Shear strength evaluation of an erosional soil system at Fourchon Beach

Jacques Pierre Boudreaux

Louisiana State University and Agricultural and Mechanical College, jboud43@tigers.lsu.edu

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_theses

Part of the Civil and Environmental Engineering Commons

Recommended Citation
https://digitalcommons.lsu.edu/gradschool_theses/2146

This Thesis is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Master’s Theses by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
SHEAR STRENGTH EVALUATION OF AN EROSIONAL SOIL SYSTEM AT FOURCHON BEACH

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science in Civil Engineering

in

The Department of Civil and Environmental Engineering

by
Jacques Pierre Boudreaux
B.S., Louisiana State University, 2009
August 2012
ACKNOWLEDGMENTS

I would first like to thank my mother, Silvana Vitorino Marinoff. This woman is by far the most caring, giving, and downright wonderful person I will ever know. For the seven years I spent at Louisiana State University (LSU), the amount of love and support I’ve received from her isn’t but the tip of the iceberg compared to the amount I’ve received in the twenty-four years of my life. Having someone like her throughout my college years, though, has been an invaluable asset and has given me peace of mind during very dark times. My mother praying for me to do well in school has basically kept me from quitting in the middle of my studies. Without her, this thesis simply would not be.

I would like to thank my advisor, Dr. John Pardue, whose perpetual encouragement and stature as one of the most innovative engineers and researchers in the country have motivated me to accomplish the tasks throughout my graduate study. Without his support, my authoring of this thesis would not have happened. I would also like to thank the members of my research committee: Dr. Guoping Zhang and Dr. Clinton Willson. It is the work of these gentlemen that puts LSU on the map for coastal research, and it is by their good graces and expertise as mentors that this thesis was able to be produced. I would like to thank Dr. Vijaikrishnah Elango for his unwavering sense of direction and endless supply of help towards the assembly of this thesis. I would also like to thank the faculty, staff, and members of the LSU Graduate Student Body in the Department of Civil & Environmental Engineering. Some of these students are: Seth Bradley, Marilany Urbano, Kendall Lemelle, Josef Hoffman, Samuel Best, Zachary Autin, James Chataigner, Christopher Akudo, Kahlia Gager, Yiyung Yue, Zaihong Zhang, Dan Hu, Alex Boudreau, Matt Rodrigue, Jacob Dillehay, and many more. Don Colvin of the LSU Mechanical Engineering Machine Shop was of great assistance to this research and to him sincere
appreciation is owed. A special thanks goes to the facility services employees of LSU, with many of whom I frequently crossed paths and got to know quite well, who relentlessly maintain one of the most unique and beautiful campuses in the world.

Many transformations have occurred in my life since my first day of college in August 2005. To say that LSU has endured a profound amount of change during my tenure here would be an accurate assessment. The most disappointing change I have experienced has probably been the handling of budget reduction issues within the last few years. Governor Jindal’s austerity combined with the LSU System’s reactions to these measures has created serious problems for the flagship university of Louisiana. This has resulted in a sickness that is already producing symptoms that will certainly be felt for years to come.

This thesis is dedicated in loving memory to Dennis John Boudreaux, who took me on many a trip to Fourchon Beach to show me how to catch fish and drink beer. It was this person, my father, who first introduced me to the unique location that this thesis is based upon.
# TABLE OF CONTENTS

ACKNOWLEDGMENTS ........................................................................................................... ii  
LIST OF TABLES ................................................................................................................... vi  
LIST OF FIGURES ................................................................................................................ vii 
ABSTRACT ............................................................................................................................. viii 

CHAPTER 1: INTRODUCTION ................................................................................................. 1  
1.1 Introduction and Background Information ................................................................... 1  
1.1.1 Coastal Louisiana Land Loss ......................................................................................... 1  
1.1.2 Ecological Engineering .................................................................................................. 3  
1.1.3 Description of Project Site .............................................................................................. 4  
1.2 Literature Review ............................................................................................................. 6  
1.2.1 Soil Shear Strength ....................................................................................................... 6  
1.2.2 Land Erosion and Its Relation to Soil Shear Strength .................................................. 6  
1.2.3 The Role of Plant Roots on Soil Shear Strength ............................................................ 8  
1.2.4 The Effect of Oil Spills on Soil Strength ....................................................................... 10  
1.3 Direct Shear Testing ....................................................................................................... 11  
1.3.1 Technical Approach ...................................................................................................... 11  
1.3.2 Theory and Pertinent Equations ................................................................................... 15  
1.4 Objectives and Layout of This Thesis ............................................................................ 17  

CHAPTER 2: EFFECTS OF WETLAND VEGETATION ESTABLISHMENT ON SOIL SHEAR  
STRENGTH ........................................................................................................................... 19  
2.1 Introduction ..................................................................................................................... 19  
2.2 Materials and Methods .................................................................................................. 20  
2.2.1 Greenhouse Study ....................................................................................................... 20  
2.2.2 Laboratory Details ..................................................................................................... 24  
2.2.3 Computational Details ............................................................................................... 26  
2.2.4 Measurements ........................................................................................................... 26  
2.3 Results and Discussion .................................................................................................. 29  
2.3.1 Test Results ............................................................................................................... 29  
2.3.2 Shear Strength Benefit Index ...................................................................................... 35  
2.4 Field Investigation ....................................................................................................... 36  
2.5 Conclusions .................................................................................................................... 40  

CHAPTER 3: SHEAR STRENGTH CHANGES ACROSS AN EROSIONAL COASTAL HEADLAND  
ENVIRONMENT .................................................................................................................... 41  
3.1 Introduction ..................................................................................................................... 41  
3.2 Materials and Methods ................................................................................................. 43  
3.2.1 Study Location ......................................................................................................... 43  
3.2.2 Laboratory Details ................................................................................................... 48  
3.2.3 Computational Details ............................................................................................... 50  
3.2.4 Measurements ........................................................................................................... 53  
3.3 Results and Discussion ................................................................................................. 60  
3.4 Applications ................................................................................................................... 71
3.4.1 Erosion Modeling and Implications for Restoration ........................................... 71
3.4.2 Vegetation and Cohesive Soils: A Mutually Beneficial Relationship ............... 77
3.4.3 Influence of Oil Spill Response and TS Lee ...................................................... 78

3.5 Conclusions ........................................................................................................... 80

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS ........................................ 82
4.1 Conclusions ............................................................................................................ 82
4.2 Recommendations for Future Research .............................................................. 83

REFERENCES ............................................................................................................. 85

APPENDIX A: DIRECT SHEAR TEST OUTPUT CURVES ........................................ 90
APPENDIX B: MANUFACTURER DIAGRAM OF DIRECT SHEAR MACHINE SETUP .... 115
VITA ............................................................................................................................ 117
LIST OF TABLES

Table 1: Normal Stress Calculations ........................................................................................................... 25
Table 2: List of Direct Shear Tests .................................................................................................................. 27
Table 3: 4-Week Direct Shear Test Results .................................................................................................... 30
Table 4: 8-Week Direct Shear Test Results ................................................................................................... 33
Table 5: 12-Week Direct Shear Test Results ................................................................................................ 34
Table 6: Normal Stress Calculations ............................................................................................................... 49
Table 7: List of Direct Shear Tests .................................................................................................................. 54
Table 8: Laboratory Data for Fourchon Beach Sand Samples ................................................................. 62
Table 9: Laboratory Data for Fourchon Beach Marsh Samples ............................................................... 65
Table 10: Shear Stresses Due to Waves ......................................................................................................... 74
Table 11: Erosion Rates ................................................................................................................................. 75
LIST OF FIGURES

Figure 1: Historical Locations of the Mississippi River Delta ............................................................. 3
Figure 2: Vicinity Map of Project Site .................................................................................................... 5
Figure 3: Site Map of Fourchon Property ............................................................................................... 5
Figure 4: Direct Shear Machine ............................................................................................................. 12
Figure 5: Shearbox Diagram ................................................................................................................ 14
Figure 6: Shear Schematic .................................................................................................................... 15
Figure 7: Weekly Tracking Photograph (Scirpus americanus) .............................................................. 22
Figure 8: Weekly Tracking Photograph (Scirpus acutus) ..................................................................... 22
Figure 9: Core Extraction ..................................................................................................................... 23
Figure 10: AGB Removal from SRC .................................................................................................... 23
Figure 11: Typical Plot of τ vs. σ ........................................................................................................... 28
Figure 12: Typical Plot of τ vs. Δx ......................................................................................................... 28
Figure 13: Typical Stem Count Graph .................................................................................................. 29
Figure 14: Shear Strength Benefit Index ............................................................................................... 36
Figure 15: Plot of τ vs. Δx for Spartina alterniflora obtained from Fourchon Beach ......................... 38
Figure 16: Typical Soil Cross-Section at Fourchon Property .............................................................. 44
Figure 17: Map of Fourchon Property With Sampling Locations ....................................................... 45
Figure 18: Typical Plot of τ vs. Δx ........................................................................................................... 59
Figure 19: Typical Plot of Δz vs. Δx ...................................................................................................... 59
Figure 20: Plot of Residual Shear Strength vs. Normal Stress—Beach Sands ..................................... 60
Figure 21: Plot of Residual Shear Strength vs. Normal Stress—Marsh Clays ....................................... 61
Figure 22: Overwash Fan at the Fourchon Property ............................................................................. 79
ABSTRACT

South Louisiana is vanishing. Subsidence due to relative sea level rise with erosion of weak wetland soils together produce devastating rates of land loss for this area. It is believed that high rates of erosion are due to weak strength properties of fine-grained sediments in the beaches, marshes, and other wetlands in coastal Louisiana. Wave action is known to initiate the movement of weak coastal soils in a manner that is related to the difference between the shear stresses applied by waves and the critical shear strength of erosional sediments.

Direct shear tests were performed on samples obtained from the field at Fourchon Beach, Louisiana, as well as on samples that were cultivated in a known soil media within a controlled environment. The role of plant roots on soil shear strength was studied by examining changes in the shear strength of vegetated soil-root composites (SRCs). Two species were used to create SRC direct shear test specimens: *Scirpus americanus* and *Scirpus acutus*. Samples were grown in fully-saturated conditions in a greenhouse, and tests were conducted on samples after 4, 8, and 12 weeks of growth after planting. A matured sample of *Scirpus acutus*, which contained a highly developed root system, was also sampled and tested. Both species were observed to add benefits in shear strength with increased effectiveness after longer growth periods. Findings indicated that *Scirpus americanus*, being more resilient during cultivation and having higher growth rates, provided the most benefits by increasing shear strength upwards of 30 percent in as little as eight weeks after planting.

Field samples were obtained from five areas at Fourchon Beach across an elevational gradient from the intertidal shoreline area to the heavily vegetated marshes containing a variety of plants, specifically *Avicennia germinans* and *Spartina alterniflora*. A sample of relict marsh
clay was also obtained from the shoreline area and tested in addition to beach sand that had been treated by workers in the aftermath of the BP oil spill. Erosion rates were calculated using a method developed for fine-grained estuarine sediments.
CHAPTER 1: INTRODUCTION

1.1 Introduction and Background Information

1.1.1 Coastal Louisiana Land Loss

Coastal Louisiana is disappearing at a staggering rate. As many as 35 square miles of coastal marshland and other wetland ecosystem environments are being lost each year (Barras, et al. 1994). Nearly 2,000 square miles of coastline have vanished since the 1930s (Couvillion, et al. 2011; EDF 2011). This is the equivalent of losing one football field every 38 minutes (Davis-Wheeler 2000). Yearly, several thousand acres of wetlands are eroded and converted to open water due to complex morphological processes, both natural and human-induced. This poses enormous problems for the State of Louisiana and ultimately for the United States of America, as coastal Louisiana is home to a diverse variety of ecology and wildlife as well as being a major contributor to the national economy in industries such as oil and gas operations, shipping, importing/exporting, seafood, and many more.

Coastal Louisiana was formed by the continual deposition of sediments from the Mississippi River. Weaving in and out of river alignments across the entire delta plain, the sediment-laden waters of the river overflowed and deposited minerals and nutrients effectively creating all of the south Louisiana deltaic plain with historical delta reaches spanning a range from as far west as the Vermillion Bay to as far east as the St. Benard Parish-Mississippi State line. Figure 1 shows former locations of the delta lobes corresponding to different eras of historic time.
During the 1930s, in response to floods that threatened development near the river banks, a flood protection system was implemented that to this day constricts the path of the Mississippi. It is the engineering of these levees and the policies upheld by the United States Army Corps of Engineers (USACE) Mississippi River Commission that is responsible for the loss of sediment deposition and nutrient replenishment in coastal Louisiana (Barry 1997). While once having regularly and naturally fed Louisiana wetlands, the very floodwaters that fathered the most agriculturally productive farmland in the nation are now directed offshore to the Gulf of Mexico in a location where the continental shelf becomes too deep for wetlands to form (Dokka 2006; Dokka, et al. 2006). The supply of sediments that formerly spilled over the banks along the length of the river has been all but eliminated—an alteration that has had a significant negative impact on the barrier islands and wetlands of coastal Louisiana (Dean 2006). In addition to this, widespread canalling within Louisiana’s coastal region has resulted in significant amounts of land loss (Davis-Wheeler 2000), which is believed to have an indirect but degenerative effect on other wetlands (Mendelsssohn 2010).

Land loss can be related to poor soil quality. High rates of erosion are due to generally weak soil shear strength (Nugent 2011; Leonard and Richard 2004; Watts, et al. 2003; Davis-Wheeler 2000). Rapid settlement of the land, or subsidence, is the reduction in ground surface elevation. Subsidence can occur due to a variety of factors, both natural and human-induced, such as: sediment compaction, organic matter oxidation, faulting, cyclonic downwarping of the crust due to regional loading, and fluid withdrawal for oil and gas activity (Mendelsssohn 2010; Georgiou, et al. 2005). Researchers attribute subsidence as a major factor to Louisiana land loss with reduction rates in ground surface elevation on average of 1.5 mm/yr, as high as 10 mm/yr in New Orleans, and as high as 25 mm/yr in certain locations in the Mississippi river delta region.
(Blum, et al. 2008; Dokka 2006; Dokka, et al. 2006; Shinkle and Dokka 2004). In summary, Louisiana soils are vulnerable to high rates of land loss due to a complex set of circumstances, with erosion and subsidence being particularly influential.

Figure 1: Historical Locations of the Mississippi River Delta

1.1.2 Ecological Engineering

*Ecological engineering* is “the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both” (Mitsch and Jorgensen 2004). It is the creating or restoring of ecosystems to serve as engineering solutions that have value to both nature and humans. The two goals of ecological engineering are: 1) the restoration of ecosystems that have been substantially disturbed by human activities such as environmental pollution or land disturbance, and 2) the development of new sustainable ecosystems that have both human and ecological value (Mitsch and Jorgensen 2004). Ecological engineering is a multidisciplinary profession that implements quantitative approaches in science and ecology to
manage the self-organization tendencies of natural processes to establish a mutually beneficial partnership between humans and nature. *Ecosystem restoration* and *restoration ecology* refer to “the return of an ecosystem to a close approximation of its condition prior to disturbance,” as defined by the National Research Council.

1.1.3 Description of Project Site

Fourchon Beach is an area on the Louisiana Gulf Coast located in south Lafourche Parish approximately 15 miles west of Grand Isle. Accessible via Louisiana Highway 3090 (from Louisiana Highway 1), Port Fourchon, LA is an industrial community maintained by the Greater Lafourche Port Commission. As a land support base for offshore oil exploration, Port Fourchon functions primarily as a distribution complex for offshore oil rigs in the Gulf of Mexico. It also acts as a terminal for foreign cargo shipping and hosts large-scale commercial fishing and recreational activity. Approximately 1700 acres in size, Port Fourchon is comprised of petroleum service facilities and numerous residential/recreational properties. Canals and bayous flow in the midst of maritime forests and coastal marshlands on into the coastal beach. In lower Lafourche Parish, generally bounded by Bayou Lafourche, Caminada Bay and the Gulf of Mexico, extending north to Leevile, LA, is private property owned by the Edward Wisner Donation. This approximately 35,000 acre parcel is called the Wisner Donation Fourchon Property (Fourchon Property). Figures 2 and 3 show this area.
Figure 2: Vicinity Map of Project Site

Figure 3: Site Map of Fourchon Property
1.2 Literature Review

1.2.1 Soil Shear Strength

Soil shear strength is a valuable parameter to examine for civil engineering applications. The safety of any geotechnical engineering structure is dependent on the shear strength of the soil beneath it (Budhu 2007). The shear strength of soils is an important aspect in many foundation engineering problems such as the bearing capacity of shallow foundations and piles, the stability of the slopes of dams and embankments, and lateral earth pressure on retaining walls (Das 2008). Understanding shear strength can lead to the classification of the condition of a soil entity (Coduto 2001), and can assist engineers in drawing critical conclusions about the overall soil mechanics of a specific environment.

From a continuum mechanics standpoint, shear strength of common engineering materials, such as steel, is governed by the molecular bonds that hold the material together. The higher the shear strength of a material, the stronger the molecular structure must be (Das 2008). However, soil shear strength operates under a different set of principles. Soil is a particulate material, so shear failure occurs when the stresses between the particles are such that they slide or roll past each other. Due to the particulate nature of soil, unlike that of a continuum, the shear strength depends on the interparticle interactions rather than the internal strength of the soil particles themselves (Coduto 2001).

1.2.2 Land Erosion and Its Relation to Soil Shear Strength

Erosion can be defined as the removal of a region of the Earth’s surface due to weathering and transport of sediments, specifically by currents or flows (Nugent 2011; Poesen 2006; Vanoni 2006; Morgan 2005). Sediment transport is the movement of solid particles due
to a network of forces involving gravity and those of the entraining fluid. Some terms that
describe the complex processes associated with the movement of sediments are erosion,
deposition, initiation, motion, suspension, and many others (Vanoni 2006). Sediment transport is
of major importance to flood alleviation, water resource management, and environmental
sustainability (Hergault, et al. 2010). In sediment transport engineering two parameters are
defined that help paint the picture of basic erosional processes. *Erosivity* refers to the intensity
of the eroding agent (i.e., water, wind, etc.) to cause detachment and transport of a sediment,
while *erodibility* defines the resistance of the sediment to those erosional processes. Erodibility
can depend on a variety of factors, but it is claimed that the actual properties of the soil are the
most important characteristics, such as: soil texture, aggregate stability, infiltration capacity,
organic and chemical content (clay content), plasticity index, and soil shear strength (Morgan
2005).

Land erosion can be classified into two categories: *sheet/rill erosion* and *gully erosion*. These are two terms that essentially describe the same process—rill erosion being gully erosion on a small scale. Gully erosion is due to local scour and is caused by flowing water in a defined channel (Carey 2006; Poesen 2006). Shear strength is of sincere importance to gully formation and *ephemeral gully erosion*, which is term explaining erosion that occurs on areas of such
topography that runoff collects and concentrates in few well-defined channels that form in local
low points and at the confluences of surface water currents before exiting (Poesen 2006). The
work of Hergault, et al. (2010) cites the shearing processes of a moving fluid as an important
parameter involving granular flow of sediment bedload transport in a supercritical flow. In
another study, hydraulic shear stress was found to control chiefly the incipient motion of
particles flowing in water (Leonard and Richard 2004). Using shear strength to explain erosive
events is done so under the government of various critical threshold conditions. Erosion is believed to occur once a critical shear stress exerted by the moving fluids over a bed of sediment is exceeded (Briaud, et al. 2004; Watts, et al. 2003; Teisson and Fritsch 1988). When this critical value is obtained, erosion will occur over a range of fluid shear stresses and sediment properties if given sufficient time (Vanoni 2006); and under critical conditions, a stream is said to be competent to move its sediment (Abdel-Rahmann 1962). Critical shear stress is an important parameter governing detachment by runoff which appears in numerous erosion models (Leonard and Richard 2004).

1.2.3 The Role of Plant Roots on Soil Shear Strength

Sundborg (1956) suggested that the cohesive force resisting entrainment of a grain is proportional to the shear strength of the sediment as determined in standard soil tests, and it acts in a direction opposite to the fluid force. Cohesive sediments can be described as those for which the resistance to initial movement or erosion depends also on the strength of the cohesive bond between the particles (Vanoni 2006). In coastal Louisiana, marshes mostly exist in cohesive marsh soils and are bound by a root network and protected by a vegetative cover, and root presence can act to increase cohesiveness (Poesen 2006; Vanoni 2006).

It has been widely recognized that plant root systems can improve soil shear strength. Studies have been conducted that indicate a distinct increase in shear strength from soil containing no roots to those containing embedded root systems (Fan and Chen 2010; Thomas and Pollen-Bankhead 2009; Zhang, et al. 2009; Zhang, et al. 2007; Abe and Ziemer 1991; Waldron and Dakessian 1981). In an experiment to evaluate the effect of roots on soil shear strength, Zhang, et al. (2009) used consolidated-drained triaxial compression tests on samples of
composites comprised of representative loess from the Loess Plateau in Northwest China and roots of *Robinia pseudoacacia*. The samples were manually prepared and the roots were placed in the soil in three different configurations: vertical, horizontal, and a cross vertical-horizontal alignment. Two sets of samples were prepared at different soil water contents. Testing was conducted with a strain-controlled triaxial compression test apparatus, and each sample was subjected to four different confining pressures at a constant shear velocity. Grain-size distribution curves, stress-strain curves, and Mohr-Coulomb calculations were performed on the test data. Test results confirmed the hypothesis that plant roots can indeed improve soil shear strength in a rather effective manner. This was confirmed by observing a significant increase in cohesion, with the horizontal-vertical root configuration showing the most dramatic increases. Soil water content also proved to have a significant effect on the shear strength properties of the composites tested. Findings indicate that with an increase in water content, a decrease in cohesion is found along with a possible effect on the internal angle of friction, having an overall reducing effect on soil shear strength.

During the past twenty years, rapid growth in the fields of biological and ecological engineering has coincided with increased interest in the use of vegetation as an effective, economical and environmentally friendly solution for slope and streambank stabilization and other similar applications (Zhang, et al. 2009). Observing soil and plant roots as a combined matrix, plant root systems act to reinforce the soil media against shear failure, much like that of steel rebar in reinforced concrete design (Thomas and Pollen-Bankhead 2009). There are many factors affecting the degree to which root systems can strengthen a soil media that would otherwise not benefit from such a shear strength increase. Some models incorporate root reinforcement as an additional shear strength term in the Mohr-Coulomb shear equation.
Thomas and Pollen-Bankhead (2009) assumed that all roots extended vertically across a horizontal shear zone, and that the root matter behaved in a manner much like laterally-loaded piles when horizontal shearing was applied. This study gave way to other research investigating the angle of alignment of each root relative to the shear plane and its effect on the incorporated term in the Mohr-Coulomb equation.

1.2.4 The Effect of Oil Spills on Soil Strength

On April 20, 2010, the BP Deepwater Horizon offshore drilling rig explosion began what would become the largest oil spill in petroleum industry history (Vucci 2010). Of the first locations to become contaminated was Belle Pass, LA, which is the westernmost boundary of the Fourchon Property. In the aftermath of the spill, there was much debate and controversy that brought remediation efforts to a halt while SSRBs (small surface residual balls, or tarballs) and oil mats continued to arrive onshore. To this day, cleanup activity prevents visitors from entering the beach that is intended for public use.

When oil spills occur, contamination of soil is obviously an immediate threat. It becomes of major interest, therefore, to explore methods of remediation and reclamation for the contaminated areas. Oil removal techniques and alternative uses for contaminated soil are often proposed, and cleanup activity becomes an object of main concern for the municipalities affected, the party held responsible for the disaster, and for the governments tasked with overseeing recovery efforts. In connection with cleanup initiatives, and for any possible applications of contaminated soils, knowledge of the geotechnical properties and behavior of contaminated soils is required (Khamehchiyan, et al. 2006).
Experiments analyzing oil contamination on soil mechanics properties have shown predominantly negative effects. Compressibility, permeability, compaction characteristics, and other strength characteristics of various types of soils all seem to be compromised due to the effects of oil contamination on soils (Khamehchiyan, et al. 2006). An observed increase in settlement and reduction of friction angle and bearing capacity in some sands, as well as an increase in compressibility in more fine-grained particles, are other effects of oil contamination. In a thorough evaluation of crude-oil contamination on soil from the Bushehr beaches in Southern Iran, Khamehchiyan, et al. (2006) indicated a decrease in strength, permeability, maximum dry density, optimum water content, and Atterberg limits. Three soil types were contaminated in levels ranging from 0 to 16% by dry unit weight, and then subjected to an array of standard geotechnical laboratory experiments including: Atterberg limits, compaction tests, direct shear tests, uniaxial compression tests, and permeability tests. Findings indicate negative effects to strength virtually across the board, with a general reducing trend in permeability and overall reduced peak shear strength of soil.

1.3 Direct Shear Testing

1.3.1 Technical Approach

Direct shear testing was the primary analysis technique for this thesis. This was performed in the Louisiana State University (LSU) Soil Mechanics Laboratory with the use of GEOTAC-manufactured automated loading frames called “GeoJacs.” Figure 4 shows the direct shear machine. The direct shear apparatus consists of two separate GeoJacs, for horizontal and vertical loading, each equipped with GEOTAC-patented load cells for detection in both directions along with a DCDT (displacement measurement device) to detect vertical
displacement. The system uses a metallic, rectangular open bath chamber situated atop a rotating ball-bearing wheel fixture to enable movement in the horizontal direction, and a dual plate shearing assembly (referred to as the “shearbox”) constructed to fit a 2.5-in diameter cylindrical soil specimen between two disc-shaped porous stones that allow dewatering in the vertical direction. The mechanical setup is connected to a computer via a system of GEOTAC interface hardware components and runs off of 120-V AC power distributed by a voltage regulator.

Figure 4: Direct Shear Machine

The GeoJac setup is used in conjunction with manufacturer software installed on the lab computer to run direct shear tests. A key feature of the system is that it allows the user to define automated loading and reading schedules. Data is gathered by obtaining signal voltages for the desired parameters at reading events under the conditions of the user-defined loading scenario. For these experiments, three parameters were programmed for signal voltage readings: vertical
load cell, horizontal load cell, and vertical DCDT. During testing, the user has the option to
view graphs of test performance, allowing the operator to examine soil behavior during crucial
points throughout the process.

During test setup, the user is prompted to specify a filepath to direct the output “direct
shear file” (.dsf) document. This read-only document can be opened with any standard text
editor or spreadsheet program. This file contains a table of signal voltages for each reading
corresponding to the absolute realtime at which they were taken, as well as other test
information, such as: load cell IDs, horizontal displacement rate, sensor excitation voltages, and
other test parameters. Each reading device comes from the manufacturer with a unique number
called a calibration factor. This unitless number is used to convert signal readout voltages to the
magnitude of the actual physical input of interest (i.e., load, pressure, temperature, etc.) and is
done so as follows:

\[ P = CF \times \left( \frac{V_S - V_0}{V_E} \right) \]  \hspace{1cm} (1-1)

Where:

- \( P \) = value of measured physical property
- \( CF \) = calibration factor
- \( V_S \) = signal voltage value for reading
- \( V_0 \) = signal voltage zero value
- \( V_E \) = excitation voltage value

A direct shear test is conducted by applying shear to a soil specimen under constant
vertical loading and was done according to ASTM D3080. Figures 5 and 6 illustrate the process
of direct shear. A test specimen, being roughly 1.25-in deep by 2.5-in diameter, is loaded into
the shearbox with the alignment pins and the bottom porous stone in place. It is then placed into
the movable bath chamber to house the test specimen assembly. Another porous stone is placed atop the specimen, the load distributor is placed atop the upper porous stone, and the setup is verified for proper alignment in the horizontal and vertical directions. During the shear phase of testing, the top plate of the shearbox remains fixed while the bottom plate moves along with the bath chamber. The top plate contains two pistons that fit onto a metal L-shaped piece that connects to the central longitudinal axis of the horizontal load cell.

![Shearbox Diagram](image)

Figure 5: Shearbox Diagram

Testing begins by initiating the consolidation phase. The vertical load cell is positioned near the vertical load distributor, and then upon pressing the “start” button, seating takes place as the specified vertical load is applied to the specimen. The vertical load cell continues to lower itself onto the load distributor until the desired normal loading is reached. At this point the software prompts to fill the bath chamber with deionized water (if required) and then to start the test, thereby beginning the first step. Vertical displacement is measured while the specimen is undergoing consolidation, and this step can be terminated at any time. After the first step, the user can terminate the consolidation phase by pressing the “done” button. The next step is the
shearing phase. At this time, the software prompts to remove the alignment pins that lock the two shearing plates in place. Next, the horizontal load frame imparts a constant horizontal displacement on the consolidated specimen while the shear force response is measured by the horizontal load cell. This entire procedure is conducted on an array of specimens over a range of constant vertical loadings to perform a direct shear analysis.

Figure 6: Shear Schematic

1.3.2 Theory and Pertinent Equations

Basic soil shear strength equations were developed using an approach not too unlike that of classic sliding friction equations from basic physics theory. According to such theory, one must know (or calculate) a parameter called the coefficient of friction, $\mu$. The normal force applied by the sliding body on the frictional surface equals the frictional resistive force that opposes sliding divided by the coefficient of friction. In geotechnical engineering, however, instead of using $\mu$, a parameter is defined called the friction angle, $\phi$ (or the effective angle of internal friction $\phi'$), and is related to $\mu$ as follows (Coduto 2001):
\[ \varphi' = \tan^{-1} \mu \]  
(1-2)

Where: \( \varphi' \) = (effective) angle of internal friction  
\( \mu \) = coefficient of friction

Similar to basic physics theory for friction equations, in geotechnical engineering the surrogate parameter for the normal force relating to the coefficient of friction is called the effective stress, \( \sigma' \). The effective stress concept was developed by Carl Terzaghi and plays an important role in most any geotechnical design or analysis. The effective stress concept is as follows (Budhu 2007):

\[ \sigma' = \sigma - u \]  
(1-3)

Where:  
\( \sigma' \) = effective stress  
\( \sigma \) = total stress due to vertical geostatic pressure  
\( \gamma \)H; where \( \gamma \) is soil unit weight and \( H \) is soil stratum thickness  
\( u \) = hydrostatic porewater pressure  
\( \gamma_w \)z_w; where \( \gamma_w \) is unit weight of water, \( z_w \) is vertical distance to groundwater table

The Mohr-Coulomb failure criterion is a theory that was introduced in the 1700s by Charles Augstin de Coulomb and that was elaborated upon by Otto Mohr in 1900. It states that failure along a plane in a material occurs by a critical combination of normal (effective) and shear stresses. Effective stress and friction angle appear frequently in commonly used equations. Shear strength is related to these parameters by another parameter called cohesion, \( c \). Cohesive strength is a term given to soils that have shear strength but exhibit zero effective stress (Coduto 2001). These soils are called cohesive soils. The following equation relates shear strength,
effective stress, and cohesion. This is called the Mohr-Coulomb failure criterion and is defined as follows (Das 2008):

\[ \tau = c + \sigma' \tan \phi \quad (1-4) \]

Where: \( \tau \) = shear strength
\( c \) = cohesion

1.4 Objectives and Layout of This Thesis

The purpose of this thesis is to characterize soil shear strength in coastal soils. It is generally accepted that soil shear strength correlates positively with erosion resistance, however, literature in this field is lacking. This thesis uses direct shear test results from tests performed on field samples in order to evaluate erosion resistance capabilities. Furthermore, it was investigated how shear strength can be improved by the presence of plant roots to increase stabilization in coastal soils. The following describes the two main research objectives of this thesis, as seen in Chapters 2 and 3, respectively:

- The objective of Chapter 2 was to understand the effect that subsurface plant matter can have on soil shear strength and to observe changes in shear strength with increased time after planting. Direct shear testing was done on vegetated samples of a known soil media that had been cultivated in a controlled environment. Direct shear test specimens were composites of soil and subsurface plant root matter of two grass species that were sampled after four, eight, and twelve weeks of growth.

- The objective of Chapter 3 was to measure soil shear strengths across different areas at the Fourchon Property and to predict erosion rates in these areas. Direct shear testing was conducted on soil samples obtained along an elevational gradient through various
subenvironments from a site on the Louisiana coastline. These areas sampled are as follows: the intertidal shoreline area, the beach dune and supratidal salt pan area, the barrier marshes amidst the inland bayous and bays, the heavily vegetated saltwater marsh and mangrove area, and a site near the entrance of the Fourchon Property that was lightly vegetated and that had been contaminated by the BP oil spill.

This thesis is comprised of four chapters, a list of references, and appendices that include supplemental information. The first chapter is the introduction, and the fourth chapter provides the overall conclusions based on the results established during this graduate study at LSU. Chapters 2 and 3 describe methodologies and results of the experimental procedures that were used for this thesis. These chapters contain multiple sections with introductions and conclusions of their own. Chapters 2 and 3 were written as independent articles with the intent of publishing.
CHAPTER 2: EFFECTS OF WETLAND VEGETATION ESTABLISHMENT ON SOIL SHEAR STRENGTH

2.1 Introduction

It has been widely recognized that plant roots can improve soil shear strength and can act to reinforce a mass of soil against shear failure (Zhang, et al. 2009). Roots, being relatively strong in tension and weak in compression, can increase the shear strength of soil media, which is relatively weak in tension and strong in compression, in a manner that is akin to the reinforcement of concrete structures by steel or fiberglass (Thomas and Pollen-Bankhead 2009). During the past twenty years, rapid growth in the field of ecological engineering has coincided with an increased interest in the use of vegetation as an effective, economical and environmentally friendly solution for slope and streambank stabilization and similar applications (Fan and Chen 2010; Zhang, et al. 2009; Waldron and Dakessian 1981).

There are many different strategies used for coastal restoration projects, marsh creation being one of them. Establishing vegetation by planting is one solution method used in practice for such applications. While it is known and has been widely accepted and recognized that plant roots can improve soil shear strength and that over time the beneficial impacts can become significant, little is known for how long after planting do the benefits on soil shear strength begin to be realized.

Coefficients in equations for erosion of cohesive sediments are determined based on laboratory testing of samples carefully extracted in-situ from the field site of interest (Rosati 2009). Analyzing soil shear strength can help explain the mechanics of erosional processes in generally weak wetland clays and cohesive sands. Erosion is said to occur once a critical shear stress exerted by moving fluids over a bed of sediment is exceeded (Briaud, et al. 2004; Watts,
et al. 2003; Teisson and Fritsch 1988). When this critical value is obtained, erosion will occur over a range of fluid shear stresses and sediment properties if given sufficient time, and under these critical conditions, a stream is said to be competent to move its sediment (Vanoni 2006; Abdel-Rahmann 1964). Plant roots can increase soil stability and ultimately increase surface erosion resistance by promoting an increase in soil stiffness and shear strength (Nugent 2011; De Baets, et al. 2005; Tengbeh 1993).

The objective of this study to measure changes in soil shear strength due to the existence of plant root systems. It is intended to understand how long after planting do root-enhanced shear strength increases begin to manifest themselves. The following sections document an experimental procedure using direct shear tests conducted at Louisiana State University (LSU). The findings established herein are intended to shed new light on the implementation of wetland vegetation—both in practice as well as research—as a method of enhancing soil stability to combat erosional processes.

2.2 Materials and Methods

2.2.1 Greenhouse Study

Plant Species and Establishment (Tray Setup)

Two species of coastal grasses were selected for this analysis. *Scirpus americanus* and *Scirpus acutus*, common names “three-square” and “hardstem bulrush,” respectively, are two perennial marsh grasses that germinate via the use of rhizomes, which are subterranean stems that propagate horizontally outward from an original plant colony that spawn new stems while functioning as nutrient distributors. In order to understand the soil shear strength improvement characteristics of these coastal grasses, a series of direct shear tests was performed on soil-root
composites (SRCs) of these species in a controlled soil media. A correlation was established between the above-ground biomass (AGB) and the shear strength properties for each grass species over time. A stock of both plant species was available from LSU. From this stock, a total of eight mother plant clusters were manually removed with a serrated-edge knife. Four 25-qt rectangular plastic bins were used as growth containers. First, each bin was filled to a depth of approximately four to five inches of soil media. Two small impressions were made, and two clusters were then transplanted into each bin. Next, water was added to completely submerge all soil media. The water level was maintained approximately one to two inches above the soil-water interface within (ground surface) and was watered at least twice per week.

Multiple cultivation scenarios were performed to obtain data in a progressing time series from four to twelve weeks as well as an extreme case of a nearly completely root-bound sample of *Scirpus acutus*. This sample was paired with the 12-week growth scenario for *Scirpus americanus* and was called a “time equals infinity” sample. This was done to examine the effects that a fully matured below-ground root system could have on soil shear strength after a sufficiently large time after planting. The plants were fertilized and stem counts were recorded; photographs were taken on a weekly basis to observe rhizomal propagation throughout the growth period. At least once every three days, the plants received water from a garden hose connected to a municipal water line. A fertilizer solution was prepared and was sprayed on the exterior of the plant stems at the same frequency that stem counts were performed. The following are photographs taken from throughout the experiment.
Figure 7: Weekly Tracking Photograph (*Scirpus americanus*)

Figure 8: Weekly Tracking Photograph (*Scirpus acutus*)
Figure 9: Core Extraction

Figure 10: AGB Removal from SRC
Sampling

At the end of each growth period, all specimens were extracted. This began by emptying the standing water from each growth chamber. Water was poured from the bin into an external container and was removed from the chamber. Using a serrated-edge knife all specimens were removed by cutting out a core of soil-root media beneath each stem cluster. The next step was to remove all AGB with a knife. All plant stems were removed at the ground surface and their weights were recorded. The SRC sample was then wrapped in aluminum foil for preservation. All samples were then packed into labeled plastic bags for storage. A soil control sample was also taken by filling a plastic bag with soil from each bin. No root or plant matter was included in this sample. The set of samples was stored at 0° C to halt growth and to preserve natural root orientations.

2.2.2 Laboratory Details

Testing was performed in the LSU Soil Mechanics Laboratory using GEOTAC automated loading frames called “GeoJacs” during the fall of 2010 and the spring of 2011. Each sample produced one test specimen. In order to perform a thorough direct shear evaluation, a minimum of three tests must be carried out (Bhudu 2007). ASTM standard D3080 was consulted, where the inclusion of root matter in the test specimens deviated from the procedure. A total of three vertical loadings were selected based on the increase in effective stress due to the addition of fill media. The tests were run at vertical loadings of 40, 100, and 300 psf (2, 5, and 14 kPa). Table 1 shows normal stress values corresponding to fill depths of soils with properties typical of those used for marsh reconstruction, such as offshore dredged sands/slurries. For the shearing phase of testing the horizontal displacement rate was set to 0.01 in/min (LSU
Geotechnical Engineering 2011) and sheared until the external limit of the shearbox, which is the dual shearing plate assembly used for direct shear tests. Saturated soil conditions were replicated in the laboratory by submerging the shearbox with deionized water.

### Table 1: Normal Stress Calculations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.5</td>
<td>4.91</td>
<td>0.00317</td>
<td>20</td>
<td>0.00032</td>
<td>18</td>
<td>0.00579167</td>
</tr>
<tr>
<td>6</td>
<td>2.5</td>
<td>4.91</td>
<td>0.00317</td>
<td>29</td>
<td>0.00048</td>
<td>18</td>
<td>0.0086875</td>
</tr>
<tr>
<td>8</td>
<td>2.5</td>
<td>4.91</td>
<td>0.00317</td>
<td>39</td>
<td>0.00064</td>
<td>18</td>
<td>0.01158333</td>
</tr>
<tr>
<td>12</td>
<td>2.5</td>
<td>4.91</td>
<td>0.00317</td>
<td>59</td>
<td>0.00097</td>
<td>18</td>
<td>0.017375</td>
</tr>
<tr>
<td>24</td>
<td>2.5</td>
<td>4.91</td>
<td>0.00317</td>
<td>118</td>
<td>0.00193</td>
<td>18</td>
<td>0.03475</td>
</tr>
<tr>
<td>48</td>
<td>2.5</td>
<td>4.91</td>
<td>0.00317</td>
<td>236</td>
<td>0.00386</td>
<td>18</td>
<td>0.0695</td>
</tr>
</tbody>
</table>

When a normal effective stress is applied to soil, a certain amount of settlement is expected as compaction and dewatering occur. In the lab, the first step of the test, the consolidation phase, was terminated when adequate settlement had been achieved. In an ideal situation, the overburden stress felt by the test specimen due to the normal load causes vertical displacement to occur in three distinct stages: an initial precompression period with a shallow slope when viewed on a semilogarithmic plot of vertical displacement with respect to time, a primary consolidation period where the slope approaches a straight vertical line on the plot, and a secondary consolidation period with a shallow slope (Das 2008). Once the sample was consolidated and had stabilized in terms of settlement, shearing took place under the testing conditions that were programmed.
2.2.3 Computational Details

As normal stress increases on an elemental mass of soil media, shear stress will also increase. Establishing a relationship of increasing shear stress to increasing normal stress is an analysis that is commonly executed. For this study, a series of curves were generated for each set of direct shear tests performed for each sampling event. Curves were created depicting shear stress versus horizontal displacement ($\tau$ vs. $\Delta x$). On a typical $\tau$ vs. $\Delta x$ plot, the trend exhibits an increase in shear stress from zero to a peak value, which classically occurs early on in the curve, followed by a gradual decrease to a lower shear stress value that remains virtually constant until the end of the test. The shear strength after one half of an inch of applied horizontal displacement was recorded for each test. From there, comparison plots were made of this shear stress versus normal stress ($\tau$ vs. $\sigma$) of all tests performed for each sampling event, and the relationship between shear stress and normal stress was analyzed.

2.2.4 Measurements

27 direct shear tests were performed for this study. Table 2 lists and describes these tests. Figure 11 is a typical plot of $\tau$ vs. $\sigma$. A typical plot of $\tau$ vs. $\Delta x$ for one growth period of *Scirpus americanus* (which contains the total set of three direct shear tests), and a corresponding graph showing the results of stem count tracking throughout the growth session are shown in figures 12 and 13, respectively.
<table>
<thead>
<tr>
<th>Test Name</th>
<th>Description of Direct Shear Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-04SRC1A-40</td>
<td><em>Scirpus americanus</em> sample 1A at 4 weeks, 40 psf normal load</td>
</tr>
<tr>
<td>DS-04SRC1B-100</td>
<td><em>Scirpus americanus</em> sample 1B at 4 weeks, 100 psf normal load</td>
</tr>
<tr>
<td>DS-04SRC2B-300</td>
<td><em>Scirpus americanus</em> sample 2B at 4 weeks, 300 psf normal load</td>
</tr>
<tr>
<td>DS-04SRC3A-40</td>
<td><em>Scirpus acutus</em> sample 3A at 4 weeks, 40 psf normal load</td>
</tr>
<tr>
<td>DS-04SRC3B-100</td>
<td><em>Scirpus acutus</em> sample 3B at 4 weeks, 100 psf normal load</td>
</tr>
<tr>
<td>DS-04SRC4A-300</td>
<td><em>Scirpus acutus</em> sample 4A at 4 weeks, 300 psf normal load</td>
</tr>
<tr>
<td>DS-08SRC1B-40</td>
<td><em>Scirpus americanus</em> sample 1B at 8 weeks, 40 psf normal load</td>
</tr>
<tr>
<td>DS-08SRC2A-100</td>
<td><em>Scirpus americanus</em> sample 2A at 8 weeks, 100 psf normal load</td>
</tr>
<tr>
<td>DS-08SRC2B-300</td>
<td><em>Scirpus americanus</em> sample 2B at 8 weeks, 300 psf normal load</td>
</tr>
<tr>
<td>DS-08SRC3B-40</td>
<td><em>Scirpus acutus</em> sample 3B at 4 weeks, 40 psf normal load</td>
</tr>
<tr>
<td>DS-08SRC3A-100</td>
<td><em>Scirpus acutus</em> sample 3A at 8 weeks, 100 psf normal load</td>
</tr>
<tr>
<td>DS-08SRC4A-300</td>
<td><em>Scirpus acutus</em> sample 4A at 8 weeks, 300 psf normal load</td>
</tr>
<tr>
<td>DS-12SRC1A-40</td>
<td><em>Scirpus americanus</em> sample 1A at 12 weeks, 40 psf normal load</td>
</tr>
<tr>
<td>DS-12SRC2A-100</td>
<td><em>Scirpus americanus</em> sample 2A at 12 weeks, 100 psf normal load</td>
</tr>
<tr>
<td>DS-12SRC1B-300</td>
<td><em>Scirpus americanus</em> sample 1B at 12 weeks, 300 psf normal load</td>
</tr>
<tr>
<td>DS-88SRC01-40</td>
<td><em>Scirpus acutus</em> sample 01 at 88 weeks, 40 psf normal load</td>
</tr>
<tr>
<td>DS-88SRC01-100</td>
<td><em>Scirpus acutus</em> sample 02 at 88 weeks, 100 psf normal load</td>
</tr>
<tr>
<td>DS-88SRC03-300</td>
<td><em>Scirpus acutus</em> sample 03 at 88 weeks, 300 psf normal load</td>
</tr>
<tr>
<td>DS-04CNTRL-40</td>
<td>Soil control sample at 4 weeks, 40 psf normal load</td>
</tr>
<tr>
<td>DS-04CNTRL-100</td>
<td>Soil control sample at 4 weeks, 100 psf normal load</td>
</tr>
<tr>
<td>DS-04CNTRL-300</td>
<td>Soil control sample at 4 weeks, 300 psf normal load</td>
</tr>
<tr>
<td>DS-08CNTRL-40</td>
<td>Soil control sample at 8 weeks, 40 psf normal load</td>
</tr>
<tr>
<td>DS-08CNTRL-100</td>
<td>Soil control sample at 8 weeks, 100 psf normal load</td>
</tr>
<tr>
<td>DS-08CNTRL-300</td>
<td>Soil control sample at 8 weeks, 300 psf normal load</td>
</tr>
<tr>
<td>DS-12CNTRL-40</td>
<td>Soil control sample at 12 weeks, 40 psf normal load</td>
</tr>
<tr>
<td>DS-12CNTRL-100</td>
<td>Soil control sample at 12 weeks, 100 psf normal load</td>
</tr>
<tr>
<td>DS-12CNTRL-300</td>
<td>Soil control sample at 12 weeks, 300 psf normal load</td>
</tr>
</tbody>
</table>
Figure 11: Typical Plot of $\tau$ vs. $\sigma$

Figure 12: Typical Plot of $\tau$ vs. $\Delta x$
2.3 Results and Discussion

2.3.1 Test Results

Table 3 summarizes direct shear data for the unvegetated soil control samples, *Scirpus americanus*, and *Scirpus acutus* SRCs after four weeks of growth. There was no shear failure exhibited for any sample. The shear response increase was measured and was termed the shear stress range. This was obtained by taking the maximum value at the terminus of the shear response curve and the minimum value near the beginning of the shear response curve after the initial strengthening period of high slope.
Table 3: 4-Week Direct Shear Test Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scirpus americanus</th>
<th>Scirpus acutus</th>
<th>Unvegetated Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal Loading [kPa]</td>
<td>Normal Loading [kPa]</td>
<td>Normal Loading [kPa]</td>
</tr>
<tr>
<td>Shear Stress Range [kPa]</td>
<td>6 10 17</td>
<td>4 14 16</td>
<td>10 16 20</td>
</tr>
<tr>
<td>Shear Stress at 0.5 in [kPa]</td>
<td>7 12 19</td>
<td>4 15 17</td>
<td>10.5 18 24.5</td>
</tr>
<tr>
<td>Stem Count(^a) [stems]</td>
<td>67</td>
<td>46</td>
<td>-</td>
</tr>
<tr>
<td>Growth Rate(^b) [stems]</td>
<td>5</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Dry AGB [g]</td>
<td>2.64 3.35 3.12</td>
<td>5.35 3.03 4.60</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes:

No shear failure was observed for any sample

\(^a\) = stem count on extraction date for both trays

\(^b\) = measure of rate of change of new stem growth for an interval of approximately 4 days (between counts)
The highest terminal value obtained was 25 kPa for the 300 psf (14 kPa) normally loaded direct shear test on the unvegetated sample, and the range covered 20 kPa of increasing shear response. The lowest terminal value obtained was 5 kPa for the 40 psf (2 kPa) normally loaded direct shear test on *Scirpus acutus*, and the range covered 4 kPa of increasing shear response. Shear stresses were recorded after 0.5 in of horizontal displacement. The highest value obtained for this parameter was 24.5 kPa, which occurred for the 300 psf (14 kPa) normally loaded direct shear test on unvegetated soil. The lowest value obtained for this parameter was 4 kPa, which occurred for the 40 psf (2 kPa) normally loaded direct shear test on *Scirpus acutus*. Stem counts after four weeks of growth were 67 and 46 for *Scirpus americanus* and *Scirpus acutus*, respectively. The growth rate, which is a measure of the rate of change of stem accumulation between stem counts, was calculated by averaging the difference in stem counts between readings throughout the growth period. *Scirpus americanus* had an average growth rate of 5 stems per approximately 4 days, while *Scirpus acutus* had an average growth rate of 3 stems per approximately 4 days. The average dry AGB masses were 3.04 and 4.33 g for *Scirpus americanus* and *Scirpus acutus*, respectively.

Table 4 summarizes direct shear data after eight weeks of growth. There was no shear failure exhibited for any sample except for the unvegetated soil sample under 300 psf (14 kPa) of normal load. The shear response increase was measured. The highest terminal value obtained was 24 kPa for the 300 psf (14 kPa) normally loaded direct shear test on *Scirpus americanus*, and the range covered 20 kPa of increasing shear response. The lowest terminal value obtained was 9 kPa for the 40 psf (2 kPa) normally loaded direct shear test on the soil control sample, and the range covered 8 kPa of increasing shear response. Shear stresses were recorded at 0.5 in of horizontal displacement for comparison, except where noted. The highest value obtained for this
parameter was 22 kPa, which occurred for the 300 psf (14 kPa) normally loaded direct shear test on *Scirpus americanus*. The lowest value obtained for this parameter was 8 kPa, which occurred for the 40 psf (2 kPa) normally loaded direct shear test on the soil control sample. Stem counts after eight weeks of growth were 122 and 161 total for *Scirpus americanus* and *Scirpus acutus*, respectively. *Scirpus americanus* had an average growth rate of 6 stems per approximately 4 days, while the same was calculated for *Scirpus acutus*. The average dry AGB masses were 4.58 and 10.20 g for *Scirpus americanus* and *Scirpus acutus*, respectively.

Table 5 summarizes direct shear data after twelve weeks of growth. The *Scirpus acutus* samples were taken from a pre-grown matured colony, where the subsurface material was comprised of little soil media and virtually nothing other than an intertwined system of its roots. There was no shear failure exhibited for any sample. The shear response increase was measured. The highest terminal value obtained was 29 kPa for the 300 psf (14 kPa) normally loaded direct shear test on *Scirpus americanus*, and the range covered 18 kPa of increasing shear response. The lowest terminal value obtained was 160 psf for the 40 psf normally loaded direct shear test on both vegetated samples, and the ranges covered 7 kPa and 5 kPa of increasing shear response for *Scirpus americanus* and *Scirpus acutus*, respectively. Shear stresses were recorded at 0.5 in of horizontal displacement for comparison. The highest value obtained for this parameter was 29 kPa, which occurred for the 300 psf (14 kPa) normally loaded direct shear test on *Scirpus americanus*. The lowest value obtained for this parameter was 6.5 kPa, which occurred for the 40 psf normally loaded direct shear test on *Scirpus acutus*. 
Table 4: 8-Week Direct Shear Test Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scirpus americanus</th>
<th>Scirpus acutus</th>
<th>Unvegetated Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Stress Range [kPa]</td>
<td>10  8  20</td>
<td>12  9  14</td>
<td>8  12  16</td>
</tr>
<tr>
<td>Shear Stress at 0.5 in [kPa]</td>
<td>9   9  22</td>
<td>9.5  9.5  15</td>
<td>8  18  17</td>
</tr>
<tr>
<td>Stem Count&lt;sup&gt;a&lt;/sup&gt; [stems]</td>
<td>122</td>
<td>161</td>
<td></td>
</tr>
<tr>
<td>Growth Rate&lt;sup&gt;b&lt;/sup&gt; [stems]</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Dry AGB [g]</td>
<td>4.17  6.10  3.48</td>
<td>12.58  11.75  6.26</td>
<td></td>
</tr>
</tbody>
</table>

Notes:

No shear failure was observed for any sample

<sup>a</sup> = stem count on extraction date for both trays

<sup>b</sup> = measure of rate of change of new stem growth for an interval of approximately 4 days (between counts)

<sup>c</sup> = shear failure at 0.41 in horizontal displacement
Table 5: 12-Week Direct Shear Test Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scirpus americanus</th>
<th>Scirpus acutus&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Unvegetated Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal Loading [kPa]</td>
<td>Normal Loading [kPa]</td>
<td>Normal Loading [kPa]</td>
</tr>
<tr>
<td>Shear Response Increase [kPa]</td>
<td>7 9 18</td>
<td>5 8 25</td>
<td>7 10 19</td>
</tr>
<tr>
<td>Shear Stress at 0.5 in [kPa]</td>
<td>7 13 29</td>
<td>6.5 9 23</td>
<td>9 12 22</td>
</tr>
<tr>
<td>Stem Count&lt;sup&gt;a&lt;/sup&gt; [stems]</td>
<td>136</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Growth Rate&lt;sup&gt;b&lt;/sup&gt; [stems]</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dry AGB [g]</td>
<td>14.10 14.60 12.10</td>
<td>21.50 14.70 28.15</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes:
No shear failure was observed for any sample

<sup>a</sup> = stem count on extraction date for both trays

<sup>b</sup> = measure of rate of change of new stem growth for an interval of approximately 4 days (between counts)

<sup>c</sup> = Scirpus acutus samples extracted from mature plant colony
*Scirpus americanus* had an average growth rate of 6 stems per approximately 4 days. Stem count growth was not tracked on *Scirpus acutus*, because the samples came from a pre-grown source. The average dry AGB masses were 13.60 and 21.45 g for *Scirpus americanus* and *Scirpus acutus*, respectively.

2.3.2 Shear Strength Benefit Index

Comparing data for the two species to the control samples, an increase in soil stability correlates positively to an increase in time. From the four-week growth scenario, comparing test results between that of the vegetated SRCs to the soil control samples, shear stresses are higher for the soil control samples by a significant amount compared to that of the vegetated counterparts of both plant species. For the eight-week growth scenario, *Scirpus americanus* begins to outperform *Scirpus acutus*, and the differences in shear stresses of the vegetated samples relative to the soil control samples are beginning to be positive. For the final growth scenario, although *Scirpus acutus* is predominantly weaker than the soil control sample, the relative differences are smaller yet than for any other time-series; *Scirpus americanus* by this point has outperformed the soil control sample almost entirely.

Figure 14 is a plot representing the benefits observed in shear strength as a result of vegetative root systems with respect to the time after planting in weeks. Both species are shown on the plot; *Scirpus americanus* is in red, and *Scirpus acutus* is in blue. The shear strength benefit index, X, is expressed in units of radians per gram divided by the planting surface area in square meters and was calculated for each growth scenario as follows:
Where: \( X \) = shear strength benefit index \([\text{radians/g}]\) per planting surface area in square meters

\( m_{\text{SRC}} \) = relationship of increase in shear stress to effective stress for vegetated soil-root composite \([\text{radians}]\), as defined below

\( m_{\text{SOIL}} \) = relationship of increase in shear stress to effective stress for soil control sample \([\text{radians}]\), as defined below

\[
m = \tan^{-1}\left( \frac{\Delta \tau}{\Delta \sigma} \right)
\]

(2-2)

Where: \( \Delta \tau \) = change in shear stress for dataset

\( \Delta \sigma \) = change in effective stress for dataset

Figure 14: Shear Strength Benefit Index

2.4 Field Investigation

To evaluate the shear strength properties of an actual marsh, an area on the Louisiana coastline was visited and samples were obtained in situ. Direct shear tests were performed on
cohesive marsh clay samples vegetated with roots of *Spartina alterniflora* (common name: smooth cordgrass) from an area in southern Lafourche Parish near Port Fourchon, Louisiana. Direct shear tests were run at normal loadings of 40, 100, and 300 psf (2, 5, and 14 kPa). For the shearing phase of testing the horizontal displacement rate was set to 0.01 in/min (LSU Geotechnical Engineering 2011) and sheared until the external limit of the shearbox. Saturated soil conditions were replicated in the laboratory by submerging the shearbox with deionized water.

The sampling site was fully and heavily vegetated and was surrounded by saltwater with other marsh in the vicinity. A team of LSU researchers was escorted in an airboat operated by Forrest Travirca, the field inspector for the Edward Wisner Donation (property owner of Fourchon Beach). Samples were gathered by inserting into the ground a thin-walled aluminum core with a diameter of 6 in. The length of the sampler was approximately 20 in; a sample was extracted to a depth of approximately 16 in. In the laboratory, a 2.5-in diameter test specimen was prepared and sheared; the AGB was removed and measured a dry weight of 51.74 g for the 6-in diameter sample. Test specimens were prepared and were obtained from a depth of approximately 2 – 4 in.

Figure 15 is a plot containing direct shear test output curves showing $\tau$ vs. $\Delta x$ for the field sample of *Spartina alterniflora* obtained from the marsh at Fourchon Beach. The red, blue, and green lines correspond to the 40 psf (2 kPa), 100 psf (5 kPa), and 300 psf (14 kPa) normally loaded tests, respectively. This figure shows the shear stress handling behavior of actual in situ SRCs. The *Spartina alterniflora* field sample contains 0.5-in horizontal displacement shear stress values of 16 kPa for the 300 psf (14 kPa) normally loaded test and 9.5 kPa for the 40 and 100 psf (2 and 5 kPa) normally loaded tests. The shear stress ranges are seen to be between 13
kPa (18 – 5 kPa) for the 300 psf (14 kPa) normally loaded test, 8 kPa (10 – 2 kPa) for the 100 psf (5 kPa) normally loaded test, and approximately the same values as those for the 100 psf test for the 40 psf (2 kPa) normally loaded test. This is comparatively low to the greenhouse-cultivated SRCs, especially when comparing to Scirpus americanus, although a sample of unvegetated control soil from the field would have been required to more appropriately make such claims.

![Spartina Alterniflora: Field Sample](image)

Figure 15: Plot of $\tau$ vs. $\Delta x$ for *Spartina alterniflora* obtained from Fourchon Beach

Direct shear tests performed on the field sample exhibit many of the same features seen from direct shear tests performed on greenhouse-cultivated SRCs. The near straight-line trend evident in each test is a common theme amongst all vegetated samples tested. For each curve, an initial period of high slope is shown. This is typical for direct shear. What happens next is a flattening of the slope and is usually brought on following a local maximum. The blue curve shows two peaks followed by a straight-line period of increasing shear stress. It is likely that the
peaks observed from approximately 0.00 – 0.05 in horizontal displacement are due to some type of root breakage or could be an indication of early shear failure of the soil. A classic direct shear curve would go on to remain relatively constant at a residual shear stress value that was slightly lower than the peak shear stress value. For all the SRCs tested in this study, this area of the curve, however, is virtually completely and unanimously transformed into a straight line of some relatively shallow slope. It seems as though the existence of plant roots is responsible for absorbing the applied shear stresses. The rate of increase in shear stress is different for plant species and seems to become affected positively with increased time after planting. The proximity of shear stress values between the two tests of lower effective stress is not an uncommon trend, but few situations were encountered during testing of the greenhouse-cultivated SRCs where the curves for the 40 and 100 psf (2 and 5 kPa) normally loaded tests were more identical to each other than those shown in Figure 15.

_Spartina alterniflora_ is considered a predominate marsh grass throughout coastal Louisiana and also thrives in many other parts of the world. Its ability to grow in a variety of environments across an elevational gradient, in a coastal headland such as Fourchon Beach, as well as its ability to adapt to hyper-saline conditions make it a plant species of interest for this research. Measuring the shear strength properties of this species can show how plant roots can act to stabilize soil against erosive action by providing benefits to shear strength. Roots of _Spartina alterniflora_, as well as the roots of the other species studied, have demonstrated the ability to strengthen soil against shear stresses applied by the presence of external forces—something that could have a drastic effect on erosion rates overall.
2.5 Conclusions

An array of direct shear tests was conducted on vegetated samples of *Scirpus americanus* and *Scirpus acutus* that had been cultivated in a controlled growing scenario within a known soil media. Samples were obtained in time-steps of 4, 8, and 12 weeks after planting. It was of interest to understand the influence of time after planting for which the roots would begin to exhibit behavior that could provide soil stabilization benefits. Erosion occurs as a result of applied shear stresses in soils, and it is believed that plant roots can stabilize soil by increasing shear strength. Based on the results of this study, the following conclusions were made:

- Soil-root composites vegetated with roots of *Scirpus americanus* were able to handle higher shear stresses than *Scirpus acutus*.

- Although exhibiting lower shear strengths than their unvegetated counterparts in the 4-week growth scenario, both species were seen to approach higher soil stability by the 12-week growth scenario. *Scirpus americanus* handled higher shear stresses than the soil control sample after 8 and 12 weeks.

- Shear strength benefit index analyses shows improvement characteristics for both species, with *Scirpus americanus* outperforming *Scirpus acutus* throughout all growth periods.
CHAPTER 3: SHEAR STRENGTH CHANGES ACROSS AN EROSIONAL COASTAL HEADLAND ENVIRONMENT

3.1 Introduction

The Louisiana coastline is disappearing at a staggering rate. The equivalent of one football field is lost every 38 minutes (Davis-Wheeler 2000). Nearly 2,000 square miles of coastline have vanished since the 1930s (Couvillion, et al. 2011; EDF 2011). The unique geomorphology of coastal Louisiana, where the seemingly overnight conversion of land to open water is due to the complex processes of subsidence and erosion induced by natural and human activities, is one major factor attributing to high rates of land loss in this area.

South Louisiana was created by the continual deposition of sediments from the U.S.’ primary drainage structure, The Mississippi River. Switching deltas from as far west as Vermillion Bay to as far east as the St. Bernard Parish-Mississippi state line throughout different eras of historic time, the sediment-laden waters of the river were once responsible for creating and then replenishing the entire landscape in the Louisiana deltaic plane. During the 1930s, in response to floods that threatened development near the river, a levee system was implemented by the Unites States Army Corps of Engineers (USACE) Mississippi River Commission that to this day constricts those very waters which are now discharged to the Gulf of Mexico where sea floor elevation is too low for wetlands to form (Dokka 2006; Dokka, et al. 2006). The supply of sediments that formerly spilled over the banks along the length of the river has been all but eliminated—an alteration that has had a significant negative impact on the barrier islands and wetlands of coastal Louisiana (Dean 2006).

Erosion can be defined as removal of the Earth’s surface due to weathering and transport of sediments, specifically by currents or flows (Nugent 2011; Poesen 2006; Vanoni 2006;
Morgan 2005). Land erosion is caused by the formation of rills and gullies and is due to local scour caused by flowing water in a defined channel (Carey 2006; Poesen 2006). Shear strength is a soil mechanics property that is influential to gully formation and ephemeral gully erosion, a term for erosion that occurs on such topography in which runoff collets and concentrates in few well-defined channels that form in local low points and at the confluences of surface water currents before exiting (Poesen 2006). Analyzing soil shear strength can help explain the mechanics of erosional processes in generally weak wetland clays and cohesive sands. Coefficients in equations for erosion of cohesive sediments are determined based on laboratory testing of samples carefully extracted in-situ from the field site of interest (Rosati 2009). Erosion is said to occur once a critical shear stress exerted by moving fluids over a bed of sediment is exceeded (Briaud, et al. 2004; Watts, et al. 2003; Teisson and Fritsch 1988). When this critical value is obtained, erosion will occur over a range of fluid shear stresses and sediment properties if given sufficient time, and under these critical conditions, a stream is said to be competent to move its sediment (Vanoni 2006; Abdel-Rahmann 1964).

Robust wetlands preserve their buffering capability and contribute to the effectiveness of the levees protecting New Orleans and other areas by maintaining vertical elevation in the presence of relative sea level rise (Dean 2006). Traversing a transect from the shoreline on inland through the coastal headland environment, a variety of changes can be observed in soil conditions as well as vegetation predominance. In a typical coastal headland environment, there exist large areas of vegetated land. Plant roots can increase soil stability and ultimately increase surface erosion resistance by promoting an increase in soil stiffness and shear strength (Nugent 2011; De Baets 2005; Tengbeh 1993).
The objective of this study is to evaluate the shear strength properties of an erosional soil system in a coastal headland environment across an elevational gradient at a site on the Louisiana coastline. This study predicts erosion rates and estimates sediments losses for different erosion events due to wave action. Direct shear testing was performed in the Louisiana State University (LSU) Soil Mechanics Laboratory on field samples obtained from Fourchon Beach, Louisiana. The aim of this research is to understand how shear strength can be linked to the erosion resistance capabilities of soils in the coastal zone, and how this parameter can be thereby improved by the existence of plant roots.

3.2 Materials and Methods

3.2.1 Study Location

Fourchon Beach

Fourchon Beach is an area on the Louisiana Gulf Coast located in south Lafourche Parish approximately 15 miles west of Grand Isle. Accessible via Louisiana Highway 3090 (LA 3090, from LA 1), Port Fourchon, LA is an industrial community maintained by the Greater Lafourche Port Commission. As a land support base for offshore oil exploration, Port Fourchon functions primarily as a distribution complex for offshore oil rigs in the Gulf of Mexico. It also acts as a terminal for foreign cargo shipping and hosts large-scale commercial fishing and recreational activity. Port Fourchon is comprised of petroleum service facilities and numerous residential/recreational properties with canals and bayous flowing in the midst of heavy vegetation and coastal marshland into the beach. In lower Lafourche Parish, generally bounded by Bayou Lafourche, Caminada Bay and the Gulf of Mexico, extending north to Leevile, LA, is private property owned by the Edward Wisner Donation. This approximately 35,000 acre parcel
is called the Edward Wisner Donation Fourchon Property (Fourchon Property). The Wisner Donation funded Dr. John Pardue’s group at LSU to initiate studies on the Fourchon Property beginning in summer 2010.

Shown in figure 16 is a typical cross section for the Fourchon Property. Fine-grained sandy beach sediments exist on the top of the soil profile. These soils are constantly subjected to wind and wave action and become stored up in dunes as the first line of defense against storms. These warehouses of sand serve as a growth area for grasses and succulents, provide habitats and nesting areas for native birds and other animals, and sit atop a cohesive clay layer. This is called the relict marsh layer. The Caminada-Moreau headland, as it is also called, is a low-profile mainland beach with marsh and mangrove cropping out on the lower beach face, reflecting rapid shoreline retreat (Williams, et al. 1992). Figure 17 below shows the Fourchon Property and the areas investigated for this study.

![Figure 16: Typical Soil Cross-Section at Fourchon Property](modified from Campbell, et al. (2004))
Figure 17: Map of Fourchon Property With Sampling Locations
Oil Spill Impacts and Response

On April 20, 2010, the BP Deepwater Horizon offshore drilling rig exploded. Located approximately 40 miles from the Louisiana coastline, the incident claimed 11 lives and resulted in a total of 4.9 million barrels spilled into the Gulf of Mexico in addition to the intended release of large amounts of chemical dispersants. Of the first locations to become contaminated was Belle Pass, LA, which is the westernmost boundary of the Fourchon Property. In the aftermath of the spill, remediation efforts were brought to a halt while SSRBs (small surface residual balls, or “tarballs”) and oil mats continued to arrive onshore. To this day, cleanup activity prevents visitors from entering the beach that is intended for public use. As bulldozers and workers patrol the nine miles of coastline at the Fourchon Property, several million pounds of contaminated beach soil have been removed since cleanup operations commenced (Forrest Travirca, personal communication 2011). Procedures involve the excavation of the upper four inches of contaminated soil, which is then transferred onto a sieving net manually operated by crew members who dispose of all material contained on the sieve, leaving the disturbed sand to be reconstituted onsite.

Tropical Storm Lee

In early September 2011, Tropical Storm Lee (TS Lee) made landfall. Prior to this storm, numerous examination points had been visited by Dr. Pardue’s group. By the time of the next site visit, an entirely different landscape was seen, as 50 to 75 feet of shoreline was gone in some locations at the Fourchon Property. Sand that had been eroded exposed oil mats that had been buried, while numerous tarballs and large, toxic oil patties had been dumped all along the new shoreline (Martin 2011). Sand that had been eroded exposed other layers of strata, putting them
in direct contact with erosive action. Storm surge returning from interior wetlands had cut new pathways through the beach in areas where barriers had been erected to prevent oiled waters from advancing. This alteration in the beach hydrology is believed to have been caused by failure on the part of BP contractors to remove the barriers that were constructed the previous year (Schleifstein 2011). The occurrence of TS Lee was critical for this research in that it presented an opportunity to observe first-hand the dynamics of a coastal barrier system and how erosive and marine transgression processes become accelerated during an extreme weather event. The effects of the storm on soil strength at the headland were studied.

Plant Species and Sampling

During field visits, samples were obtained to analyze shear strength and to monitor the impact of the oil spill. Two plants were encountered during sampling. *Spartina alterniflora* (common name: smooth cordgrass) is a rhizomal perennial grass species that thrives throughout coastal Louisiana as well as many other areas in the world. *Avicennia germinans* (common name: black mangrove) is a shrub-like plant that is known to exist in areas of tropical to subtropical climate, with the northernmost areas containing this species being along the Gulf Coast.

Samples were gathered across a variety of subhabitats in the coastal headland environment at the Fourchon Property. For each sampling event, a total of up to six samples were taken. The following describes the five sampling events (shown in Figure 17) and their corresponding sample dates.

- Sampling Event 1 (SEI): Intertidal Beach/Shoreline 6/14/11
- SEII: Beach Dune/Salt Pan 6/21/11
- SEIII: Back of Dune/Barrier Marsh 8/4/11
• SEIV: Heavily Vegetated Marsh 8/10/11
• SEV: Lightly Vegetated Oil Mat 8/17/11

Samples were also obtained from the shoreline at a newly formed inlet near the SEII sampling site after TS Lee. Disturbed sand was also collected from an area that had been treated by BP contractors.

For the sandier soils encountered, samples were extracted with 4-in cores using sharpened PVC pipes of approximately 12 inches in length. For the more cohesive clay media found in the marshes, a set of 6-in diameter thin-walled aluminum irrigation pipes of approximately 20 inches in length were used. All samples were extracted in-situ and had varying degrees of vegetation and sometimes contained none. Samples were obtained by first manually inserting the sampler into the ground. Approximately 8 in of soil media was gathered for beach sands sampled with PVC pipe (marsh samples were approximately 16 inches). Using a shovel, the outside of the sampler was exposed on one side so that the sample could be extracted in situ. Plastic bags were placed around the bottom of the sampler and secured with duct tape. For moist soil samples, any remaining void space at the top of the sampler was filled with packing material and was similarly encased. Samples were transported to the laboratory in their vertical orientation.

3.2.2 Laboratory Details

Testing was performed in the LSU Soil Mechanics Laboratory using GEOTAC automated loading frames called “GeoJacs” during the summer and fall of 2011 and the spring of 2012. Each sample produced at least one test specimen, and in-situ soil water content was determined according to ASTM D2216. In order to perform a thorough direct shear evaluation, a
minimum of three tests must be carried out (Bhudu 2007). ASTM standard D3080 was consulted, where the inclusion of root matter in the test specimens deviated from the procedure. For this study, a total of six vertical loadings were selected based on the increase in effective stress due to the addition of fill media. The tests were run at vertical loadings of 40, 100, 300, 500, 1000, and 2088.6 psf (2, 5, 14, 24, 48, and 100 kPa). High-stress conditions were analyzed under normal loadings at the 500 psf (24 kPa) mark and beyond, while low-stress conditions were analyzed at the loadings below this mark. Table 6 shows normal stress values corresponding to fill depths of a typical soil, which were used in determining low-stress loadings.

For the shearing phase of testing, two horizontal displacement rates were selected: 0.025 in/min for coarser-grained sand media and 0.01 in/min for cohesive clay material (LSU Geotechnical Engineering 2011) and sheared until the external limit of the shearbox (the dual shearing plate assembly used for direct shear). An alternate test was sometimes conducted for a sample, where a duplicate test was run at the alternate shearing rate for the type of soil media encountered after fashioning a second test specimen. This was done for qualitative comparison. Saturated soil conditions were replicated in the laboratory by submerging the shearbox with deionized water in order to reflect field conditions when desired.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.5</td>
<td>4.91</td>
<td>20</td>
<td>0.00032</td>
<td>18</td>
<td>0.00579167</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>2.5</td>
<td>4.91</td>
<td>29</td>
<td>0.00048</td>
<td>18</td>
<td>0.0086875</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>2.5</td>
<td>4.91</td>
<td>39</td>
<td>0.00064</td>
<td>18</td>
<td>0.0115833</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>2.5</td>
<td>4.91</td>
<td>59</td>
<td>0.00097</td>
<td>18</td>
<td>0.017375</td>
<td>5</td>
</tr>
<tr>
<td>24</td>
<td>2.5</td>
<td>4.91</td>
<td>118</td>
<td>0.00193</td>
<td>18</td>
<td>0.03475</td>
<td>11</td>
</tr>
<tr>
<td>48</td>
<td>2.5</td>
<td>4.91</td>
<td>236</td>
<td>0.00386</td>
<td>18</td>
<td>0.0695</td>
<td>22</td>
</tr>
</tbody>
</table>
When a normal stress is applied to a soil specimen a certain amount of settlement is expected, as compaction and dewatering can sometimes take multiple hours to occur. Once an adequate degree of settlement has been achieved, the first step of the test, the consolidation phase, was terminated. In an ideal situation, the overburden stress felt by the test specimen due to the normal load causes vertical displacement to occur in three distinct stages: an initial precompression period with a shallow slope when viewed on a semilogarithmic plot of vertical displacement with respect to time, a primary consolidation period where the slope is virtually a straight line on the plot, and a secondary consolidation period with a shallow slope (Das 2008). Once the sample was consolidated and had stabilized in terms of settlement, shearing took place under the testing conditions that were programmed.

3.2.3 Computational Details

Geotechnical Engineering Theory

As normal stress increases on an elemental mass of soil media, shear stress will also increase. Establishing a relationship of increasing shear stress to increasing normal stress is an analysis that is commonly executed. For this study, a series of curves were generated for each set of direct shear tests performed for each sampling event. Curves were created depicting shear stress versus horizontal displacement (τ vs. Δx) as well as vertical displacement versus horizontal displacement (Δz vs. Δx). On a typical τ vs. Δx plot, the trend exhibits an increase in shear stress from zero to a peak value, which classically occurs early on in the curve, followed by a gradual decrease to a lower shear stress value that remains virtually constant until the end of the test. For these curves, two values were recorded: the peak shear strength (maximum value) and the residual shear strength (smaller than maximum, usually constant through the end of shearing).
From there, comparison plots were made of peak and residual shear strength versus normal stress ($\tau$ vs. $\sigma$) of all tests performed for each sampling event, and the relationship between shear stress and normal stress was then studied. The residual shear stress was used for further analysis.

Equation 1 is called the Mohr-Coulomb failure criterion, and it relates shear stress to normal stress as follows (Das 2008):

$$\tau = c + \sigma \tan \phi$$  \hspace{1cm} (3-1)

Where:
- $\tau$ = shear strength [kPa]
- $\sigma$ = normal (effective) stress applied [kPa]
- $c$ = cohesion [kPa]
- $\phi$ = internal angle of friction [$^\circ$]

Erosion Modeling

Erosion occurs when a wave-induced shear stress exceeds the threshold shear strength of the sediment. Erosion is believed to stop once exposed soil is encountered that has shear strength equal to or greater than the wave-induced shear stress. Mass erosion may occur when wave shear stresses are encountered well in excess of the threshold value. This can detach and erode large amounts of cohesive sediment from the bed at a time. There is little research and development on the mass erosion of cohesive sediment (Whitehouse, et al. 2000).

The rate of erosion of fine-grained sediment, $\frac{dm}{dt}$, expressed as a dry mass of soil eroded per unit area per unit time is related to the magnitude of the excess shear stress due to wave action, ($\tau_w - \tau_e$), by the dimensional coefficient, $m_e$, known as the erosion constant (Whitehouse, et al. 2000).
\[
\frac{dm}{dt} = m_e (\tau_w - \tau_e) \quad \text{for} \quad \tau_w > \tau_e \tag{3-2a}
\]

\[
\frac{dm}{dt} = 0 \quad \text{for} \quad \tau_w \leq \tau_e \tag{3-2b}
\]

Where:
- \( \frac{dm}{dt} \) = rate of erosion \([\text{kg/m}^2/\text{s}]\)
- \( \tau_w \) = wave-induced shear stress \([\text{Pa}]\)
- \( \tau_e \) = threshold bed shear stress for erosion \([\text{Pa}]\)
- \( m_e \) = erosion constant \([\text{kg/N/s or m/s}]\)

Calculating bed shear stress due to waves can be done so as (Rosati 2009; Whitehouse, et al. 2000):

\[
\tau_w = \frac{1}{2} \rho_w f_w (U_w)^2 \tag{3-3}
\]

Where:
- \( \rho_w \) = density of seawater \([\text{kg/m}^3]\) (assumed 1,025)
- \( f_w \) = wave friction factor
- \( U_w \) = wave orbital velocity \([\text{m/s}]\)

Calculating wave orbital velocity can be done so as (Rosati 2009):

\[
U_w = \frac{gHT}{2L} \tag{3-4}
\]

Where:
- \( g \) = acceleration due to gravity \([\text{m/s}^2]\)
- \( H \) = significant height of wave train \([\text{m}]\)
- \( T \) = wave period \([\text{s}]\)
- \( L \) = wavelength \([\text{m}]\)
Calculating wave friction factor depends on flow roughness. This requires the calculation of the wave Reynolds number, $R_w$, and the relative roughness, $r$, which are done so as (Whitehouse, et al. 2000):

$$R_w = \frac{U_w A}{\nu}$$

$$f_w = B R_w^{-N}$$

Where:

- $R_w =$ Reynolds number of wave
- $A =$ semi-orbital excursion = $U_w T / 2\pi$ [m]
- $\nu =$ kinematic viscosity [m$^2$/s] of water (assumed $10^{-6}$)
- $B =$ 2 for $R_w \leq 5 \times 10^5$ (laminar flow)
  = 0.0521 for $R_w > 5 \times 10^5$ (turbulent flow)
- $N =$ 0.5 (laminar flow)
  = 0.187 (turbulent flow)

3.2.4 Measurements

Approximately 60 direct shear tests were performed for this study. Table 7 lists and describes these tests. Also shown are typical plots of $\tau$ vs. $\Delta x$ and $\Delta z$ vs. $\Delta x$ in figures 18 and 19, respectively. For a direct shear evaluation, the results of each sample from a sampling event were compared with each other according to peak and residual shear stress exhibited. From figure 18, the peak and residual shear stresses for the 300 psf (14 kPa) normally-loaded unvegetated sample extracted from the beach dune/salt pan are 14 and 12.5 kPa, respectively. From figure 19, it can be seen how the soil sample behaved against shear in terms of settlement.
Table 7: List of Direct Shear Tests

<table>
<thead>
<tr>
<th>Sampling Event I (SEI)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-0614-A-40</td>
<td>40 psf test on Sample A taken at shoreline subhabitat</td>
</tr>
<tr>
<td>DS-0614-B-100</td>
<td>100 psf test on Sample B taken at shoreline subhabitat</td>
</tr>
<tr>
<td>DS-0614-C-300</td>
<td>300 psf test on Sample C taken at shoreline subhabitat</td>
</tr>
<tr>
<td>DS-0614-D-500</td>
<td>500 psf test on Sample D taken at shoreline subhabitat</td>
</tr>
<tr>
<td>DS-0614-E-2088.6</td>
<td>2088.6 psf test on Sample E taken at shoreline subhabitat</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sampling Event II (SEII)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-0621-A-40</td>
<td>40 psf test on Sample A taken at beach dune subhabitat</td>
</tr>
<tr>
<td>DS-0621-A2-40</td>
<td>40 psf test on Sample A taken at beach dune subhabitat, alternate displacement rate</td>
</tr>
<tr>
<td>DS-0621-B-100</td>
<td>100 psf test on Sample B taken at beach dune subhabitat</td>
</tr>
<tr>
<td>DS-0621-C-2088.6</td>
<td>2088.6 psf test on Sample C taken at beach dune subhabitat</td>
</tr>
<tr>
<td>DS-0621-D-1000</td>
<td>1000 psf test on Sample D taken at beach dune subhabitat</td>
</tr>
<tr>
<td>DS-0621-D2-1000</td>
<td>1000 psf test on Sample D taken at beach dune subhabitat, alternate displacement rate</td>
</tr>
<tr>
<td>DS-0621-E-500</td>
<td>500 psf test on Sample E taken at beach dune subhabitat</td>
</tr>
<tr>
<td>DS-0621-F-300</td>
<td>300 psf test on Sample E taken at beach dune subhabitat</td>
</tr>
<tr>
<td>Sampling Event III (SEIII), vegetated with <em>Spartina alterniflora</em> and <em>Avicennia germinans</em> for low- and high-stress conditions, respectively</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>DS-0804-A-40</td>
<td>40 psf test on Sample A taken at barrier marsh subhabitat</td>
</tr>
<tr>
<td>DS-0804-B-2088.6</td>
<td>2088.6 psf test on Sample B taken at barrier marsh subhabitat</td>
</tr>
<tr>
<td>DS-0804-C-500</td>
<td>500 psf test on Sample C taken at barrier marsh subhabitat</td>
</tr>
<tr>
<td>DS-0804-D-1000</td>
<td>1000 psf test on Sample D taken at barrier marsh subhabitat</td>
</tr>
<tr>
<td>DS-0804-E-100</td>
<td>100 psf test on Sample E taken at barrier marsh subhabitat</td>
</tr>
<tr>
<td>DS-0804-E2-100</td>
<td>100 psf test on Sample E taken at barrier marsh subhabitat, alternate displacement rate</td>
</tr>
<tr>
<td>DS-0804-F-300</td>
<td>300 psf test on Sample F taken at barrier marsh subhabitat</td>
</tr>
<tr>
<td>DS-0804-F2-300</td>
<td>300 psf test on Sample F taken at barrier marsh subhabitat, alternate displacement rate</td>
</tr>
</tbody>
</table>
Table 7 Continued

<table>
<thead>
<tr>
<th>Sampling Event IV, Low Zone (SEIVL), vegetated with <em>Spartina alterniflora</em> and <em>Avicennia germinans</em> for low- and high-stress conditions, respectively</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-0810-AL-500</td>
</tr>
<tr>
<td>DS-0810-AL-1000</td>
</tr>
<tr>
<td>DS-0810-AL-2088.6</td>
</tr>
<tr>
<td>DS-0810-BL-40</td>
</tr>
<tr>
<td>DS-0810-BL-100</td>
</tr>
<tr>
<td>DS-0810-BL-300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sampling Event IV, High Zone (SEIVH), vegetated with <em>Spartina alterniflora</em> and <em>Avicennia germinans</em> for low- and high-stress conditions, respectively</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-0810-AH-500</td>
</tr>
<tr>
<td>DS-0810-AH-1000</td>
</tr>
<tr>
<td>DS-0810-AH-2088.6</td>
</tr>
<tr>
<td>DS-0810-AH2-2088.6</td>
</tr>
<tr>
<td>DS-0810-BH-40</td>
</tr>
<tr>
<td>DS-0810-BH-100</td>
</tr>
<tr>
<td>DS-0810-BH-300</td>
</tr>
</tbody>
</table>
Table 7 Continued

<table>
<thead>
<tr>
<th>Sampling Event V (SEIV), vegetated with <em>Spartina alterniflora</em> for 2088.6 psf (100 kPa), 100 psf (5 kPa), and 300 psf (14 kPa) normally-loaded tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-0817-A-500</td>
</tr>
<tr>
<td>DS-0817-B-2088.6</td>
</tr>
<tr>
<td>DS-0817-B2-2088.6</td>
</tr>
<tr>
<td>DS-0817-C-100</td>
</tr>
<tr>
<td>DS-0817-D-300</td>
</tr>
<tr>
<td>DS-0817-E-40</td>
</tr>
<tr>
<td>DS-0817-F-1000</td>
</tr>
</tbody>
</table>
Table 7 Continued

<table>
<thead>
<tr>
<th>Disturbed Sand Samples (DS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disturbed Sand 40</td>
</tr>
<tr>
<td>Disturbed Sand 100</td>
</tr>
<tr>
<td>Disturbed Sand 100 ALT</td>
</tr>
<tr>
<td>Disturbed Sand 300</td>
</tr>
<tr>
<td>Disturbed Sand 500</td>
</tr>
<tr>
<td>Disturbed Sand 1000</td>
</tr>
<tr>
<td>Disturbed Sand 1000 ALT</td>
</tr>
<tr>
<td>Disturbed Sand 2088.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exposed Relict Marsh Clay Samples (EC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed Clay 40</td>
</tr>
<tr>
<td>Exposed Clay 100</td>
</tr>
<tr>
<td>Exposed Clay 300</td>
</tr>
<tr>
<td>Exposed Clay 500</td>
</tr>
<tr>
<td>Exposed Clay 500 ALT</td>
</tr>
<tr>
<td>Exposed Clay 1000</td>
</tr>
<tr>
<td>Exposed Clay 2088.6</td>
</tr>
</tbody>
</table>
Figure 18: Typical Plot of $\tau$ vs. $\Delta x$

Figure 19: Typical Plot of $\Delta z$ vs. $\Delta x$
### 3.3 Results and Discussion

Figures 20 and 21 are $\tau$ vs. $\sigma$ plots for the sand and clay direct shear tests, respectively. Each plot contains data points of residual shear strengths for each sampling event at each normal loading. Mohr-Coulomb parameters, such as cohesion and friction angle, were calculated. Shown in the figures are linear regression lines for low-stress conditions (less than 500 psf (24 kPa)) as solid lines and high-stress conditions (500 psf (24 kPa) and greater) as dotted lines. The disturbed sand samples and exposed clay samples obtained from the erosional inlet at the shoreline were tested as reference samples and are indicated in black on both figures.

![Figure 20: Plot of Residual Shear Strength vs. Normal Stress—Beach Sands](image-url)
Tables 8 and 9 summarize the direct shear data for beach and marsh samples, respectively, as shown from these plots and also include other qualitative and laboratory data for each sampling event with their respective reference sample sets. Vertical displacement during shearing was recorded for each test, and as a method of comparison, the 300 psf (14 kPa) normally loaded test result was used for this parameter. Termed the nominal vertical displacement, the vertical displacement recorded from this direct shear test was chosen because of the proximity to the median value of normal loadings, and also since for nearly all tests it contained plant roots of *Spartina alterniflora*. 

Figure 21: Plot of Residual Shear Strength vs. Normal Stress—Marsh Clays
Table 8: Laboratory Data for Fourchon Beach Sand Samples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SAMPLING EVENT</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SEI (Intertidal)</td>
<td>SEII (Dune/Salt Pan)</td>
</tr>
<tr>
<td>Nominal Vertical Displacement(^a) [in]</td>
<td>0.022</td>
<td>0.038</td>
</tr>
<tr>
<td>Shear Stress Range [kPa]</td>
<td>93</td>
<td>78</td>
</tr>
<tr>
<td>Cohesion (LO-(\sigma)) [kPa]</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Cohesion (HI-(\sigma)) [kPa]</td>
<td>-8</td>
<td>0</td>
</tr>
<tr>
<td>Internal Angle of Friction (LO-(\sigma)) [°]</td>
<td>32</td>
<td>33</td>
</tr>
<tr>
<td>Internal Angle of Friction (HI-(\sigma)) [°]</td>
<td>46</td>
<td>37</td>
</tr>
<tr>
<td>Soil Water Content [%]</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Presence of Vegetation [kPa]</td>
<td>NONE</td>
<td>NONE</td>
</tr>
<tr>
<td>Shear Failure Observed [kPa]</td>
<td>2, 5, 14, 24</td>
<td>2, 5, 14</td>
</tr>
</tbody>
</table>

Notes:
Normal loading given in kPa for test in which presence of vegetation and/or shear failure observed
\(^a\) = nominal vertical displacement value taken from 14kPa normally loaded test during shearing phase
\(^b\) = vertical displacement behavior erratic for all tests in this sampling event, nonconclusive result for this parameter
\(^c\) = shear response behavior erratic for all tests in this sampling event, nonconclusive result for this parameter
The shear stress range is the difference in residual shear strengths observed from the highest stress normal loading of 2088.6 psf (100 kPa) to the lowest stress normal loading of 40 psf (2 kPa) and is an obvious measure of variability for all the sampling events. Cohesion and friction angle are parameters that describe the shear strength of soils. The values for cohesion and friction angle were derived from linear regression analyses, as calculated by the Mohr-Coulomb equation. Soil water content is a measure of the ratio of dry soil to water by mass and is known to have an effect on overall soil strength in a generally weakening sense. Also shown are the presence of vegetation and occurrence of shear failure, which is believed to be influenced heavily on the presence of reinforcing root matter.

For Table 8, the sampling events included are the intertidal shoreline area, beach dune/salt pan area, back barrier marsh area, lightly vegetated oil mat area, and the disturbed sand samples. The maximum value of vertical displacement was observed at 0.038 in for the unvegetated beach dune subhabitat, while the lowest value of vertical displacement was in fact a negative value of -0.020 in (an increase in vertical position of the soil surface during shearing and an indication of dilation during shearing) for the back beach/barrier marsh sample vegetated with Spartina alterniflora. The maximum value of shear stress range was 56 kPa for the lightly vegetated oil mat near the entrance to Fourchon Beach, while the highest value was 93 kPa for the intertidal beach zone. Low-stress cohesion was and varied from 1 kPa to 3 kPa across the beach sand areas. High-stress cohesion had much more variability. The highest value of low-stress internal angle of friction was obtained at the back barrier marsh at 57 degrees, while the lowest value of low-stress internal angle of friction was 32 degrees and was observed for the disturbed
sand samples and for the intertidal shoreline area. High-stress internal angle of friction varied between 23 degrees at the barrier marsh to 46 at the intertidal shoreline area. Of all sampling events, the highest frequency of shear failure occurred at the intertidal beach and lightly vegetated oil mat subhabitat, with the least frequent shear failure occurring at the barrier marsh. The reference sample comprised of remediated sand that had been disturbed by oil spill workers was totally air dry and generally weaker than the other sampling events. It contained the lowest internal angle of friction at a value of 29 degrees and also had the lowest shear stress range of 45 kPa.

For Table 9, the results came from the SEIV heavily vegetated marsh sampling event. The samples were divided into approximately 8 inch soil horizons where soil strength parameters were observed to vary significantly. SEIVH is the upper layer or “high zone” of the heavily vegetated marsh/mangrove site visited, while SEIVL is the “low zone.” The EC exposed clay sampling event was used as the reference sample set. The maximum vertical displacement occurred in the low zone with a magnitude of 0.140 in, while the minimum occurred at the high zone with a magnitude of 0.045 in. The maximum shear stress range was observed at the high zone with a value of 56 kPa, while the minimum was observed at the low zone with a value of 29 kPa. Low-stress cohesion was 7 kPa for both zones, while high-stress cohesion was 37 and 10 kPa for the high and low zones, respectively. Internal angle of friction was 54 degrees for the high zone and 43 degrees for the low zone at low effective stress, while for high effective stress it was 17 and 38 degrees for the high and low zones, respectively.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>SAMPLING EVENT</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SEIVH High Zone</td>
<td>SEIVL Low Zone</td>
</tr>
<tr>
<td>Nominal Vertical Displacement [in]</td>
<td>0.045&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.140&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Shear Stress Range [kPa]</td>
<td>56</td>
<td>29</td>
</tr>
<tr>
<td>Cohesion (LO-σ) [kPa]</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Cohesion (HI-σ) [kPa]</td>
<td>37</td>
<td>10</td>
</tr>
<tr>
<td>Internal Angle of Friction (LO-σ) [°]</td>
<td>54</td>
<td>43</td>
</tr>
<tr>
<td>Internal Angle of Friction (HI-σ) [°]</td>
<td>17</td>
<td>38</td>
</tr>
<tr>
<td>Soil Water Content&lt;sup&gt;c&lt;/sup&gt; [%]</td>
<td>(87, 55)</td>
<td>(192, 35)</td>
</tr>
<tr>
<td>Presence of Vegetation [kPa]</td>
<td>ALL</td>
<td>ALL</td>
</tr>
<tr>
<td>Shear Failure Observed [kPa]</td>
<td>NONE</td>
<td>24, 48, 100</td>
</tr>
</tbody>
</table>

Notes:
Normal loading given in kPa for test in which presence of vegetation and/or shear failure observed

<sup>a</sup> = nominal vertical displacement value taken from 14kPa normally loaded test during shearing phase
<sup>b</sup> = nominal vertical displacement value taken from 24 kPa alternate run as worst-case scenario
<sup>c</sup> = soil water content values given as an ordered pair of *Spartina alterniflora* followed by *Avicennia germinans*
Shear failure was observed only in the high-stress direct shear tests carried out on samples vegetated with *Avicennia germinans* in the low soil horizon. The reference sample was obtained near the erosional inlet that formed after TS Lee. It contained a soil water content of 44 percent and had a vertical displacement not lower than either of the low or high zone tests. The reference sample showed a shear stress range equal to that of the low zone and also had an internal angle of friction of 29 degrees, slightly larger than that of the low zone. It contained cohesion values of 13 and 28 kPa for low and high effective stress conditions, respectively. Internal angle of friction was 39 and 18 degrees for low and high effective stress conditions, respectively. Shear failure did not occur for any of the samples vegetated with remnant roots of *Avicennia germinans*. Soil water content was measured at 44 percent.

The average shear stress range for all tests performed was approximately 55 kPa. For direct shear tests conducted at the extreme case 100 kPa normal loading, the average residual shear strength was approximately 70 kPa. For marsh samples, the average internal angle of friction was 45 degrees at low effective stress and 24 degrees at high effective stress, while cohesion averages were 7 kPa for low effective stress and 25 kPa for high effective stress. Beach samples had cohesion averages of 2 kPa and 6 kPa for low and high effective stress, respectively, and internal angle of friction averages of 38 degrees and 32 degrees for low and high effective stress, respectively.

In a study on shear strengths of undisturbed and remolded soil from typical Chinese forests, Zhang, et al. (2007) utilized direct shear testing to evaluate cohesion and internal angle of friction. Vertical loadings were 100, 200, 300, and 400 kPa, and shearing was conducted at three different rates of constant vertical displacement, with the
termination limit at approximately 6 mm (approximately half the distance of the tests conducted herein). Results showed shear strengths ranging from approximately 35 kPa at the lower ended 100 kPa normally-loaded test (the highest normal loading for this study) up to nearly 200 kPa for the high-stress loading of 400 kPa. The shear strengths observed were usually between 35 and 50 percent of the normal loading applied for each direct shear test. The samples were five different types of vegetated soil that were obtained from forested areas and farmlands in China; no plant species were identified and instead descriptions of forest type (i.e., needle-leaved forest) were given.

For a variety of reasons, direct shear testing is used to assess shear strength of soils. Its ease of operation and quickness make this a popular laboratory procedure. Advantages of the direct shear test may include a direct visual process with relatively low cost (Fan and Su 2008; Wu and Watson 1998). However, the predefined shear plane and incomplete control over specimen drainage inherent to direct shear tests makes undrained shear strength results for clays nonconservative (Nugent 2011). Triaxial testing is another method by which soil shear strength can be measured.

The average water content for the beach sand samples from the Fourchon Property was approximately 10 percent. Soil water content ranged from a minimum of 3 percent at the lightly vegetated oil mat to 22 percent at the moderately vegetated barrier marsh located near open waters and bayous running parallel to the shoreline. The disturbed sand sample was classified as air-dry (~0 percent). Soil water content was measured for the marsh samples, but because of differences between soil horizons the values were recorded discretely with magnitudes of 87 and 192 percent at the location containing Spartina alterniflora for the high and low zones, respectively, and 55 and 35
percent at the location containing *Avicennia germinans* for the high and low zones, respectively.

Zhang, et al. (2009) used triaxial compression testing to evaluate the influences of roots on soil shear strength. Consolidated-drained triaxial compression tests were conducted on eight groups of samples at two different soil water contents of 12.7 and 20.0 percent. Samples of soil obtained from the Loess Plateau in Northwest China were manually combined with roots of *Robinia pseudocacia* in three different orientations: vertical, horizontal, and vertical-horizontal (cross). An unvegetated plain soil sample set was also tested. Shear strengths calculated at a nominal vertical loading of 200 kPa ranged from an average of 113 kPa for tests conducted on the samples of higher water content to an average of 145 kPa for the less wet samples. Also calculated were cohesion and internal angle of friction. At the 12.7 percent soil water content, friction angle decreased gradually from 27 percent for the plain soil sample to 23 for the vertical and cross root configurations. Cohesion grew from 29 kPa for the plain soil to 74 kPa for the cross root configuration. At the 20.0 percent soil water content, friction angle again remained somewhat constant from 22.3 percent for the plain soil to 26.2 percent for the cross root configuration. Cohesion was 18 kPa for the unvegetated sample and increased to 26 kPa for the cross root configuration. Findings indicated that roots can effectively improve soil shear strength by increasing the cohesion of soil and plants or trees with the cross root orientation are expected to be the most adaptive to reinforcing soil and stabilizing slope. Zhang, et al. (2009) defined a parameter called the integrated cohesion, which is a summation of soil cohesion and cohesion due to roots, and this parameter was used throughout the study.
In a study to measure the erosion rates of cohesive sediments in Venice Lagoon, Italy, Amos, et al. (2009) stated that resistance to erosion is due to the submerged weight of bed material as defined by the balance of forces used to define Stoke’s Law and appears to correlate positively with shear strength. A benthic flume sea carousel was used to measure the in-situ stability of cohesive coastal sediments between intertidal and sub-tidal locations at the site. The higher values of erosion rate were found to be a result of exposure that influences consolidation, density, and organic adhesion—namely, due to high boat activity and bottom fishing. To first order, erosion resistance may be considered analogous to the failure envelope of a standard Mohr-Coulomb plot (Lambe and Whitman 1969) with the surface intercept (cohesion) being the surface erosion threshold (Migniot 1968).

The critical shear strength of soils is the magnitude of shear stress that must be met or exceeded by external forces in order to initiate movement of soil particles. This threshold for erosion determines whether sediment deposited on the bed of an estuary or in the sea can be eroded by the prevailing current and wave conditions (Whitehouse, et al. 2000) and then in what manner erosion can be predicted to continue. Much is known about the threshold of erosion of cohesive sediments; less known, however, are the rates of erosion that take place once the threshold has been exceeded (Amos, et al. 2009). Erosion resistance almost always increases with depth. Under a constant fluid bed shear stress, an eroding cohesive sediment will eventually cease to erode when the erosion strength of the exposed cohesive sediment becomes equivalent to the induced shear stress (Whitehouse, et al. 2009). Alternatively, a re-initiation of erosion can also occur with increased velocity giving higher shear stresses than the strength of the exposed layer.
In a study to obtain a simple critical shear stress function for cohesive soft bottom sediments, Otsubo and Muraoka (1988) defined two threshold erosion shear stresses for various mud types based on their rheological and settling properties examined through a series of experiments. The first shear stress was defined as the limit of particle movement, while the other was defined as the limit of bed destruction. Critical shear strength was measured by conducting a hydraulic experiment in which an acrylic pipe 10 m long with a 7 m wide rectangular cross section was filled with water that flowed over an alluvial bed of a mud samples over an array of known soil-water contents. The flow velocity was accelerated very slowly until the sediment bed was destroyed by the current. Turbidity, current velocity, head differential across the pipe, and other data were collected to determine the mud threshold. Other geotechnical engineering properties such as Atterberg limits, particle size, and specific gravity were also determined using standard methods. Results showed critical shear stresses to be on the order of $10^{-2}$ to $10^0$ Pa, and these values were retroactively expressed as functions of yield value. In another study by Sharif and Atkinson (2012) to model surface erosion of cohesive soils affected by turbulent bursts, critical shear stresses of kaolinite were reported to exist in the range of approximately 0.5 to 4.0 Pa.

As effective (normal applied) stress increases, shear stress also increases for any given soil entity. Direct shear testing is a powerful tool to understand the characteristics of this increase in strength and how shear failure may present itself in a practical setting. The erosional shear strength property of soil is an entirely different parameter that is called the critical shear stress. In literature, cohesion, as determined by use of the Mohr-
Coulomb failure criterion, appears the most influential to critical shear strength and can even be synonymous to critical shear strength in some cases for certain types of soils.

3.4 Applications

3.4.1 Erosion Modeling and Implications for Restoration

Description of Procedure

\[
\frac{dm}{dt} = m_e(\tau_w - \tau_e) \quad (3-2a, \text{restated})
\]

Equation 3-2a (modified slightly from Section 3.2) was used to predict erosion rates. This expresses erosion rates, dm/dt, as a differential with units of kilograms per square meter per second. This is directly proportional to what is called the excess critical shear stress, \((\tau_w - \tau_e)\), as induced by wave action. Shear stresses/strengths are in units of Pascals. Linking \(\frac{dm}{dt}\) and \((\tau_w - \tau_e)\) is a dimensional coefficient called the erosion constant, \(m_e\), which varies according to soil type and has been seen to exist in magnitudes on the order of \(10^{-4}\) to \(10^{-1}\) with units of kilograms per Newton per second.

There are a number of factors that can contribute to the coastal erosion. All along the Gulf Coast, erosional and depositional characteristics are highly variable and can be affected by a variety of other processes such as currents, tides, and wind. Specifically in Louisiana, the presence of the Mississippi River brings another element of variability to the physical processes affecting coastal erosion. Whitehouse, et al. (2000) developed this equation based on laboratory flume experiments to study the erosion of cohesive sediments with wave action regarded as the primary driving force. More complex models do exist that take into account other components of the dynamic nature of a headland
system, and some of these phenomena are considered in the empirical coefficients of equation 3-2a. There has been little, if any, such analyses performed for fine-grained barrier island sediment (Rosati 2009) or for mass erosion events on coastal headlands.

Equation 3-2a expresses erosion rates purely as a function of shear. If the critical shear strength of the sediment is greater than or equal to the wave-induced shear stress, then the result is an erosion rate equal to zero. If the soil has a critical shear strength that is low compared to the wave-induced shear stress, and/or if the wave-induced shear stress is high relative to the critical soil shear strength, then the erosion rate will be a positive value indicating the transient loss of sediment for the duration of time that wave shear stresses remain in excess of the critical shear strength of the sediment.

Determination of Critical Shear Strength

Relict marsh clay was targeted as the main soil layer to which mass erosion events pose a threat. Because clays drain so slowly (several orders of magnitudes slower than sands), clays in saturated environments are said to exist under undrained conditions. Porewater pressures can influence strength properties and can significantly decrease the normal effective stress, thereby decreasing the overall shear strength. The excess porewater pressure will eventually dissipate, but only after a large amount of time has passed. The shear strength will then slowly approach its true value. If the clay is truly saturated and undrained, the shear strength will not increase with increasing normal stress. Effectively then, the friction angle will be equal to zero. It would be of poor judgment, therefore, to set the shear strength of the soil equal to the shear stress applied.
All samples were extracted in situ by inserting the sampler perpendicularly into the ground at each location. There was a wide variety of terrains encountered and along with these terrains the slope varied as well. The test specimens were obtained from a depth of approximately 4 in below the ground surface for beach soil and from two depths of approximately 4 and 12 in below the ground surface for marsh soil (for the two soil horizons). Four inches is roughly the same excavation depth to which oil spill cleanup workers were instructed to perform treatment operations along the shoreline. The direct shear method forces shearing along a predefined plane parallel to the top surface of the soil specimen. While this is not necessarily the most conservative method for measuring shear strength in certain soils, such a shear plane seemed the most logical for an analysis of wave-induced erosion.

The shear imposed by a direct shear apparatus is different than that of the critical shear stress mentioned in the literature. For erosion modeling, of interest are the surface erosion properties, and the critical shear strengths found in literature are of very small magnitudes. For mass erosion events, an entire composite of headland detaches at once, which would indicate shear failure of the cohesive relict clay layer found at the headland of the Fourchon Property. For sandy beach soil found near the ground surface of the headland, critical shear strength was set to zero (Rosati 2009), while for relict marsh clays the critical shear strengths were assumed to be of significantly higher values related to the findings in Table 9.
Determination of Wave-Induced Shear Stress

WAVCIS is an acronym for Wave-Current-Surge Information System for Coastal Louisiana and is maintained by the Coastal Studies Institute of the School of the Coast and Environment at LSU. Data was obtained from wave gauge CIS-09, which is located at the Grand Isle Blocks at (N 29° 06.09’, W 89° 58.69’) approximately 10 miles off the Louisiana coast from Fourchon Beach. Table 10 shows three different wave scenarios and the parameters used to determine the \( \tau_w \) for each scenario. Three wave scenarios were determined. Wave height, \( H \), period, \( T \), and wavelength, \( L \), were obtained first. Orbital velocity and Reynolds Number were calculated and a friction factor was determined. Wave-induced shear stresses of 93, 295, and 529 Pa were calculated for typical, moderate, and storm conditions, respectively.

<table>
<thead>
<tr>
<th>Wave Scenario</th>
<th>WAVCIS PARAMETERS</th>
<th>CALCULATED PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( H ) [m] ( T ) [s] ( L ) [m]</td>
<td>( U_w ) [m/s] ( R_w ) ( f_w ) ( \tau_w ) [Pa]</td>
</tr>
<tr>
<td>Typical</td>
<td>0.42 5.12 1.02</td>
<td>10.3 8.65E+07 0.0017 93</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.9 8 1.60</td>
<td>22.1 6.20E+08 0.0012 295</td>
</tr>
<tr>
<td>Storm</td>
<td>1.3 8.6 1.72</td>
<td>31.9 1.39E+09 0.0010 529</td>
</tr>
</tbody>
</table>

Notes:
Velocity of wave propagation of 0.20 m/s assumed for all scenarios

In deepwater portions of the northern Gulf of Mexico, wave energy is generally very low. The low-lying nature of the lower Louisiana delta plain makes this area vulnerable to coastal physical processes in the Gulf. The frequent occurrences of hurricanes, tropical storms, and cold fronts have the capability to transform a typical significant wave height of 0.07 – 0.08 m to a significant wave height of over 2 m during
storms at the south-central/south-east areas along the Louisiana coast (Georgiou, et al. 2005).

Erosion Rates and Mass Erosion Events

Table 11 shows erosion rates calculations for the three different wave scenarios. Based on the assumptions and the selection process regarding the critical shear strengths of headland soils and the values determined for wave-induced shear stresses, erosion rates were calculated using Equation 3-2a. This corresponds to erosion rates of 0.093, 0.295, and 0.529 kg/m²/s for each wave scenario as they appear in the table.

<table>
<thead>
<tr>
<th>Wave Scenario</th>
<th>( m_e ) [kg/N/s]</th>
<th>( (\tau_e - \tau_w) ) [Pa]</th>
<th>( dm/dt ) [kg/m²/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical</td>
<td>0.001</td>
<td>93</td>
<td>0.093</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.001</td>
<td>295</td>
<td>0.295</td>
</tr>
<tr>
<td>Storm</td>
<td>0.001</td>
<td>529</td>
<td>0.529</td>
</tr>
</tbody>
</table>

Notes:
Erosion constant selected at 0.001 kg/N/s based on erosional/depositional properties in Table 8 from Whitehouse, et al. (2000)

The coastal headland environment could be considered a real life coastal soil mechanics laboratory. Wave energy constantly collides into tons of beach sand and completely reshapes the landscape. From the shoreline to the marshes, soil properties varied drastically. At the Fourchon Property, black streaked tan to light gray sand was dense, moist and compact at the intertidal shoreline area. No vegetation existed here. Moving progressively inland, the beach sand became lighter, fluffier, drier, and vegetation began to appear. What also changed was the elevation, as dunes had formed
and were built up several feet to serve as the first on-land buffer against wave action.

Moving back to the barrier bayous and marshes, the sand was finer-grained and dense. Vegetation was beyond prevalent, as dwarf *Avicennia germinans* and stunted clumps of *Spartina alterniflora* struggled to survive adjacent to the hyper-saline salt pan whilst being constantly buried in sand that was being deposited by wind and waves from the dunes and shoreline.

Fine-grained clays contain true cohesive strength. Cohesion can also be brought about by the existence of plant roots. Naturally, cohesive strength and plant roots work together to form a mutually beneficial partnership. As vegetation grows and thrives in coastal marshes, biomass is deposited on the ground surface of the marsh as plants die. This organic matter decomposes and provides nutrients for other functions throughout the marsh environment. A constant supply of organic matter encourages a fine-grained, carbon-rich, cohesive layer of soil to exist at the top of the soil profile. This, in turn, invites newer marsh grasses to grow and populate the area through rhizomal colonization and other functions unique only to plants that exist in coastal environments like the Fourchon Property.

The relict marsh clay that sits beneath several inches of beach sand at a typical coastal headland is, in essence, holding the entire beach together. Several hundred years ago this layer would have probably looked a lot like the soil encountered in the vegetated marsh/mangrove areas and certainly would have behaved similarly under an experimental procedure such as the one in this study. The differences in cohesion between those in Table 6 for the beach sediment and those in Table 7 for the marsh clays are striking. An
average of 15 kPa for the marsh sediments greatly outweighs the cohesion values for the sand samples.

3.4.2 Vegetation and Cohesive Soils: A Mutually Beneficial Relationship

Cohesion is a measure of stiffness in fine-grained soils. Cohesive strength can come as a result of many different processes that occur at the particulate level which affect not only the bonding between soil particles but also the frictional strength, which is otherwise indicated by the internal angle of friction. True cohesion is shear strength that is truly the result of bonding between the soil particles (Das 2008); common factors of true cohesion are cementation, valence bonding and electromagnetic attractions that occur in clay cations. Apparent cohesion is shear strength that appears to be caused by bonding between soil particles, but is really frictional strength in disguise (Das 2008); common factors of apparent cohesion are negative porewater pressures brought on by capillary action and negative excess porewater pressures caused by dilation of soils during

Marsh vegetation, such as *Avicennia germinans*, *Iva frutescens*, *Spartina alterniflora*, *Juncus romerianus* and many others, all exist in the harsh coastal environment and grow within cohesive marsh clays because of highly specialized adaptations that have come as a result of several years’ worth of evolution. For example, *Avicennia germinans* is able to tolerate high levels of salinity because of its ability to absorb saltwater and convert it into salt crystals that are excreted on the surface of its leaves to be washed off in rain or during flooding or to be eliminated altogether.

Vertically extending through the ground near a species of *Avicennia germinans* are roots
called pneumatophores, and they contain small porous bumps called lenticels that allow the plant to harvest atmospheric oxygen. This feature keeps the plant alive during flooding, when an \( \text{O}_2 \) deficiency is experienced in its below-ground root zone. Just as vegetation on sand dunes is beneficial for the sand on the beach by trapping and entraining sediment, vegetation in cohesive soils is beneficial for the muds and clays in the marsh by providing extra cohesive strength and erosion resistance through the reinforcing properties of plant roots. Vegetation provides protection against scouring and minimizes the erosion risk by reducing flow velocity. As velocity falls, sediment is deposited forming an ideal environment for new vegetative growth (Carey 2006).

3.4.3 Influence of Oil Spill Response and TS Lee

Several million pounds of beach have been removed from the Fourchon Property. This has essentially left behind a shoreline of loosened and disturbed soil. Beneath this fine-grained beach sand, a layer of mud exists with high amounts of organic matter and plant roots. This sediment was once, itself, a barrier marsh that has been buried beneath several years’ worth of sand deposition and that has been encroached by gulf waters with relative sea level rise and erosion of more seaward sediments. Together, this relict marsh clay beneath a layer of fine-grained beach sand makes up a typical soil section at the shoreline of the Fourchon Property. The Caminada-Moreau headland, as it is also called, is a low-profile mainland beach with marsh and mangrove cropping out on the lower beach face, reflecting rapid shoreline retreat (Williams, et al. 1992). When wave energy is of such magnitudes that a breach occurs across the beach, an overwash event is said to happen. This cuts a new inlet from the shoreline to the bays, bayous, and marshes located behind the beach. Inlet formation is a natural function that occurs in headland
and barrier island environments, especially as a result of extreme weather events.

Overwashing a method by which barrier island migration and coastal headland rollover occur—classic features of marine transgression in coastal systems.

![Figure 22: Overwash Fan at the Fourchon Property](image)

After TS Lee, an inlet formed connecting gulf waters to back barrier bays and marsh through the entire width of the beach. Storm surge cut a path through an area that was known to have been treated by BP cleanup operations. The sediment from near the shoreline was overwashed into the back barrier marshes, and a new waterway was created, effectively separating one side of the Fourchon Property from the other. At the shoreline where the inlet began, thick cohesive clay material with vertically-extending
mangrove pneumatophores was observed and sampled. At this location, the storm had eroded all sand and left only relict marsh clay.

A sample of untreated beach sand at the shoreline was taken in June of 2011 at the intertidal shoreline area. The relatively moist soil contained no vegetation and exhibited no cohesion with an internal angle of friction of 49 degrees. Comparing to the disturbed sand sample collected in November of 2011, the unvegetated air dry soil had an internal angle of friction of 29 degrees with a cohesion value of 4 kPa. This indicates that in the intertidal shoreline area of the beach, friction angle was decreased by 25 percent as a result of oil spill remediation procedures. The more stable relict clay foundation would certainly experience a higher wave-induced shear stress with the upper layers of sand having been substantially weakened as such.

3.5 Conclusions

Direct shear tests were performed on samples obtained from the Fourchon Property to evaluate the shear strength properties of an erosional soil system in a coastal headland environment. Samples were extracted in situ and processed in the LSU Soil Mechanics Laboratory.

The residual shear stress range, which is a measure of variability of residual shear strengths, had an average of 76 kPa for beach sands and 42 kPa for marsh clays. The maximum shear stress was observed at the intertidal shoreline area with a value of 93 kPa, while the minimum shear stress was observed in the low soil horizon of the heavily vegetated marsh with a value of 29 kPa. The reference samples had residual shear stress ranges of 45 kPa for the disturbed and remediated sand and 29 kPa for the exposed clay
layer samples at the shoreline following TS Lee. Cohesion was low for the beach soils when compared to marsh samples, although high degrees of variance were seen when evaluating this parameter between low and high effective stress conditions. Internal angle of friction varied similarly between low and high effective stress. The existence of plant roots was seen to affect both cohesion and friction angle in a beneficial way. Overall, plant roots demonstrated the ability to absorb energy brought on by applied shear stresses by promoting stabilization in a manner that either resisted shear failure and/or benefitted most or all shear strength properties of soils analyzed herein.

Erosion rates were calculated for three different wave scenarios. The typical scenario showed an erosion rate of 0.093 kg/m²/s, the moderate scenario had an erosion rate of 0.295 kg/m²/s, and the storm scenario had an erosion rate of 0.529 kg/m²/s. Every second, wave energy was predicted to erode one-half of a kilogram of sand for a one square meter area. An equivalent weight distributed across the one meter by one meter area would equate to an erosion rate of 0.203 mm of soil a second. 17.5 m or nearly 50 tons would erode over the course of 24 hours. Putting this into perspective, TS Lee, which made landfall on September 2\textsuperscript{nd} or 3\textsuperscript{rd} in 2011 and remained in the vicinity of the Fourchon Property for at least 48 hours, was observed to have eroded as much as 75 ft of sediment along certain stretches of the beach. Oil spill cleanup activity was observed to decrease by 25 percent the internal angle of friction of a typical beach sand obtained from the intertidal shoreline area.
CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The overall goal of this thesis was to characterize shear strength as a key indicator of erosion resistance for soils in a coastal headland environment. It was believed that the self-organization properties of vegetative root systems can provide benefits to shear strength. A site on the Louisiana coastline was studied, and direct shear test results from samples obtained in the field as well as from samples prepared in the laboratory were used to draw the following conclusions.

Erosion rates were calculated using a modeling procedure for fine-grained sediments (Whitehouse, et al. 2000; Rosati 2009). At the Fourchon Property, erosion rates for beach sediments were calculated as high as 0.529 kg/m²/s using WAVCIS data obtained during the onslaught of TS Lee in September 2011. According to this value, a 0.203 mm depth of soil would be eroded every second for a one-meter by one-meter square area. Across the nine miles of shoreline at the Fourchon Property, nearly three quarters of a million tons of beach sediment was predicted to have been lost over the course of 24 hours, as calculated by this method.

At the Fourchon Property, shear strength varied drastically across the five different areas visited. Testing was also performed on samples of an exposed relict marsh clay layer that was encountered at the shoreline following TS Lee as well as on samples of disturbed sand that had been treated by workers in the aftermath of the BP oil spill. Some soils were resilient against an imposed shearing motion and were able to handle high magnitudes of shear stress without failure. Other soils were vulnerable to
shear failure and exhibited lower levels of residual shear strength. Plant roots were found to be enormously influential on soil shear strength by promoting an increase in cohesion and internal angle of friction.

The beneficial aspects of plant roots on shear strength have been well recognized, however, certain behavioral components of employing plant roots to combat erosional processes remains unknown. Plant roots can significantly improve soil stabilization properties in as little as 8 or 12 weeks after planting and can thereby enhance erosional resistance of coastal soils. In many cases, plant roots were seen to eliminate the presence of shear failure altogether by absorbing energy of applied shear stresses. This ability, while also providing an enhancement in soil cohesion and friction angle, could certainly be something desired for the practical implementation of plant roots to increase soil stabilization against erosion.

4.2 Recommendations for Future Research

This thesis is an experimental account of direct shear test results to interpret soil shear strength as an indicator of erosion resistance for coastal soils. Although direct shear testing is a commonly used method, its results can be considered nonconservative for certain types of soils. A variety of laboratory procedures could be employed in addition to more advanced test design with the direct shear method. Future studies like this one should be combined with other compatible research areas. Those involving the enhancement of soil strength properties with the use of biota, such as exopolymers, for example, could be a fruitful research endeavor. In situ geotechnical experiments as well as advancement in modeling for this research area are other recommended options. The
use of geotechnical engineering exercises in this field could yield breakthroughs and should be employed within a framework of standardized laboratory procedures for measuring the erosional resistance behavior of all coastal soil types—specifically for those of root-enhanced soil systems.
REFERENCES


ASTM. 2004. Standard no. D3080 standard test method for direct shear test of soils under consolidated drained conditions. ASTM.


Migniot, C. 1968. Etudes des proprieties physiques de differents sediments tres fins et de leur comportement sous des actions hydrodynamiques. La Houille Blanche.


Rosati, J.D. 2009. Barrier island migration over a consolidating substrate. Department of Oceanography and Coastal Science, LSU, Baton Rouge, LA.


APPENDIX A: DIRECT SHEAR TEST OUTPUT CURVES
FOURCHON BEACH SAMPLES
**DIRECT SHEAR DATA SPREADSHEET**

**SAMPLING EVENT IV—SALTWATER MARSH SUBHABITAT, LOW ZONE (08/10/11)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Test Conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NO TEST CONDUCTED</td>
</tr>
<tr>
<td>2</td>
<td>NO TEST CONDUCTED</td>
</tr>
<tr>
<td>3</td>
<td>NO TEST CONDUCTED</td>
</tr>
<tr>
<td>4</td>
<td>NO TEST CONDUCTED</td>
</tr>
<tr>
<td>5</td>
<td>NO TEST CONDUCTED</td>
</tr>
<tr>
<td>6</td>
<td>NO TEST CONDUCTED</td>
</tr>
</tbody>
</table>

**Graph:**

- **Axes:**
  - Y-axis: Shear Stress [gpd]
  - X-axis: Normal Stress [gpd]

- **Symbols:**
  - CRITICAL
  - RESIDUAL

**Plot:**

- Data points plotted on the graph show the relationship between shear stress and normal stress for the sampling event.
GREENHOUSE SAMPLES
4-WEEK GROWTH

Scirpus Americanus - 40 psf

Scirpus Americanus - 100 psf
Scirpus Americanus - 300 psf

Scirpus Acutus - 40 psf
Scirpus Acutus - 100 psf

Scirpus Acutus - 300 psf
8-WEEK GROWTH

Scirpus Americanus - 40 psf

Scirpus Americanus - 100 psf
Scirpus Americanus - 300 psf

Scirpus Acutus - 40 psf
Scirpus Acutus - 100 psf

Scirpus Acutus - 300 psf
12-WEEK GROWTH

Scirpus Americanus - 40 psf

Scirpus Americanus - 100 psf
Scirpus Americanus - 300 psf

Scirpus Acutus - 40 psf
Scirpus Acutus - 100 psf

Scirpus Acutus - 300 psf
UNVEGETATED SOIL, 4-WEEK SCENARIO

Soil Control - 40 psf

Soil Control - 100 psf
UNVEGETATED SOIL, 8-WEEK SCENARIO

Soil Control - 300 psf

Soil Control - 40 psf
Soil Control - 300 psf

Horizontal Force [lbs]

Time [min]
APPENDIX B: MANUFACTURER DIAGRAM OF DIRECT SHEAR MACHINE SETUP
2.3.1. Computer:
Jacques Pierre Boudreaux was born in Baton Rouge, Louisiana in 1988. Having lived in East Baton Rouge Parish since birth, Jacques was raised in a multilingual household by his father of Cajun French heritage and his mother of Brasilian descent. Jacques attended Broadmoor High School and then Louisiana State University (LSU), where he graduated with a Bachelor of Science in Civil Engineering in December 2009. He passed the Fundamentals of Engineering examination and earned his Engineering Intern License in 2009. From the fall semester of 2004 until starting a graduate assistant position at LSU in the spring semester of 2010, Jacques was an employee of a world-renowned consulting engineering firm, where he started as a file clerk and later became a student intern. Jacques has been an active musician in the south Louisiana music scene since his early teenage years, while also having toured to play shows in several other states in the U.S.

Throughout college, Jacques was involved in a variety of extra-curricular activities. He was a member of the LSU chapters of the American Society of Civil Engineers (ASCE) as well as the Louisiana Water Environment Association. As an undergraduate senior, he traveled with a team of students to Orlando, Florida to compete in the annual ASCE Geo-Challenge, where the team designed and constructed a retaining wall made of cardboard and packing paper to retain sand. Jacques traveled to Las Cruces, New Mexico with the 2012 LSU environmental engineering senior design class to assist students competing in the WERC/New Mexico State University-sponsored International Environmental Design Competition.
As a graduate research assistant, Jacques worked under John Pardue, Ph.D., PE on a variety of research assignments. He was involved in research projects headed by Dr. Pardue in the wake of the 2010 BP oil spill. Throughout his graduate study, Jacques visited Fourchon Beach on the Louisiana coastline frequently and generated thesis data from samples obtained there. Jacques plans to start a career as a practicing coastal engineer and has ambitions of being a key player in coastal restoration efforts for years to come. The degree of Master of Science in Civil Engineering from LSU will be awarded to Jacques at the August 2012 commencement.