Effects of Organic Matter and Salinity on Fine-Grained Sediment Erosion

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ABSTRACT

Coastal Louisiana was formed by Mississippi river sediments deposited over thousands of years. These highly erodible and compressible alluvial deposits consist of soft clay and silt with layers of sand and organic matter. Global climate change, sea level rise, loss of barrier islands, increasing number and intensity of storms, oil and groundwater extraction, and geologic subsidence have resulted in wetland loss, water quality degradation, ground loss, and other challenges in south Louisiana. The critical shear stress, at which soil starts to erode, was determined using a jet erosion device on reconstituted dredged sediment. The main findings from this research are a lower organic content generated higher settling velocity for coastal deposits; a higher organic content increased the sediment erosion potential regardless of salinity; and increased water salinity increased sediment erosion potential by reducing the critical shear stress by 27% regardless of organic content.

INTRODUCTION

The Mississippi River Delta is the river delta at the confluence of the Mississippi River with the Gulf of Mexico, in Louisiana. It is a 12,000 km^2 area of land that stretches from Vermilion Bay on the west, to the Chandeleur Islands in the east, on Louisiana's southeastern coast. The modern Mississippi River Delta was formed over the last approximately 4,500 years as the Mississippi River deposited sand, clay and silt along its banks and in adjacent basins. The Mississippi River Delta is a river-dominated delta system, influenced by the largest river system in North America. As the river changed course, the natural flow of freshwater and sediment changed as well, resulting in periods of land building and land loss in different areas of the delta. Louisiana's wetlands are generally considered one of the most important environments in the United States, as they support the second largest commercial fishery in the United States (NOAA 2010), contain five of the nation's top 20 ports (Bureau of Transportation Statistics 2013), and 20 % of the nation's oil and gas supply comes from, or is transported through, these wetlands (LA DNR 2004). Coastal Louisiana encompasses an area of about 37,780 km^2 of wetlands and open water (Figure 1).

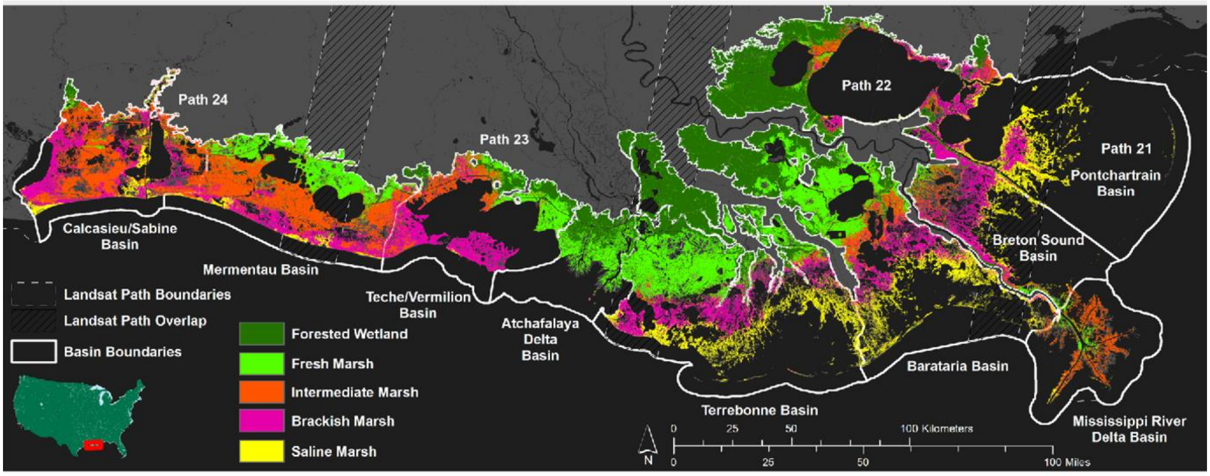

Figure 1. Wetland Marsh zones in coastal Louisiana (Sasser et al. 2014).

These wetlands are composed of forested wetlands, fresh, intermediate, brackish, and saline marsh. Wetlands are areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Depending on the salinity of the environment and types of supported vegetation, there are many types of wetlands in the United States, such as swamps, freshwater marsh, brackish marsh, etc. Table 1 summarizes the different marsh environments typically encountered in south Louisiana coast.

Table 1. Salinity range for Louisiana Marsh type.

Marsh Type	Salinity Range (ppt)	Vegetation Diversity
Freshwater marsh	0-2 ppt	Very high plant species diversity
Intermediate marsh	2+-10 ppt	High plant species diversity
Brackish marsh	10+-20 ppt	Moderate plant species diversity
Saline (salt) marsh	> 20 ppt	Low plant species diversity

Geology of Louisiana – Peat and organic matter deposits

Peat is an accumulation of partially decayed vegetation or organic matter. Fibrous peat, generally found near the ground surface, is composed of the fibrous remains of plants. It is fibrous, spongy, moderately tough, and non-plastic. Amorphous peat is a type of peat in which the original structure of the plants has been destroyed due to decomposition of cellulose. Amorphous peat is heavy, compact, and plastic when wet. There are several districts in south Louisiana in which there are large areas covered with peat. The depth of peat formation in south Louisiana ranges from 0.3 to 1 m or more. The formation back of the shorelines of Lake Maurepas and the west half of Lake Pontchartrain have been formed from woody vegetation, the peat derived primarily from Cypress (Dodson 1942). Extensive areas between the Mississippi river and Lake Pontchartrain where the dense vegetation has decayed and accumulated on the surface of the silty clay have resulted in peat to a depth of over 1 m. Figure 2 shows the structure and composition of silty clay soil (Figure 2a) and fibrous organic peat (Figure 2b) found in southeast Louisiana. The organic peat formation has larger voids, more fibers, and less soil particles compared to the silty clay. The peat formation is highly compressible and low in shear strength.

(a) (b)

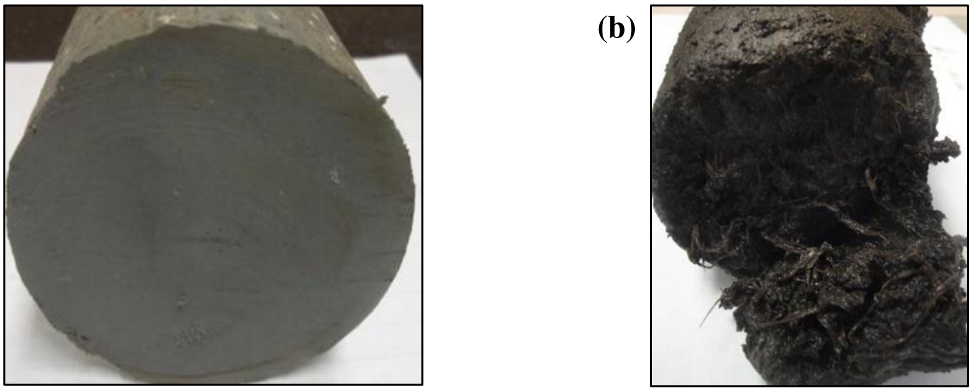

Figure 2. Soil Sample of coastal Louisiana (a) Silty Clay and (b) Organic Peat.

Louisiana Wetland Erosion

The path of the Mississippi River changed significantly before the levees were constructed in the 1930s, moving from east to west and depositing sand, silt, clay sediments and organic matter during floods. Coastal Louisiana was formed by sediments brought by the Mississippi River over several thousands of years. Coastal property development, global climate change, oil and water extraction, increased number and intensity of hurricane and tropical storm events, and various natural and man-made factors have resulted in water quality degradation, decline in fisheries, wetlands loss, reduced storm and surge protection, and other challenges in littoral areas. The loss of marshland in coastal Louisiana has also exposed infrastructure to open water conditions and has made the nearby areas less suitable for human occupation as well as various wildlife species (Reed 2004). The Louisiana coast has been declining steadily since the 1930s; over 5,000 km^2 have been lost, an area roughly the size of Delaware. The last 20 years have seen an increased rate of land loss that will continue to worsen if no action is taken. Figure 3 indicates one potential land change scenario over the next 50 years, assuming that no action to prevent future land loss and no attempts at coastal reconstruction. The areas marked in red will be lost or inundated without intervention (CP&RA 2017).

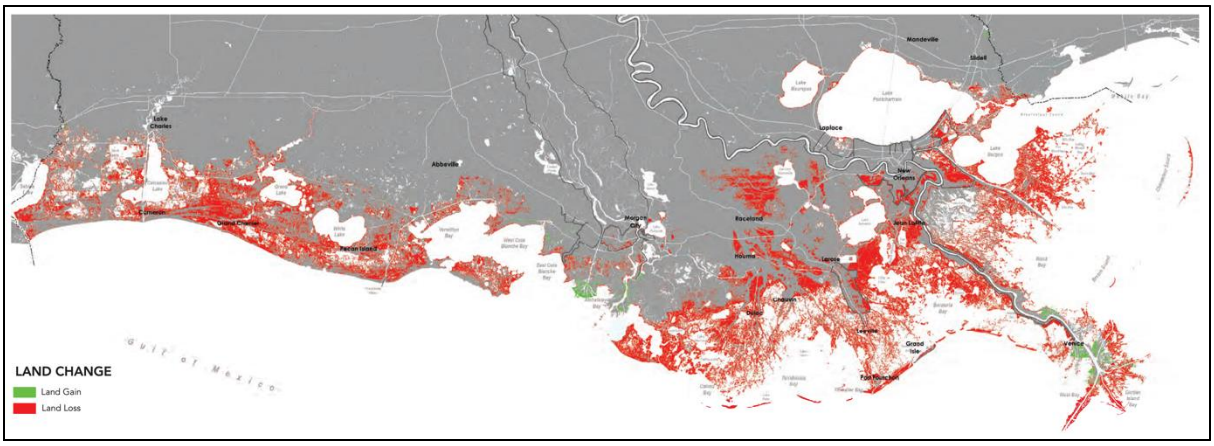

Figure 3. Predicted land change along the Louisiana coast over the next 50 years under the Medium Environmental Scenario (CP&RA, 2017).

During the planning, design, and construction of a coastal restoration/wetland creation project, engineers and scientists use (i) geotechnical engineering parameters, (ii) settling characteristics, and (iii) erosion properties of coastal sediments that are mixed with different portions of organic matter and are affected by different degree of salinity (fresh, intermediate, brackish, or saline). The engineering properties and material characteristics of the dredged material are input parameters to several mathematical models that have been used to predict the long-term behavior of coastal processes. Therefore, proper characterization of the dredged material is a major factor in the correct design of coastal restoration and land reclamation projects. This will contribute to cost-savings, time-savings, and improved outcomes of Louisiana Coastal Restoration project implementation. Using actual coastal sediments from Louisiana, this paper evaluates the effects of organic matter and salinity on settling and erosion characteristics of coastal sediments.

LABORATORY TESTING PROGRAM

Representative silt-clay sediment dredged material and organic matter (peat) were obtained from two locations near New Orleans, LA. Two samples (Samples A and B) were prepared to evaluate the effects of organic matter and salinity. Slurry (solids + Tap water) Sample A was prepared from silt-clay type dredged material only and slurry Sample B was prepared with only organic peat matter. An initial solids concentration of approximately 100 g/L was used to prepare all the slurry samples. Table 2 shows the results for sediment characterization including: (a) natural moisture content, (b) Atterberg Limits (liquid limits and plastic limits), (c) specific gravity of solids, and (d) organic content. The laboratory tap water, used to prepare the slurry, was characterized by the determination of (a) pH, (b) salinity, and (c) temperature.

Table 2. Properties of dredged slurry samples

Test ID	Moisture Content (%)	Liquid Limit (%)	Plasticity Index (%)	Organic Content (%)	Specific Gravity	pH	Salinity (ppt)	Slurry Solids Conc. (g/L)
A	28.3	41	21	1.0	2.63	8.7	2.41	103
B	201.9	259	141	29.7	2.28	5.7	1.18	99

Column Settling Test: Column settling tests (CST) were conducted to evaluate the effects of organic matter on the settling characteristics of coastal sediments. This test was run for 15 days in a controlled laboratory environment in general accordance with the procedure outlined by the US Army Corps of Engineers (USACE 1987). At the beginning of the experiment, the column is filled with the homogeneous slurry. Figure 4(a-d) shows photographs from the column settling tests for the slurry samples, 12 hours and 15 days from the start of the tests.

Mini Jet Erosion Test: The "mini" Jet Erosion Test apparatus (JET here after) was used to evaluate the erosion characteristics of the sediments. The JET has been used for assessing the erosion of cohesive soils in river channel degradation, bridge scour, and earthen spillway erosion. Hanson et al. (2002) developed an analytical procedure to determine the soil erodibility parameters for a submerged circular jet following the basis of jet diffusion principles developed by Stein et al. (1993) for a submerged planar jet impinging on a soil surface. JET experiments are relatively rapid, inexpensive, and are appropriate for any soil type. The JET was used in this study because the soils were relatively weak and the experimental setup required saline water. The JET allowed for the easiest experimental setup considering the project needs while still measuring the desired properties.

Samples were put inside the JET soil specimen mold in three layers. Each layer was compacted such that the required sample mass could completely fill the mold and the target dry density was achieved. All samples were remolded to the same dry density and water content, then tested at three levels of salinity. The target dry density for Sample A and Sample B was 1.48 g/ cm^3 and 0.66 g/cm^3, respectively. The JET apparatus consists of the following parts: water inlet, rotatable plate (containing the jet nozzle and gauge depth), jet nozzle, depth gauge, submergence tank, foundation ring, and water outlet. The jet nozzle is 3.18 mm in diameter and the submergence tank is 70 mm in height with a wall thickness of 6.4 mm. The foundation ring is 180 mm in diameter and 51 mm in height. The soil specimen mold containing the sample was 944 cm^3 (10.1 cm in dimeter and 11.8 cm in height). Figure 4e shows the JET apparatus attached to the soil specimen mold. The water flowed into the water inlet from a constant head tank stored on a tripod that was connected to a water supply tank with a pump. Two excess flow ports were located near the top of the head tank to control the water level. All JET were performed using a constant head of 2.4 m.

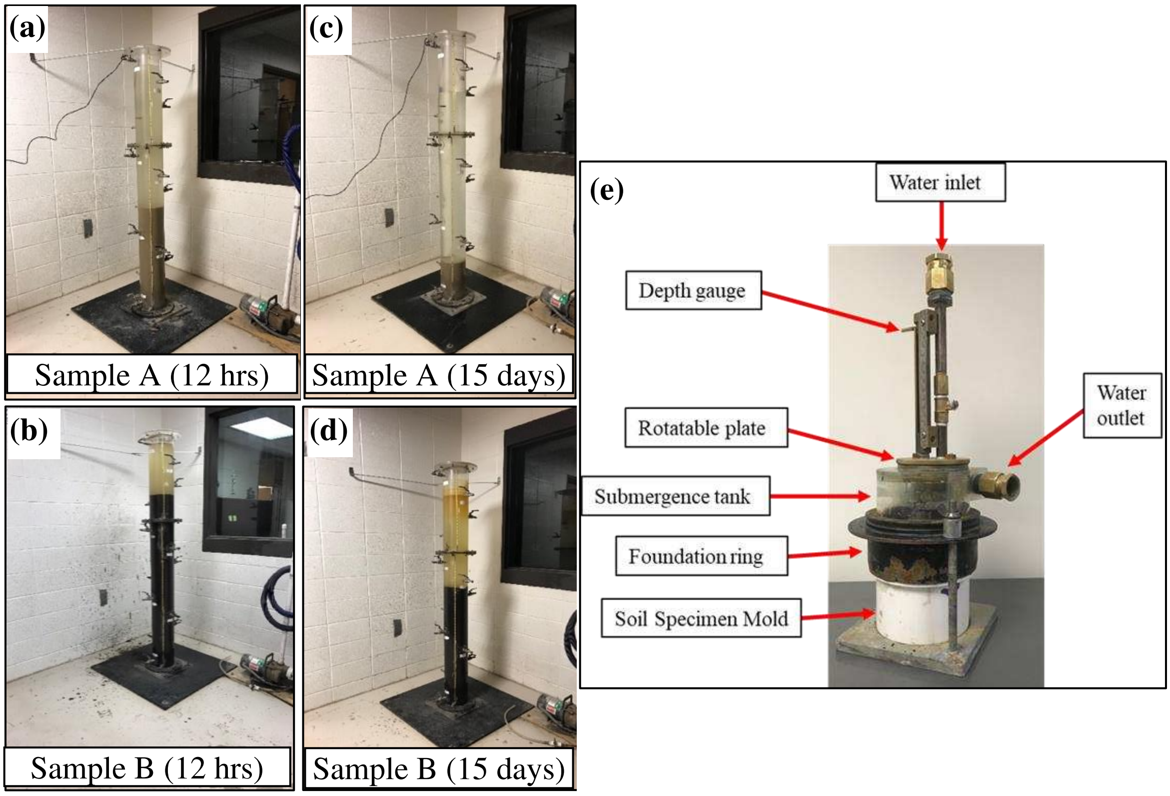

Figure 4. Experimental setup: (a) Sample A column settling test after 12 hours; (b) Sample B column settling test after 12 hours; (c) Sample A column settling test after 15 days; (d) Sample B column settling test after 15 days; (e) JET apparatus and soil specimen mold.

The goal was to test the samples at three salinity concentrations (i.e., S=0.2ppt, S=10-20ppt, and S=30-40ppt). Tap water and a sodium chloride / magnesium chloride mix (rock salt) were used. The smallest salinity, S=0.2ppt, was tap water. A predetermined amount of rock salt was mixed with tap water and well mixed to prepare the remaining solutions. The solution was allowed to sit for at least 24 hours prior to testing to ensure desired salinity concentration was achieved. Two JET were performed per salinity for Samples A and B. The experiments were conducted at room temperature (19±2C). Variation in water temperature was due to natural fluctuations in the laboratory while the solution sat overnight to equilibrate with the salt. Tran et al. (2019) established that the impacts of water temperature on cohesive sediments are negligible below 28C, therefore the water temperature did not influence the results. Figure 5 shows the samples at the end of testing.

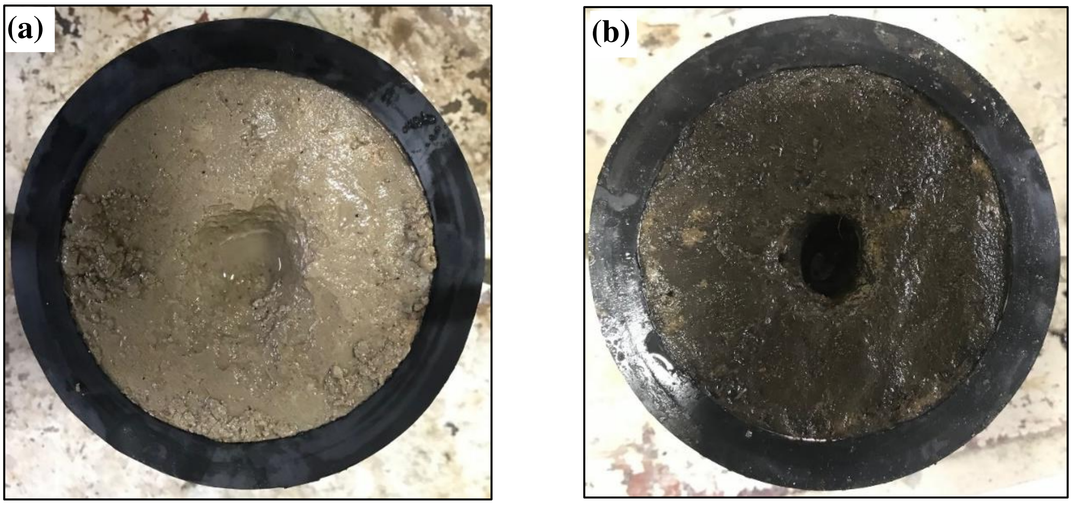

Figure 5. Samples after JET test: (a) Sample A (Silt-Clay); (b) Sample B (Organic Peat).

Before JET initiation, the initial depth to the soil surface was recorded at time zero using the gauge depth. The submergence tank was filled with water to allow for soil saturation within the mold. The jet nozzle was closed to protect the soil surface during initial filling of the submergence tank. Testing did not start until the submergence tank was completely filled and the water level in the head tank had reached a constant head. At test initiation the jet nozzle was opened to allow the jet to directly impinge the soil surface. Scour depth measurements were taken with the depth gauge while the impinging jet was closed. Al-Madhhachi et al. (2011) suggested scour measurements be recorded every 5 to 10 minutes for a cohesive soil. The scour depth was measured using a 5 minute time interval with more initial measurements according to the following time step: 30 seconds, 60 seconds, 2 minutes, 3 minutes, 4 minutes, 5 minutes, 10 minutes, 15 minutes, and continuing with 5 minute intervals until reaching 120 minutes. This time interval was selected to increase initial recorded scour measurements. The water salinity and temperature were maintained and recorded using a YSI model 85 handheld system (YSI Incorporated, Yellow Springs, Ohio). These measurements were recorded following the same time interval as scour depth measurements. All JET data were analyzed to determine the critical shear stress between varying water salinity using the scour depth method. The scour depth method uses an iterative approach that minimizes the error between measured and estimated scour depths in solving for the critical shear stress (Wahl 2016). The critical stress was assumed to occur when the rate of scour was equal to zero at the equilibrium scour depth (Hanson and Cook 1997) and was calculated as

$$\tau\_c = \tau_0 \left(\frac{J_p}{J_e}\right)^2$$

where τ_0 is the maximum shear stress due to the jet velocity at the nozzle (Pa), Jp is the potential core length from the jet origin (cm), and Je is the equilibrium scour depth (cm).

RESULTS AND DISCUSSION

Sediment Settling Characterization

According to the USACE (1987), the settling process of sediments can be categorized into four basic categories. If the particle maintains its individuality and does not change in size, shape, or density during the settling process, it is known as *discreet settling*. *Flocculent settling* occurs when particles agglomerate during the settling period with a change in physical properties and settling rate. *Zone settling* is characterized by a lattice structure formed by flocculent suspension which settles as a mass. The high solids concentration blocks the release of water and hinders settling of neighboring particles and a distinct interface between the slurry and the supernatant water is exhibited during the settling process. *Compression settling* occurs where settling takes place by compression of the lattice structure. All of the above sedimentation processes may occur simultaneously in a disposal or marsh creation area, and any one may control the design of the project. Figure 6 shows the effects of organic matter (percentage organic content) of the dredged sediments on its settling characteristics. H_0 represents the initial height of the slurry at the start of the settling column test; H represents the interface height (between solids and supernatant water) at any given time. The silt-clay slurry (Sample A) in Figure 6 settled sooner and at a faster rate compared to the slurry with higher percentages of organic matter. Even after 15 days, a high amount of organic matter stayed in suspension in the slurry for Sample B. The settling curves also clearly define zone settling and compression settling components. As also seen from Figure 6, the sediments with lower organic content settled at a faster rate.

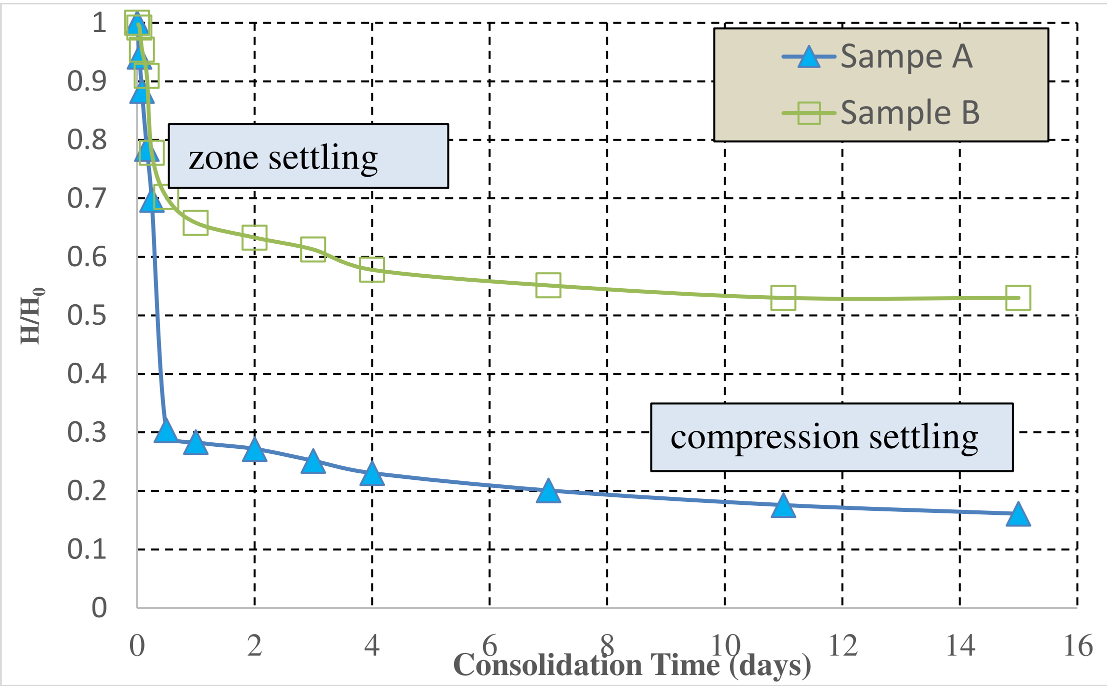

Figure 6. Effect of Organic matter on settling characteristics of dredged sediments.

Laboratory test data for the first 24 hours (1.0 day) of the settling column test, during which zone settling was observed, was used to perform a linear regression. The slope of the regression line, which corresponds to the zone settling velocity, ranged from 0.361 m/day (organic content = 29.7%) to 1.372 m/day with organic content = 1.0%. This higher settling velocity resulted in a shorter duration of the zone settling portion of the test.

Sediment Erosion Characterization

Figure 7 shows the observed scour depths with the JET apparatus on the two samples as a function of salinity. Figure 7a was tested with fresh water (0.2 ppt) and Figure 7b was brackish water (10-20 ppt). The final scour depths of Sample A were smaller than Sample B in both experiments, indicating that Sample A was more resistant to erosion. This was expected because the target density of Sample A was over two times higher than Sample B and increased density has been correlated with increased erosion resistance (Hanson and Robinson 1993). It was not possible to test with saline water (i.e., 30-40 ppt). Although the water was mixed until no salt crystals were observed, the saline water clogged the JET nozzle. Still, the data in Figure 7 highlight that the increased salinity in Figure 7b increased the maximum scour for both samples, regardless of density. The figure indicated that an increased salinity decreased the erosion resistance.

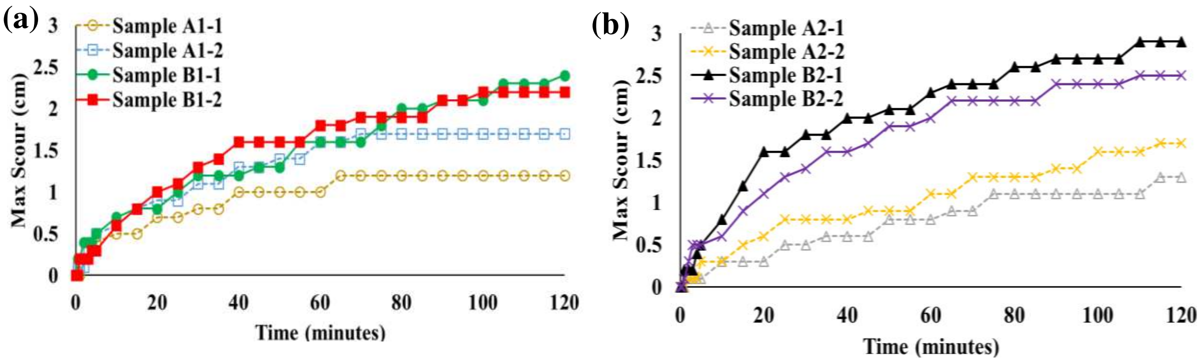

Figure 7. Observed JET scour depth with salinity: (a) fresh water; (b) brackish water.

The critical shear stresses from Figure 7 are shown in Table 3. The average critical shear stress, τ_c, was higher for both Samples A and B with fresh water. Again, this indicates that higher salinity reduces critical shear stress, making the samples less erosion resistant. The differences in calculated critical shear stresses between replicate samples may have been due to natural variability in the collected coastal sediments prepared in the molds. Although the magnitude of difference of the average critical shear stress as a function of salinity was lower in Sample A than Sample B (4.9 Pa vs. 2.8 Pa, respectively), the salinity reduced the critical shear by approximately 27% for both materials. Sample B was half the density and three times the water content of Sample A due to the high organic content (Table 2). The smaller absolute difference in critical shear stress in Sample B may have been due to the relatively loose sample, high water content, and high organic content.

Table 3. Critical shear stress of samples A and B as a function of water salinity.

Sample ID	Dry Density (g/cm^3)	Water Content (%)	Water Salinity	Water Temperature	τ_c (Pa)	$\tau_{c,avg}$ (Pa)
A1-1	1.48	29.1	0.2 ppt	19.7	20.3	18.2
A1-2				17.4	16.2	
A2-1			10-20 ppt	20.5	14.9	13.3
A2-2				19.1	11.7	
B1-1	0.66	91.3	0.2 ppt	20.9	9.43	10.3
B1-2				19.5	11.1	
B2-1			10-20 ppt	20.7	5.53	7.46
B2-2				19.5	9.39	

The results of this study showed that the increased organic matter decreased the zone settling velocity and the critical shear stress. The zone settling velocity and critical shear stress are important parameters used in design and analysis of Louisiana wetland creation projects. With abundance of organic matter present in coastal sediments, studying the effects of organic matter on settling velocity and critical shear stress of coastal sediments will help in more realistic engineering design and cost savings. Additionally, increased water salinity decreased the critical shear stress of both samples, with and without high organic contents. There have been mixed results on the impacts of water salinity on critical shear stress. For example, Winterwerp and van Kesteren (2004) found that as salinity increased from 0.1-5 ppt, the critical shear stress increased. However, Aruluanandan and Heinzen (1977) observed that increased pore fluid salinity reduced the critical shear stress. Therefore, there is a need for site specific erosion testing using the same water quality (i.e., salinity) as what is anticipated in the field.

CONCLUSIONS

Global climate change, increasing number and intensity of storm events, amplified human activity, and other natural hazards are putting more people and property at risk along Louisiana's coast. This paper presents the results of laboratory tests to evaluate the settling and erosion characteristics of coastal sediments containing different percentages of organic matter. The main findings from this research are: (i) A lower organic content generated higher settling velocity for coastal deposits; (ii) For inorganic silt clay sediments with low organic content, the zone settling velocity is related to the percentage of organic matter by the equation: $y = -1.372x$; (iii) For Organic Peat slurry, the zone settling velocity is related to the percentage of organic matter by the equation: $y=-0.361x$; (iv) A higher organic content increased the sediment erosion potential regardless of salinity; (v) Increased water salinity increased sediment erosion potential by reducing the critical shear stress by 27% regardless of organic content. Study settling characteristics of dredged/diverted sediments as well as their geo-hydro-dynamic properties with respect to salinity and organic matter percentages will provide engineers and researchers with better tools to generate more realistic estimates of the time/rate of settlement, and outcome of long-term performance measures for actual coastal restoration projects.

REFERENCES

Al-Madhhachi, A. T., Hanson, G. J., Fox, G. A., Tyagi, A. K., and Bulut, R. (2011). "Measuring erodibility of cohesive soils using laboratory jet erosion tests." *World Environmental and Water Resources Congress ASCE, 2350-2359.*

Aruluanandan, K. and Heinzen, R.T. (1977). "Factors influencing erosion in dispersive clays and methods of identification." *International Association of Scientific Hydrology Publication*, 122, 75-81.

Bureau of Transportation Statistics (2013) Table 2–57: tonnage of top 50 U.S. Water Ports, Ranked by Total Tons. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_57.html (Jan 15, 2020)

Coastal Protection & Restoration Authority (2017). "Louisiana's Comprehensive Master Plan for a Sustainable Coast." http://coastal.la.gov/our-plan/2017-coastal-master-plan/

Dodson, William Rufus (1942). "Observations and studies on the peat deposits of Louisiana," LSU Agricultural Experiment Station Reports, 350.

Hanson, G. J., Robinson, K. M., and Cook, K. R. (2002). "Scour below an overfall: Part II. Prediction." *Transactions of the ASAE,* 45(4), 957-964.

Hanson, G.J. and Robinson, K.M. (1993). "The influence of soil moisture and compaction on spillway erosion." *Transactions of the ASAE*, 36(5), 1349-1352.

Hanson, G. J. and Cook K. R. (1997). Development of excess shear stress parameters for circular jet testing. *ASAE Paper No. 972227. St. Joseph, Mich.: ASAE.*

Louisiana Department of Natural Resources (LA DNR), Technology Assessment Division (2004) Louisiana energy facts annual 2003. http://dnr.louisiana.gov/assets/docs/energy/newsletters/energy_facts_annual/LEF_2003.pdf.

National Oceanic and Atmospheric Administration (NOAA) (2010) Annual commercial landing statistics. http://www.st.nmfs.noaa.gov/st1/commercial/landings/annual_landings.html.

Reed, D. J., & Wilson, L. (2004). "Coast 2050: A new approach to restoration of Louisiana coastal wetlands." *Physical Geography*, *25*(1), 4-21.

Sasser, C.E., Visser, J.M., Mouton, Edmond, Linscombe, Jeb, and Hartley, S.B., (2014). "Vegetation types in coastal Louisiana in 2013: U.S. Geological Survey Scientific Investigations Map 3290," 1 sheet, scale 1:550,000. *https://dx.doi.org/10.3133/sim3290.*

Stein, O. P., Julien, P. Y., and Alonso, C. V. (1993). Mechanics of jet scour downstream of a headcut. *J. of the Hydraulic Research of IAHR, 31(6), 732-738*.

Tran, T., Karim, M.Z., Kuili, S., Tucker-Kulesza, S., and Derby, M. (2019). "Temperature effects on cohesive geomaterial erodibility." *ASCE Journal of Materials in Civil Engineering*, 32(2), 06019017. doi.org/10.1061/(ASCE)MT.1943-5533.0003046

U.S. Army Corps of Engineers. (1987). "Confined disposal of dredged material," Engineer Manual 1110-2-5027, Washington, DC.

Wahl, T. L. (2016). "The submerged jet erosion test: past-present-future." *USSD Int. Symp. Mech. Intern. Eros. Dams Levees*, Salt Lake City, UT, USA.

Winterwerp, J. C. and Van Kesteren, W. G. (2004). *Introduction to the physics of cohesive sediment dynamics in the marine environment*, Elsevier Science.