Laboratory Scour Testing of Hard Cohesive Soils in Alabama

by

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Abstract

Establishing scour parameters in order to estimate the loss of soil adjacent to bridge piers is a crucial element in the design of highway bridges crossing over rivers and streams. Although there are numerous design criteria for estimating scour in cohesionless soils, methods for calculating scour in cohesive soil are limited. By conducting scour tests using an Erosion Function Apparatus (EFA), erosion functions were established for six different soil formations found throughout southern Alabama. The erosion functions were modified to incorporate the effects of sample swell during testing. Correlations between scourability and conventional geotechnical parameters were established using the results of the EFA tests. These correlations were compared to trends seen in previous studies at Auburn University. The scourability of these clay formations were observed to be dependent upon the Standard Penetration Test N value, insitu moisture content, and percentage of soil passing the number 200 sieve.

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List of Abbreviations

FHWA	Federal Highway Administration
HEC	Hydraulic Engineering Circular
EFA	Erosion Function Apparatus
ALDOT	Alabama Department of Transportation
SPT	Standard Penetration Test
SRICOS	Scour Rate in Cohesive Soils
SERF	Sediment Erosion Rate Flume
RETA	Rotating Erosion Test Apparatus
CME	Central Mining Equipment
ASTM	American Society for Testing and Materials

Chapter 1 – Introduction

1.1 Background

An important criterion for a bridge foundation is the penetration depth of bridge supports, which are often deep foundations (piles, drilled shafts, etc.) to achieve the required capacity. The flow of water around these foundations often causes erosion of soils adjacent to the supports, thus greatly reducing the original depth of penetration and thus the load carrying capacity. This phenomenon is known as scour and is a crucial element in bridge design. According to the Federal Highway Administration, scour of bridge foundation material is the most common source of bridge failure (Richardson and Davis 2001). On average, 22 bridges collapse or are closed in the United States every year due to scouring of the structures foundation material (Briaud et al. 2013). The renovation of bridges that have not yet failed can be very complex and costly to the public. Therefore, evaluating the scour potential of soils is critical in the design of bridges over water.

The current means of scour depth prediction consists of Hydraulic Engineering Circular No. 18 (HEC-18) (Arneson et al. 2012) and HEC-20 (Lagasse et al. 2012). HEC-20 "*Stream Stability at Highway Structures*" presents the preliminary analysis of a new or existing bridge foundation to evaluate whether or not the structure is scour critical. Upon the affirmation of a scour critical structure, HEC-18 "*Evaluating Scour at Bridges*" is used to perform a scour analysis for the foundation material. Until recently, HEC-18 scour depth analyses were only applicable to cohesionless soils. In

2012 HEC-18 integrated studies performed at Texas A&M University to predict scour depth in cohesive soils (Briaud et al. 2013). Though the HEC-18 model for cohesive soils incorporates the “critical velocity” (minimum velocity at which scour occurs), the median grain size is the only soil parameter included in calculating maximum depth of scour. The model includes associations between scour rate and soil parameters but does not offer these parameters as variables in computing scour depth. This is, however, a dramatic improvement from the cohesionless HEC-18 model which offered no consideration of soil parameters as variables in scour depth calculation.

Over the years extensive studies have been conducted related to the scourability of cohesive soils. The development of the Erosion Function Apparatus (EFA) by Briaud et al. (2001) provided a quantitative means for measuring scour rate and magnitude. Since then the EFA has been redesigned by numerous institutions to determine a more precise and streamlined analysis of scourability of cohesive soils (Walker 2013). A recent EFA modification at Auburn University by Walker (2013) included an ultrasonic sensor mounted in the EFA flume which allowed a continuous data stream for real-time measurement of soil specimen height. This provided a more quantitative assessment of scour volume in comparison to more subjective visual measurements.

Evaluation of scour potential of cohesive and cohesionless soils is of vital importance to the design of bridge foundation supports. Individualistic assessment of scourability is highly dependent upon the geotechnical parameters of the soil as well as the hydraulic conditions in which the soil is subjected to. Research and observation both suggest that prediction of scour depth using HEC-18 methods are conservative when grain size is the only soil characteristic parameter for model input. A portion of this conservatism is due to the time dependency of the scour, while the remainder is due to the scour mechanism which is not entirely dependent on grain size. Furthermore, there are certain soils, such as the hard cohesive soils prevalently seen in southern Alabama, which are more resistant to scour and may not have appreciable scour within the lifespan of a highway structure. If the ultimate HEC-18 scour depth is used in design, the approach may be unnecessarily conservative. Using the EFA, erosion functions may be developed that are consistent and representative of the hard cohesive soils found below the geologic fall line of Alabama. The erosion functions can then be correlated to conventional geotechnical soil parameters. These correlations would provide a more individualistic assessment of the scour to be expected over the design life of a bridge.

1.2 Research Objectives

The objectives of the study included:

- Perform EFA tests on cohesive soil samples provided by the Alabama Department of Transportation (ALDOT).
- Generate erosion functions for each soil formation.
- Incorporate the swelling of soil samples in erosion function analyses.
- Establish correlations between scourability and conventional geotechnical parameters including Atterberg limits, grain size, shear strength, and Standard Penetration Test (SPT) N-values.

1.3 Scope of Study

The scope of work included the following:

- Acquisition of additional samples of particular cohesive soil formations from ALDOT.
- EFA testing of acquired samples to develop scour parameters.
- Geotechnical index testing to establish conventional geotechnical parameters.
- Developing means for incorporating swell rate of soils into scour evaluation.

Chapter 2 – Literature Review

2.1 Background

Scour is a specific type of erosion involving the loss of soil particles due to the flow of water in a stream bed. This action can be further characterized as aggradation and degradation, contraction scour, and local scour (Arneson et al. 2012).

Aggradation and degradation is a long-term form of scour depicting the overall river bed elevation change due to upstream sedimentation or lack thereof. It is influenced by both natural (flooding) and non-natural (man-made) events. Although both aggradation and degradation depend on accumulation of sediments from upstream flow, each has a far different effect. Aggradation results in a gross increase in stream bed height due to the accumulation of sediment from upstream origins. Degradation, on the other hand, results in a gross decrease of stream bed height due to a deficiency in up stream sediment supply (Arneson et al. 2012).

Unlike degradation, contraction scour is an effect of the presence of a structure (commonly a bridge support or abutment) in the stream. Contraction scour occurs due to the structure constricting the flow of water, causing a change in flow characteristics. The soil loss from contraction scour may or may not be uniform across the stream bed and can be related to flow velocity changes resulting from flood events (Arneson et al. 2012).

Local scour refers to the erosion of soil adjacent to bridge supports due to the acceleration of water around the structures that are inhibiting flow. Unlike other scour types, local scour is unique to an individual entity of the entire structure, for example a particular pile in a bridge crossing a river. Scour occurs due to the acceleration of water around a bridge support inducing excessive shear stress on the neighboring soil.

The scour of soil surrounding bridge supports is highly dependent upon the size and shape of the support. In the 2001 HEC-18 version, Richardson and Davis characterized the maximum scour depth by the dimensions of the support as well as the flow characteristics of the stream. The following equation is given in HEC-18 and is used for calculating the maximum pier scour depth in cohesionless soils:

$$\frac{y_s}{a} = 2.0 * K_1 * K_2 * K_3 * \left[\frac{y_1}{a}\right]^{-0.35} * Fr_1^{0.43} \tag{2-1}$$

Where:

y_s = Scour depth, ft (m)

y_1 = Flow depth directly upstream of the pier, ft (m)

K_1 = Correction factor for pier nose shape

K_2 = Correction factor of angle of attack of flow

K_3 = Correction factor for bed condition

a = Pier width, ft (m)

L = Length of pier, ft (m)

Fr_1 = Froude Number directly upstream of pier = $V_1/(gy_1)^{0.5}$

V_1 = Mean velocity of flow directly upstream of pier, ft/s (m/s)

g = Acceleration of gravity (32.2 ft/sec^2) (9.81 m/sec^2)

Until 2012 Equation 2-1 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 2-2.

$$y_s = 2.2 * K_1 * K_2 * a^{0.65} * \left[\frac{2.6\, V_1 - V_c}{\sqrt{g}}\right]^{0.7} \quad (2\text{-}2)$$

Where:

V_c = Critical velocity at which soil begins to erode, 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 2-3 as a general means for determining critical velocity.

$$V_c = K_u * y^{1/6} * d^{1/3} \quad (2\text{-}3)$$

Where:

K_u = Unit correction factor (11.17 ft-lb-s English units, 6.19 m-kg-s SI units)

y = Upstream flow depth, ft (m)

d = Particle grain size, ft (m)

According to Briaud et al. (2013), because the critical velocity is incorporated into Equation 2-2 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 2-3. 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.

2.2 Scour Rate in Cohesive Soils

Extensive research has been presented on the subject of the rate of scour of cohesive soils. Some of the more visible work was performed by Briaud et al. (1999, 2001a, 2001b, 2004, 2009, 2011). The Scour Rate in Cohesive Soils method (SRICOS) was developed by Briaud et al. (1999) to determine erosion functions in sands, clays, and rocks. Briaud's research group was responsible for developing the EFA as a device for measuring the erosion function for cohesive soils. The EFA, shown in FIG. 2-1, is a hydraulic flume designed to erode a cylindrical soil specimen at a constant flow.

FIG. 2-1. Erosion Function Apparatus (EFA) at Auburn University.

A stepping motor forces the specimen upwards to protrude the material 1 mm into the flume. A sump pump transporting water from the reservoir into the flume allows water to flow through the flume at a constant velocity inducing a uniform shear stress over the specimen face. Over the duration of a test the volume of material eroded is determined by reducing height change data recorded from the ultrasonic sensor installed above the soil specimen. Erosion rate is then determined analytically after the sample has scoured 1 mm. From the erosion function, two parameters can be determined: critical shear stress, τ_c, and initial erodibility, S_i. While the HEC-18 analysis estimates the amount of scour in a single event, SRICOS integrates the erosion rate into the calculation to determine the amount of scour in a single or multiple events. In this method a relationship can be derived between velocity/shear stress and the erosion rate of the soil. In a case where the flow velocity is below the magnitude necessary to induce critical shear stress, the soil particles are assumed to not be mobilized and scour will not occur. However, when the velocity is large enough that the generated shear stress is greater than the critical shear stress the sample will scour at the rate measured by the EFA. The SRICOS method has been incorporated into HEC-18 since 2001.

Mehta et al. (1989) suggest that the scour of cohesive bed materials is likely one or all of three processes: 1) aggregate by aggregate erosion (much like erosion of granular soils), 2) mass erosion of stream bed material, or 3) re-entrainment of a stationary unconsolidated material. The University of Florida researchers go on to claim that sediment composition, pore and eroding fluid composition, and the manner in which bed material was deposited may have an effect on erosion resistance. In such case it would be important to match the chemical composition of water used in scour tests to that of the water in the field.

Further studies at the University of Florida, by Sheppard et al. (2005), have used a mechanism much like the EFA known as the Sediment Erosion Rate Flume (SERF). The machine functions very similarly to the EFA but instead of a 1 mm protrusion the sample is advanced automatically by a stepping motor. A continuous data stream is provided by ultrasonic sensors to develop a scour rate. A second machine constructed at the University of Florida, known as the Rotating Erosion Test Apparatus (RETA), was designed to evaluate the scour of stiff material and rock. In this mechanism the sample is stationary while a cylinder rotates specimen. Water is filled between the specimen and the rotating cylinder. Following the test the amount of scour is determined by taking the difference in masses of the eroded and non-eroded sample. In this test the shear stress is measured directly rather than being calculated from the flow velocity. This poses a great advantage over previously mentioned tests because calculating shear stress from flow velocity is an indirect measurement based on numerous tests that may be run over considerably long durations. A major disadvantage to this mechanism, however, is that false scour mechanisms may occur representing vertical scour rather than horizontal. Also, because the material is very stiff the apparatus will frequently shutdown due to excessive resistance from the specimen. The testing of cohesive soils with the SERF has been limited to man-made sand and clay mixtures (Sheppard et al. 2006).

Strum et al. (1998, 2004, 2008) have conducted studies of scour in Georgia soil formations over the years. Early research from this Georgia Institute of Technology (Georgia Tech) group concentrated on generalized pier scour in idealized conditions, however the more recent studies relate more to particular formations throughout the state. Strum et al. (2004) evaluated scour by means of laboratory and field testing at various sites throughout Georgia. The flume developed at Georgia Tech was used to conduct laboratory tests similar to the EFA. The Shelby tube soil specimens were set in the rectangular, tilting, recirculating open-channel flume for erodibility measurements. The bed of the flume was lined with small gravel in order to ensure a fully developed boundary layer with fully-rough turbulent flow (Strum et. al. 2004). It is important to note that the relatively small gravel size (d_{50} = 3.3 mm) was much larger than the 1 mm protruded soil sample used in the EFA and SERF mechanisms. Two of the three mechanisms suggested by Mehta et al. (1989) were observed in the study. Furthermore, Ravisangar et al. (2001) investigated the impact of clay chemical properties on erosion, suggesting that because clay is dependent upon the soil structure, pH may be a variable for erodibility. Strum et al. (2008) conducted additional erosion tests on samples from five other states in the Georgia Tech flume. The results of the two studies were integrated to develop erodibility classification for Georgia soils shown in FIG. 2-2.

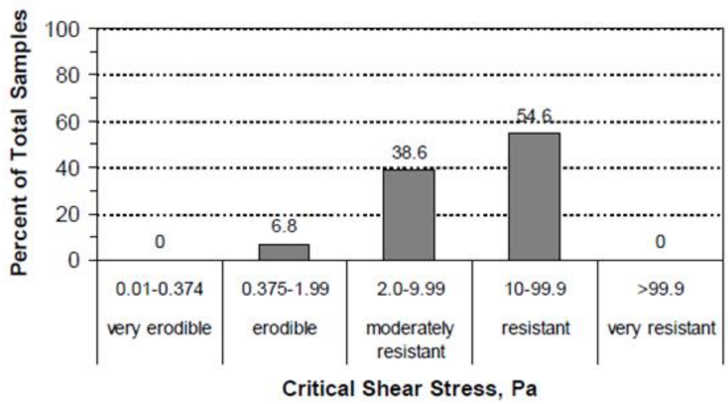

FIG. 2-2. Erodibility Classification of Georgia Soil Samples (Sturm et al. 2008).

2.3 Previous Scour Research at Auburn University

The Erosion Function Apparatus at Auburn University has been used to evaluate scour potential of Alabama soils since 2001. The device has been altered over the years to provide a more precise and streamlined method of analysis.

Crim et al. (2003) used the EFA to test Shelby tube samples from six locations throughout Alabama in order to determine erosion functions (scour rate versus shear stress). These samples were provided by the ALDOT and included a bridge site on Goose Creek in Wilcox County, a culvert site on US 84 in Covington County, a dual railroad bridge on the Linden Bypass in Marengo County, a bridge on Alabama State Road 123 over Choctawhatchee River in Dale County, and a bridge site over the Pea River in Elba, AL. Critical shear stress and initial erodibility were determined from the erosion functions. In order to make correlations between soil erosion properties and soil classification parameters, Crim found the following soil properties for each tested sample: soil description, particle size distribution, plasticity index, and SPT blow count. The study concluded that more cohesive soil behavior, quantified from the determined erosion functions, corresponded to locations with minimal historical scour. Correlations suggested that an increase in particle size results in an increase in critical shear stress, a decrease in initial erodibility results in and increase in critical shear stress, and an increase in plasticity index results in an increase in critical shear stress. It was also concluded that critical shear stress was not strongly related to SPT blow count.

Mobley et al. (2009) modified the original EFA at Auburn University to allow for testing of a smaller diameter core tube, as the EFA was originally equipped to accept samples directly from a Shelby tube. The ALDOT provided soil samples from three locations in Alabama: A stiff clay from a culvert replacement project in Talladega County, a hard silt from a bridge crossing over the Sucarnoochee River in Sumter County, and a Mooreville chalk from a bridge crossing over Bogue Chitto Creek in Dallas County. Mobley saw large variations in erosion behavior for the soils and stated that sample preparation and discontinuities in the in situ soil may result in erratic erosion function development. These variations, they concluded, result in much difficulty in determining erosion parameters. Despite these difficulties, the study did corroborate Crim et al. (2003) conclusion that an increase in soil cohesion results in greater erosion resistance.

Walker (2013) continued research with the EFA at Auburn University. The machine was modified again to include an ultrasonic sensor, much like the SERF used in Sheppard et al. (2005), and to allow for testing continuous samples. The sensor provided the ability to determine patterns of erosion rather than determining just one scour rate over the duration of the test. The addition allowed for more precise measurements in the change of specimen height in comparison to visual measurements which Walker also recorded. The ALDOT provided six soil formations that were tested with the redesigned EFA: Bucatunna Clay in Monroe County, Yazoo Clay in Conecuh County, Demopolis Chalk in Sumter County, Mooreville Chalk in Dallas County, Prairie Bluff Chalk in Marengo County, and Porter's Creek Clay in Sumter County. Walker tested the samples at 0.3, 0.6, 1.0, 1.5, 2.0, and 3.0 meters per second (m/s).

Walker found that the three chalk formations (Demopolis, Mooreville, and Prairie Bluff Chalk) were scour resistant up to a flow velocity of 3.0 m/s. Though a few individual trials had scour characteristics, the cases were considered isolated and all other trials suggested that the formation was scour resistant. Table 2-1 presents the average scour rate determined (visually and with the ultrasonic sensor) at each flow velocity for Bucatunna Clay. The critical velocity of the formation was determined to be 0.45 m/s. Walker saw that the Bucatunna material scoured in small flakes, resulting in very uniform erosion. Extensive swelling was seen over the duration of tests where the velocity was below the critical velocity.

Table 2-1. Scour Rate of Bucatunna Clay (Walker 2013).

Velocity (m/s)	Scour Rate (mm/hr)	
	Ultrasonic	Visual
0.3	0	0
0.6	3.91	3.99
1.0	4.07	3.49
1.5	5.59	5.63
2.0	6.66	6.0
3.0	11.01	9.0

Table 2-2 presents the average scour rate at each flow velocity for Yazoo Clay. As seen, there are extensive variations in erosion behavior. Walker noted that some samples had extremely high scour rates while other samples, tested at the same velocity, did not scour at all. Due to the high variability in results the formation was not tested at 3.0 m/s and a critical velocity was not determined. Walker attributed this variability to the high sand content of the material which is uncharacteristic to the geologic formation.

Table 2-2. Scour Rate of Yazoo Clay (Walker 2013).

Velocity (m/s)	Scour Rate (mm/hr)	
	Ultrasonic	Visual
0.3	0	0
0.6	0	0
1.0	7.33	7.33
1.5	0.70	0.70
2.0	4.29	5.45

Table 2-3 shows the average scour rate at each velocity for Porter's Creek Clay. The critical velocity for Porter's Creek Clay was found to be 0.4 m/s. Walker observed that the Porter's Creek material contained many weathered lines and planes and scoured along these planes in flakes and often in chunks.

Table 2-3. Scour Rate of Porter's Creek Clay (Walker 2013).

Velocity (m/s)	Scour Rate (mm/hr)	
	Ultrasonic	Visual
0.3	0	0
0.6	3.98	3.98
1.0	9.17	9.17
1.5	10.19	10.19
2.0	10.86	10.86
3.0	15.67	15.67

Walker experienced much difficulty in advancing the soil sample into the EFA flume. This was especially seen in the more stiff materials, most notably the chalk formations. The stiff materials were advanced manually rather than by the calibrated stepping motor.

Walker determined the insitu moisture content, SPT blow count, plasticity index, and determined the grain size distribution of each formation in order to generate correlations between conventional geotechnical parameters and scour rates of soils. Walker discovered that the scour resistant formations had higher SPT N values, lower insitu moisture content, higher percentages of fine particles (percent passing the No. 200 sieve), and smaller mean particle diameters. The study did not confirm any correlation between plasticity index and scour parameters, though the plasticity index for each material was highly variable. FIG. 2-3, FIG. 2-4, and FIG. 2-5 are plots constructed by Walker, relating scour potential to these dependent geotechnical parameters.

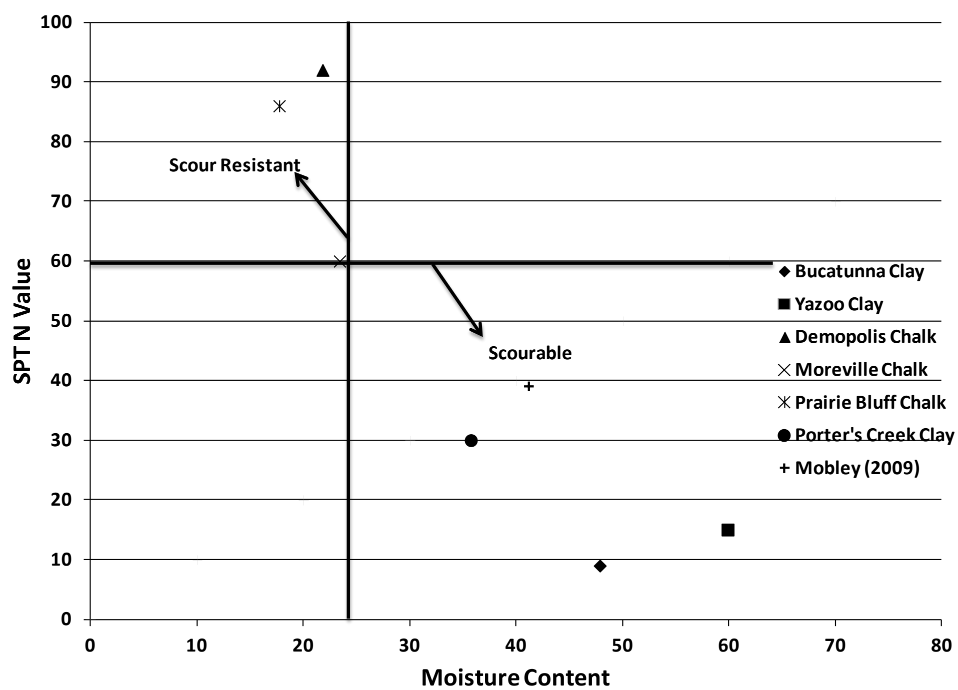

FIG. 2-3. Scour Correlation between Moisture Content and SPT N Value (Walker 2013).

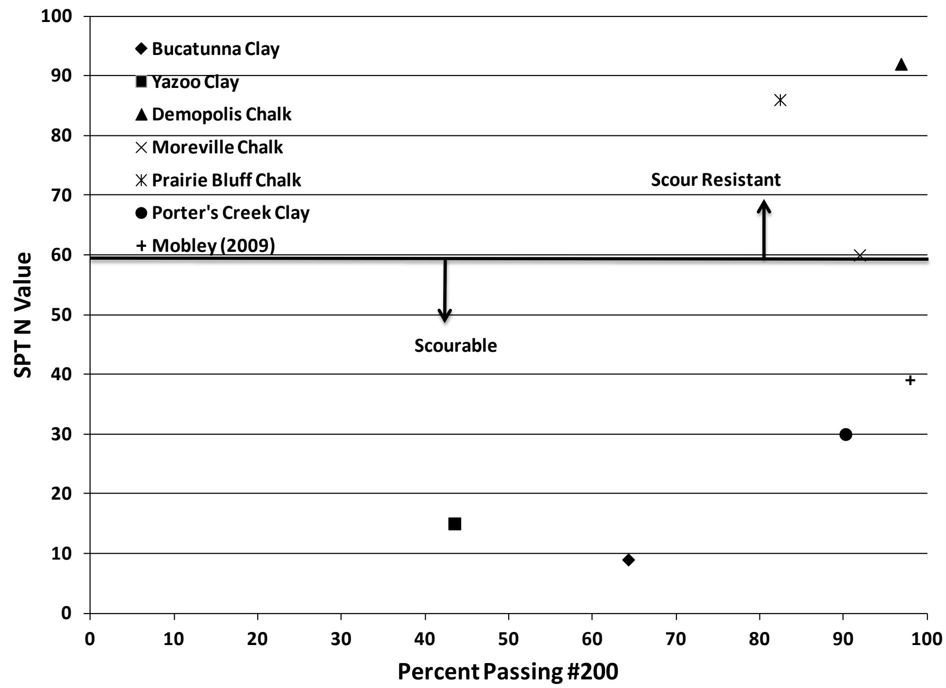

FIG. 2-4. Scour Correlation between Percent Passing #200 and SPT N Value (Walker 2013).

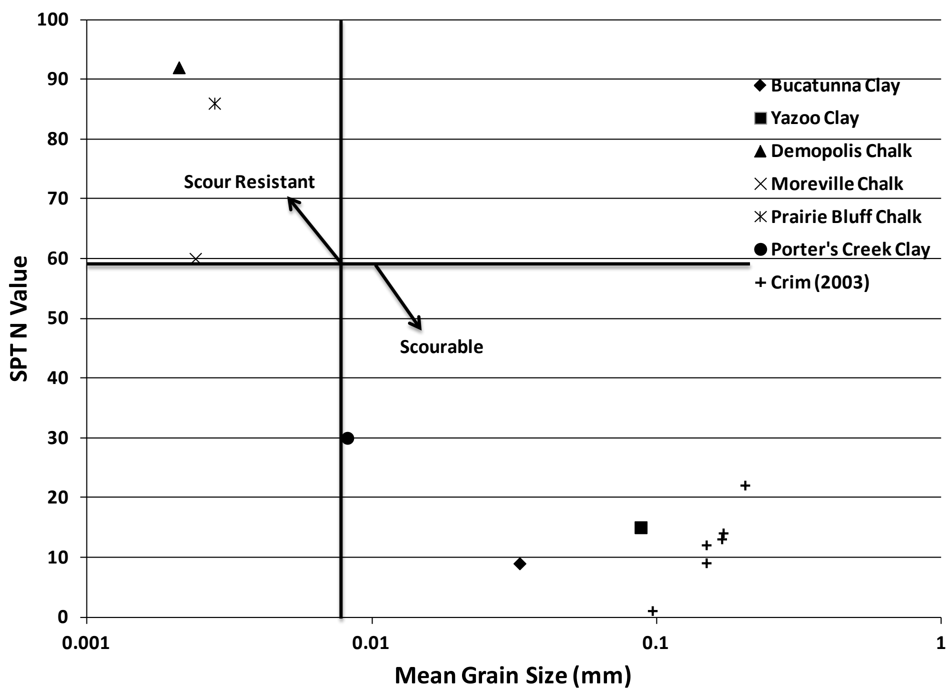

FIG. 2-5. Scour Correlation between Mean Grain Size and SPT N Value (Walker 2013).

Chapter 3 – Testing Equipment and Procedure

3.1 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. FIG. 3-1 shows a picture of the updated EFA at Auburn University and its critical components.

FIG. 3-1. Auburn University EFA and Critical Component Diagram.

Table 3-1 lists the critical components and gives the primary purpose of these features. The ultrasonic sensor (shown in FIG. 3-1a) will be explained in greater detail in the section 3.2.

Table 3-1. 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

The pump intake is located at the bottom of a water reservoir on the back side of the apparatus. This reservoir (shown in FIG. 3-2) 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 continuous use of the main pump will cause an extreme increase in temperature over time.

FIG. 3-2. EFA Reservoir.

Despite these efforts for temperature regulation, the temperature of the water still increases. As will be explained later, the ultrasonic sensor measurements for specimen height are affected by changes in water temperature. Therefore, another sensor (shown in FIG. 3-1d) 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 was 3 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 (2008) 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. FIG. 3-3 shows a photograph of this computer as well as a screenshot of the digital readout seen throughout testing.

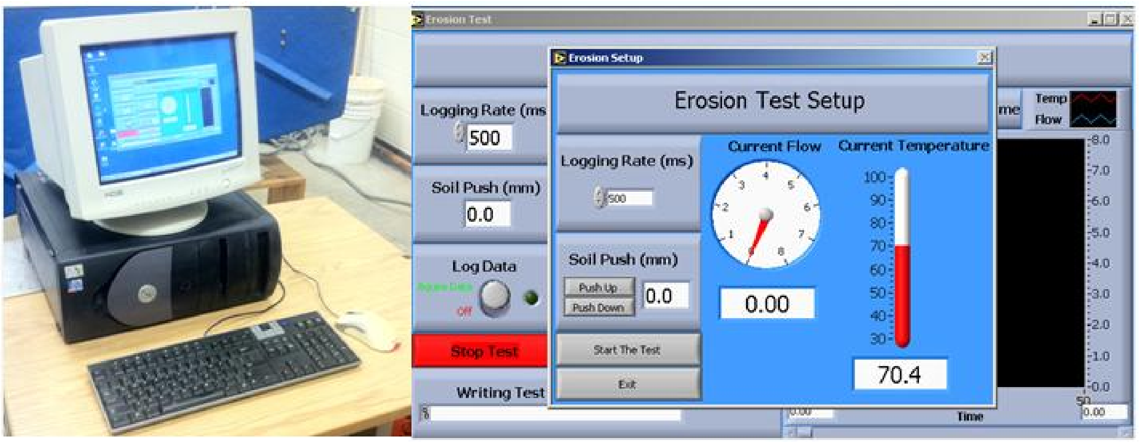

FIG. 3-3. EFA Control Station for Advancing Sample and Monitoring Temperature and Velocity.

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.

3.2 Ultrasonic Sensor

Integrating the ultrasonic sensor into the EFA allows for establishing a pattern or patterns of erosion throughout a single test. Instead of recording the initial and final height of a specimen, the sensor enables analysis of multiple erosion events that may occur by providing a continuous stream of specimen height measurements. As previously mentioned, the SERF apparatus constructed by Sheppard et al. (2005) included an ultrasonic sensor. The SERF ultrasonic sensor was created by SeaTek and included 12 transducers: eight transducers being used to take measurements of a 7.3 cm sample and all 12 transducers were used to measure a 9.5 cm sample.

The ultrasonic sensor used by Walker (2013) and in this study was also created by SeaTek and consisted of 16 transducers. These transducers have a surface diameter of 0.5 cm, an acoustic footprint of 0.8 cm at a distance of 5 cm, and operate at a frequency of 5 MHz (Jette 2010). Photographs of the sensor installed in the Auburn EFA are shown in FIG. 3-4.

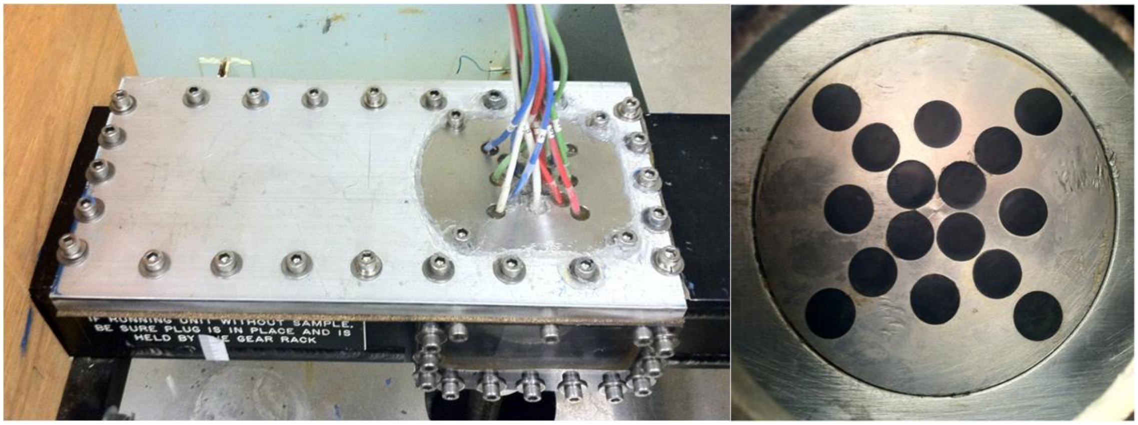

FIG. 3-4. Auburn University Ultrasonic Sensor Photographs.

The ultrasonic sensor is constructed of stainless steel. The device was set in the aluminum EFA flume so that both its top and bottom were perfectly flush with that of the flume. Dual O-rings and an ample amount of silicone sealant allowed the sensor to be sealed to the flume. It was critical to make the device flush with the flume inner wall. The sensor protruding into the flow channel would result in irregular flow patterns. The transducers are required to be fully submerged in order to operate properly. Therefore, the sensor cannot be fixed above the flume inner wall, as the pocket would trap air during flow. In the case of a Shelby tube soil sample (diameter of 71.1 mm), all 16 transducers conduct height measurements across the soil cross section. For the Central Mining Equipment (CME) continuous sampler (diameter of 57.2 mm), as used in this study, 12 transducers are used in measurements.

3.3 Data Acquisition

The data acquisition system used in this study, as well as in the Walker (2013) study, includes a data-logger that was provided by SeaTek and designed specifically for the 5 MHz ultrasonic sensor. The SeaTek 5 MHz data-logger operates under an alternating current (AC) power supply and is shown in FIG. 3-5. The system has the capacity to communicate with one to four external analog channels of which the output voltage of said channels must be between 0 and 4 Volts. The standard connection for the SeaTek data acquisition package is an RS232 serial port connection.

FIG. 3-5. SeaTek 5 MHz Ultrasonic Sensor Data-Logger.

This serial port connection transmits data from the SeaTek package to the terminal emulator software package known as CrossTalk. Incorporating parameters specified by the user, this CrossTalk package then translates and formats the incoming raw data to produce a text file. This text file is made up of ASCII characters which are accepted in an Excel spreadsheet.

Once the CrossTalk software has been launched a new session is then opened by selecting "File" => "New" and then choosing "Session" => "OK", as shown in FIG.

3-6. At this time the signal connection settings are defined by selecting “Settings” => “Connection”, entering values shown in FIG. 3-7, and clicking “OK”.

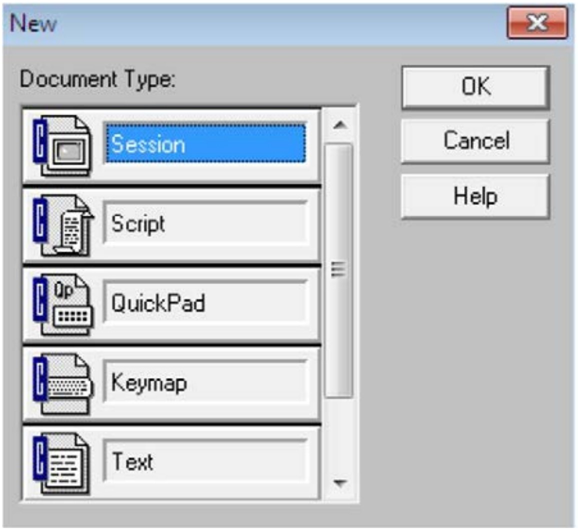

FIG. 3-6. Starting New Session in CrossTalk.

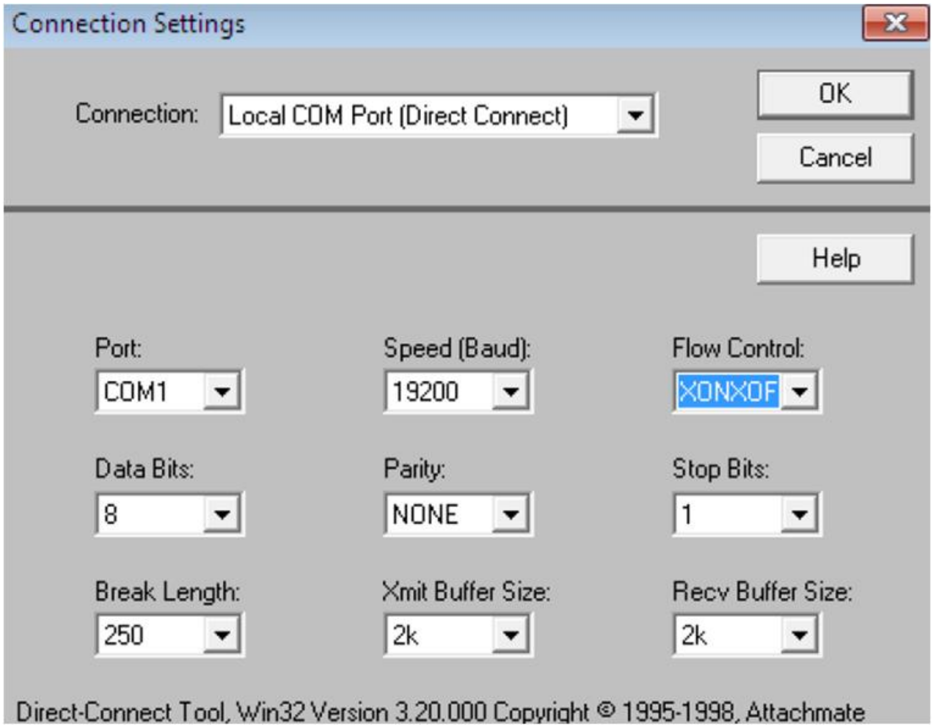

FIG. 3-7. Defining Connection Settings for CrossTalk – SeaTek Package Signal.

CrossTalk now requires that an input script be chosen. This is achieved by selecting "Script" => "Run", choosing the designated EFA test script titled "SEATEK.AU SCRIPT.XWC" embedded in the "C:\ATTMAPS\XTALK32" folder, and selecting "OK" as shown in FIG. 3-8.

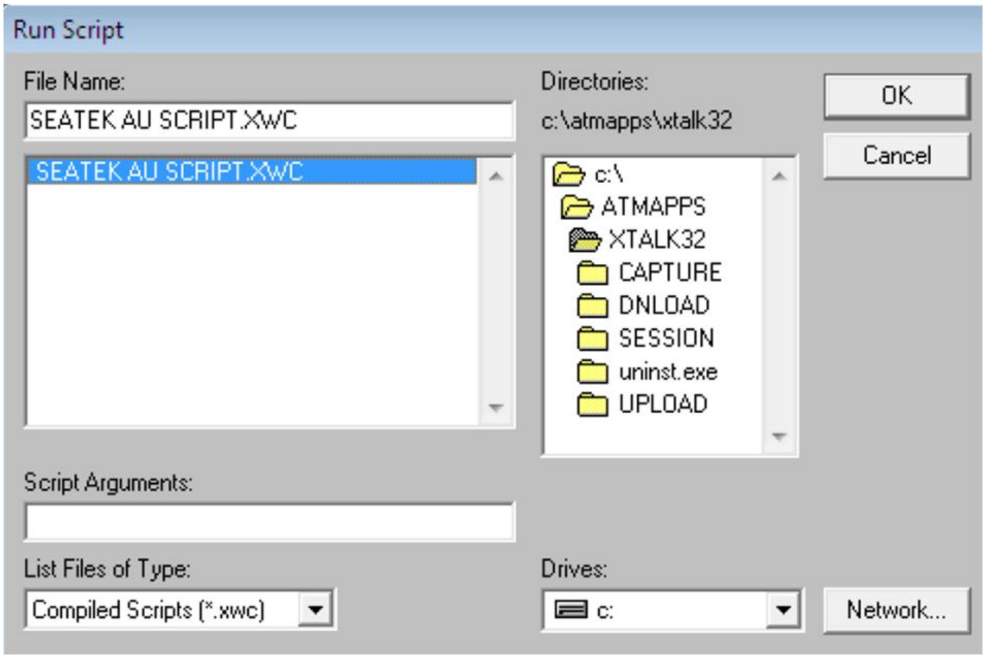

FIG. 3-8. Selecting SeaTek File as CrossTalk Input Script.

After the "SEATEK.AU SCRIPT.XWC" is selected a response box will emerge in which "Begin Data Collection" is selected by the user. Upon this selection, the Script Dialog box appears and shall be completed as shown in FIG. 3-9. By correctly filling out the script dialog entries the user has specified the transducer settings for CrossTalk and data collection may now commence. Before the user selects "OK", however, it is critical to verify that water is flowing through the flume and the sensors are fully submerged. Once this verification is made the user selects "OK" and the text file will begin to be generated.

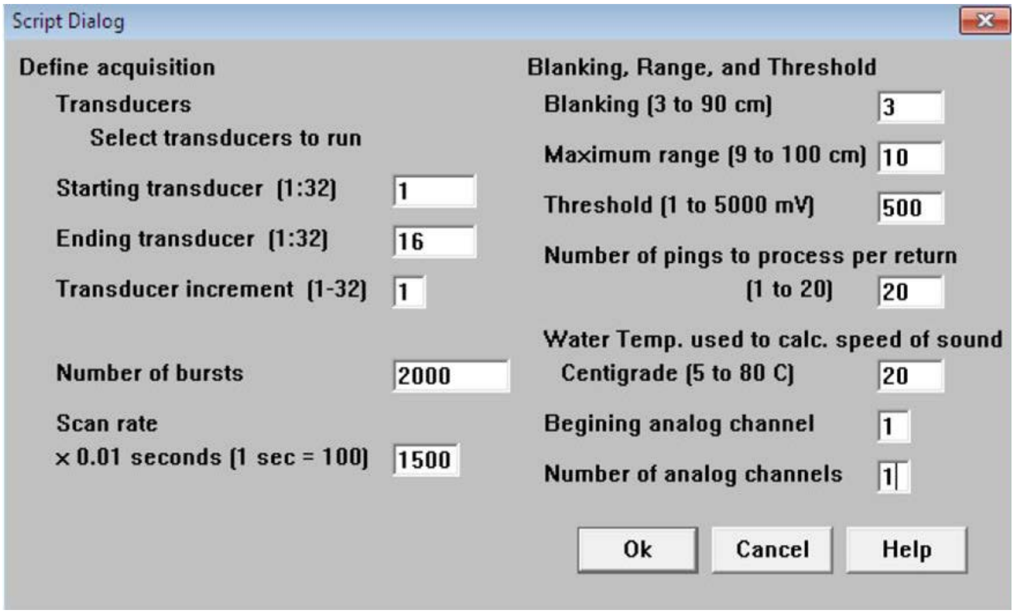

FIG. 3-9. Specify Settings for Sensor Transducers in CrossTalk.

3.4 Data Reduction

The text file generated by CrossTalk contained a time stamp, a distance measurement for each of the 16 transducers, and a voltage reading from the temperature sensor. This data, though partially reduced and formatted from its original form by CrossTalk, must undergo extensive data reduction to be translated from an individual, uncorrected distance measurement to an accurate representation for total volume change of the specimen. Walker (2013) produced an Excel spreadsheet to manage this task by incorporating a temperature correction factor to be applied to each raw distance measurement and converting these corrected height measurements to a value representing the volume of the sample. The change in this volume over time depicts the volume of erosion experienced. The average height change of the specimen is then determined by dividing this erosion volume by the cross-sectional area of the sample.

Walker calibrated the EFA temperature sensor (thermistor) by plotting readings for temperature (recorded from the EFA control station, FIG. 3-3) against the direct voltage output generated from the temperature sensor itself. A linear regression curve for the plot, shown in FIG. 3-10, was used by Walker to determine the correction factor for the temperature sensor which is shown in Equation 3-1.

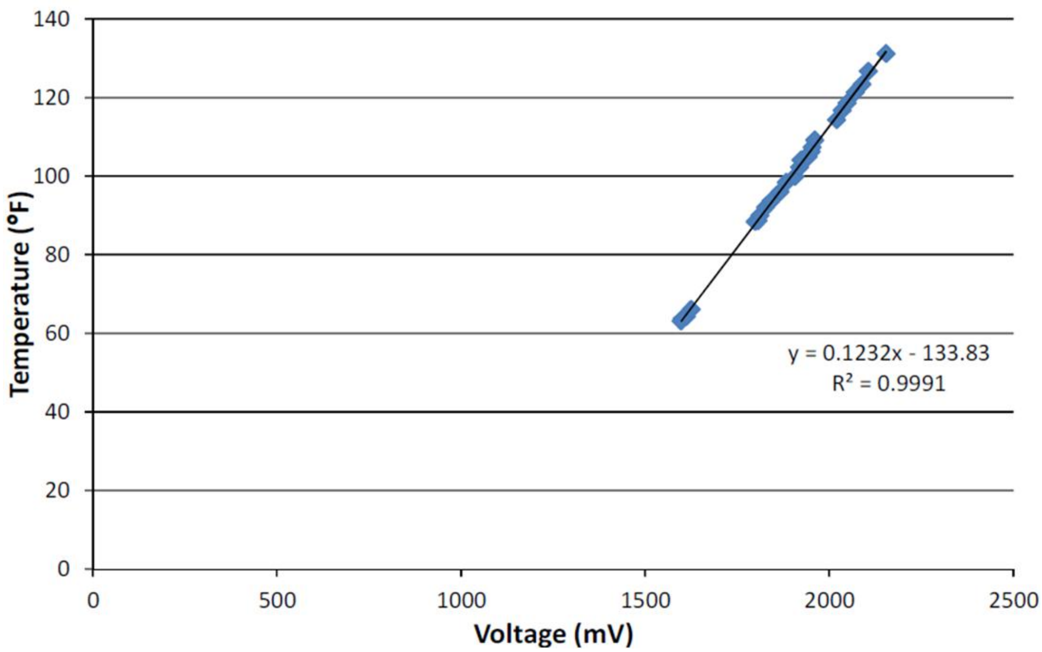

FIG. 3-10. Temperature Calibration for EFA Thermistor (Walker, 2013).

$$Voltage\ (mV) = 8.117 * (°F) + 1086.28 \tag{3-1}$$

An individual correction factor is applied to each sensor scan. Likewise, the speed of sound (corresponding to the corrected temperature at the time of scan) is calculated for each individual scan. An initial speed of sound is calculated based on the input temperature the user provided (20°C) in the data acquisition setup shown in FIG. 3-9. Walker calculates speed of sound, SOS, in meters per second using Equation 3-2, where temperature (T) is taken as degrees Celsius. The elapsed time, in seconds, is determined using Equation 3-3, where SOS1 represents the initial speed of sound and "initial measurement" represents the initial measured distance. Lastly, the temperature corrected distance for each scan is determined using Equation 3-4 which includes the corresponding speed of sound for the scan, SOS2.

$$SOS = 0.0029T^3 - 0.055T^2 + 4.95T + 1402.3 \tag{3-2}$$

$$Elapsed\ Time = \left[\frac{SOS1*100}{Initial\ Measurement}\right]^{-1} \tag{3-3}$$

$$Corrected\ Distance = SOS2 * Elapsed\ Time * 100 \tag{3-4}$$

(Walker 2013)

Walker then developed a means to convert the change in corrected distance measurements to volume of erosion. Each transducer is assigned a tributary area (A_t) in order to determine a weighted average across the sensor. For a single transducer, the volume of erosion over a certain time interval is determined by multiplying the change in measured height by the tributary area of that transducer. As shown in Equation 3-5, the total volume of erosion over that time interval is simply the sum of this value for each of the 12 transducers, with D_i and D_f representing the initial and final measurements for each transducer, respectively..

$$\sum_{n=1}^{12} (D_i - D_f) * A_t \tag{3-5}$$

(Walker 2013)

The average height change over that increment is simply the volume of erosion divided by the cross-sectional area of the entire sample. This calculation infers that the scour occurred uniformly across the soil surface (Walker 2013). For this study, testing was terminated once 1 mm of scour occurred.

As specified in the data acquisition setup shown in FIG. 3-9, scans were made once every 15 seconds. In the Excel spreadsheet walker averaged four distance measurements to result in a change in height per minute. For cases where a transducer returned a blank reading (i.e. 0.00) a nested if-statement in the spreadsheet allowed the average measurement value of adjacent transducers to be calculated and take the place of the blank reading (Walker 2013).

3.5 Verification of Sensor Operation

Following the method Walker established for sensor verification, 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. The dummy specimen, constructed by Walker 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.

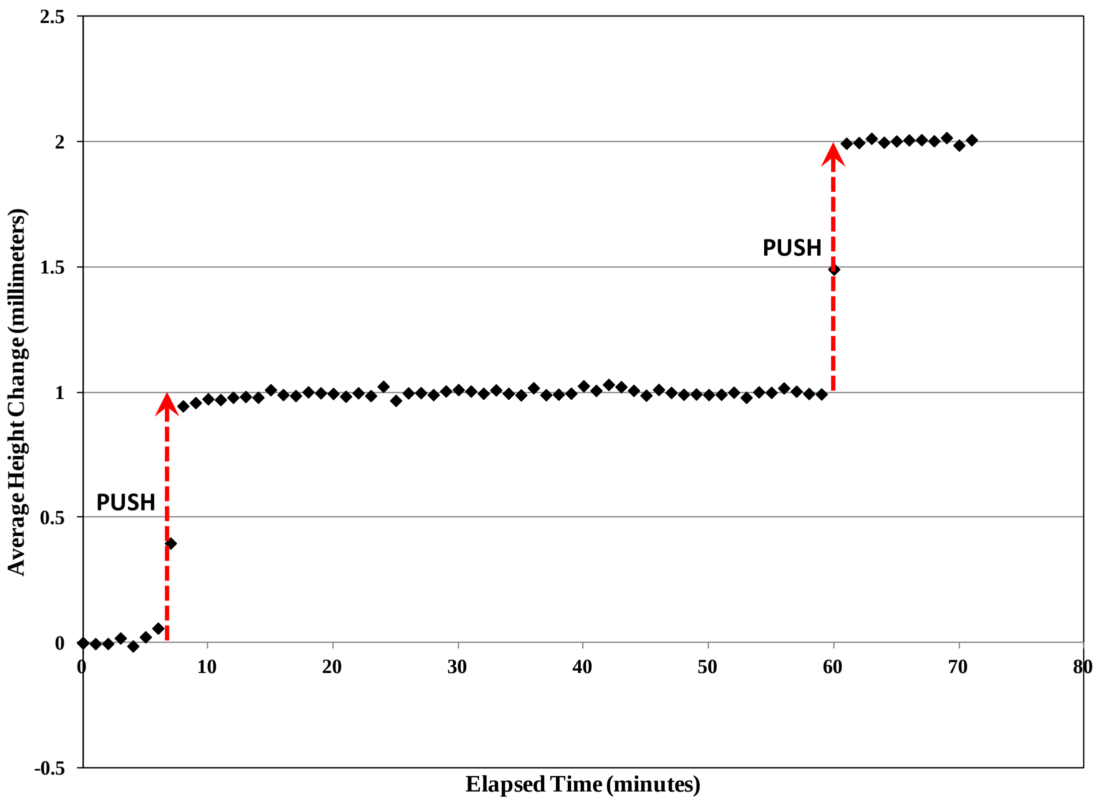

FIG. 3-11. Verification of Sensor Operation.

FIG. 3-11 shows the results of a verification test run prior to EFA soil testing. 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 that will be tested.

3.6 Testing Procedure

3.6.1 Sample Procurement

Alabama Department of Transportation drill crews provided all of the soil samples used throughout the study. Prior to drilling tours, geologists from ALDOT specified drilling locations and depths for the particular soils. During drilling, material acquired from split spoon samples was examined by an on-site geologist to verify that the targeted formation had been located. The drill crew then conducted Standard Penetration Tests (SPT) across the soil layer. At this time the ALDOT team would begin taking samples for EFA testing.

As previously stated, the majority of the clay formations tested were extremely dense and stiff. This hard material made it difficult to advance samples into the EFA, as explained earlier, and also caused issues in drilling. The common method of Shelby tube sampling was not possible for these stiff materials. Therefore, the ALDOT used a Central Mining Equipment (CME) bearing head continuous sample tube system for acquiring undisturbed core samples. This continuous sampler is basically a 1.52 m long split spoon sampler with two acrylic tube inserts stacked inside. The tubes are 762 mm long and have inner and outer diameters of 57.2 and 63.5 mm, respectively.

A hollow stem auger is used to drill down to the target soil layer and the sampler is slid into the stem until the bottom of the sampler is flush with the end of the auger. At this time the auger is engaged and the sampler is pushed in unison with the drill. The auger is allowed to rotate around the sampler freely while the sampler itself never rotates. Once the sampler has reached its capacity it is brought to the surface, split in half, the tubes are collected and end caps are sealed to the ends of the tubes with tape. FIG. 3-12 shows a photograph taken during sample procurement.

FIG. 3-12. Photograph of ALDOT Drilling for Yazoo Clay.

The sample name and depth are written on the tubes and the samples are stored vertically. It was recommended that a minimum of 5 ft (about two acrylic tube lengths) of non-cracked, testable material was acquired before sampling was complete. In some cases this was not possible due to inhomogeneities in the sampled material such as crushed rock or mixed soil types.

3.6.2 Sample Preparation

After the samples were acquired the sealed tubes were taken directly to Auburn University to be stored in a moisture room to preserve the natural moisture content of the material. Again, the samples were stored vertically to simulate insitu state soil conditions. Prior to an EFA test, an 8” to 10” section was cut from the tube using a Racine powered hacksaw as shown in FIG. 3-13.

FIG. 3-13. Cutting a Test Section from 2.5 ft Tube using Power Hacks

As seen in the photograph, a vise holds the sample in place while the sawing arm moves back and forth cutting the tube. If the vise is compressed too hard on the tube then the sample will crack. Therefore, the vise was tightened just enough to hold the sample in place.

This test section was then taken to the EFA and advanced approximately 3 to 5 mm using the stepping motor. In the case of the extremely stiff samples, the sample was extruded manually using the manual crank wheel shown in FIG. 3-1 F. The test specimen was then trimmed using a spatula so that the surface of the specimen was relatively smooth and flush with the end of the acrylic tube. FIG. 3-14 shows a sample being trimmed prior to an EFA test.

FIG. 3-14. Trimming the Sample Specimen Prior to an EFA Test.

3.6.3 EFA Testing Procedure

After the test specimen was prepared an EFA test was performed according to the procedure set forth by Walker (2013). This 25 step procedure provides visual guidance and detailed descriptions of conducting an EFA test. The procedure outlines the preliminary steps in preparing the apparatus for testing, as well as thorough explanations of launching the data acquisition system. Recommendations pertaining to cleaning and maintaining the apparatus following a test are also given. In order to standardize the test method as much as possible, the Walker procedure was followed meticulously in this study.

3.7 Testing Parameters

Walker (2013) studied work performed by Briaud et al. (1999), Crim (2003), and Mobley (2009), and considered the maximum velocity expected in Alabama rivers to develop a testing regimen based on six test velocities. In order to parallel Walker's work and make comparisons between results, a similar testing regime was used in this study.

EFA tests were performed at the same velocities Walker established: 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. The "critical velocity" of the formation was determined by slowly and progressively subjecting a sample to a larger and larger velocity and recording the velocity at which the material began to scour. The "minor critical velocity" of the material was the velocity at which the sample barely began to scour while the "major critical velocity" of the material was the velocity at which massive scour (i.e. very large flakes or chunks) occurred. The formation was deemed "scour resistant" for velocities below this minor critical velocity.

Once the critical velocity was determined, general EFA testing began at the next highest velocity increment. For instance, if the critical velocity was determined to be 0.49 m/s, scour testing would commence at the velocity increment 0.6 m/s. If the critical velocity was relatively close to a velocity increment (for example, 0.34 m/s) testing would start at the nearest velocity increment (i.e. 0.3 m/s). A minimum of three EFA tests were conducted at each velocity increment unless the amount of testable material for the formation was limited. In this case where testable material of a formation was limited, EFA tests were performed at consecutive velocity increments until the material was depleted.

The formations tested in the study did not always erode at a constant rate over the duration of a test. As will be discussed later, the material often had a pattern of erosion where the sample scoured over different periods throughout the test. In such case the EFA test was separated into multiple scour events, each with an individual scour rate.

It is important to note that this is not the same phenomenon as the “multiple events test” performed by Walker (2013) where the shear stress of the material was intentionally manipulated throughout the test. The “multiple events test” was used by Walker to “model the performance of a formation against changing shear cycles” for formations that had critical velocities greater than 3.0 m/s (Walker 2013). Because all formations tested in this study had critical velocities considerably less than 3.0 m/s, this test was not applicable.

3.8 Geotechnical Testing

Numerous 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. 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 standard. FIG. 3-15 and FIG. 3-16 are photographs taken during grain size analyses. Atterberg limit testing was performed according to the ASTM D4318 – 10 "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." FIG. 3-17 and FIG. 3-18 are photographs taken during Atterberg limit testing.

FIG. 3-15. Mechanical Sieve Shaker used in Grain Size Analysis.

FIG. 3-16. Hydrometer Analysis for the Fine Grained Fraction of Material.

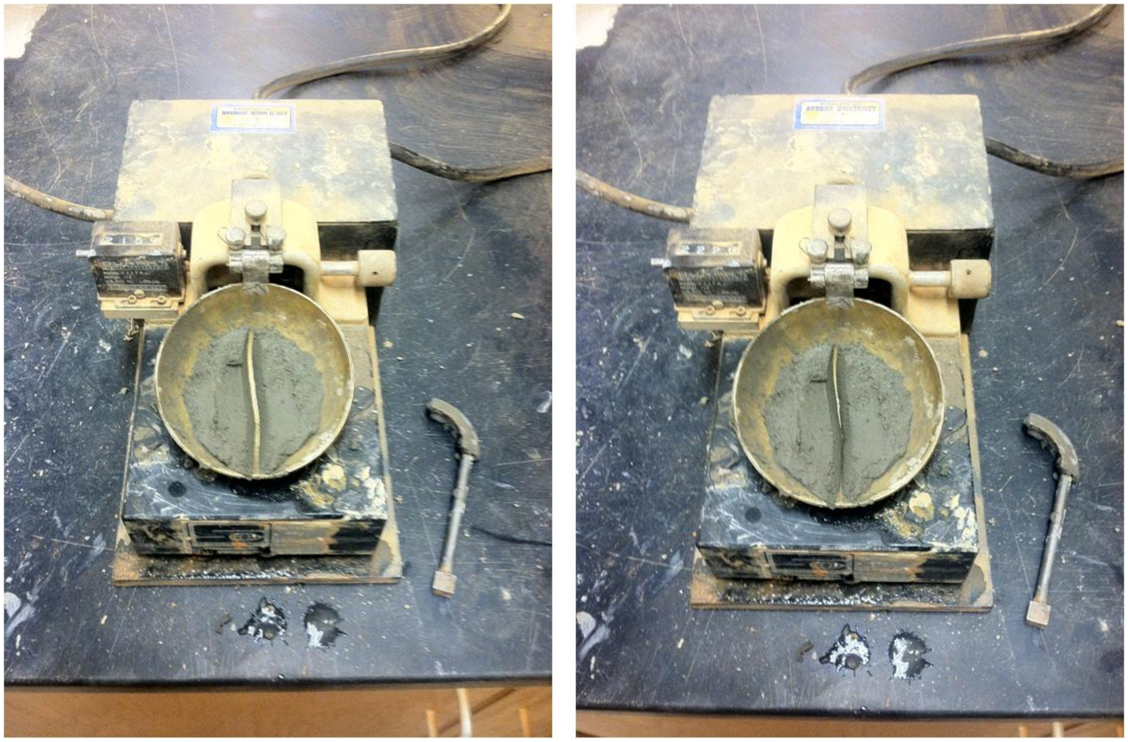

FIG. 3-17. Atterberg Limit Testing: Liquid Limit.

FIG. 3-18. Atterberg Limit Testing: Plastic Limit.

Chapter 4 – Test Results

4.1 Sampling Overview

Since scour research commenced at Auburn around 2001, the ALDOT has provided samples of various soils throughout the state of Alabama for scour analysis. With the exception of Talladega County, all samples have been procured from sites south of the fall line where ALDOT is most concerned about bridge scour. FIG. 4-1 shows the drilling locations for samples analyzed from 2001 to 2009 (Crim 2003 and Mobley 2009), 2012 (Walker 2013), and in 2013 for this study.

Samples taken strictly for this study are shown as red points in the figure. However, it should be noted that this study included samples taken in the summer of 2012 (Yazoo, Nanafalia, Naheola, and Clayton). The most recent samples were acquired in June (Naheola) and August (Porter’s Creek and Bucatunna) of 2013.

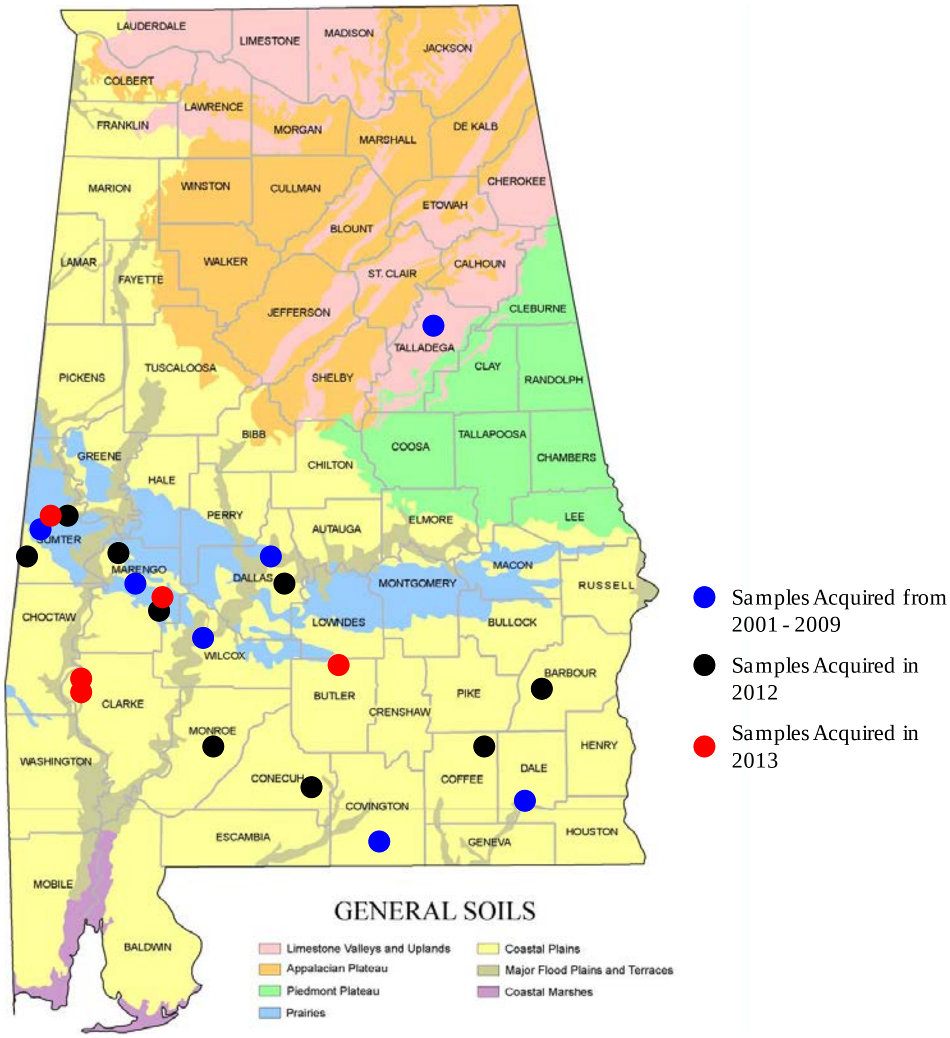

FIG. 4-1. ALDOT Drilling Locations for Auburn University Scour Research.

4.2 Nanafalia Clay

Nanafalia clay was originally intended to be tested by Walker (2013). The material was sampled in 2012, but due to time constraints in Walker's study no EFA or geotechnical testing was performed.

4.2.1 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 2.5 meters below ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 13 blows (Walker 2013). 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.

4.2.2 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 minor critical velocity of 0.60 m/s. 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 minor critical velocity of 0.60 m/s and large chunks were being lost after 2.5 m/s. Table 4-1 shows a summary of the critical velocity tests for Nanafalia clay.

Table 4-1. Critical Velocity Summary for Nanafalia Clay.

Test No.	Critical Velocity	
	Minor (m/s)	Major (m/s)
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 increment. The test was run for a total of 66 minutes in which no scour was seen.

Four tests were conducted at the 0.6 m/s velocity increment. 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 most was 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. 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 4-2 shows a summary of results from the 0.6 m/s velocity increment. For tests with multiple scour events the value in parentheses represents the particular scour event number for the respective test.

Table 4-2. Nanafalia Clay Results at 0.6 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Nanafalia Clay 23.5_2 (1)	15	0.95	3.80
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
Nanafalia Clay 23.5_3 (2)	6	0.19	1.90
Nanafalia Clay 23.5_4	69	0.00	0.00
Nanafalia Clay 21.0_1	47	0.00	0.00

Four tests were performed at the 1.0 m/s velocity increment. 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 4-3 shows a summary of results from the 1.0 m/s velocity increment. 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 4-3. Nanafalia Clay Results at 1.0 m/s.

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

Three tests were conducted at the 1.5 m/s velocity increment. 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 4-4 shows a summary of results from the 1.5 m/s velocity increment.

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

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

Three 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 4-5 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 4-5 shows a summary of results from the 2.0 m/s velocity increment.

Table 4-5. Nanafalia Clay Results at 2.0 m/s.

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

Three tests were conducted at the 3.0 m/s velocity increment. 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 FIG. 4-2, FIG. 4-3, and FIG. 4-4. 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 4-6 shows a summary of results from the 2.0 m/s velocity increment.

Table 4-6. Nanafalia Clay Results at 3.0 m/s.

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

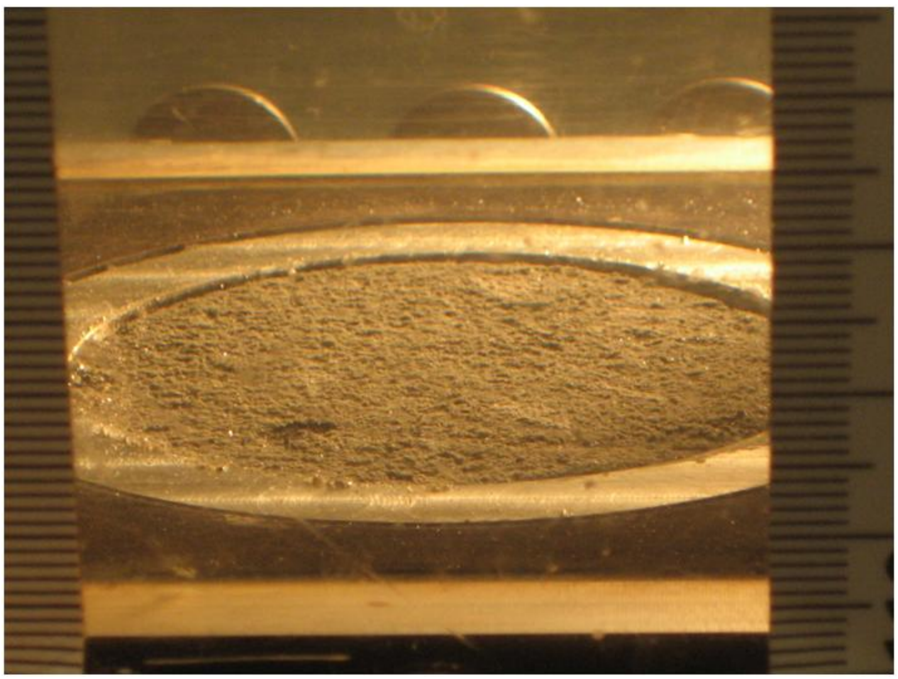

FIG. 4-2. "Nanafalia Clay 21.5_8" Sample Prior to 3.0 m/s EFA Test.

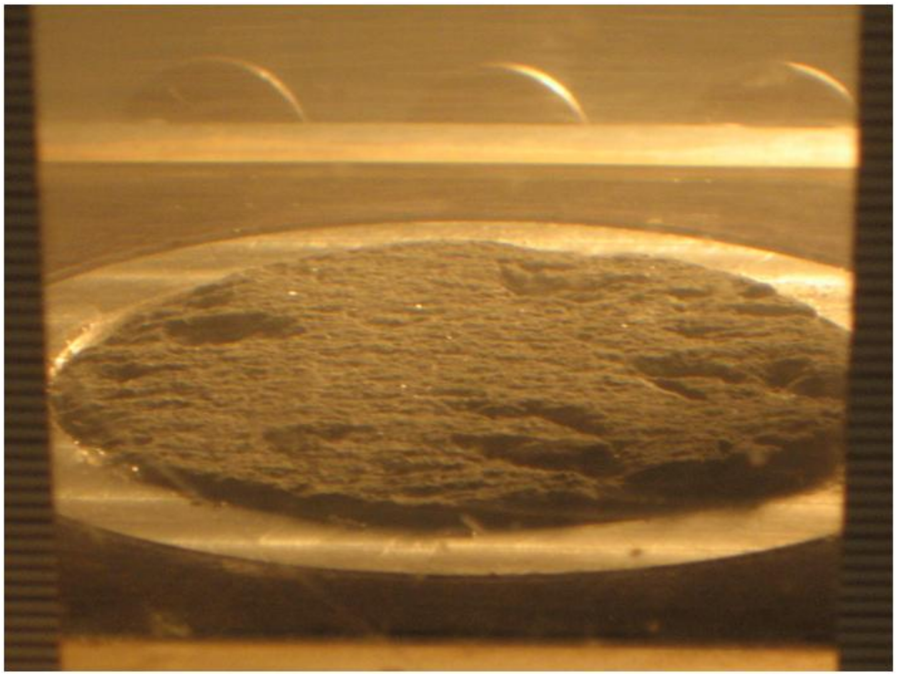

FIG. 4-3. "Nanafalia Clay 21.5_8" Sample During the 3.0 m/s EFA Test.

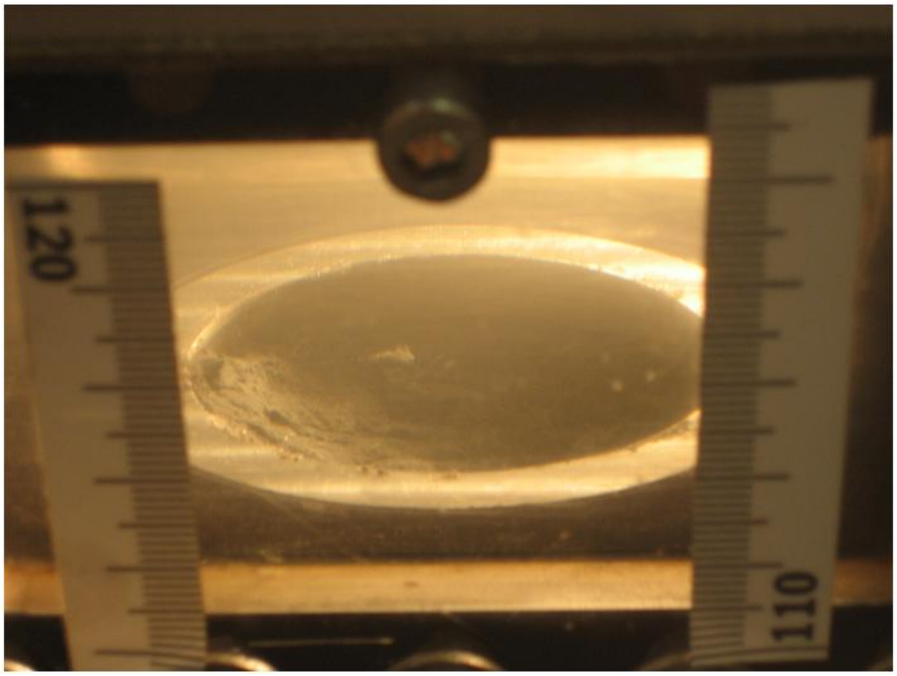

FIG. 4-4. "Nanafalia Clay 21.5_8" Sample at the End of 3.0 m/s EFA Test.

The results from each EFA test conducted on the Nanafalia formation may be found in **Appendix A**.

4.2.3 Geotechnical Testing

An average insitu moisture content of 24.1% for the Nanafalia clay was determined according to ASTM D2216 – 10 standards. A full grain size analysis, shown in FIG. 4-5, 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 – 10 standards. 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.

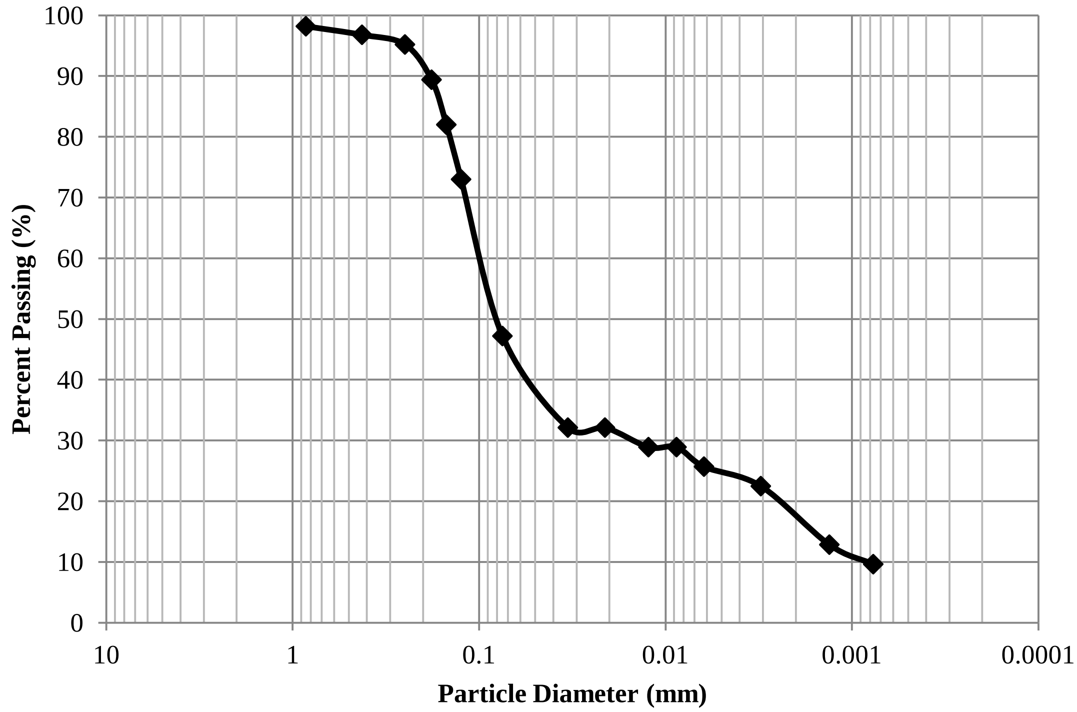

FIG. 4-5. Nanafalia Clay Grain Size Distribution.

4.3 Naheola Clay (Yellow Material)

Naheola clay was originally intended to be tested by Walker (2013). The material was first sampled in 2012, but due to time constraints in Walker's study no EFA or geotechnical testing was performed. The formation was drilled again in 2013 and this second sampling will be discussed in **4.5 Naheola Clay (Re-drilled)**. As shown in FIG. 4-6, the 2012 sample consisted of two different colored soils; one portion being a yellow-brownish material and the other having a dark grey color. 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.

FIG. 4-6. Photograph of Naheola-Dark (left) and Naheola-Yellow (right) Formations.

4.3.1 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 3.9 meters below ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 16 blows. (Walker 2013) 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.

4.3.2 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 minor critical velocity tests were performed. By testing for major critical velocity too much soil would have been sacrificed and there would not be enough material available for the remaining EFA tests. Table 4-7 shows a summary of the critical velocity tests for the yellow Naheola clay.

Table 4-7. Critical Velocity Summary for Yellow Naheola Clay.

Test No.	Critical Velocity	
	Minor (m/s)	Major (m/s)
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. One test, titled "Naheola Clay 17.5_1", was conducted at the 0.3 m/s velocity increment. 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. 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 increment. 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 increment, the amount of soil remaining for the following EFA tests was extremely limited.

Three tests were conducted at the 1.0 m/s velocity increment. 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 4-8 presents a summary of results from the 1.0 m/s velocity increment.

Table 4-8. Yellow Naheola Clay Results at 1.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Naheola Clay 17.5_3	3	CHUNK	NA
Naheola Clay 17.5_4	3	CHUNK	NA
Naheola Clay 17.5_5 (1)	4	0.19	2.85
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 4-9 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 FIG. 4-7 and FIG. 4-8, respectively.

Table 4-9. Yellow Naheola Clay Results at 2.0 m/s.

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

FIG. 4-7. "Naheola Clay 17.2_1" Sample Prior to 2.0 m/s EFA Test.

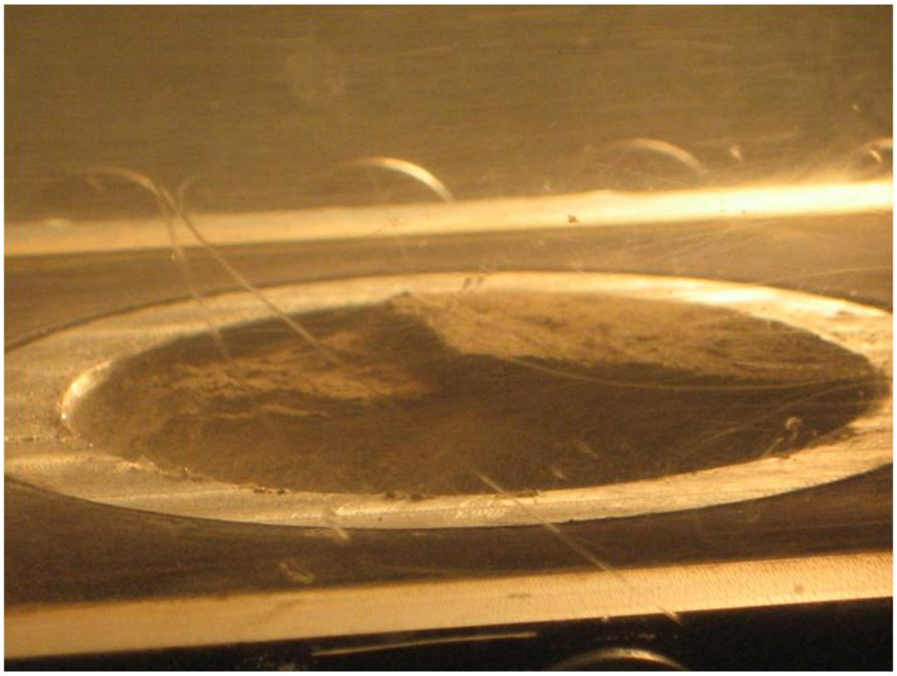

FIG. 4-8. "Naheola Clay 17.2_1" Sample at the End of 2.0 m/s EFA Test.

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 **4.4 Naheola Clay (Dark Material)** and **4.5 Naheola Clay (Re-drilled)**. The results from each EFA test conducted on the yellow Naheola formation may be found in **Appendix B**.

4.3.3 Geotechnical Testing

An average insitu moisture content of 31.4% for the yellow Naheola clay was determined according to ASTM D2216 – 10 standards. A full grain size analysis, shown in FIG. 4-9, 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 – 10 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.

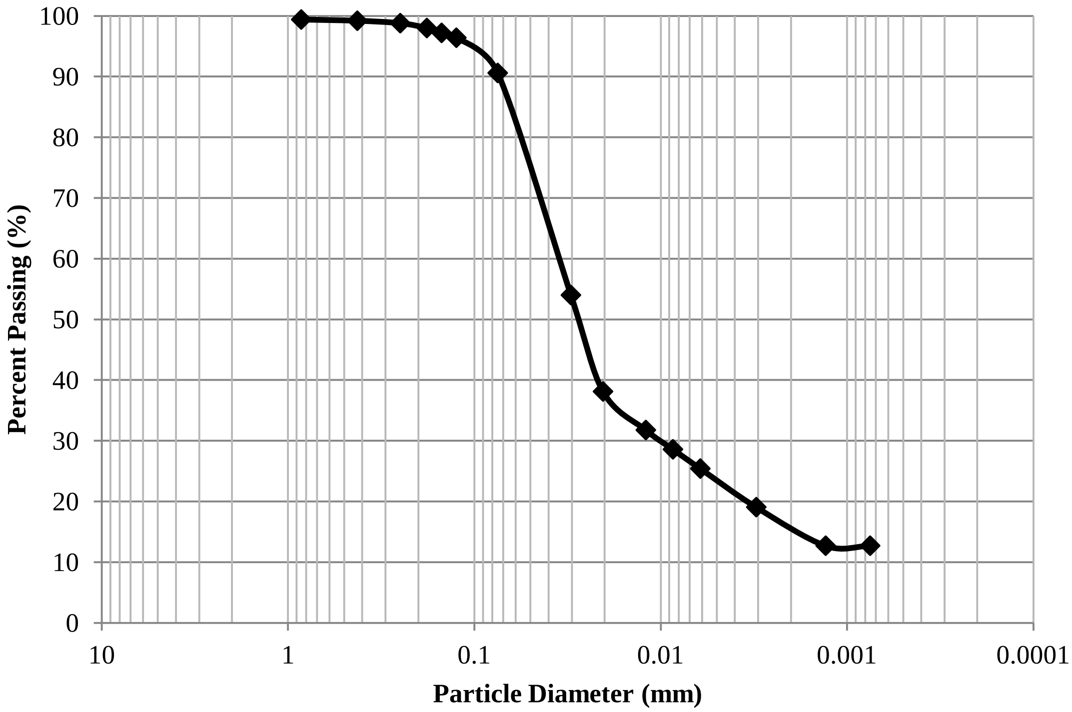

FIG. 4-9. Yellow Naheola Clay Grain Size Distribution.

4.4 Naheola Clay (Dark Material)

As previously stated, the Naheola formation was originally intended to be tested by Walker (2013). Because of the noticeable difference in color of the 2012 drilled sample (shown in FIG. 4-6), 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.

4.4.1 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 3.9 meters below ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 16 blows. (Walker 2013) 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 3" sections of the sample, one at a depth of approximately 17 feet and the other near 16 feet.

4.4.2 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 minor critical velocity 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 minor and major critical velocities of approximately 0.5 m/s. Table 4-10 shows a summary of the critical velocity tests performed on the yellow Naheola clay.

Table 4-10. Critical Velocity Summary for Dark Naheola Clay.

Test No.	Critical Velocity	
	Minor (m/s)	Major (m/s)
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 0.3 m/s velocity increment was not tested. One test, titled “Naheola Clay 17.0_1”, was conducted at the 0.6 m/s velocity increment. 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.

One test, titled “Naheola Clay 17.0_2” was performed at the 1.0 m/s velocity increment. 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 FIG. 4-10 and FIG. 4-11, 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 4-11 presents the results of the 1.5 m/s EFA test.

Table 4-11. Dark Naheola Clay Results at 1.5 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Naheola Clay 16.0_1 (1)	8	0.55	4.13
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

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)**.

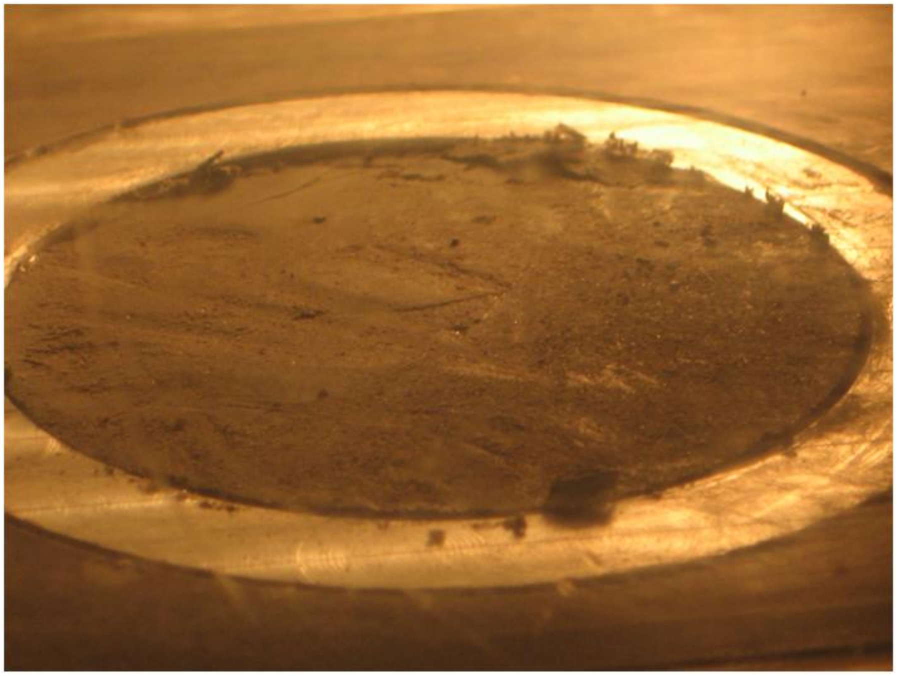

FIG. 4-10. "Naheola Clay 16.0_1" Sample Prior to 1.5 m/s EFA Test.

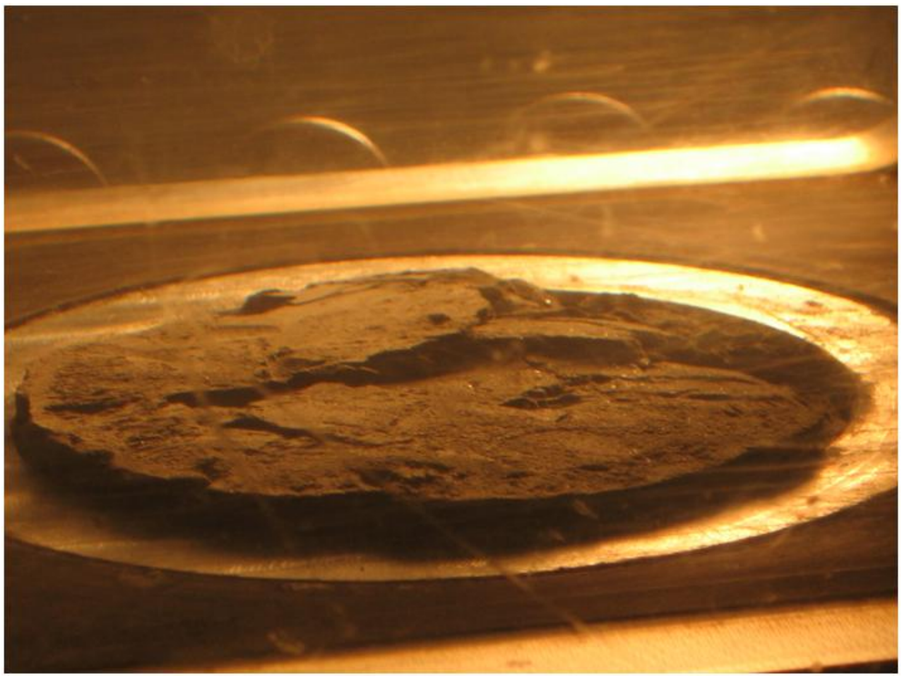

FIG. 4-11. "Naheola Clay 16.0_1" Sample at the End of 1.5 m/s EFA Test.

The results from each EFA test conducted on the dark Naheola formation may be found in **Appendix C**.

4.4.3 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 FIG. 4-12, 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 – 10 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.

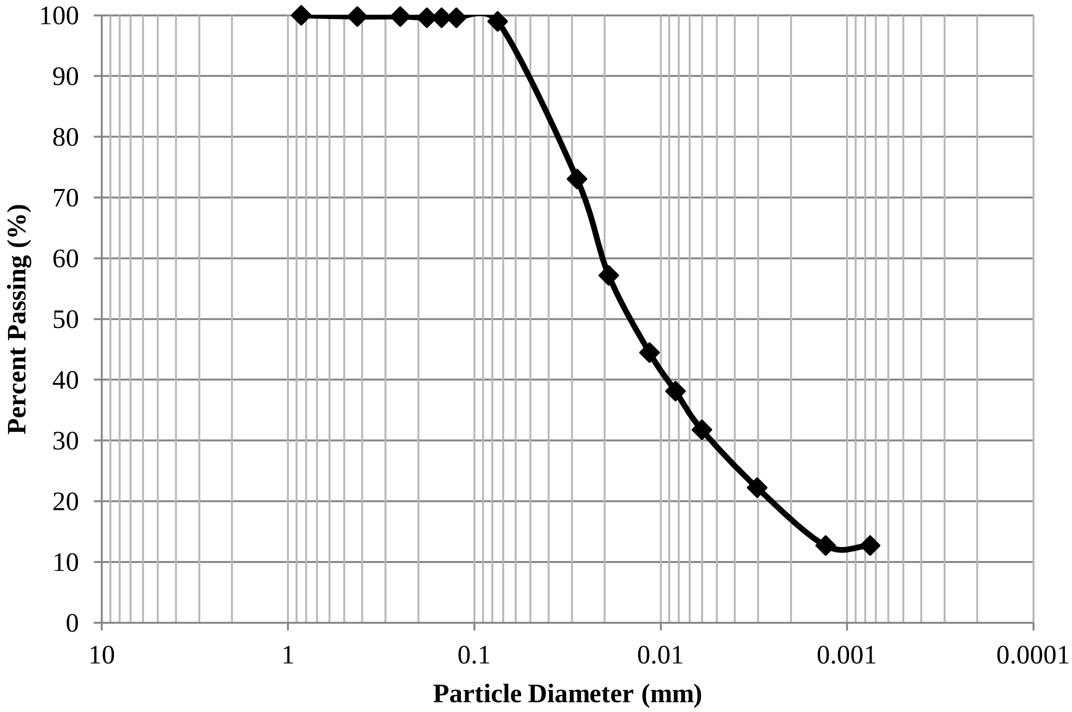

FIG. 4-12. Dark Naheola Clay Grain Size Distribution.

4.5 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.

4.5.1 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 (Walker 2013). An on-site geologist verified the formation with split spoon samples taken at approximately 17 feet below 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 six inch 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.

4.5.2 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 major critical velocity test was conducted during this test. In the second test minor scour occurred at a velocity of 1.6 m/s and the major velocity 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 minor critical velocity was determined. Table 4-12 shows a summary of the critical velocity tests performed on the re-drilled Naheola clay.

Table 4-12. Critical Velocity Summary for Re-drilled Naheola Clay.

Test No.	Critical Velocity	
	Minor (m/s)	Major (m/s)
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 4-12, the re-drilled Naheola clay was not tested at the 0.3 m/s velocity increment.

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 4-13 shows the results of the single test performed at 0.6 m/s.

Table 4-13. Re-drilled Naheola Clay Results at 0.6 m/s.

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

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 4-14 presents the results from this test.

Table 4-14. Re-drilled Naheola Clay Results at 1.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Naheola Clay_19.5_2(1)	3	0.10	2.00
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 increment. 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. FIG. 4-13 and FIG. 4-14 are photographs taken at the start and end of the 2.0 m/s test, respectively. Table 4-15 shows the results of the 2.0 m/s test.

Table 4-15. Re-drilled Naheola Clay Results at 2.0 m/s.

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

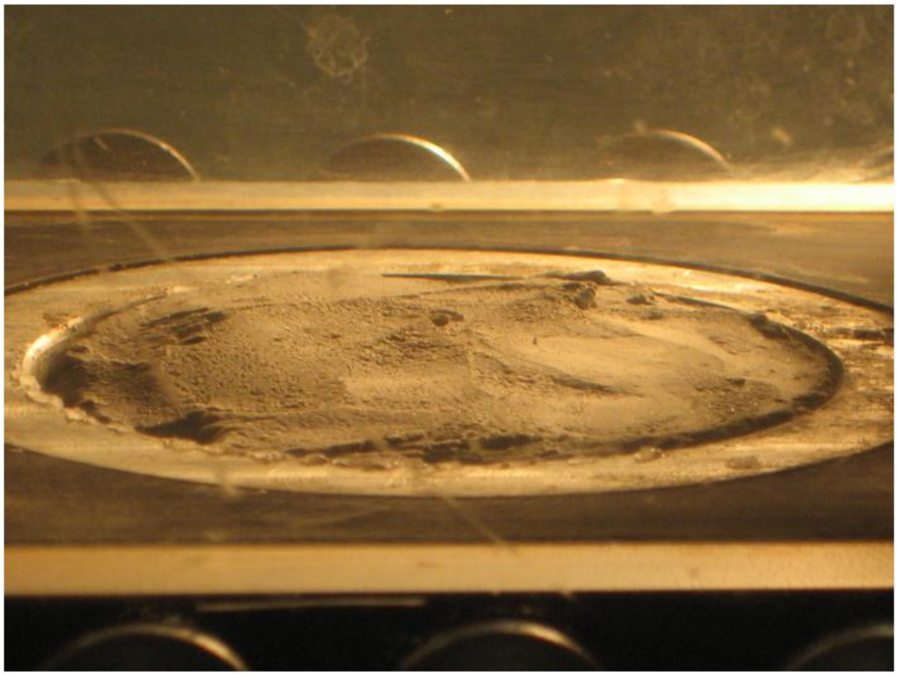

FIG. 4-13. "Naheola Clay 19.5_4" Sample at the Start of 2.0 m/s EFA Test.

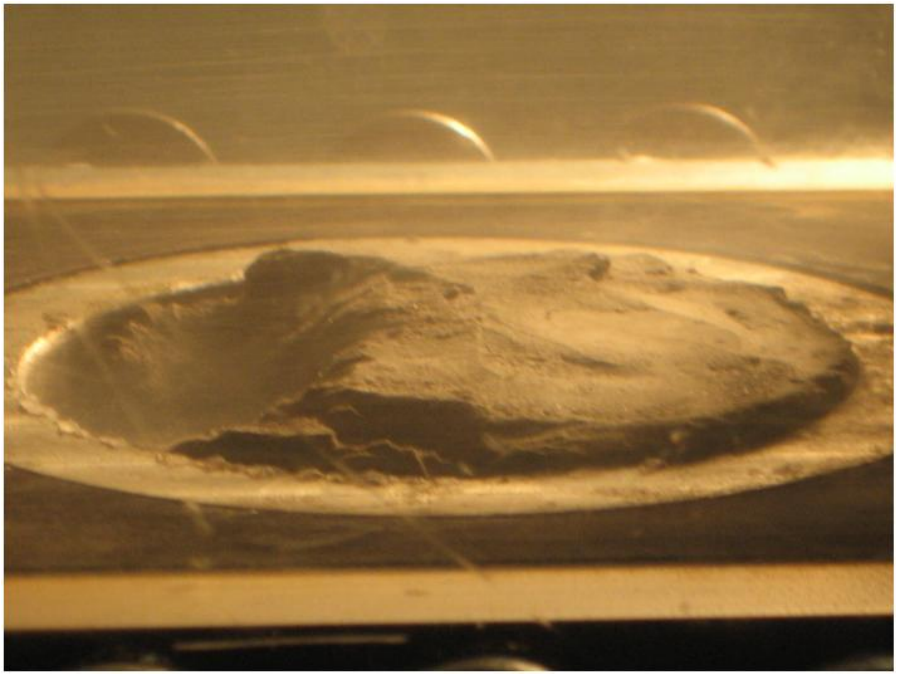

FIG. 4-14. "Naheola Clay 19.5_4" Sample at the End of 2.0 m/s EFA Test.

One test, titled “Naheola Clay 19.5_5”, was performed at the 3.0 m/s velocity increment. The single scour event lasted only 2 minutes and was very 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 very rapid scour may be considered to be “chunk” scour, as the sample was lost over a very short period of time. Table 4-16 presents the results from this test.

Table 4-16. Re-drilled Naheola Clay Results at 3.0 m/s.

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

The results from each EFA test conducted on the re-drilled Naheola formation may be found in **Appendix D**.

4.5.3 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 FIG. 4-15, 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 – 10 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.

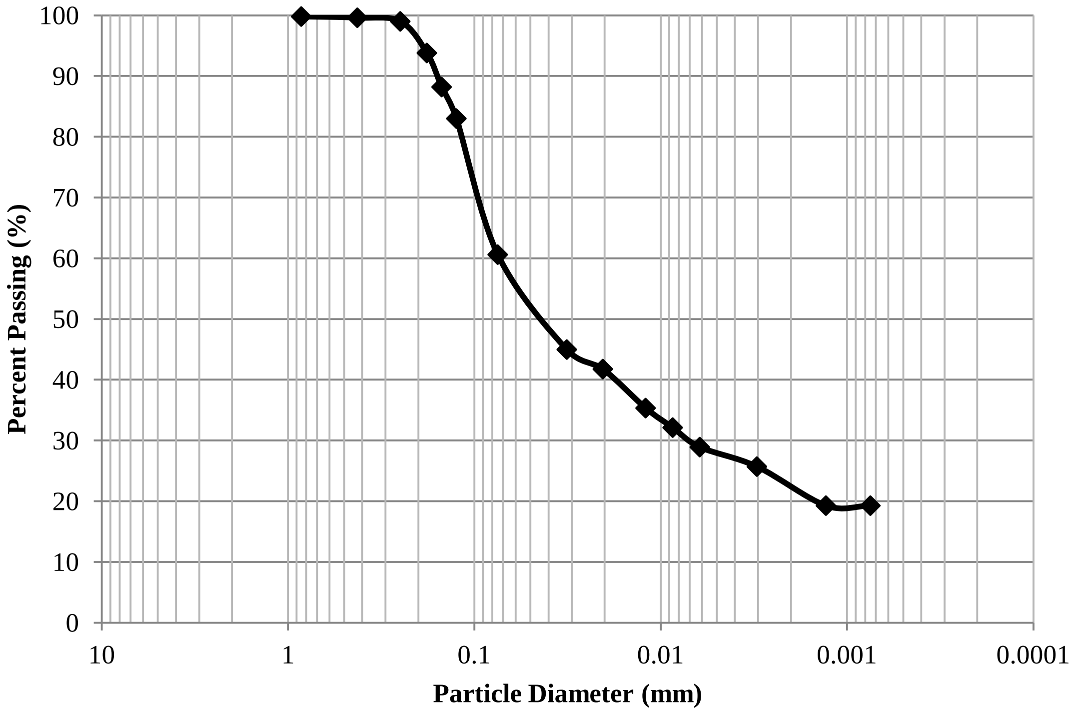

FIG. 4-15. Re-drilled Naheola Clay Grain Size Distribution.

4.6 Clayton Clay

The Clayton clay formation was originally intended to be tested by Walker (2013). The material was sampled in 2012, but due to time constraints in Walker's study no EFA or geotechnical testing was performed.

4.6.1 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 7.3 meters below ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 23 blows. (Walker 2013) 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 6-8" 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' 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 the drilling was discontinued. The EFA tests were performed on the 2012 Clayton sample ranging between depths of approximately 29.0 and 30.0 feet.

4.6.2 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 minor critical velocity of 0.90 m/s and extensive soil was being lost at 2.5 m/s. Table 4-17 shows a summary of critical velocity tests performed on the Clayton formation.

Table 4-17. Critical Velocity Summary for Clayton Clay.

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

A total of 12 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 0.3 m/s velocity increment was not tested.

One test, titled “Clayton 29.5_3”, was conducted at the 0.6 m/s velocity increment. 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. FIG. 4-16 shows a photograph of the sample prior to swelling while FIG. 4-17 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.

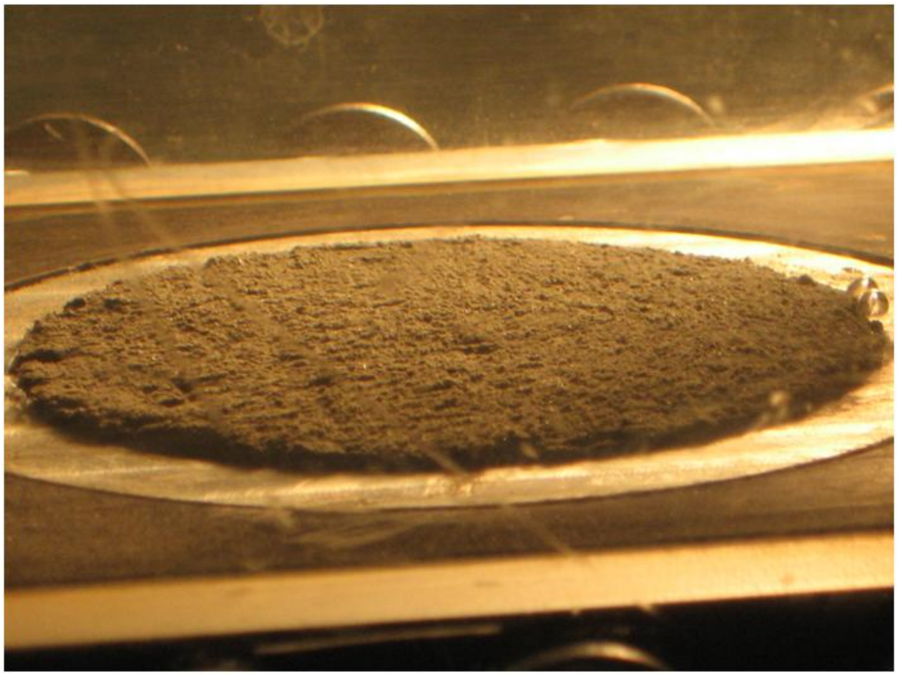

FIG. 4-16. "Clayton 29.5_3" Approximately 20 Minutes into Test.

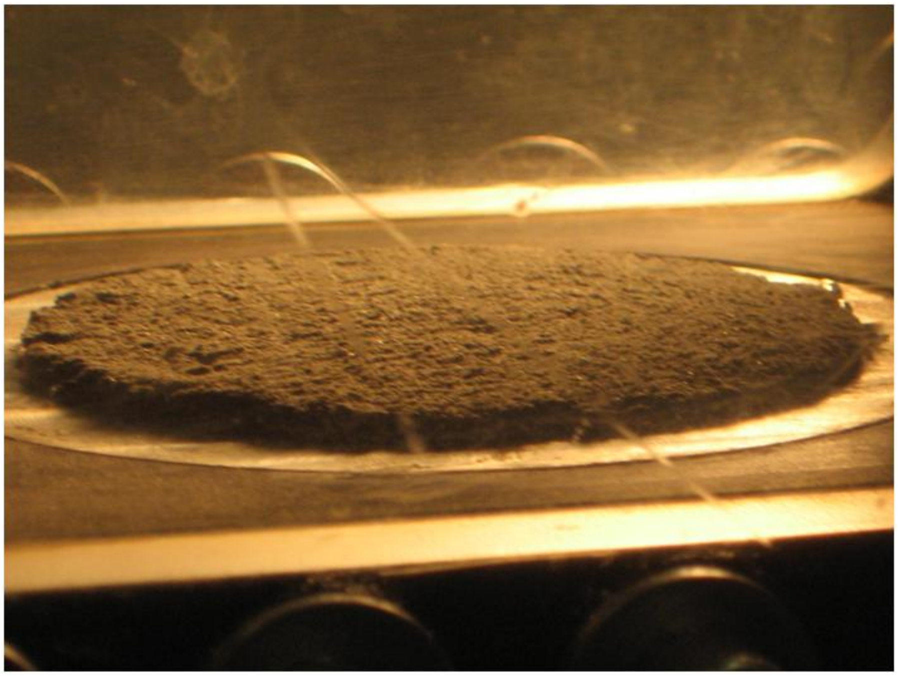

FIG. 4-17. "Clayton 29.5_3" Approximately 45 Minutes into Test.

Two tests were conducted at the 1.0 m/s velocity increment. 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 4-18 shows a summary of results from the 1.0 m/s velocity increment. Because there was limited Clayton material, no additional tests were performed at 1.0 m/s.

Table 4-18. Clayton Clay Results at 1.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Clayton 29.5_4 (1)	8	0.43	3.23
Clayton 29.5_4 (2)	4	0.10	1.50
Clayton 29.5_4 (3)	2	0.07	2.10
Clayton 29.5_5 (1)	3	0.38	7.60
Clayton 29.5_5 (2)	17	CHUNK	NA

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 4-19 presents the results of the 1.5 m/s EFA test.

Table 4-19. Clayton Clay Results at 1.5 m/s.

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

Three tests were conducted at the 2.0 m/s velocity increment, 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 washed away approximately 26 minutes into the test. FIG. 4-18, FIG. 4-19, and FIG. 4-20 are photographs taken at critical moments throughout the 2.0 m/s test. The massive swelling that occurred is very apparent in the photographs. Table 4-20 shows the results of the 2.0 m/s test.

Table 4-20. Clayton Clay Results at 2.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Clayton 29.0_1	6	1.06	10.60
Clayton 29.0_4	5	CHUNK	NA
Clayton 29.0_7 (1)	1	0.10	6.00
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

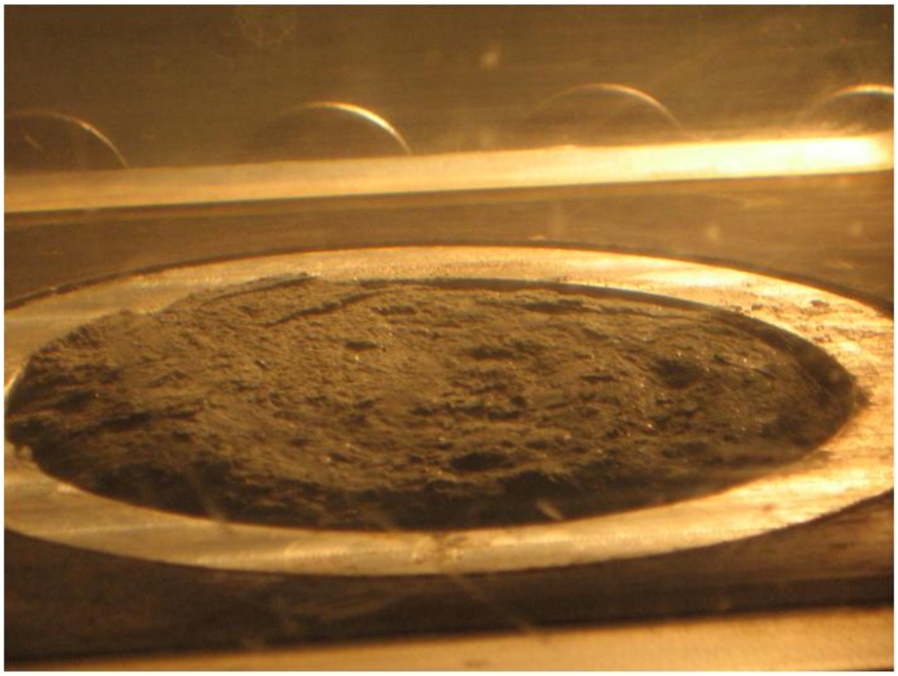

FIG. 4-18. "Clayton 29.0_7" Approximately 8 Minutes into Test.

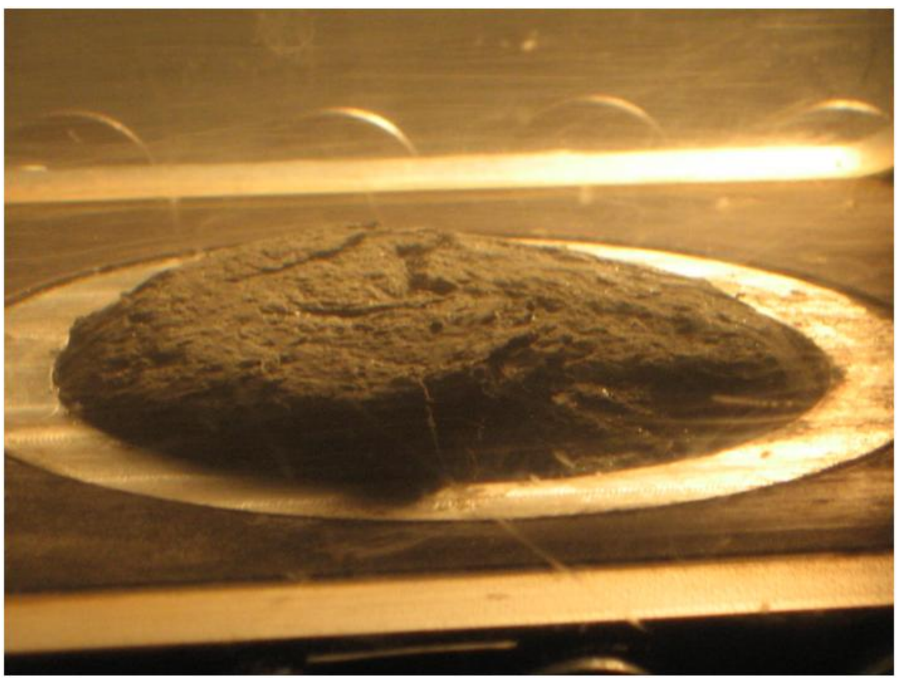

FIG. 4-19. "Clayton 29.0_7" Approximately 23 Minutes into Test.

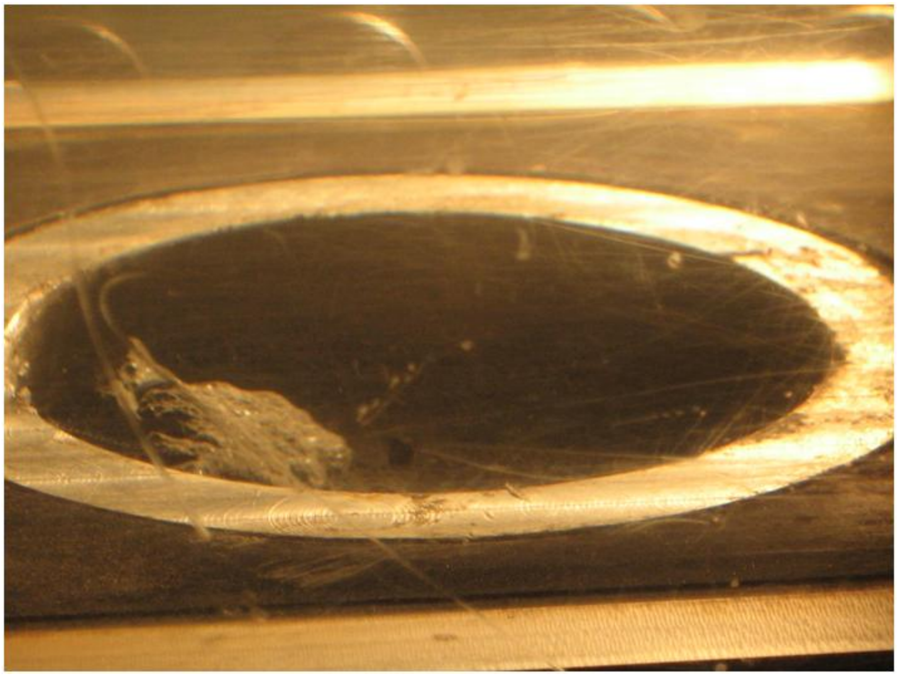

FIG. 4-20. "Clayton 29.0_7" Approximately 27 Minutes into Test.

Three tests were performed at the 3.0 m/s velocity increment. 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 where 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 4-21 shows a summary of results from the 3.0 m/s velocity increment.

Table 4-21. Clayton Clay Results at 3.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Clayton 29.0_1	2	0.42	12.60
Clayton 29.0_5	5	CHUNK	NA
Clayton 29.0_8 (1)	1	0.23	13.80
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

The results from each EFA test conducted on the Clayton formation may be found in **Appendix E**.

4.6.3 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 FIG. 4-21, 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 – 10 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.

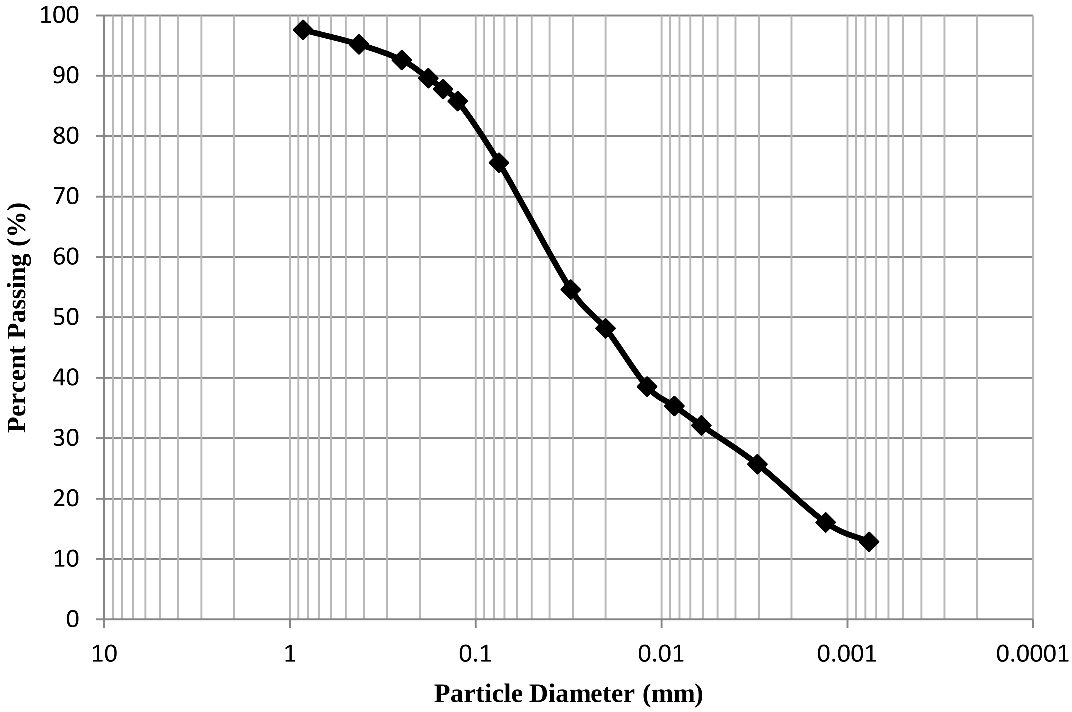

FIG. 4-21. Clayton Clay Grain Size Distribution.

4.7 Bucatunna Clay

Bucatunna clay was previously tested by Walker (2013). Walker conducted tests to determine geotechnical parameters and used the updated EFA to establish erosion properties for the clay formation. Because the material sampled in 2012 was extremely limited, additional drilling was necessary in order to perform further testing of the formation; however ALDOT drillings conducted in August of 2013 were unsuccessful in acquiring a testable section of Bucatunna clay. Therefore, testing would have to proceed with the limited material remaining from the 2012 drillings.

4.7.1 Sampling

On August 8, 2013, ALDOT attempted to drill for Bucatunna on County. Rd. 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 3.34 meters below ground surface. The SPT test performed by the ALDOT drill crew resulted in an N value of 6 blows. (Walker 2013) The samples tested were at a depth of approximately 26.0 feet.

4.7.2 EFA Testing

Three critical velocity tests were performed on Bucatunna clay material. The first two tests both resulted in minor critical velocities of 0.70 m/s and no major critical velocity was determined in order to conserve testable material. The final critical velocity test resulted in a minor critical velocity of 0.50 m/s and extensive soil was being lost at a velocity of approximately 1.20 m/s. Table 4-22 presents the summary of critical velocity tests performed on the Bucatunna formation.

Table 4-22. Critical Velocity Summary for Bucatunna Clay.

Test No.	Critical Velocity	
	Minor (m/s)	Major (m/s)
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 minor critical velocities shown in Table 4-22, the Bucatunna clay was not tested at the 0.3 m/s velocity increment.

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 velocity increments. Table 4-23 shows the results of the single test performed at 0.6 m/s.

Table 4-23. Bucatunna Clay Results at 0.6 m/s.

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

One test, titled “Bucatunna 26.0_2”, was performed at the 1.0 m/s velocity increment. 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 4-24 shows the results from this test.

Table 4-24. Bucatunna Clay Results at 1.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Bucatunna 26.0_2(1)	1	0.09	5.40
Bucatunna 26.0_2(2)	27	CHUNK	NA

At this point during the testing the amount of testable material remaining was extremely limited. Therefore, the 1.5 m/s testing increment 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 FIG. 4-22 and FIG. 4-23. Table 4-25 presents the results of the 2.0 m/s EFA test.

Table 4-25. Bucatunna Clay Results at 2.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Bucatunna26.0_3(1)	1	0.15	9.00
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

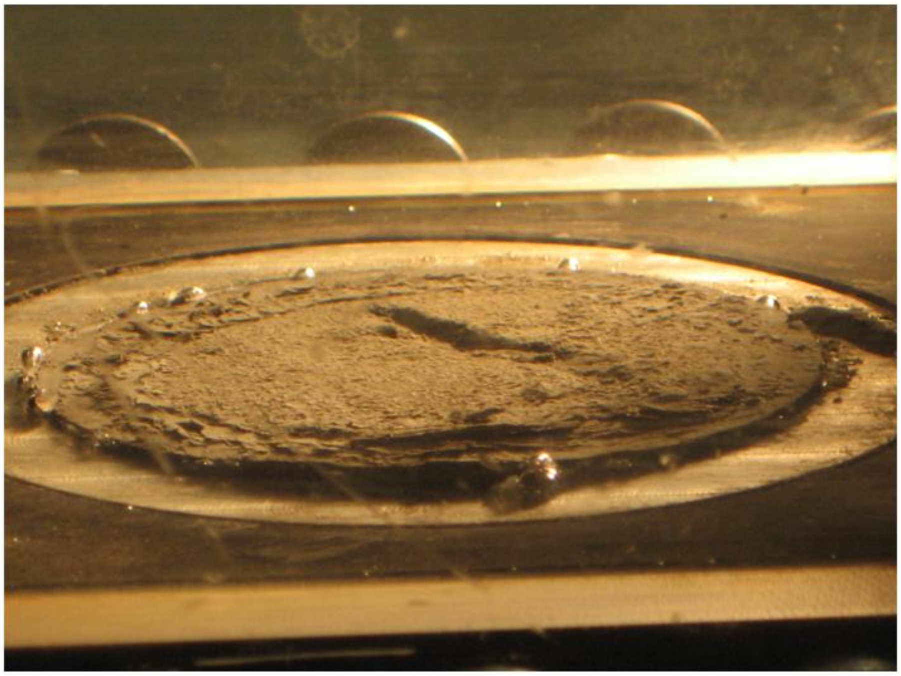

FIG. 4-22. "Bucatunna 26.0_3" Sample Approximately 3 Minutes into 3.0 m/s EFA Test

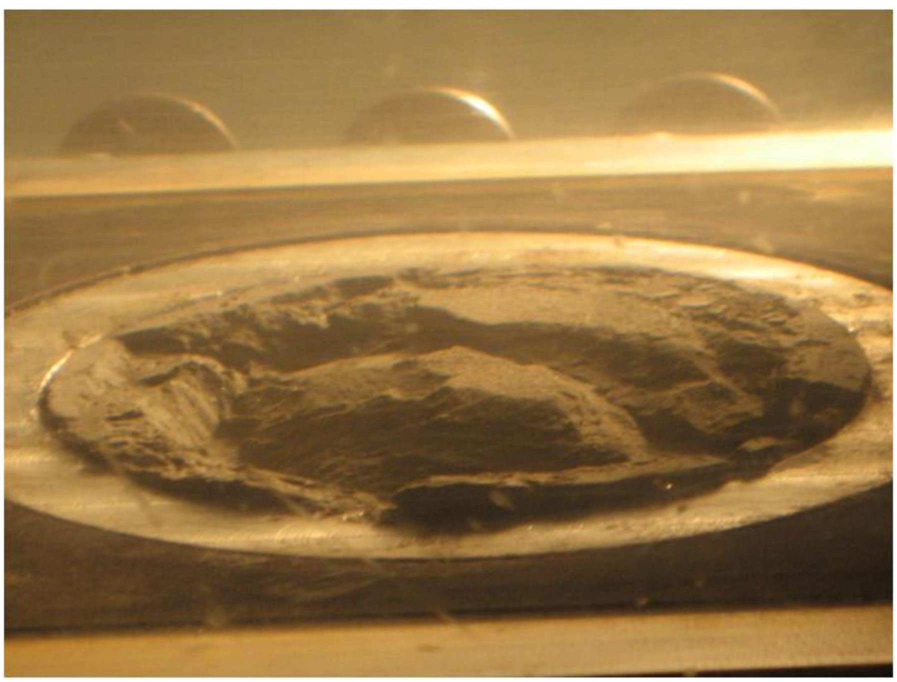

FIG. 4-23. "Bucatunna 26.0_3" Sample Approximately 15 Minutes into 3.0 m/s EFA Test.

The one 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. The results from each EFA test conducted on the Bucatunna formation may be found in **Appendix F**.

4.7.3 Geotechnical Testing

An average insitu moisture content of 47.9% for the Bucatunna clay was determined according to ASTM D2216 – 10 standards. A full grain size analysis, shown in FIG. 4-24, 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 65 percent. The mean grain size diameter of the material was 0.033 mm. Atterberg limit testing was performed according to ASTM D4318 – 10 standards. The tests resulted in average values for liquid limit of 68, plastic limit of 39, and a plasticity index of 29. As previously stated, the SPT test performed by ALDOT resulted in an N value of 6 blows. (Walker 2013)

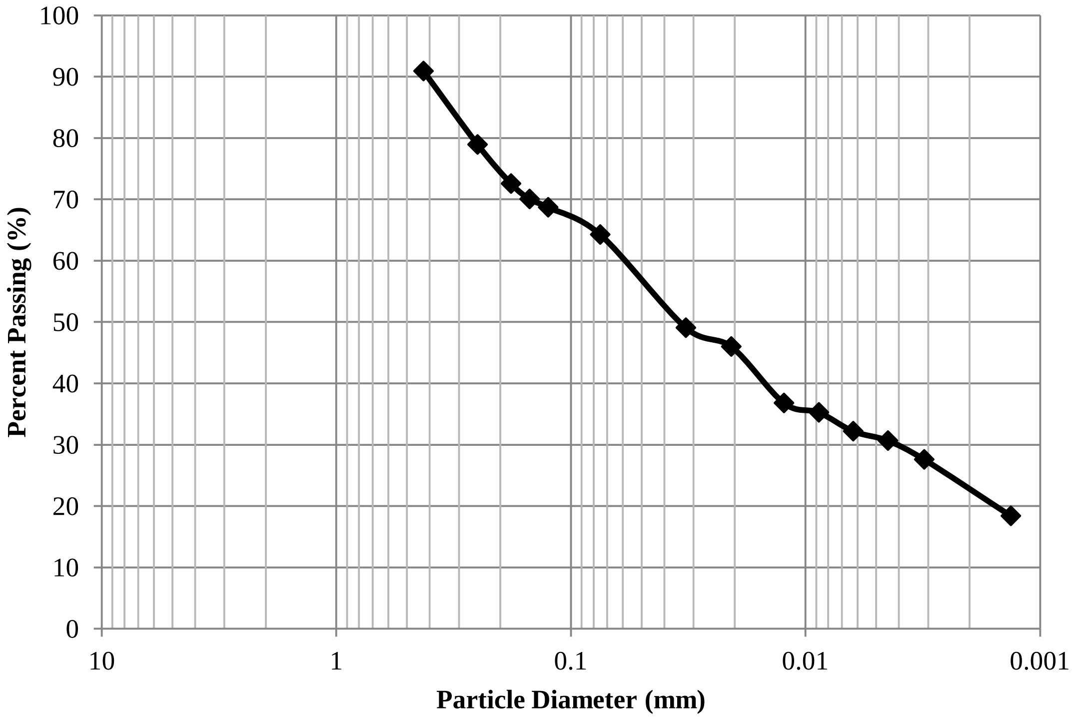

FIG. 4-24. Bucatunna Clay Grain Size Distribution (from Walker 2013).

4.8 Porter's Creek Clay

Porter's Creek clay was previously tested by Walker (2013). Walker conducted tests to determine geotechnical parameters and used the updated EFA to establish erosion properties for the clay formation. Because the Porter's Creek material sampled in 2012 was depleted, additional drillings were conducted to acquire samples to be used to conduct supplementary EFA tests on the formation.

4.8.1 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 (Walker 2013). 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 13blows. Roughly one foot of the recovered sample was considered testable. The 12" section used in testing was located at a depth of approximately 24.0 to 25.0 feet below the ground surface.

4.8.2 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 4-26 shows a summary of critical velocity tests performed on the Porter's Creek formation.

Table 4-26. Critical Velocity Summary for Porter's Creek Clay.

Test No.	Critical Velocity	
	Minor (m/s)	Major (m/s)
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 minor critical velocities were relatively close to 0.3 m/s, testing began at the 0.3 m/s velocity increment.

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 "Porters Creek 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 “Porters Creek24.0_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. FIG. 4-25 and FIG. 4-26 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 “Porters Creek24.5_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 (Porters Creek24.5_1(2)) may have been negated by severe swelling, thus resulting in a conservative scour rate. In the third test, titled “Porters Creek24.5_5”, no scour was observed but the sample swelled an astounding 3.1 mm in 19 minutes. Table 4-27 shows the results of the 0.3 m/s EFA test.

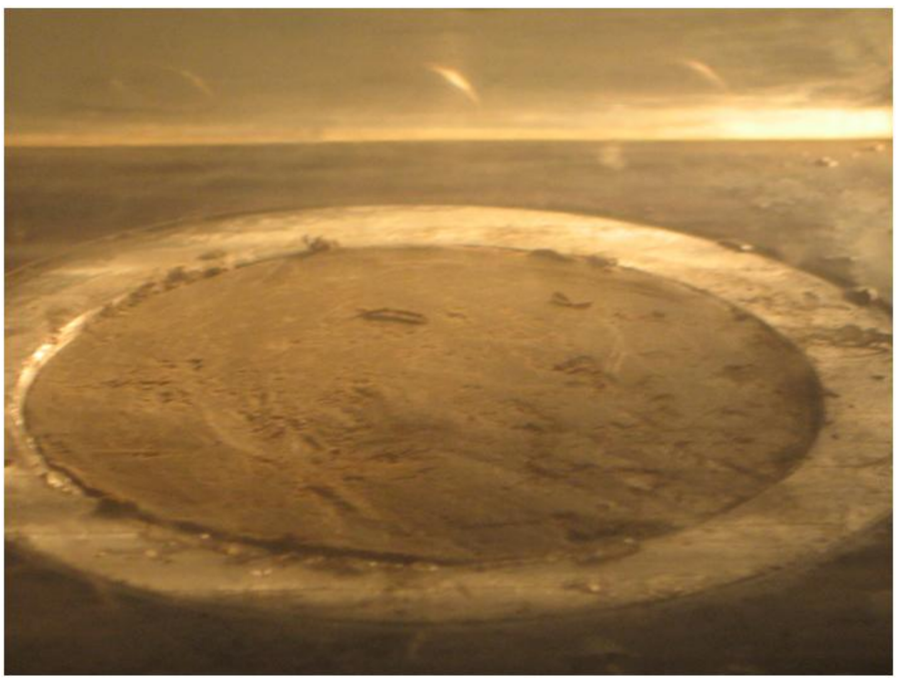

FIG. 4-25. "Porters Creek 24.0_4” Sample at Start of 0.3 m/s EFA test.

FIG. 4-26. "Porters Creek 24.0_4" Sample 15 minutes After Push.

Table 4-27. Porter's Creek Clay Results at 0.3 m/s.

Sample:	**Elapsed Time (min)**	**Soil Loss (mm)**	**Scour Rate (mm/hr)**
Porters Creek24.0_4(1)	4	0.30	4.50
Porters Creek24.0_4(2)	6	1.18	11.80
Porters Creek24.0_4(3)	22	CHUNK	NA
Porters Creek24.5_1(1)	2	0.71	21.30
Porters Creek24.5_1(2)	3	0.27	5.40
Porters Creek24.5_1(3)	10	2.69	16.14
Porters Creek24.5_5	22	0.00	0.00

Four EFA tests were run at the 0.6 m/s increment. In the first test, titled "Porters Creek24.0_1", the sample washed away before the velocity had reached 0.6 m/s. In the three subsequent tests, titled "Porters Creek24.5_2", "Porters Creek24.5_3", and "Porters Creek24.5_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 4-28 below.

Table 4-28. Porter's Creek Clay Results at 0.6 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Porters Creek24.0_1	0	WASH	NA
Porters Creek24.5_2	4	1.71	25.65
Porters Creek24.5_3	2	0.72	21.60
Porters Creek24.5_4	6	2.06	20.60

One test, titled "Porters Creek24.0_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 4-29 presents the results of the sole test performed at 1.0 m/s.

Table 4-29. Porter's Creek Clay Results at 1.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Porters Creek24.0_2(1)	3	1.09	21.80
Porters Creek24.0_2(2)	1	0.45	27.00
Porters Creek24.0_2(3)	8	CHUNK	NA

Although one test was performed at 1.5 m/s, titled "Porters Creek24.0_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. The results from each EFA test conducted on the Porter's Creek formation may be found in **Appendix G**.

4.8.3 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 FIG. 4-27, 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 – 10 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.

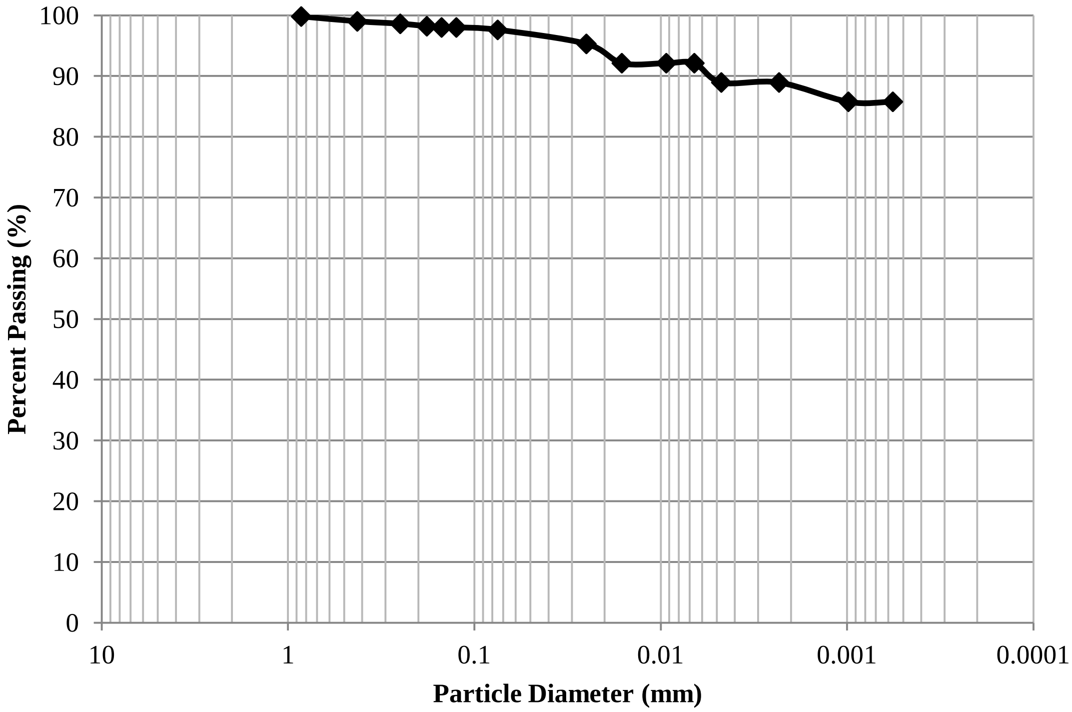

FIG. 4-27. Porter's Creek Clay Grain Size Distribution.

4.9 Yazoo Clay

Yazoo clay was previously tested by Walker (2013). Walker conducted tests to determine geotechnical parameters and used the updated EFA to establish erosion properties for the clay formation. The Yazoo material sampled in 2012 was used to conduct supplementary EFA tests on the formation.

4.9.1 Sampling

The Yazoo Clay was acquired on April 6, 2012 in Conecuh County, Alabama by and 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 4.11 meters below ground surface.

(Walker 2003) According to Walker, the SPT performed resulted in an N value of 15 blows. A 1.5 foot section, ranging from a depth of 21.0 feet to 22.5 feet, was used to perform EFA tests during this study.

4.9.2 EFA Testing

Three critical velocity tests were performed on the Yazoo clay samples. A minor and major critical velocity was 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 4-30 shows a summary of the critical velocity tests for the Yazoo clay formation.

Table 4-30. Critical Velocity Summary for Yazoo Clay.

Test No.	Critical Velocity	
	Minor (m/s)	Major (m/s)
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. When Walker (2013) conducted EFA tests on Yazoo clay the formation did not scour at 0.3 m/s. Therefore, the 0.3 m/s velocity increment was not tested in order to conserve the limited material remaining from the 2012 Yazoo sampling.

One 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 were to erode at 0.3 m/s.

Three tests were performed at the 1.0 m/s velocity increment. 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 4-31 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 we 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. FIG. 4-28 and FIG. 4-29 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 4-31 shows the results of this 1.0 m/s EFA test on the Yazoo material.

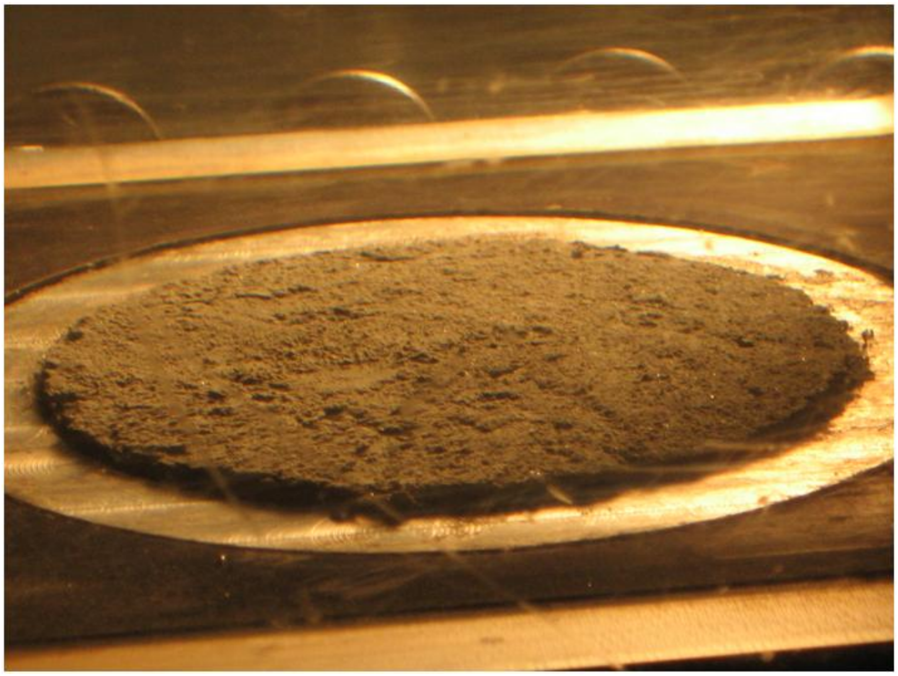

FIG. 4-28. "Yazoo21.0_4" Sample After Push.

FIG. 4-29. "Yazoo21.0_4" Sample Approximately 57 Minutes After Push.

Table 4-31. Yazoo Clay Results at 1.0 m/s.

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

Three tests were conducted at the 1.5 m/s velocity increment. 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 4-32 presents a summary of results from the 1.5 m/s velocity increment.

Table 4-32. Yazoo Clay Results at 1.5 m/s.

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

Four tests were performed at the 2.0 m/s increment. 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 4-33 shows the results from the 2.0 m/s EFA test on the Yazoo clay formation.

Table 4-33. Yazoo Clay Results at 2.0 m/s.

Sample:	Elapsed Time (min)	Soil Loss (mm)	Scour Rate (mm/hr)
Yazoo22.0_1(1)	1	0.1	6.00
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
Yazoo22.0_3(1)	3	0.34	6.80
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
Yazoo22.0_4(2)	5	0.46	5.52
Yazoo22.0_4(3)	19	CHUNK	NA

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 4-34 presents a summary of results from the 3.0 m/s velocity increment.

Table 4-34. Yazoo Clay Results at 3.0 m/s.

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

The results from each EFA test conducted on the Yazoo formation may be found in **Appendix H**.

4.9.3 Geotechnical Testing

An average insitu moisture content of 59.9% for the Yazoo clay was determined according to ASTM D2216 – 10 standards. A full grain size analysis, shown in FIG. 4-30, 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 44 percent. The mean grain size diameter of the material was 0.088 mm. Atterberg limit testing was performed according to ASTM D4318 – 10 standards. The tests resulted in a liquid limit value of 57. As previously stated, the SPT test performed by ALDOT resulted in an N value of 15 blows. (Walker 2013)

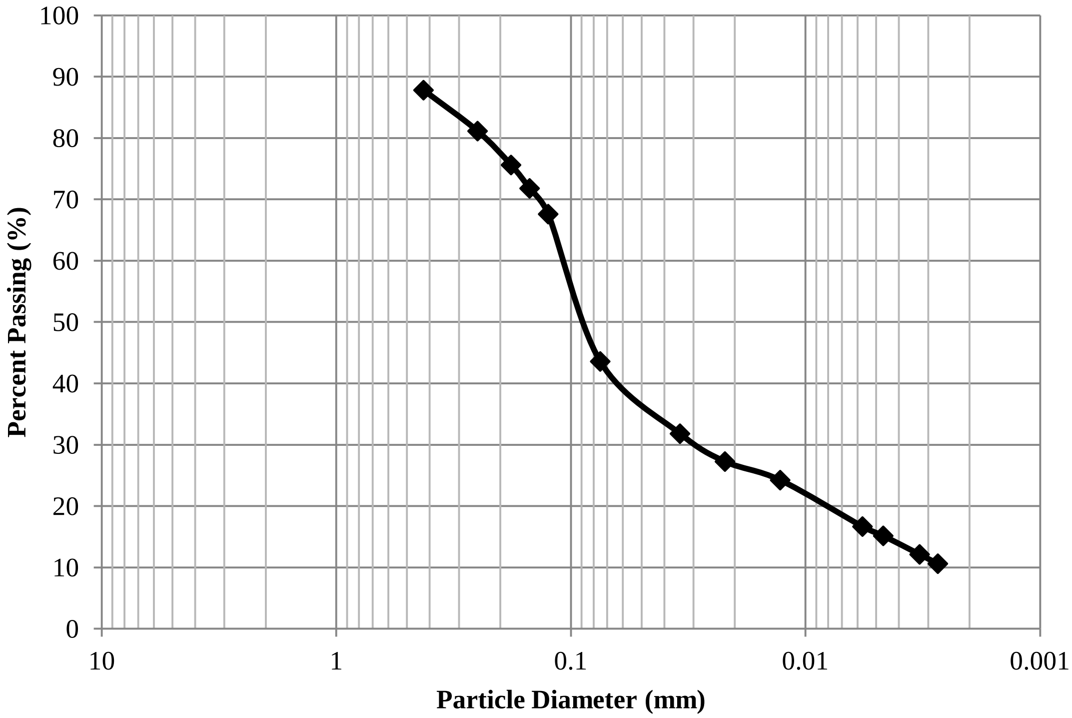

FIG. 4-30. Yazoo Clay Grain Size Distribution (from Walker 2013).

Chapter 5 – Discussion

5.1 EFA Testing Observations

A total of eight clay formations were tested in the study. This total includes the Naheola formation which was separated into three separate materials (Naheola – Yellow, Naheola – Dark, and Naheola – Re-drilled). Three formations tested by Walker (2013) were also tested in this study; however, only two of those formations (Bucatunna and Yazoo) were tested using the same material Walker used in testing. Because there was insufficient Porter's Creek material remaining after Walker's study, the tests conducted on the Porter's Creek formation were performed using samples taken in 2013.

All formations scoured at a velocity of 1.5 m/s and greater. Average minor critical velocities ranged between 0.30 m/s and 1.60 m/s. The Porter's Creek formation produced the lowest minor critical velocity, with an average value of 0.32 m/s, while the largest minor critical velocity was observed in the Re-drilled Naheola clay material, having an average value of 1.55 m/s. The Nanafalia, Naheola – Dark, Clayton, Bucatunna, and Yazoo formations had very similar minor critical velocities, ranging between 0.63 and 0.71 m/s. The Naheola – Yellow formation had a relatively lower critical velocity of 0.46 m/s. With the exception of the Porter's Creek formation, the critical velocities determined in this study were considerably higher than those found by Walker. The Yazoo clay had an average critical velocity of 0.67 m/s, while Walker found this value to be 0.4 m/s. Likewise, the Bucatunna critical velocity was determined to be 0.63 m/s, though Walker observed minor scour occurring at 0.45 m/s. The respective values for the minor critical velocity of Porter's Creek clay matched reasonably well. The average critical velocity for this material was determined to be 0.32 m/s and Walker found this value to be approximately 0.4 m/s.

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 median erosion rate at this velocity was determined to be 8.6 mm/hour, though rates as high as 21.3 mm/hr were observed. The dark Naheola formation seemed to be the most scour resistant, as it was the only material not to scour at velocities below 1.5 m/s and had a scour rate of merely 2.0 mm/hr at this velocity. The largest scour rate observed was 79.8 mm/hr 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 **Chapter 4**, this "Naheola Clay19.5_5" sample may be considered as a "chunk" scour, due to the sample being lost in large chunks over a very short period of time. With that said, the re-drilled Naheola material was considerably scour resistant when excluding this outlying value. A scatterplot of the erosion rates versus velocity for all the tested materials is shown in FIG. 5-1. As previously mentioned, the Porter's Creek material appeared to be considerably more scourable than the other formations.

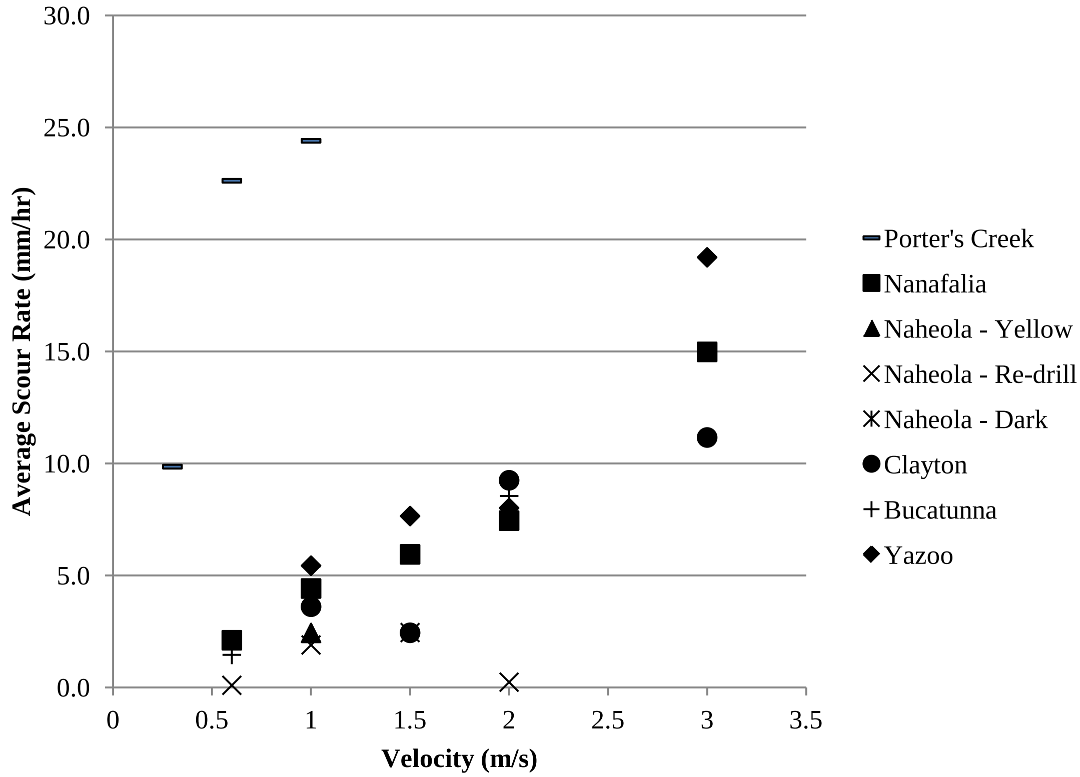

FIG. 5-1. Scour Rate versus Velocity for All Tested Materials.

The results for Bucatunna corresponded well between the two studies. Because testable Bucatunna material was limited for this study, there were only three velocities tested. However, the data still managed to be appreciably correlated. A plot with the results from both studies is shown in FIG. 5-2.

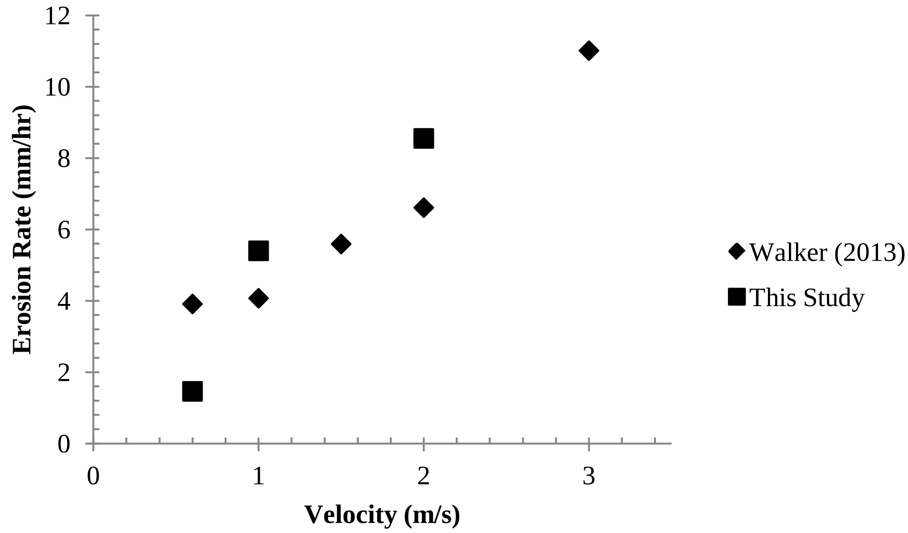

FIG. 5-2. Comparison of Bucatunna Clay Results.

Walker experienced much difficulty in testing the Yazoo clay formation. Walker stated that EFA testing was eventually suspended due to extremely high variability in results. Thus said, Walker tested just three velocities and those velocities produced extremely inconsistent data. FIG. 5-3 shows the Yazoo results for both studies.

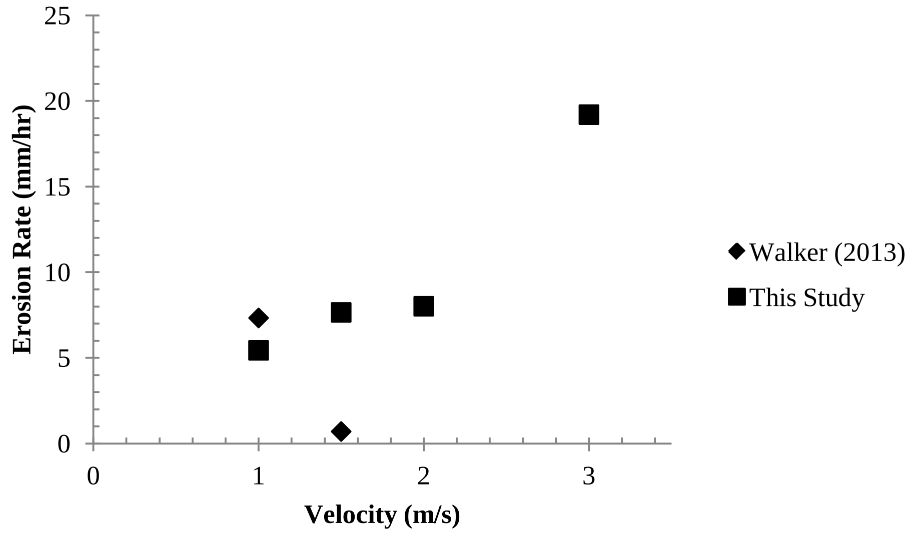

FIG. 5-3. Comparison of Yazoo Clay Results.

Though each study individually produced strongly correlated data for Porter's Creek, the scour rates experienced in this study were significantly higher than those of Walker's. This may be attributed to testing samples that were taken at different times and locations. Walker tested the Porter's Creek material up to a velocity of 3.0 m/s, while in this study it was impossible to keep the sample intact at velocities greater than 1.0 m/s. Results for both studies are shown in FIG. 5-4.

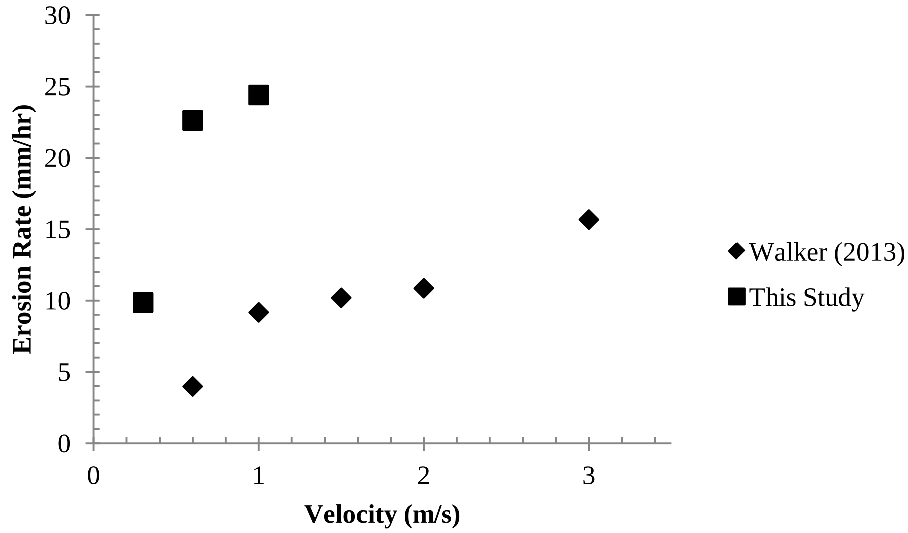

FIG. 5-4. Comparison of Porter's Creek Clay Results.

5.2 Sample Swelling

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 **Chapter 4** 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 FIG. 5-5. Photographs corresponding to points 1 through 5 are shown in FIG. 5-6.

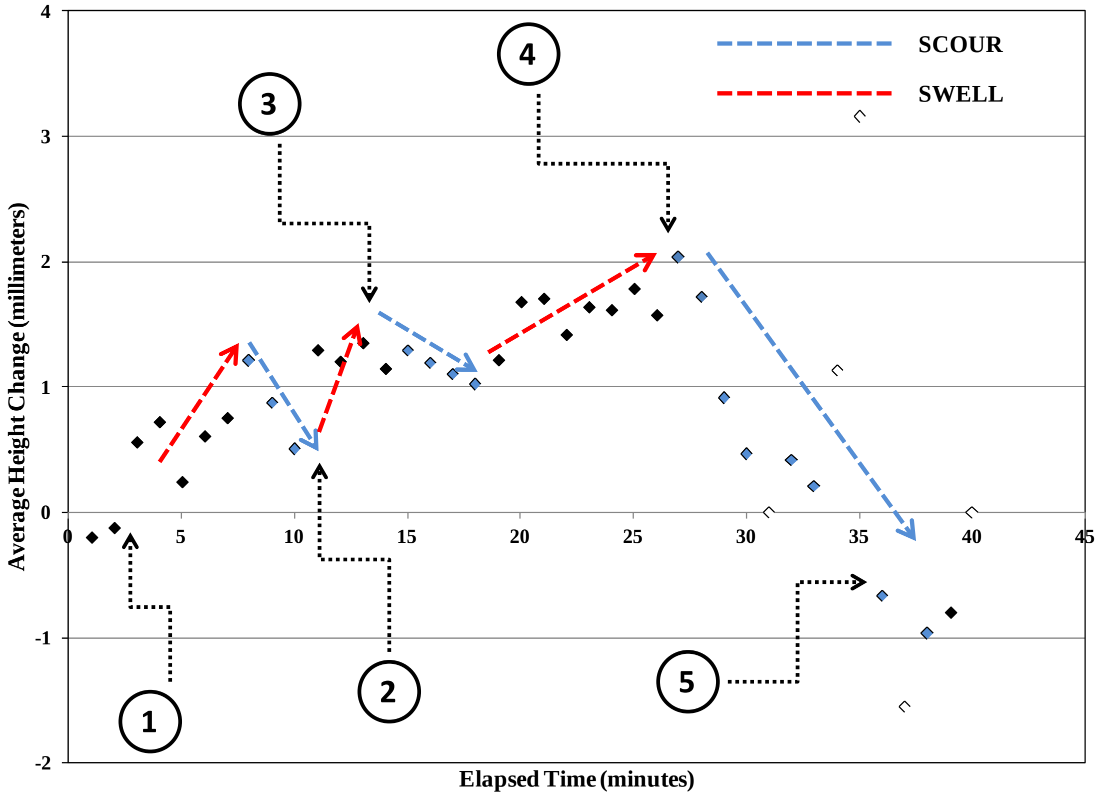

FIG. 5-5. "Scour-Swell" Pattern from "Porters Creek 24.5_1" EFA Test.

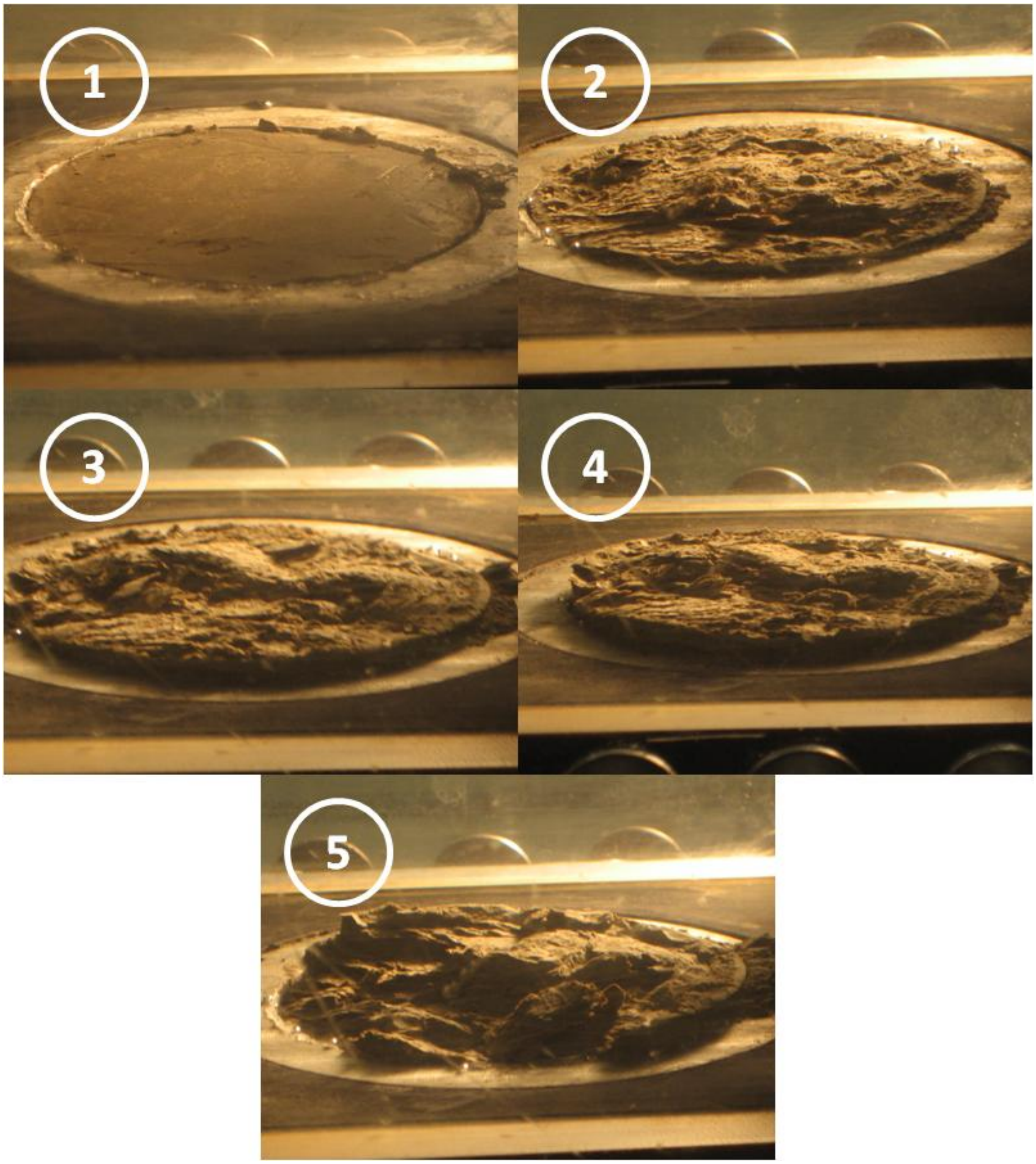

FIG. 5-6. Photographs Taken at Critical Points During "Porters Creek 24.5_1" EFA Test.

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.

5.3 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 a part of this study, Fang and Chen (2013) performed analyses 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 (5-1):

$$\tau = \rho f V^2/8 \tag{5-1}$$

Where:

ρ = Density of water

V = Flow velocity

The fiction factor (f) was computed using Equation (5-2) presented by Crowe et al. (2009) [after Swamee and Jain (1976)].

$$f = \frac{0.25}{[log_{10}(\frac{k_S}{3.7D}+\frac{5.74}{Re^{0.9}})]^2} \tag{5-2}$$

Where:

k_s = Roughness

D = Equivalent diameter

Re = Reynolds's number

Supplementary to the EFA test results from this study, Fang and Chen included EFA results from Walker (2013) in the construction of the erosion functions. This was done to allow for a larger sample size, in an effort to provide scour parameters indicative of a formation with less variance. FIG. 5-7 through FIG. 5-20 are the erosion functions determined by Fang and Chen (2013). The regression equations shown contain variables for erosion rate (Erate), velocity (Vel), and shear stress (τ). The erosion rates were plotted, with vertical lines of plus and minus one standard deviation, at each velocity increment tested. It should be noted that Fang and Chen included the re-drilled Naheola sample as a part of the dark Naheola sample in their analyses.

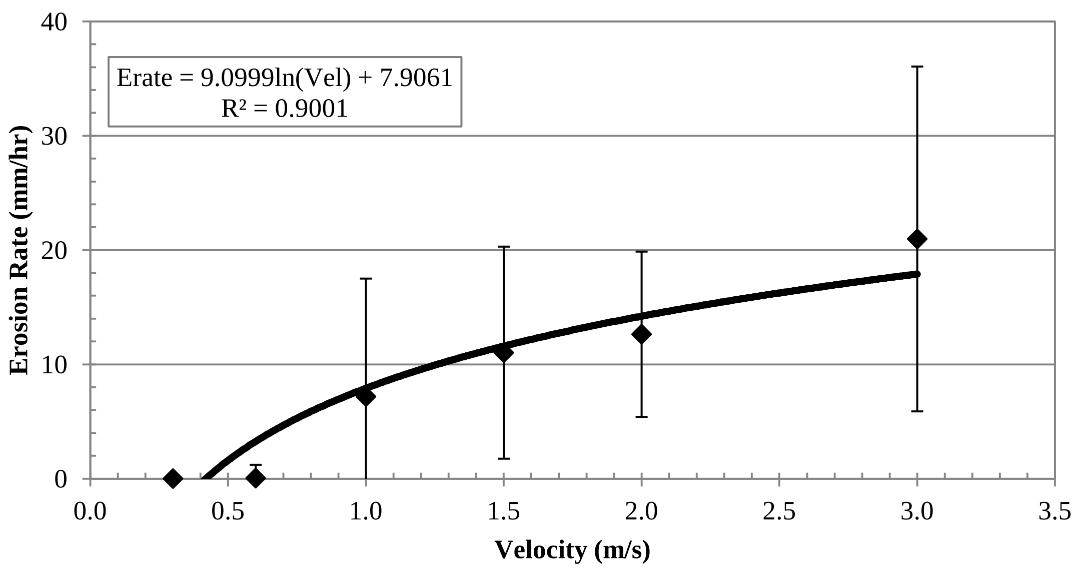

FIG. 5-7. Velocity-based Erosion Function for Nanafalia Clay (Fang and Chen 2013).

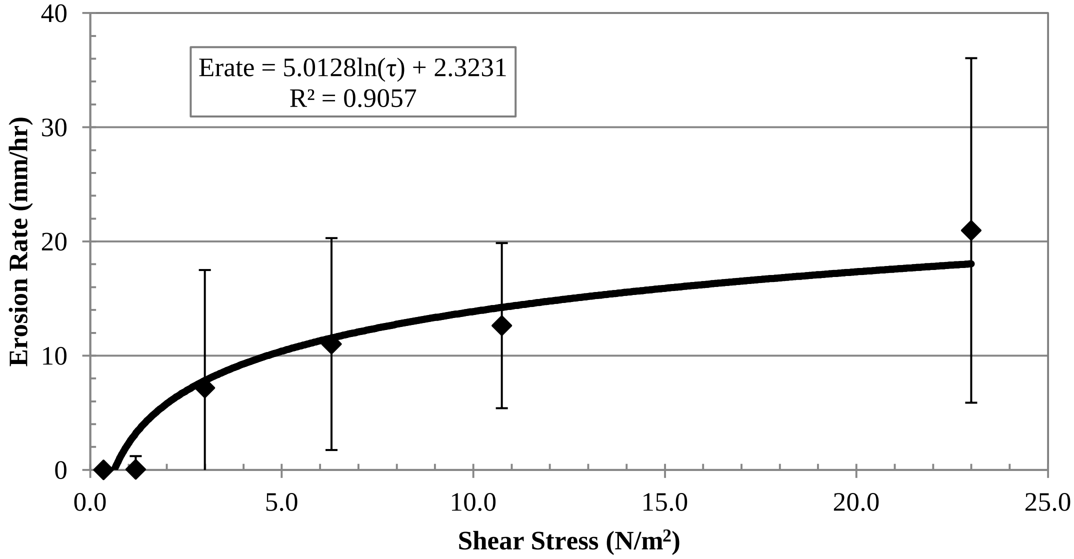

FIG. 5-8. Shear Stress-based Erosion Function for Nanafalia Clay (Fang and Chen 2013).

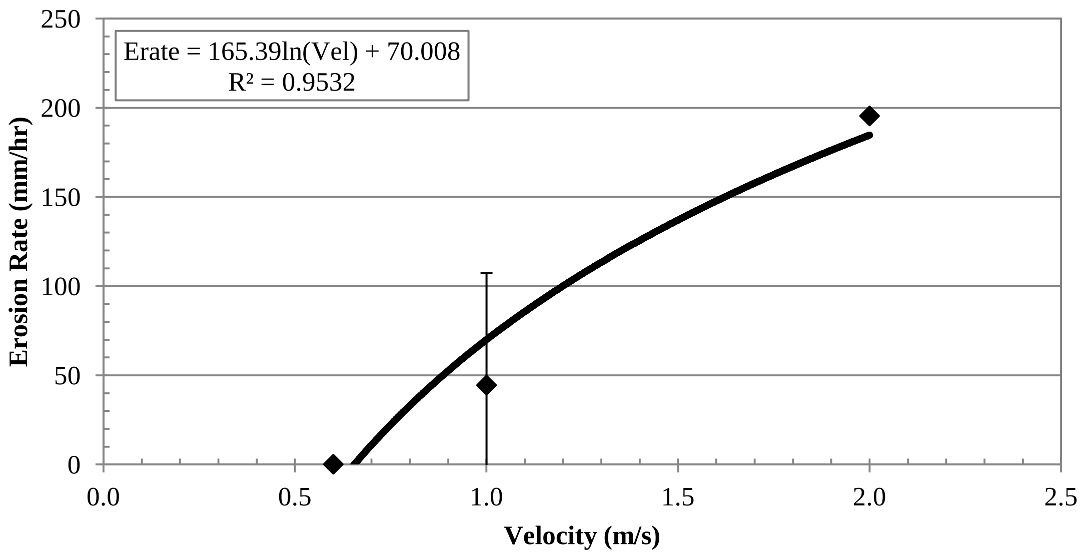

FIG. 5-9. Velocity-based Erosion Function for Yellow Naheola Clay (Fang and Chen 2013).

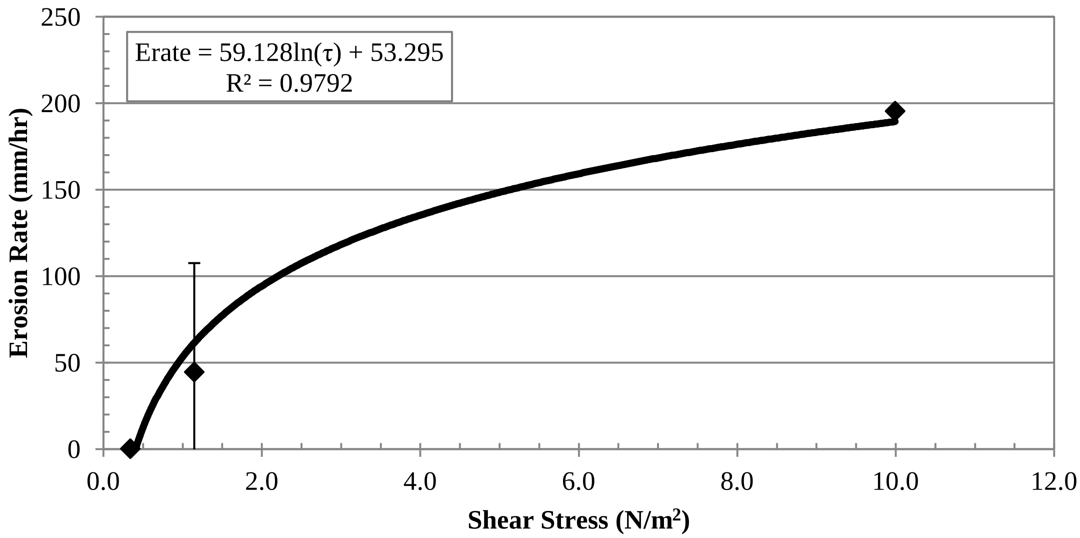

FIG. 5-10. Shear Stress-based Erosion Function for Yellow Naheola Clay (Fang and Chen 2013).

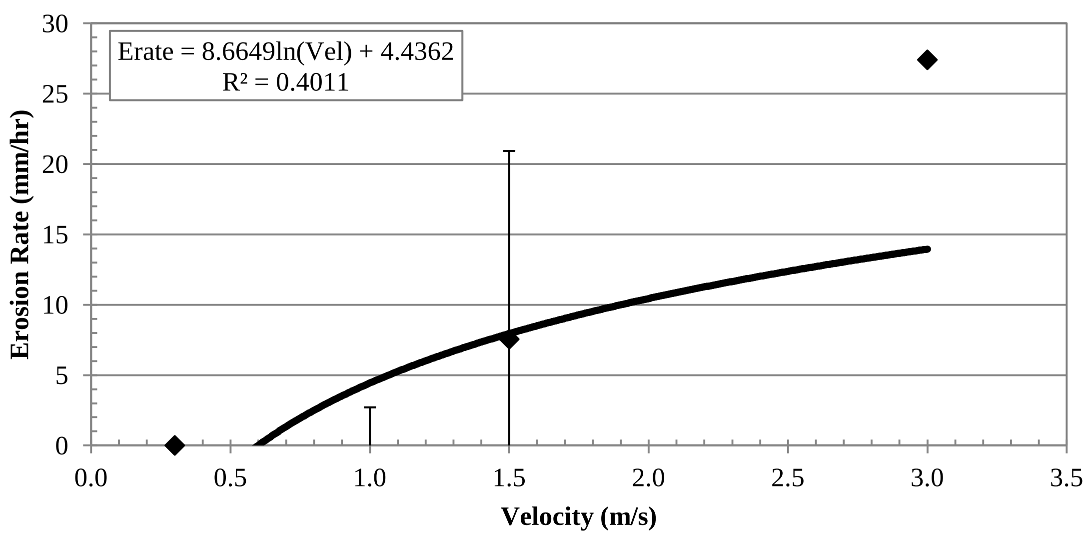

FIG. 5-11. Velocity-based Erosion Function for Dark Naheola Clay (Fang and Chen 2013).

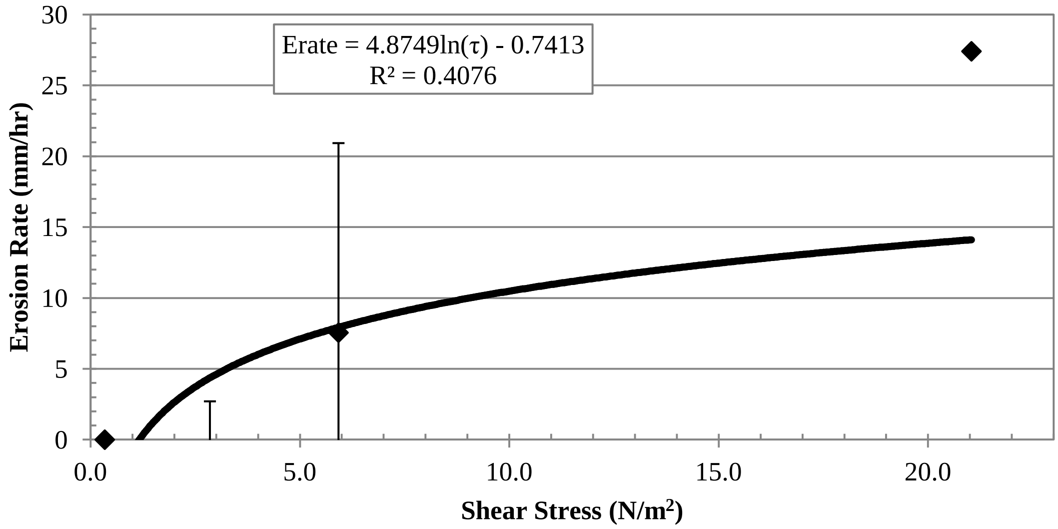

FIG. 5-12. Shear Stress-based Erosion Function for Dark Naheola Clay (Fang and Chen 2013).

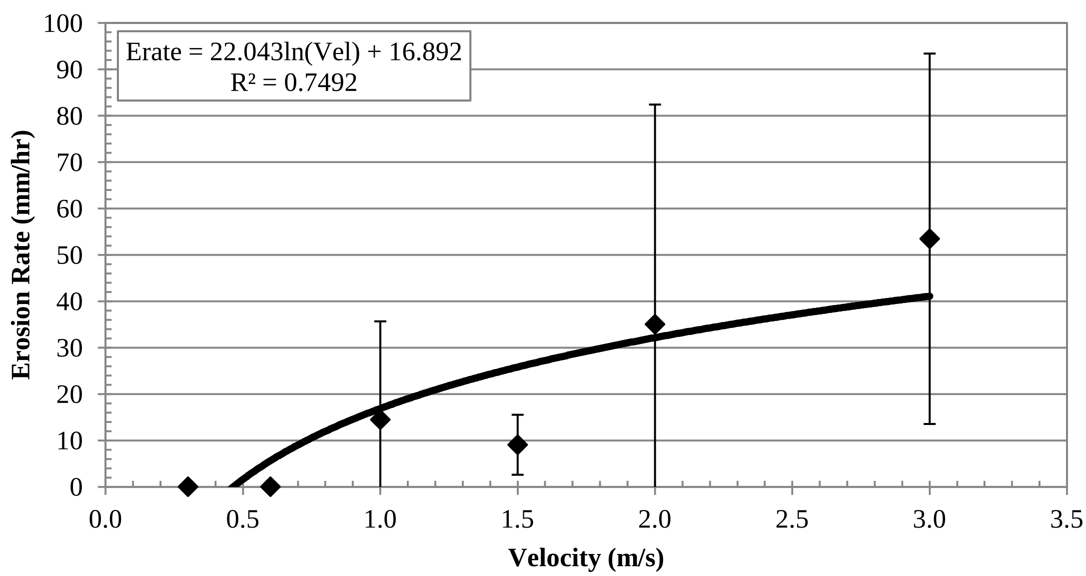

FIG. 5-13. Velocity-based Erosion Function for Clayton Clay (Fang and Chen 2013).

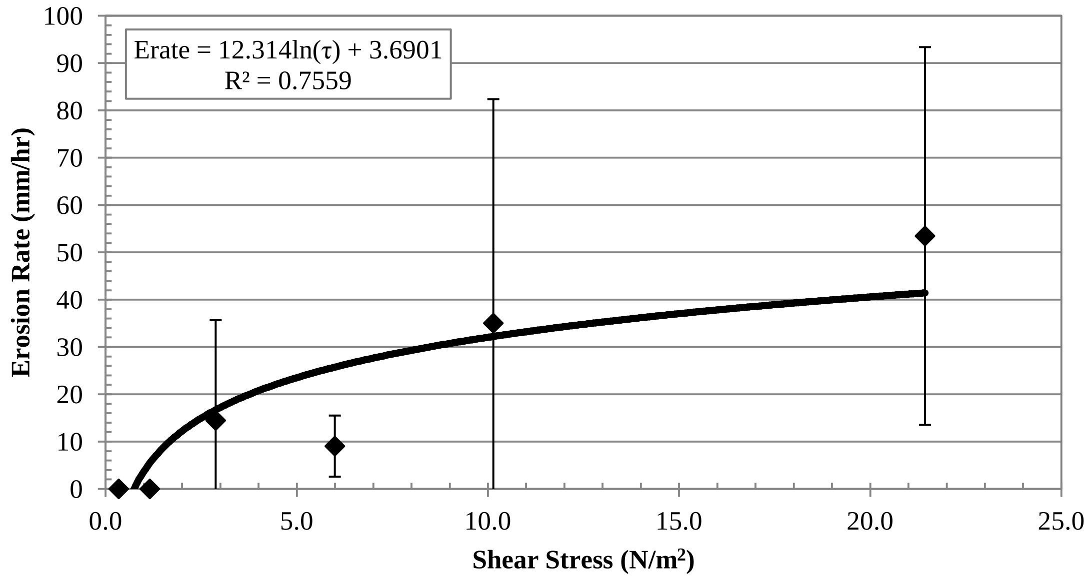

FIG. 5-14. Shear Stress-based Erosion Function for Clayton Clay (Fang and Chen 2013).

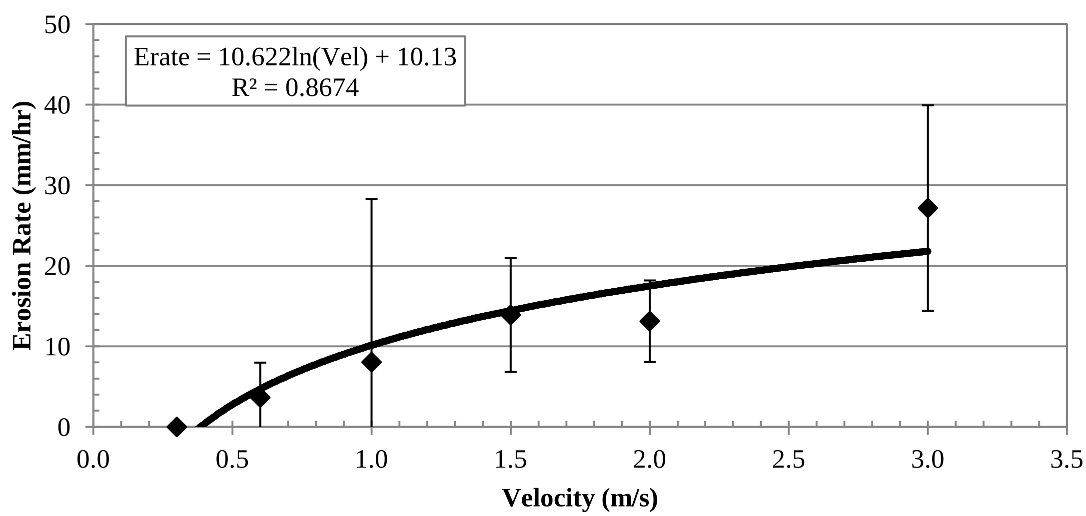

FIG. 5-15. Velocity-based Erosion Function for Bucatunna Clay (Fang and Chen 2013).

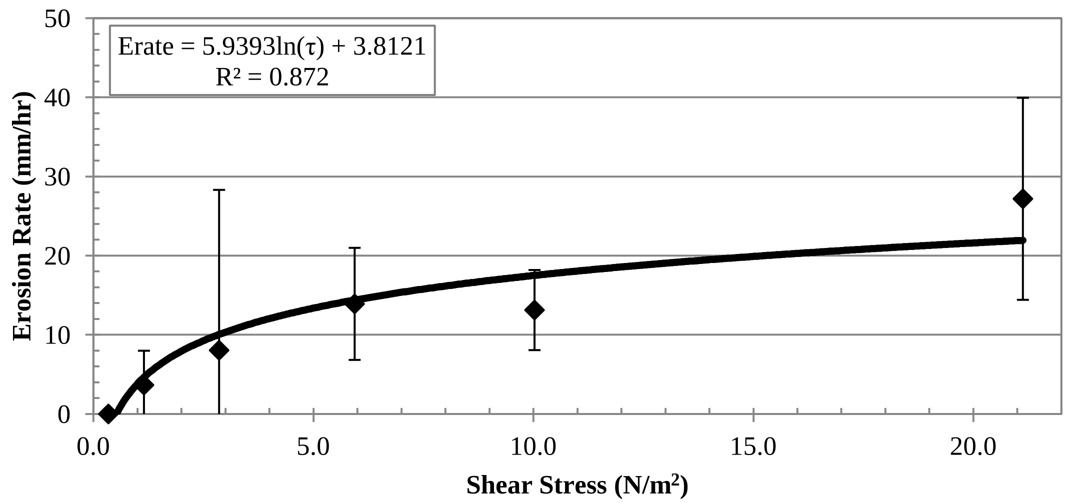

FIG. 5-16. Shear Stress-based Erosion Function for Bucatunna Clay (Fang and Chen 2013).

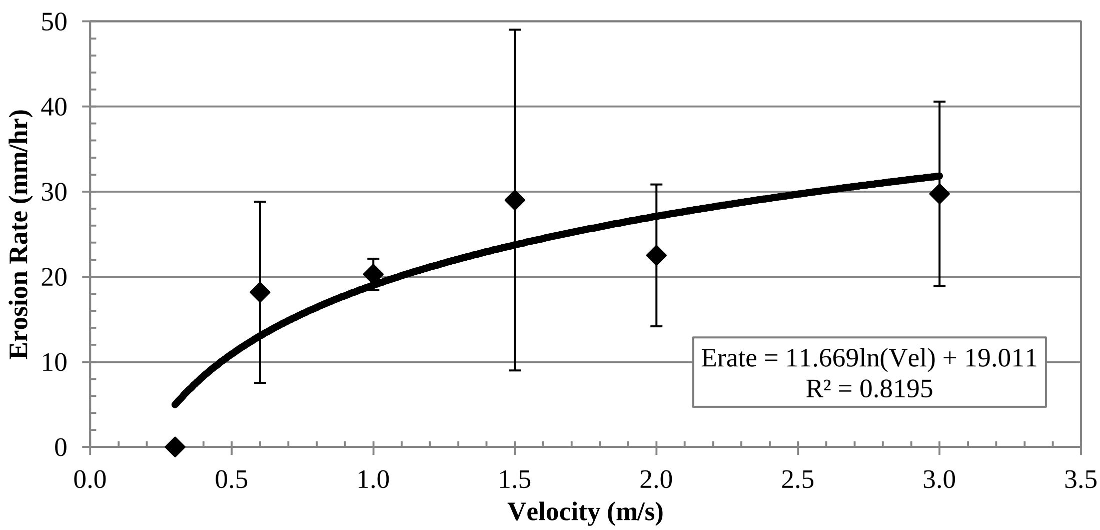

FIG. 5-17. Velocity-based Erosion Function for Porter's Creek Clay (Fang and Chen 2013).

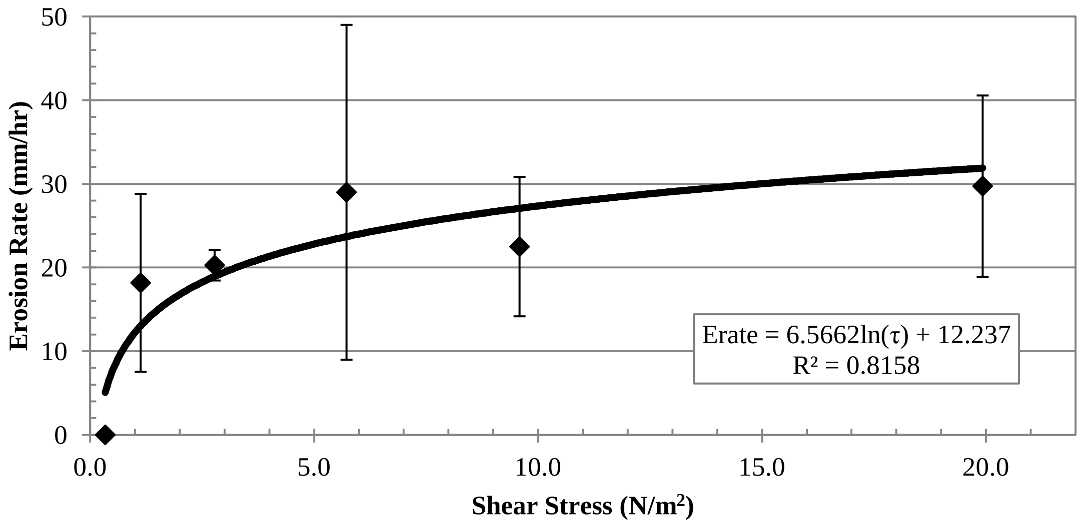

FIG. 5-18. Shear Stress-based Erosion Function for Porter's Creek Clay (Fang and Chen 2013).

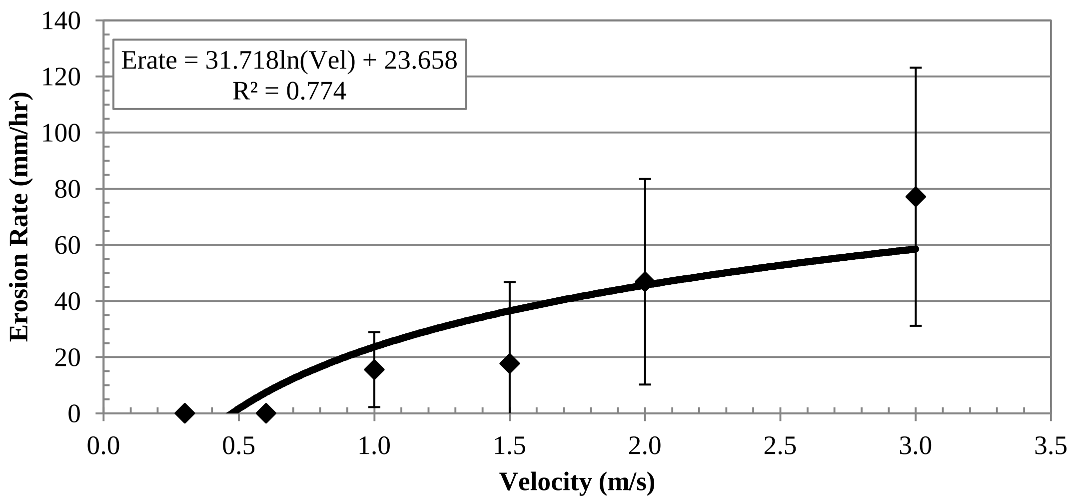

FIG. 5-19. Velocity-based Erosion Function for Yazoo Clay (Fang and Chen 2013).

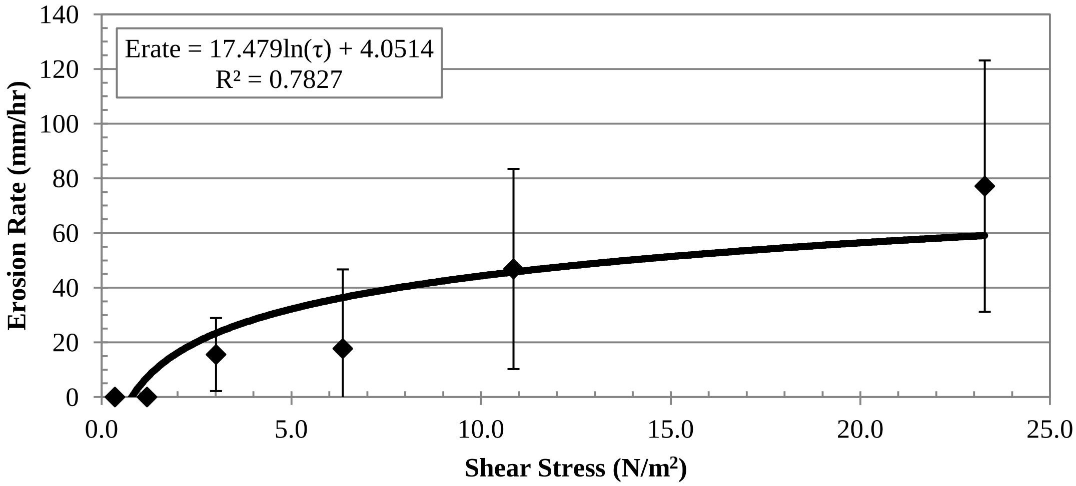

FIG. 5-20. Shear Stress-based Erosion Function for Yazoo Clay (Fang and Chen 2013).

As presented in **Chapter 4**, the critical velocities of the various materials were determined visually during the EFA tests. The critical velocities that Fang and Chen determined from the scour functions are shown in Table 5-1, as well as initial erosion rate and critical shear stress for the respective materials. 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 this critical velocity. The initial erosion rate is based on the tangent-slope of the erosion curve at the critical shear stress. The results correspond to the conclusions of Strum et al. (2008) shown in FIG. 2-2. Each of the tested formations fell significantly below the shear stress threshold (1.99 N/m^2) where Strum found soils to be erodible. The most erodible sample, Porter's Creek, fell into the range Strum classified soils as being "very erodible".

Table 5-1. Summary of Critical Velocity, Critical Shear Stress, and Initial Erosion Rate.

Soil Type	Critical Velocity (m/s)	Critical Shear Stress (N/m^2)	Initial Erosion Rate (mm/hr)
Nanafalia	0.42	0.63	7.97
Naheola - Yellow	0.65	0.41	145.63
Naheola - Dark	0.59	1.15	4.23
Clayton	0.47	0.74	16.62
Bucatunna	0.39	0.53	11.29
Porter's Creek	0.2	0.15	42.33
Yazoo	0.47	0.79	22.04

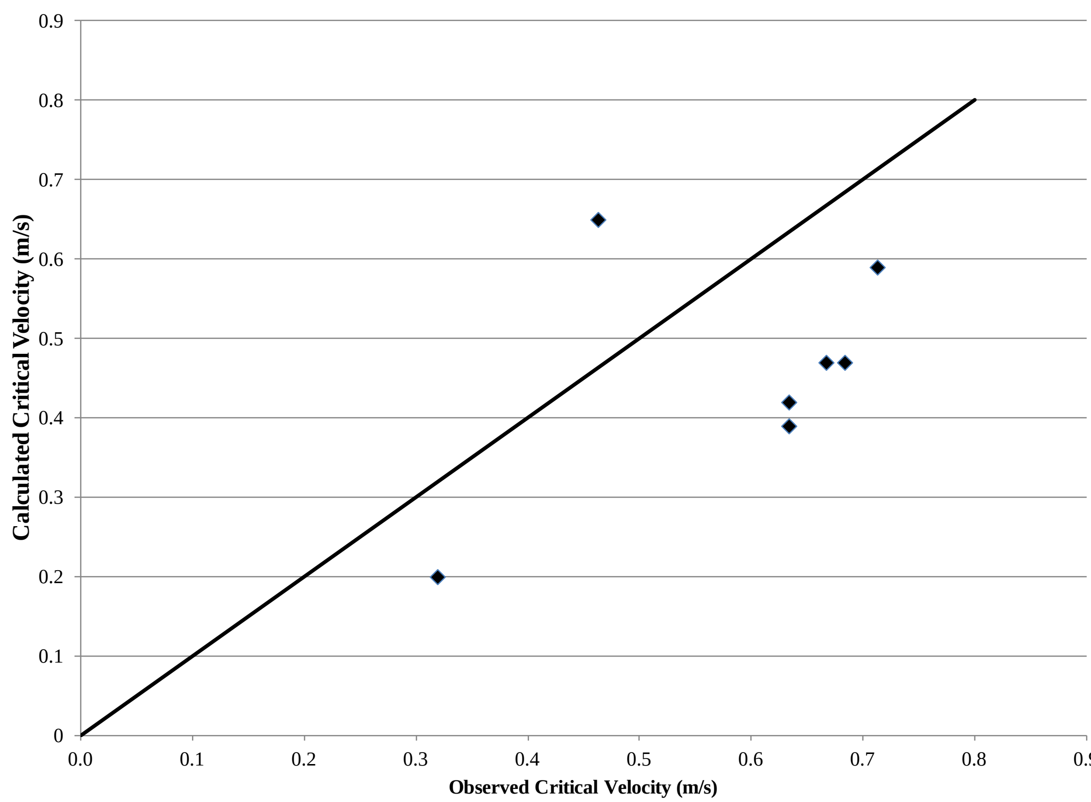

FIG. 5-21. Comparison between Observed and Calculated Critical Velocity.

FIG. 5-21 shows the critical velocities calculated by Fang and Chen (2013) compared to the 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 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.

5.4 Geotechnical and Scour Parameter Correlations

The data was synthesized in include results from Walker (2013), Mobley (2009), and Crim (2003). This produced a total of 14 soils that were analyzed for correlations between scour and geotechnical parameters. Three of these materials, all of which were tested by Walker, did not scour at velocities 3.0 m/s and lower. The 11 remaining soils were each scourable. Numerous trends were seen in the data, the majority of which corresponded with those seen by Walker (2013).

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. FIG. 5-22 shows a plot of scourability as it relates to SPT N value and insitu moisture content.

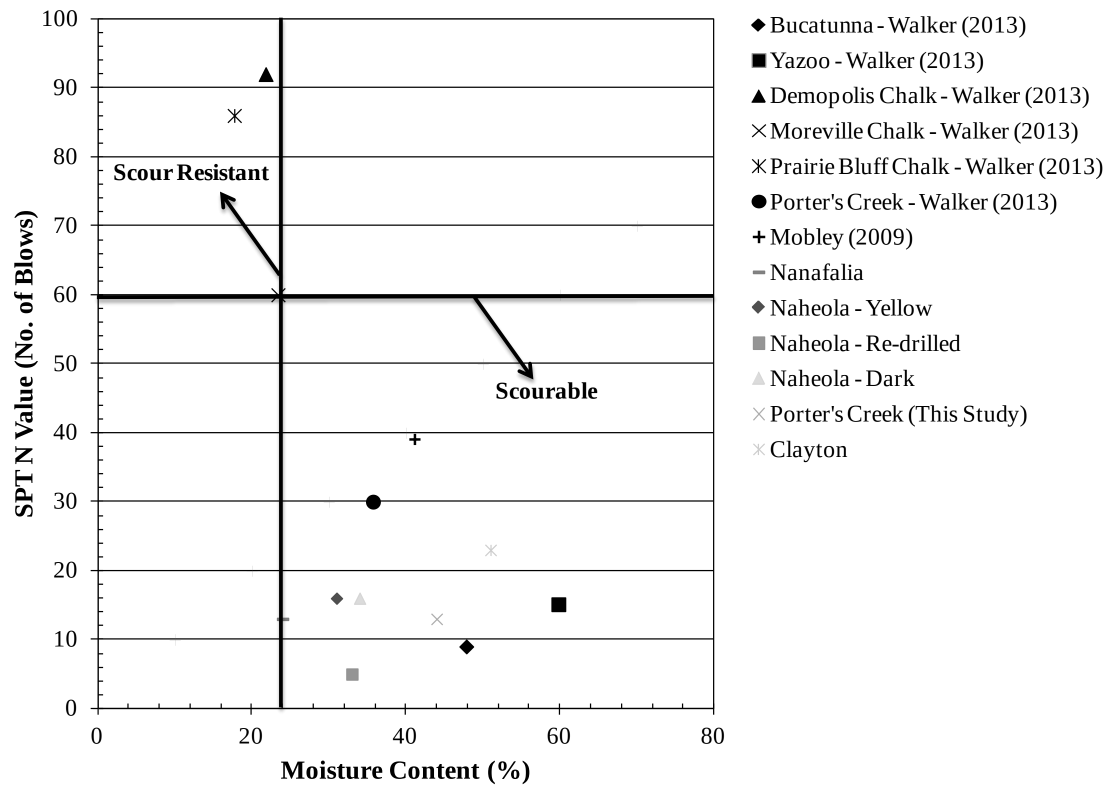

FIG. 5-22. Scourability versus SPT N Value and Moisture Content.

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. FIG. 5-23 shows a plot of scourability as it relates to SPT N value and fines percentage.

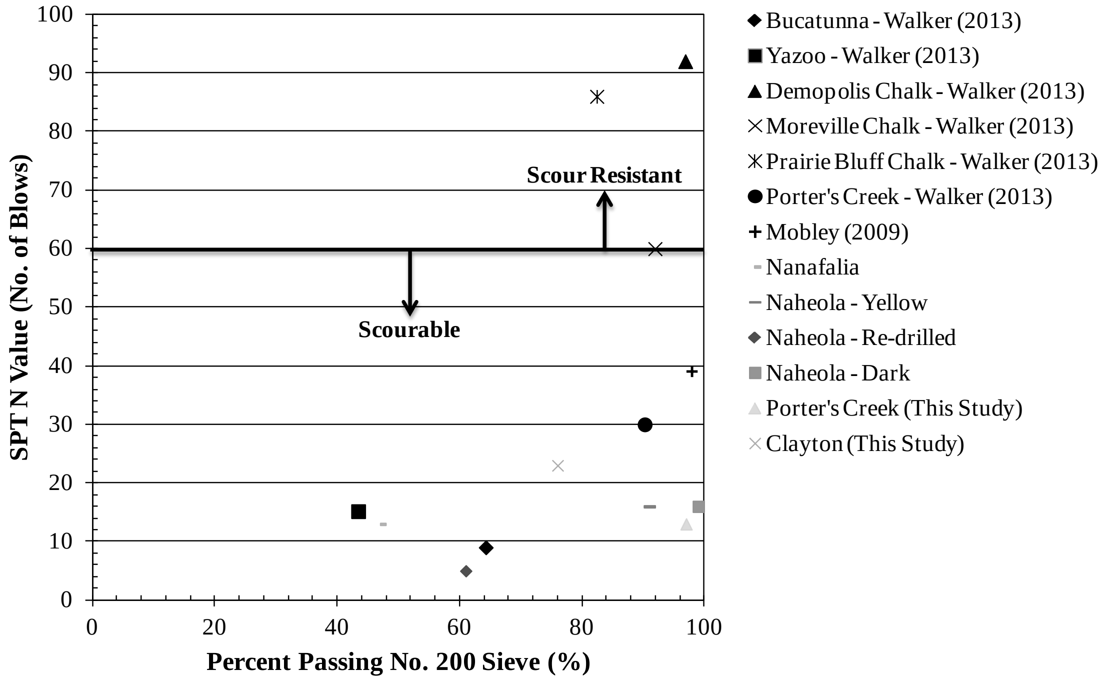

FIG. 5-23. Scourability versus SPT N Value and Percent Passing the No. 200 Sieve.

Walker 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. FIG. 5-24 shows a plot of scourability as it relates to SPT N value and mean grain size diameter.

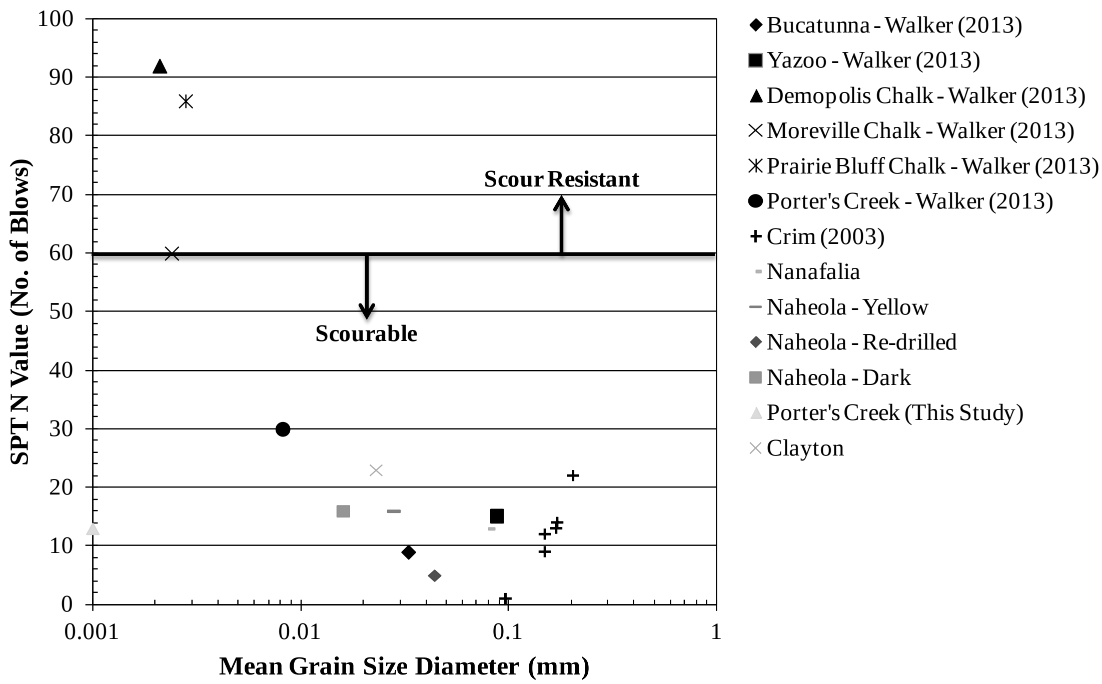

FIG. 5-24. Scourability versus SPT N Value and Mean Grain Size.

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 numerous 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 6 – Summary, Conclusions, and Recommendations

6.1 Summary

Predicting the scour magnitude of soil adjacent to bridge piers is a critical element in the bridge design. An appropriate estimation requires determining accurate scour parameters that are unique to the riverbed soil. Although there are numerous methods for estimating scour in cohesionless soils, methods for calculating scour in cohesive soil are limited. By conducting scour tests on multiple soil formations found throughout southern Alabama using an Erosion Function Apparatus, correlations between scourability and some conventional geotechnical parameters were established. These correlations were compared to trends seen in previous studies at Auburn University by Crim (2003), Mobley (2009), and Walker (2013). Sampling was performed by the Alabama Department of Transportation using a Central Mining Equipment continuous sample tube system.

Six different clay formations were tested in the study. These formations include: Nanafalia Clay, Naheola Clay, Porter's Creek Clay, Clayton Clay, Bucatunna Clay, and Yazoo Clay. Because of a distinct difference in appearance, the Naheola formation was divided and tested as two separate materials: Naheola (Yellow) and Naheola (Dark). Additional sample of Naheola, drilled at a different time and location, was also tested. Three formations tested by Walker (2013) were also tested in this study. These formations include Bucatunna, Yazoo, and Porter's Creek Clay.

All tested formations scoured at velocities larger than 1.5 m/s. The Porter's Creek material scoured at the lowest velocity of all the soils, while the re-drilled Naheola sample appeared to resist scour the most. Sample swelling was observed in each formation during most EFA tests. This affected the measured scour rate and, therefore, adjustments were made to incorporate swelling into the scour functions that were determined. Results from this study, as well as from Walker (2013), Mobley (2009), and Crim (2003), were synthesized to draw correlations between scourability and conventional geotechnical parameters.

6.2 Conclusions

A summary of the pertinent scour and soil parameters are shown in Table 6-1. The following correlations were concluded from the study:

- Scour was dependent upon SPT N value, insitu moisture content, and mean particle size diameter of the soil
- Scour resistant soils had SPT N values of 60 and greater
- Scour was observed in soils with insitu moisture contents less than 23%
- The majority of formations with mean grain sizes greater than 0.0082 mm were scourable

Table 6-1. Summary of Results.

Soil Formation	Critical Velocity (mm/hr)	Critical Shear Stress (N/m^2)	Initial Erosion Rate (mm/hr)	SPT N Value (Blows)	Moisture Content (%)	Mean Grain Size (mm)
Nanafalia	0.42	0.63	7.97	13	24	0.080
Naheola - Yellow	0.65	0.41	145.63	16	31	0.028
Naheola - Re-drill	0.59	1.15	4.23	5	33	0.044
Naheola - Dark	0.59	1.15	4.23	16	34	0.016
Porter's Creek	0.20	0.15	42.33	13	44	<0.001
Clayton	0.47	0.74	16.62	23	51	0.023
Bucatunna	0.39	0.53	11.29	6	48	0.033
Yazoo	0.47	0.79	22.04	15	59	0.088

6.3 Recommendations

Of the 14 formations tested in this study as well as Walker (2013), Mobley (2009), and Crim (2003), only three of the samples were scour resistant at velocities 3.0 m/s and below. In order to make more precise and accurate correlations for scourability as it relates to soil parameters, it is suggested that additional EFA tests be performed on soils less likely to scour below 3.0 m/s. As previously stated, soils with SPT N values below 60 were seen to scour. It should be noted, however, that none of the soils tested had N values between 39 and 59. Therefore, it is recommended that further EFA testing be conducted on materials with and SPT N value falling in this range.

Although sample swelling was incorporated into the development of the erosion functions, quantifying swell rate of a material may be beneficial in determining the long-term gross erosion rate of a formation. In many cases throughout this study swelling was so significant that the sample actually became taller over the test duration even though scour had occurred. A value for swell rate must be incorporated into the change in sample height in order to determine the scour rate over the entire duration.

This may be accomplished using the EFA by testing a sample at a very low velocity (so no scour occurs) to measure the magnitude of swell over a given time.

Because the majority of the tested soils were extremely stiff, extruding these materials into the EFA proved to be rather difficult. The stepping motor installed in the EFA did not have the capacity to overcome the excessive skin friction that was developed between the soil and the acrylic tube. It is recommended that an alternative system be installed in place of the stepping motor to allow for the extrusion of exceedingly stiff clays and chalks. This system must have the ability to extrude samples in increments of exactly one millimeter.

Lastly, in addition to the recommended sampling of formations with SPT N values between 39 and 39, it is recommended that additional EFA tests be performed on clays with a broad range of soil characteristics. This should be performed in an effort to further validate the correlations made in this study, and possibly generate new correlations.

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Appendix A – Nanafalia Clay

VELOCITY = 0.3 M/S

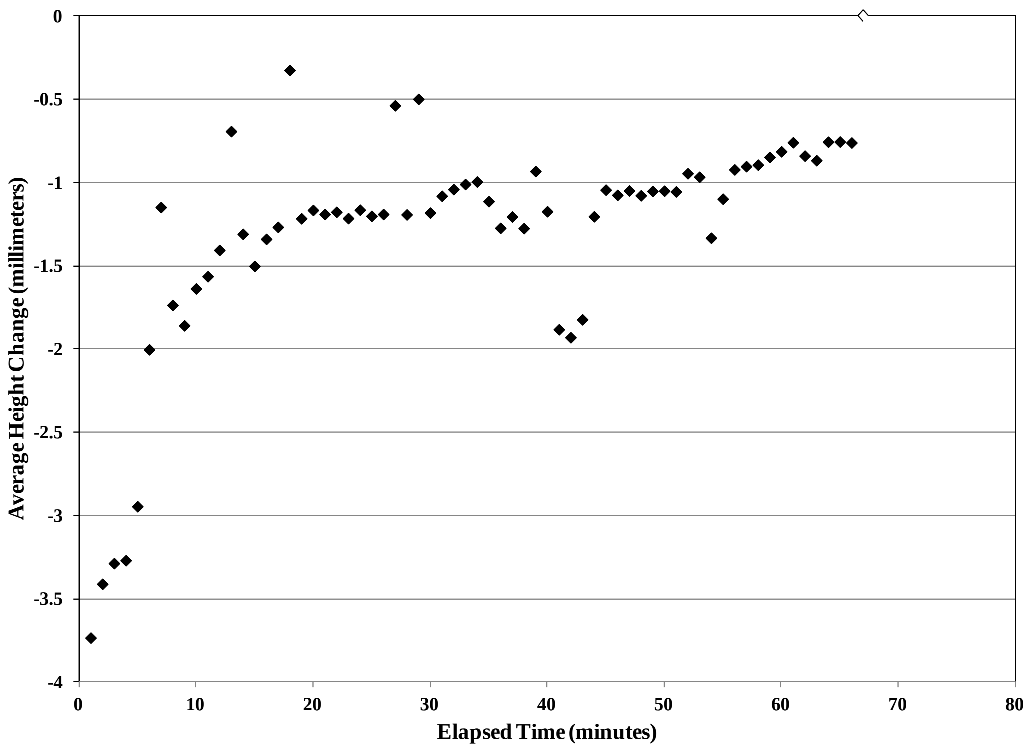

FIG. A- 1. "Nanafalia Clay 23.5_1" EFA Test Results.

VELOCITY = 0.6 M/S

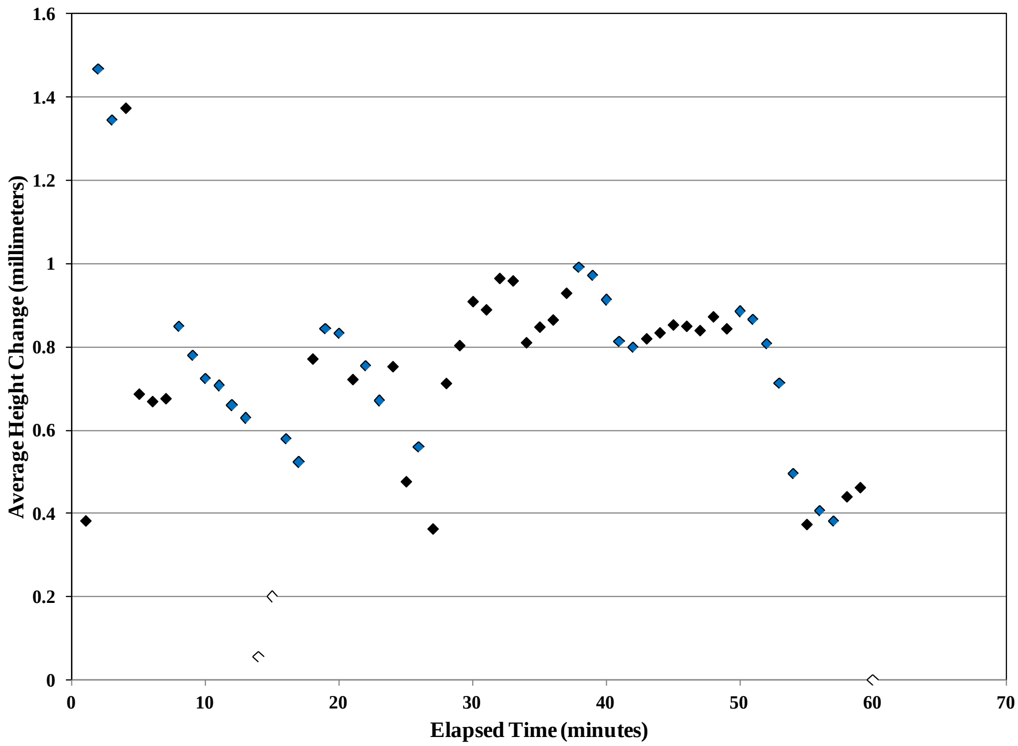

FIG. A- 2. "Nanafalia Clay 23.5_2" EFA Test Results.

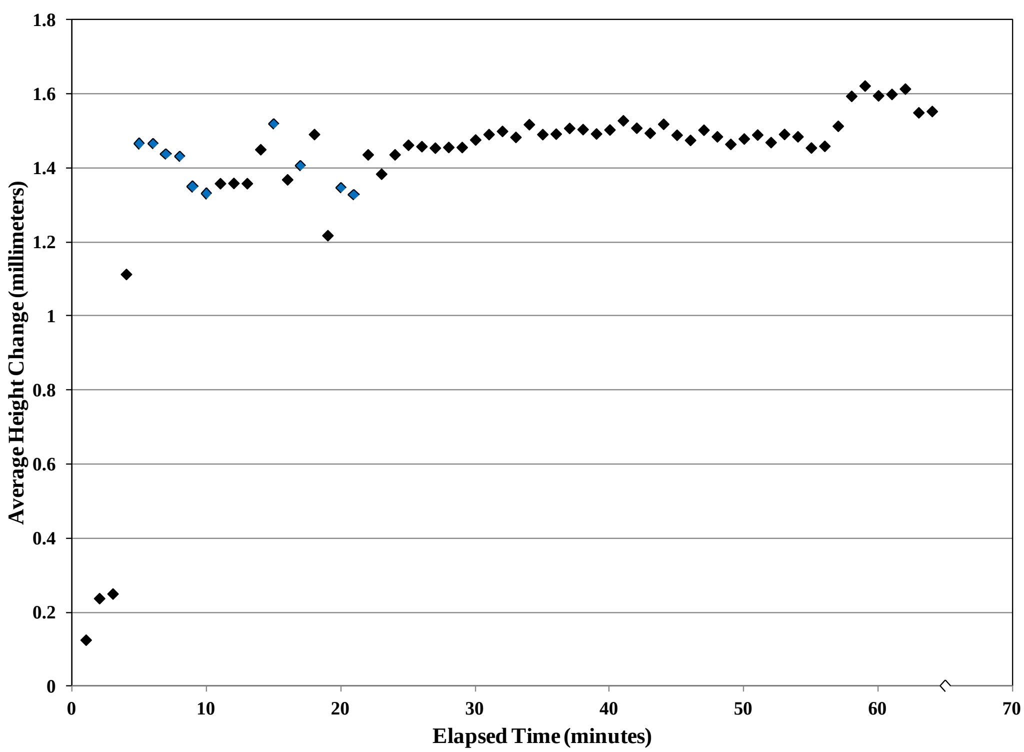

FIG. A- 3. "Nanafalia Clay 23.5_3" EFA Test Results.

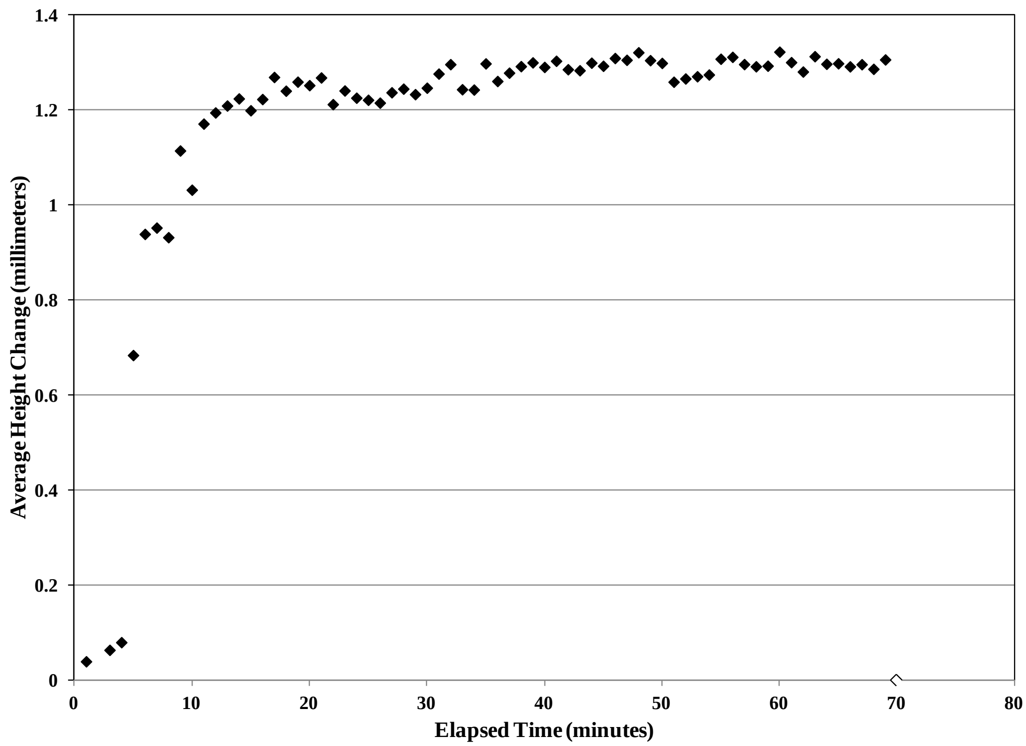

FIG. A- 4. "Nanafalia Clay 23.5_4" EFA Test Results.

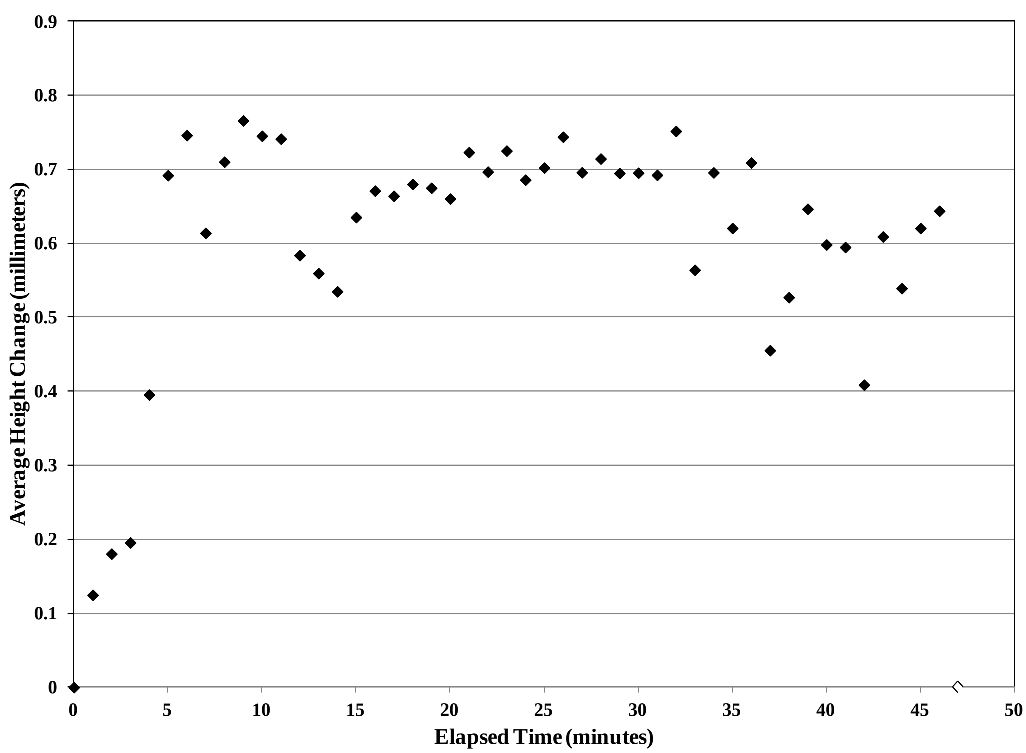

FIG. A- 5. "Nanafalia Clay 21.0_1" EFA Test Results.

VELOCITY = 1.0 M/S

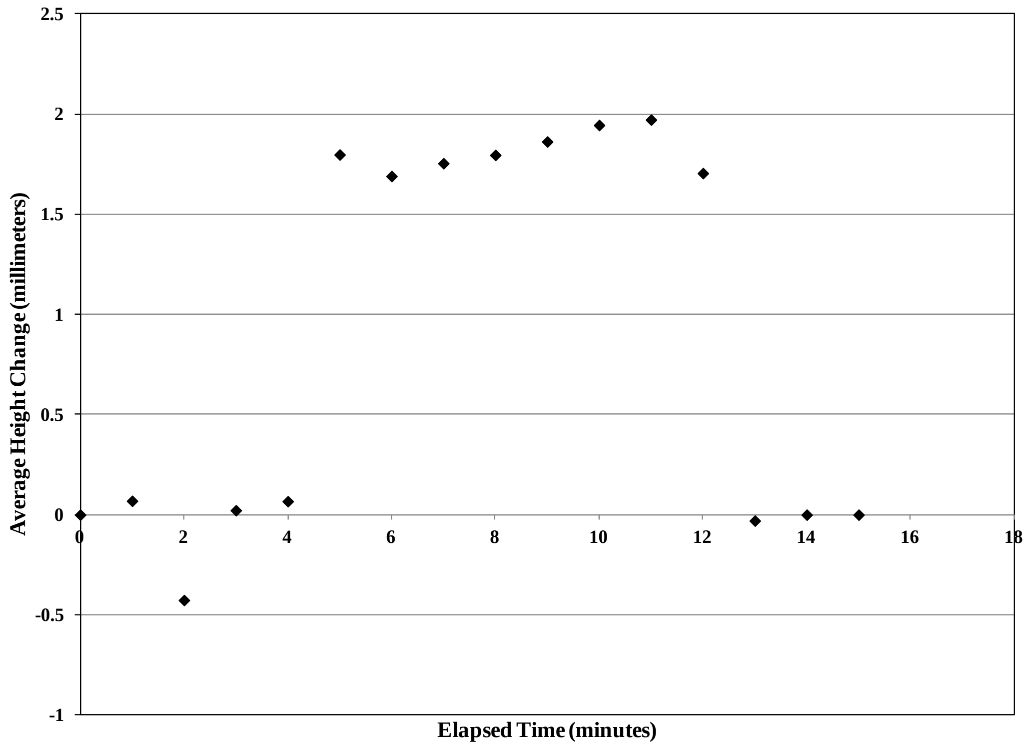

FIG. A- 6. "Nanafalia Clay 23.0_1" EFA Test Results.

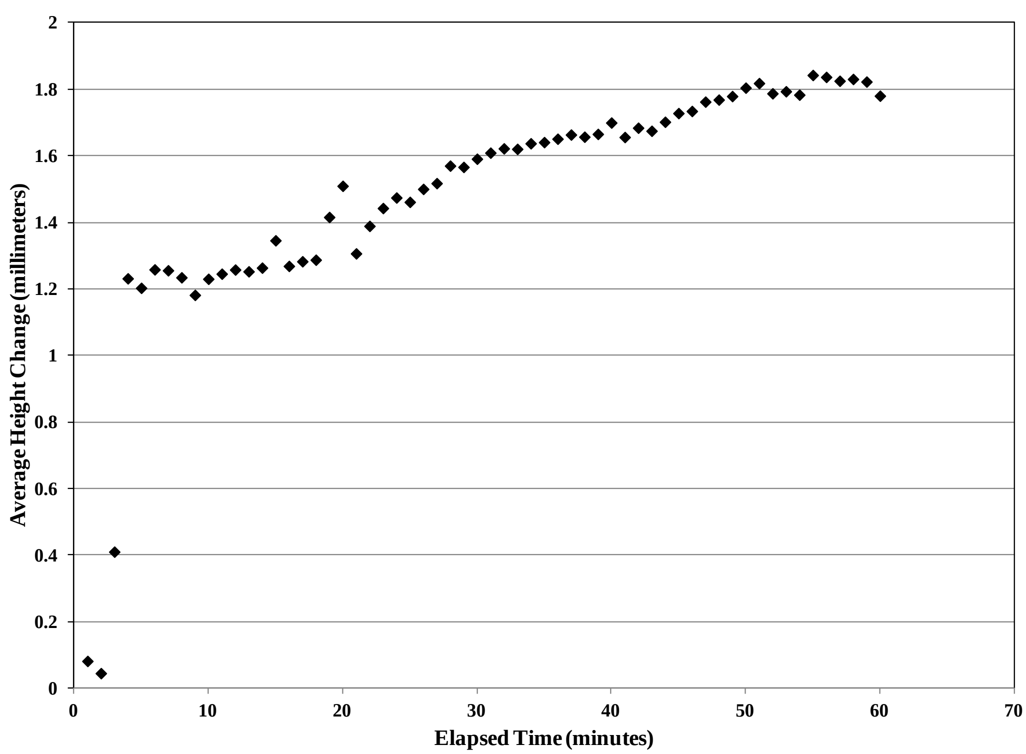

FIG. A- 7. "Nanafalia Clay 23.0_2" EFA Test Results.

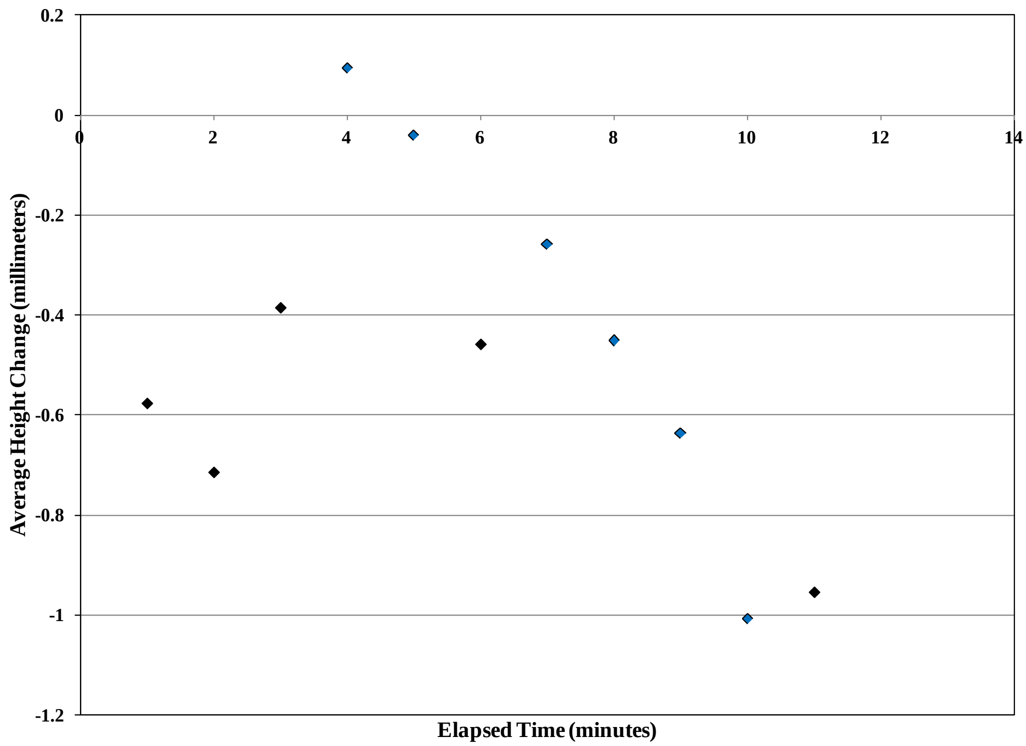

FIG. A- 8. "Nanafalia Clay 23.0_3" EFA Test Results.

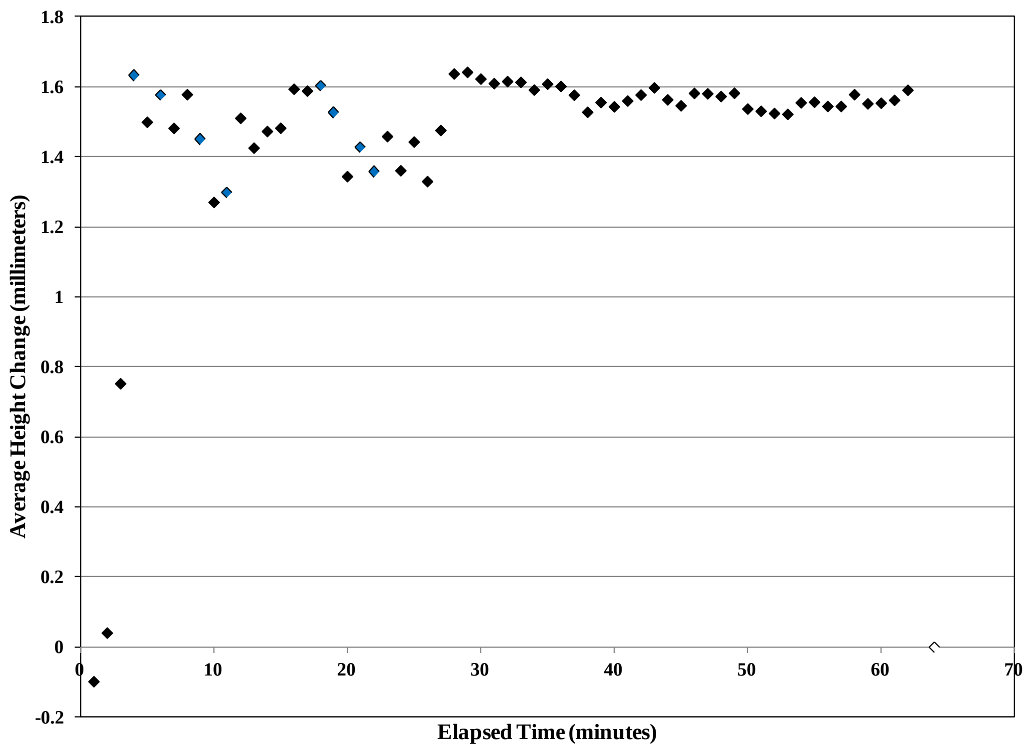

FIG. A- 9. "Nanafalia Clay 23.0_4" EFA Test Results.

VELOCITY = 1.5 M/S

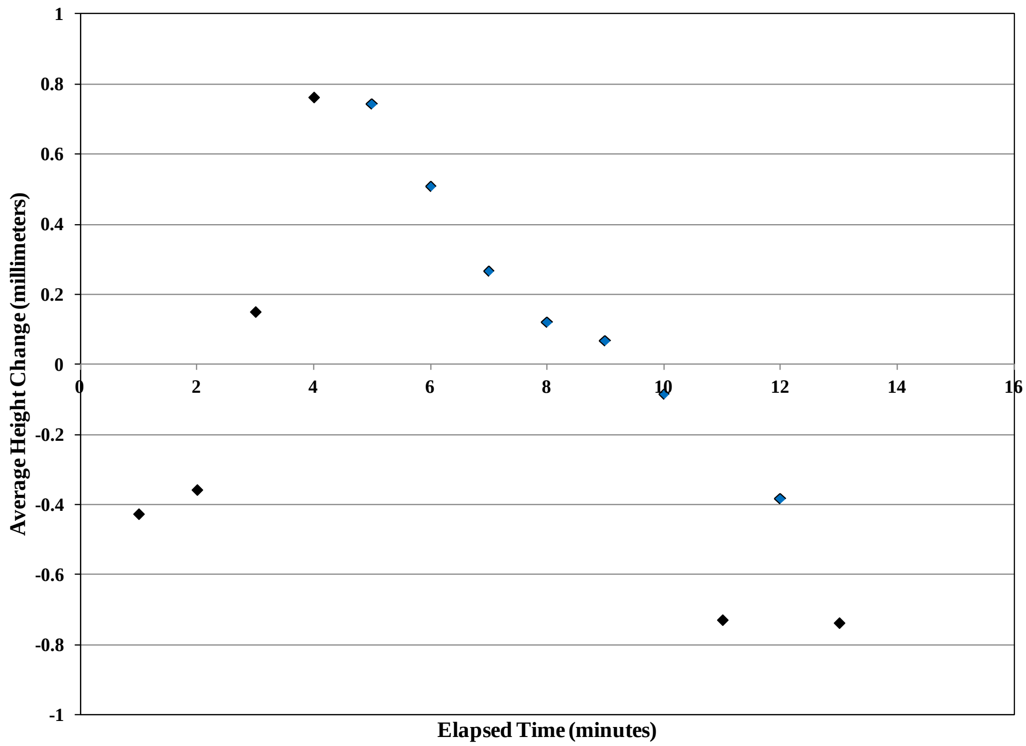

FIG. A- 10. "Nanafalia Clay 21.5_1" EFA Test Results.

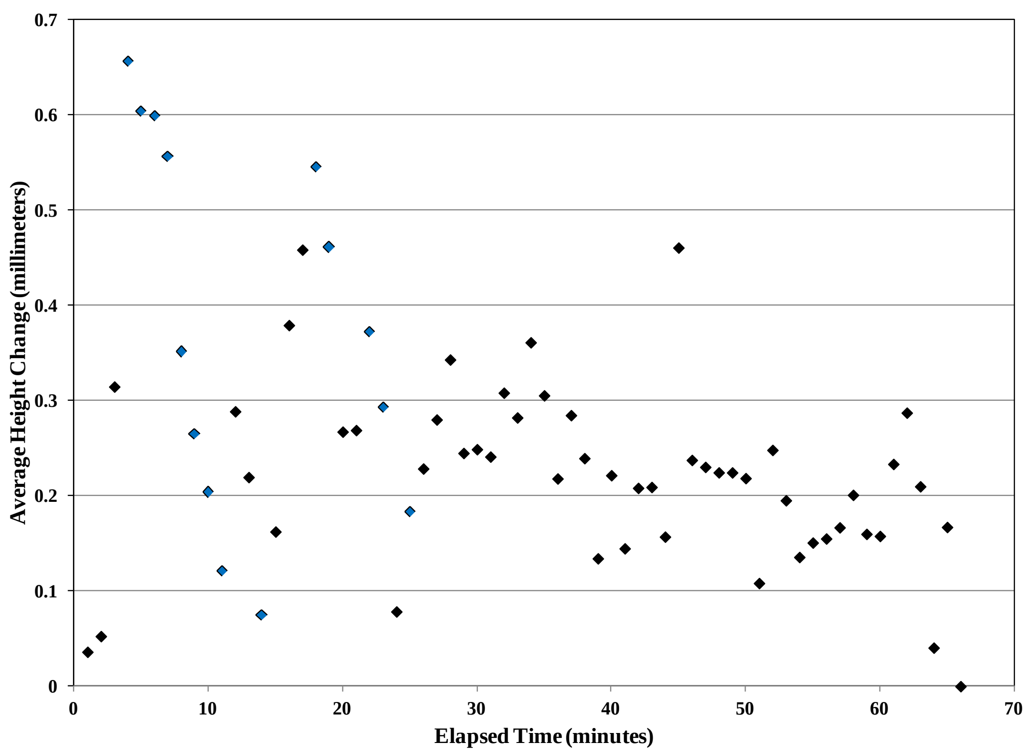

FIG. A- 11. "Nanafalia Clay 21.5_2" EFA Test Results.

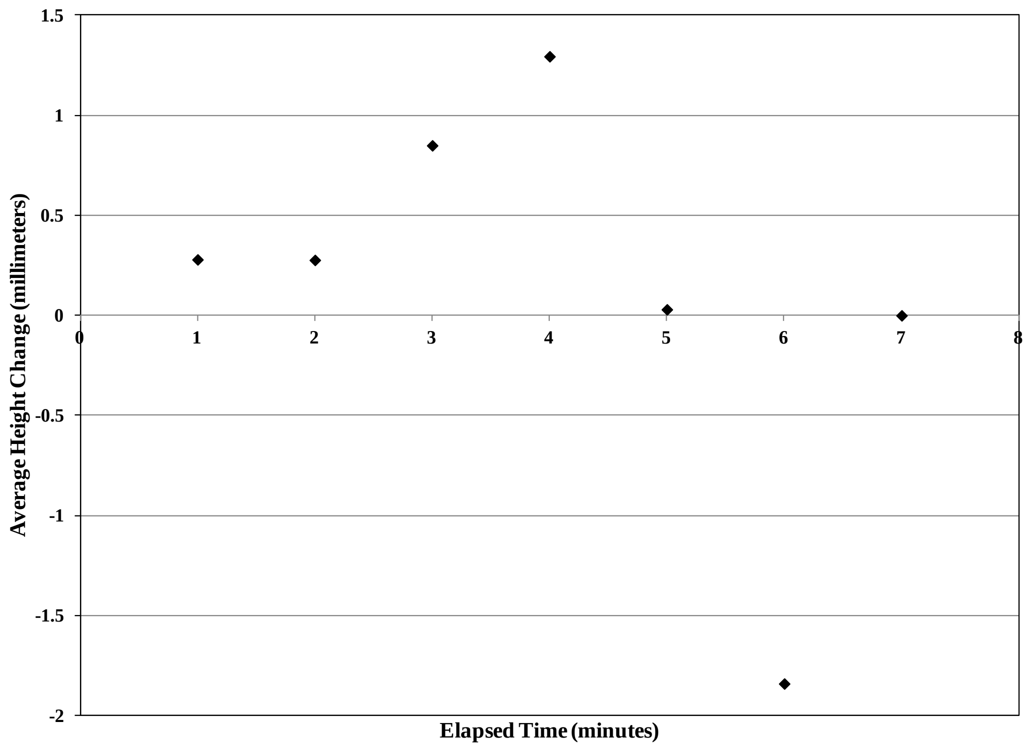

FIG. A- 12. "Nanafalia Clay 21.5_3" EFA Test Results.

VELOCITY = 2.0 M/S

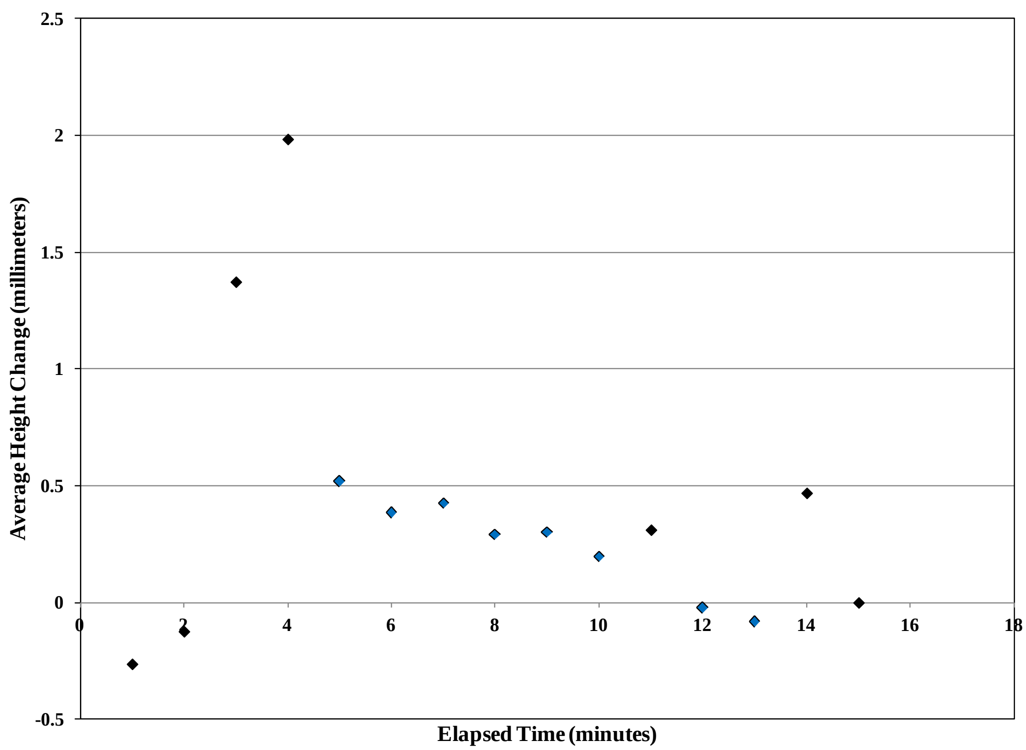

FIG. A- 13. "Nanafalia Clay 21.5_4" EFA Test Results.

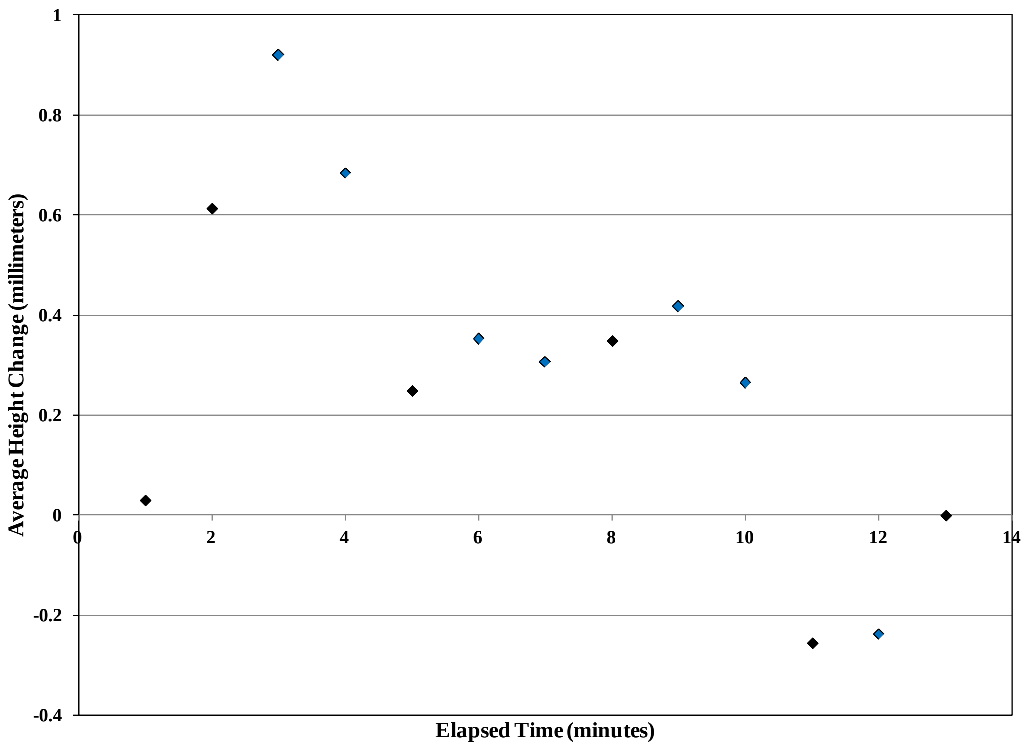

FIG. A- 14. "Nanafalia Clay 21.5_5" EFA Test Results.

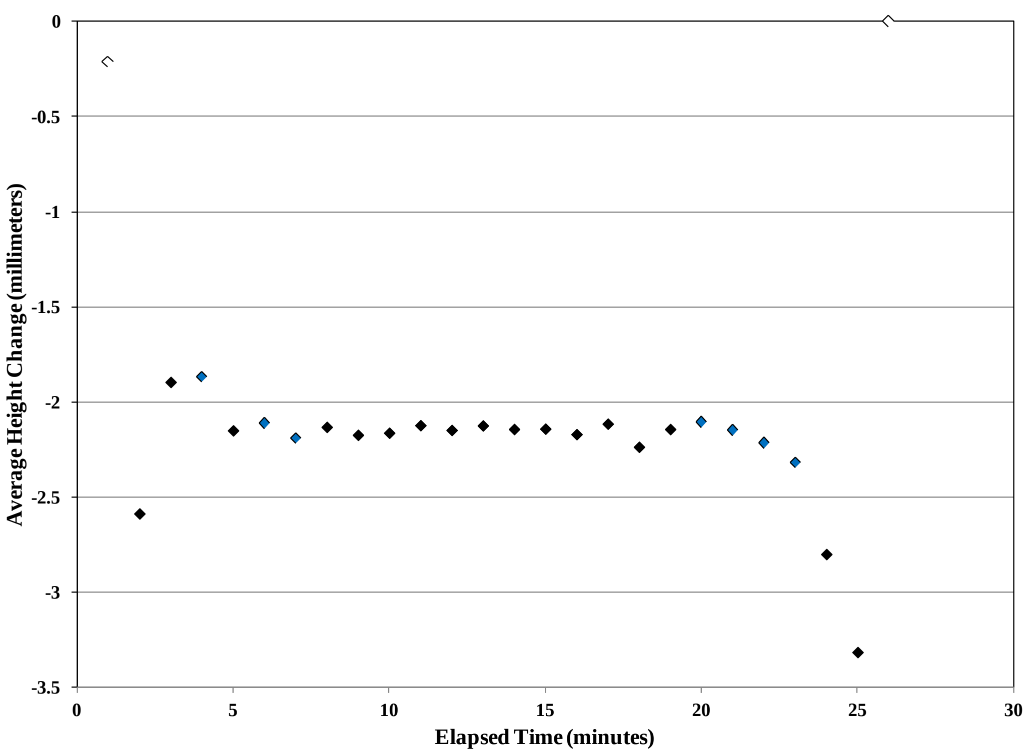

FIG. A- 15. "Nanafalia Clay 21.5_6" EFA Test Results.

VELOCITY = 3.0 M/S

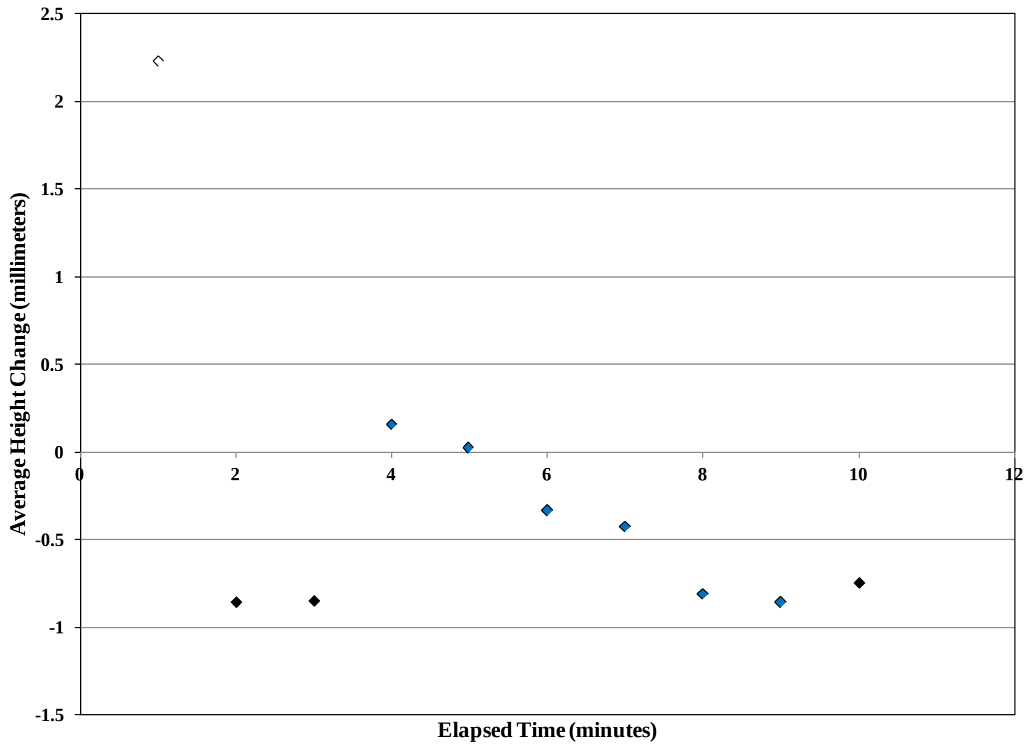

FIG. A- 16. "Nanafalia Clay 21.5_7" EFA Test Results.

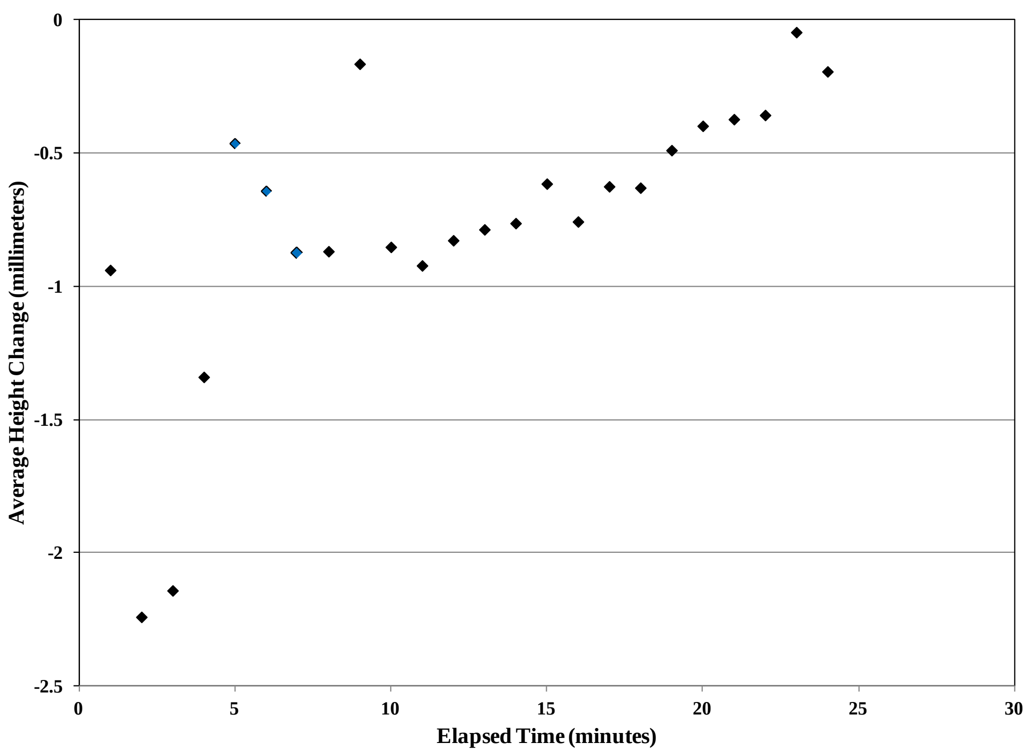

FIG. A- 17. "Nanafalia Clay 21.5_8" EFA Test Results.

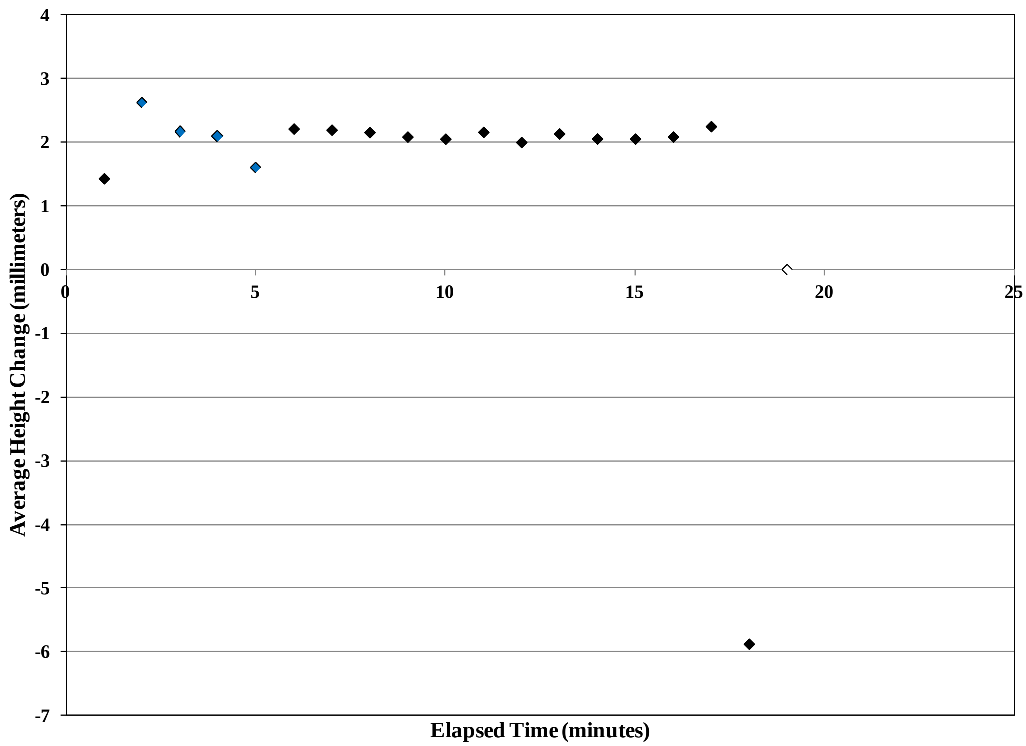

FIG. A- 18. "Nanafalia Clay 21.5_9" EFA Test Results.

Appendix B – Naheola (Yellow) Clay

VELOCITY = 0.3 M/S

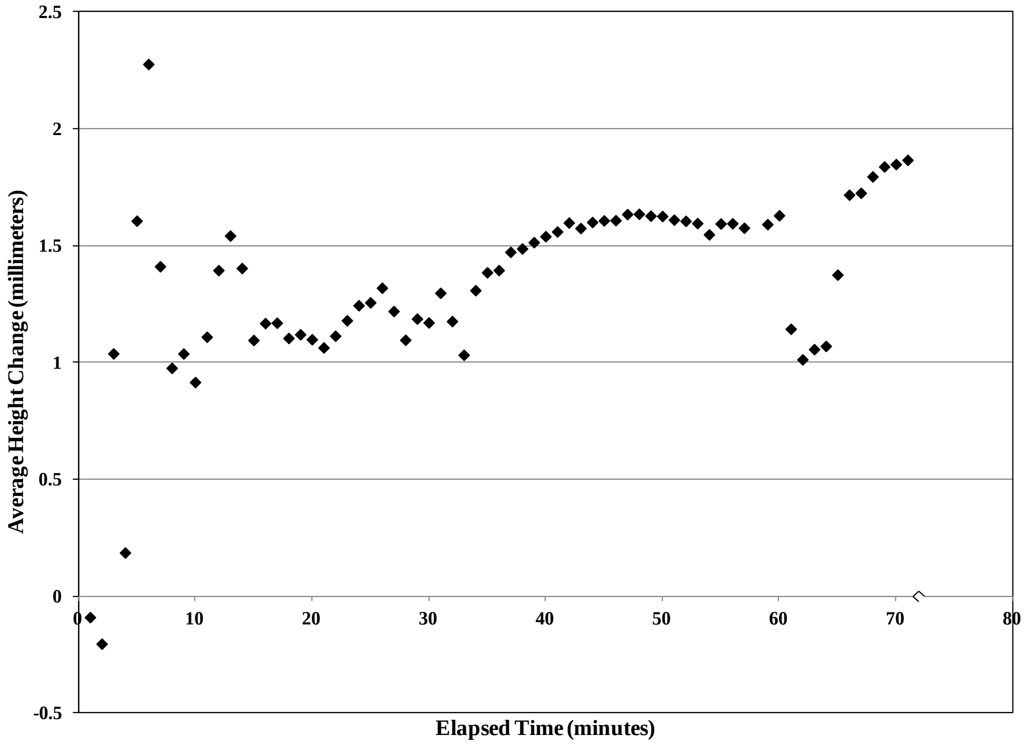

FIG. B- 1. "Naheola Clay 17.5_1" EFA Test Results.

VELOCITY = 0.6 M/S

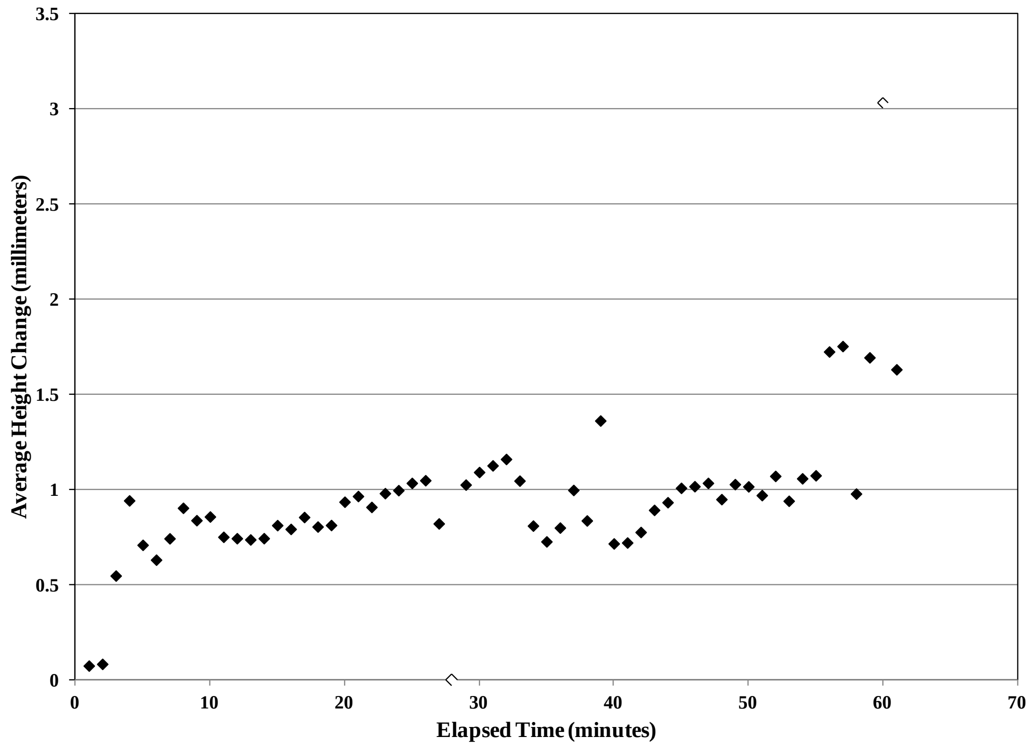

FIG. B- 2. "Naheola Clay 17.5_2" EFA Test Results.

VELOCITY = 1.0 M/S

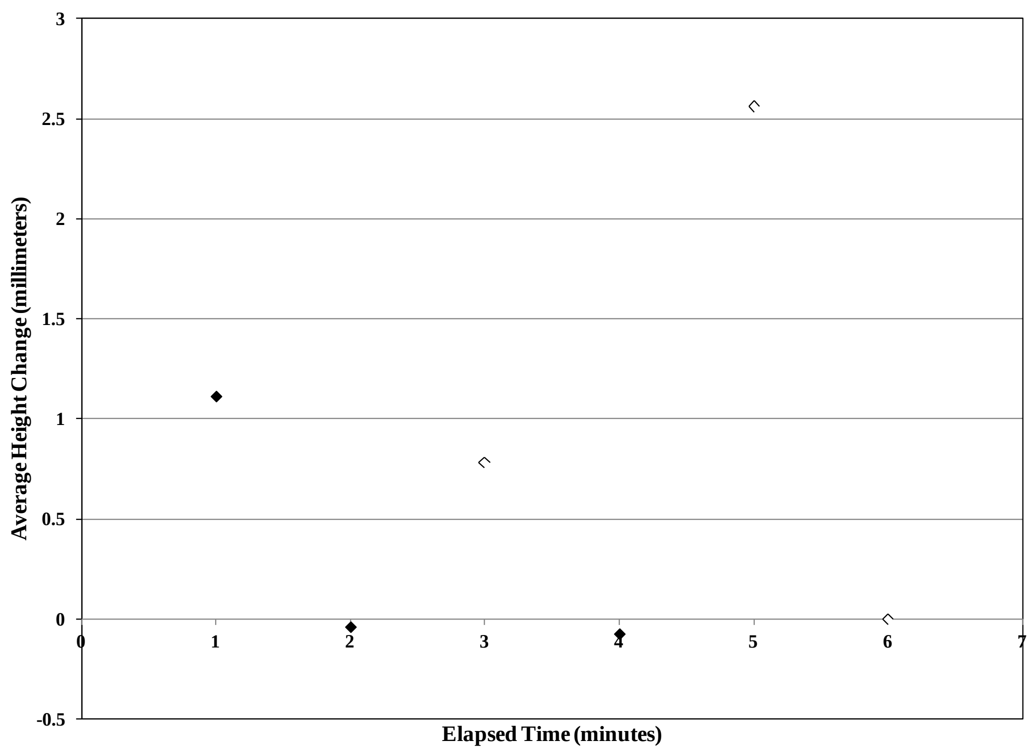

FIG. B- 3. "Naheola Clay 17.5_3" EFA Test Results.

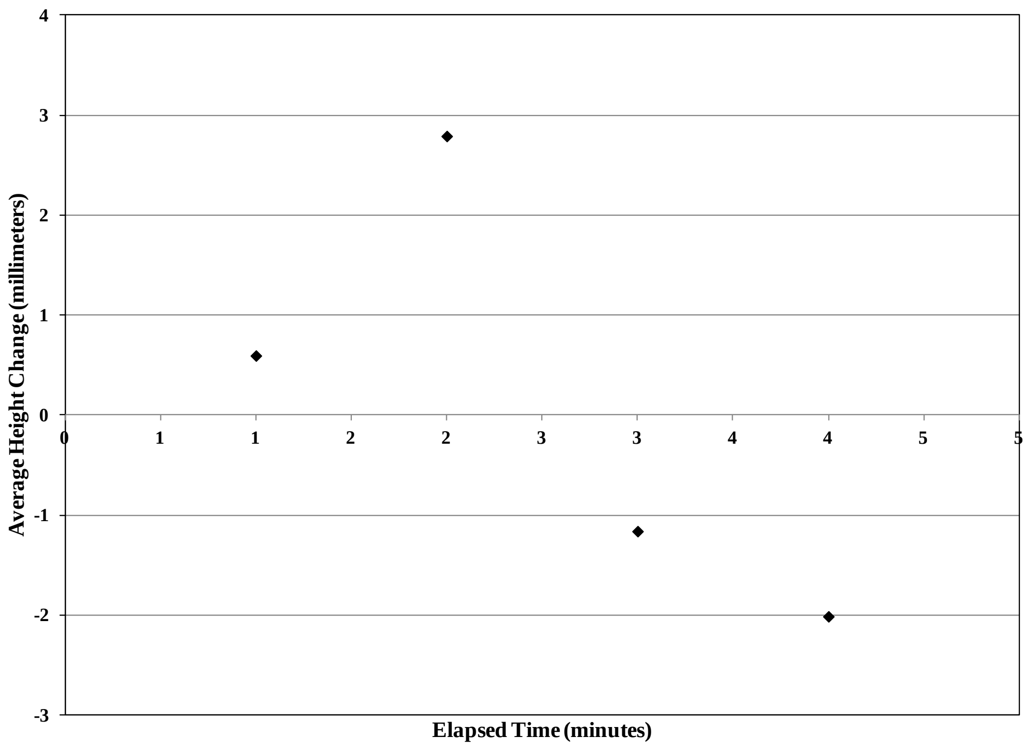

FIG. B- 4. "Naheola Clay 17.5_4" EFA Test Results.

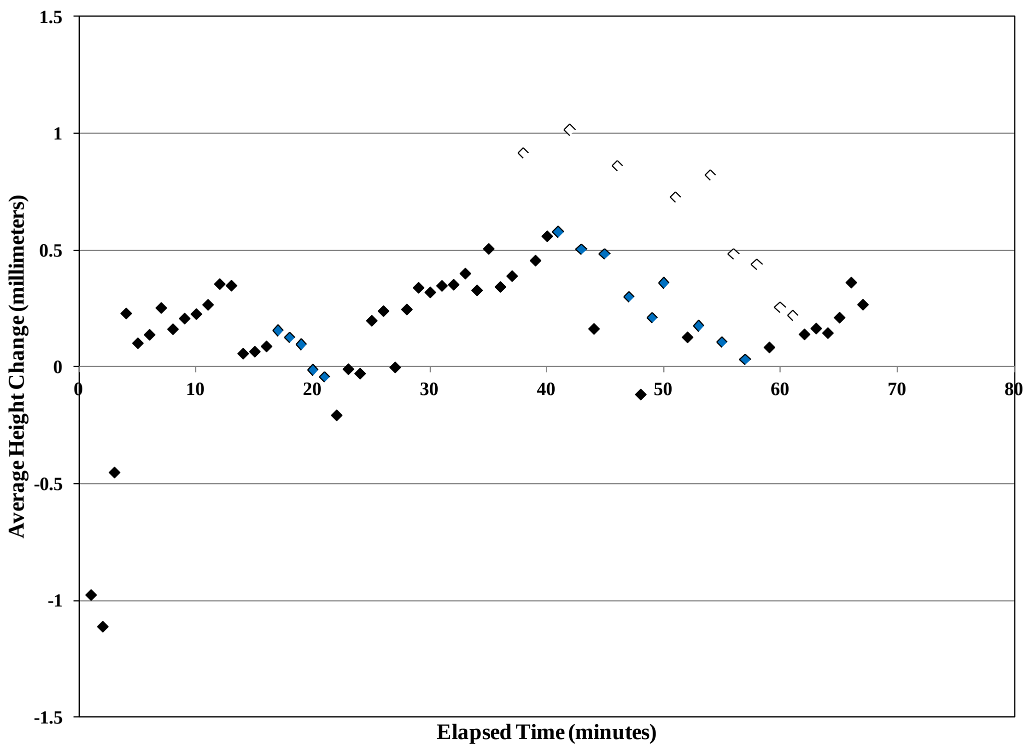

FIG. B- 5. "Naheola Clay 17.5_5" EFA Test Results.

VELOCITY = 2.0 M/S

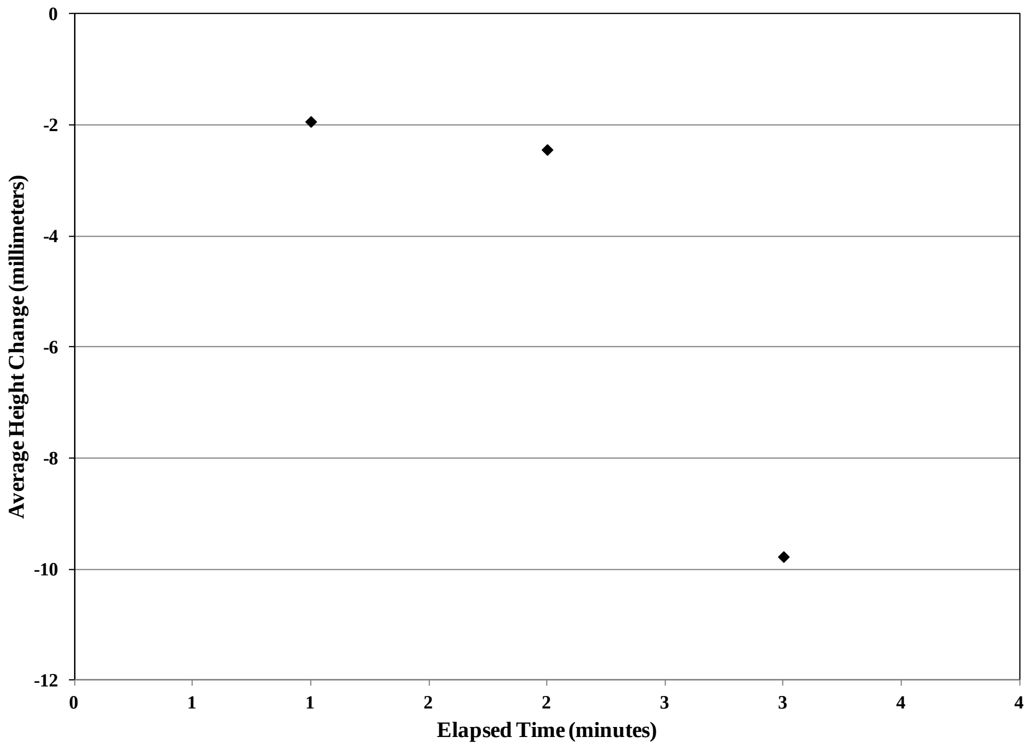

FIG. B- 6. "Naheola Clay 17.2_1" EFA Test Results.

Appendix C – Naheola (Dark) Clay

VELOCITY = 0.6 M/S

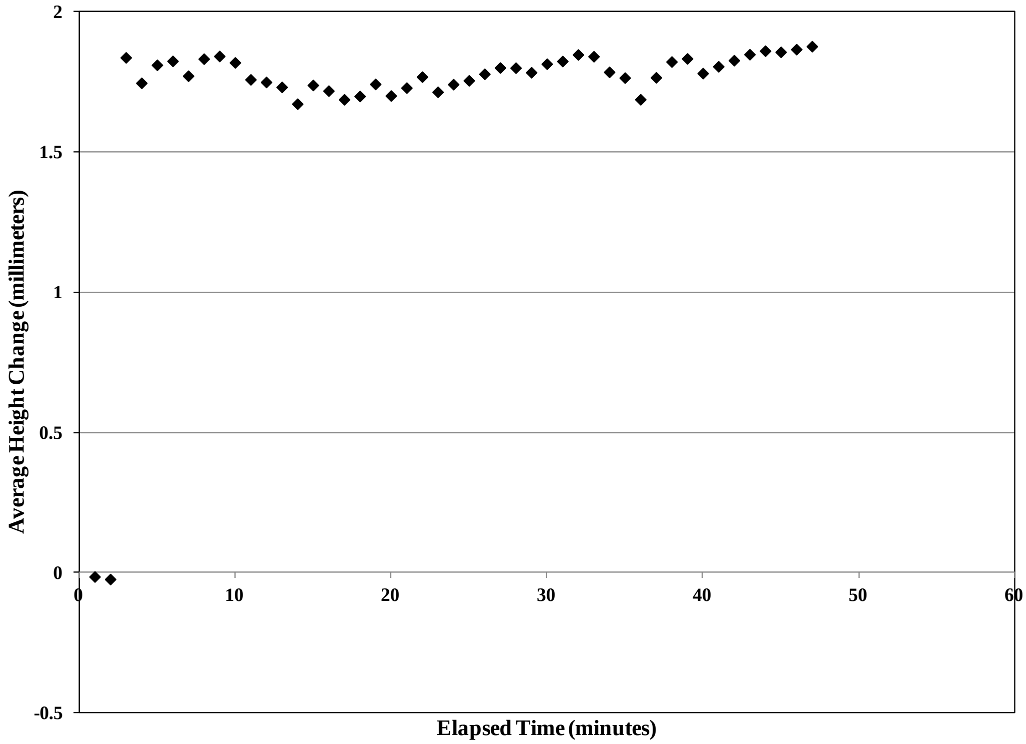

FIG. C- 1. "Naheola Clay 17.0_1" EFA Test Results.

VELOCITY = 1.0 M/S

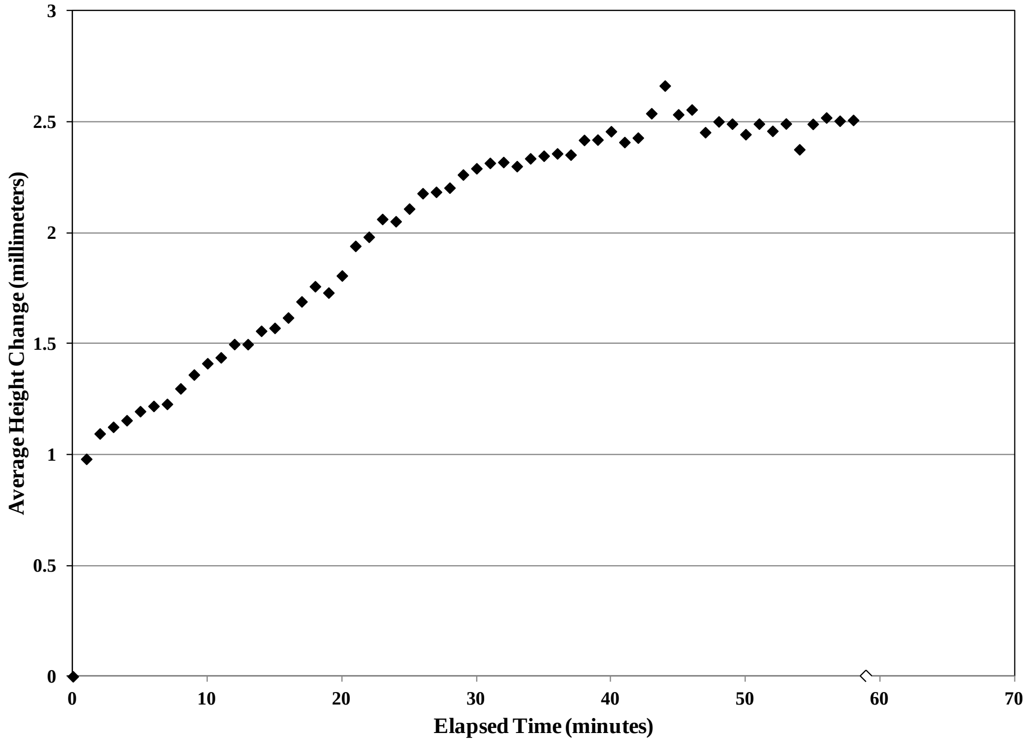

FIG. C- 2. "Naheola Clay 17.0_2" EFA Test Results.

VELOCITY = 1.5 M/S

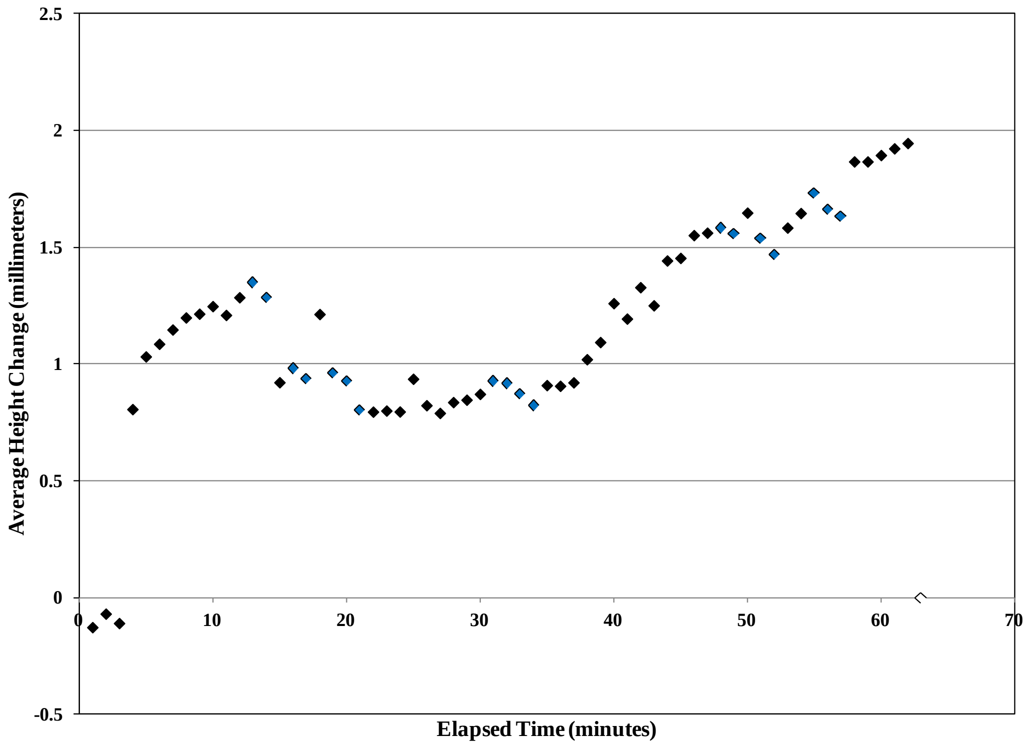

FIG. C- 3. "Naheola Clay 16.0_1" EFA Test Results.

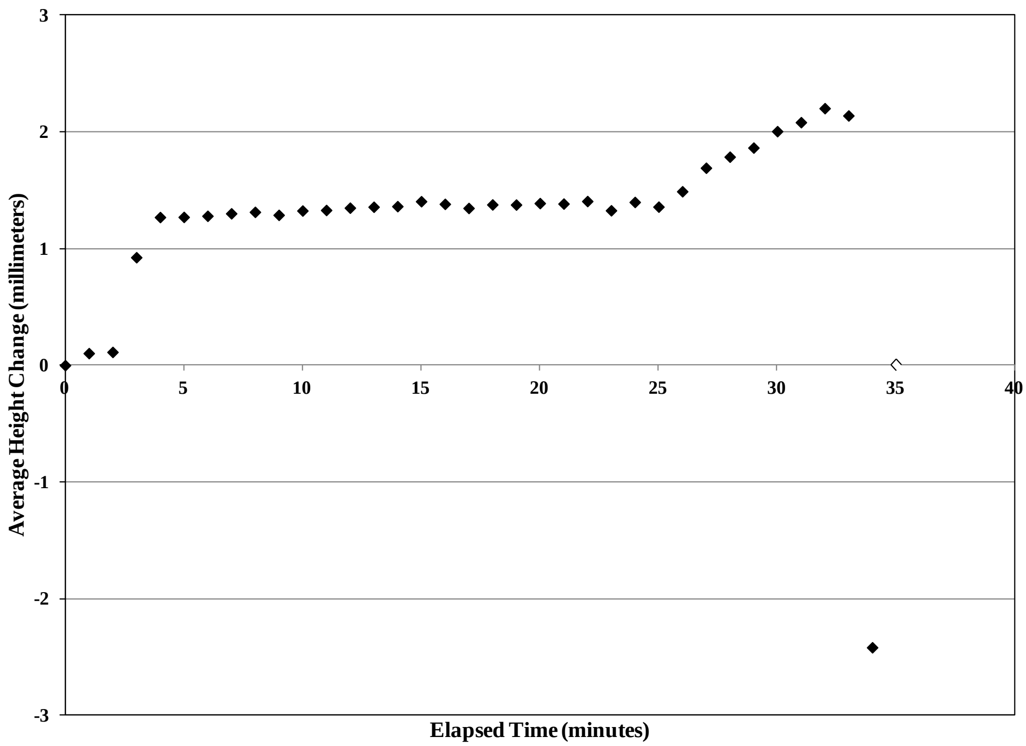

FIG. C- 4. "Naheola Clay 16.0_2" EFA Test Results.

Appendix D – Naheola (Re-drill) Clay

VELOCITY = 0.6 M/S

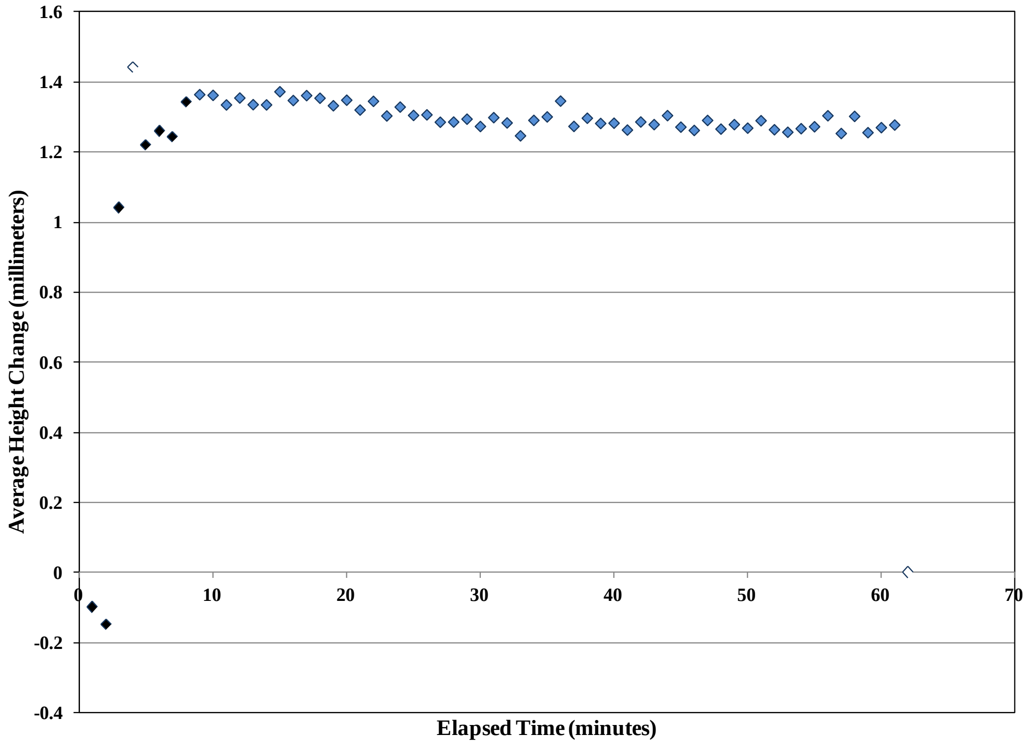

FIG. D- 1. "Naheola Clay 19.5_1" EFA Test Results.

VELOCITY = 1.0 M/S

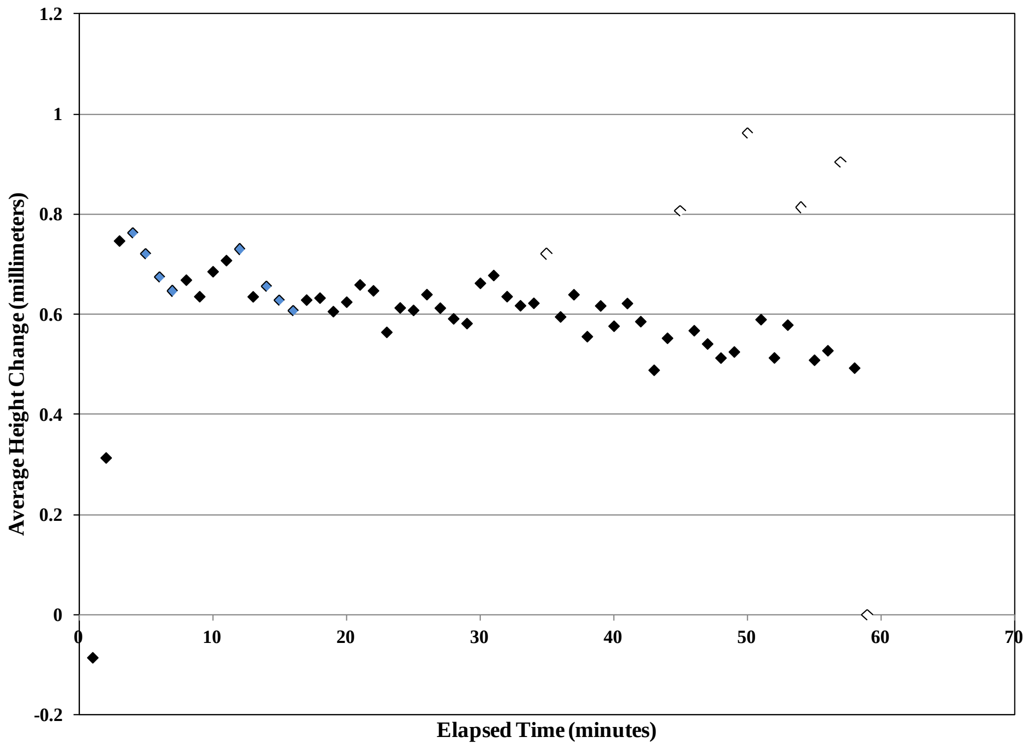

FIG. D- 2. "Naheola Clay 19.5_2" EFA Test Results.

VELOCITY = 1.5 M/S

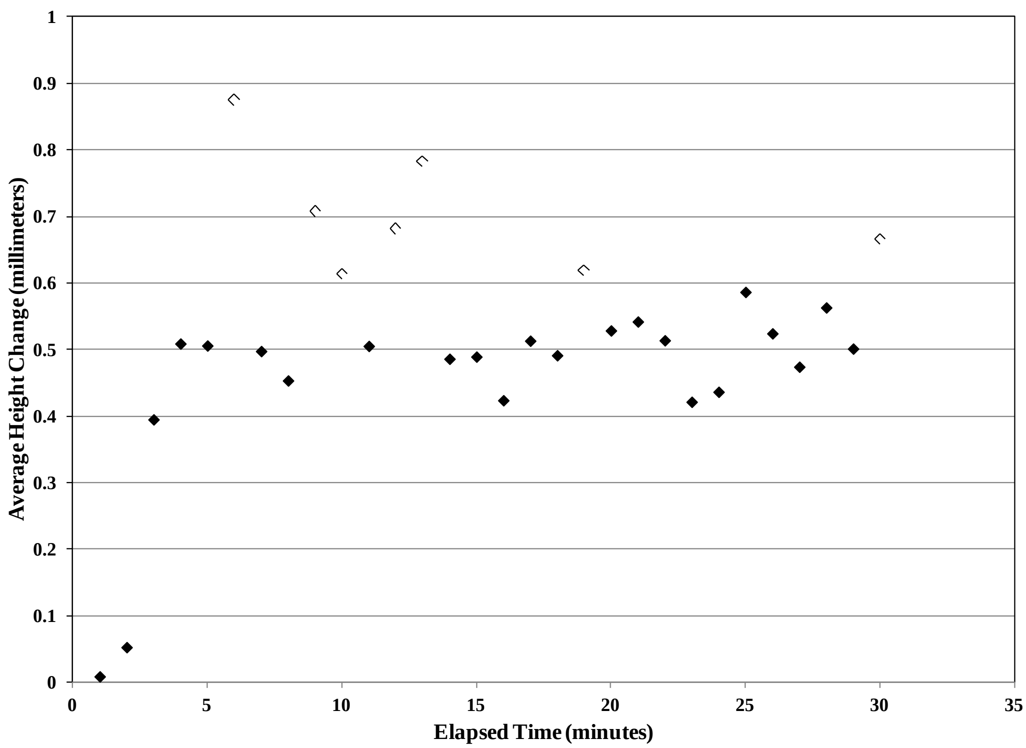

FIG. D- 3. "Naheola Clay 19.5_3" EFA Test Results.

VELOCITY = 2.0 M/S

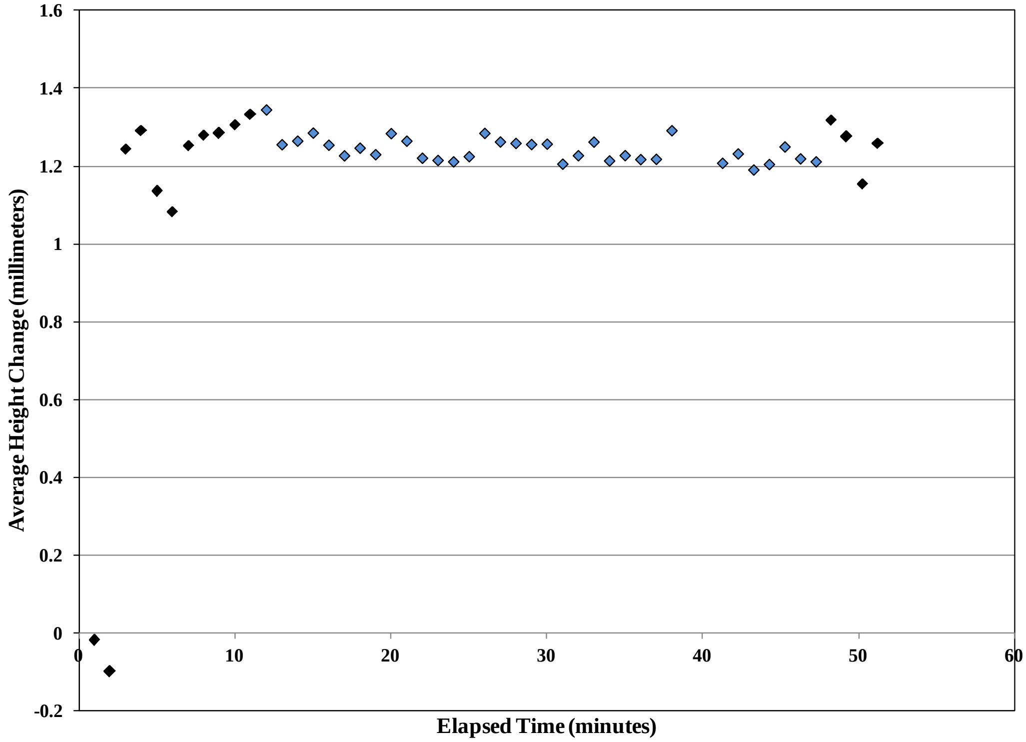

FIG. D- 4. "Naheola Clay 19.5_4" EFA Test Results.

VELOCITY = 3.0 M/S

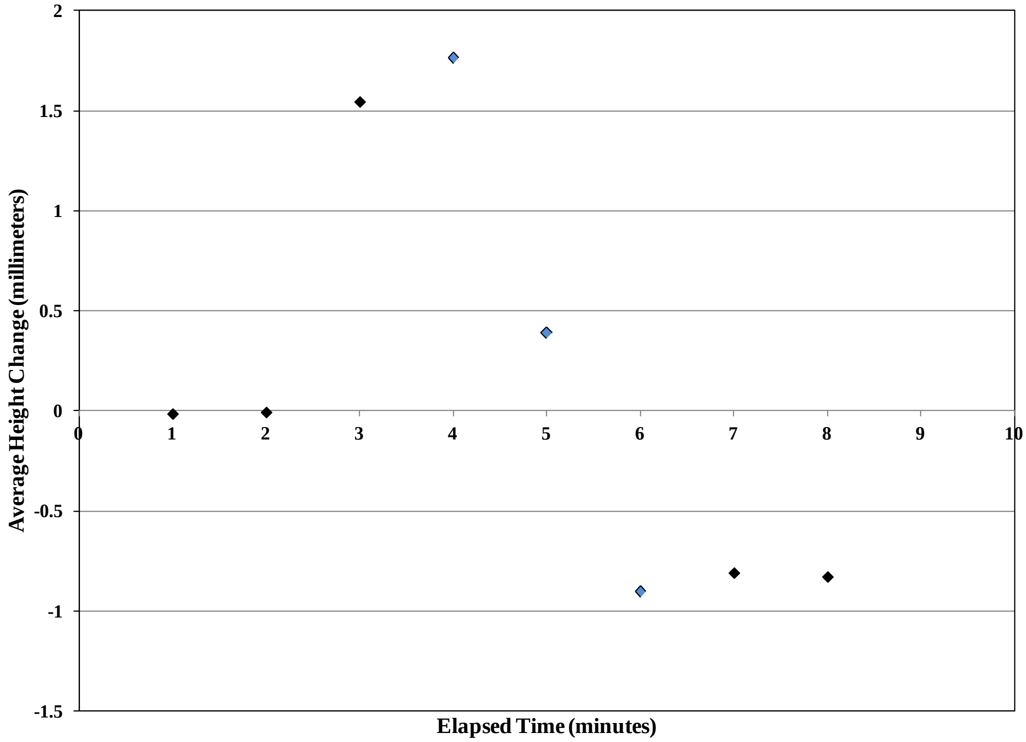

FIG. D- 5. "Naheola Clay 19.5_5" EFA Test Results.

Appendix E – Clayton Clay

VELOCITY = 0.6 M/S

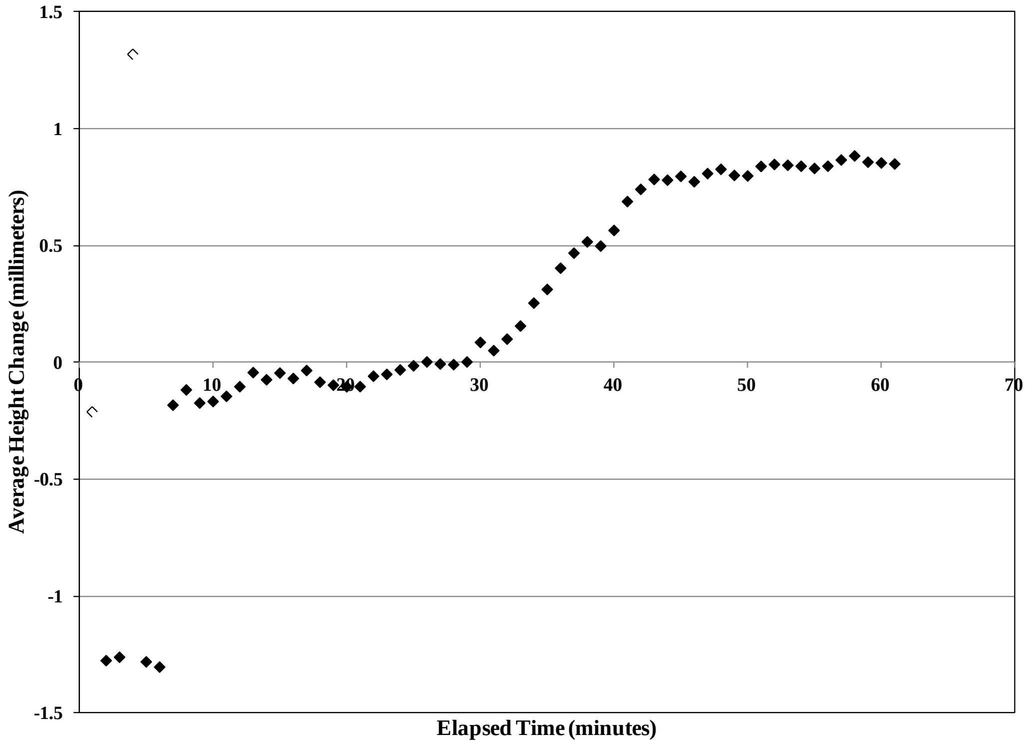

FIG. E- 1. "Clayton 29.5_3" EFA Test Results.

VELOCITY = 1.0 M/S

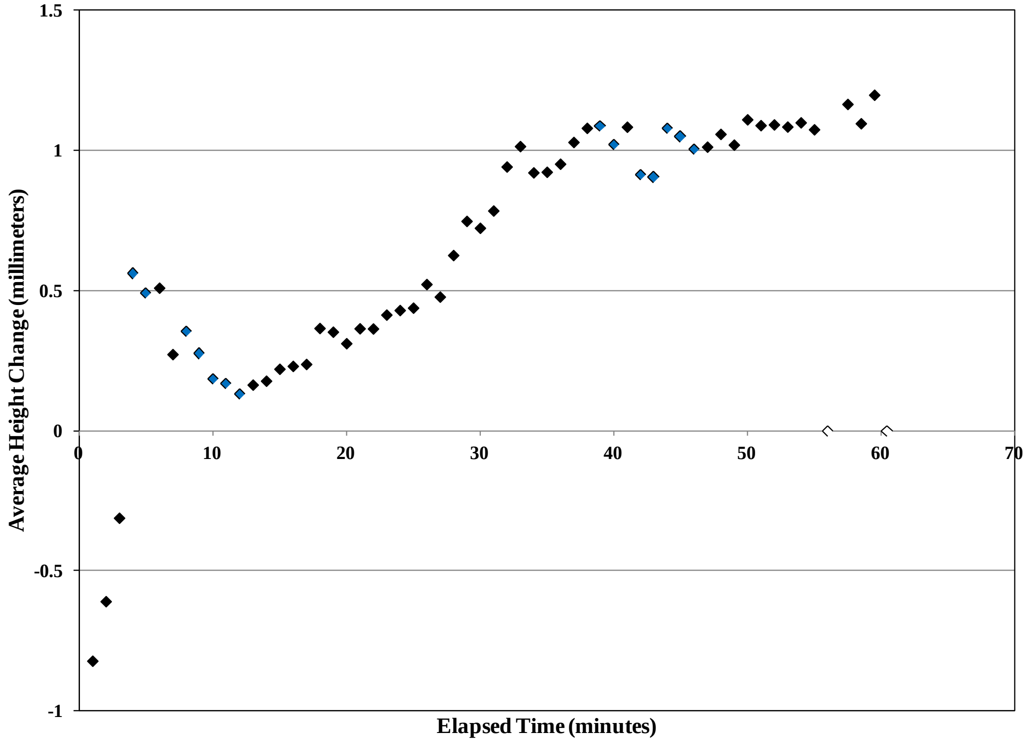

FIG. E- 2. "Clayton 29.5_4" EFA Test Results.

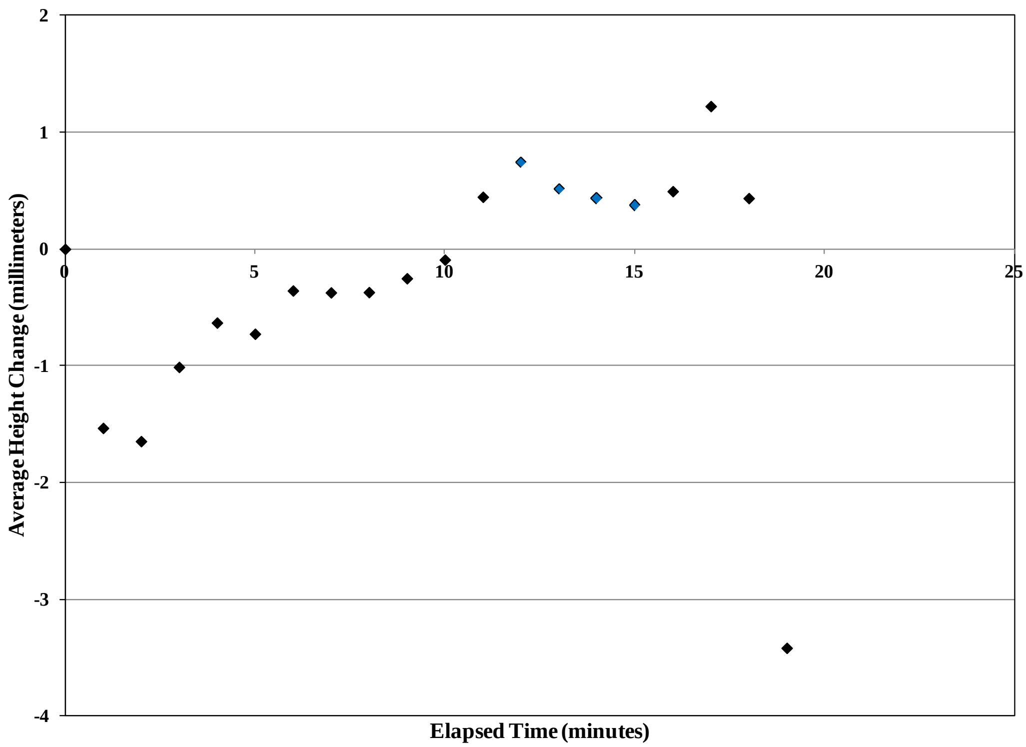

FIG. E- 3. "Clayton 29.5_5" EFA Test Results.

VELOCITY = 1.5 M/S

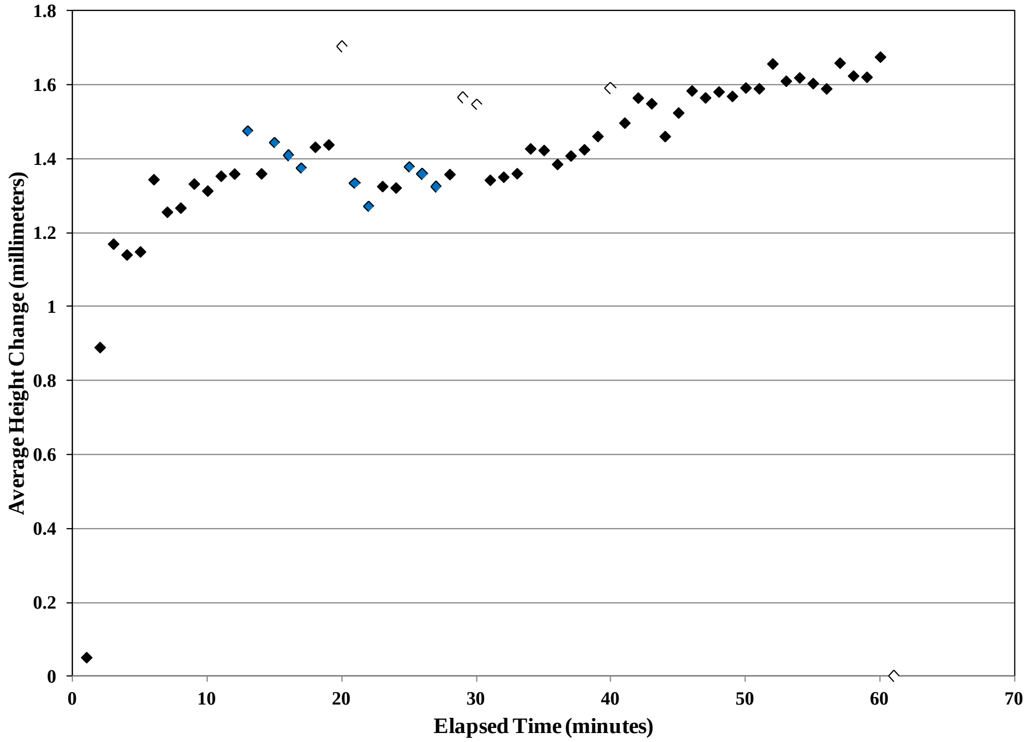

FIG. E- 4. "Clayton 29.0_3" EFA Test Results.

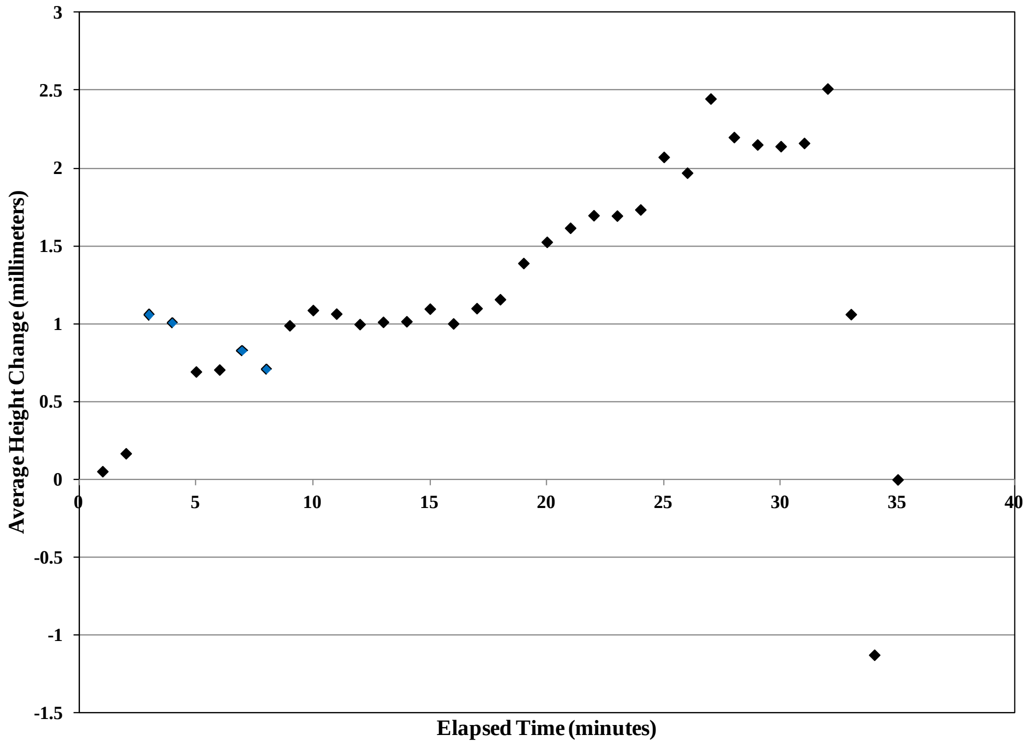

FIG. E- 5. "Clayton 29.0_6" EFA Test Results.

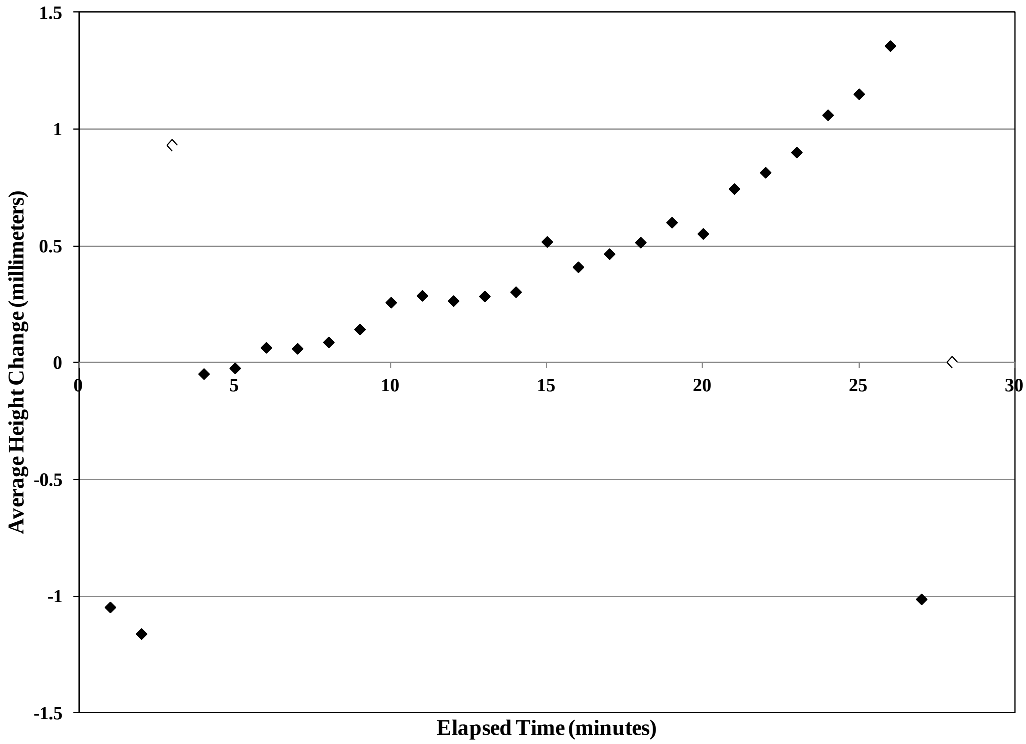

FIG. E- 6. "Clayton 29.5_6" EFA Test Results.

VELOCITY = 2.0 M/S

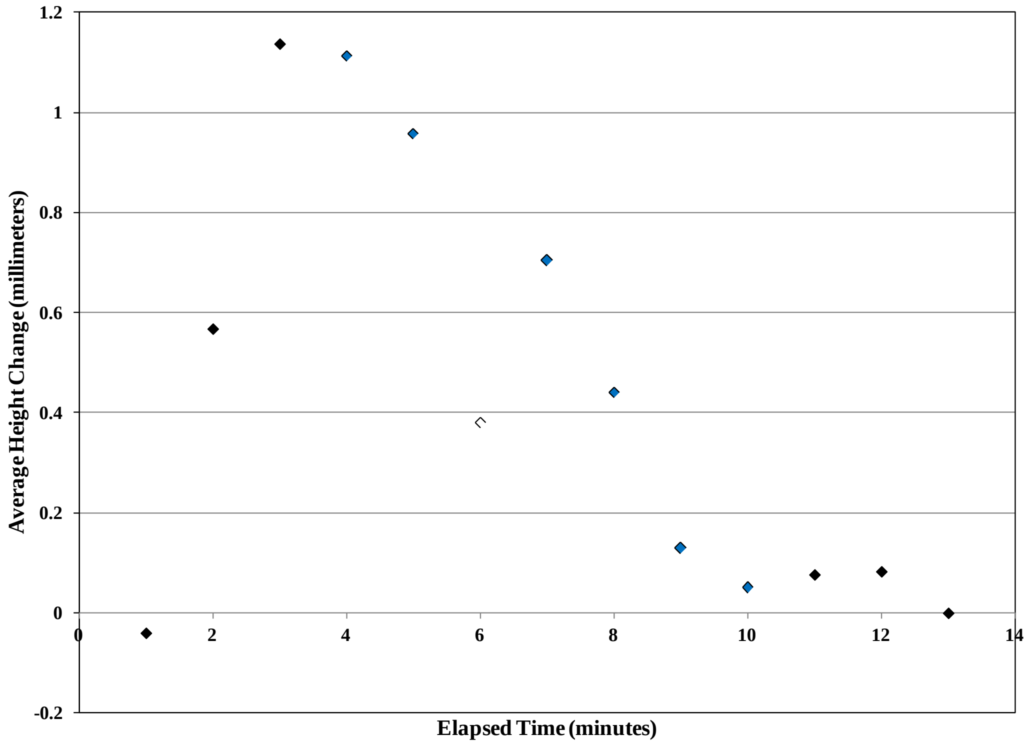

FIG. E- 7. "Clayton 29.0_1" EFA Test Results.

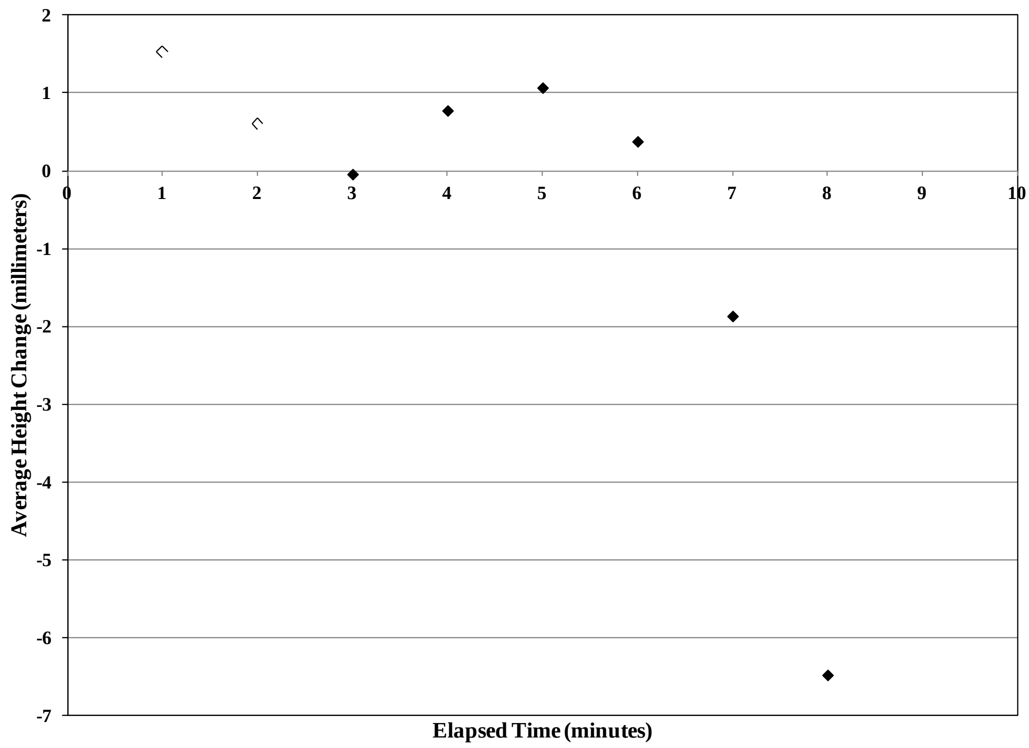

FIG. E- 8. "Clayton 29.0_4" EFA Test Results.

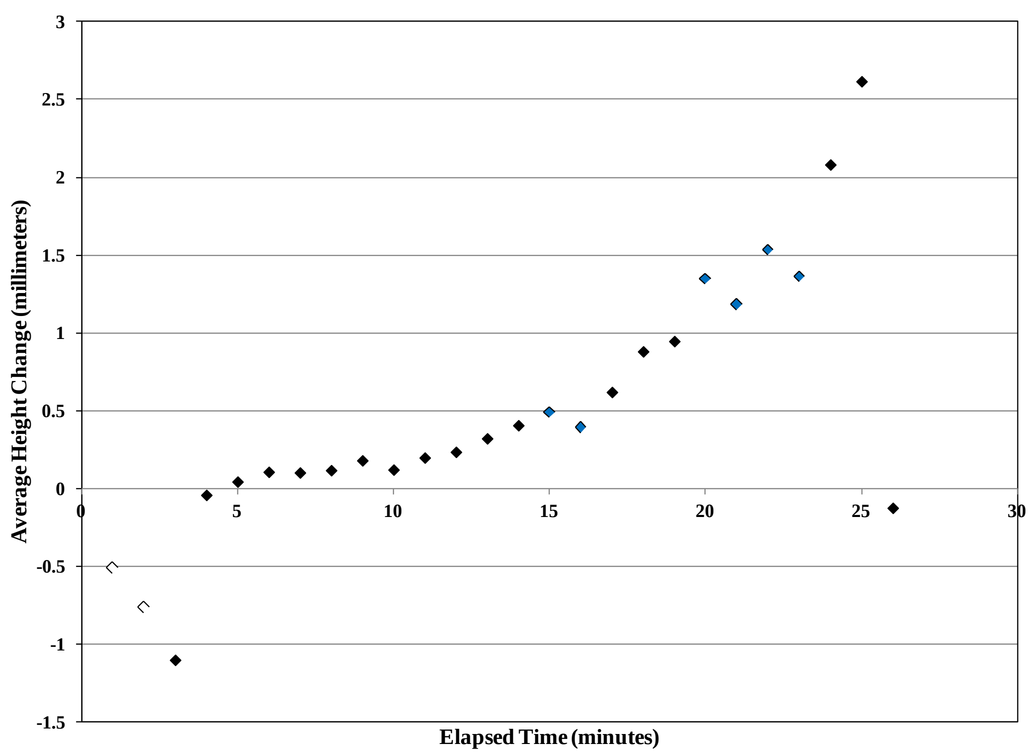

FIG. E- 9. "Clayton 29.0_7" EFA Test Results.

VELOCITY = 3.0 M/S

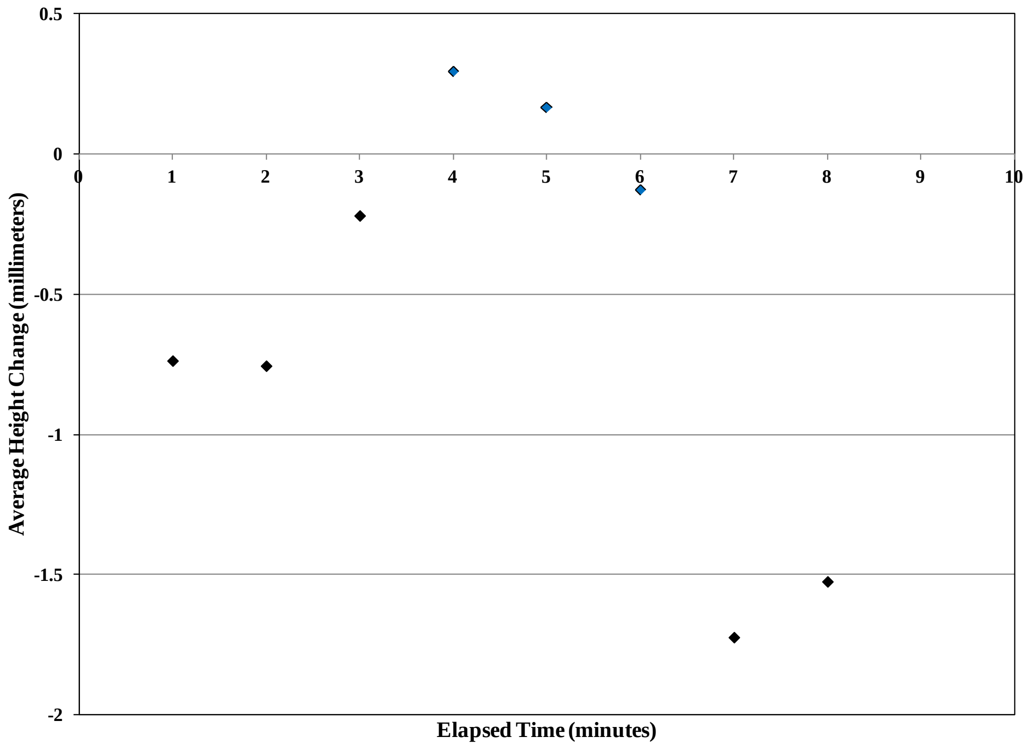

FIG. E- 10. "Clayton 29.0_2" EFA Test Results.

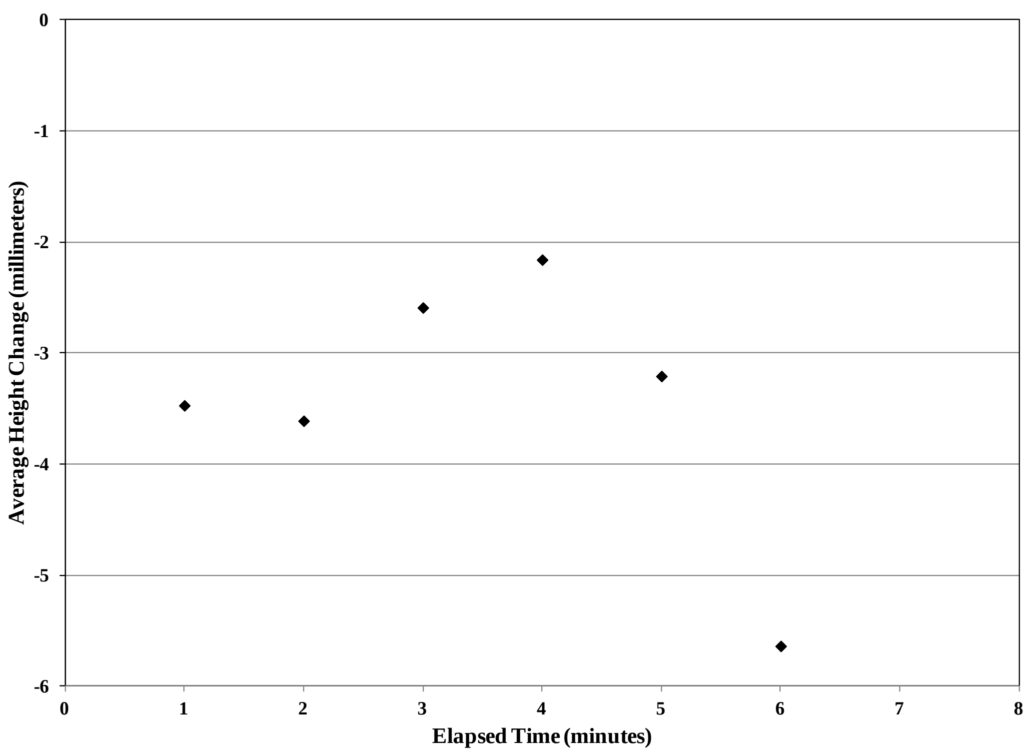

FIG. E- 11. "Clayton 29.0_5" EFA Test Results.

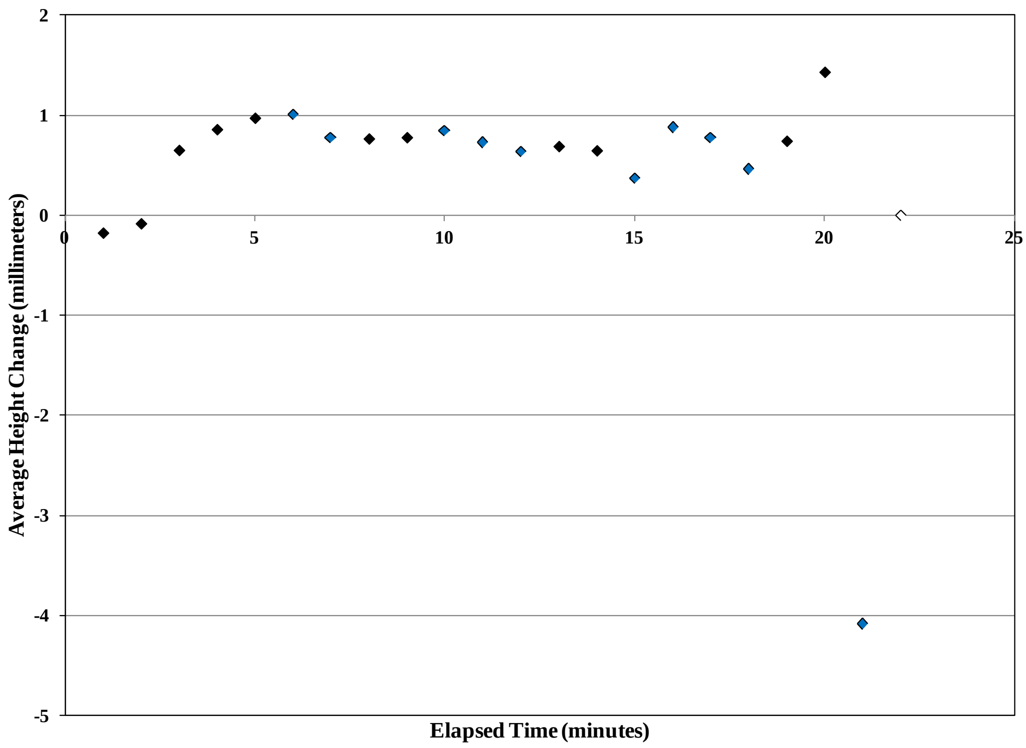

FIG. E- 12. "Clayton 29.0_8" EFA Test Results.

Appendix F – Bucatunna Clay

VELOCITY = 0.6 M/S

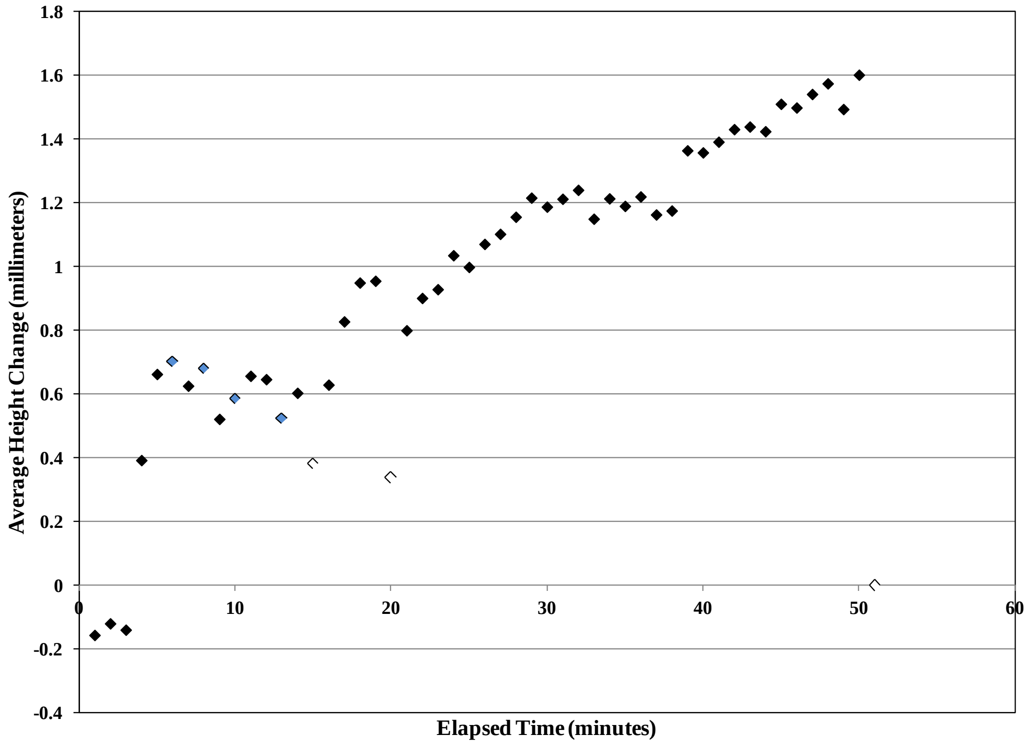

FIG. F- 1. "Bucatunna26.0_1" EFA Test Results.

VELOCITY = 1.0 M/S

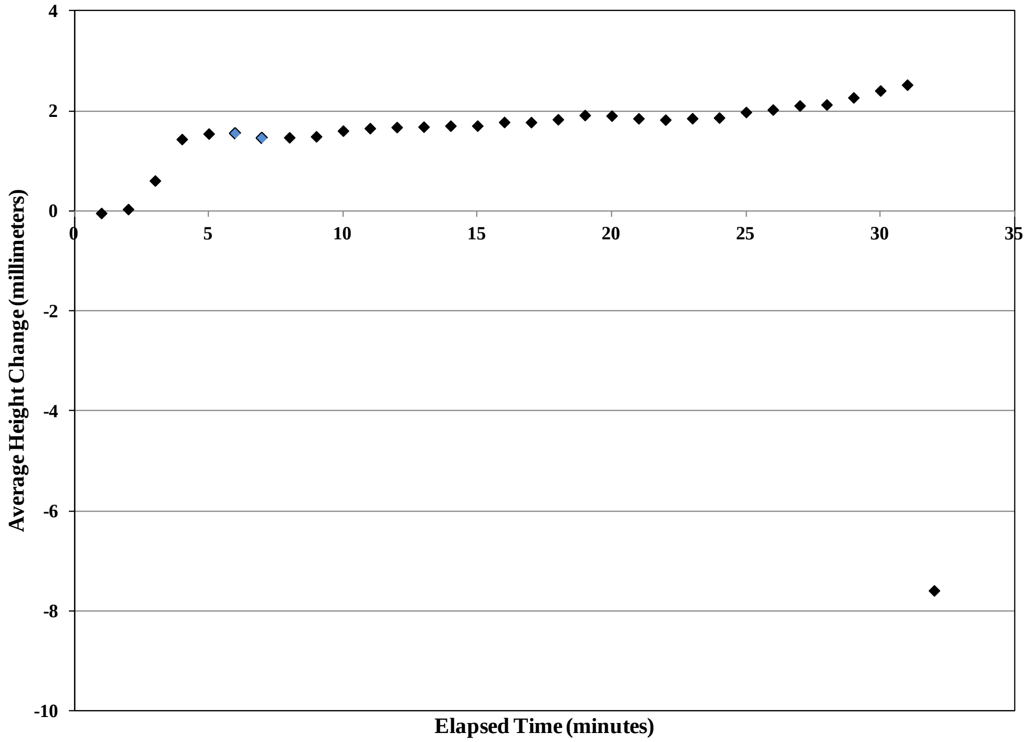

FIG. F- 2. "Bucatunna26.0_2" EFA Test Results.

VELOCITY = 2.0 M/S

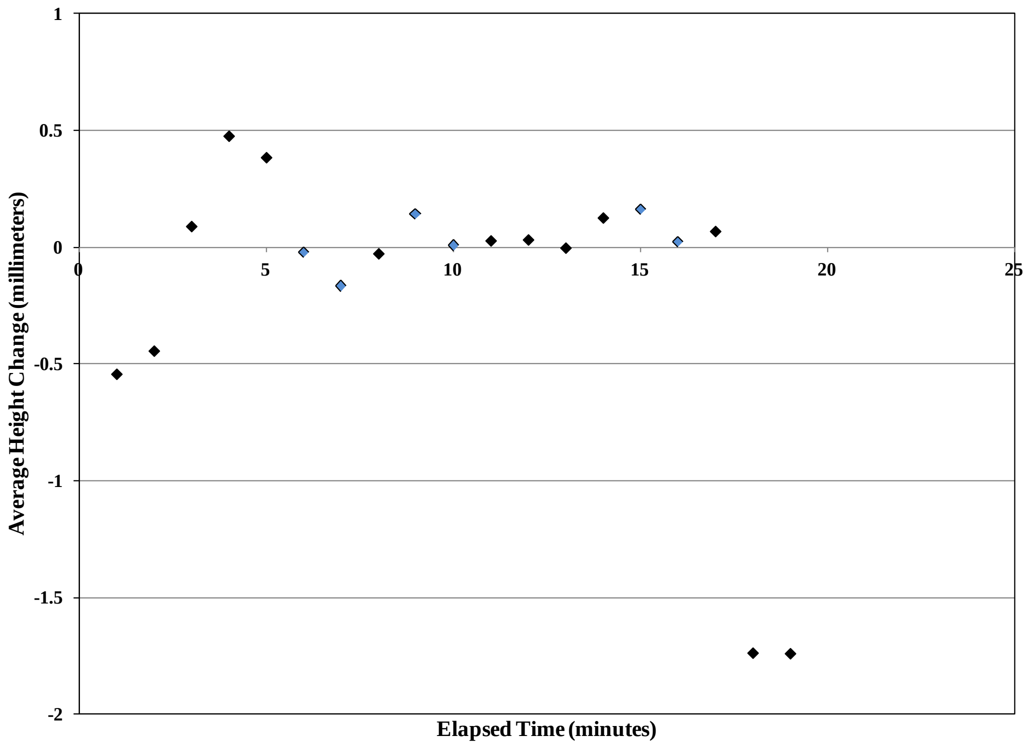

FIG. F- 3. "Bucatunna26.0_3" EFA Test Results.

VELOCITY = 3.0 M/S

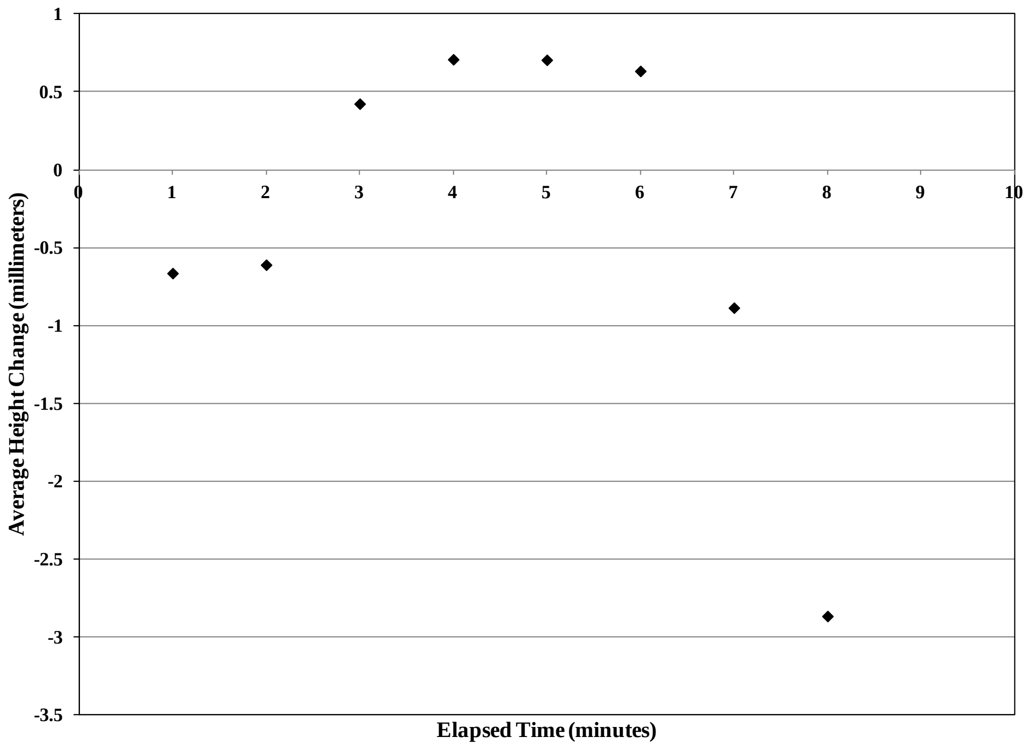

FIG. F- 4. "Bucatunna26.0_4" EFA Test Results.

Appendix G – Porter's Creek Clay

VELOCITY = 0.3 M/S

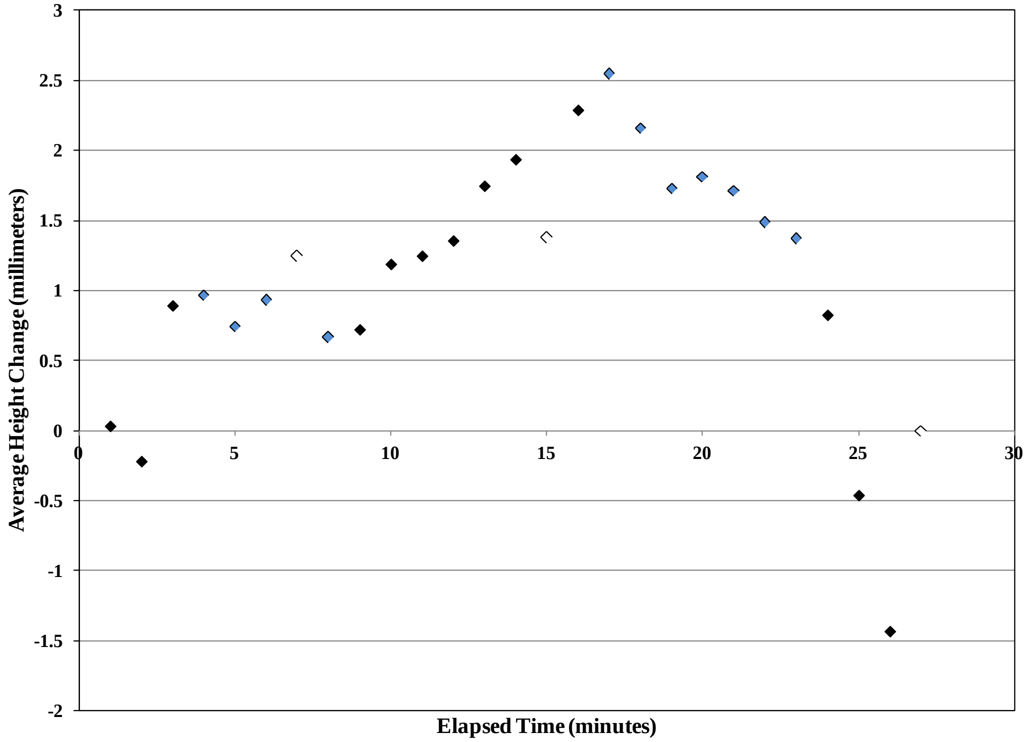

FIG. G- 1. "Porters Creek 24.0_4" EFA Test Results.

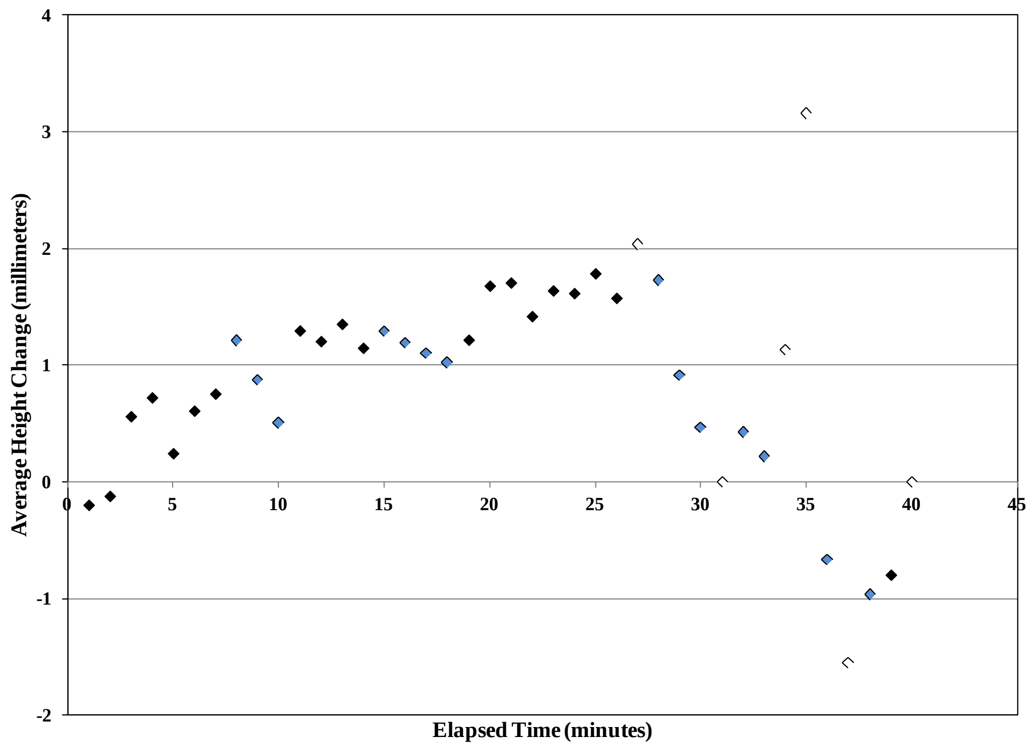

FIG. G- 2. "Porters Creek 24.5_1" EFA Test Results.

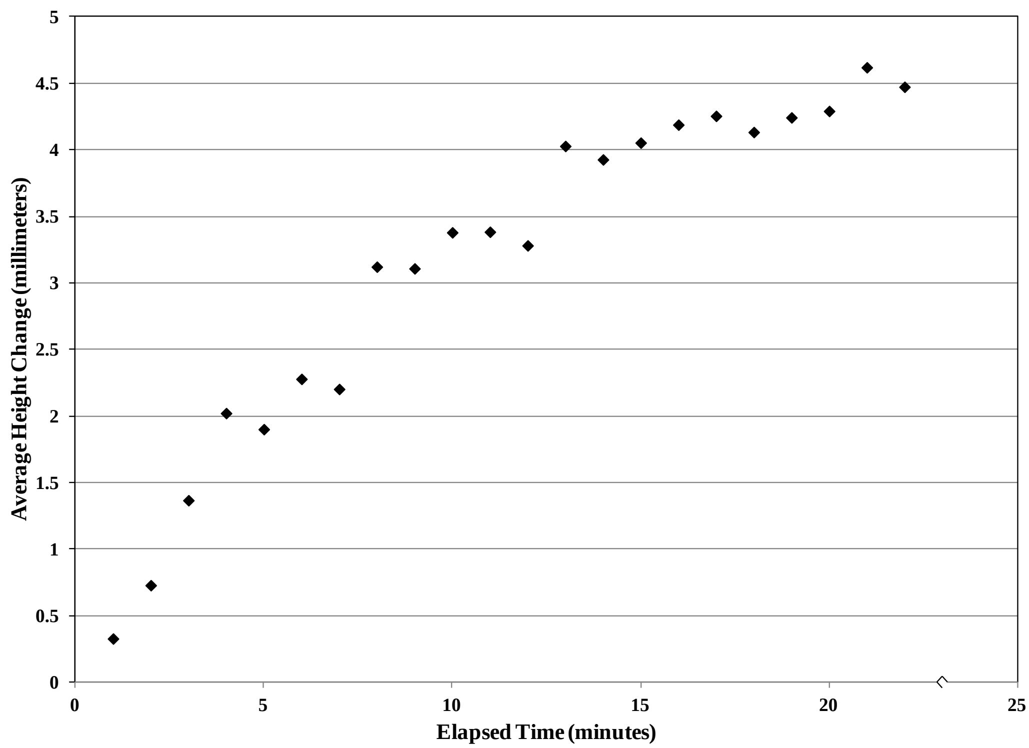

FIG. G- 3. "Porters Creek 24.5_5" EFA Test Results.

VELOCITY = 0.6 M/S

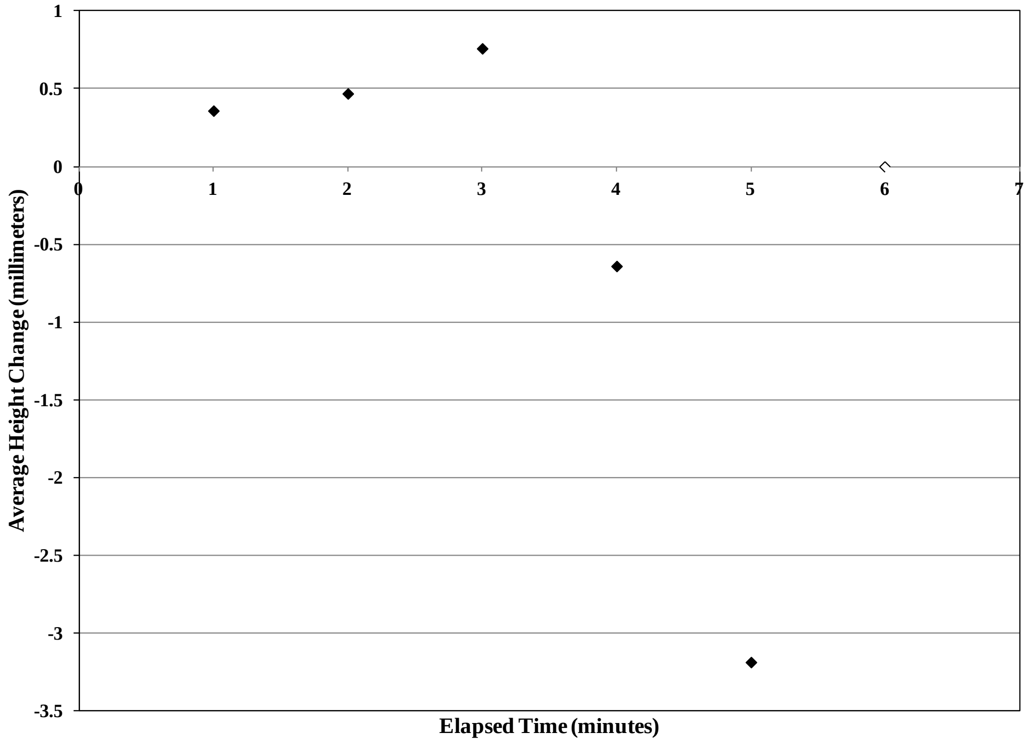

FIG. G- 4. "Porters Creek 24.0_1" EFA Test Results.

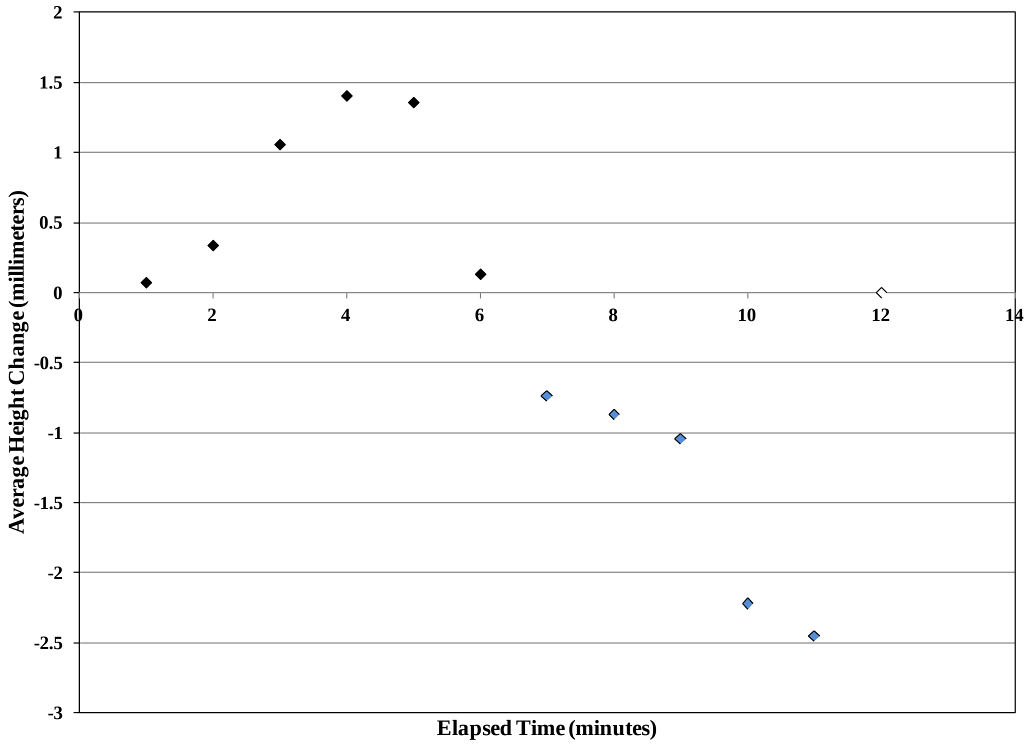

FIG. G- 5. "Porters Creek 24.5_2" EFA Test Results.

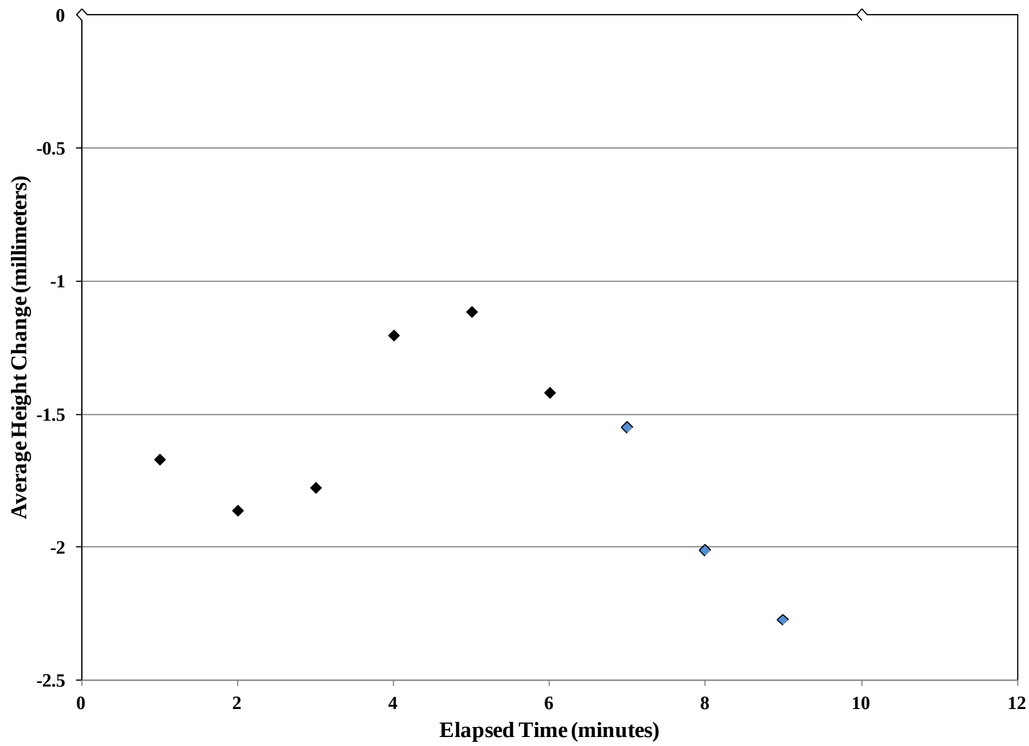

FIG. G- 6. "Porters Creek 24.5_3" EFA Test Results.

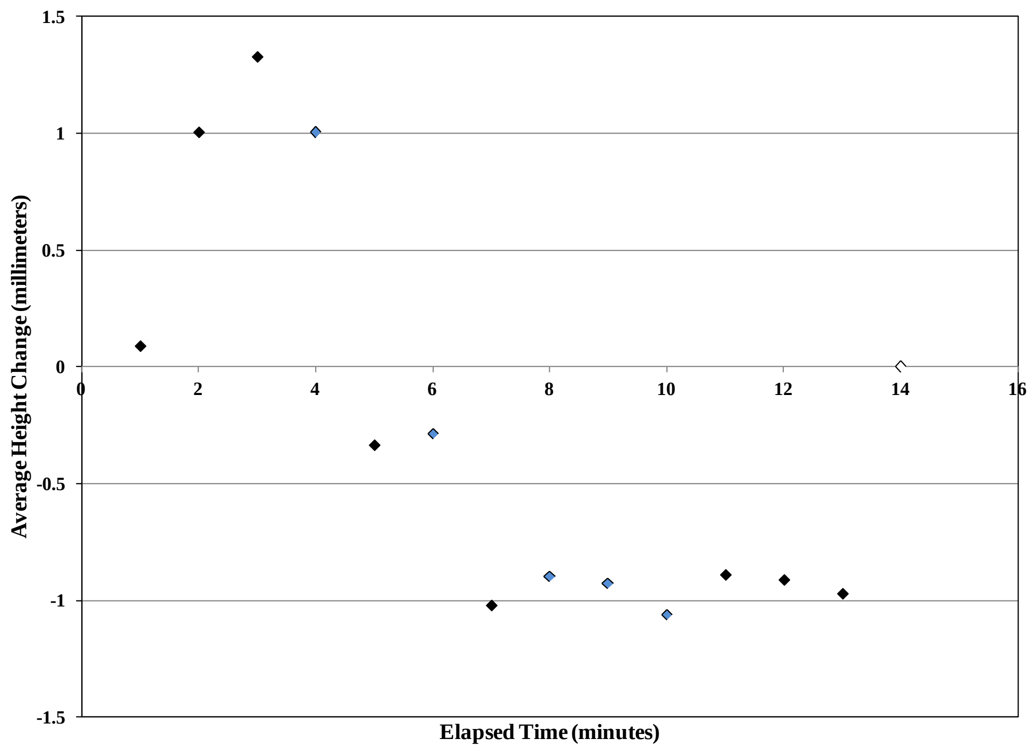

FIG. G- 7. "Porters Creek 24.5_4" EFA Test Results.

VELOCITY = 1.0 M/S

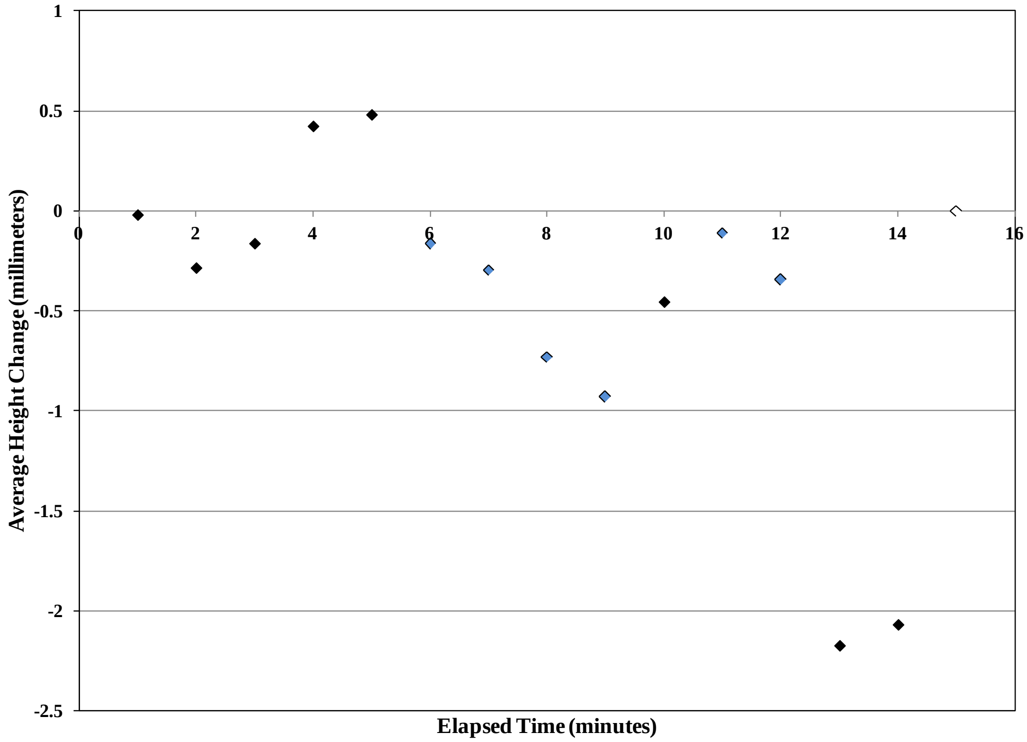

FIG. G- 8. "Porters Creek 24.0_2" EFA Test Results.

VELOCITY = 1.5 M/S

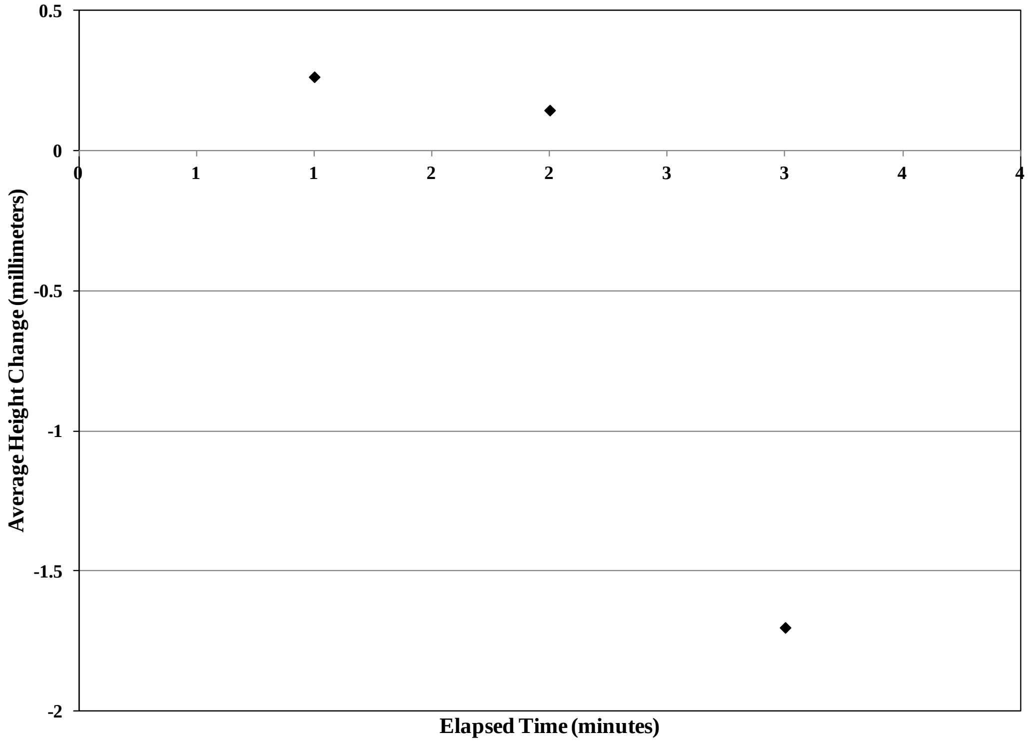

FIG. G- 9. "Porters Creek 24.0_3" EFA Test Results.

Appendix H – Yazoo Clay

VELOCITY = 0.6 M/S

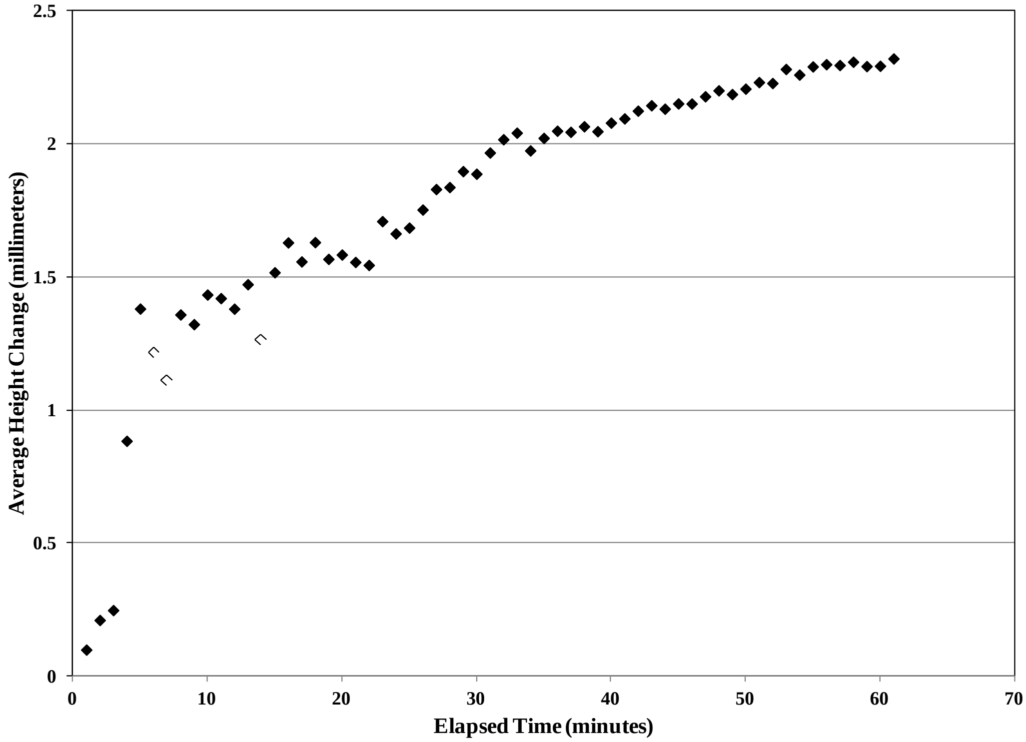

FIG. H- 1. "Yazoo 21.0_2" EFA Test Results.

VELOCITY = 1.0 M/S

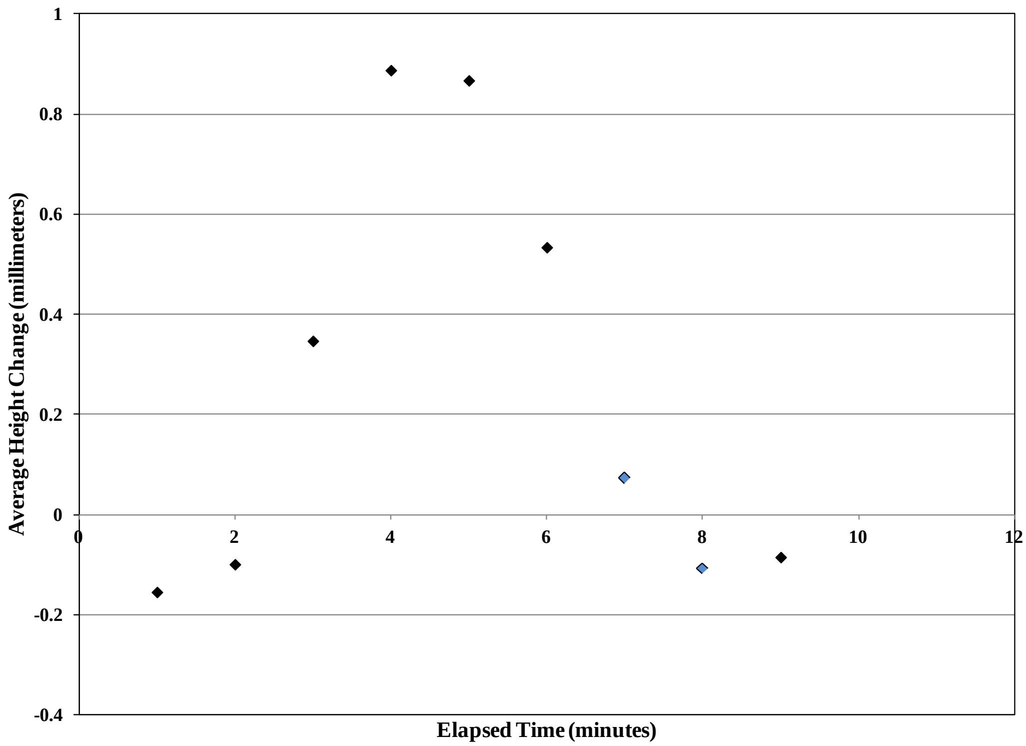

FIG. H- 2. "Yazoo 21.0_1" EFA Test Results.

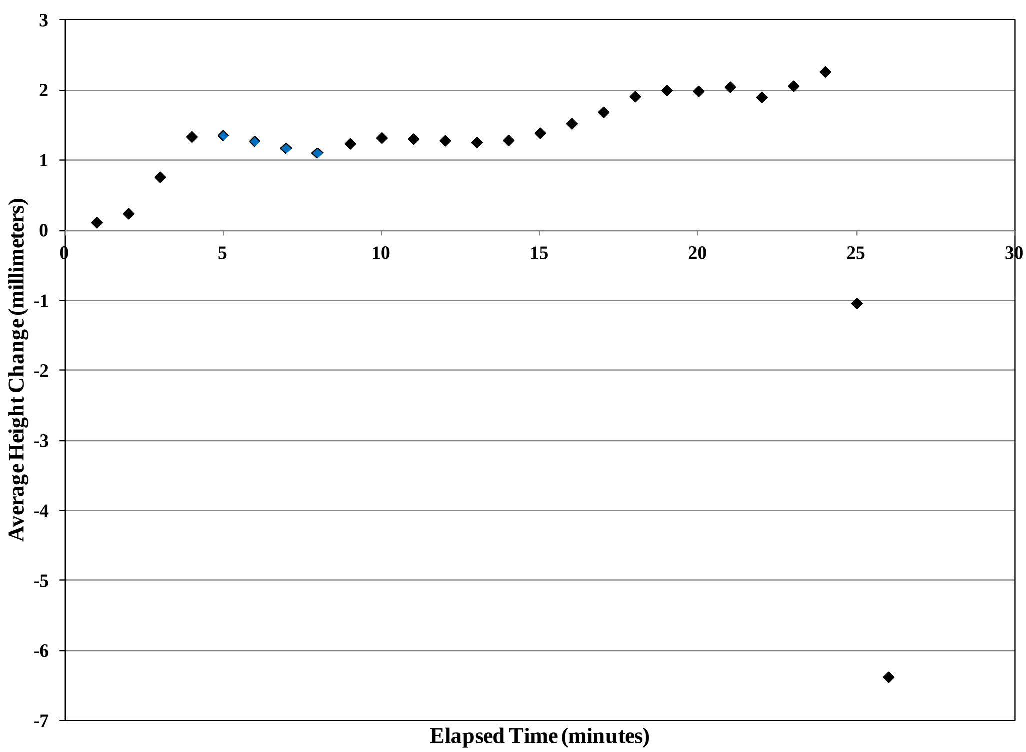

FIG. H- 3. "Yazoo 21.0_3" EFA Test Results.

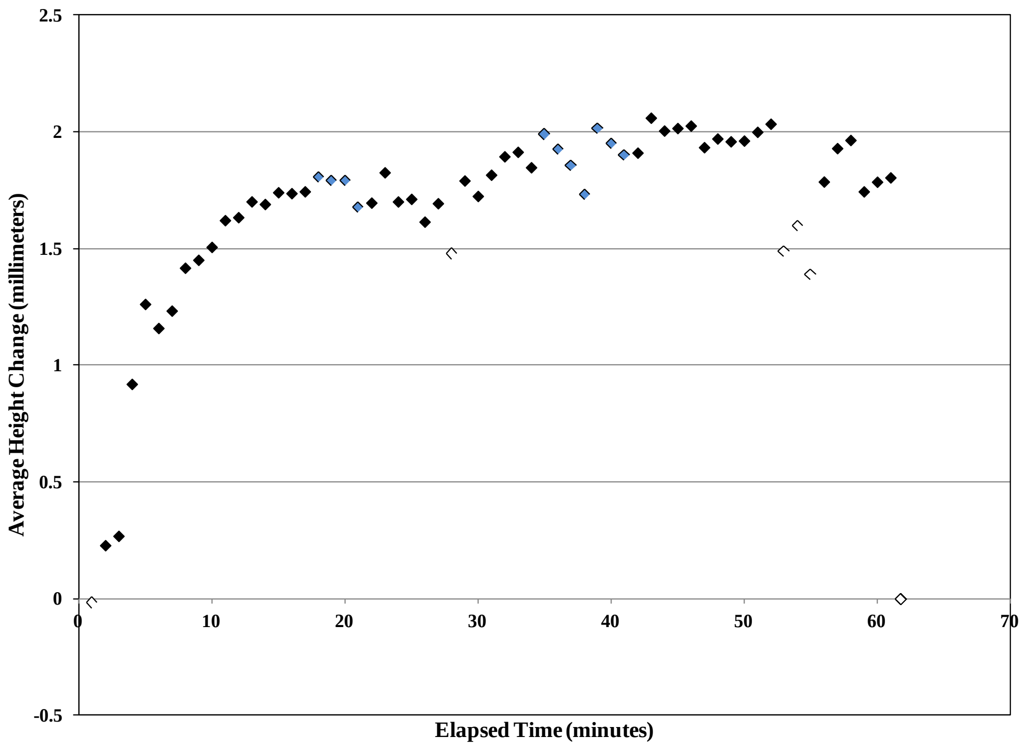

FIG. H- 4. "Yazoo 21.0_4" EFA Test Results.

VELOCITY = 1.5 M/S

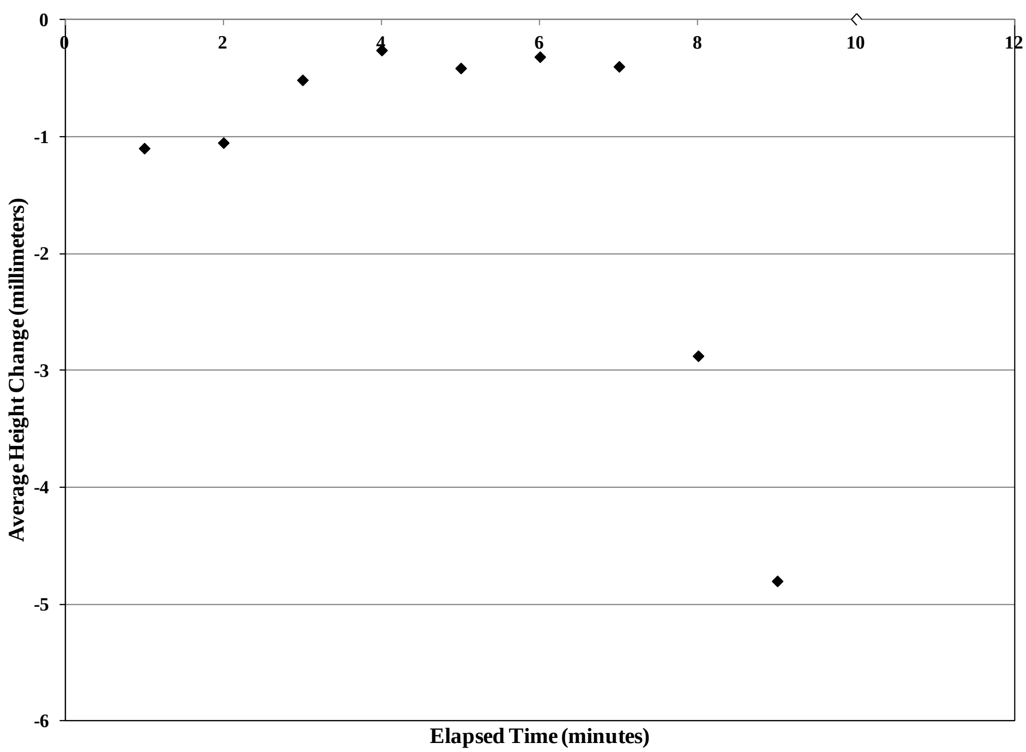

FIG. H- 5. "Yazoo 21.0_5" EFA Test Results.

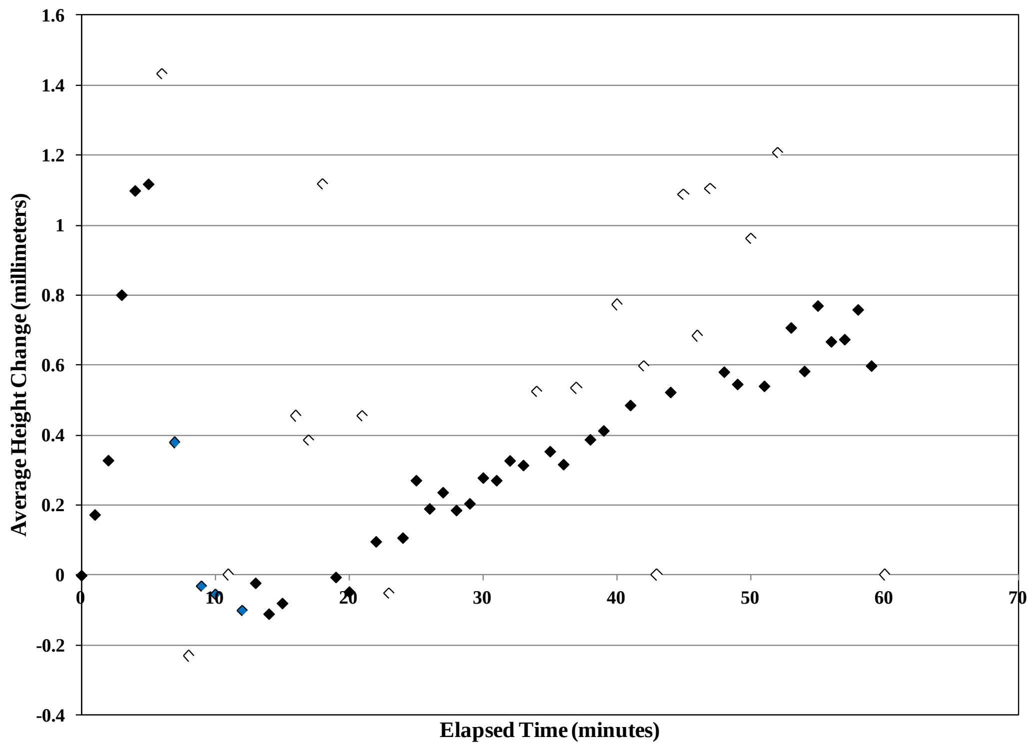

FIG. H- 6. "Yazoo 21.0_6" EFA Test Results.

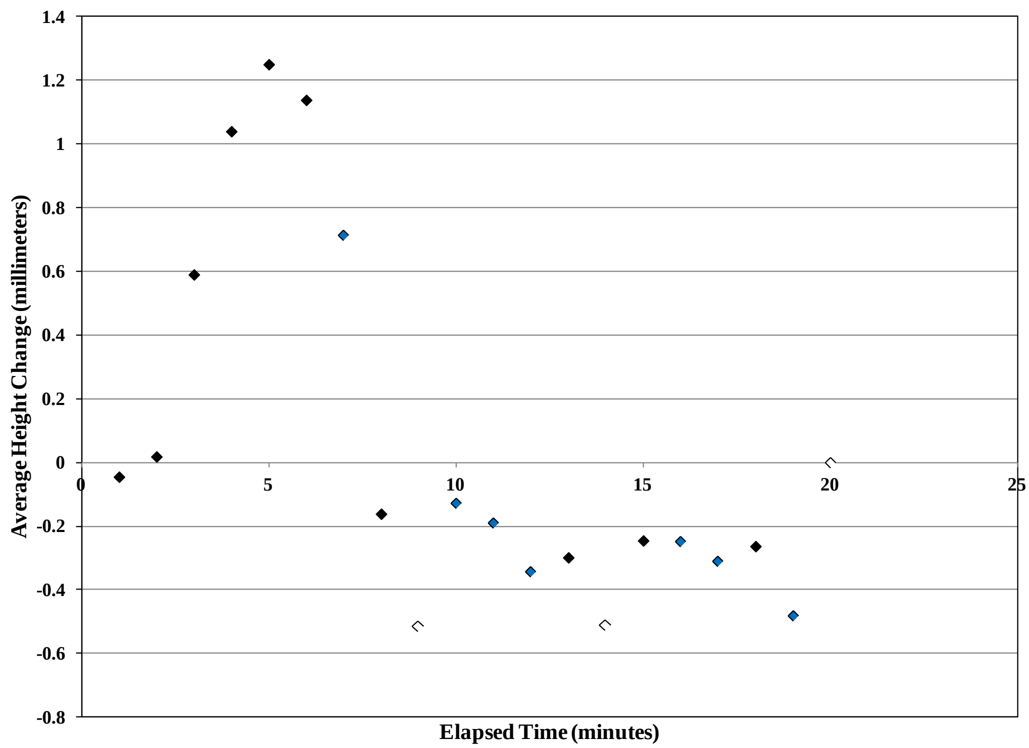

FIG. H- 7. "Yazoo 21.0_7" EFA Test Results.

VELOCITY = 2.0 M/S

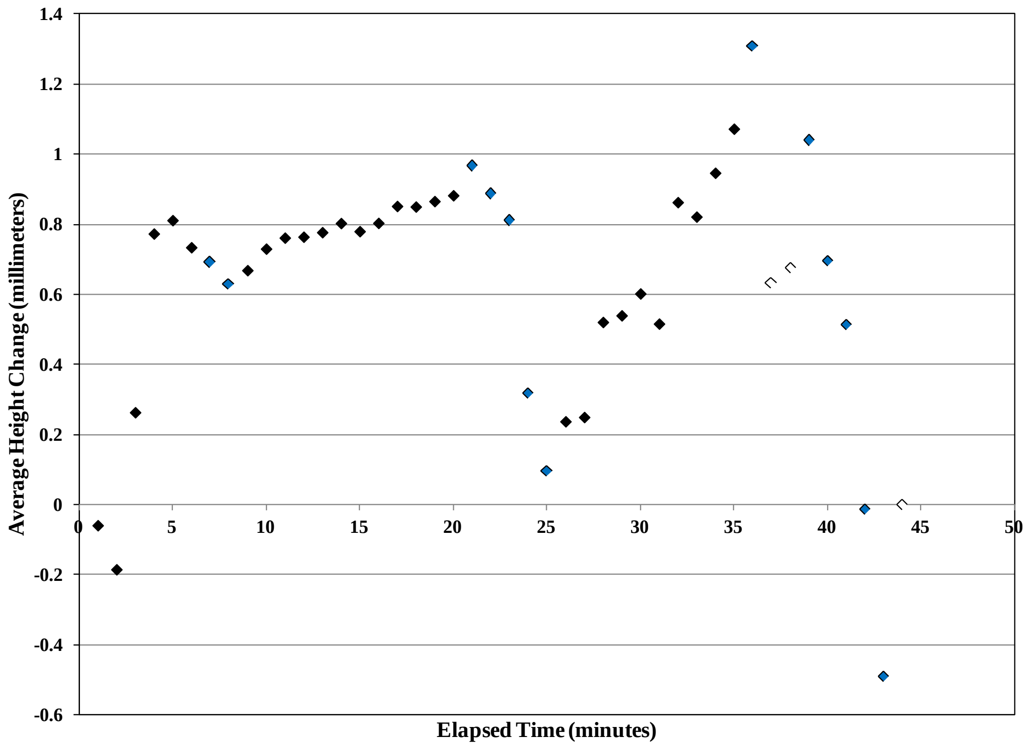

FIG. H- 8. "Yazoo 22.0_1" EFA Test Results.

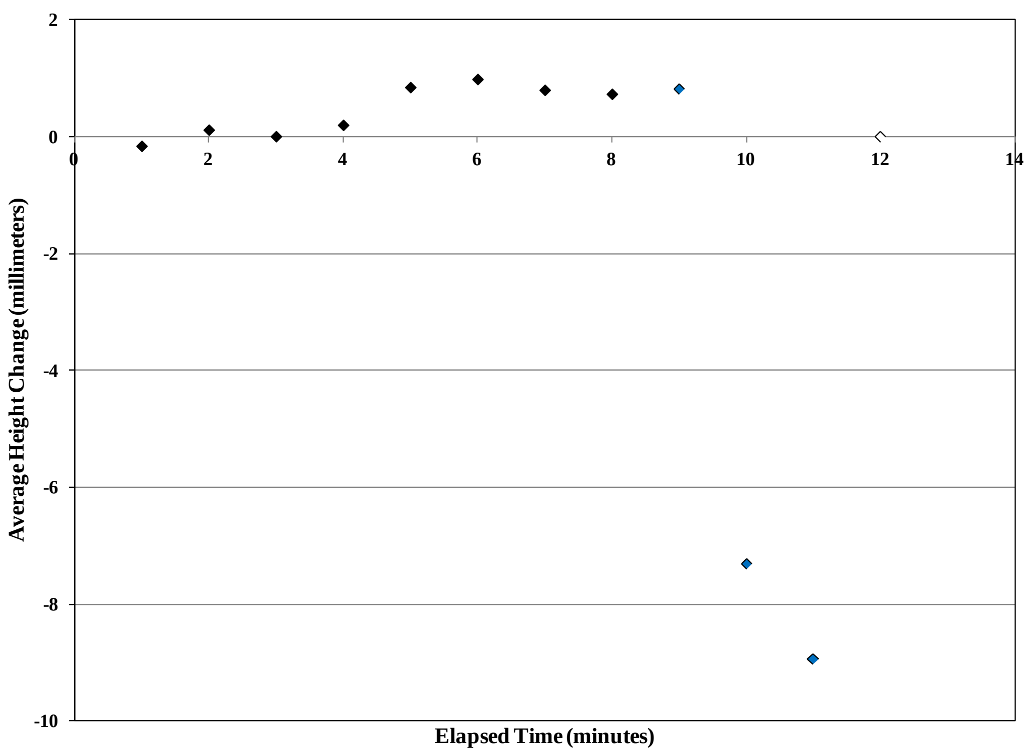

FIG. H- 9. "Yazoo 22.0_2" EFA Test Results.

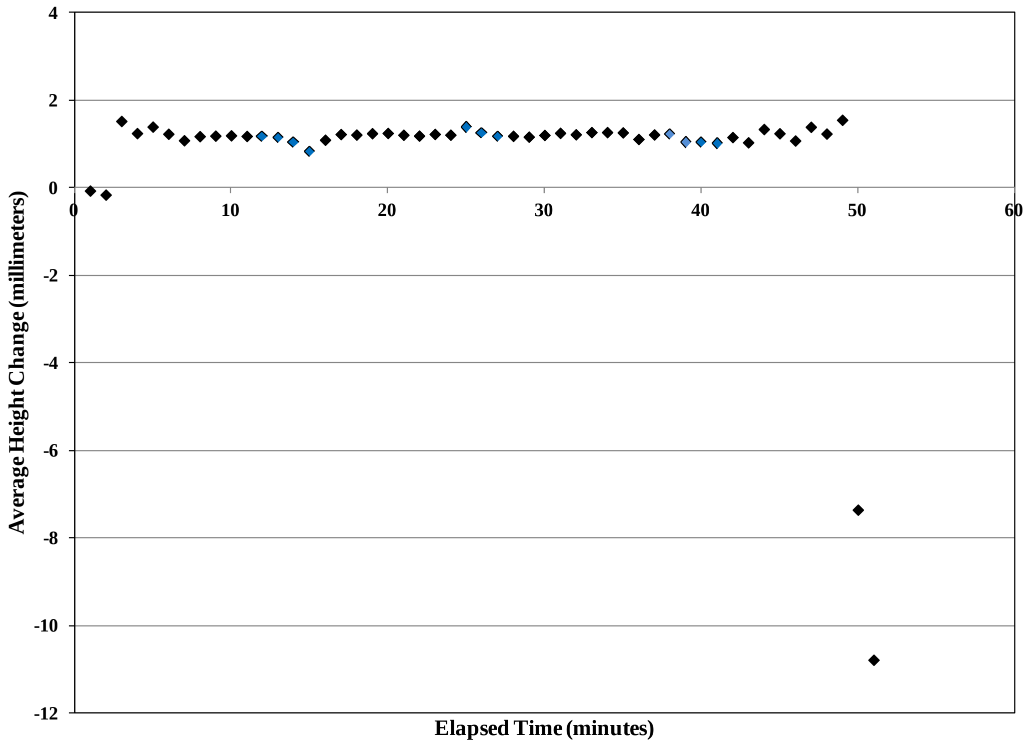

FIG. H- 10. "Yazoo 22.0_3" EFA Test Results.

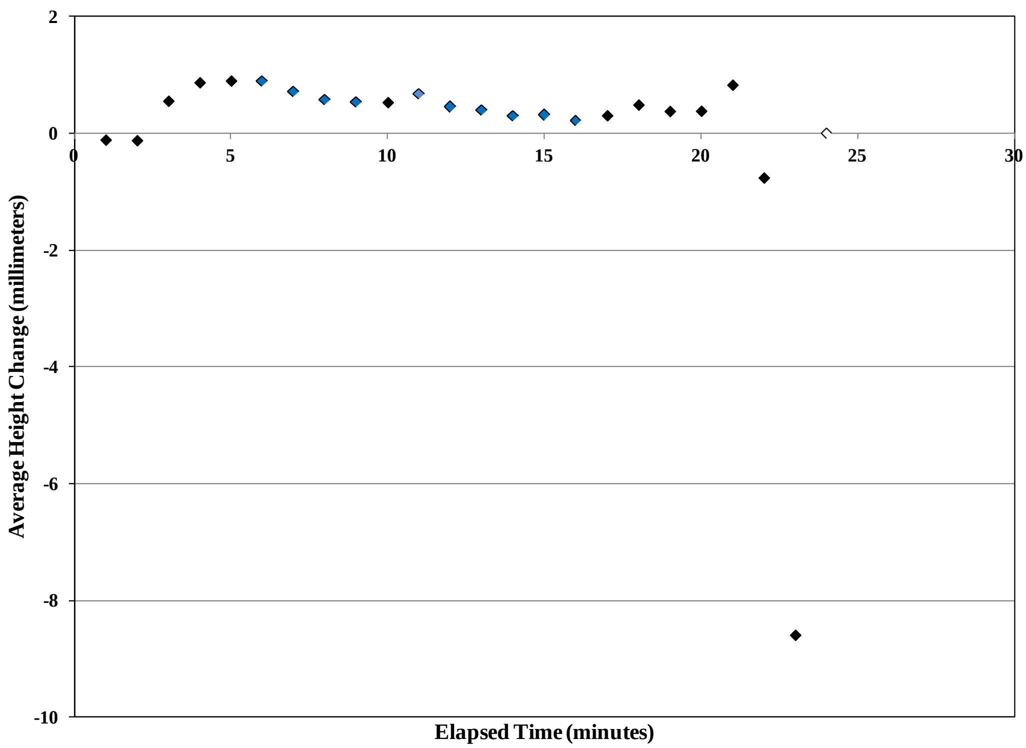

FIG. H- 11. "Yazoo 22.0_4" EFA Test Results.

VELOCITY = 3.0 M/S

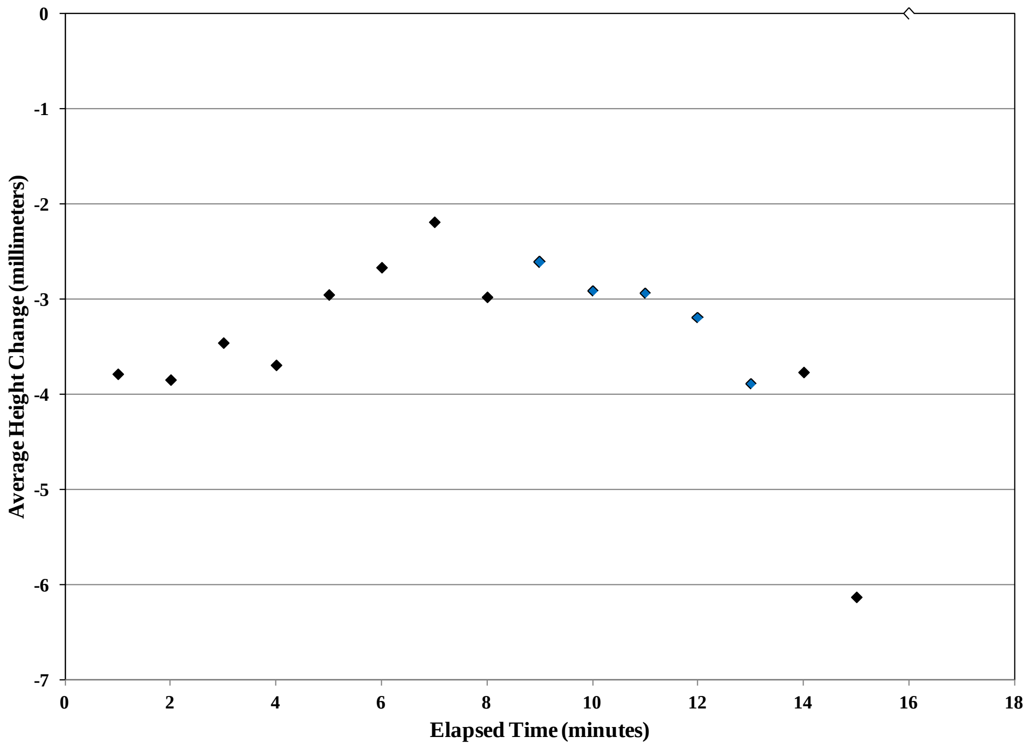

FIG. H- 12. "Yazoo 22.5_2" EFA Test Results.

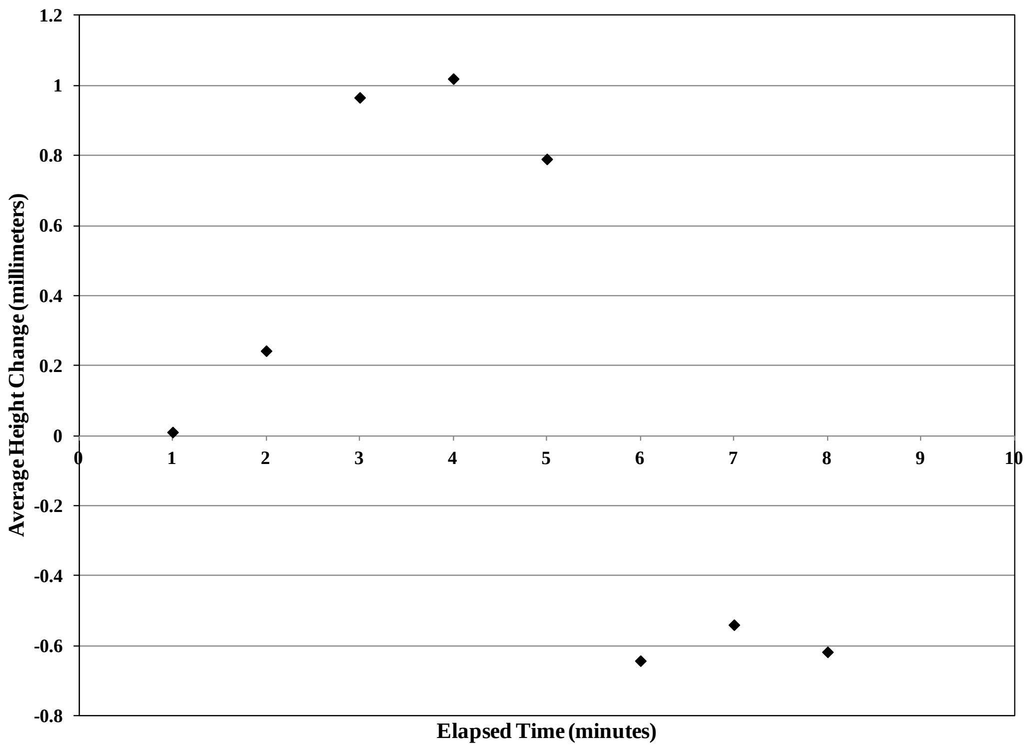

FIG. H- 13. "Yazoo 22.5_3" EFA Test Results.

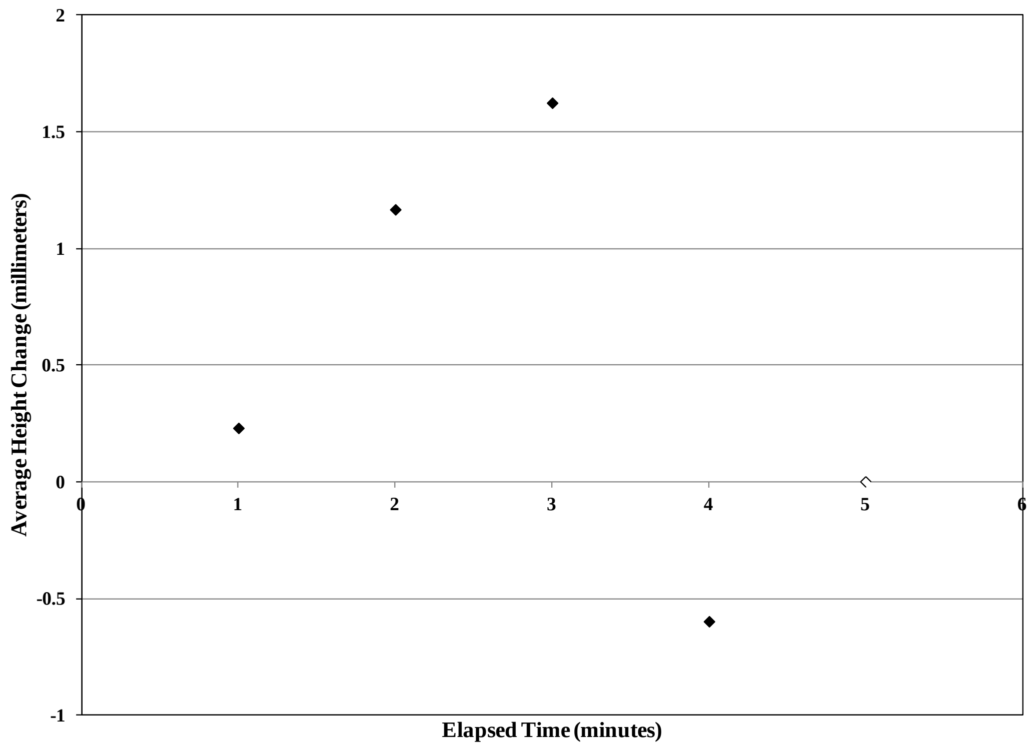

FIG. H- 14. "Yazoo 22.5_4" EFA Test Results.

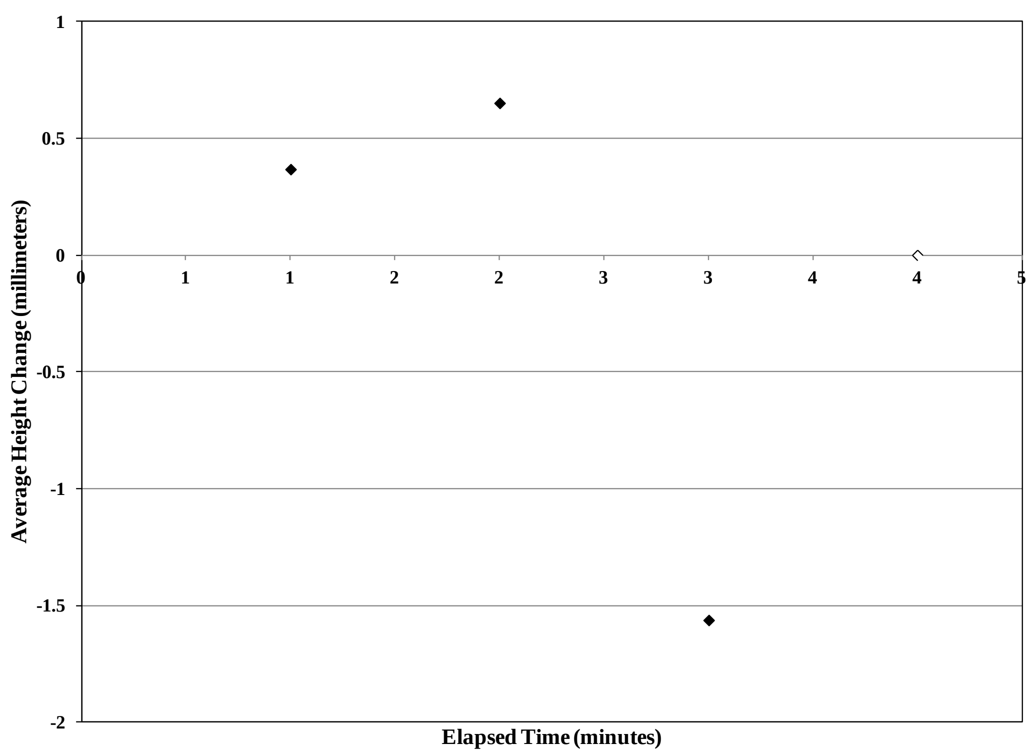

FIG. H- 15. "Yazoo 22.5_5" EFA Test Results.