Erosional resistance of cohesive sediments in coastal saltmarshes

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EROSIONAL RESISTANCE OF COHESIVE SEDIMENTS IN COASTAL SALTMARSHES

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

Hem Raj Pant
B.E., Tribhuvan University, 2007
August 2013
To

My Parents

My Family

And

My Teachers
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ABSTRACT

Louisiana’s saltmarshes, one of the most productive wetlands in the nation, are undergoing severe erosion due to hydrodynamic forces (storm surge) and sea level rise. The erosional behavior of coastal saltmarshes, which possess cohesive sediments as their integral components, are very difficult to analyze and understand. The erosional resistance of cohesive sediments determines the stability and sustainability of coastal wetlands. This erosional resistance is expressed as an erosion threshold or critical shear stress, which depends on various soil properties (e.g. water content, root content, organic matter content, and pore water salinity) affecting saltmarsh erodibility integratively.

A cohesive strength meter was deployed to measure the critical shear stress in Bay Jimmy (Barataria Bay), an oil spill site, and Terrebonne Bay, a normal saltmarsh. Results show that erosion threshold is positively correlated with organic matter and root contents. In fact, both roots and organic matters assist with the aggregation of mineral particles through bridging effect. However, when the organic matter content exceeds 10%, the critical shear stress decreases with organic matter content, as observed for the Terrebonne Bay sediments.

The erosion threshold of the sediment surface of Bay Jimmy was found to be less than that of Terrebonne Bay, which may be attributed to the lower pore water salinity and possibly reduced inter particle binding due to residual crude oil retained by the cohesive sediments. However, the higher root content at depth in Bay Jimmy ensured greater stability than that found in Terrebonne Bay. Therefore the possible critical mechanism of erosions in Bay Jimmy and Terrebonne Bay are surface erosion and undercut erosion respectively.
CHAPTER 1 INTRODUCTION

1.1 General background and problem statement

The resilience and functionality of coastal marshlands relies heavily on the stability of the physical foundations of the marshes—wetland soils on which marshes grow and thrive. In other words, the stability of wetland foundation soils directly controls the resilience and health of the coastal ecosystem (Howes et al. 2010). In fact, the interdependence between marsh vegetation and soil is well documented, and its importance is reflected in a few recent studies focusing on the sustainability and resiliency of coastal wetlands. Among those are, for example, Howes et al. (2010), Turner (2011), and Day et al. (2000).

Coastal erosion, a huge problem facing all coastal communities around the world, is dominantly controlled by soil stability or strength. In general, soil erosion, the gradual removal of surface material from a soil mass by moving water, depends upon both the energy of the flowing water (i.e., the driving force exerting a flow shear stress to soil surface) and the soil’s ability to resist erosive failure (i.e., the resistance of a soil to shear failure). According to the literature, a cohesive soil’s erosion resistance is directly related to its undrained shear strength. That is, if the flow-induced shear stress exceeds a cohesive soil’s undrained shear strength, erosion or removal of soil particles commences as a result of soil failure. As such, this shear stress is also termed “critical shear stress”, an indicator of undrained shear strength of cohesive soils.

Much of the Northern Gulf Coast is underlain by thick cohesive soils. In particular, the fine-grained cohesive sediment brought to the deltaic coast by the Mississippi River dominates the central northern part of the Gulf Coast in Southern Louisiana. These cohesive sediments also make up the foundations to the coastal wetlands along the Gulf Coast. Coastal wetlands are the
Earth’s most energetic, productive ecosystems, and Louisiana includes more than 40% of the tidal wetlands in the 48 conterminous United States and contributes nearly 80% of total wetland losses (USGS, 2013).

Over the past several decades, severe land loss, as a result of erosion, subsidence, and sea level rise, has been observed along the Gulf Coast. In fact, this is also a critical issue facing all coastal communities around the world. In the past 200 years, the US has lost more than 50% of its wetlands (Williams, 2001). Moreover, the land loss is ever increasing at an alarming rate. Every year Louisiana is losing 75 square kilometers of wetlands due to both natural and man-made processes (USGS, 2013), and by 2050 Louisiana is likely to lose 640,000 acres of coastal wetlands and marshes (http://www.restoreorretreat.org/coastal_erosion.php). Fig.1.1 shows the projected land loss in coastal Louisiana between 1932 and 2050.

![Figure 1.1 Projected land loss in Louisiana from 1932 to 2050 (http://coastal.louisiana.gov)](http://coastal.louisiana.gov)

The coastal wetlands in Louisiana are of vital importance to the nation’s economy, energy, and security. The devastation and death caused by 2005 and 2008 hurricanes further demonstrated the vital importance of sustainable coastal ecosystems to the protection of the
coastal civil and energy infrastructure, safety and lives of coastal communities and fisheries and shipping industries. In fact, Louisiana’s wetlands are home to many oil and gas pipelines, and a sustainable and stable coastal ecosystem can protect the critical oil and gas infrastructure from storm surges and hurricanes. This infrastructure produces or transports nearly 1/3 of the US’s oil and gas supplies and is tied to 50% of the nation’s refining capacity. Furthermore, as the most productive ecosystems on Earth, the wetlands in Louisiana provide 26%, by weight, of commercial fish in the lower 48 states. Finally, ten major navigation routes are located in Southern Louisiana, and five of the busiest ports in the US, ranked by total tons, are also located there. These facilities handle 19% of the annual US waterborne commerce. Therefore, healthy, sustainable, and stable coastal wetlands in Northern Gulf Coast have great economic, energy, and security importance. To maintain sustainable and resilient coastal wetlands, the cohesive soils as the foundations of the wetlands, must be fully understood to prevent erosion and other land loss. As such, the study of soil erosion and critical shear stress in Louisiana coastal wetlands is deemed timely and necessary.

1.2 Research objectives

The overall goal of this task is to study the critical shear stress or erosional resistance of cohesive soils of selected wetlands in Northern Gulf Coast and hence accumulate some important data for future numerical modeling of coastal erosion and wetland restoration. The knowledge of soil erosional resistance, combined with other hydrodynamic data (e.g., wave measurements, flow shear strength), can be used to analyze and further predict the stability, survivability, and rate of erosion of coastal wetlands. Specifically, the major objectives of this research are:
(1) To conduct field and laboratory measurements of the critical shear stress of cohesive wetland soils using a portable cohesive strength meter.

(2) To further characterize the wetland soils in the laboratory and determine other properties that are expected to affect soil stability.

(3) To understand the erosional resistance of wetland soils by establishing some correlations (if any exist) of critical shear stress with other index and physical properties of the tested soils.

(4) To compare the test results from two different sites and hence understand geographical variability of wetland soils’ critical shear stress.

(5) To study the effect of oil contamination on sediment stability and erodibility.

1.3 Thesis outline

The first chapter describes the problem statement, brief introduction and research objectives. The importance of coastal wetlands of Louisiana is explained.

Chapter 2 mainly provides relevant literature of cohesive sediments’ erodibility and stability. This chapter further deals with the composition of cohesive sediments, factors affecting sediment erodibility, and erosional behavior.

Chapter 3 describes the site characteristics, experimental instruments, methods and materials used during the project period. Furthermore, the determination of critical shear stress from the raw data and soil properties is explained.

Chapter 4 presents test data obtained from the in-situ and laboratory testing from the two sites. The results and subsequent analysis with discussion and relevant significance are provided.

Finally, Chapter 5 summarizes current research and provides conclusions and recommendations for future works.
CHAPTER 2 LITERATURE REVIEW

Numerous researchers have shown keen interest in the erosion studies of coastal wetlands and saltmarshes in the recent past because of its complexity and relevance to the social and ecological aspects of life. The vulnerability of Louisiana’s coastal saltmarshes to erosion is sure to affect the human communities and natural ecosystems. Therefore, detailed investigation of Louisiana’s coastal saltmarsh sediments and their resistance against erosive forces is essential for coastal ecosystem preservation.

This chapter presents the concept of sediment erosion for cohesive sediments and non-cohesive sediments and various factors affecting sediment stability. Furthermore, it describes previous studies carried by other authors on cohesive sediment erosion and includes the following topics: sediment characteristics, cohesive sediment composition, soil properties affecting sediment erodibility, modes of erosion, and measurement of erosion resistance.

2.1 Sediment characteristics

Sediment characteristics and behavior are different for cohesive and noncohesive sediments. Furthermore, sediment erosion resistance against hydrodynamic and wind forces, transport and deposition phenomena are also significantly different for both types of sediment. Unified soil classification system (USCS) defines coarse grained soil as soils retaining more than 50 percent on a sieve No. 200 (75 μm) whereas more than 50 percent of fine grained and cohesive soils pass through the same sieve. Cohesive soils consist of fines; silt (2 μm -75 μm) and clay with particle size less than 2 μm. A Clay particle has charges on its surface and is cohesive in nature while, silt is considered cohesive to non-cohesive sediment (Huang et al., 2006). Body forces govern the erosion behavior of cohesionless sediments where interparticle forces are absent. In contrast, cohesive sediments possess electrochemical forces that are
influenced by water and organic content and pore water pH (Ravisangar et al., 2001 Black et al., 2002; Krishnappan et al., 2007). Interparticle forces are dominant to gravitational forces in cohesive sediments.

2.1.1 Cohesionless sediments

Various laboratory and in-situ experiments are performed on coarse grained sediments like sand to study the erosional behavior and incipient motion of the particles (Haan et al., 1994; Huang et al. 2006). Forces acting on a cohesionless grain are: Drag force ($F_D$) and buoyant force ($F_B$) as active forces and particle weight ($F_W$) and friction as resisting forces. At incipient motion:

$$\frac{F_D}{(F_W-F_B)} \geq \tan \phi$$

(2.1)

The applied shear stress at which particle motion is initiated is called as critical shear stress ($\tau_c$) which is a function of submerged specific weight of the sediment, sediment grain size, fluid density, and dynamic viscosity.

$$\tau_c = f(\gamma_s - \gamma_w, d, \rho_w, \mu)$$

(2.2)

Using incipient condition, the general form of the Shields parameter is:

$$\tau_{*c} = \frac{\tau_c}{(\gamma_s-\gamma_w)\rho} = f \left( Re_{*c} = \frac{d \rho_w}{\nu} \right)$$

(2.3)

where $\tau_{*c}$ is dimensionless Shields parameter, $Re_{*c}$ is critical boundary Reynolds number and $\nu$ is kinematic viscosity. Equation 2.3 is presented graphically in Figure 2.1. Under given flow conditions, the Shields parameter greater than critical line will result in motion (Figure 2.1).
Cohesionless sediments start rolling and sliding upon applied shear stress reaching critical shear stress. At low values of bed shear stress, particles move by rolling and sliding. In other words, particles move as bed load with close contact to bed. At higher shear stress when upward velocity exceeds fall velocity, sediments move in suspension as suspended load.

![Figure 2.1 The Shields diagram as updated by Yalin and Karahan (1979)](image)

2.1.2 Cohesive sediments

Coastal embayments, estuaries, mudflats, and areas of continental shelf mainly consist of cohesive sediments. Cohesive sediments are composed of silt (2 μm -75 μm) and clay (<2 μm) particles collectively called mud. The erosional behavior of cohesive sediments is more complicated than that of noncohesive sediments and particle incipient motion is difficult to define using a single parameter. In addition, erosional behavior of mixed cohesive and noncohesive sediments is also difficult to understand (Torfs, 1995; Mitchener and Torfs, 1996; van Ledden et al., 2004) and small size coarse particles can exhibit a certain degree of cohesion.
when present with cohesive material (Torfs, 1995). The strength of a cohesive bond depends on clay mineralogy and water chemistry. For instance, silt and fine sand behave like noncohesive materials in a fresh water environment but exhibit cohesion in a saline environment. Surface area per unit volume (specific surface area) of a particle increases with a decrease in its particle size, and interparticle forces dominate over gravitational force (Huang et al., 2006) and influence sediment behavior.

According to Mehta and Dyer (1990), cohesive sediments are different from noncohesive sediments in two fundamental aspects. Firstly, with significant physico-chemical effects due to strong surface ionic charges, cohesive sediments tend to form aggregates of low density or flocs. Therefore, flocs are present both in the sediment bed and water column. This process of flocculation and preservations of floc depends on the concentration and turbulence of the flow. If turbulence is low, particle interactions are not strong enough for flocculation while the turbulence that is too high will result in flocs’ breakage (Mikkelsen, 2002). The size, structure, and density of flocs basically depend on hydrodynamic forces, interparticle collisions, and electrochemical forces. The various processes (aggregation and breaking, sedimentation, and erosion) involved in mud floc dynamics are presented in Figure 2.2. Clay particles stick together to form the primary particles, which are the basic building blocks of flocs. Sediment aggregation is further assisted by the presence of extracellular polymeric substances (EPS) and mucus excreted by bacteria. Sediment particles can even undergo sediment aggregation during suspension due to the presence of organic matter content resulting in the formation of micro and macro flocs. Secondly, flocs undergo consolidation once deposited on the sediment bed and consequently increase the density and shear resistance of the sediment bed, thus exhibiting time dependent characteristics.
2.2 Cohesive sediment composition

Cohesive sediments typically consist of three phases --solid, liquid and gas-- and are a heterogeneous mixture of particulate and porous material (Hillel, 1982; Winterwerp and van Kestern, 2004). It is evident that coastal cohesive sediments are basically a mixture of fine sand, mud, and organic matter content. Lumborg and Windelin (2003) classified intertidal flats based on percentage of mud content in the sediment mixture as sand flats (sand content > 95%), mixed mud flats (10-50% mud), and mud flats (mud content > 50%). Furthermore, the solid phase of cohesive sediments consists of inorganic and organic materials (Hayter, 1983). Inorganic minerals include clay minerals (e.g. silica, alumina, illite, montmorillonite, and kaolinite) and non-clay minerals (e.g. quartz, mica, carbonates, and feldspar) that are originated from chemical and physical weathering of bedrock respectively (Winterwerp and van Kestern, 2004; Grabrowski et al. 2011). Clay minerals that resulted from chemical weathering are the most electrochemically active components in the sediment mixture and major contributors for cohesion. Organic materials may exist as living organisms (e.g. bacteria, benthic algae), detritus,
extracellular polymeric substances (EPS), and organic colloids (Grabrowski et al. 2011). Additionally, organic materials are electro-chemically as active as inorganic materials and contribute to cohesion and adhesion as well (Winterwerp and van Kesteren, 2004). Therefore, even the smallest amount of organic matter has a significant impact on sediment aggregation and resistivity against erosion forces. In a coastal environment, water predominantly occupies the liquid phase of the cohesive sediment. Gases may not be as dominant in estuarine sediments exposed to air at low tides as in riverine sediments. Organic material breakdown results in the formation of gases within the sediment (Gebert et al., 2006; Sanders et al., 2007). Integrated biofilms produced by microorganisms (e.g., diatoms) are basically found on sediment surface, while extracellular polymeric substances (EPS), a major component of biofilm that is secreted by bacteria, may present at depth in the sediment (Fig. 2.3). Structure and interactions of different subcomponents present in cohesive sediment determine the erodibility of cohesive sediments.

Figure 2.3 Microstructure and composition of cohesive sediments (Grabrowski et al., 2011), after Gillott (1987)
2.3 Cohesive sediment erodibility

Cohesive sediment is an important component of coastal marshes that play vital role in the stability of coastal marshlands. Since it is a big stake holder of the coastal ecosystem, its stability against hydrodynamic forcing should be investigated in order to understand the vulnerability of coastal marshlands in Gulf Coast to erosion by waves and storm surges. Understanding coastal soil’s erodibility is not easy or simple, because of the complex behavior of coastal cohesive sediments, when compared to relatively clean granular sandy soils. Marshlands that are directly in contact with coastal waters are unstable and fragile due to the continuous attack of water waves. Thus coastal soil is most vulnerable to erosional loss due to frequent hydrodynamic forces and wind forces.

The stability of coastal marshes depends on the hydrodynamic forcing that is responsible for erosion and the resisting forces that the sediment bed offers. When the erosive driving forces (waves, surge, and current) overcome the resistive forces (cohesion, gravity, friction, and adhesion), erosion takes place (Grabowski, et al. 2011). Erodibility that measures the resistance offered by the soil surface is expressed as a threshold or as an erosion rate (Sanford, 2008). Critical flow velocity or critical erosional shear stress that initiates the erosion is considered as the “erosion threshold”, while erosion rate measures the mass of sediment eroded per unit time beyond the erosion threshold. Significant erosion occurs beyond critical shear stress whereas negligible or no erosion occurs below the critical shear stress. It is noteworthy that cohesive sediment has critical shear stress ($\tau_{cr}$) for erosion significantly greater than the shear stress required to settle sediments ($\tau_s$) (Figure 2.4). The additional stress is required to overcome interparticle bonds to initiate sediment transport. In contrast, these two stresses are the same for non-cohesive sediments.
Erosion thresholds for cohesionless soils can be predicted based on flow and sediment characteristics (grain size and density) and erosion models are well advanced (Tolhurst et al. 1999; Grabowski, et al., 2011). However, prediction of the erodibility of cohesive sediments that are common in coastal marshes is difficult because the interparticle attraction in cohesive soils is influenced by a number of factors, including those environmental factors such as organic matter content, pH, salinity, water content, and even soil biota or biofilms (Black et al. 2002; Winterwerp and van Kesteren, 2004; Grabowski, et al. 2011). Detailed description of various properties affecting sediment erodibility is presented in Chapter 2.5.

Both critical shear stress and erosion rate are important parameters in numerical models of cohesive sediment transport. Most of the erosion models estimating sediment erosion rates consider critical shear stress as a major parameter in their formulation. For instance, based on Parthenaides erosion experiments, Ariathurai (1974) proposed following erosion equation which includes critical shear stress:

\[
E = M \left( \frac{\tau_b - \tau_{cr}}{\tau_{cr}} \right) \quad \text{for} \quad \tau_b > \tau_{cr} \tag{2.4}
\]
where $M$ is an erosion rate parameter, $\tau_b$ is the turbulent mean bed shear stress, and $\tau_{cr}$ is a critical shear stress. Following the research of Partheniades, various other researchers carried out erosion experiments in the 1970s and “80s”. The equation (2.4) was later generalized (Mehta, 1981; Lick, 1982; Sheng, 1984) and used widely for its simplicity (Winterwerp and van Kesteren, 2004).

\[
E = M \left( \frac{\tau_b - \tau_{cr}(z,t)}{\tau_{cr}(z,t)} \right)^n \quad \text{for } \tau_b > \tau_{cr} \tag{2.5}
\]

where $n$ is generally unity; however other values are also found (Harrison and Owen, 1971; Kusuda et al., 1985). The critical shear stress ($\tau_{cr}$) often varies with depth and time due to consolidation and physico-chemical effects. Additionally, several equations are proposed by various researchers to estimate critical shear stress ($\tau_{cr}$). Mitchener and Torfs (1996) proposed:

\[
\tau_{cr} = 0.015 (\rho_B - 1000)^{0.84} \tag{2.6}
\]

where $\rho_B$ is bulk density in Kg/m$^3$ and $\tau_{cr}$ is critical erosion shear stress in N/m$^2$. Smerdon and Beasley (1959) correlated critical shear stress with plasticity index.

\[
\tau_e = 0.163 \ P I^{0.84} \tag{2.7}
\]

Thus, critical shear stress or erosion threshold which measures the resistance of a particular sediment bed against erosion driving forces is an essential parameter of an erosion model. In addition its correlation with various soil properties is highly important in the cohesive sediment erosion studies and sediment transport.
2.4 Erosional behavior

The coastal sediment erosion process depends on the complex interaction of hydrodynamic forces and sediment bed structure and bed material properties. Bottom shear stress from hydrodynamic processes is eventually a combination of wind waves and currents (Soulsby, 1997). The mode of erosion varies with the intensity of bottom shear stress, which is defined as shearing force on sediment bed due to friction (Mehta, 1981). Depending on the intensity of applied shear stress, various modes of observed erosion are: entrainment, floc erosion, surface erosion, and mass erosion (Mehta, 1991; Winterwerp and van Kestern, 2004) as summarized in Figure 2.5(a)-(d).

In entrainment mode of erosion, a sediment bed is fluidized when sediment is soft and behaves like viscous fluid. Hence sediment water interface is destabilized and fluid mud is entrained from the sediment bed. Floc erosion occurs as a detachment of individual floc from the bed surface. Floc erosion occurs when the flow bed shear stress exceeds the adhesion of flocs to the bed. Surface erosion is a drained failure process in which flocs attached to a bed water interface by inter-particle electro-chemical bonds break by hydrodynamic lift and drag. When the bed is over-consolidated or there are flow/wave induced pressure fluctuations, the top of the bed liquefies due to swelling. In contrast, mass erosion is an undrained failure process in which sediment erosion occurs at considerably high shear stress (greater than undrained shear strength). For example, cliff erosion is mass erosion which is characterized by the detachment of lumps of material under turbulent flow or waves over irregular beds (Mehta, 1991; Winterwerp and van Kestern, 2004). For both surface and mass erosion, the resistance by sediments is different. The resistance offered by a sediment bed against surface erosion is called erosional strength of soil (Zreik et al. 1998). On the other hand, undrained or yield strength determines the mass erosion...
(Millar and Quick, 1998). Figure 2.6 summarizes the erosional and depositional characteristics of the sediment bed as a function of erosion rates and critical shear stress for deposition, surface erosion, and mass erosion.

Figure 2.5 (a) Entrainment of mud layer (b) floc erosion (c) surface erosion (drained failure) (d) mass erosion (undrained failure) (Winterwerp and van Kestern, 2004)

Aberle et al. (2004) mentioned two erosion mechanisms associated with the bed structure. Type I or depth-limited erosion occurs when flow shear stress exceeds the critical shear stress (erosion threshold) and particles are eroded from the surface (Mehta and Partheniades, 1982). These loosely held particles and flocs forming fluffy layers are often found in cohesive sediment beds. As the applied bed shear stress tends to bed shear strength, type I erosion starts to cease at
certain depth. On the other hand, type II or steady state erosion has constant bed shear strength with depth and constant erosion rate (Parchure and Mehta, 1985; Paterson and Black, 1999). In the natural state, most of the cohesive sediments are layered and different, indicating occurrence of type I erosion. However, it is difficult to determine the onset of erosion with visual observation in cohesive sediments. Therefore an abrupt increase in concentration of suspended particulate matter (SPM) or an increase in turbidity of eroding fluid is used to determine the initiation of erosion. For example, Tolhurst et al., (1999) defined critical shear stress for a cohesive strength meter test as a stress corresponding to the point where light transmission falls just below 90% through the eroding fluid.

![Diagram](image)

**Figure 2.6** Idealized diagrammatic representation of erosional characteristics with erosion rates and critical shear stress (Huang at al., 2006) after Vermeyen, 1995.
2.5 Soil properties affecting cohesive sediment erodibility

As mentioned before, unlike that of cohesionless sediments, the characterization and prediction of erosion, suspension, transportation, and deposition phenomena of cohesive sediments is not amenable with grain size and distribution. Winterwerp et al., (1990) mentioned 28 parameters used by Delft Hydraulics to characterize cohesive sediments (Table 2.1). In addition to physical, electro-chemical properties, biological factors also have a significant effect on sediment stability. In fact, at times sediment bed strength may be controlled by biological factors rather than physical and electrochemical factors (Black et al., 2002; Paterson, 1994).

Table 2.1: List of parameters (excluding biological effects) used to characterize cohesive sediments (after Winterwerp et al., 1990)

<table>
<thead>
<tr>
<th>Physico-chemical properties of the overflowing fluid</th>
<th>Characteristics of bed structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Chlorinity</td>
<td>19 Specific surface</td>
</tr>
<tr>
<td>2 Temperature</td>
<td>20 Mineralogical composition</td>
</tr>
<tr>
<td>3 Oxygen content</td>
<td>21 Grain size distribution and sand content</td>
</tr>
<tr>
<td>4 Redox potential</td>
<td>22 consolidation</td>
</tr>
<tr>
<td>5 pH</td>
<td>a) Consolidation curve and density profile</td>
</tr>
<tr>
<td>6 Na-, K-, Mg-, Ca-, Fe-, Ai- ions</td>
<td>b) Permeability</td>
</tr>
<tr>
<td>7 Sodium adsorption ratio (SAR)</td>
<td>c) Pore pressure and effective stress</td>
</tr>
<tr>
<td>8 Suspended sediment concentration</td>
<td>23 Rheological parameters</td>
</tr>
<tr>
<td></td>
<td>a) Upper and lower yield stress</td>
</tr>
<tr>
<td></td>
<td>b) Bingham viscosity</td>
</tr>
<tr>
<td></td>
<td>c) Equilibrium slope of mud deposits</td>
</tr>
<tr>
<td>Physico-chemical properties of the mud</td>
<td>24 Atterberg limits (liquid and plastic limit)</td>
</tr>
<tr>
<td>9 Chlorinity</td>
<td>Water-bed exchange processes</td>
</tr>
<tr>
<td>10 Temperature</td>
<td>25 Settling velocity</td>
</tr>
<tr>
<td>11 Oxygen content</td>
<td>a) as a function of sediment concentration and Floc density</td>
</tr>
<tr>
<td></td>
<td>b) as function of salinity</td>
</tr>
<tr>
<td>12 Redox potential</td>
<td>26 Critical shear stress for deposition</td>
</tr>
<tr>
<td>13 pH</td>
<td>27 Critical shear stress for erosion</td>
</tr>
<tr>
<td>14 Gas content</td>
<td>28 Erosion rate</td>
</tr>
<tr>
<td>15 Organic content</td>
<td></td>
</tr>
<tr>
<td>16 Na-, K-, Mg-, Ca-, Fe-, Ai- ions</td>
<td></td>
</tr>
<tr>
<td>17 Cation exchange capacity (CEC)</td>
<td></td>
</tr>
<tr>
<td>18 Bulk density (density profile)</td>
<td></td>
</tr>
</tbody>
</table>
The erosional resistance of cohesive sediments in the saltmarshes determines the wetland stability and sustainability, and erodibility (erosional resistance) of the sediment is measured in terms of erosion threshold such as critical shear stress or erosion rate. A number of factors can affect the erodibility or erosion threshold of cohesive sediments. They are divided into physical, geochemical, and biological origins, as summarized in Figure 2.7 (Grabrowski et al., 2011). These factors are interconnected and act together to determine the degree and rate of erosion. Since erodibility depends on a number of factors that are inter-related, a detailed investigation is required in order to gain insight into the erosional threshold of coastal cohesive sediments. To date, many researchers have found that these factors are connected in such a complex manner that the prediction and evaluation of erosional resistance based on only one factor can be very misleading. Some of these properties and previous research results are explained in this section.

![Figure 2.7 Sediment properties and processes that affect erodibility (Grabrowski et al., 2011)](image-url)
2.5.1 Physical factors influencing erodibility

Physical factors affecting erosion resistance of the sediment are water content, bulk density, average particle size, and particle size distribution (e.g. clay content). Although effective particle size is a widely used parameter in different cohesionless soil models, at present it is still under study for the cohesive soils model. However, various researchers found an increase in critical shear stress with decreasing particle size below 120 μm (e.g. Hjulstrom and Postma plots (Figure 2.8); Roberts et al., 1998). For a particular bulk density, erosion rate increases significantly with an increase in particle size for the smaller particles, until the maximum rate is attained, followed by a decrease in erosion rate for the larger particles (Roberts et. al., 1998). In a study of the movement of quartz particles, Lick et al., 2004, reported an increase in shear stress for the particle size less than 100 μm and a change in erosion pattern from single particle erosion to aggregates erosion. For natural marine mud, a negative correlation between critical shear stress and average particle size was reported by Thomsen and Gust, 2000 (Figure 2.9). The reduction in erosion resistivity of the unconsolidated bed with particle size is due to a decrease in density. However, Dade et al., 1992, found positive correlation between critical shear stress and particle size (grain diameter between 10-170 μm). Therefore, particle size correlation can be positive or negative depending on how aggregates are deposited and sediment beds are formed (Grabowski et al., 2011). Since cohesive sediments are mixtures of clay, silt and fine sands, their relative proportions also have significant effect on erodibility. For instance, when the clay content is low (i.e., 2% bentonite by weight), the clay can help adhere sand and silt particles together (Lick et al., 2004). When the clay content is high (e.g., 5-10% by weight), the sand or silt grain skeleton framework changes to a clay mineral framework, indicating that a non-cohesive sediment is converted to a cohesive sediment (van...
Ledden et al., 2004; Winterwerp and van Kesteren, 2004; Grabowski et al. 2010). Below this range, clay particles are unable to form a matrix. When the clay content approaches to that of a pure clay (mud content > 30-50% by weight), the mixture exhibits a reduced erosional threshold. For mixed sand/mud mixture bed, mud content between 30 to 50% enhances the sediment erodibility maximum and a transition of erosion behavior from sandy to muddy occurs for mud content between 3-15% (Mitchner and Torfs, 1996).

![Figure 2.8](image1.png)  
(a) Hjulstrom and (b) Postma plots for erosion thresholds for varying particle size. (From Dade et. al., 1992; Grabowski et. al., 2011)

![Figure 2.9](image2.png)  
Figure 2.9 Critical shear stress variations with particle size for different beds
Water content is one of the major factors which influences the erodibility of cohesive sediment, because the undrained shear strength and other mechanical properties of a clayey soil are highly dependent upon water content (Gillot, 1987; van Ledden et al., 2004; Winterwerp and van Kesteren, 2004). In fact, these researchers emphasized that the water content, not the bulk density, determines the erosion behavior of cohesive sediments. There is an increase in cohesion or cohesive strength of clay with a decrease in water content (Lambe and Whitman, 1979). Figure 2.10 shows the effect of water content on undrained shear strength of the mud. Lick and McNeil, 2001, found a decrease in erosion rate of up to 100 times with an increase in bulk density for the river sediments while Bale et.al., 2007, showed a 5-8 times increase in erosion thresholds with an increase in density. An increase in erosion threshold or stability of sediment bed with an increase in bulk density was also reported by various other researchers (Bale et.al., 2007; Mitchener and Torfs, 1996; Roberts et.al., 1998). For example, results from Bale et.al. 2007, is presented Figure 2.11.

![Figure 2.10 Relationship between undrained shear strength of IJmuiden mud and water content](Van Kesteren, 2004)
2.5.2 Geochemical factors influencing erodibility

Geochemical factors include clay mineralogy, sodium absorption ratio (SAR), salinity, pH, and organic matter content. Cation exchange capacity is defined as the number of milliequivalents of exchangeable cations per 100 grams of dry soil. Kaolinites have low CEC and are less electro-chemically active and less erodible than illite and montmorillonite (Morgan, 2005; Partheniades, 2007). Flocculation of clay water suspension is enhanced when electrolyte concentration is increased or when lower valence cations in pore fluid of clay are changed to higher valence cations (Verwey and Overbeek, 1948). At low SAR, an increase in CEC reduces thickness of the diffused double layer and increasing bed strength whereas, at high SAR repulsive forces are dominant causing low strength beds (figure 2.12). Furthermore, the clay mineral absorbs more water at a high SAR than at a low SAR, resulting in expansion and dispersion of the minerals which produces high porosity soil and low strength soil (Rowell 1994; Brady and Weil 2001) (Figure 2.13). Similarly, the effect of pH is also significant in sediment stability; low pH values lead to stronger cohesive bonds. High pH results in a decrease in H+ ions leading to a larger double layer thickness (Winterwerp and van Kesteren, 2004).
Figure 2.12 Critical shear stress variation with cation exchange capacity and sodium adsorption ratio (Kandiah, 1974; Grabowski et al., 2011; Winterwerp and van Kesteren, 2004)

Figure 2.13 Critical shear stress variation with sodium absorption ratio and salinity for Illite clays (Kandiah, 1974; Winterwerp and van Kesteren, 2004; Grabowski et al., 2011)
Another factor affecting sediment stability is salinity, which modifies interparticle bonds via enhanced flocculation. Parchure and Mehta (1985), while performing laboratory flume experiments in lacustrine mud, found doubled critical shear stress when salinity is increased up to 2 ppt. Furthermore, the effect of salinity on erosion resistance beyond 10 ppt is virtually negligible. However, Spears et al. (2008) reported a positive effect of salinity on erosion threshold and concluded that most significant effects occur at 35 g NaCl/Kg. Organic matter content is also one of the critical factors affecting the erodibility of soils. A positive correlation was reported between organic matter content and erosion threshold for riverine sediments (Aberle et al., 2004; Gerbersdorf et al., 2007). The stabilizing role of soil organic matter has been supported by various researchers such as Land et al., 2012; Zhang et al., 2005; Chenu et al., 2000; Lick and McNeil, 2001. One possible mechanism for this correlation is that organic matter content affects the inter-particle attraction or adhesion. Evans (1980) defined soil with less than 2% organic carbon or 3.5% equivalent organic content as an erodible soil. Erosion resistance of soil increases linearly when organic content increases up to 10% (Voroney et al., 1981; Morgan, 2005; Brady and Weil, 2002). Furthermore, organic matter content is also correlated positively with the water content but negatively with the bulk density of a cohesive soil (Avnimelech et al., 2001). Therefore, its effects might be influenced by bulk properties of sediments.

2.5.3 Biological factors influencing erodibility

Finally, cohesive soils contain microorganisms (e.g., bacteria, fungi, diatoms, etc.) and their contribution to bioturbation, biostabilization and biodestabilization is noteworthy (Black et al., 2002). Amos et al. (2003 and 2004) described the significance of biogenic stabilization via extracellular polymeric substances (EPS) that act as binding agents to adhere sediment constituent particles together and hence result in an increase in critical shear stress. They found
that a critical shear stress of about 0.5 Pa for lacustrine sediment with a bulk density of less than 1100 kg/m$^3$ is typically due to the presence of biofilms or EPS, as compared to the negligible critical shear stress of a stationary fluid mud with a bulk density of 1100 kg/m$^3$. Based on literature, sediment stabilization mechanism includes physical binding by biological elements, an increase in cohesion due to organic coating and a formation of cohesive matrix (Paterson et al., 1998; Black et al., 2002) and these processes are the result of EPS secreted by benthic organisms.

A striking feature of coastal wetlands is the abundance of live vegetation and hence the associated root system. In fact, root content can also affect the erosional resistance and the rate of erosion, because roots often provide a net-like structure to encompass soil particles. As such, they reinforce a cohesive soil through such a structural network. In addition, roots can take some of the shear stress applied to the soil through tension (Simon et al., 2006), and hence directly strengthen the soil. This typically results in an increase in the erosional threshold. Roots increase the organic content and help the growth of microbial communities. A soil sample with roots can achieve an increased shear strength of at least 500% in clay and sandy clay soils. A clayey soil showed an increment of shear strength up to 850% for a root density of 1.8 g/cm$^3$ (Tengbeh, 1993). He further reported that root-free soils lose shear strength while drying around plastic limit whereas, root permeated soils show increase in shear strength at all moisture contents. This was attributed to continuous effects of reinforcement and adhesion by roots and slower rate of drying due to the presence of roots. Even when the vegetation above the sediment bed surface disappears, the stabilizing effects of roots can’t be ignored (De Baets et al. 2007). In fact, Ghidiey and Alberts (1997) found a notable decrease in erodibility of soil as dead root mass and dead root length increased.
Louisiana’s coastal wetlands are cohesive marshes protected by vegetation cover and roots make significant contribution to the cohesion (Poesen 2006; Vanoni 2006). Howes et al. (2010) identified that high salinity (18-30 ppt) marshes of Louisiana’s coast such as Breton Sound are more resistive to storm erosion than low salinity wetlands due to higher soil strengths provided by more robust and deeper rooting of marsh plants. They presented a conceptual model of soil shear strength along the depth in terms of unvegetated strength and vegetated strength for different salinity marshes (figure 2.14). According to this model, in highly saline marshes roots contribute to the strength profile to a greater depth and the profile shifts toward right. Additionally, the theoretical failure plane shifts deeper than that of the low salinity marshes, which is an indication of improved soil strength and soil resistance to erosion.

![Soil strength model in varying saline marshes (Howes et al., 2010)](image)

**Figure 2.14** Soil strength model in varying saline marshes (Howes et al., 2010)

Taki (2001) explained the bridging effect of roots contributing to the fine sediment resistance against resuspension at high moisture contents. For negatively charged mud particles (d<20-30 μm), various ions and organic matter dispersed in the pore fluid formulate bridging arrays A, B, and C, whereas partially non-contact particles are anchored together by adhesion of fibrous roots.
forming chains of particles (Figure 2.15). Therefore, the bridging forces between non-contact chains of particles generate anchoring forces, which is ultimately responsible for increase in cohesion of a soil matrix.

![Diagrammatic representation of fine sediments configuration](image)

Figure 2.15 Diagrammatic representation of fine sediments configuration (Taki, 2001)

Furthermore, Zhang et al. (2009) conducted consolidated drained triaxial compression tests on soil specimens consisting of loess and roots of *Robinia pseudopacacia* in three different orientations: horizontal, vertical, and a cross vertical-horizontal alignment. They confirmed that plant roots effectively increase soil shear strength by a significant improvement in cohesion. In addition, vertical-horizontal alignment of roots produced the most effective results. Plant roots apparently act as steel rebar as in reinforced concrete in soil-root matrix against shear failure (Thomas and Pollen-Bankhead 2010).

The general conclusion of the above literature is that sediment stability depends on physical, chemical and biological factors which are mutually interdependent. With no two sites being similar, sediment behavior prediction is really difficult for cohesive sediments. Although these factors might be same in all coastal saltmarshes and wetland soils, the dominant factor can be different for all sites. The uncertainties of qualitative and quantitative impact of each factor motivates for further study of cohesive sediment erodibility.
2.6 Effect of oil contamination on soil strength

One of the greatest oil spill accidents, The Deep water horizon explosion occurred on April 20, 2010, in the Gulf of Mexico. This disaster caused a huge amount of crude oil to spew into the Gulf. The ecological components of coastal environments including beaches, coastal saltmarshes, and the biota living in them, and flora and fauna are immediately affected as a result of oil spills. The stabilizing vegetation of the saltmarshes will suffocate and die due to multiple coatings of crude oil. Once the oil has seeped into sediments, roots are exposed to the toxicity of oil, hence halting the growth of plants (Corn and Copeland, 2010). Consequently, saltmarshes become less stable and easily liable for erosion and subsidence under hydrodynamic forces. Even if oil seeps deep into bottom sediments, there are chances of resuspension by wave currents and storm events, potentially indicating the long-term effects of an oil spill. Furthermore, remediation and reclamation of contaminated land requires intensive effort and cost, yet the recovery process is questionable (Corn and Copeland 2010). The application of cleanup methods may require geotechnical evaluation of sediment behavior and properties in soil-oil matrix.

Light hydrocarbons from spilled oil evaporate depending on the type of hydrocarbon and climate conditions (e.g. temperature and wind conditions) while remaining hydrocarbons will permeate into the soil (Gawel, 2006). Oil movement is affected by soil condition, with moist soil conditions permitting more rapid movement than saturated or dry soil conditions. Crude oil intrusion affects soil behavior by (Gawel, 2006):

- Affecting soil structure by sediment coating
- Changing water holding capacity of soil
- Decreasing cation/anion exchanging capacity
- Reducing efficient water and air movement within the soil matrix
Khamehchiyan et al. (2007) did extensive laboratory tests to study the effects of crude oil contamination on the geotechnical properties of clayey and sandy soils. The soil samples were prepared using crude oil content of 2%, 4%, 8%, 12% and 16% by dry weight, and various geotechnical laboratory tests were conducted including Atterberg’s limits, compaction test, direct shear test, uniaxial compression test, and permeability test. The test results showed a decrease in maximum dry density and optimum water content, Atterberg limits (only for the clayey soil sample), permeability, and strength of all soil samples. Similar results were reported by Rahman et al. (2010). Furthermore, cohesion is reduced significantly in clayey soils while the friction angle is increased. Some researchers (Alsanad et al., 1995; Meegoda et al., 1998) noticed an increase in the maximum dry density of up to 4% oil content followed by a decrease in density. Habib-ur-Rehman et al. (2007), found a decrease in cation exchange capacity of 58% for oil contaminated clayey soil. In addition, reduction in strength at low confining pressures is due to a reduction in cohesion which is the result of reduced specific surface area by agglomeration. Some results from Khamehchiyan et al. (2007) study are shown in Fig. 2.16 and 2.17.

Figure 2.16 Variation in dry density of soil samples with oil content (Khamehchiyan et al., 2007)
The major points of soil-oil matrix interactions are:

- The adsorbed water around clay particles is responsible for plastic properties of soil. But, presence of non-polar fluids such as crude oil around soil particles restricts its plastic properties (Gillot, 1987).

- Although reduction in permeability is small even at 16% oil content, this reduction can be attributed to a reduction in pore spaces due to trapped oil (Khamehchiyan et al., 2007).

- Crude oil reduces soil shear resistance by reducing surface contacts and bonding as observed in sand particles by Handy & Spangler (2007). In addition to this, liquid oil impairs the interlocking mechanism as it acts as lubricating agent.

### 2.7 Organic matter effect on sediment aggregation

Organic matter may influence the physical, chemical and biological properties of soils such as: plasticity, shrinkage, compressibility, water holding capacity, and strength of soil (Mitchell and Soga, 2005). Soil organic matter, which is complex physically and chemically, may react and interact with soil in many ways (Oades, 1989). Depending on the state of organic matter, soil properties vary. For instance, decomposed organic matter usually reduces undrained
strength and stiffness of soil due to high water content, whereas organic matter consisting fibers act as reinforcement (Mitchell and Soga). Organic matter largely influences the formation of mud flocs and the stability of the sediment bed in marine environments. Organic matter in coastal mud exists as particulate organic matter and dissolved organic matter. Furthermore, organic matter may originate from within the sediment or from outside the sediment area (Winterwerp and van Kesteren, 2004). Organic substances found in marine sediments can be grouped in three forms (Berner, 1980; Winterwerp and van Kesteren, 2004):

- Polysaccharides and proteins consisting of peptides and amino acid,
- Lipids, cellulose and lignin consisting of aliphatic and aromatic hydrocarbons,
- Humic acids.

Polysaccharides and proteins are flocculating agents; lipids and hydrocarbons are neutral while humic acids are deflocculating agents. Generally organic matter consists of polymers which may be charged or neutral. Charged polymers, also known as poly-electrolytes in the natural environment, do not play significance role as non-ionic polymers. For example, polysaccharides are non-ionic polymers formed by bacteria or algae that can adsorb on mineral surfaces and alter the properties of the minerals and organic matter itself (Winterwerp and van Kesteren, 2004). The absorption to clay minerals occurs via Van der Waals forces, bipolar forces and hydrogen bonding. Bipolar forces are stronger than Van der Waals forces and effective in clay-polymer interaction. According to Hunter (2001) a clay particle may adhere to long polymers, forming loops and tails (Fig. 2.18 from Winterwerp and van Kesteren, 2004) and when another particle attaches to this polymer, it forms strong pairing known as bridging. This results in the formation of 10 to 100 times larger flocs (Gregory, 1985). Clay-polymer interaction is further characterized by the inclusion of water, as water is bipolar in nature.
Flocs are open structures with high water content and the polymeric effect is responsible for clay attachment in flocs (Winterwerp and van Kesteren, 2004). Flocculation of clay particles containing some organic matter increases the aggregate settling velocity significantly (Kranck, 1984; Manning et al., 2011) (Fig. 2.19). This is very important in a coastal environment, where cohesive sediments are often in suspension by waves and currents. Flocculation, which is inevitable in coastal sediments, has prime effects on deposition, erosion, and consolidation rates. Furthermore, particle flocculation is a principle mechanism, which depends on complex interactions between sediments, fluid and flow characteristics, and in particular, particles’ aggregation (Manning, 2004a). Floc sizes (D) range from individual clay particles to several centimeters long stringer-type flocs (Fig. 2.20) and even a single floc may consist of $10^6$ individual particulates (Manning et al., 2011).

Figure 2.18 Diagrammatic representation of polymer adsorbed to a clay particle (Hunter, 2001)

Figure 2.19 Sketch of flocculation and destabilization by adsorbed polymers (Manning et al., 2011), adopted from Gregory, 1978
Arnarson and Keil (2001) emphasized the significance of organic matter and its interaction with minerals for organic material preservation. This is attributed not only to the adsorption of organic matter to minerals but also to the adhering nature of organic matter which acts as a glue between mineral particles (Bock and Mayer, 2000; Arnarson and Keil, 2001; Land et al., 2012; Van Olphen, 1977). Similarly, Chenu et al. (2000) attributed the stabilizing effect of soil aggregates by organic matter to increase in cohesion of aggregates through binding of particles and decrease in wettability of aggregates due to hydrophobic coatings. With an increase in organic matter, microbial activity and consequently EPS and biofilm production and the number of stable aggregates increase (Land et al., 2012; Martens and Frankenberger, 1992). Land et al., (2012) found a linear relationship between fine aggregation percent and organic matter percent (Fig. 2.21). Moreover, sediment aggregation due to organic matter is more effective than the changes in ionic strength because of a rise in salinity. They also attributed increased critical shear strength as observed by Howes et al. (2010) in coastal saltmarsh to the combined binding effect of saltmarsh roots and organic matter. Different modes of particle associations determine the erosional strength of cohesive sediments which may be controlled by surface coating of organic matter (O’Melia and Tiller, 1993; Ravisangar et al., 2005).
Figure 2.21 Variation of Percent fine aggregation with percent organic matter (Land et al., 2012)

An increase in soil organic matter helps to maintain soil pore structure (Dexter, 1988) and mechanical resistance to shear stress and compression (Gupta et al., 1987). According to Dexter (1988) and Gupta et al. (1987) organic matter acts as a mechanical spring in soil against deformation and a matrix for water absorption capacity. In addition, the resilience of soil after the removal of stress is also enhanced (Dexter 1988). Zhang et al. (2005) in a study of the mechanical resilience of degraded soil amended by using peat as an organic matter noticed a decrease in resistance to compression but improved soil pore structure and resilience to mechanical stress.

Overall, the stabilizing effect of organic matters on cohesive sediments in marine environments is one of the major factors contributing to erosional resistance. Its contribution to erosional strength is mainly attributed to the adsorption of organic polymers to minerals and a gluing effect by which a bridging mechanism is developed among particles.
CHAPTER 3 METHODOLOGY

This chapter outlines the methods employed to measure the erodibility of fine sediments in coastal saltmarshes. The chapter begins with site selection and description and the schedule of field visits. This is followed by the measurement of erosion resistance by a cohesive strength meter and the estimation procedure of critical shear stress from raw data. Additionally, there is a description of instrument, and its working mechanism is explained. Finally, in-situ testing and soil sampling and laboratory testing is presented. Laboratory testing includes critical shear stress or erosion threshold measurement by a cohesive strength meter on undisturbed soil samples and standard methods followed to characterize various soil properties.

3.1 Site selection and description

For the investigation of erosion resistance and stability of saltmarshes against waves and currents, two comparable sites in Terrebonne Bay and Barataria Bay were selected for the task (Fig. 3.1), with the following considerations:

- The two sites should have been subjected to comparable hydrodynamic conditions.
- The two sites should be currently affected by severe erosion and land loss.
- The sites must also be accessible with reasonable costs and time (e.g., close to boat launching sites).

Barataria Bay is located between Bayou Lafourche, to the west, and the Mississippi River delta, to the east. The exact location for the test site is in Bay Jimmy with coordinates (29°26’40.23” N, 89°53’19.93” W), as shown in Fig. 3.2. The test site in Terrebonne Bay is close to Cocodrie, Louisiana and its coordinates are (29°13’25.06” N, 90°36’21.4” W) (Fig. 3.3). The ‘pin’ in the map indicates the side and general area around which erosion tests were conducted. At both sites, clear signs of severe marsh edge erosion were observed.
during site visits and field experimentation. In addition, the site in Barataria Bay is also affected by the BP Deepwater Horizon Oil Spill, while the Terrebonne Bay site is a normal saltmarsh. Dark and black layers of crude oil could be easily observed in Barataria Bay at various spots around the edges of the saltmarsh. However, crude oil is almost absent in comparison to the edges as we move offshore to the saltmarsh edge. The vegetation, Spartina Alterniflora or smooth cord grass, is abundant at both sites.

Figure 3.1 Two selected sites for field testing
Figure 3.2 Location of test site in Bay Jimmy

Figure 3.3 Location of test site in Terrebonne bay
3.2 Schedule of site visits and field testing

During the project period, a total of 10 field visits to the two selected test sites were conducted. The activities for each field visit typically included site inspection, visual survey, undisturbed tube soil sampling (using 4 in. diameter aluminum tubes), and critical shear stress measurement by a cohesive strength meter (CSM) (Table 3.1). These field visits were distributed in fall, winter, early spring, spring, and summer over the years 2011 and 2012. However, usually due to the cold or bad weather (e.g., rains) in winter, only one visit was scheduled during winter. Scheduling of site visits was also affected by other factors, such as availability of boats, weather, budget for field work, and research team’s schedule.

Table 3.1: Field visit dates and in-situ activities

<table>
<thead>
<tr>
<th>Date</th>
<th>Site</th>
<th>In-situ activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>09/09/2011</td>
<td>Terrebonne Bay</td>
<td>Site survey and inspection</td>
</tr>
<tr>
<td>09/23/2011</td>
<td>Barataria Bay</td>
<td>Site survey and soil sampling</td>
</tr>
<tr>
<td>12/13/2011</td>
<td>Terrebonne Bay</td>
<td>2 CSM tests and soil sampling</td>
</tr>
<tr>
<td>03/05/2012</td>
<td>Terrebonne Bay</td>
<td>6 CSM tests and soil sampling</td>
</tr>
<tr>
<td>03/26/2012</td>
<td>Barataria Bay</td>
<td>7 CSM tests and soil sampling</td>
</tr>
<tr>
<td>04/18/2012</td>
<td>Barataria Bay</td>
<td>6 CSM tests and soil sampling</td>
</tr>
<tr>
<td>07/06/2012</td>
<td>Terrebonne Bay</td>
<td>7 CSM tests and soil sampling</td>
</tr>
<tr>
<td>07/23/2012</td>
<td>Terrebonne Bay</td>
<td>2 CSM tests</td>
</tr>
<tr>
<td>08/07/2012</td>
<td>Barataria Bay</td>
<td>4 CSM tests and soil sampling</td>
</tr>
<tr>
<td>09/01/2012</td>
<td>Barataria Bay</td>
<td>3 CSM tests and soil sampling</td>
</tr>
</tbody>
</table>

It is worth noting that six of the seven CSM tests conducted on March 26, 2012 in Barataria Bay were directly performed on the weathered residue of heavy crude oil that was on the top surface of the coastal wetland soil. Therefore, these data cannot be used to represent the soil’s erosion resistance. From this lesson, it was realized that the top hard layer of weathered oil residue on soil surface needed to be removed before the erosion testing. However, one of the tests on oil-covered soil surface which showed sufficient light transmission range was used to
estimate the approximate value of critical shear stress, and later it was compared with critical shear stress on a relatively oil-free soil surface or after removing oil layer cover from the soil surface.

3.3 Measurement of erosion resistance

Coastal saltmarshes are of great significance for coastal communities and the overall coastal ecosystem, protecting them from natural catastrophes (e.g. hurricane and storms). The erosion resistivity of these marshes is very important in the investigation of coastal soil erosion and subsidence. In addition, it is of great importance that the measurement of critical shear stress is accomplished in-situ. This will enable a better understanding of factors affecting critical shear stress and precise measurement of critical shear stress. Various devices have been developed to measure the erosion threshold in-situ including Field flumes, Jet-test device, Sea Carousel device, and Cohesive strength meter. For this investigation on coastal soil stability, a cohesive strength meter was used to measure erosion threshold and is described in the chapters below.

3.3.1 Cohesive strength meter

Most of the erosion devices are unable to generate high erosion stress on the stabilized bed (Tolhurst et al., 2002; Vardy et al., 2007) and also their placement on vegetated beds like in the saltmarshes is difficult (Vardy et al., 2007). A high pressure (60 psi) Mark IV cohesive strength meter (CSM) (Partrac, Ltd., UK; Fig. 3.4) was employed to measure the critical shear stress of coastal cohesive soils both in-situ and in the laboratory. The CSM was originally designed by Paterson (1989) and is a compact, light, and portable device. To date, it has been widely used to measure the stability of cohesive sediments because it is simple to operate, and it’s setup and measurement is rapid (Tolhurst et al. 1999; Tolhurst et al.,2000a; Tolhurst et al., 2000b; Friend et al., 2003; Tolhurst et al., 2003; Watts et al., 2003; Vardy et al., 2007).
Once the sensor head, which is connected with an onboard computer through the sensor head cable, is inserted to the sediment surface (Fig. 3.5), and an automatic default test is initiated. During testing, the CSM applies a vertical water jet that strikes the sediment surface with a jet of water from a built-in water reservoir by pressurized air contained in an external air tank. The water jet pressure is increased gradually by the pressurized air inside the tank as the test progresses. The jet characteristics (e.g. jet pulse duration, subsequent pressure increments, and data logging duration) depend on the test type selected and are already predefined. Simultaneously, during jet firing and pressure increments, the optical sensor inside the sensor head at a height of 1 cm above the sediment bed measures the light transmission through the water cylinder with time. Thereafter, this recorded data is used to estimate critical shear stress as explained in Chapter 3.3.2. An important part of CSM testing, the erosion chamber or test chamber consists of an infrared light transmitter and receiver, jet nozzle, and fill tube. The jet
nozzle, which is at a height of 20 mm from the sediment bed, is enclosed in a cylindrical chamber of internal diameter 29 mm. Therefore, the area covered by sensor head is 660 mm². The detail description of test chamber is presented in Figure 3.5. Owing to its unique design, the CSM can measure small-scale spatial and temporal variations in sediment stability quickly (Vardy et al., 2007; Tolhurst et al., 2000a; Tolhurst et al., 2000b; Tolhurst et al., 1999). However, a smaller test section may result in higher critical shear stress if, for example, biofilms are present as some researchers reported for CSM, as compared to other erosion devices, and hence erosion threshold measured with various devices may not be comparable because of differences in operation methodology, definition of erosion threshold, nature of force applied or flow characteristics, and method of calibration (Tolhurst et al., 2000a; Tolhurst et al., 2000b; Widdows et al., 2007).

Figure 3.5 Sketch of sensor head inserted into the soil surface and a real image (right)
In addition, this automated and computer controlled CSM is supplied with twenty-two pulse programs that can be used for various cohesive soils of different cohesive strength and overall forty-one default test programs (coarse tests and fine tests). In fact, the original CSM was developed for the characterization of intertidal mudflats that usually exhibit different critical erosional stress and are susceptible to erosion by waves and tidal currents in coastal environments, and the shear resistance of the mudflat surface is of great importance to the prediction and modeling of coastal cohesive soils (Tolhurst et al., 1999). Depending on the nature of sediments (cohesionless, cohesive or mixed), particular test routines can be used for erosion threshold measurement (Vardy et al., 2007). For example, for less stable beds, test with smaller pressure increment and a relatively long interval logging time can be used. Vardy et al. (2007) during the calibration of CSM with garnet sand used “test fine 1” for grain sizes < 600 µm and used “test sand 9”, a coarse test for grain sizes > 600 µm. Of these various pre-designed testing programs, “Mud 8”, and “Mud 7”, were used frequently for our investigation. However, “Mud 17”, and “Fine 1” were also selected on very few occasions to run the erosional resistance tests. The characteristics of these pre-configured pulse testing programs are as follows:

- **Test Mud 7:**
  - Jet fired for 1.00 s
  - Data logged for 30.00 s
  - Data logged for every 1.00 s
  - Test started at 0.30 psi
  - Incrementing by 0.30 psi per test up to 12.00 psi
Test Mud 8:

- Jet fired for 1.00 s
- Data logged for 30.00 s
- Data logged for every 1.00 s
- Test started at 0.50 psi
- Incrementing by 0.50 psi per test up to 20.00 psi

Test Mud 17:

- Jet fired for 1.00 s
- Data logged for 30.00 s
- Data logged for every 1.00 s
- Test started at 2 psi
- Incrementing by 2 psi per test up to 60.00 psi

Test Fine 1:

- Jet fired for 1.00 s
- Data logged for 3.00 s
- Data logged for every 0.1 s
- Test started at 0.10 psi and incrementing by 0.1 psi up to 2.4 psi
- Incrementing by 0.3 psi from 2.7 psi up to 6.0 psi and by 2.0 psi from 8.0 psi up to 60.0 psi
3.3.2 Determination of critical shear stress

The critical shear stress ($\tau_{cr}$) was obtained from the CSM raw data, which describes the dependence of light transmission (at a percentage) on time. On the same plot, the applied water jet pressure or the horizontal applied shear stress was also plotted against time. Values of the horizontal applied shear stress were calculated from the vertical water jet pressure using the equation given by calibration of Tolhurst et al. (1999):

$$\tau_o (Nm^{-2}) = 66.6734 * (1 - e^\left(\frac{-P}{310.09433}\right)) - 195.27552 * (1 - e^\left(\frac{-P}{1622.56738}\right))$$

where $P$ is the vertical water jet pressure (KPa). This calibration was based on suspension criteria of quartz sands given by Bagnold (1966) and modified by McCave (1971). This was verified visually by using the Shields curve as modified by Miller et al., 1977 for sands movement (Watts et al., 2003; Tolhurst et al., 1999). As illustrated in Fig. 3.6, a sharp drop of light transmission typically marks the onset of erosion of soil particles that are brought to suspension. Two straight lines can be drawn: the first one through the linear portion of points before the start of erosion and the other through the linear points after erosion. The intersection of these two straight lines represents the starting point of erosion. With the corresponding time of this intersection point, the critical shear stress can be located from the applied shear stress vs. time plot. As described by Tolhurst et al. (1999) the transmission curve or erosion profile primarily consists of three parts:

(i) Initial horizontal profile where no or negligible erosion occurs such that sediment concentration is almost zero.

(ii) Slope indicating initiation of erosion and hence drop in light transmission occurs.

(iii) An asymptotic profile where light transmission approaches zero with increasing jet pressure and hence suspended sediment concentration is optimum.
3.4 In-situ testing and soil sampling

The critical shear stress of the coastal cohesive soils in the two selected testing sites was determined by the aforementioned CSM. A brief description of the testing procedures is provided here: first a clean, undisturbed test spot with an area of 4 x 4 inch that is suitable for the CSM test was located. In general, such a spot should be free of visible shells or other sandy grains, and no vegetation should be present within the selected area; second, the sediment surface was slightly cleaned very gently and carefully using a spatula or knife to remove the disturbed top soil or unwanted freshly deposited organic materials. As such, the cohesive soils or muds were exposed with a relatively flat surface. CSM was then prepared for the test with all the relative components connected and afterwards the sensor head was pressed or inserted into the ground at
the prepared test spot. To prevent the change in the critical shear stress caused by water salinity and chemistry, site water was always used in the built-in water reservoir. After the completion of each test, the sensor head was cleaned properly and the whole system was flushed before starting another test. Fig. 3.7 shows an in-situ CSM test being performed in the Terrebonne Bay site.

Figure 3.7 An in-situ CSM test being performed in the Terrebonne Bay site

As pointed earlier, the critical shear stress is affected by many different factors of physical, chemical, and biological origins. The in-situ CSM tests can yield the critical shear stress directly; however, other important soil properties cannot be obtained. In addition, in-situ CSM tests can only obtain the critical shear stress of the top surface layer of the in-situ soil, but not of the soils in the vegetation root zone or other depths. Therefore, undisturbed soil samples (Fig. 3.8) were also obtained using 4 in. diameter and 3 ft long vibacore, thin-walled aluminum tubes for subsequent laboratory testing (soil properties and CSM testing).
In addition to the tube samples, other disturbed samples were also obtained for the measurement of organic matter content and/or root content on each in-situ CSM test spot. Soil material adjacent to the test spot was taken from a depth of up to 2 inch and then stored in ziplock bags. On the April 18, 2012, six CSM tests were conducted in Barataria Bay site at three different spots. At each spot, two tests were conducted and disturbed soil samples were collected in order to measure the organic matter content and investigate its effect on sediment stability. Similarly, during the August and October, 2012 visits to Barataria Bay, disturbed soil samples were collected to measure organic matter and/or pore water salinity. On the July 6, 2012 visit to the Terrebonne Bay site, disturbed samples were also collected for each of the CSM test sites (Table 3.1) for the measurement of organic matter content and root content. Disturbed soil samples from the July 23, 2012 visit to Terrebonne Bay site were used to measure water content and organic matter content.
3.5 Laboratory testing

Laboratory testing was mainly conducted on the undisturbed tube samples collected from the two test sites. Although the sample tube length was 3 ft, usually the recoverable soil samples that extruded from each tube were approximately 2 – 2.5 ft. The tubes were all cut into 3 inch long sections for different types of laboratory testing (Fig. 3.9). During sample tube cutting, optimum attention was paid to ensure minimum vibrations and sudden jerks so that the soil is undisturbed.

![Diagram showing preparation of tube sample for CSM testing in the laboratory](image)

In total four types of tests were performed usually on each tube sample.

- CSM testing: for each sample section cut from the parent tubes, the soil material that was disturbed by cutting (usually with a handsaw) was first removed and saved for water content and organic matter content measurement. Each section was also equivalent to a depth below the ground surface, and thus the vertical critical shear strength profile along depth could be obtained. For each cut section, generally two CSM tests were performed and their average was taken to represent the critical shear stress at that depth (Fig. 3.10).
Physical index testing: In addition to the water content and organic matter content measurements on each cut section, Atterberg limits (including both liquid limit and plastic limit) measurements were also conducted on each sample tube, which usually require soil material from several cut sections. After CSM testing, soil was extruded from each cut section and mixed to achieve homogenization. Then the composite samples mixed from the entire 3 ft long tube were used for the determination of Atterberg limits, specific gravity, and particle size distribution. All these physical index tests were performed by following relevant ASTM standard methods.


Root content measurement: Root content was determined for each 3 in long section cut from the vibracore tubes, which means that root content was measured for different soil layers at a vertical spacing of 3 in. Since root content measurement is not currently included in the ASTM standards, the following method was adopted: First, a representative portion of soil sample was air-dried to obtain the total dry weight of the soil. Then this same material was washed (i.e., wet sieving) through two sieves with a mesh size of #30 and #40 to separate roots from soil (Fig. 3.11). After washing and wet
sieving, the roots were air-dried to obtain their dry roots. Finally, the root content ($R_C$) was calculated via the following formula:

$$\text{Root content } (R_C) = \frac{\text{Mass of dry roots } (M_R)}{\text{Mass of soil solids } (M_S)}$$

Figure 3.10 Running cohesive strength meter test on small 3 inch soil sample tube

Figure 3.11 Washing in sieves to separate roots from soil
Pore-water salinity and pH: a salinity refractometer and a benchtop pH meter were used to measure pore water salinity and pH. The common requirement for both tests is the extraction of pore-water from the soil sample which is achieved by spinning soil samples in vials in a centrifuge (Fig. 3.12(a) and (b)). Once the pore-water is separated, the salinity refractometer, which is calibrated to grams NaCl / 100 grams H$_2$O, is used to measure salinity (Fig. 3.13(a)), while a benchtop pH meter calibrated against two buffers of pH 7 and pH 10 is used to measure pH (Fig. 3.13(b)).

Figure 3.12 (a) Centrifuge for separating soil and pore water (b) extracted soil pore water
In summary, laboratory testing on thin-walled tube samples of 3 ft in length can yield the following soil properties along a depth of 2-3 ft: critical shear stress, water content, organic matter content, root content, and pore water salinity for few samples, and liquid limit, plastic limit, specific gravity, and particle size distribution for each sampling sites.
CHAPTER 4 RESULTS AND ANALYSIS

This chapter presents the overview of the results of erosion tests performed in Barataria and Terrebonne Bay and in soil samples in the laboratory. The erosion threshold values along with soil index properties of each site are analyzed and discussed. Furthermore, correlations between organic matter content or root content and critical shear stress are presented.

4.1 Terrebonne Bay site

4.1.1 In-situ testing

In-situ testing (3/5/2012)

Most in-situ CSM tests were only performed on the soil surface, and the results obtained are just the critical shear stress of sediment surface. However, one attempt was made to run in-situ CSM tests over a limited depth in order to characterize the erosion resistance of marsh soils at different depths (the 3/5/2012 field visit). The results of such an attempt were shown in Fig. 4.1, where the critical shear stress at the Terrebonne Bay site increases from 0.6 Pa at the surface to 1.02 Pa at a depth of 0.15 m, and then decreases to 0.66 Pa at a depth of 0.25-0.30 m. This profile is consistent with the field observation that the eroded marsh edge usually exhibits a stepped pattern (Fig 4.2). The increased erosion resistance reflects that the soil has a higher undrained shear strength at the depth of 0.15-0.20 m. This depth is typically where the roots of vegetation prevail and grow. The transevaporation of marsh plants require water from the roots, which in turn absorbs water from the surrounding soil. As such, the high intake of water by the roots from the soil helps consolidate the soil around the roots; thus the undrained shear strength of soil increases. However, at a depth below the root zone, the soil is not as affected by roots’ water intake, and hence the soil is not consolidated as much as the soil within the root zone, resulting in a lower soil shear strength.
In-situ testing (7/6/2012)

In a separate field experiment, seven CSM tests were performed at four different spots along a transect perpendicular to the shoreline at the same site in upper Terrebonne Bay together with the subsequent laboratory measurements of organic matter content and root content. Results
are shown in Fig. 4.2 and 4.3. These tests were conducted in the summer season, and the vegetation at this time was fully mature and much denser than that of the previous field tests. Freshly deposited sediment, organic matter, and sea shells that were probably brought to the site by storms were observed on the wetland surface.

![Graph](image1.png)
Figure 4.3 Variation of critical shear stress with organic matter content at Terrebonne Bay

![Graph](image2.png)
Figure 4.4 Variation of critical shear stress with root content at Terrebonne Bay

Usually, a certain range of organic matter content can be positively correlated with the critical shear stress. An organic matter content between 8 to 10% was found to result in a critical
shear stress of >1.0 N/m² and beyond 10% it reduces the critical shear stress significantly (Fig. 4.3). This range is quite similar to that observed in the core samples (as discussed later). Overall, there exists a positive correlation between organic matter content and critical shear stress when the organic matter content is <10%. Beyond 10%, the organic matter tends to decrease the stability of marsh soil. Also, for the examined distance (~10 m), the organic matter content is found to increase along the distance away from the shoreline. The critical shear stress was also found to correlate positively with the root content (Fig. 4.4).

The variation of the critical shear stress along the distance landward from the shoreline is shown in Figure 4.5. Except the first point at a distance of about 2 m, the critical shear stress in general decreases with the landward distance from the marsh edge. This is possibly true because the area near the marsh edge (e.g., within a distance of 0-8 m from the shoreline toward the marsh) has the highest elevation due to deposition that is encouraged by vegetative entrapment of sediment. A debris line parallel to the marsh edge is often seen in the field, which is the footprint of flooding and wave action.

![Figure 4.5 Variation of critical shear stress along the perpendicular distance to the shoreline](image)

Figure 4.5 Variation of critical shear stress along the perpendicular distance to the shoreline
**In-situ testing (7/23/2012)**

During this site visit, two CSM tests were performed, together with subsequent laboratory measurements of water content and organic matter content. Results are shown in Figs. 4.6 and 4.7. The water content at the two tested spots was 55.12% and 58.93%, while the organic matter content was 3.43% and 4.09%. The variation of water content can be considered negligible as compared to the organic matter content, because of the large range of variation in water content that usually exists in coastal wetlands. As such, the organic matter content increases with water content, and the critical shear stress also increases with organic matter content. A positive correlation between critical shear stress and organic matter content can be observed in Fig. 4.6. As stated earlier, a positive correlation can be observed between critical shear stress and organic matter content when organic matter content < 10%. Notice that the range of organic matter content from this visit is below 5%, thus supporting the aforementioned idea that an appropriate range of organic matter content can enhance sediment stability.

![Figure 4.6 Variation of critical shear stress with organic matter content](image)
Summary of in-situ testing results

A total of seventeen in-situ CSM tests were conducted in the Terrebonne Bay site, thirteen of which were performed on the surface sediment. The results of these thirteen tests are plotted in Fig. 4.8. Significant variations can be observed. The critical shear stress ranges from 0.45 Pa to 2.2 Pa, and the average is 1.15 Pa.
4.1.2 Laboratory testing

In addition to in-situ measurements of the critical shear stress for wetland soil erosion, un-disturbed soil samples were taken to the laboratory for further testing. The results from the laboratory testing on all undisturbed tube samples are presented here. Usually, two CSM tests were performed on 3 inch sampling units and critical shear stress was averaged to get representative erosion threshold for each unit.

Laboratory testing (12/13/2011)

Figures 4.9, 4.10, and 4.11 show the changes in the critical shear stress with depth along with the water content, organic matter content, and root content, respectively. It was found that the critical shear stress initially increases slightly with depth and, below the depth of 0.38 m, decreases with depth (Figure 4.9). This trend was also observed from the in-situ testing result (Figure 4.1). A similar mechanism can be envisioned to explain the change of critical shear stress with depth. At a depth less than 0.3–0.4 m, roots are prevalent, and the evapotranspiration of vegetation causes the roots to take in water from the surrounding soil.

The removal of water by roots helps consolidate the soil, leading to an increase in shear strength. For the soil at depths below 0.4 m, the roots are usually absent and thus the soil strength is low. The variation of water content with depth does not follow a specific pattern, but its value at various depths is generally greater than that on the marsh surface. Up to a depth of 0.10 m, there is a large decrease in water content and an increase in erosion resistance. For the next 0.13 m, there is a continuous and significant increase in water content, but the erosion resistance and critical shear stress increases slightly. This is due to the fact that water content is not the only factor affecting the soil’s erosion resistance. Furthermore, below the depth of 0.3 m, the water
content is almost constant at about 150%, but the erosion resistance decreases significantly from 1.2 Pa at a depth of 0.30 m to 0.29 Pa at a depth of 0.53 m.

As shown in Fig. 4.10, if the entire plot is analyzed, the soil’s erosion resistance does not seem to be correlated with the organic matter content. According to the literature (e.g., Brady and Weil, 2002; Morgan, 2005), a positive correlation usually exists between a soil’s erosion resistance and organic matter content when the latter falls in a range 0 to 10%. For the wetland soils in the upper Terrebonne Bay site, an organic matter content of 7 to 10% can have positive impact on sediment stability. This range of organic matter content maintained a critical shear stress greater than 1.0 Pa. Furthermore, the variation of organic matter content from 7 to 10% does not cause a significant variation in critical shear stress, possibly indicating that this range of organic matter content is the optimum range that most enhances sediment stability. Finally, the organic matter content is found to depend upon water content and, whenever the water content increases, the organic matter content also increases. Beyond 10% organic matter content, there is a significant decrease in the soil’s erosion resistance.

The wetland soil’s erosion resistance is also affected by root content. As shown in Figure 4.11, the critical shear stress increases with root content. However, at very shallow depth of 0 to 0.1 m, the two parameters doesn’t appear well correlated. Possible reasons for this may be that the root content at this shallow depth cannot be accurately measured, and the soil is just freshly deposited; hence a coherent integration of soil and roots has not been established (i.e., the roots cannot play its role of reinforcement in the soil). Another possibility is that the water content and/or organic matter content are the major parameters affecting sediment stability at very shallow depths. Interestingly, at depths greater than 0.3 m, the critical shear stress line becomes parallel to the root content line, indicating that root content greatly affects sediment stability.
Figure 4.9 Variation of critical shear stress and water content with depth

Figure 4.10 Variation of critical shear stress and organic matter content with depth
Laboratory testing (3/5/2012)

The variation of critical shear stress, water content, organic matter content and root content along the depth are shown in Figures 4.12, 4.13 and 4.14. As mentioned before, water content at a depth is slightly greater than that at the sediment surface, and water content variation closely followed the organic matter content variation (Fig. 4.12 and 4.13). Up to a depth of 0.15 m, water content is negatively correlated with critical shear stress; however, below this depth positive correlation was found. Contrastingly from the results of December, 2011, organic matter content even in the range of 7 to 10% does not show positive correlation with critical shear stress. In fact, critical shear stress dropped significantly at depths 0.2 to 0.3 m and 0.4 to 0.5 m despite organic matter and water content being in their usual ranges. The probable reason for this may be a substantial decrease in root content, as low as 1.2% (Fig. 4.14) and/or organic matter (roots, rhizomes) at aforementioned depths were decomposed which apparently led to higher
organic matter content but lower root content. Hence, the impact of root content on erodibility cannot be neglected and cohesive sediment stability may depend on more than one parameter.

Figure 4.12 Variation of critical shear stress and water content with depth

Figure 4.13 Variation of critical shear stress and organic matter content with depth
Laboratory testing (7/6/2012)

The results of this laboratory testing show that at shallow depths the erosion threshold is on the lower side due to high water content and organic matter content greater than 10% (Fig. 4.15 and 4.16). As expected, a positive correlation is observed between erosional resistance and root content and organic matter content (Fig. 4.16 and 4.17). Furthermore, pore water salinity was measured along the depth, which was found to increase marginally with depth from 23 ppt at surface to 27 ppt at a depth of 0.40 m (Fig. 4.18). This range of pore water salinity is higher than that observed in Barataria Bay which is around 15 ppt. Although there is an increment in critical shear stress with depth, that may not be solely contributed by an increase in salinity because both root content and organic matter content are also strongly correlated. Howes et al. (2010) reported higher erodibility of lower saline wetlands due to shallow rooting. Therefore, a higher erosion threshold at the surface in Terrebonne Bay might also be contributed to higher salinity.
Figure 4.15 Variation of critical shear stress and water content with depth

Figure 4.16 Variation of critical shear stress and organic matter content with depth
Figure 4.17 Variation of critical shear stress and root content with depth

Figure 4.18 Variation of critical shear stress and pore water salinity with depth
Overall conclusions of laboratory testing are:

- Basically, water content showed a negative correlation with critical shear stress at shallow depth (up to 0.15 m); however, at higher depth it is positively correlated with organic matter content and hence, depending on the range of organic matter content positive correlation with critical shear stress may exist.

- Organic matter content is positively correlated with critical shear stress and hence with sediment stability. However, organic matter content greater than 10% is found to reduce erosional resistance of wetland soil.

- Root content is also a major parameter influencing the cohesive sediments’ stability which basically improves erodibility.

- Generally in cohesive sediments, the integrative contribution of several parameters influences the sediment stability. Therefore, their collective contribution is noteworthy.

4.2 Barataria Bay site

4.2.1 In-situ testing

In-situ testing (3/26/2012)

During this visit six CSM tests were run directly on the crude oil surface and two CSM tests on a reasonably oil-free or no-oil sediment surface. The crude oil layer was virtually dry and solid but relatively soft (Fig. 4.19). Data for five tests out of six tests, where the ‘Mud 8’ test was used, showed that there is no significant fall in light transmission, indicating that the initiation of erosion is prevented by the presence of a thick layer of oil (Fig. 4.20). In addition, the credibility of CSM use on oil contaminated sediments is questionable. Despite that, a higher pressure test, ‘Mud 17’ was used once on such an oily surface which showed significant increase in soil resistance with an erosion threshold as high as 4.18 Pa (Fig. 4.22). Finally two tests
conducted on a relatively non-oily surface showed a significant decrease in the erosion threshold (Fig. 4.21 and 4.22). The effect of oil contamination on erodibility of coastal sediments will be discussed in Chapter 4.4.

In-situ testing (4/18/2012)

Fig. 4.23 shows the variation of critical shear stress and organic matter content at the tested spots. It appears that the critical shear stress is not always positively correlated with organic matter content. As discussed earlier, there exists a range of organic matter content at
which a soil’s strength can be increased. Beyond this range, a soil might become more prone to erosion. For this site, the organic matter content normally ranges from 20% to 40%. When organic matter content is greater than 35%, the critical erosion stress decreases below its average value (i.e., <1.22 Pa) (Fig. 4.23). Higher values of organic matter content in Barataria Bay are due to the entrapped oil in the sediment pores. During organic matter testing, heating of soil samples at 440°C produced large volume of smoke.

In-situ testing (8/7/2012)

In this in-situ testing, critical shear stress was measured at three different spots along the transect perpendicular to the shoreline similar to the testing performed in Terrebonne Bay. The test site at this time of year was characterized by the presence of mature and dense vegetation. Critical shear stress was found to increase substantially around 7-8 m from the shoreline (Fig. 4.24), which was also observed for Terrebonne Bay. During field observations, this area was typically found to have the highest elevation due to sediment and debris deposition brought to
the site by waves. This mainly results in the quick drainage of soil surface during wetting, and which ultimately increased the sediment density around the area. In addition, organic matter content at this distance is the highest among the three spots. Finally, a positive correlation between critical shear stress and organic matter content is also maintained for these test results.

**In-situ testing (10/1/2012)**

This site visit was held after Hurricane Isaac hit the Gulf of Mexico in late-August 2012. Significant wetland soil was lost due to erosion and subsidence. The saltmarsh edges (marked with red in the figure) which were used for testing during earlier visits were drowned completely (Fig. 4.25). The image before Hurricane Isaac was taken late-March 2012. The results show that the pore water salinity is nearly equal at each spot, and correlation between organic matter content and critical shear stress is positive when organic matter content less than 35%, which is consistent with previous results (Fig. 4.26).
Summary of in-situ testing results

Results from all in-situ tests conducted at the Barataria Bay site were averaged and only the average data are presented in this section. In total, fifteen in-situ CSM tests were performed on the sediment surface at this site, and the obtained critical shear stresses are plotted in Fig. 4.27. The range of these critical shear stresses is from 0.4 Pa to 2.0 Pa, with an average of 1.02 Pa. Compared with the results from the Terrebonne Bay site, the critical shear stress at the Barataria
Bay site shows a smaller variation (e.g., 0.4-2.0 Pa vs. 0.45-2.2 Pa) and a smaller average (e.g., 1.02 Pa vs. 1.15 Pa). Therefore, the marsh soil in the Barataria site may be more vulnerable to erosion than the marsh soil at the Terrebonne Bay site.

4.2.2 Laboratory testing

Laboratory testing (9/23/2011)

Figures 4.28-4.30 show the variations of critical shear stress, water content, organic matter content and root content with depth. Except at shallow depth (< 0.15 m), water content and organic matter content variations with depth run fairly parallel, maintaining a positive correlation with each other. At shallow depth (e.g. on the surface), oil contamination is high which often leads to incorrect water content and organic matter content measurement. Nevertheless, both of these variables show positive correlation with critical shear stress (Fig. 4.28 and 4.29). Again, as observed in the laboratory testing of Terrebonne Bay, it is hard to correlate critical shear stress and root content at shallow depth but positive correlation is
maintained at depth. Notably the erosion threshold and root content of Barataria Bay along the depth is on a higher side than that of Terrebonne Bay.

Figure 4.28 Variation of critical shear stress and water content with depth

Figure 4.29 Variation of critical shear stress and organic matter content with depth
Laboratory testing (3/26/2012)

The results of this testing indicate that all the four parameters: critical shear stress, water content, organic matter content and root content show positive correlation with each other except at shallow depth (Figs. 4.31, 4.32, and 4.33). Remarkably, water content at the surface is very low, around 28%, and organic matter content at 0.08 m depth is approximately 55%. Clearly, true measurement of soil properties in oil contaminated soil is very difficult, especially at the surface. Moreover, measurements of water content and organic matter content are overestimated because of the crude oil that has seeped into the sediment pores. Critical shear stress is greater than 1.0 Pa throughout the depth; however at shallow depth (< 0.15 m) this value is around 1.5 Pa (Fig 4.31). Ignoring a few peak values, the range of organic matter content for Barataria Bay is generally between 15 to 40% (Figs. 4.29, 4.32, 4.35, 4.38, and 4.41) and positive correlation exists with critical shear stress when organic matter content is less than ~ (30-35%).
Figure 4.31 Variation of critical shear stress and water content with depth

Figure 4.32 Variation of critical shear stress and organic matter content with depth
Laboratory testing (4/18/2012)

The results of this testing (Fig. 4.34 – 4.36) are contrasting to the results of the above two laboratory testings. As presented in Fig. 4.34 and 4.35, both water content and organic matter content are negatively correlated with critical shear stress over the entire testing sample depth. However, root content is positively correlated with critical shear stress over the same depth. Therefore, this result has two significances:

- Firstly, root content is also a major parameter influencing the stability of wetland soil and hence dominated the overall erosional resistance of coastal cohesive sediments.
- Secondly, the contribution of true organic matter and crude oil to the organic matter content is important for deriving a rigid correlation or conclusion when sediments are contaminated with oil.
Figure 4.34 Variation of critical shear stress and water content with depth

Figure 4.35 Variation of critical shear stress and organic matter content with depth
Data for root content along the depth is not available for this testing. Nevertheless, Fig. 4.37 and 4.38 show the variation of critical shear stress, water content, and organic matter content along the depth. Positive correlation between water content and organic matter content and their positive correlation with erosion threshold or critical shear stress is clearly noticeable. In addition, pore water salinity was measured along the depth for this sample which ranged from 14 ppt to 16 ppt and showed a positive correlation with critical shear stress as presented in Fig. 4.43(a). This probably indicates that the pore water salinity is also an important parameter influencing the erosional resistance of saltmarsh sediments as it substantially assists sediments’ aggregation. Various researchers (Parchure and Mehta, 1985; Spears et al. 2008; Howes et al. 2010) emphasized the positive effect of salinity on stability of cohesive sediments.
Figure 4.37 Variation of critical shear stress and water content with depth

Figure 4.38 Variation of critical shear stress and organic matter content with depth
Laboratory testing (10/1/2012)

As aforementioned, this field visit was held after Hurricane Isaac, 2013. Due to considerable marsh edge erosion and land subsidence, the sample taken in the field was virtually extracted at a greater distance from the original marsh edge. The sampling area was mostly dark, with little decaying vegetation indicating the presence of high organic matter content (Fig 4.39).

![Figure 4.39 A typical surrounding of sampling area](image)

The results show that the organic matter content and water content lines are parallel to each other, showing a strong correlation (Figs 4.40 and 4.41). Notably, organic matter content increased gradually with depth, from 27% at the surface to 49% at 0.4 m depth, whereas critical shear stress relatively decreased with depth owing to negative effect of high organic matter content on sediments’ erosional resistance. The presence of high organic materials in the soil is also supported by a very high liquid limit (109.60%) and plastic limit (80.97%) as compared to the average liquid limit (68%) and plastic limit (43%) obtained from the four previous field visits. Furthermore, the correlation between critical shear stress and root content is not clear (Fig. 4.42). The possible reason may be that the roots in highly organic soils cannot hold sediments together. In other words, roots cannot provide a network-like structure and hence they do not facilitate effective reinforcement. Salinity along the depth also decreased for this soil sample.
from 20 ppt to 15 ppt showing positive correlation with critical shear stress (Fig 4.43a). But this range of salinity is greater than that observed for the August 2012 sample (Fig 4.43b).

Figure 4.40 Variation of critical shear stress and water content with depth

Figure 4.41 Variation of critical shear stress and organic matter content with depth
Figure 4.42 Variation of critical shear stress and root content with depth

Figure 4.43 (a) Pore water salinity variation of August 2012 sample and (b) October 2012 sample with depth along with respective critical shear stress
4.3 Correlation between erosion threshold and soil properties

4.3.1 Critical shear stress and organic matter content

According to the literature (e.g., Brady and Weil, 2002; Morgan, 2005), a positive correlation usually exists between a soil’s erosion resistance and organic matter content when the latter is from 0 to 10%. However, Righetti and Lucarelli (2007) reported that 12-14% of organic matter content is an optimum content with adhesive effects. Various researchers (Zhang et al., 2005; Howes et al., 2011 and Land et al., 2012; Gerbersdorf et al., 2007) also reported the positive effect of organic matter content on soil strength and stability. Land et al., 2012 found an increase in % fine aggregation with organic matter content.

Critical shear stress and organic matter content of various tube samples from Terrebonne Bay are plotted together as shown in Fig 4.44. There exists a positive correlation between critical shear stress and organic matter content (OMC). Significant increase in critical shear stress was observed for Terrebonne Bay samples when the OMC is < 10%. The basic reason for a positive correlation may be the resulting particle aggregation of cohesive sediments due to adsorption of organic matters to clay minerals via Van der Waals and bipolar forces, and the bridging effect of organic matters acting as glue between fine particles. However, organic matter may not always increase the sediments’ erosional resistance. Figure 4.45 presents the negative effect of OMC on cohesive sediment’s stability causing decrease in critical shear stress when OMC > 10%. This decrease in critical shear stress may be attributable to the fact that a high OMC corresponds to the presence of high water content which consequently reduces the soil shear strength and soil stiffness. Additionally, soil with high OMC is likely to have greater proportion of decaying organic matter, which generally does not improve soil strength and stability. On the other hand results from Barataria Bay do not support a positive correlation between critical shear stress and
OMC (Fig. 4.46). As mentioned in Sections 4.2.1 and 4.2.2, the OMC in Barataria Bay is usually overestimated due to the presence of oil contaminated sediments. In addition, the non-uniform distribution of oil over the entire test site results in erroneous OMC. Consequently, correlation between critical shear stress and OMC is not coherent.

Figure 4.44 Critical shear stress variation with organic matter content when OMC < 10%

Figure 4.45 Critical shear stress variation with organic matter content when OMC > 10%
4.3.2 Critical shear stress and root content

Root content present in the soil has a significant soil stabilization effect. Baets et al., (2007) and Ghidey and Alberts (1997) reported a decrease in erodibility even with an increase in dead root mass and length. Tengbeh (1993) found an increase in shear strength by 850% for a root density of 1.8g/cm$^3$. Furthermore, plant roots act in a similar way to a rebar in concrete mass acting against shear failure (Thomas and Pollen-Bankhead 2009).

The effect of root content on critical shear stress from the two sites is presented in Fig. 4.47. Clearly both parameters are positively correlated with each other. Critical shear stress was found to increase even up to 6% of root content. Erosion threshold can increase by more than two times when root content increases from 1% to 6%. Note that the measured root content in the present context is apparently not associated with live vegetation. In fact, they are free and dead roots. The relatively weaker correlation (Fig. 4.47) appears reasonable, because the root content was measured over 3 in depth while the erosion threshold was usually measured on surface. Figure 4.48 presents the average critical shear stress and corresponding average root content of seven
sampling tubes from the two sites. The positive effect of root content on sediment stability is clearly observable. Furthermore, the linear trend line is plotted as presented in Figure 4.49.

Figure 4.47 Critical shear stress variation with root content

Figure 4.48 Average critical shear stress and root content per sample tube with standard error
So far, the effect of roots on soil stabilization has been investigated in terms of critical shear stress. In order to have further insight into the mechanism of the stabilizing effect of roots on the stability of saltmarsh sediments through particle aggregation and adhesion, electron microscope images were also observed. The observation of these images supported the reinforcing effect of roots to the surrounding soil. Fine soil particles were found to attach around the root surface. In fact, particle aggregates were also observed along the root surface, clearly indicating that roots assist particle aggregation around their peripheral (Fig. 4.50 and 4.51). This bridging effect is mainly responsible for the increase in critical shear stress and undrained shear strength of saltmarsh sediments. Taki (2001) also reported the positive effect of roots on sediment stability which provide anchorage to partially non-contact particles forming the chains of particles (bridging effect).
Figure 4.50 Particle aggregation around root fiber

Figure 4.51 Adhering of fine particles around root fiber
4.3.3 Water content and organic matter content

In most of the laboratory and in-situ testing, positive correlation was found to exist between critical shear stress and water content, and water content and organic matter content. Linear regression analysis was used between water and organic matter content, and expectedly positive correlation was observed (Fig 4.52 and 4.53). Usually, the clay and organic matter interactions are characterized by the adsorption of water, as water is bipolar in nature and the strong positive correlation between organic matter and water content supports this statement. Moreover, the effect of water content on erosion threshold, which normally should be negative, is not evident when organic matter improves the sediment erodibility. For instance, as shown in Figure 4.54, positive correlation between critical shear stress and water content was observed for Terrebonne Bay for OMC < 10%. Generally, the increase in water content has a negative effect on undrained shear strength and hence on the erosional resistance of soil but above results show that the effect of other soil properties may dominate the effect of water content.

![Graph showing relationship between water content and organic matter content.](image)

Figure 4.52 Relationship between water content and organic matter content in Barataria Bay
Figure 4.53 Relationship between water content and organic matter content in Terrebonne Bay

\[ y = 12.47x + 23.95 \]
\[ R^2 = 0.73 \]

Figure 4.54 Critical shear stress variation with water content in Terrebonne Bay

\[ y = 0.01x + 0.19 \]
\[ R^2 = 0.65 \]

4.4 Effect of oil contamination on sediment erodibility

This study includes the field observations of the characteristics of sediments which are contaminated with oil in Barataria Bay. During frequent site visits over spring, summer, and fall,
various spots affected with crude oil were observed. Depending on the conditions of various such spots, the effect of crude oil spill on sediment erodibility is categorized in two parts:

(1) Decreasing sediment erodibility by acting as a sediment blanket.

(2) Increasing sediment erodibility once dried and disintegrated.

The first stage when the oil blanket is dry and relatively hard, it acts as a cover for sediments. It is difficult for a water current to infiltrate the oil cover (Fig. 4.55). As explained in Chapter 4.2.1, the erosion threshold is also high in such case (although, the use of CSM is questionable on such a surface). However, during the same period, oil infiltration into sediment pores affects the biological growth of vegetation and plant roots. Thus initially, the oil cover may act as a protective layer in terms of erosion threshold, but it affects plants biologically.

The second stage is the result of vegetation dying by oil intrusion and sediment-oil surface drying. Based on field observations, the destabilizing effect of oil intrusion can be divided into four different stages as shown in Fig. 4.55-4.58. The weathering and disintegration of the dried surface is followed by the formation of number of small eroding spots which gradually spread out under the effect of hydrodynamic forces. Finally, these weak spots assist heavy surface and undercut erosion once the erosion driving forces crosses the critical shear stress of soil.

![Figure 4.55 Vegetation dying and drying of crude oil surface](image)
Figure 4.56 Formation fluffy layer by disintegration of dried oil blanket

Figure 4.57 Formation and spreading of weak eroding spots by mild surface erosion

Figure 4.58 Heavy surface and undercut erosion
4.5 Comparison between soil properties of Barataria Bay and Terrebonne Bay sites

Tables 4.1 and 4.2 compare the physical properties and critical shear stresses for the soil from the two sites, respectively. The soil in Barataria Bay has relatively larger mean particle size and smaller specific gravity, but higher plastic and liquid limits, indicating that the soil in this site has more organic matters than the Terrebonne Bay site. The higher organic matter content in Barataria Bay may be caused by the presence of oil spill contamination. The direct organic matter content measurement (Table 4.2) validates this observation.

Table 4.1: Physical properties of soils in the two sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean particle size (mm)</th>
<th>Specific gravity</th>
<th>Liquid limit (%)</th>
<th>Plastic Limit (%)</th>
<th>Plasticity index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barataria Bay</td>
<td>0.092</td>
<td>2.29</td>
<td>68.58</td>
<td>43.18</td>
<td>25.39</td>
</tr>
<tr>
<td>Terrebonne Bay</td>
<td>0.070</td>
<td>2.54</td>
<td>57.73</td>
<td>28.53</td>
<td>29.21</td>
</tr>
</tbody>
</table>

As shown in Table 4.2, the surface soil at the Terrebonne Bay site has a slightly greater critical shear stress than the surface soil at the Barataria Bay site, but the deep soil in the former has a much smaller critical shear stress than the latter. These results are also shown in Figs. 4.59 and 4.60. Since wetland erosion usually initiates at the sediment surface, the Terrebonne site is more stable than the Barataria Bay site. However, the below-surface soil in Barataria Bay has a higher critical shear stress than that in Terrebonne Bay, suggesting that the latter site is more prone to the undercut-type erosion. In fact, during field visits, it was observed that the Terrebonne Bay site had places where undercut erosion was undergoing. Finally, as mentioned previously, the Barataria Bay site has some very weak spots that are much less stable than the Terrebonne Bay site. These weak spots may be affected by the oil spill, and hence are more prone to erosion. In summary, if the two sites are subjected to the same hydrodynamic erosional
driving force, the sequence of erosion will be: 1) surface erosion in the weak area in Barataria Bay; 2) undercut erosion in Terrebonne Bay; 3) surface erosion in the weak area (if any) in Terrebonne Bay; 4) general surface erosion in Barataria Bay; 5) general surface erosion in Terrebonne Bay; and 6) undercut erosion in Barataria Bay.

Table 4.2: Critical shear stress, root content, and organic matter content of two sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Average in-situ critical shear stress (N/m²)</th>
<th>Average sample tube critical shear stress (N/m²)</th>
<th>Average sample tube critical shear stress on surface (N/m²)</th>
<th>Average organic matter content (%)</th>
<th>Average root content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barataria Bay</td>
<td>1.02</td>
<td>1.25</td>
<td>0.778</td>
<td>21.9</td>
<td>4.0</td>
</tr>
<tr>
<td>Terrebonne Bay</td>
<td>1.15</td>
<td>0.88</td>
<td>0.780</td>
<td>9.6</td>
<td>2.28</td>
</tr>
</tbody>
</table>

The root content and organic matter content of the two sites are compared in Fig. 4.61. Both parameters in Barataria Bay are nearly two times greater than those in Terrebonne Bay. Therefore, the higher root content (or dense vegetation) in Barataria Bay is responsible for the overall stability of the site (if no oil spillage is present). In contrast, the smaller root content in Terrebonne Bay is responsible for the relatively abundant undercut erosion observed in this site.

Figure 4.59 Average critical shear stress of two sites (a) in-situ (b) laboratory testing
Figure 4.60 Average critical shear stress of the soil below the surface of two sites

Figure 4.61 Average root and organic matter content for two sites
CHAPTER 5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

This research includes extensive in-situ and laboratory testing of critical shear stress of wetland soil in coastal Louisiana. Two sites, Barataria Bay and Terrebonne Bay, were selected to perform in-situ CSM tests. Additionally various soil properties (e.g., particle size, Atterbergs’ limits, specific gravity, pore water salinity, water content, organic matter content, and root content) were also measured to characterize the soils in two sites. A cohesive strength meter was deployed to measure the in-situ surface erosion threshold of wetland soil while undisturbed soil samples in the laboratory were used to measure critical shear stress along the depth. The soil samples obtained from the field were cut into 3 in samples which were used for CSM testing and subsequent testing of soil properties.

5.2 Conclusions

Based on the obtained results, the following conclusions can be drawn:

- For the Terrebonne Bay site, both surface erosion at some weaker areas and undercut erosion are the major causes of marshland loss. For places where the surface soil’s critical shear stress is greater than that of soil in depth, undercut erosion will initiate first, leading to the loss of deeper soil layers and hence marsh edge damage.

- For the Barataria Bay site, surface erosion is the major cause for marshland loss, because this site is characterized by a stronger soil below the ground surface.

- For both sites, the critical shear stress ranges from 0.4 to 2.2 Pa, and the average values are 1.02 to 1.15 Pa. These values may provide insight into what hydrodynamic conditions cause the initiation of erosion.
The surface erosion threshold and hence the stability of Terrebonne Bay is greater than that of Barataria Bay. However, the former is more prone to undercut erosion, most likely due to less root content in depth. Also, the impact on coastal soil stability from the different hydrodynamic history of the two sites cannot be neglected.

Both organic matter and root contents in Barataria Bay are greater than those in Terrebonne Bay. However, organic matter content in Barataria Bay is overestimated due to intrusion of crude oil into the sediments.

In general, a certain range of organic matter content can have a positive influence on sediment stability. Organic matter content up to 10% for Terrebonne Bay and up to 30-35% for Barataria Bay were found to enhance sediment stability. However, the optimum limit of organic matter content in Barataria Bay is difficult to determine, as in some cases organic matter content beyond 30% was also found to have high critical shear stress.

Beyond 10% organic matter content in Terrebonne Bay, there is a significant decrease in critical shear stress value.

There exists a positive correlation between water content and organic matter content for both sites. Therefore, an increase in water content may not essentially decrease the sediment stability as long as organic matter content improves the critical shear stress. Hence the erosion study of cohesive sediments requires insight into the integrative interactions of various soil properties.

The critical shear stress increases with root content as roots provide reinforcement to the surrounding soil, and thus vegetation roots play an important role in controlling marsh erosion and marshland loss.
- Critical shear stress may increase by more than two times when root content increases from 1% to 6%.

- The average root content of Barataria Bay (4%) is approximately two times greater than that of Terrebonne Bay (2.28%).

- At shallower depth (~ 0.15m), the correlation between root content and critical shear stress is not clear, possibly due to difficulty in measurement of root content or due to freshly deposited sediments in which roots have yet to reinforce the soil.

- At shallower depth, water content is negatively correlated with critical shear stress (but mostly positively correlated with organic matter content) indicating its major influence on sediment stability at the surface, but at a greater depth organic matter and root content have major impact on sediment stability.

- In-situ CSM tests at Terrebonne Bay showed that the critical shear stress initially increases with depth and then decreases. A similar pattern was also seen from laboratory testing of tube samples obtained from this site.

- Field observation of Barataria Bay reveals that initially, crude oil acts as a protective layer when it is dry and relatively hard and solid. On such a surface, water infiltration into sediments is unlikely. However, the crude oil layer continues to harm the growth of vegetation.

- Furthermore, once the oil layer is disintegrated and vegetation is dead, there are formations of weak eroding spots which later assist heavy surface and undercut erosion.

- These weak spots in Barataria Bay are characterized by very low critical shear stress.
5.3 Recommendations

- The erosion threshold measured with a cohesive strength meter should be checked with other erosion devices because the light transmission measured by CSM could be erroneous.

- Additionally, cohesive strength meter use over oil-contaminated sediments when oil is liquid is questionable. Therefore, CSM should be used after removing the top oil layer.

- The measurement of water content and organic matter content of Barataria Bay requires correction due to over estimation by oil contamination.

- Additional tests such as triaxial and shear test can be performed in order to further characterize oil-contaminated sediments.

- This study mainly focused on three soil properties, namely water content, organic matter content and root content, but for future research the variation of critical shear stress with other soil properties (e.g. plastic limit, liquid limit, plasticity index, mud content, cation exchange capacity and extracellular polymeric substance) should be investigated.

- Since erosion study is rarely investigated from the geotechnical perspectives, correlation between soil index properties and critical shear stress for cohesive sediments can assist for future erosion models.

- Finally, for future research, use of SEM images to study the sediment aggregation in normal and oil-contaminated sediments could provide comprehensive results and conclusions.
REFERENCES


VITA

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