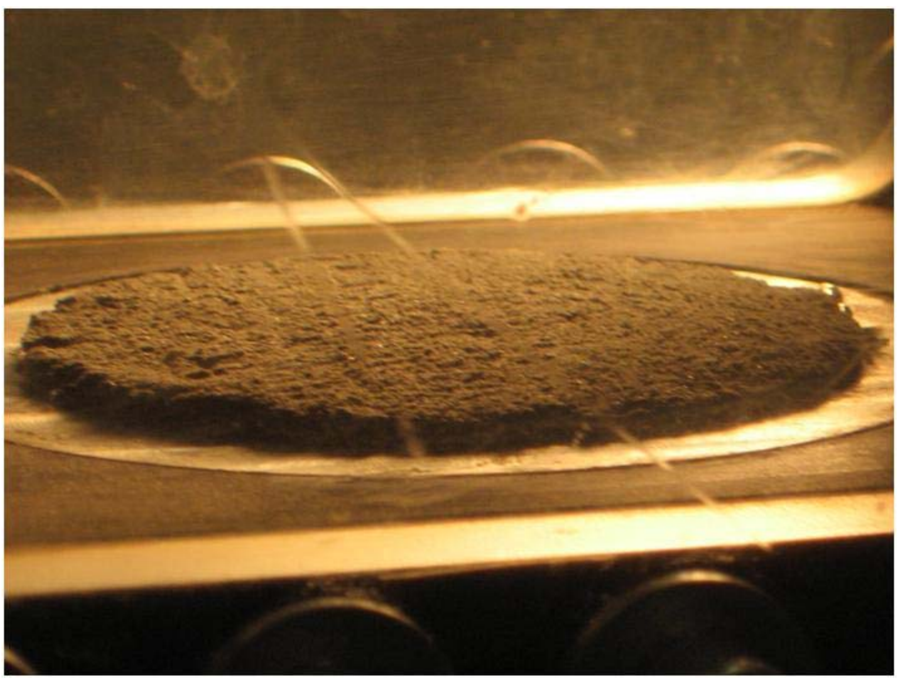

Figure C-16. Clayton 29.5_3 Approximately 45 Minutes into Test.

Two tests were conducted at the 1.0 m/s velocity. The first test, titled "Clayton 23.5_2", lasted 60 minutes in which a total of three individual scour events were observed. Although scour certainly occurred, the swell was so extreme that the sample actually grew more than 1 mm by the end of the test. Scour happened sporadically and the previously discussed scour-swell pattern was also apparent during this test. The second test, titled "Clayton 29.5_5", lasted 19 minutes where two scour events were seen. The first event showed relatively extensive scour over a three minute period and the second event occurred approximately 17 minutes into the test where the entire sample was lost in a few large chunks. Table C-18 shows a summary of results from the 1.0 m/s velocity. Because there was limited Clayton material, no additional tests were performed at 1.0 m/s.

Table C-18. Clayton Clay Results at 1.0 m/s.

<table>
<tr><th>Sample:</th><th>Elapsed Time (min)</th><th>Soil Loss (mm)</th><th>Scour Rate (mm/hr)</th><th>Overall Scour Rate (mm/hr)</th></tr>
<tr><td>Clayton 29.5_4 (1)</td><td>8</td><td>0.43</td><td>3.23</td><td rowspan="3">-0.52</td></tr>
<tr><td>Clayton 29.5_4 (2)</td><td>4</td><td>0.10</td><td>1.50</td></tr>
<tr><td>Clayton 29.5_4 (3)</td><td>2</td><td>0.07</td><td>2.10</td></tr>
<tr><td>Clayton 29.5_5 (1)</td><td>3</td><td>0.38</td><td>7.60</td><td rowspan="2">29.45</td></tr>
<tr><td>Clayton 29.5_5 (2)</td><td>17</td><td>CHUNK</td><td>NA</td></tr>
</table>

Three EFA tests were performed at a velocity of 1.5 m/s. These tests produced a total of five scour events. The first test, titled "Clayton 29.5_6", lasted 26 minutes before the entire sample washed away in one instant. Scour seemed to be occurring throughout the test however swelling was too extensive to see it in the sensor measurements. The second test, titled "Clayton 29.0_3", lasted approximately one hour in which two scour events occurred. Scour occurred sporadically throughout the test and a scour-swell patterned was evident in the plot. The last test at 1.5 m/s, titled "Clayton 29.0_6", lasted approximately 32 minutes and two scour events were seen. Scour was seen at the beginning of the test and then the sample proceeded to swell more than 1.25 mm. Eventually the sample was lost in a few large chunks, representing the second scour event. Table C-19 presents the results of the 1.5 m/s EFA tests.

Table C-19. Clayton Clay Results at 1.5 m/s.

Sample:	**Elapsed Time (min)**	**Soil Loss (mm)**	**Scour Rate (mm/hr)**	**Overall Scour Rate (mm/hr)**
Clayton 29.5_6	26	CHUNK	NA	15.09
Clayton 29.0_3 (1)	9	0.2	1.33	2.22
Clayton 29.0_3 (2)	2	0.06	1.80	
Clayton 29.0_6 (1)	5	0.35	4.20	9.81
Clayton 29.0_6 (2)	32	CHUNK	NA	

Three EFA tests were conducted at the 2.0 m/s velocity, producing a total of six individual scour events. In the first test, titled "Clayton 29.0_1", one scour event occurred over a six minute period. The second test, titled "Clayton 29.0_4", lasted approximately five minutes and the sample was lost in two large chunks when the flow reached a velocity of 2.0 m/s. The last test, titled "Clayton 29.0_7", produced four separate scour events over the 26 minute test duration. Massive swelling resulted in a net increase in sample height of more than 2.6 mm. The sample swelled more than 1 mm in the last two minutes of the test. Eventually the entire top half of the sample was washed away approximately 26 minutes into the test. Figure C-17, Figure C-18, and Figure C-19 are photographs taken at critical moments throughout the 2.0 m/s test. The massive swelling that occurred during the test is very apparent in the photographs. Table C-20 shows the results of the 2.0 m/s tests.

Table C-20. Clayton Clay Results at 2.0 m/s.

Sample:	**Elapsed Time (min)**	**Soil Loss (mm)**	**Scour Rate (mm/hr)**	**Overall Scour Rate (mm/hr)**
Clayton 29.0_1	6	1.06	10.60	7.86
Clayton 29.0_4	5	CHUNK	NA	89.72
Clayton 29.0_7 (1)	1	0.10	6.00	7.49
Clayton 29.0_7 (2)	1	0.17	10.20	
Clayton 29.0_7 (3)	1	0.17	10.20	
Clayton 29.0_7 (4)	26	CHUNK	NA	

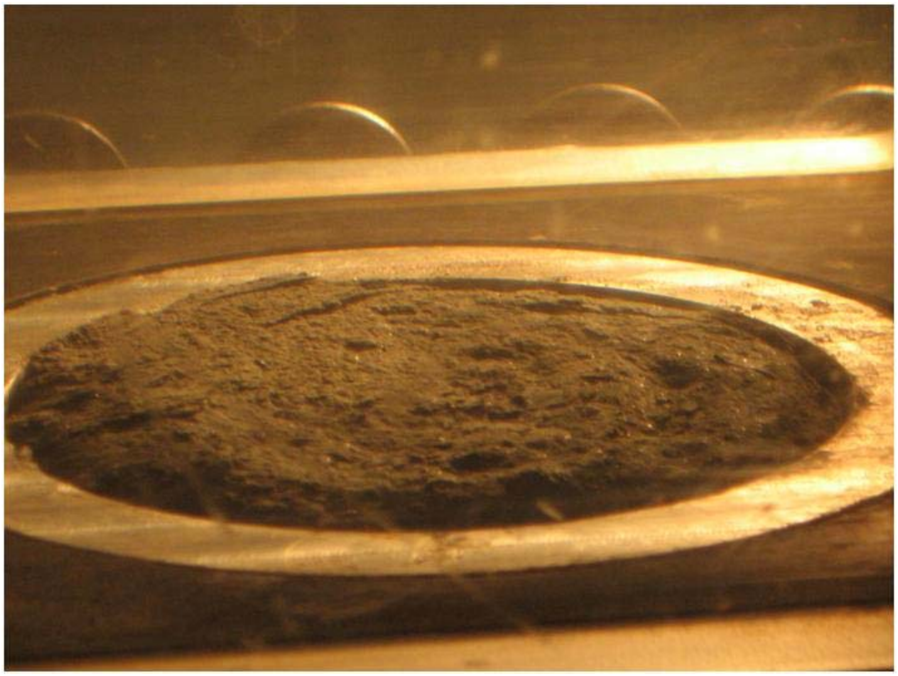

Figure C-17. Clayton 29.0_7 Approximately 8 Minutes into Test.

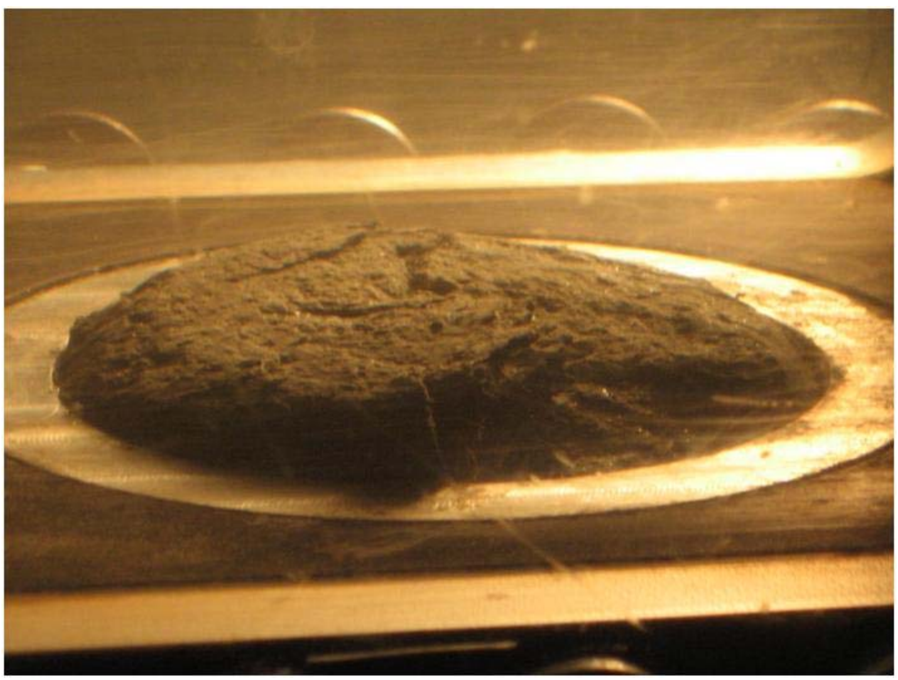

Figure C-18. Clayton 29.0_7 Approximately 23 Minutes into Test.

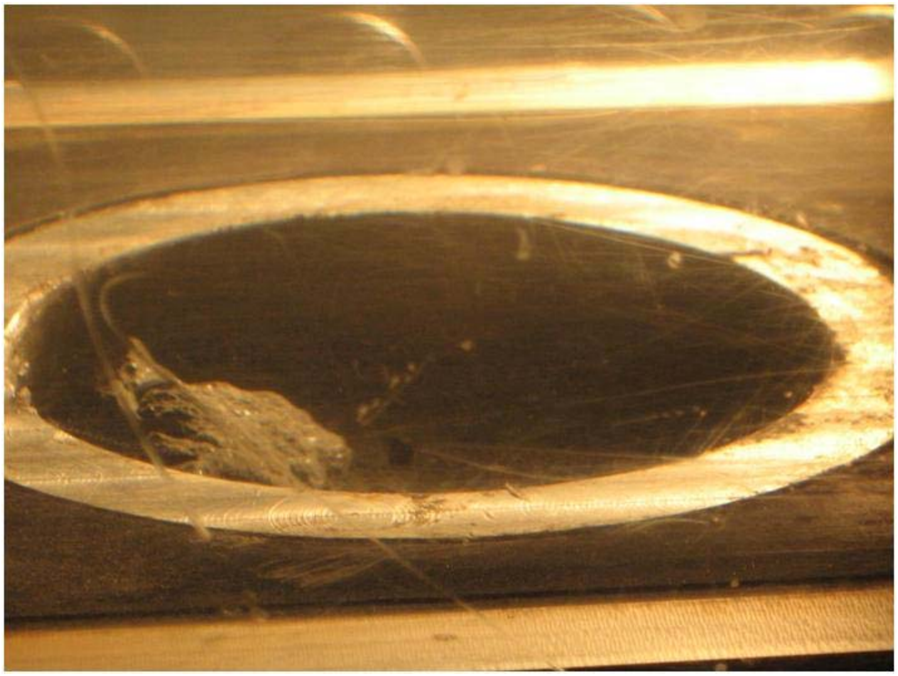

Figure C-19. Clayton 29.0_7 Approximately 27 Minutes into Test.

Three EFA tests were performed at the 3.0 m/s velocity. The first test, titled "Clayton 29.0_1", lasted two minutes in which very rapid and uniform scour occurred. The second test, titled "Clayton 29.0_5", lasted a total of five minutes when the entire sample was lost once the velocity reached 3.0 m/s. The third test, titled "Clayton 29.0_8", lasted approximately 21 minutes and four individual scour events took place. In the first three events, the scour-swell pattern was seen. Scour would occur, the sample would begin to swell, scour would stop, and then the sample would continue to scour again. Very serious swelling was witnessed in the last five minutes of the test and the sample scoured in one large chunk about 20 minutes into the test. Table C-21 shows a summary of results from the 3.0 m/s velocity.

Table C-21. Clayton Clay Results at 3.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Clayton 29.0_1	2	0.42	12.60	30.29
Clayton 29.0_5	5	CHUNK	NA	99.57
Clayton 29.0_8 (1)	1	0.23	13.80	30.52
Clayton 29.0_8 (2)	5	0.47	5.64	
Clayton 29.0_8 (3)	2	0.42	12.60	
Clayton 29.0_8 (4)	20	CHUNK	NA	

C.5.3 Geotechnical Testing

An average insitu moisture content of 51.4% for the Clayton soil was determined according to ASTM D2216 – 10 standards. A full grain size analysis, shown in Figure C-20, was determined for the material using the ASTM D422 – 63 test method. Because none of the material was retained on the No. 10 sieve a coarse grain size analysis was not performed. The "fines percentage" (percent passing the No. 200 sieve) was determined to be 76 percent. The mean grain size diameter of the material was 0.023 mm. Atterberg limit testing was performed according to ASTM D4318 standards. The tests resulted in average values for liquid limit of 41, plastic limit of 25, and a plasticity index of 17. As previously stated, the SPT test performed by ALDOT resulted in an N value of 23 blows.

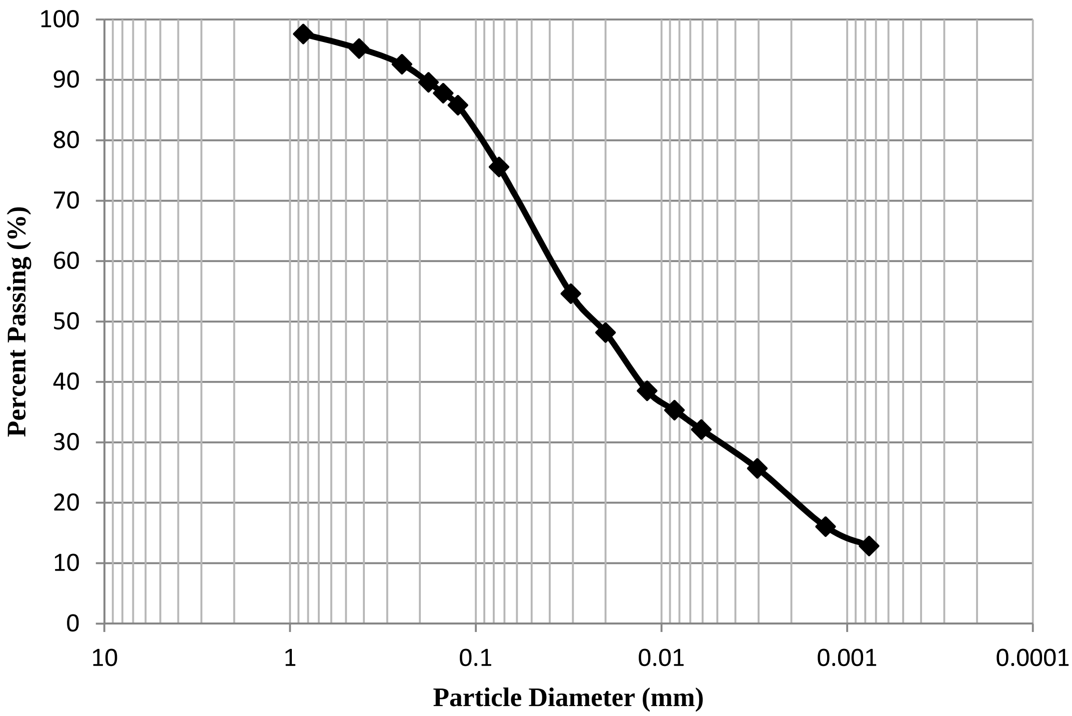

Figure C-20. Clayton Clay Grain Size Distribution.

C.6 Bucatunna Clay (Retest)

Because the material sampled in 2012 was extremely limited, additional drilling was necessary in order to perform further testing of the formation; however drilling by ALDOT conducted in August of 2013 was unsuccessful in acquiring a testable section of Bucatunna clay. Therefore, testing proceeded with the limited material remaining from the 2012 borings.

C.6.1 Sampling

On August 8, 2013, ALDOT attempted to drill for Bucatunna on County Road 3 in Choctaw County, AL. The Bucatunna soil was encountered during the drilling, however, there was such a large portion of sand mixed with the clay that no samples contained testable material. The ALDOT crew continued to drill past 40 feet until eventually the drill tapped into a layer of Yazoo clay underlying the sandy Bucatunna layer. After extensive effort in attempting to retrieve a cohesive sample of Bucatunna Clay, it was concluded that drilling operations for Bucatunna formation would be suspended.

The 2012 drilled Bucatunna formation sample was drilled in Monroe County, AL on April 5, 2012. The geologist for ALDOT classified the formation as a dark grey brown clay. An on-site geologist verified the formation with split spoon samples taken at approximately 11 feet below ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 6 blows. The samples tested were at a depth of approximately 26.0 feet.

C.6.2 EFA Testing

Three critical velocity tests were performed on Bucatunna clay material. The first two tests both resulted in a critical velocities of 0.70 m/s for minor scour and the critical velocity for major scour was not determined in order to conserve testable material. The final critical velocity test resulted in a critical velocity of 0.50 m/s for minor scour and extensive soil was being lost at a velocity of approximately 1.20 m/s. Table C-2 presents the summary of critical velocity tests performed on the Bucatunna formation.

Table C-22. Critical Velocity Summary for Bucatunna Clay.

Test No.	Critical Velocity (m/s)	
	Minor Scour	Major Scour
Critical Velocity Test 1	0.70	Not Tested
Critical Velocity Test 2	0.70	Not Tested
Critical Velocity Test 3	0.50	1.20

A total of four EFA tests were performed on the Bucatunna clay material and the tests were further separated to provide a total of eight individual scour events. In order to conserve the limited testable material and considering the magnitude of the critical velocities shown in Table C-2, the Bucatunna clay was not tested at the 0.3 m/s velocity.

One scour test, titled “Bucatunna 26.0_1”, was conducted at a velocity of 0.6 m/s. The test lasted a total of 50 minutes in which approximately 0.17 mm of soil loss was measured by the sensors. The scour occurred during the first seven minutes of the test and then the sample proceeded to swell 1.1 mm over the next 37 minutes. Only one test was performed at this velocity in order to save testable material for subsequent velocities. Table C shows the results of the single test performed at 0.6 m/s.

Table C-23. Bucatunna Clay Results at 0.6 m/s.

Sample:	**Elapsed Time (min)**	**Soil Loss (mm)**	**Scour Rate (mm/hr)**	**Overall Scour Rate (mm/hr)**
Bucatunna 26.0_1	7	0.17	1.46	-2.56

One EFA test, titled "Bucatunna 26.0_2", was performed at the 1.0 m/s velocity. Two separate scour events occurred throughout the test which lasted a total of 31 minutes. Scour occurred at the start of the test and then the sample began to swell more than 1 mm. Eventually the sample washed away instantaneously 27 minutes after the sample was extruded. Table C-24 shows the results from this test.

At this point during the testing the amount of testable material remaining was extremely limited. Therefore, the testing at 1.5 m/s was skipped and testing proceeded at a velocity of 2.0 m/s. A single test, titled "Bucatunna 26.0_3", was conducted at a velocity of 2.0 m/s. The test lasted a total of 18 minutes in which four different scour events were seen. Some soil was lost with the velocity increase and therefore that portion of the soil loss was not considered during analysis. The sample was lost in a few large pieces 14 minutes after the sample was advanced. Photographs taken during the test are shown in Figures C-21 and C-22. Table C-25 presents the results of the 2.0 m/s EFA test.

Table C-24. Bucatunna Clay Results at 1.0 m/s.

Sample:	**Elapsed Time (min)**	**Soil Loss (mm)**	**Scour Rate (mm/hr)**	**Overall Scour Rate (mm/hr)**
Bucatunna 26.0_2(1)	1	0.09	5.40	64.41 (Not used)
Bucatunna 26.0_2(2)	27	CHUNK	NA	

Table C-25. Bucatunna Clay Results at 2.0 m/s.

Sample:	**Elapsed Time (min)**	**Soil Loss (mm)**	**Scour Rate (mm/hr)**	**Overall Scour Rate (mm/hr)**
Bucatunna26.0_3(1)	1	0.15	9.00	18.26
Bucatunna26.0_3(2)	1	0.14	8.40	
Bucatunna26.0_3(3)	1	0.14	8.40	
Bucatunna26.0_3(4)	14	CHUNK	NA	

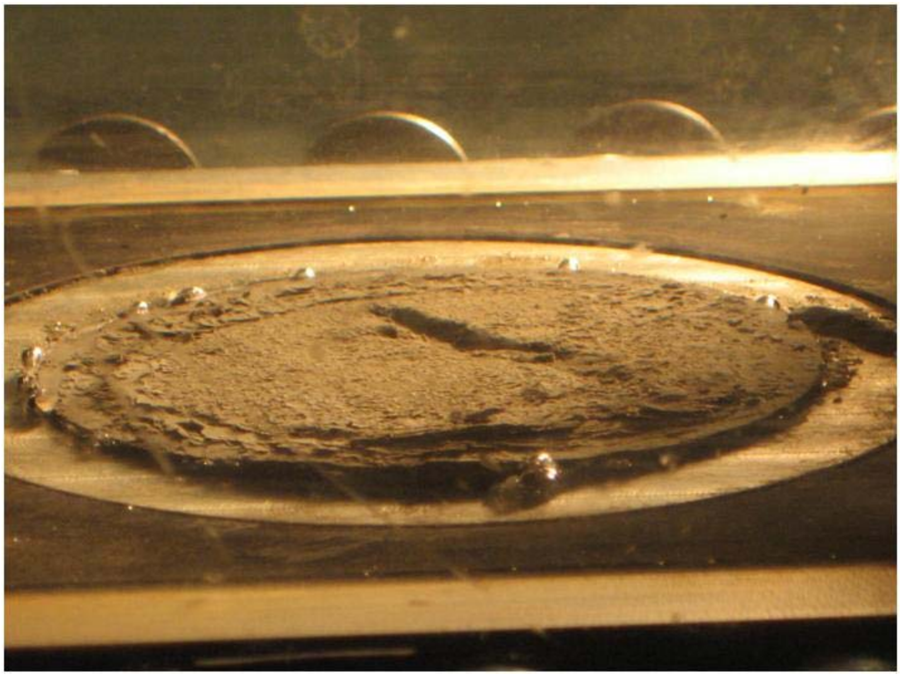

Figure C-21. Bucatunna 26.0_3 Sample Approximately 3 Minutes into 3.0 m/s EFA Test

Figure C-22. Bucatunna 26.0_3 Sample Approximately 15 Minutes into 3.0 m/s EFA Test.

The one EFA test, titled "Bucatunna 26.0_4", performed at 3.0 m/s lasted a total of eight minutes. The sample eroded away when the velocity had not yet reached 3.0 m/s.

C.7 Porter's Creek Clay (Resampled)

Because the Porter's Creek material sampled in 2012 was depleted, additional borings were conducted to acquire samples to be used to conduct supplementary EFA tests on the formation.

C.7.1 Sampling

The Porter's Creek sample was drilled on August 5, 2013 off of State Road 25 in Marengo County, AL. The geologist for ALDOT classified the formation as a stiff brown clay. An on-site geologist verified the formation with split spoon samples taken at approximately 19 feet below ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 13 blows. Roughly one foot of the recovered sample was considered testable. The 12" section used in testing was located at a depth of approximately 24 to 25feet below the ground surface.

C.7.2 EFA Testing

Eight critical velocity tests were performed on Porter's Creek clay samples. These tests were conducted by simultaneously determining critical velocities during the general EFA tests. Table C-2 shows a summary of critical velocity tests performed on the Porter's Creek formation.

Table C-26. Critical Velocity Summary for Porter's Creek Clay.

Test No.	Critical Velocity (m/s)	
	Minor Scour	**Major Scour**
Critical Velocity Test 1	0.30	0.45
Critical Velocity Test 2	0.30	0.30
Critical Velocity Test 3	0.30	0.30
Critical Velocity Test 4	0.30	0.30
Critical Velocity Test 5	0.30	0.30
Critical Velocity Test 6	0.35	0.35
Critical Velocity Test 7	0.40	0.40
Critical Velocity Test 8	0.30	0.30

A total of nine EFA tests were performed on the Porter's Creek clay material and the tests were further broken down to provide a total of fifteen individual scour events. Because all critical velocities were relatively close to 0.3 m/s, testing began at the 0.3 m/s velocity.

Three EFA tests were performed at a velocity of 0.3 m/s. These tests produced a total of seven scour events. The first test, titled "PortersCreek 24.0_4", lasted 26 minutes and produced three separate scour events. In the first event scour was relatively significant, but because swelling was so extreme the scour was difficult to discern from the erosion graph. In other words, the scour rate for the first event was most likely not a true depiction of total soil loss but rather a net change in specimen height. The "PortersCreek24.0_4" sample grew approximately 1.88 mm in the nine minutes between the first and second scour events. The scour-swell pattern was seen throughout the test until the majority of the sample was lost instantaneously 22 minutes after the push. Figure C-23 and Figure C-2 show photographs taken at the start of the test and 15 minutes after the sample was advanced, respectively. The second test conducted at 0.3 m/s, titled "PortersCreek24.5_1" was similar to the first. The test lasted just under 40 minutes and produced three scour events. It was noted that the second scour rate (PortersCreek24.5_1(2)) may have been negated by severe swelling, thus resulting in a conservative scour rate. In the third test, titled "PortersCreek24.5_5", no scour was observed but the sample swelled an astounding 3.1 mm in 19 minutes. Table C shows the results of the 0.3 m/s EFA test.

Figure C-23. Porter's Creek 24.0_4 Sample at Start of 0.3 m/s EFA Test.

Figure C-24. Porter's Creek 24.0_4 Sample 15 minutes After Push.

Table C-27. Porter's Creek Clay Results at 0.3 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
PortersCreek24.0_4(1)	4	0.30	4.50	12.15
PortersCreek24.0_4(2)	6	1.18	11.80	
PortersCreek24.0_4(3)	22	CHUNK	NA	
PortersCreek24.5_1(1)	2	0.71	21.30	5.67
PortersCreek24.5_1(2)	3	0.27	5.40	
PortersCreek24.5_1(3)	10	2.69	16.14	
PortersCreek24.5_5	22	0.00	0.00	-29.77

Four EFA tests were run at the 0.6 m/s. In the first test, titled "PortersCreek24.0_1", the sample washed away before the velocity had reached 0.6 m/s. In the three subsequent tests, titled "PortersCreek24.5_2", "PortersCreek24.5_3", and "PortersCreek24.5_4", a single scour event was observed in each test. Although some scour occurred during the velocity increase for these tests, the scours witnessed after the velocity reached 0.6 m/s are the shown in Table C-28 below.

Table C-28. Porter's Creek Clay Results at 0.6 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
PortersCreek24.0_1	0	WASH	NA	118.35 [1]
PortersCreek24.5_2	4	1.71	25.65	29.55
PortersCreek24.5_3	2	0.72	21.60	30.17
PortersCreek24.5_4	6	2.06	20.60	16.88

[1] This huge scour rate was not used in the final data analysis.

One EFA test, titled "PortersCreek24.0_2", was performed at 1.0 m/s. The sample scoured completely after eight minutes and produced a total of three scour events. The initial soil loss before the target velocity was reached was not included in any of the scour events. The sample continued to erode once the 1.0 m/s velocity was reached (representing the first event), then scour stopped and the sample proceeded to swell more than 0.8 mm over the next two minutes. The specimen then began to scour very rapidly (representing the second event) and eventually eroded away in very large chunks over a matter of seconds. Table C-29 presents the results of the sole test performed at 1.0 m/s.

Table C-29. Porter's Creek Clay Results at 1.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
PortersCreek24.0_2(1)	3	1.09	21.80	23.00
PortersCreek24.0_2(2)	1	0.45	27.00	
PortersCreek24.0_2(3)	8	CHUNK	NA	

Although one test was performed at 1.5 m/s, titled "PortersCreek24.0_3", the entire sample washed away before the sample was pushed. As shown, the Porter's Creek formation proved to be highly erodible. Because there was extremely limited testable material remaining at this point in testing, it was decided that the remaining material be used to conduct additional tests at velocities below 1.5 m/s. With that said, no tests on the Porter's Creek material were performed at the 2.0 and 3.0 m/s velocity increments, as the samples would most likely erode before a target velocity can be achieved and valuable soil would be sacrificed.

C.7.3 Geotechnical Testing

An average insitu moisture content of 43.6% for the Porter's Creek soil was determined according to ASTM D2216 – 10 standards. A full grain size analysis, shown in Figure C-2, was determined for the material using the ASTM D422 – 63 test method. Because none of the material was retained on the No. 10 sieve a coarse grain size analysis was not performed. The "fines percentage" (percent passing the No. 200 sieve) was determined to be 98 percent. The mean grain size diameter of the material was not determined because a 48 hour hydrometer test was not sufficient for this very fine material, however the mean grain size diameter was considered to be much less than 0.001 mm. Atterberg limit testing was performed according to ASTM D4318 standards. The tests resulted in average values for liquid limit of 114, plastic limit of 40, and a plasticity index of 74. As previously stated, the SPT test performed by ALDOT resulted in an N value of 13 blows.

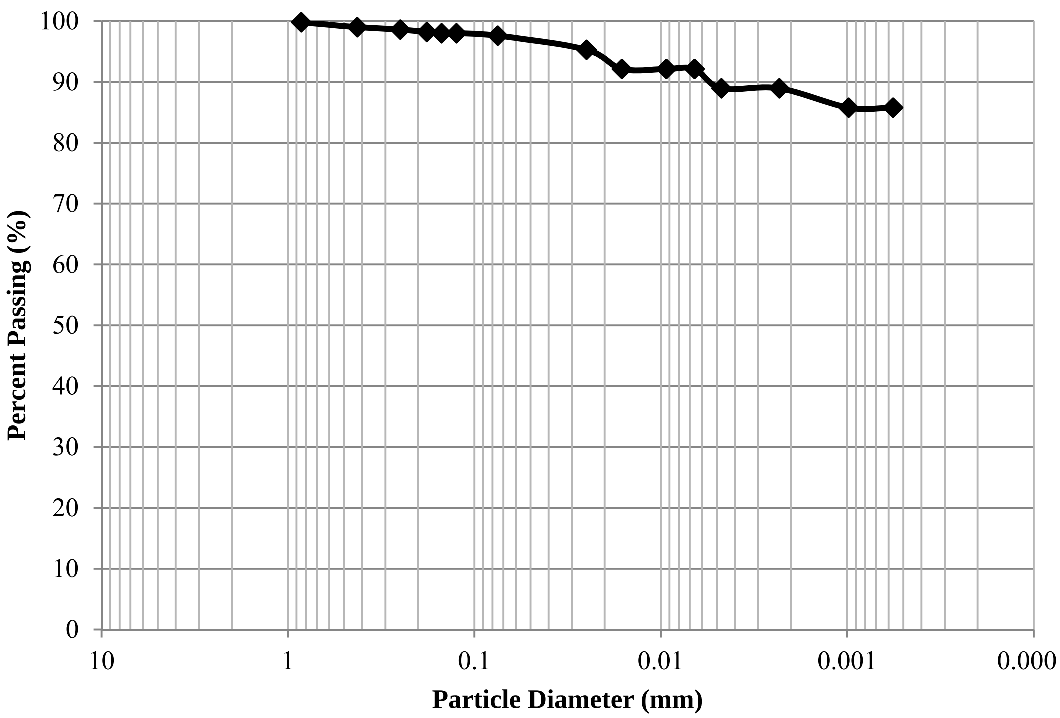

Figure C-25. Porter's Creek Clay Grain Size Distribution.

C.8 Yazoo Clay (Retest)

The Yazoo material sampled in 2012 was used to conduct supplementary EFA tests on the formation.

C.8.1 Sampling

The Yazoo Clay was acquired on April 6, 2012 in Conecuh County, Alabama by ALDOT drill crew. The sample was collected near a stream with a visible outcrop of the formation viewed in the streambed. The geologist for ALDOT classified the formation as a light colored stiff grey clay. An on-site geologist verified the formation with split spoon samples taken at approximately 13.5 feet below the ground surface. The SPT performed resulted in an N value of 15 blows. A 457 mm section, ranging from a depth of 21 feet to 22.5 feet, was used to perform EFA tests during this study.

C.8.2 EFA Testing

Three critical velocity tests were performed on the Yazoo clay samples. The critical velocities for minor and major scours were determined in each of the three tests. Minor particle loss was observed at 0.6, 0.7, and 0.7 m/s while massive erosion was seen at velocities of 1.1, 1.5, and 1.1 m/s. These critical velocities were determined visually throughout various EFA tests. Table C-30 shows a summary of the critical velocity tests for the Yazoo clay formation.

Table C-30. Critical Velocity Summary for Yazoo Clay.

Test No.	**Critical Velocity (m/s)**	
	Minor Scour	**Major Scour**
Critical Velocity Test 1	0.60	1.10
Critical Velocity Test 2	0.70	1.50
Critical Velocity Test 3	0.70	1.10

A total of 15 EFA tests were performed on the Yazoo clay formation and the tests were further broken down to provide a total of 27 individual scour events. Initial EFA tests conducted on Yazoo clay did not exhibit scour at 0.3 m/s. Therefore, the test at 0.3 m/s velocity was not performed in order to conserve the limited material remaining from the 2012 Yazoo sampling.

One EFA test, titled “Yazoo21.0_2”, was conducted at a velocity of 0.6 m/s. The sample did not scour at this velocity but approximately 1 mm of swell was observed over the 52 minute test duration. This corroborated the decision to not conduct a test at 0.3 m/s, as the sample should have eroded at 0.6 m/s if it was to erode at 0.3 m/s.

Three EFA tests were performed at the 1.0 m/s velocity. In the first test, titled "Yazoo21.0_1", significant scour was observed before the velocity reached 1.0 m/s. However, the respective data shown in Table C-31 represents scour that occurred after the target velocity was reached. The second test, titled "Yazoo21.0_3", lasted 26 minutes in which two scour events were observed. The scour representing the first event occurred immediately after the target velocity was met. The sample swelled but did not scour the next 24 minutes and ultimately eroded in one large chunk. The last test, titled "Yazoo21.0_4", lasted 61 minutes and experienced three scour events. The scour-swell pattern was very apparent in this test, and although scour certainly occurred the sample still grew nearly 1 mm in height. Some erratic data points were observed over the last 10 minutes of the test. Figure C-26 and Figure C-277 are photographs taken at the beginning and end of the "Yazoo21.0_4" test. Due to the extreme swelling experienced throughout the test, the substantial scour that occurred was not nearly as evident in the erosion graph as it was visually. Table C-31 shows the results of this 1.0 m/s EFA test on the Yazoo material.

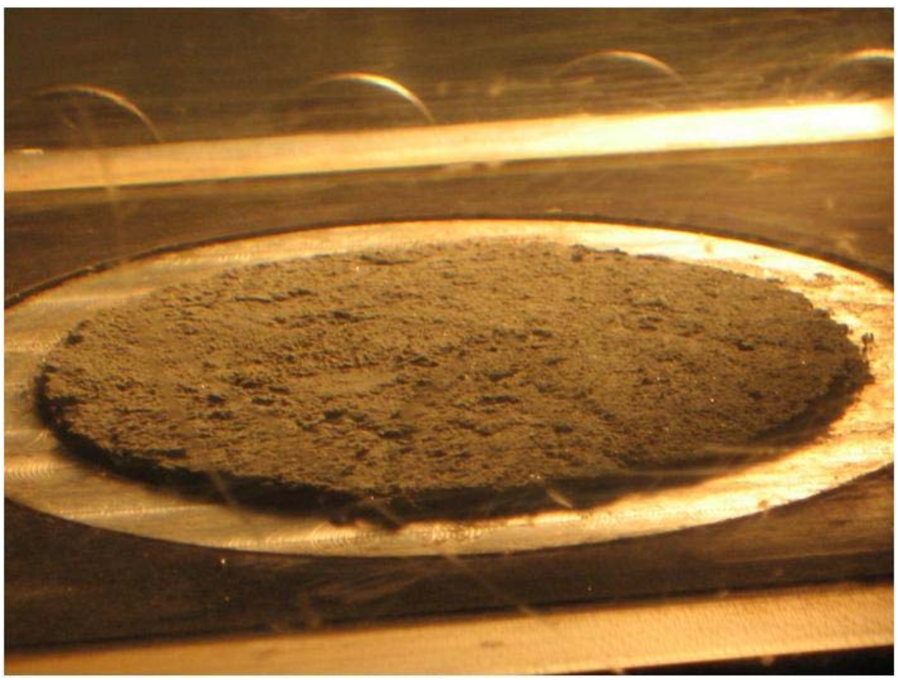

Figure C-26. Yazoo 21.0_4 Sample after Push.

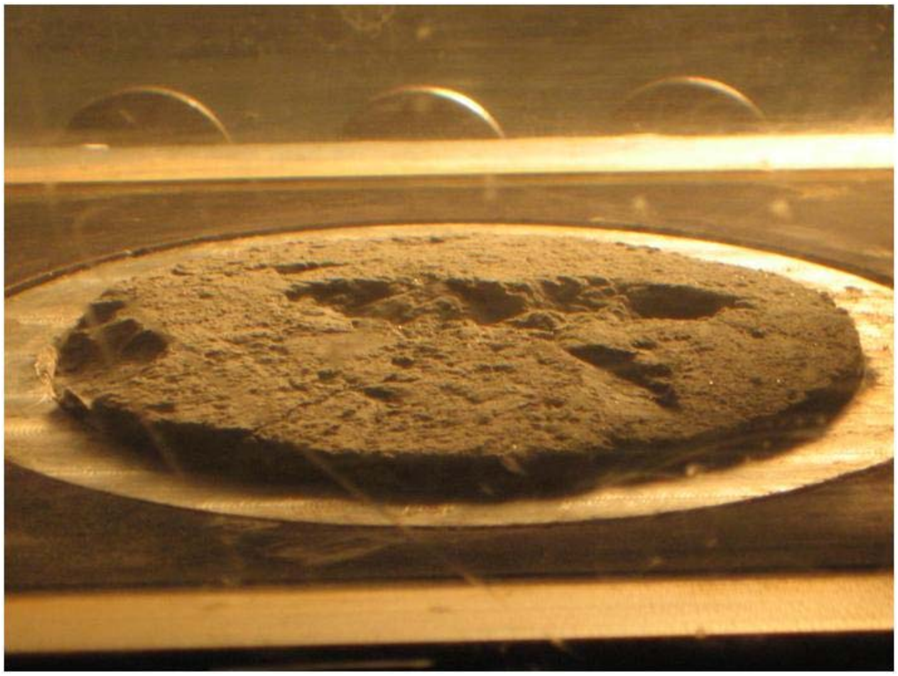

Figure C-27. Yazoo 21.0_4 Sample Approximately 57 Minutes after Push.

Table C-31. Yazoo Clay Results at 1.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Yazoo21.0_1	1	0.18	10.80	13.02
Yazoo21.0_3(1)	3	0.26	5.20	44.24
Yazoo21.0_3(2)	21	CHUNK	NA	
Yazoo21.0_4(1)	3	0.12	2.40	-2.10
Yazoo21.0_4(2)	3	0.26	5.20	
Yazoo21.0_4(3)	2	0.12	3.60	

Three EFA tests were conducted at the 1.5 m/s velocity. For the first test, titled "Yazoo21.0_5", the sample washed away before the target velocity was reached. In the second test, titled "Yazoo21.0_6", the sample eroded significantly before the target velocity was met, however, the erosion rate shown in the summary table is representative of the scour that occurred after the velocity reached 1.5 m/s. The third and final test, titled "Yazoo21.0_7", lasted approximately 19 minutes in which two scour events were witnessed. Like in the previous test, some soil was lost before the velocity reached 1.5 m/s. Scour occurred throughout the entire test but excessive swelling compensated for it and sensor measurements were not indicative of the true soil loss. Scour was constant during the first occurrence and considerable swelling was observed following this event. Swelling continued throughout the second scour event. Some of the loose particles on the sample surface caused some erratic points on the erosion plot but the erosion rate slope was still easy to establish. Table C-32 presents a summary of results from the 1.5 m/s velocity.

Table C-32. Yazoo Clay Results at 1.5 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Yazoo21.0_5	0	WASH	NA	68.86
Yazoo21.0_6	5	0.48	5.76	0.89
Yazoo21.0_7(1)	5	1.05	12.60	8.09
Yazoo21.0_7(2)	3	0.23	4.60	

Four EFA tests were performed at the 2.0 m/s velocity. The first test, titled “Yazoo22.0_1”, resulted in three individual scour events. The scour-swell pattern was highly evident throughout the entire test. In each of the three events, the sample would undergo significant swelling and then it would begin to scour. Scour would cease momentarily while swelling increased, and the specimen would proceed to scour again. Net change in specimen height between the second in third events exceeded 1.2 mm. In the second test, titled “Yazoo22.0_2”, the sample washed away approximately 10 seconds after the velocity reached 2.0 m/s. The third test, titled “Yazoo22.0_3”, lasted about 50 minutes in which four scour events were witnessed. The specimen showed very minimal to no scour over the first 12 minutes of the test, but then eroded 0.34 mm in less than four minutes. The swell-scour relationship was once again apparent in this test, as the sample scoured on three more occasions after swelling had occurred. Three scour events were seen in the last test at 2.0 m/s, titled “Yazoo22.0_4”. The first two events were divided by a brief, two minute lapse where no scour was observed. Approximately 22 minutes into the test (19 minutes after the sample was advanced) the entire sample scoured in one large chunk. Table C-33 shows the results from the 2.0 m/s EFA test on the Yazoo clay formation.

Four EFA tests were performed at a velocity of 3.0 m/s. In the first test, titled “Yazoo22.5_2”, two individual scour events were witnessed. There was some scour that occurred during the velocity increase but the first scour event is indicative of the scour that happened after the velocity had reached 3.0 m/s. Soil loss was dramatic and constant throughout the first scour event. The entire sample washed away approximately 10 minutes after the specimen was advanced (14 minutes after the test was started). The three ensuing tests, titled “Yazoo22.5_3”, “Yazoo22.4”, and “Yazoo22.5”, were nearly identical in their outcome. In each test, the samples swelled and cracked immediately after being submerged, and were all washed away once the velocity was increased. Table C-34 presents a summary of results from the 3.0 m/s velocity increment.

Table C-33. Yazoo Clay Results at 2.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Yazoo22.0_1(1)	1	0.1	6.00	4.96
Yazoo22.0_1(2)	4	0.87	13.05	
Yazoo22.0_1(3)	7	1.80	15.43	
Yazoo22.0_2	0.1	CHUNK	NA	99.43
Yazoo22.0_3(1)	3	0.34	6.80	24.37
Yazoo22.0_3(2)	2	0.19	5.70	
Yazoo22.0_3(3)	3	0.22	4.40	
Yazoo22.0_3(4)	47	CHUNK	NA	
Yazoo22.0_4(1)	3	0.36	7.20	41.10
Yazoo22.0_4(2)	5	0.46	5.52	
Yazoo22.0_4(3)	19	CHUNK	NA	

Table C-34. Yazoo Clay Results at 3.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)	Overall Scour Rate (mm/hr)
Yazoo22.5_2(1)	4	1.28	19.20	47.50
Yazoo22.5_2(2)	10	CHUNK	NA	
Yazoo22.5_3	1	WASH	NA	32.34
Yazoo22.5_4	0	WASH	NA	95.85
Yazoo22.5_5	0	WASH	NA	132.86

Appendix D Results of Data Analysis of EFA Scour Rates

The following tables show results of data analysis from EFA testing data of all scourable formations tested at different flow velocities. Each table includes total swelling and erosion (scour) depths (mm), overall or average sour rate (mm/min and mm/hr) considering both erosion and swelling, maximum and minimum scour and swelling rates (mm/hr) of the sample during each replicate test. Maximum and minimum scour and swelling rates were based on scour and swelling rates each minute using average height changes per minute but presented as mm/hr (not mm/min). The approach to determine overall scour rates considering both erosion and swelling at different testing velocities was discussed in the section 3.3.2 and finally used to develop the erosion function. In some tests the total swelling was more than total soil scour during each test, therefore, those tests resulted in overall negative scour rates (mm/hr), which are highlighted as red color numbers in Tables D-1 to D-7. Tables D-1 to D-7 summarize EFA testing results from Phases I and II testing for six scourable soil formations. Some soil formations that were tested during both Phase I and Phase II testing, and results for the same soil formation are summarized together based on flow velocity used for tests.

Table D-1 Results of Data Analysis from EFA Testing Data of Buccatunna Clay at 0.6 and 1.0 m/s flow velocities.

Test Sample	Test velocity (m/s)	Total swelling (mm)	Total scour (mm)	Average scour rate (mm/min)	**Average scour rate (mm/hr)**	Max. scour rate (mm/hr)	Min. scour rate (mm/hr)	Max. swelling rate (mm/hr)	Min. swelling rate (mm/hr)
Buccatunna 27.0_3	0.6	19.27	-20.52	0.04	**2.19**	227.89	0.31	245.06	0.02
Buccatunna 27.0_4	0.6	1.96	-3.85	0.11	**6.67**	35.36	0.40	27.13	1.58
Buccatunna 27.0_5	0.6	-0.04	-1.74	0.12	**7.10**	21.57	0.36	3.37	3.37
Buccatunna 27.0_6	0.6	4.18	-4.25	0.00	**0.28**	46.50	0.22	55.33	1.25
Buccatunna 27.0_7	0.6	0.76	-2.54	0.14	**8.22**	56.53	1.77	10.84	1.07
Buccatunna 26.0_1	0.6	2.45	-1.73	-0.04	**-2.56**	37.05	0.39	27.73	0.34
Buccatunna 27.5_2	1.0	0.39	-1.84	0.10	**6.20**	57.63	0.08	23.05	2.42
Buccatunna 27.5_3	1.0	0.22	-2.04	0.23	**13.65**	35.35	2.66	14.08	3.73
Buccatunna 27.5_4	1.0	2.69	-3.80	0.04	**2.65**	51.10	0.14	41.57	0.84
Buccatunna 27.5_5	1.0	-0.08	-1.52	0.11	**6.85**	25.76	0.33	5.81	1.07
Buccatunna 27.5_6	1.0	0.09	-1.38	0.09	**5.56**	13.95	0.74	6.81	0.15
Buccatunna 27.5_7	1.0	0.64	-2.25	0.15	**8.77**	29.61	0.73	17.16	0.60
Buccatunna 27.5_8	1.0	1.61	-4.97	0.21	**12.62**	70.42	0.89	33.25	1.34

Table D-2 Results of Data Analysis from EFA Testing Data of Buccatunna Clay at 1.5, 2.0 and 3.0 m/s flow velcoties.

Test Sample	Test velocity (m/s)	Total swelling (mm)	Total scour (mm)	Average scour rate (mm/min)	**Average scour rate (mm/hr)**	Max. scour rate (mm/hr)	Min. scour rate (mm/hr)	Max. swelling rate (mm/hr)	Min. swelling rate (mm/hr)
Buccatunna 27.5_9	1.5	3.45	-4.86	0.13	**7.70**	57.80	4.39	84.62	4.00
Buccatunna 26.5_2	1.5	0.88	-5.20	0.43	**23.88**	86.54	7.73	20.64	8.47
Buccatunna 26.5_3	1.5	0.27	-1.78	0.30	**18.14**	30.17	6.42	8.24	1.80
Buccatunna 26.5_4	1.5	0.19	-1.67	0.12	**7.42**	29.73	2.03	14.68	2.20
Buccatunna 26.5_5	1.5	0.64	-2.50	0.21	**12.39**	62.43	0.49	22.08	1.30
Buccatunna 26.5_6	2.0	1.26	-3.36	0.21	**12.63**	66.48	0.89	37.83	17.10
Buccatunna 26.5_7	2.0	0.45	-1.92	0.08	**4.63**	16.05	0.95	14.24	1.69
Buccatunna 26.5_8	2.0	1.34	-3.26	0.19	**11.52**	49.40	1.27	37.65	1.08
Buccatunna 26.5_9	2.0	0.35	-2.14	0.22	**13.42**	36.64	4.19	19.35	2.77
Buccatunna 26.5_10	2.0	0.26	-2.39	0.30	**18.28**	41.75	4.43	15.49	15.49
Buccatunna 26.0_3	2.0	0.57	-3.31	0.30	**18.26**	108.34	0.15	10.26	0.25
Buccatunna 26.0_4	3.0	0.37	-4.24	0.77	**46.38**	118.78	0.21	0.00	0.00
Buccatunna 23.0_1	3.0	-0.10	-2.81	0.41	**24.90**	46.36	5.00	0.00	0.00
Buccatunna 23.0_2	3.0	-0.80	-2.40	0.53	**31.93**	49.28	1.71	0.00	0.00
Buccatunna 23.0_3	3.0	-0.47	-2.27	0.55	**32.78**	43.04	8.56	0.00	0.00
Buccatunna 26.5_11	3.0	2.41	-3.50	0.18	**10.94**	69.68	9.49	93.54	2.87
Buccatunna 26.5_12	3.0	1.22	-3.91	0.27	**16.12**	99.61	0.90	58.52	33.75

Table D-3 Results of Data Analysis from EFA Testing Data of Yazoo Clay at 1.0, 1.5, 2.0 and 3.0 m/s flow velocities.

Test Sample	Test velocity (m/s)	Total swelling (mm)	Total scour (mm)	Average scour rate (mm/min)	**Average scour rate (mm/hr)**	Max. scour rate (mm/hr)	Min. scour rate (mm/hr)	Max. swelling rate (mm/hr)	Min. swelling rate (mm/hr)
Yazoo Clay 18.5_3	1.0	0.07	-1.26	0.30	**17.84**	51.69	6.07	12.39	6.04
Yazoo Clay 18.5_4	1.0	0.96	-3.16	0.31	**18.80**	76.18	4.70	19.54	4.00
Yazoo Clay 18.5_5	1.0	0.06	-1.64	0.22	**13.49**	46.07	0.03	19.24	16.85
Yazoo Clay 18.5_6	1.0	0.72	-2.35	0.20	**12.27**	65.59	0.37	27.96	0.85
Yazoo Clay 18.5_7	1.0	4.10	-9.63	0.11	**6.77**	205.54	0.16	23.30	0.01
Yazoo Clay 21.0_1	1.0	0.06	-1.15	0.22	**13.02**	27.68	1.23	1.29	1.29
Yazoo Clay 21.0_3	1.0	1.74	-9.12	0.74	**44.24**	320.05	0.80	13.44	1.90
Yazoo Clay 21.0_4	1.0	3.15	-2.34	-0.03	**-2.10**	32.63	0.03	23.87	0.19
Yazoo Clay 18.5_8	1.5	4.29	-8.24	0.18	**10.78**	113.04	0.22	87.68	0.21
Yazoo Clay 18.5_9	1.5	11.47	-11.45	0.00	**-0.04**	73.12	1.70	83.38	0.27
Yazoo Clay 21.0_5	1.5	0.00	-5.74	1.15	**68.86**	148.61	4.97	5.81	5.81
Yazoo Clay 21.0_6	1.5	6.30	-6.70	0.01	**0.89**	67.42	0.45	43.91	0.38
Yazoo Clay 21.0_7	1.5	1.04	-2.52	0.13	**8.09**	52.41	0.18	23.25	2.64
Yazoo Clay 18.5_10	2.0	1.71	-12.45	1.07	**64.39**	378.18	4.20	70.77	2.17
Yazoo Clay 22.0_1	2.0	2.10	-3.59	0.08	**4.96**	40.59	0.10	21.77	0.16
Yazoo Clay 22.0_2	2.0	0.34	-10.28	1.66	**99.43**	487.70	4.06	8.30	4.82
Yazoo Clay 22.0_3	2.0	2.93	-14.71	0.41	**24.37**	534.28	0.04	18.89	0.04
Yazoo Clay 22.0_4	2.0	0.90	-10.48	0.68	**41.10**	469.96	0.32	26.75	0.25
Yazoo Clay 22.5_2	3.0	1.38	-8.50	0.79	**47.50**	226.83	1.71	28.65	7.47
Yazoo Clay 22.5_3	3.0	0.12	-1.74	0.54	**32.34**	85.94	4.65	6.16	6.16
Yazoo Clay 22.5_4	3.0	0.62	-2.22	1.60	**95.85**	133.33	133.33	0.00	0.00
Yazoo Clay 22.5_5	3.0	0.00	-2.21	2.21	**132.86**	132.86	132.86	0.00	0.00

Table D-4 Results of Data Analysis from EFA Testing Data of Porter's Creek Clay at 0.3, 0.6, 1.0, 1.5, 2.03, and 3.0 m/s flow velocities.

Test Sample	Test velocity (m/s)	Total swelling (mm)	Total scour (mm)	Average scour rate (mm/min)	**Average scour rate (mm/hr)**	Max. scour rate (mm/hr)	Min. scour rate (mm/hr)	Max. swelling rate (mm/hr)	Min. swelling rate (mm/hr)
Porter's Creek Clay 24.0_4	0.3	3.24	-5.67	0.20	**12.15**	77.20	5.86	54.67	3.41
Porter's Creek Clay 24.5_1	0.3	7.62	-9.42	0.09	**5.67**	229.07	1.39	121.40	1.62
Porter's Creek Clay 24.5_5	0.3	4.15	-0.68	-0.50	**-29.77**	8.78	0.78	55.11	0.26
Porter's Creek Clay 24.5_2	0.6	0.41	-3.86	0.49	**29.55**	73.54	2.84	0.00	0.00
Porter's Creek Clay 24.5_3	0.6	0.00	-3.02	0.50	**30.17**	100.10	8.00	0.00	0.00
Porter's Creek Clay 24.5_4	0.6	0.67	-2.64	0.28	**16.88**	80.18	1.30	10.42	2.87
Porter's Creek Clay 19.5_2	0.6	1.08	-2.23	0.16	**9.83**	45.19	0.27	17.14	2.48
Porter's Creek Clay 19.5_3	0.6	1.84	-2.34	0.06	**3.33**	48.64	1.64	24.57	3.01
Porter's Creek Clay 19.5_4	0.6	0.70	-3.59	0.32	**19.27**	57.40	1.39	37.04	3.79
Porter's Creek Clay 19.0_1	1.0	-0.17	-2.38	0.32	**19.12**	67.19	0.67	28.47	28.47
Porter's Creek Clay 19.5_5	1.0	-0.53	-1.77	0.33	**19.73**	37.54	6.07	5.91	5.91
Porter's Creek Clay 19.5_7	1.0	0.40	-2.45	0.41	**19.28**	66.88	5.72	37.83	13.05
Porter's Creek Clay 24.0_2	1.0	0.69	-3.76	0.38	**23.00**	109.67	1.09	28.59	6.29
Porter's Creek Clay 19.0_2	1.5	-0.67	-2.45	0.35	**20.83**	42.05	1.35	0.00	0.00
Porter's Creek Clay 19.0_3	1.5	0.06	-2.14	0.30	**17.85**	37.81	1.71	13.16	5.45
Porter's Creek Clay 19.0_5	1.5	-0.26	-1.58	0.31	**18.37**	30.03	7.99	0.00	0.00
Porter's Creek Clay 24.0_3	1.5	0.00	-1.97	0.98	**58.96**	110.77	7.14	0.00	0.00
Porter's Creek Clay 19.0_6	2.0	1.48	-4.08	0.52	**31.13**	88.71	5.77	71.03	71.03
Porter's Creek Clay 19.0_7	2.0	-0.41	-1.28	0.24	**14.50**	18.84	3.10	0.00	0.00
Porter's Creek Clay 19.0_8	2.0	-0.59	-1.23	0.36	**21.88**	19.46	8.64	0.00	0.00
Porter's Creek Clay 19.0_9	3.0	0.02	-1.17	0.29	**17.24**	38.85	5.22	2.08	2.08
Porter's Creek Clay 19.0_12	3.0	-0.36	-2.00	0.59	**35.43**	67.26	8.33	0.00	0.00
Porter's Creek Clay 19.0_14	3.0	-0.31	-1.52	0.61	**36.53**	76.05	1.37	0.00	0.00

Table D-5 Results of Data Analysis from EFA Testing Data of Clayton Clay at 1.0, 1.5, 2.0 and 3.0 m/s flow velocities.

Test Sample	Test velocity (m/s)	Total swelling (mm)	Total scour (mm)	Average scour rate (mm/min)	**Average scour rate (mm/hr)**	Max. scour rate (mm/hr)	Min. scour rate (mm/hr)	Max. swelling rate (mm/hr)	Min. swelling rate (mm/hr)
Clayton 29.5_4	1.0	2.25	-2.05	-0.01	**-0.52**	49.24	0.04	10.65	0.13
Clayton 29.5_5	1.0	2.36	-6.77	0.49	**29.45**	231.13	0.98	43.72	0.15
Clayton 29.0_3	1.5	2.09	-1.41	-0.03	**-1.56**	22.12	0.13	15.82	0.35
Clayton 29.0_6	1.5	2.59	-4.71	0.16	**9.81**	131.28	0.15	28.58	0.23
Clayton 29.5_6	1.5	2.68	-4.69	0.25	**15.09**	142.16	0.26	12.89	1.11
Clayton 29.0_1	2.0	0.53	-1.45	0.13	**7.86**	34.65	1.46	19.42	0.37
Clayton 29.0_4	2.0	1.63	-9.11	1.50	**89.72**	276.69	38.40	49.04	17.62
Clayton 29.0_7	2.0	3.22	-4.35	0.12	**7.49**	164.41	0.26	42.93	0.89
Clayton 29.0_2	3.0	0.25	-2.77	0.50	**30.29**	95.67	1.09	11.93	11.93
Clayton 29.0_5	3.0	0.45	-7.09	1.66	**99.57**	208.26	8.32	0.00	0.00
Clayton 29.0_8	3.0	1.79	-6.88	0.51	**30.52**	331.21	0.74	41.34	0.76

Table D-6 Results of Data Analysis from EFA Testing Data of Nanafalia Clay at 0.6, 1.0, 1.5, 2.0 and 3.0 m/s flow velocities.

Test Sample	Test velocity (m/s)	Total swelling (mm)	Total scour (mm)	Average scour rate (mm/min)	**Average scour rate (mm/hr)**	Max. scour rate (mm/hr)	Min. scour rate (mm/hr)	Max. swelling rate (mm/hr)	Min. swelling rate (mm/hr)
Nanafalia Clay 21.0_1	0.6	0.99	-1.35	0.02	**1.02**	15.22	0.18	12.02	0.02
Nanafalia Clay 23.5_2	0.6	2.76	-3.30	0.02	**1.04**	41.20	0.19	22.80	0.41
Nanafalia Clay 23.5_3	0.6	1.51	-0.96	-0.02	**-1.23**	16.40	0.01	7.65	0.04
Nanafalia Clay 23.5_4	0.6	0.85	-0.54	-0.01	**-0.66**	4.95	0.04	10.94	0.06
Nanafalia Clay 23.0_1	1.0	1.58	-2.61	0.26	**15.44**	104.11	6.46	4.95	1.61
Nanafalia Clay 23.0_2	1.0	1.39	-0.61	-0.04	**-2.34**	12.18	0.09	7.70	0.21
Nanafalia Clay 23.0_3	1.0	0.06	-2.01	0.28	**16.74**	34.53	8.11	12.00	3.22
Nanafalia Clay 23.0_4	1.0	2.16	-1.57	-0.02	**-1.14**	10.87	0.00	12.80	0.11
Nanafalia Clay 21.5_1	1.5	0.53	-2.27	0.19	**11.58**	38.64	1.18	20.68	20.68
Nanafalia Clay 21.5_2	1.5	1.80	-2.63	0.02	**1.47**	13.39	0.00	18.22	0.06
Nanafalia Clay 21.5_3	1.5	0.30	-3.14	0.95	**56.79**	112.17	0.15	0.00	0.00
Nanafalia Clay 21.5_4	2.0	1.97	-2.50	0.08	**4.55**	88.02	3.52	33.12	0.54
Nanafalia Clay 21.5_5	2.0	0.15	-1.39	0.25	**14.85**	31.14	2.67	6.14	1.04
Nanafalia Clay 21.5_6	2.0	0.07	-4.38	0.31	**18.49**	142.56	1.12	5.59	0.11
Nanafalia Clay 21.5_7	3.0	2.36	-4.10	0.29	**17.44**	185.05	3.05	6.85	6.85
Nanafalia Clay 21.5_8	3.0	2.51	-3.70	0.13	**7.96**	78.10	0.30	42.20	0.45
Nanafalia Clay 21.5_9	3.0	2.67	-9.55	0.63	**37.50**	487.69	0.11	36.37	1.94

Table D-7 Results of Data Analysis from EFA Testing Data of Naheola Clay (**Yellow**) at 0.6, 1.0 and 2.0 m/s flow velocities.

Test Sample	Test velocity (m/s)	Total swelling (mm)	Total scour (mm)	Average scour rate (mm/min)	**Average scour rate (mm/hr)**	Max. scour rate (mm/hr)	Min. scour rate (mm/hr)	Max. swelling rate (mm/hr)	Min. swelling rate (mm/hr)
NaheolaClay17.5_2	0.6	2.31	-2.36	0.00	**0.18**	38.74	0.39	31.50	0.29
NaheolaClay17.5_4	1	1.79	-4.80	1.51	**90.35**	237.06	51.11	0.00	0.00
NaheolaClay17.5_5	1	1.89	-2.50	0.02	**1.26**	58.50	0.41	14.89	0.29
NaheolaClay17.2_1	2	0.00	-9.77	3.26	**195.45**	439.87	30.33	0.00	0.00

Table D-8 Results of Data Analysis from EFA Testing Data of Naheola Clay (**Dark**) at 0.6, 1.0, 1.5, 2.0 and 3.0 m/s flow velocities.

Test Sample	Test velocity (m/s)	Total swelling (mm)	Total scour (mm)	Average scour rate (mm/min)	**Average scour rate (mm/hr)**	Max. scour rate (mm/hr)	Min. scour rate (mm/hr)	Max. swelling rate (mm/hr)	Min. swelling rate (mm/hr)
Naheola Clay 19.5_1	0.6	1.27	-1.00	-0.01	**-0.56**	13.31	0.04	5.93	0.03
Naheola Clay 17.0_1	0.6	2.31	-2.36	0.00	**0.18**	38.74	0.39	31.50	0.29
Naheola Clay 19.5_2	1.0	1.95	-2.46	0.02	**1.05**	24.65	0.29	26.18	0.24
Naheola Clay 17.0_2	1.0	2.07	-0.57	-0.12	**-6.96**	7.79	0.02	8.01	0.09
Naheola Clay 19.5_3	1.5	0.90	-1.39	0.04	**2.14**	22.60	0.18	15.23	0.19
Naheola Clay 16.0_1	1.5	2.74	-1.79	-0.04	**-2.27**	21.79	0.00	16.53	0.28
Naheola Clay 16.0_2	1.5	1.41	-4.83	0.38	**22.79**	273.49	0.07	12.10	0.28
Naheola Clay 19.5_4	2.0	1.27	-1.01	-0.01	**-0.65**	9.39	0.17	10.14	0.05
Naheola Clay 19.5_5	3.0	0.87	-2.70	0.46	**27.41**	82.43	0.78	5.80	5.80