The biomechanics of salt marsh vegetation applied to wave and surge attenuation

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THE BIOMECHANICS OF SALT MARSH VEGETATION APPLIED TO WAVE AND SURGE ATTENUATION

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
James Chatagnier
B.S., Louisiana State University and A&M College
May 2012
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ABSTRACT

The Northern coast of the Gulf of Mexico is threatened by storm surge and waves from tropical storms. It has been long known that marsh vegetation attenuates storm surge and waves and is vital for sustaining marsh edges. However, little is known about the relationship between plant properties and the amount of storm surge and wave reduction the plants provide. In order to better understand the stiffness properties and physical dimensions of saltmarsh vegetation, which are directly related to their ability to attenuate waves and storm surge, this study has been conducted. Stiffness of salt marsh vegetation was determined through direct bending and through board drop testing at several locations along the Southeast Louisiana Gulf Coast from August 13, 2009 to September 15, 2011.

Biomechanical properties of salt marshes, including plant dimension and bending stiffness modulus, were measured on coastal marshlands on the Southeast gulf coast of Louisiana, and are correlated with plant total height, stem height, stem diameter, plant stem density, and seasonal variations and botanical behavior. Two methods were employed, including direct stem bending and indirect board drop tests. The dataset is analyzed in depth to develop empirical equations of plant stiffness and compared with those found in the literature based on vegetation on river floodplains. These wave and surge measurements along with vegetation data are applicable to calibrating wave models that incorporate the reduction of energy due to wetland vegetation.

The mitigation of wave energy and storm surge is critical to the survival of Louisiana’s wetlands and coastline. Salt marsh vegetation has the ability to mitigate the potential damage caused by storm surges and large waves. This study will improve our understanding of the role of vegetation in attenuating waves and storm surge and the accuracy of the parameterization of
the vegetation effects in the-state-of-the-art wave models. The successful quantification of wave and surge attenuation by salt marshes will be a positive contribution to Louisiana’s hurricane protection and coastal restoration efforts.
1 INTRODUCTION

A healthy, sustainable marsh coastline is critical to the salvation of the Louisiana coastline ecosystem and the prosperity of southern Louisiana economically. Louisiana provides 26% (by weight) of the commercial fish landings in the lower 48 states. Louisiana’s marshes provide a winter home for more than five million migratory waterfowl, and also provide a stop-over habitat for millions of neo-tropical migratory birds and 17 threatened or endangered species. When nutrient rich waters flow through, Louisiana’s wetlands filter nutrients that would otherwise flow directly into the Gulf of Mexico. Concentrations of these nutrients in the northern Gulf of Mexico contribute to the growing problem of low oxygen conditions in offshore coastal waters. The coastal Louisiana oil and gas infrastructure produces or transports nearly one-third of the nation’s oil and gas supply, and is tied to 50% of the nation’s refining capacity. The wetlands protect this critical infrastructure from storm surge. Louisiana’s coastal wetlands also protect ten major navigation routes in the U.S. and five of which are of the busiest ports in the U.S., ranked by total tons. Together, these facilities handle 19% of the annual U.S. waterborne commerce. (CRPA, 2007)

1.1 Spartina alterniflora

*Spartina alterniflora*, also commonly known as smooth cordgrass, is the dominant flowering plant of the regularly flooded intertidal zone along the Gulf and Atlantic coasts of the United States. Because of its intertidal location, smooth cordgrass is the coastal plant species that is in most frequent and direct contact with waves, the primary cause of shoreline erosion (Knutson et al., 1982). *S. alterniflora* is known for its extensive roots and below-ground
production and is often prolific on marsh edges in areas exposed to moderate wave energy (Feagin et al., 2009).

Figure 1.1 - Emergent *Spartina alterniflora* (USDA-NRCS PLANTS Database)

1.2 Vegetation Used in Wave Attenuation

It has been shown that vegetation can dissipate energy from waves. (e.g. Knutson et al 1982, Kobayashi 1993, Roland and Douglass 2005, Augustin et al 2009, Lovstedt and Larson 2010). The typical approach for predicting wave attenuation by vegetation is based on the time averaged conservation of energy balance equation of wave energy in which the local flow field is estimated using linear wave theory. The effects of the vegetation are included only in the dissipation term in the energy equation to obtain local wave height. (e.g. Kobayashi et al, 1993)
By absorbing surging water from storms, Louisiana’s wetlands provide a natural buffer to one of the most hurricane prone regions in the U.S. While wetlands cannot prevent significant damage from major hurricanes such as Hurricanes Katrina (2005) and Rita (2005), wetlands are known to significantly reduce storm surges associated with more frequent tropical storms and smaller hurricanes. Data gathered by the Army Corps of Engineers allowed scientists to estimate that every 2.7 miles of wetland reduce storm surge by an average of one foot (Corps of Engineers, 1963). These reductions in storm surge can mean the difference between an area that survives a storm and one that suffers significant damage in Louisiana’s flat, low-lying areas. Louisiana’s coastal infrastructure represents a total asset value of approximately $96 billion.
indicated by a 2004 study. Louisiana’s wetlands enhance protection of this infrastructure, much of which directly serves the nation’s need for energy, navigation, and fisheries (CWPPRA, 2006). Coastal Louisiana has lost an average of 34 square miles of land, primarily marsh, per year for the last 50 years (1950-2000). Coastal Louisiana lost 1,900 square miles of land, roughly an area the size of the state of Delaware, from 1932 to 2000. If nothing more is done to stop this land loss, Louisiana could potentially lose approximately 700 additional square miles of land, or an area about equal to the size of greater Washington, D.C. – Baltimore area, in the next 50 years (USGS, 2005). Figure 1.3 shows land loss (in red) of southeast Louisiana from 1932 projected to 2050. The figure the land loss from 1932-2000 is historical. The land loss between 2000 and 2050 is projected based on historical trending if no further action is taken to restore the coast. The relationship between the biomechanical properties of wetland vegetation and their effect on wave and storm surge attenuation has been little investigated. This study hopes to help fill that gap.

Figure 1.3 - Southeast Louisiana land loss from 1932 to 2050 (adapted from USGS, 2005)
1.4 Objectives

The general objective of this project is to quantify the biomechanical properties of saltwater marsh vegetation on the eastern gulf coast of Louisiana, with special focus on *Spartina alterniflora*. With this base of information, the parameterization of vegetation biomechanical properties can be used to model the attenuation of waves and storm surge as they progress across salt marsh areas. With an eventual abundance of data, GIS techniques could be used to separate attenuation parameters by dominant species of salt-marsh vegetation based on their biomechanical properties. The bending stiffness, density, and physical dimensions of saltmarsh vegetation are needed to parameterize state of the art wave and storm surge numerical models. The primary objectives of this study are:

1. To determine the bending strength, plant geometry, and density of saltmarsh vegetation (specifically *Spartina alterniflora*)
2. To investigate the seasonal variation of these parameters
3. To correlate bending stiffness with plant dimensions and plant dimension ratios
4. To determine if the board drop test (developed by Eastgate) could be correlated with directly measured bending stiffness and plant densities.

1.5 Organization of Thesis

The first chapter provides background information, motivation, and objectives of this study. The value of Louisiana’s wetlands and the need to preserve them are also discussed.

Chapter 2 describes the United States Army Corps of Engineers study which the method of this study is based upon, previous studies of wave attenuation by vegetation, the parameter MEI, plant stiffness and bending, and the property of plants called “turgor pressure.”
In Chapter 3, the data is described and detailed descriptions of the materials and methods used in this thesis are given.

Chapter 4 shows results of the data analysis visually along with explanations of the data shown.

In Chapter 5, the results of the data analysis are discussed.

Chapter 6 gives summarizes this study, states conclusions and gives recommendations for future work.
2 LITERATURE REVIEW

2.1 USASCE Study

A report titled “Determination of Resistance Due to Shrubs and Woody Vegetation” was published by U.S. Army Corps of Engineers Engineering and Research Development Center’s Coastal and Hydraulics Lab in October 2000. The purpose of this study was to investigate the effect of vegetation, particularly ground cover plants, small trees, and shrubs, on flow resistance. Research in a flume resulted in the collection of data from more than 220 experiments with 20 different plant species. Plants with single or multiple stems, with and without leaves, were evaluated while plant density, spacing, and size were varied in the experiments. The method for measuring plant stiffness modulus is derived from this study. Plant stiffness modulus \( (E_S) \) was calculated using the Euler-Bernoulli beam equation for a solid circular cross section, shown in Equation 1:

\[
E_S = \frac{F_{45}H^2}{3I} = 6.791 \left( \frac{F_{45}H^2}{D_s^4} \right)
\]

Equation 1: Stiffness Modulus

where, \( F_{45} \) is the horizontal force needed to bend the plant to an angle of 45 degrees. \( H \) is the height at which the force \( F_{45} \) is pulled, measuring from the base of the stem. \( I \) is the second moment of inertia calculated for a solid circular cross section \( (I = \pi D_s^4/64) \). The stem diameter \( (D_s) \) is measured at a height \( H/4 \) from the base of the stem.

To determine a relationship that defines plant stiffness, data was collected both in the laboratory and in the field. Freeman (1997) collected data in floodplains and sand bars to
determine if stiffness in the field could be predicted from plant size parameters such as stem
diameter and plant height to reduce the number of parameters that must be collected to determine
plant stiffness modulus. One observation Freeman noticed in his data was that plant stiffness was
measurably different in the upstream and downstream directions in streams subject to periods of
high water at velocities high enough to keep the plant bent for prolonged periods. This
observation was not noticed or did not exist where plants were not subject to these flow
conditions.

Stiffness modulus can be estimated from the relationship of $E_S$ to the ratio of stem height
(H) over stem diameter ($D_S$) indicated by the data collected in the laboratory and in the field. The
analysis of these measurements and in the field and in the laboratory led to the development of
Equation 2 to explain the relationship between $H/D_S$ and $E_S$ (N/m$^2$).

$$E_S = 7.648E06 \left( \frac{H}{D_S} \right) + 2.174E04 \left( \frac{H}{D_S} \right)^2 + 1.809E03 \left( \frac{H}{D_S} \right)^3$$

Equation 2: "Rahmeyer Predicted" Regression

2.2 MEI

Values of MEI for a given vegetation can be perceived as an “equivalent to plastic
stiffness” number (Kouwen, 1988). In the parameter MEI, $E =$ the modulus of elasticity of the
vegetation, $I =$ the second moment of area of the vegetation stems, and $M =$ relative density
defined as a ratio of the stem count to a reference number of stems per unit area. For
convenience, the reference number is taken to be 1 stem per unit area. The product of $EI$ is the
flexural rigidity of the vegetation, and the product of MEI is the flexural rigidity of the vegetation of a unit area. The products EI and MEI both have the same units of force times length squared (area). Note that the parameter, M, is considered a ratio and is dimensionless (Kouwen and Li, 1980). The degree to which vegetation resists bending depends on the flexural rigidity and density of the vegetation (i.e. MEI). While the drag force due to the flowing of water determines the bending moments imposed on the vegetation (Kouwen and Li, 1980).

2.2.1 The Board Drop Test

Eastgate suggested the use of a “Board Test,” when he reported on a number of flow tests carried out over a natural grass lining installed in a flume, as a field test for determining which n-VR (n=manning’s n, V=water velocity, R=hydraulic radius) curve applies to a given vegetative lining. The test consisted of standing a 1829 mm (6ft) by 305 mm (1 ft) board weighing 4.85kg vertically on one end and allowing it to fall over freely. The board rotates about the end in contact with the ground. When the board hits the grass, it slides length wise in the direction of motion. This imparts a friction force, which along with the weight of the board, deflects the grass in a manner similar to flowing water. The distance between the ground and edge of the fallen end of the board was recorded each time by Eastgate. (Kouwen, 1988)

Kouwen (1988) thought that the board drop test obviously reflected the combined effect of density, stiffness, and length of the grass on the ability of the grass to resist bending under flow conditions. These are the parameters directly affecting the relative roughness of the vegetative lining under a flow induced shear. Kouwen suggested that the board drop test may be a good method for the determination and evaluation of MEI. A schematic of the board drop test is shown below in Figure 2.1.
Figure 2.1 - Schematic of Board Drop Test (Kouwen, 1988)

Figure 2.2 shows Eastgate’s board drop measurements plotted against the corresponding stiffness values obtained through the fitting MEI to Eastgate’s flow data by Kouwen (1980). This figure shows a very good relationship between the board drop height and MEI. A line fitted through the data points in Figure 2.2 is given by Equation 3 as follows:

\[ MEI = 3122 \times BH^{2.82} \]

Equation 3 - MEI from Board Drop Height

where, BH is the distance between the ground and the dropped edge (the upper edge before the drop) of the board in meters. The units of MEI are N\cdot m^2.
2.2.2 MEI from Grass Height

Kouwen (1980, 1988) commented that the values for MEI calibrated by comparing the flow resistance from natural grass linings to artificial flexible linings are much larger for long grass than for the same grass after cutting. Figure 2.3 shows the relationship between vegetation length and MEI, which was also noted by Temple (1987). In the figure, the open points are for green and growing grasses and the solid points are for dormant grasses. For the dormant grasses the correlation between MEI and grass length is 83%. For green grasses the correlation is much stronger (95%). These results can be directly applied for the design and analysis as the friction factor for a vegetated area can be derived from a single parameter for the lining, specifically the average vegetation stem length. Equation 4 and Equation 5 give the relationship between MEI
and stem height (h) for green and dormant vegetation respectively. The equation for green and dormant vegetation combined is also shown in Figure 2.3.

green: \[ MEI = 319h^{3.3} \]  
Equation 4 - MEI from Stem Height (Green Vegetation)

dormant: \[ MEI = 25.4h^{2.26} \]  
Equation 5 - MEI from Stem Height (Dormant Vegetation)

Figure 2.3 - MEI vs Stem Height (Kouwen, 1988)
2.3 Plant Stiffness

The effective stiffness of vegetation is a function of shape, size, elastic stiffness, and the arrangement of material in the plant stem structure. With the exception of wood, most plant materials are much stronger in tension than in compression. This results from the fact that the mechanical behavior of the cell wall infrastructure is dominated by the material properties of cellulose, which has a high tensile strength, a very high tensile modulus and the capacity for considerable elastic extension in the direction of cellulose molecules (Niklas, 1992). In early studies, soft tissue in which the fibrous stiff tissue is embedded was considered to make a negligible contribution to the integrity of the stem, except to fix the supporting tissue in its proper place (Schulgasser and Witztum, 1997). Soft tissue thin walled tubes of circular cross section are efficient structural members; they are optimally economical in preventing failure when the member is subjected to bending moments which are liable to be imposed in an arbitrary direction (Schulgasser and Witztum, 1992).

2.3.1 Turgor Pressure

Another factor affecting vegetation stiffness is turgor pressure. Turgidity ($\psi_p$) refers to how fully protoplasts within cells are hydrated and is defined as the difference between water potential ($\psi_w$) and solute potential ($\psi_s$), or $\psi_p = \psi_w - \psi_s$. Turgor pressure is biomechanically important because it profoundly influences the tensile stresses generated within cell walls and the mechanical stiffness of thin walled cells and thin walled tissues (Niklas, 1992). Turgor pressure increases strength by placing cell walls in a state of axial tension. Any bending moment applied which results in failure on the compression side must first overcome this residual pre-existing “good” tensile stress, so the moment which can be applied is greater than that had there been no turgor pressure (Schulgasser and Witztum, 1997).
2.4 Previous Wave/Storm Surge Attenuation Studies

The effect of vegetation on wave attenuation has been studied in the laboratory. Very little data has been collected on vegetation’s effect on storm surge and associated waves. Knutson et al. (1982) concluded that plant (*Spartina alterniflora*) drag coefficients may be a function of many parameters such as stem stiffness, stem deflection, stem roughness, and the abundance of leaf material with respect to stem size. He found that marsh grasses are most effective in damping waves when water depth is less than plant height. Under these conditions, waves are damped as they travel through grass, but during extreme coastal storms and hurricanes, wind set up may elevate water depth to a level several times higher than the plants. Under these conditions, wave damping by the plants will be comparatively small.

Danard and Murty (1994) showed mathematically that a vegetation canopy, especially one that projects above the water surface can significantly dissipate storm surges...
3 DATA DESCRIPTION AND METHODOLOGY

This chapter describes the data gathered for this study and the methodology used in the analysis. Data was collected over a time span from August 13, 2009 through September 15, 2011. To gather data, field trips were arranged, but not at regular intervals. Field trip dates were dependent on the attendee’s schedules, the weather, and the need for a data at that particular time of the year. Table 1 show dates that data were collected, the area in which the data was collected, and what type of data was collected. Data from dates 6-19-2010, 7-10-2010, and 12-14-2010 are courtesy of Kim Marsh, a fellow graduate student in the Department of Oceanography and Coastal Sciences who was trained in the method used in this study.

Table 1 - Field Trip Dates and Descriptions

<table>
<thead>
<tr>
<th>Field Trip Date</th>
<th>Area of Field Trip</th>
<th>Type of Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-13-2009</td>
<td>Breton Sound, LA</td>
<td>Bending, Soils</td>
</tr>
<tr>
<td></td>
<td>Chandeleur Sound, LA</td>
<td></td>
</tr>
<tr>
<td>12-22-2009</td>
<td>Terrebonne Bay, LA</td>
<td>Bending, Board Drop</td>
</tr>
<tr>
<td>4-8-2010</td>
<td>Terrebonne Bay, LA</td>
<td>Bending, Board Drop, Soils</td>
</tr>
<tr>
<td>5-12-2010</td>
<td>Graveline Bayou, MS</td>
<td>Bending, Soils</td>
</tr>
<tr>
<td>6-19-2010</td>
<td>Breton Sound, LA</td>
<td>Bending</td>
</tr>
<tr>
<td>7-10-2010</td>
<td>Breton Sound, LA</td>
<td>Bending</td>
</tr>
<tr>
<td>7-31-2010</td>
<td>Breton Sound, LA</td>
<td>Bending, Board Drop</td>
</tr>
<tr>
<td>8-20-2010</td>
<td>Barataria Bay, LA</td>
<td>Bending, Board Drop</td>
</tr>
<tr>
<td>12-02-2010</td>
<td>Terrebonne Bay, LA</td>
<td>Bending, Board Drop, Soils</td>
</tr>
<tr>
<td>12-14-2010</td>
<td>Breton Sound, LA</td>
<td>Bending</td>
</tr>
<tr>
<td>4-4-2011</td>
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</tr>
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<tr>
<td>9-15-2011</td>
<td>Terrebonne Bay, LA</td>
<td>Bending</td>
</tr>
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</table>

Getting to salt marsh sites required the use of a boat. Boats were acquired through LSU Field Support Group or though Louisiana Universities Marine Consortium (LUMCON).
3.1 Data Description

3.1.1 Bending Data

A total of 469 bending measurements were collected on live salt marsh plants. Data was collected on four species of salt marsh vegetation; *Spartina alterniflora* (Smooth Cordgrass), *Juncus roemerianus* (Black Needlerush), *Spartina patens* (Saltmeadow Cordgrass), and *Scirpus robustus* (Saltmarsh Bulrush). The numbers of plants tested of each species are 204, 134, 89, and 24, respectively. Thirty-four dormant *Spartina alterniflora* plants were also tested to compare with live *Spartina alterniflora* data. A large variation in time of year was achieved with the *Spartina alterniflora* data, but data from the other species was only collected at one or a couple times of the year. Table 2 shows dates which species were tested, and the area that the data is from. In Table 2, *Spartina alterniflora*, *Juncus roemerianus*, *Spartina patens*, and *Scirpus robustus* are abbreviated SA, JR, SP, and SR, respectively.

Table 2 - Bending Data Collection Information

<table>
<thead>
<tr>
<th>Date of Data Collection</th>
<th>Area of Collection</th>
<th>Species Tested</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Breton Sound, LA</td>
<td>SA</td>
</tr>
<tr>
<td>12-22-2009</td>
<td>Terrebonne Bay, LA</td>
<td>SA</td>
</tr>
<tr>
<td>4-8-2010</td>
<td>Terrebonne Bay, LA</td>
<td>SA</td>
</tr>
<tr>
<td>5-12-2010</td>
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<td>JR</td>
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<td>6-19-2010</td>
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</tr>
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<td>SA, JR, SP</td>
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<td>Breton Sound, LA</td>
<td>SA, JR SP</td>
</tr>
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<td>8-20-2010</td>
<td>Barataria Bay, LA</td>
<td>SA, SR</td>
</tr>
<tr>
<td>12-02-2010</td>
<td>Terrebonne Bay, LA</td>
<td>SA</td>
</tr>
<tr>
<td>12-14-2010</td>
<td>Breton Sound, LA</td>
<td>SP</td>
</tr>
<tr>
<td>4-4-2011</td>
<td>Terrebonne Bay, LA</td>
<td>SA, SR</td>
</tr>
<tr>
<td>4-29-2011</td>
<td>Terrebonne Bay, LA</td>
<td>SA</td>
</tr>
<tr>
<td>6-8-2011</td>
<td>Terrebonne Bay, LA</td>
<td>SA</td>
</tr>
<tr>
<td>7-1-2011</td>
<td>Barataria Bay, LA</td>
<td>SA</td>
</tr>
<tr>
<td>9-15-2011</td>
<td>Terrebonne Bay, LA</td>
<td>SA</td>
</tr>
</tbody>
</table>
For each plant that bending data is collected, total height, stem height, and stem diameter measurements are collected. The horizontal force needed to bend the plant to a 45° angle is recorded. A detailed description of the method for collecting this data is given in section 3.2.1 Bending Data Methodology.

### 3.1.2 Board Drop Data

A total of 30 board drop tests were conducted on *Spartina alterniflora* at data collection sites in the Terrebonne Bay, Breton Sound, and Barataria Bay areas. Table 3 shows dates and areas that board drop data tests were ran.

<table>
<thead>
<tr>
<th>Date of Data Collection</th>
<th>Area of Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-22-2009</td>
<td>Terrebonne Bay, LA</td>
</tr>
<tr>
<td>4-8-2010</td>
<td>Terrebonne Bay, LA</td>
</tr>
<tr>
<td>7-31-2010</td>
<td>Breton Sound, LA</td>
</tr>
<tr>
<td>8-20-2010</td>
<td>Barataria Bay, LA</td>
</tr>
<tr>
<td>12-02-2010</td>
<td>Terrebonne Bay, LA</td>
</tr>
<tr>
<td>6-8-2011</td>
<td>Terrebonne Bay, LA</td>
</tr>
</tbody>
</table>

Parameters collected for a board drop test are plant density and board height. Starting on 7-31-2010, plant canopy height was also recorded. A detailed description of the method for collecting this data is given in section 3.2.2 Board Drop Test Methodology.

### 3.1.3 Soil Testing Data

Tests were run on soil samples to collect data on soil retrieved from salt marsh sites. Parameters investigated include: percent water content by weight, percent organic content by weight, atterberg limits (i.e. liquid limit, plastic limit, and plasticity index), soil pore water pH,
soil pore water salinity, and particle size distribution. All tests mentioned were run on all soil samples. Table 4 gives information about collected soil samples.

### Table 4 - Soil Data Collection Information

<table>
<thead>
<tr>
<th>Area</th>
<th>Sample Name</th>
<th>Depth (ft)</th>
<th>Date Sampled</th>
<th>Dominant Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breton Sound, LA</td>
<td>BS BKT</td>
<td>0-0.5</td>
<td>8/13/2009</td>
<td>Spartina alterniflora</td>
</tr>
<tr>
<td>Chandeleur Sound, LA</td>
<td>CS TOP</td>
<td>0-1</td>
<td>8/13/2009</td>
<td>Spartina alterniflora</td>
</tr>
<tr>
<td>Chandeleur Sound, LA</td>
<td>CS BOT A</td>
<td>1-1.5</td>
<td>8/13/2009</td>
<td>Spartina alterniflora</td>
</tr>
<tr>
<td>Chandeleur Sound, LA</td>
<td>CS BOT B</td>
<td>1-1.5</td>
<td>8/13/2009</td>
<td>Spartina alterniflora</td>
</tr>
<tr>
<td>Graveline Bayou, MS</td>
<td>MS A</td>
<td>0.5-1.0</td>
<td>5/12/2010</td>
<td>Juncus roemerianus</td>
</tr>
<tr>
<td>Graveline Bayou, MS</td>
<td>MS B</td>
<td>0.5-1.0</td>
<td>5/12/2010</td>
<td>Juncus roemerianus</td>
</tr>
<tr>
<td>Terrebonne Bay, LA</td>
<td>TB C</td>
<td>0-0.5</td>
<td>12/2/2010</td>
<td>Spartina alterniflora</td>
</tr>
</tbody>
</table>

#### 3.2 Methodology

**3.2.1 Bending Data Methodology**

Field methods were chosen to gather a representative sample of vegetation properties at a given location. Plants were sampled randomly from an area of uniform vegetation of approximately 2m by 2m. These plants were tested for stiffness in a similar way to that described in Freeman et al., (2000) except plants were pulled from half the stem height and no nets around the leafy parts of the were used. Datasets of 15 plants were chosen to attempt to capture the significant range of vegetation while keeping times spent for data collection to a reasonable amount. Redundant measurements of similar plants were made to address variation of stiffness for plants of the same dimensions and species. Care was taken to not be bias toward the largest of plants since the larger plants were less tedious to measure. Datasets were taken from several
locations along the Louisiana Gulf coast (including one location in Mississippi). The procedure for measurement of a single plant is listed below:

1. A random plant is selected in the desired area to be tested

2. Total plant height and stem height are measured using a plant measuring jig (shown below in Figure 3.1). Stem height is the point at which the last leaf branches from the plant and total height is the height of the plant with the leaves pulled upward. *S. alterniflora*, *S. patens*, and *S. robustus* have similar stem and leaf orientation. *J. roemerianus* does not have leaves that branch from the stem, therefore the stem height was considered the total plant height. The plant measuring jig is made from yard sticks. The vertical member is used to measure plant total height and stem height. The horizontal member provides a base and added rigidity. The diagonal member, set to a 45° angle, is used to align plants to a 45° angle when determining bending force).

![Plant Measuring Jig](image)
3. A small binder clip is placed halfway up the stem

4. A spring force gage (shown in Figure 3.2) is attached to the binder clip on the plant (as shown in Figure 3.3) and pulled horizontally until the plant is at a 45° angle. The applied force is recorded. (Correct angle is achieved using the plant measuring jig as shown in Figure 3.4)

Figure 3.2 - Spring Force Gages

Figure 3.3 - Spring Gage is Attached to Plant
5. The plant is cut at its base, numbered, and placed in a bucket with a few inches of water in it to keep the plant from drying.

6. This process is repeated until a dataset of 15 plants have been measured then the dataset of 15 is bundled and labeled.

7. GPS coordinates are taken for the sampled area

8. To avoid plant shrinkage, immediately following a field trip the maximum stem diameter at one quarter of the stem height of each plant is measured in the lab.

Data was organized by date collected. For each dataset of 15 plants averages and standard deviations are computed for both measured and calculated parameters. Calculated parameters include: stem height/total height ratio, stem height/stem diameter ratio, bending stiffness modulus (E_s), second moment of inertia (I), and flexural rigidity in bending (E_s·I). Equations for
bending stiffness modulus and second moment of inertia are found in section 2.1 of the Literature Review.

All plants tested had round stems except for *Scirpus robustus*, which has a very sharply triangular stem. For comparison with circular stems, *S. robustus* stem were assigned an equivalent diameter based on equivalence of area. The area of a circle was set equal to the area of a triangle. The equation was solved for diameter as a function of height of a triangle.

![Figure 3.5 - Measuring Plant Bending Force in the Field](image_url)
3.2.2 Board Drop Test Methodology

The board drop test, first suggested by Eastgate (1966) and used by Kouwen (1988) among others, is used as a means to provide a field test for determining MEI (density x stiffness modulus x second moment of inertia). To account for the lower density and higher stiffness of coastal vegetation the board drop test board used in this study was made double the width of the board used by Eastgate. The wider stance of this study’s board added to the stability of the board upon contacting the vegetation and reduce roll of the board, resulting in the board being more level upon completion of the test. A table comparing Eastgate’s board with the board used in this study is given below in Table 5. This study’s board weight per unit area is within 15% of the weight per unit area of Eastgate’s board, so test results should be comparable.

Table 5 - Board Drop Comparison

<table>
<thead>
<tr>
<th></th>
<th>Eastgate’s Board</th>
<th>This Study’s Board</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>6 ft</td>
<td>6 ft</td>
</tr>
<tr>
<td>Width</td>
<td>1 ft</td>
<td>2 ft</td>
</tr>
<tr>
<td>Area</td>
<td>6 ft²</td>
<td>12 ft²</td>
</tr>
<tr>
<td>Weight</td>
<td>10.7 lb</td>
<td>24.4 lb</td>
</tr>
<tr>
<td>Weight per Area</td>
<td>1.78 lb/ft²</td>
<td>2.03 lb/ft²</td>
</tr>
</tbody>
</table>

The procedure for the board drop test is given below:

1.) An area of visibly uniform vegetation is selected for testing, and density over a unit area is hand counted.

2.) The board drop test board is stood on one edge along the border of the area that is to be tested.
3.) From a vertical position the board is allowed to fall over under the weight of gravity. Care is taken to align the board perpendicular with the wind to reduce the wind’s effect on the results of the test.

4.) The fall of the board is arrested by the vegetation of the test area resulting in the board being propped up by the vegetation, with the falling side being more elevated than the side that was in contact with the ground.(as in Figure 3.6)

5.) The distances from the two high corners of the board to the soil below is measured then averaged to get the drop height (BH) of the test.

6.) The vegetation density and canopy height are recorded. (Recording canopy height was not begun until 7/31/2010).

Figure 3.6 - Completed Board Drop Test
3.2.3 Soil Testing Methodology

Soil testing was performed on random samples from selected sites. The objective of doing this is to characterize soil parameters that promote healthy growth of salt-marsh grasses. Also, results were analyzed to investigate if any significant relationships exist between soil properties. The ASTM test standards, if applicable, are given in the appendix to this document. The tests that were performed are:


- ASTM D422 Standard Test Method for Particle-Size Analysis of Soils

- Pore Water Salinity: Soil samples in vials are spun in a centrifuge (Figure 3.7) to separate the liquid and solid phases of the soil. Once separated, pore water is poured into one vial (as in Figure 3.8) and mixed. A salinity refractometer (see Figure 3.9) is used to measure pore water salinity. The salinity refractometer is calibrated to grams NaCl / 100 grams H₂O, however other salts are likely present in the pore water.

- Pore-Water pH: Soil pore water is extracted with the same method that is used in the Pore Water Salinity test. Pore water pH is determined using a bench top pH meter as in Figure 3.10. The bench-top pH meter was calibrated using buffers of pH 4 and pH 10.
Figure 3.7 - Centrifuge

Figure 3.8 - Extracted Pore Water

Figure 3.9 - Salinity Refractometer

Figure 3.10 - Measuring Pore Water pH
4 RESULTS AND DISCUSSION

4.1 Bending Stiffness Modulus

To compare the seasonal variation of stem height and total height of *Spartina alterniflora*, stem and total heights were plotted against date, as shown in Figure 4.1. Total and stem height are offset to the left and right, respectively, for visualization. Data is from all observed sites along Louisiana’s gulf coast. It was found that the growing season around April and continues through winter, ending with the plant flowering then becoming dormant. The increase in height through the growing season is shown in the figure. Early in the growing season, there is a large difference between stem and total heights. As the plant matures this difference decreases. Also, the range of plant sizes increases toward the end of the growing season. This is due to the emergence of new plants late in the growing season.

![Figure 4.1 - Temporal Change of S. alterniflora Stem and Total Heights](image)

Figure 4.1 - Temporal Change of S. alterniflora Stem and Total Heights
In Figure 4.2, measured bending stiffness modulus (i.e. modulus calculated from plant dimensions and 45° bending force pulled from half stem height.) is plotted against stem height over stem diameter ratio (stem slenderness) for all plants sampled. The vertical axis is bending stiffness modulus in N/m² plotted on a log scale. The horizontal axis represents the plant’s stem slenderness. Short stocky stems are shown to the left, while long slender stems are shown to the right of the graph. The increase in stiffness modulus with stem slenderness appears to be more dramatic for the _S. robustus_ data. This fact may be due to an increase in stem stiffness due to the efficiency of its triangular shape, or this observation may be an artifact of the conversion of triangular stem height to an equivalent round stem diameter. It should be noted that variance in the data increases with increase in stem slenderness, especially with the _J. roemerianus_ data. It was noticed that _J. roemerianus_ was susceptible to buckling. The increase in scatter of the data in the lower range may be due to unnoticed buckling of the stems.

Figure 4.2 - Bending Stiffness Modulus vs Stem Height/Stem Diameter
Figure 4.3 is the same as Figure 4.2 except that data from all four plants are plotted as one series. It was found that the relationship between bending stiffness modulus and stem height over stem diameter ratio for all four species can be described with the equation $E_s = 473253x^{1.5943}$, with a coefficient of determination ($R^2$) of 0.8525. Notice that other than the cluster of *S. alterniflora* in the bottom left hand of the data, the points where data for one species ends and data for another begins is virtually indistinguishable. It is reasonable to believe that all non-woody salt marsh vegetation could be described with the mentioned relationship. However, the increase in bending stiffness modulus with the increase in stem height over stem diameter ratio may be an artifact of the method used. To test this thought, it would be wise to compare rods of a uniform material of constant cross section to see if length of the rods changes the apparent bending stiffness modulus.

Also shown in the figure is the "Rahmeyer Predicted" Regression from Freeman et al, 2000. Freeman’s data was collected from woody vegetation (small trees and shrubs) that lined vegetated hydraulic channels. The Rahmeyer regression equation was fitted to a plant height over stem diameter ratio of 50 to 300. In the figure, the Rahmeyer equation is plotted starting at stem height over stem diameter ratio ($H_S/D_S$) of 50 but was extrapolated to a $H_S/D_S$ of 500. Note that Freeman et al. did not collect stem heights in its data. Main differences in between plants sampled in Freeman et al.’s data and the data presented in this study are that Freeman et al.’s plants were woody plant material and had solid circular stems. Woody plant material offers some strength in compression, while grasses offer most all of their strength in tension. As expected, with these significant differences, the vegetation studied in Freeman et al. has a significantly higher bending stiffness than the vegetation observed in this study.
Figure 4.3 - Stiffness Modulus, Stem Height/Stem Diameter Relationship

The difference in bending stiffness modulus between live and dormant *S. alterniflora* is shown in Figure 4.4. All dormant plants had a stem height over stem diameter over ratio that was greater than 75. In Table 6, the averages of parameters for live and dormant vegetation with a slenderness ratio of a value greater than 75 are compared. While pre-dormancy and post-dormancy dimensions of *S. alterniflora* are similar, there was a large reduction (52%) in bending stiffness modulus of dormant plants. This reduction is believed to be due to a reduction in turgor pressure, which keeps plant cells in a tensioned state. Also, there are some outliers on the lower range of stiffness modulus data for the dormant plants. Similar to the same phenomenon in *J. roemerianus* data as mentioned above, this may be due to unnoticed buckling of the stems during the measuring of the 45° bending force.
Table 6 - Comparison of Live and Dormant *S. alterniflora* of Like Slenderness

<table>
<thead>
<tr>
<th></th>
<th>Live <em>S. alterniflora</em></th>
<th>Dormant <em>S. alterniflora</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Height (m)</td>
<td>1.036</td>
<td>1.098</td>
</tr>
<tr>
<td>Stem Height (m)</td>
<td>0.799</td>
<td>0.891</td>
</tr>
<tr>
<td>Stem Diameter (mm)</td>
<td>7.25</td>
<td>8.11</td>
</tr>
<tr>
<td>Stem Ht./Total Ht</td>
<td>0.769</td>
<td>0.814</td>
</tr>
<tr>
<td>Stem Ht./Stem Dia.</td>
<td>112.65</td>
<td>112.86</td>
</tr>
<tr>
<td>Stiffness Modulus, E (N/m²)</td>
<td>5.06E+08</td>
<td>2.40E+08</td>
</tr>
<tr>
<td>2nd Moment of Inertia, I (m⁴)</td>
<td>1.69E-10</td>
<td>2.48E-10</td>
</tr>
<tr>
<td>Stiffness, EI (N·m²)</td>
<td>0.0649</td>
<td>0.0411</td>
</tr>
</tbody>
</table>

Figure 4.5 shows average bending stiffness (EI) with standard deviation for data set of 15 *S. alterniflora* versus season in which data was collected. The averages from ~0.0253 N·m² to ~0.0671 N·m². Note that these values represent the average stiffness of single plants and does not reflect the effect of density. Data was gathered from multiple locations along the southeast
Louisiana Gulf Coast, which contributed to the scatter in this graph. To get a better grasp of the seasonal variation of EI one must confine his study area to one location.

![Seasonal Variation of EI for S. alterniflora](image)

Figure 4.5 - Seasonal Variation of EI for S. alterniflora

Average bending stiffnesses (EI) of 3 plant species is plotted against density in Figure 4.6. The graph shows that *S. alterniflora* has the superior bending stiffness of the species for which data was collected. *S patens* has a much lower bending stiffness than *S. alterniflora*, while they occur at similar densities, and is even low when compared to *J. roemerianus*. It should be noted that data for *S. patens* was taken from only one area and may not represent the full range of bending stiffnesses of which the plant is capable. Stiffnesses for *J. roemerianus* are equal to those found on the very lower end of the range for *S alterniflora*. However, it does occur at much higher densities, which is not represented in the stiffness values of this graph. It should be noted that the data for *J. roemerianus* on this chart is only from the Graveline Bayou, MS location and may not represent the typical range of stiffness of which this plant is capable.
4.2 MEI

In Figure 4.7, observed MEI values for *S. alterniflora* are plotted against date. EI values are the averages of observed data sets and densities (M) are from board drop data from the same area and date. No observable trends are noticeable. The average value for MEI is 6.14 N-m² while the data ranges from as little as 2 N-m² to as much as 15 N-m². Notice that if observed densities were uniform, this figure would have the same look as Figure 4.5. Values for MEI appear to be more level than values for strictly EI. This is likely due to the fact that areas of plants with high EI values (i.e. tall plants) occurred at lower densities than areas of plants with low EI values (i.e. short plants). So as EI increases, plant density is likely to be lower, and as EI increases, plant density is likely to be higher.
Observed MEI values are plotted against density observed during board drop tests in Figure 4.8. Values for MEI are obtained as described above for Figure 4.7. MEI values continue to increase with density to the right of the graph. When density is taken into account, it appears that *J. roemerianus* is the superior vegetation for absorbing energy. This is despite the superior stiffness (EI) of *S. alterniflora*. The large increase in densities of *J. roemerianus* makes up for its lack in individual plant stiffness (EI) making it appear to be the superior energy absorbing saltmarsh vegetation. *S. patens* is the poorest performer for which data was collected, having both low densities and very weak bending stiffness when compared to other plants sampled.

In the field it was noticed that large areas of *J. roemerianus* were more difficult to come by, indicating that patches of high MEI *J. roemerianus* may not be consistent enough to have a significant impact on wave and storm surge attenuation. It was also noticed that *J. roemerianus*
was more susceptible to stem buckling. This was noticed both when gathering bending data and by observing lain over areas in patches of *J. roemerianus*. Also, it is unknown if its wave tolerance can match that of *S. alterniflora*. Flume experiments studying the effectiveness of *J. roemerianus* in wave and storm surge attenuation compared with that of *S. alterniflora* would be useful.

![Figure 4.8 - Measured MEI vs Density](image)

In Figure 4.9, directly observed MEI values for green *S. alterniflora* are plotted versus observed stem heights. Also plotted are Kouwen’s equations for MEI correlated to grass height for live grasses and dormant, equations 4 and 5 in this paper, respectively. MEI increases slightly as stem height increases in the directly observed data. The two outliers around a stem height of 0.11 and 0.14 m are due to short stiff plants that occurred at unusually high densities. Kouwen’s equation for height calibrated MEI for green vegetation (Equation 4) vastly overestimates directly observed MEI for stem heights greater than 0.4 meters. Also, Kouwen’s equation for
dormant plants underestimates values lower in the range, but correlates well with values higher in the range. This is thought to be only a coincidence. The large discrepancy between directly observed values and Kouwen’s equations for MEI calibrated to stem height is most likely a function of the vast differences in method used to obtain MEI.

![Figure 4.9 - Observed MEI vs Stem Height](image)

Height calibrated MEI (using Equation 4) is plotted against date for live *S. alterniflora* in Figure 4.10. Data is from multiple locations in the Eastern Louisiana Gulf coast. Increases in MEI are seen from spring/summer into winter due to the increase in stem heights (also seen in Figure 4.1). Results are plotted on a log scale to show the small variation of MEI with smaller stem heights.

The significance of this result is that, if MEI does in fact directly correlate with stem height for saltwater vegetation, there may be an increase in storm surge and wave attenuation as
the growing season continues. In effect, it may be beneficial for a large storm to hit the Gulf Coast later in hurricane season rather that earlier.

![Figure 4.10 - Height Based MEI vs Date](image)

Note that directly measured MEI values (i.e. non-calibrated values) only take into account stem geometry and stiffness. Calibrated values, while correlated to stem dimensions, were derived from flume tests, in which other variables such as number of leaves, leaf surface area, etc. influenced effective MEI results. The large discrepancy between calibrated MEI values and measured MEI values are likely the result of direct measurements not taking into account drag induced on water by leaves and other mechanisms.

### 4.3 Board Drop

In Figure 4.11, board drop height is plotted against observed density for all tests. In the data for Terrebonne Bay on April 8, 2010 (TB 4/8/2010) only 1 density measurement was
observed due to time constraints in the field. The data suggests a slight negative correlation between board drop height and density may exist, but due to limited data it is not certain at the moment. For each measured density, two board drops were performed, except for the date mentioned above.

It was noticed that larger stem heights usually occurred in areas of lower density. Therefore, assuming a negative correlation exists between board drop height and density, large stem heights occur at lower densities, and that the board drop test does in fact reflect MEI, these findings are suggest that the ability to predict MEI solely based on stem height is plausible.

Figure 4.11 - Board Drop Height vs Density

Directly observed MEI values are plotted against board drop heights from the same location in Figure 4.12. No correlation between these two parameters is observable.
The inability to correlate these results exemplifies the amount of local variation of *S. alterniflora*. It was noticed in the field that stem density in one square meter would vary greatly (almost double at times) between adjacent quadrants inside the said square meter. This fact could be contributing to the randomness seen in the figure. Kouwen (1988) suggested that it is not possible to directly determine M, E, and I for natural vegetation due to the great variability of the lining. Therefore the combined effect of M, E, and I can only be viewed as one quantifiable parameter, MEI. It is reasonable to assume that the board drop test provides a more accurate measure of MEI due to the fact that it relies upon the collective effect of all plants under the test area.

Figure 4.12 - Measured MEI vs Board Drop Height

Figure 4.13 shows calibrated board drop MEI (Equation 3) versus board drop heights for *S. alterniflora* vegetation. The average board drop calibrated MEI value is 293 N-m². However the data ranges from 11.37 N-m² to as much as 1286.54 N-m². More data points occurred in the
lower range of the data leading one to believe that high MEI values may be sporadic and do not represent the MEI of large areas. It should be understood that the function shown in the graph was not obtained for salt marsh grasses. The true relationship between board drop height and MEI for salt marsh grasses may be vastly different.

Calibrated board drop height is plotted against date in Figure 4.14. These calibrated MEI values are the same data that is plotted in the previous figure. The data with the largest calibrated MEI value is from 8/20/2010. This data is from the Barataria Bay area. Board drop MEI data did not correlate to date as well as the height based MEI data. However, the height based MEI predictions are not influenced by density, while the board drop measured MEI is influenced by density. Decreasing density with increase in height may be the reason for the board drop MEI data not correlating with date.

![Graph of Board Drop Calibrated MEI vs Board Drop Height](image)

Figure 4.13 - Board Drop Calibrated MEI vs Board Drop Height
4.4 Summary of Plant Dimensions, Stiffness, and MEI Values

Table 7 shows a summary of plant parameter averages for all species tested. Again note that data for \( S. \) alterniflora was collected from several locations at various times during the year, while data for other species is limited often from only one area or one time of year. Therefore data for \( S. \) alterniflora should represent more of a seasonal and locational average, while data for the other species will not reflect such a broad average. The stem height over total height parameter can be thought of as a measure of leafiness of the plant (i.e. what portion of the plant is leaves) This parameter may be useful when considering what portion of water flow drag caused by plants is due to rigid stems and what portion is caused by leaves. Also, note that stem diameters for \( S. \) robustus are equivalent circular diameters based on triangular stem heights using equivalence of area. While densities for both the \( Spartneras \) are similar, densities for \( J. \) roemerianus are an order of magnitude higher.
### Table 7 - Plant Properties Summary

<table>
<thead>
<tr>
<th></th>
<th>Stem Height (m)</th>
<th>Total Height (m)</th>
<th>Stem Diameter (mm)</th>
<th>Stem Height/Total Height</th>
<th>Stem Height/Stem Diameter</th>
<th>Bending Stiffness Modulus, E (N/m²)</th>
<th>Second Moment of Inertia, I (m^4)</th>
<th>Bending Stiffness, EI (N-m²)</th>
<th>Density (/m²)</th>
<th>Measured MEI (N-m²)</th>
<th>Height Calibrated MEI (N-m²)</th>
<th>Board Drop Calibrated MEI (N-m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>S. alterniflora</em></td>
<td>0.278</td>
<td>0.716</td>
<td>7.97</td>
<td>0.364</td>
<td>37.69</td>
<td>1.598E+08</td>
<td>3.395E-10</td>
<td>0.0341</td>
<td>247</td>
<td>6.14</td>
<td>15.81</td>
<td>293</td>
</tr>
<tr>
<td><em>J. roemerianus</em></td>
<td>0.929</td>
<td>0.929</td>
<td>3.08</td>
<td>1</td>
<td>308.88</td>
<td>5.758E+09</td>
<td>5.794E-12</td>
<td>0.0242</td>
<td>1451</td>
<td>14.90</td>
<td>281.5</td>
<td>—</td>
</tr>
<tr>
<td><em>S. patens</em></td>
<td>0.403</td>
<td>0.710</td>
<td>2.04</td>
<td>0.571</td>
<td>200.67</td>
<td>2.950E+09</td>
<td>1.062E-12</td>
<td>0.0028</td>
<td>212</td>
<td>0.60</td>
<td>16.46</td>
<td>—</td>
</tr>
<tr>
<td><em>S. robustus</em></td>
<td>0.321</td>
<td>0.651</td>
<td>3.10*</td>
<td>0.496</td>
<td>101.11</td>
<td>2.010E+09</td>
<td>5.220E-12</td>
<td>0.0107</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>11.14</td>
</tr>
</tbody>
</table>

*Based on equivalence of area to an equilateral triangle
4.5 Soil Properties

Presentation and analysis of soil properties are shown in this section. Table 8 shows a summary of all testing results for all soil samples collected. All samples were taken from shallow depths ranging from the surface to depths of approximately 1.5 ft. All samples tested, except those for moisture and organic content, were sieved through a No. 40 (425 μm) sieve to remove all large and fibrous plant material that may have affected results. Percent water content by weight ranges from 82.3% to 180.9%. Percent organic content by weight ranges from 5.6% to 15.9%. Plastic limit (PL) ranges from 22 to 32 percent water content by weight, Liquid limit (LL) ranges from 50 to 100 percent water content by weight, and plasticity index (PI) ranges from 28 to 68 percent water by weight. Pore water pH ranges from pH of 3.39 to a pH of 6.89. Salinity, expressed as grams NaCl per 1000 grams H₂O (ppt), 1.8 to 4. Pore water pH values are most likely not accurate for all samples except MS A, MS B, and TB C. Low pHs are likely due to chemical reactions (i.e. decaying plant matter, etc.) occurring during storage of the samples. All other collected parameters are expected to be accurate.

Table 8 - Summary of Soil Testing Results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (ft)</th>
<th>% wt. water</th>
<th>% Organic</th>
<th>PL</th>
<th>LL</th>
<th>PI</th>
<th>Pore water pH</th>
<th>Salinity (ppt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS BKT</td>
<td>0-0.5</td>
<td>93.9%</td>
<td>7.4%</td>
<td>22</td>
<td>59</td>
<td>37</td>
<td>5.22</td>
<td>29</td>
</tr>
<tr>
<td>CS TOP</td>
<td>0-1</td>
<td>132.3%</td>
<td>10.7%</td>
<td>30</td>
<td>65</td>
<td>35</td>
<td>4.29</td>
<td>36</td>
</tr>
<tr>
<td>CS BOT A</td>
<td>1-1.5</td>
<td>121.6%</td>
<td>10.0%</td>
<td>22</td>
<td>53</td>
<td>31</td>
<td>3.39</td>
<td>40</td>
</tr>
<tr>
<td>CS BOT B</td>
<td>1-1.5</td>
<td>82.3%</td>
<td>5.6%</td>
<td>22</td>
<td>50</td>
<td>28</td>
<td>3.39</td>
<td>40</td>
</tr>
<tr>
<td>TB A</td>
<td>1</td>
<td>165.6%</td>
<td>12.9%</td>
<td>32</td>
<td>100</td>
<td>68</td>
<td>4.18</td>
<td>24</td>
</tr>
<tr>
<td>TB B</td>
<td>1</td>
<td>149.3%</td>
<td>12.0%</td>
<td>31</td>
<td>98</td>
<td>67</td>
<td>3.97</td>
<td>26</td>
</tr>
<tr>
<td>MS A</td>
<td>0.5-1.0</td>
<td>84.5%</td>
<td>15.9%</td>
<td>24</td>
<td>75</td>
<td>51</td>
<td>6.89</td>
<td>18</td>
</tr>
<tr>
<td>MS B</td>
<td>0.5-1.0</td>
<td>163.0%</td>
<td>7.7%</td>
<td>30</td>
<td>96</td>
<td>66</td>
<td>6.86</td>
<td>27</td>
</tr>
<tr>
<td>TB C</td>
<td>0.5-1</td>
<td>180.9%</td>
<td>10.3%</td>
<td>31</td>
<td>96</td>
<td>65</td>
<td>6.56</td>
<td>29</td>
</tr>
</tbody>
</table>
Figure 4.15 shows pH, salinity and percent organic content by weight plotted against percent water content by weight. No obvious correlations were found by comparing these parameters. Average salinity was 2.86 grams NaCl per 100 grams H₂O, average pH was 5.17 (this value is suspected of being erroneous) and average percent organic content by weight is 9.29. Attempts were made to correlate atterberg limits with percent water content and percent organic content, as well as other parameters, but no correlations were found.

A soil plasticity chart showing soil classification of all samples taken is shown in Figure 4.16. Area in which the sample was taken is indicated by color (Black = Breton Sound, Magenta = Chandeleur Sound, Blue = Terrebonne Bay, Red = Graveline Bayou, MS) All Terrebonne Bay samples were taken from the same location were of very similar plasticity. The Breton Sound sample is very similar in plasticity to the Chandeleur Sound samples. It was noticed that different strata of an area performed better or worse than other strata in an area. CS BOT A and CS BOT
B seem more stable than the layer above it, CS TOP. The chart shows that the upper sample had a higher liquid limit and a slightly higher plasticity index when compared to the bottom samples. It is unsure if this plasticity difference plays a role in the stability of the lower strata or if this is a function of wave action heights. The samples from Mississippi show a large discrepancy between samples. This is most likely due to the fact that the MS A sample was taken from about 20 ft from the water’s edge while MS B was sampled 10 ft from the water’s edge. Feagin et al (2009) found that inland saltmarsh sediments eroded much more easily than marsh edge sediments. The difference in plasticity of samples MS A and MS B may be one of the key differences between interior marsh and marsh edge sediments. All samples were classified as fat clays (CH) using the Unified Soil Classification System.

![Soil Plasticity Chart](image)

Figure 4.16 - Soil Plasticity Chart

Figure 4.17 shows the particle gradation of all samples achieved though hydrometer analysis. Curves toward the top of the chart have finer particles than curves toward the bottom of
the chart. The Terrebonne Bay (TB) samples had the finest particles, and differences between samples were very slight. This is expected due to the fact that Terrebonne Bay samples were taken from the same sampled site at the same depth. The Graveline Bayou (MS B) sample appears to be very similar to the Terrebonne Bay samples, which also agrees with MS B having a very similar plasticity to the Terrebonne Bay samples in the plasticity chart shown above. MS A has a slightly coarser gradation than MS B. Both Chandeleur Sound (CS) BOT (bottom) samples were very similar while CS TOP was slightly coarser. The trend of coarser samples having a lower liquid limit and plasticity index, when considering one location, is consistent between the MS and CS samples. The Breton Sound (BS) sample had a particle gradation that was between those of the Terrebonne Bay and Chandeleur Sound samples.

![Figure 4.17 - Particle Gradation: Hydrometer Analysis](image)

Figure 4.17 - Particle Gradation: Hydrometer Analysis
4.6 Suggested Modification to Method

It should be noted that one of the major assumptions of the Euler-Bernoulli beam equation is that the force applied is perpendicular the member it is being applied to (i.e. no torsional or axial loads are present). Hence, the method used should not investigate bending stiffness does not give an accurate representation of a material property of the vegetation (namely elastic modulus). The method should be thought of as a common and agreed upon method for analyzing and comparing the stiffness of vegetation. However, to make the method slightly more accurate, the equation for bending stiffness modulus should be multiplied by \( \sin(45^\circ) \) because the force applied to the plant is applied at a 45° angle to the stem. This would give the following equation for bending stiffness:

\[
E_s = \frac{F_{45}H^2}{3I} \sin(45^\circ) = 6.791 \left( \frac{F_{45}H^2}{D_s^3} \right) \sin(45^\circ)
\]

Equation 6 - Modified Bending Stiffness

However, this modification for accuracy may be in vain due to the fact that most of the other assumptions of the Euler-Bernoulli equation are violated. These violated assumptions include (Shigley, 1986):

- Only very small deflections are applied
- The beam is initially straight and cross-section is constant throughout
- The material is isotropic and homogenous
- The material is linearly elastic and will not deform plastically
- Cross-sections of the beam remain plane during bending
- The beam has an axis of symmetry in the plane of bending
Also, to acquire a better relationship between densities (which varies greatly even at one sampling site) and plant dimensions, and bending stiffness a new method to acquire bending stiffness measurements is proposed. This new method would be slightly easier than selecting random plants and more closely relate plant properties to density:

1. Select desired sight for data collection

2. Lay a square apparatus with an inner area of 0.25 m² made of PVC pipe over selected area.

3. Cut all vegetation at their base within this area to get a count for density (plant dimensions could also be gotten from these plants)

4. Measure plant stiffness in the same manner as mentioned previously from the perimeter of the now bare piece of ground. Pulling plants into the cleared area.

Pulling plants will make maneuvering the plant measuring jig much easier and will ensure that plants are pulled in all directions. Freeman et al. (2000) commented that plants were more easily bent in the direction in which water flowed. It was also noticed in this study that vegetation along the marsh edge was weaker in the direction of oncoming wave action, so randomizing the direction in which the plants are pulled is important in obtaining consistent results.
5 SUMMARY AND CONCLUSIONS

The Northern coast of the Gulf of Mexico is threatened by storm surge and waves from tropical storms. It has been long known that marsh vegetation attenuates storm surge and waves and is vital for sustaining marsh edges. However, little is known about the relationship between plant properties and the amount of storm surge and wave reduction the plants provide. In order to better understand the stiffness properties and physical dimensions of saltmarsh vegetation, which are directly related to their ability to attenuate waves and storm surge, this study has been conducted. Stiffness of salt marsh vegetation was determined through direct bending and through board drop testing at several locations from August 13, 2009 to September 15, 2011. The data was analyzed for observable trends and averages.

It was found that the growing season for *S. alterniflora* begins around April and continues through early winter, ending with the plant flowering then becoming dormant. Early in the growing season, there is a large difference between stem and total heights. As the plant matures this difference decreases. It was found that the relationship between bending stiffness modulus and stem height over stem diameter ratio for all four species tested can be described with the equation $E_s = 473253x^{1.5943}$, with a coefficient of determination ($R^2$) of 0.8525. However, the increase in bending stiffness modulus with the increase in stem height over stem diameter ratio may be an artifact of the method used. While pre-dormancy and post-dormancy dimensions of *S. alterniflora* are similar, there was a large reduction (52%) in bending stiffness modulus of dormant plants. This reduction is believed to be due to a reduction in turgor pressure, which keeps plant cells in a tensioned state. It was found that *S. alterniflora* has the superior bending stiffness (EI) of the species for which data was collected. *S. patens* has a much lower
bending stiffness than both *S. alterniflora*, while occurring at similar densities, and is even low when compared to *J. roemerianus*.

The average value for directly measured MEI is 6.14 N-m² while the data ranges from as little as 2 N-m² to as much as 15 N-m² for *Spartina alterniflora*. No observable temporal trends for directly measured MEI were noticed for *S. alterniflora*. When density is taken into account, it appears that *J. roemerianus* is the superior vegetation for absorbing energy (i.e. highest MEI). This is despite the superior stiffness (EI) of *S. alterniflora*. Using Equation 4 and Equation 5 MEI increases as stem height increases, increasing more dramatically as stem height gets larger. Using height calibrated MEI, increases in MEI are seen from spring/summer into winter due to the increase in stem heights. The significance of this result is that, if MEI does in fact directly correlate with stem height for saltwater vegetation, there may be an increase in storm surge and wave attenuation as the growing season continues. In effect, it may be beneficial for a large storm to hit the Gulf Coast later in hurricane season rather that earlier.

Board drop data suggests a slight negative correlation between board drop height and density may exist, but due to limited data it is not certain at the moment. It was noticed that larger stem heights usually occurred in areas of lower density. Therefore, assuming a negative correlation exists between board drop height and density, large stem heights occur at lower densities, and that the board drop test does in fact reflect MEI, these findings are suggest that the ability to predict MEI solely based on stem height is plausible. No correlations between directly observed MEI and board drop MEI were found. The inability to correlate these results exemplifies the amount of local variation of *S. alterniflora*. Kouwen (1988) suggested that it is not possible to directly determine M, E, and I for natural vegetation due to the great variability of the lining. Therefore the combined effect of M, E, and I can only be viewed as one quantifiable
parameter, MEI. It is reasonable to assume that the board drop test provides a more accurate measure of MEI. The average board drop calibrated MEI value is 293 N-m². However the data ranges from 11.37 N-m² to as much as 1286.54 N-m².

Soil analysis found Percent water content by weight ranges from 82.3% to 180.9%. Percent organic content by weight ranges from 5.6% to 15.9%. Plastic limit (PL) ranges from 22 to 32 percent water content by weight, Liquid limit (LL) ranges from 50 to 100 percent water content by weight, and plasticity index (PI) ranges from 28 to 68 percent water by weight. Pore water pH ranges from pH of 3.39 to a pH of 6.89. Salinity, expressed as grams NaCl per 100 grams H₂O, 1.8 to 4. Attempts were made to correlate atterberg limits with percent water content and percent organic content, as well as other parameters, but no correlations were found. It was found that more stable salt marsh deposits may have lower plasticities and liquid limits than less stable soils. All samples were classified as fat clays (CH) using the Unified Soil Classification System.

It was suggested that the method used should not investigate bending stiffness does not give an accurate representation of a material property of the vegetation. The method should be thought of as a common and agreed upon method for analyzing and comparing the stiffness of vegetation. However, to make the method slightly more accurate, the equation for bending stiffness modulus should be multiplied by \( \sin(45\degree) \). A new equation for measuring bending stiffness is suggested. However, this modification for accuracy may be in vain due to the fact that most of the other assumptions of the Euler-Bernoulli equation are violated. Also, to acquire a better relationship between densities (which varies greatly even at one sampling site) and plant dimensions and bending stiffness a new method to acquire bending stiffness measurements is proposed.
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VITA

James Chatagnier is from Eunice, Louisiana. He is a 2004 graduate of St. Edmund Catholic High School in Eunice, LA. James attended Louisiana State University at Eunice for one year immediately following high school and transferred to LSU – Baton Rouge fall 2005. He graduated with a bachelor’s degree in civil engineering spring 2009.

James entered the LSU civil engineering graduate program to pursue a master’s degree in August 2009. He worked under Dr. Guoping “Gregg” Zhang (advisor) and Dr. Q. Jim Chen (co-advisor) His interests are geotechnical engineering, coastal engineering, and wetland restoration.