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Posted Date: 22 December 2025

doi: 10.20944/preprints202512.1927.v1

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Article

Application of 3D-Printing Technology in a Modified Oedometer for Characterization of Dredged Coastal Wetland Sediments

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Abstract

In Louisiana's marsh creation projects designed to mitigate wetland loss, riverine sediments are hydraulically dredged and transported through pipelines. These dredged materials are extremely soft, with moisture contents well above 100%, resulting in significant consolidation settlements even under minimal self-weight loads. Conventional one-dimensional (1-D) oedometer consolidation tests are commonly used to assess consolidation behavior; however, they are limited to soils with much lower moisture contents. At higher moisture levels, the soft slurry tends to overflow due to the weight of the standard stainless-steel dial cap and porous stone, which together apply a seating pressure of 1.07 kPa (0.01 TSF). This study presents a modified oedometer setup utilizing 3D-printed dial caps made from lightweight materials such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), reducing the seating pressure to 0.21 kPa (0.002 TSF). This modification enables testing of dredged soils with moisture contents up to 100% without overflow. Settling column tests were also integrated with the modified oedometer tests, allowing for the development of void ratio-effective stress relationships spanning from 0.02 kPa (0.0002 TSF) to 107.25 kPa (1 TSF). The results demonstrate that combining settling column and modified oedometer tests provides an effective approach for evaluating the consolidation behavior of high-moisture slurry soils.

Keywords: 3D printing; modified oedometer test; settling-column test; wetland marsh creation

1. Introduction

Several ongoing and completed coastal protection and restoration projects in Louisiana involve creating marshes in open coastal areas by hydraulically dredging riverine sediments and transporting them through pipelines. The settlement behavior of fine-grained dredged soils is routinely monitored and predicted, and laboratory consolidation testing serves as an essential tool for characterizing the settlement of marsh soils. In this study, a standardized laboratory method is recommended to enable full utilization of conventional oedometers and other laboratory equipment for consolidation testing. The proposed techniques incorporate procedures outlined in Terzaghi [1], EM 1110-2-19062 [2], Gibson et al. [3], Appendix D of EM 1110-2-5027 [4], Method B of ASTM D2435 [5], the Geotechnical Standards of the Louisiana Coastal Protection and Restoration Authority [6], and the method proposed by Azimi [7]. This research aims to experimentally investigate dredged soil sediments from coastal wetlands through the application of 3D-printing technology in the development of a modified oedometer.

Dredged soils are soft and highly moisturized, and thus form a large strain deformation. In the conventional consolidation oedometer test, the seating load at the initial consolidation test stage is an essential factor for the consolidation test of dredged soils. The conventional oedometer comes up

with a seating pressure of 1.07 kPa (0.01 TSF), including the weight of the stainless-steel dial cap and the porous stone, which could ensure the success of testing soil samples with a moisture content up to 70% for the dredged soils [8]. For this reason, we focused our research attention on how to modify the conventional 1-D consolidation test to allow the handling of slurry samples with higher moisture contents. As the first modification, the small-scale settling column test is used to handle those slurry samples with high moisture contents ($\geq 70\%$). For a dredged soil sample with a water content greater than 70%, after it was moved in the 1-D oedometer, as soon as the conventional stainless-steel dial cap was placed, which was equivalent to the initial (seating) pressure of 1.07 kPa (0.01 TSF), a portion of the soil specimen would be squeezed out of the consolidation ring [9]. Therefore, the conventional 1-D consolidation test couldn't proceed, because the traditional initial seating pressure is too high for the highly moisturized dredged soil sample.

Geotechnical researchers have devoted considerable effort to developing appropriate settling column apparatuses for assessing the consolidation properties of very soft, slurry-like dredged soils. Pioneering this field, Monte and Krizek [10] introduced a settling column apparatus measuring 20 cm in diameter and 50 cm in height for one-dimensional consolidation testing, coupled with a hydraulic conductivity test, to investigate a kaolinite clay slurry with an initial water content of about 250% (approximately four to five times its liquid limit). Their study demonstrated effective consolidation of the slurry under low effective stresses and provided valuable insights into the consolidation behavior of such materials. Carrier and Keshian [11] conducted a 30-day settlement test on a mud layer, deriving average void ratios and effective stresses to establish critical data points on a compressibility curve. Similarly, Katagiri and Imai [12] developed an apparatus consisting of a removable sedimentation pipe, a pre-consolidation pipe, and a piston to investigate the influence of initial water content on the compressibility, hydraulic conductivity, and settlement characteristics of highly saturated clays. They tested samples with varying water contents prepared from the same soil. Imai [13] also examined the settling behavior of slurries with different initial water contents, exploring correlations between water content, solid particle concentration, and settlement characteristics, yielding important findings. In addition, Sridharan and Prakash [14] investigated the compressibility behavior of both segregated and homogeneous fine-grained sediments consolidated under self-weight conditions. Using glass jars with a diameter of 6.1 cm, they carefully sampled the consolidated soils layer by layer with a horizontal-ended spatula to precisely determine moisture content, which was essential for calculating the void ratio.

Cuthbertson et al. [15] studied sand/clay sedimentation in estuaries and tidal inlets by performing settling column tests and taking electrical resistivity measurements to determine the consolidation behavior, which was validated by a hindered settling model. François and Corda [16] investigated the one-dimensional self-weight consolidation of dredged mud, proposing two original experiments to determine constitutive relations. At the end of their research, they recommended conducting self-weight consolidation tests in plexiglass columns. Been and Sills [17] conducted experimental research on the consolidation of soft soil in a settling column with measurements of density (using an accurate, non-destructive X-ray technique), total stress, pore pressure and settlement, revealing their susceptibility to wall friction compared to those with individual particles or flakes. Furthermore, Gao et al. [18] extensively investigated the settling behavior of dredged materials, revealing the diminishing impact of column wall effects with increasing column diameter, making them negligible for settling columns larger than 14.5 cm. This critical insight influenced the selection of the appropriate cylinder size for our research endeavors. Moreover, Gibson et al. [3,19] along with Cargill [20–22] authored technical reports and papers for the United States Army Corps of Engineers (USACE), introducing a practical approach based on finite strain consolidation principles. The USACE method, introduced in 1986, utilizes a specialized 15.2 cm (6 inches) Plexiglass apparatus consisting of 18 internal rings, each measuring 1.3 cm ($\frac{1}{2}$ inch) thick. This method allows moisture content analysis, establishing the void ratio-effective stress relationship, and it provides valuable the insights into soil consolidation properties.

Recently, Shi et al. [23] developed a filtration device to test dredged slurries' compressibility and permeability. A geotextile-type filter was employed in the device, and it consists of a cubic vacuum chamber, a Buchner funnel, a vacuum control system, and a monitoring setup. It allows filtration and consolidation under different vacuum pressures, collecting and quantifying the filtrate for further analysis. Similarly, Lee et al. [24] conducted self-weight consolidation tests in a cylindrical acrylic chamber with added features like valves and piezometers for measuring pore water pressure. Khaleghi et al. [25] introduced a complex oedometer to assess the thermal, hydraulic, and mechanical behavior of geomaterials, featuring a loading system, thermal setup, linear vertical displacement transducer (LVDT), pore-water pressure measurement, pressure cells, and data logger. Its corrosion-resistant interior and airtight cylindrical chamber provides unique insights. However, its complexity presents challenges in laboratory implementation and development.

In this study, small-scale settling column tests and one-dimensional (1-D) consolidation tests using a modified oedometer were combined to evaluate slurry samples with water contents exceeding 100%. This approach enabled the characterization of consolidation behavior across a wide range of void ratios and effective stresses. 3D printing technology was employed to fabricate the dial cap using Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) materials. A successful outcome was achieved, as the newly developed setup reduced the seating pressure significantly to 0.21 kPa (0.002 TSF), including the weight of the porous stone. Consequently, with the 3D-printed dial cap, dredged soil samples with moisture contents up to 100% could be successfully tested for their consolidation properties using the modified oedometer test. Simplified acrylic settling columns were also utilized to perform self-weight consolidation tests. Combined with the results from the settling column tests, the void ratio–effective stress relationship could be extended to stresses below 0.21 kPa (0.002 TSF).

2. The Dredged Soil Properties and Slurry Sample Preparations

The slurry soil samples used in the studies were made using the soil mass excavated from the No-Name Bayou Swamp production site in coastal Louisiana. These samples represented the natural state of the dredged soils. Prior to the consolidation tests on the slurry soil samples, fundamental geotechnical lab tests were conducted. According to the Unified Soil Classification System (USCS), as detailed by Howard [26], the dredged soil samples were classified as clays with low plasticity (CL). The specific gravity (G_s), was found to be 2.6 [9], in accordance with ASTM D854 [27]. Additionally, Atterberg limits, as per the ASTM D4318 [28] standard, were measured and shown in Figure 1 [9]. To prepare the slurry soil samples, the soil mass was initially dried in an oven for 24 hours, as depicted in Figure 2(a), and then ground into a finer consistency. The ground dry soil mass served as the initial material for creating the slurry samples. Water was added to the crushed dry soil to produce a uniform slurry with a targeted moisture content. This wet soil sample was then transferred to a mixing bucket for a thorough blending until it became homogeneous slurry, as illustrated in Figure 2(b) and 2(c). The produced slurry samples had three different moisture contents: 210.1%, 180.3%, and 150.2%. In order to mimic the natural environment and reduce the initial moisture content prior to initiating oedometer tests, self-weight settling column tests were conducted.

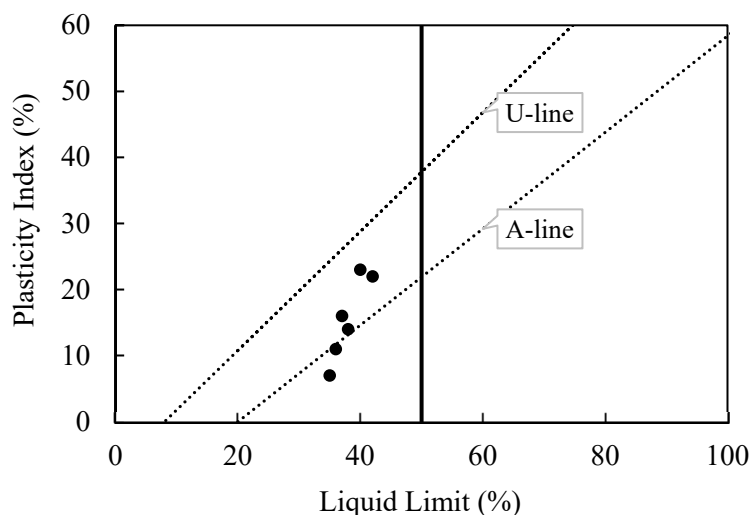


Figure 1. Atterberg limits of the soil samples from the No-Name Bayou Marsh Creation site in coastal Louisiana.

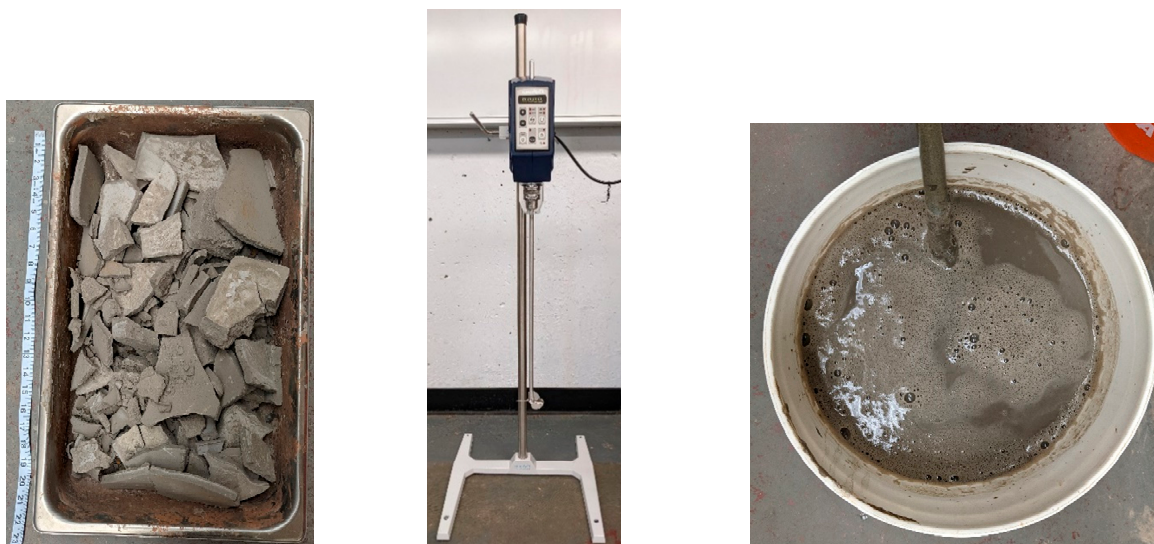


Figure 2. (a) Oven dried soil sample (b) Mixing grinder (c) Prepared slurry sample for settling column consolidation test.

3. The Simplified Self-Weight Consolidation Method

The self-weight settling column consolidation tests were conducted before the conventional 1-D oedometer tests started. Once a slurry sample was prepared with a pre-designed initial moisture content, it was moved in a settling cylinder for the self-weight consolidation test. In this research, three different diameters of acrylic plexiglass cylinders were utilized with the same height as 25.4 cm (10 inches). Those cylinders were 15.2, 20.3 and 25.4 cm (6, 8, and 10 inches) in inner diameters, respectively, as shown in Figure 3(a). A measuring tape marked into the scale of millimeter was attached to the side of each settling cylinder to take the settlement readings (location of the interface of water/top surface of settled soils). The cylinders were initially filled with slurry approximately to a depth of 20.3 cm (8 inches).

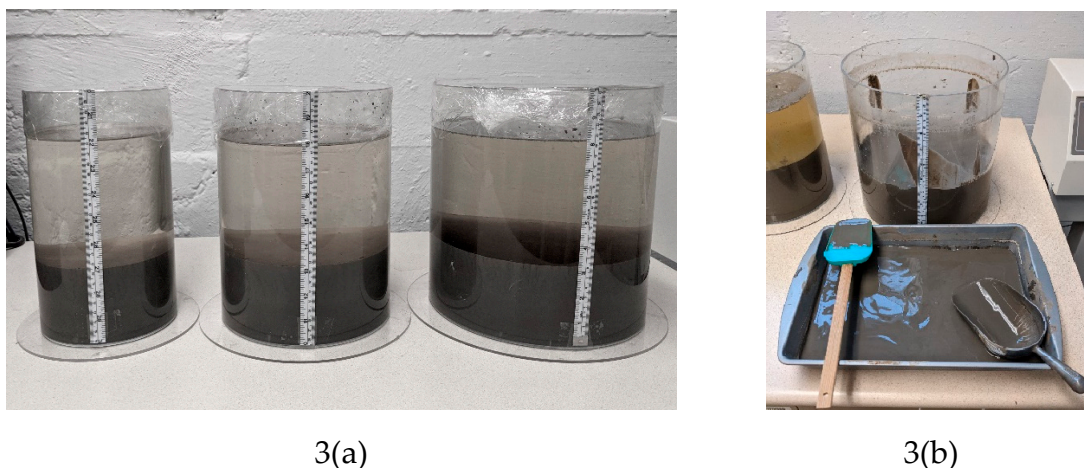


Figure 3. (a) The self-weight consolidation/settling column tests using acrylic plexiglass cylinders with diameters 25.4 cm, 20.3 cm, 15.2 cm (10", 8", and 6") (Right to left). (b) Soil sample removal after completion of a self-weight consolidation test.

In the USACE method [22] for self-weight settling column tests, the used Plexiglass apparatus was complex and uncommon, leading to difficulties in replication and procurement due to its rarity. Potential leakage in the USACE equipment is a notable concern, as even minor leaks could affect the test results by creating additional drainage paths in the sample. In contrast, the proposed research suggests the use of readily available Acrylic Plexiglass cylinders from common stores, offering a smoother surface, reducing friction during the test, and providing a reliable containment system for slurry samples, ensuring more dependable and accurate results.

Upon placing the testing cylinder containing the prepared slurry sample, the self-weight settling column test commenced, with intermittent measurements focused on identifying the water/slurry interface. The readings were taken at specific time intervals of 0, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, and 240 minutes, and then twice daily, following the methodology outlined by Azimi et al. [29]. Throughout the test, close attention was paid to the slurry's consistency, clarity of the discharged water, and any indications of agglomeration within the slurry. If approximately no additional settlement was observed for one week, it would be considered that the self-weight settling column test is accomplished. In the lab experiments, no significant changes were observed in the settlement of the slurry sample after four weeks. Consequently, it was taken into consideration that the ideal period for the completion of a settling column test is four weeks.

Each test took nearly four weeks to complete the self-weight consolidation. Once the self-weight consolidation test was completed, the free water on the top of the cylinder, which was expelled out of the original slurry, was gradually poured out, and the amount of the free water was measured. Upon the completion of each settling column test, the settled soils were prepared for the modified oedometer consolidation tests. Firstly, a hand pump was utilized to remove the water from the top of the settling cylinder. Then, the settled soil was removed layer by layer and placed on a tray for moisture content measurements, as demonstrated in Figure 3(b). Soil specimens were collected from various depths to perform oedometer consolidation tests. After the completion of the settling column tests, the average moisture content of the settled soils was around 150% on the top, and it decreased to about 60% at the bottom of the settling column cylinder [9], as shown in Figure 3(a). To determine the moisture contents, multiple soil samples were taken at the same depth and tested following the procedures outlined in ASTM D2216 [30].

The settlement vs. time plot from the settling column tests were employed to specify the first part of the primary consolidation curve. In the research, the effect of the cylinder diameter, i.e., effect of the friction between the cylinder wall and slurry soils were studied on the self-weight consolidation settlement. Three acrylic plexiglass cylinders, as shown in Figure 3(a) with diameters

25.4, 20.3 and 15.2 cm, (10, 8, and 6 inches) respectively, were used to find out an acceptable minimum cylinder diameter.

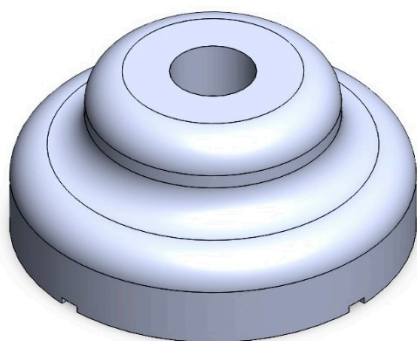
In the research presented in this paper, we conducted settling column tests following the well-established methodology proposed by Azimi et al. [29], which aligns with the original USACE method described by Cargill [22]. To determine the location of the slurry/water interface, measurements were recorded prior to extracting the free water using a manual pump. Careful sampling was then conducted to collect test specimens in layers of an approximately equal thickness, around 2.54 cm (1 inch) each, using a precise rubber-padded spatula and trowel to ensure minimal disturbance to the underlying layers. Figure 3(b) visually represents the sampling process with a test cylinder. The weight of each layer (w) was established by computing the mass per unit depth of the settled soil specimen using Eq. (1). These meticulous procedures allowed us to compute the effective stresses and void ratios in each settling column test, contributing to a comprehensive understanding of the soil's behavior under specific conditions.

$$w = \frac{W_t - W_e}{h_s} \quad (1)$$

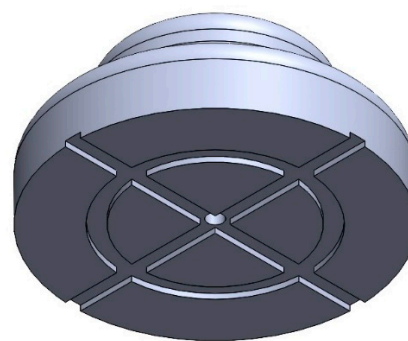
The experimental procedure involved comprehensive measurements of the slurry's properties. The total weight of the slurry-containing cylinder (W_t) was determined after eliminating all free-standing water and the empty cylinder weight (W_e) was measured before conducting the test. After completion of the test, we recorded the ultimate vertical depth of the slurry (h_s). Sampling was conducted meticulously, with the one-inch-thick layer's mass calculated using Eq. 1. We acquired samples from the full depth of the tested specimen, and every extracted layer was weighed. ASTM D2216 [30] was followed for the moisture content determination, and the test was performed in a controlled oven at a constant temperature of $110^\circ\text{C} \pm 5^\circ\text{C}$. The test results were analyzed and presented in the Results and Discussion section.

4. 3D Printing of the Dial Caps

In the process of creating the new dial caps for the modified oedometer test using SOLIDWORKS software, it is crucial to develop a meticulous 3D model that adheres to precise specifications and dimensions. This involves utilizing the software's diverse array of tools and features to craft detailed sketches, extrusions, and cuts that will form the part. Once the model is completed, it must be exported in a compatible format for 3D printing.



4(a)



4(b)

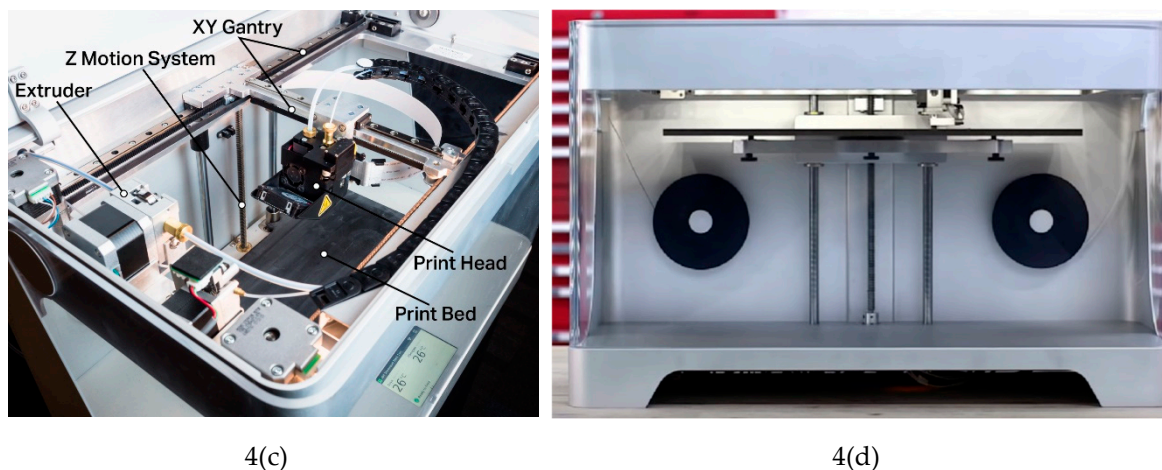


Figure 4. Sketch of the dial cap using SOLIDWORKS for 3D printing: (a) Top isometric view, (b) Bottom isometric view; MARKFORGED 3D printer (c) Different components [31], (d) Printing dial cap.

To bring the model to fruition, the 3D printing process requires several critical steps. Firstly, the 3D model must be imported into the MARKFORGED 3D printer software. Subsequently, the model is sliced into numerous layers, and a tool path is generated for the printer to follow. The printer must then be configured with the appropriate materials, including PLA and ABS, for this particular application. The print settings are then fine-tuned, and the printer begins constructing the dial cap layer by layer, carefully building up the part using the designated material.

After print settings are optimized for speed, it could take approximately 3-4 hours to print the part using PLA as the printing material. If ABS is used instead, the print time might increase to around 5-6 hours due to the higher melting point of ABS and the need for a higher printing temperature. Upon completion of the printing process, the part is extracted from the printer, and any necessary support structures are removed. The resulting component is then ready to replace the original stainless-steel dial cap in the consolidation testing.

5. The 1-D Consolidation Tests Using the Modified Oedometer

After completing the settling column tests, the consolidated slurry soils were sampled from different depths in the settling columns for the oedometer consolidation tests. Transferring soil samples from the settling column to the modified oedometer requires a careful handling to minimize any disturbances. We used specialized rubber-padded spatulas and trowels to sample the consolidated soil from the settling column (Figure 3). The steel specimen ring of the oedometer, overlying the bottom piece of porous stone, was positioned within the apparatus, and the sampled soil was gently placed in the ring. Subsequently, the top porous stone and the modified dial cap were positioned to complete the setup. As presented in Figure 5, the 3D-printed dial cap weighs only 20.2 grams (PLA) or 20.1 grams (ABS) while the conventional stainless-steel dial cap weighs 387.5 grams. As part of the justification work for the dial cap replacement, deflections of the 3D-printed dial caps of their own were studied as well, in an effort to see how significant the deformations were. The results of finite element analyses using software SolidWorks and the experimental test results of deflection of the dial caps were compared in the Results and Discussion section.

The lightweight 3D printed dial caps provided a stunning outcome that the newly achieved seating pressure was about 0.21 kPa (0.002 TSF), including the pressure that came up from the weight of the porous stone, as opposed to the traditional 1.07 kPa (0.01 TSF). From the preliminary results obtained, the maximum water content of the slurry soil sample was not able to go beyond 70% if the conventional stainless steel dial cap was used. However, if the 3D-printed dial cap was used, the maximum water content of the slurry samples could go up to as high as 100%. After a slurry soil sample with a water content of 100% was tested successfully using this 3D-printed dial cap, it was observed that, at the end of consolidation test with the pressure of 107.25 kPa (1 TSF), the final

settlement of the specimen was almost 50% of its initial height, which indicated that a large strain deformation occurred in the consolidation test. During the successful consolidation test, the following loading schedule was adopted: 0.21, 0.53, 1.07, 2.68, 5.36, 10.72, 26.81, 53.62 and 107.25 kPa (0.002, 0.005, 0.01, 0.025, 0.05, 0.10, 0.25, 0.50, and 1.00 TSF).

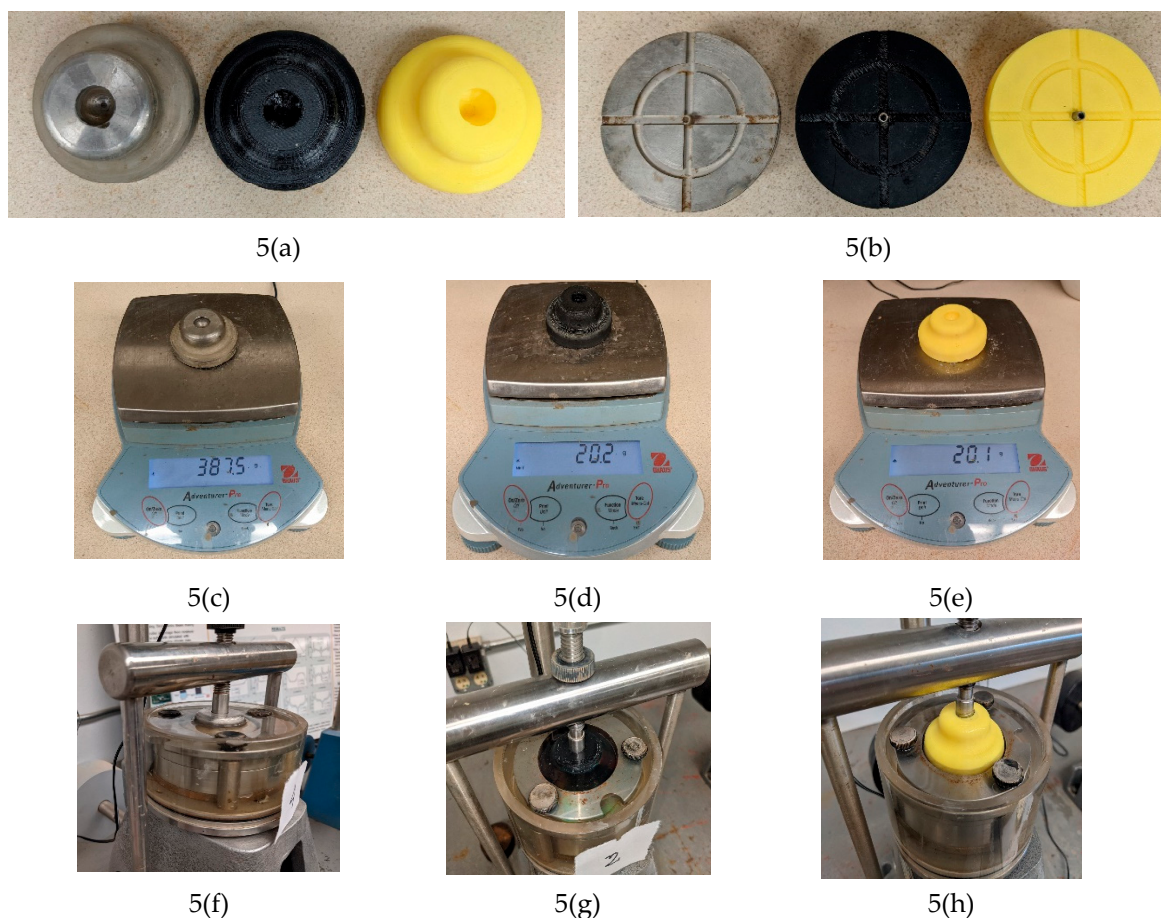


Figure 5. (a) Top views, stainless steel, 3D printed Acrylonitrile Butadiene Styrene (ABS) and polylactic acid (PLA) dial caps (left to right), (b) Bottom views, stainless steel, 3D printed ABS and PLA dial caps (left to right), (c) Stainless-steel dial cap with a weight of 387.5 grams, (d) PLA dial cap with a weight of 20.2 grams, (e) ABS dial cap with a weight of 20.1 grams, (f) Consolidation tests in-progress using Stainless-steel dial cap, (g) Consolidation test in progress using the PLA dial cap, (h) Consolidation test in progress using the ABS dial cap.

The 1-D consolidation tests were completed following the ASTM D-2435 [5] standard and Appendix D of EM 1110-2-5027 [4]. Consolidation settlement readings were taken at the times 0.1, 0.2, 0.5, 1.0, 2.0, 4.0, 8.0, 15.0, and 30.0 minutes, 1, 2, 4, 8, and 24 hours. At the time of 24 hours, primary consolidation was completed for most of the applied load mentioned above. As moisture content of the slurry soil specimen got significantly higher, the consolidation started immediately as soon as the soil specimen was placed in the oedometer. In every loading cycle, the settlement was much more remarkable in the first few hours and quickly decreased as time passed. No substantial settlement was observed in the last few hours of the 24-hour loading cycle.

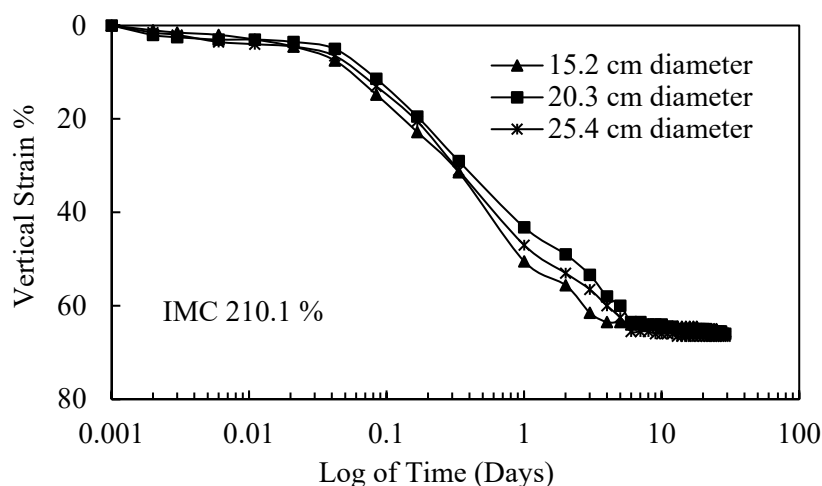
The modified oedometer consolidation test results were analyzed following Method B of ASTM D-2435 [5] and presented in the Results and Discussion section. As described in the beginning of this paper, combined consolidation results were presented from both the settling column and the modified 1-D oedometer tests. Void ratio variations from the two tests were plotted against the effective stresses applied. Void ratio results at each effective stress were averaged from the three tests using different diameter settling columns with slurry samples having the same initial moisture content. Then those were combined with the test results obtained from the modified oedometer tests.

The void ratio vs. effective stress profile plotted have covered a spectrum of consolidation pressures ranging from 0.02 kPa (0.0002 TSF) to 107.25 kPa (1 TSF).

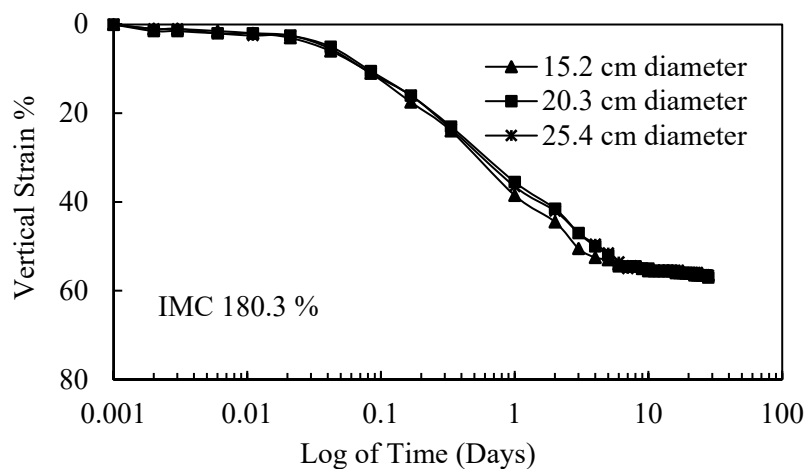
6. Results and Discussion

6.1. The Self-Weight Consolidation Tests

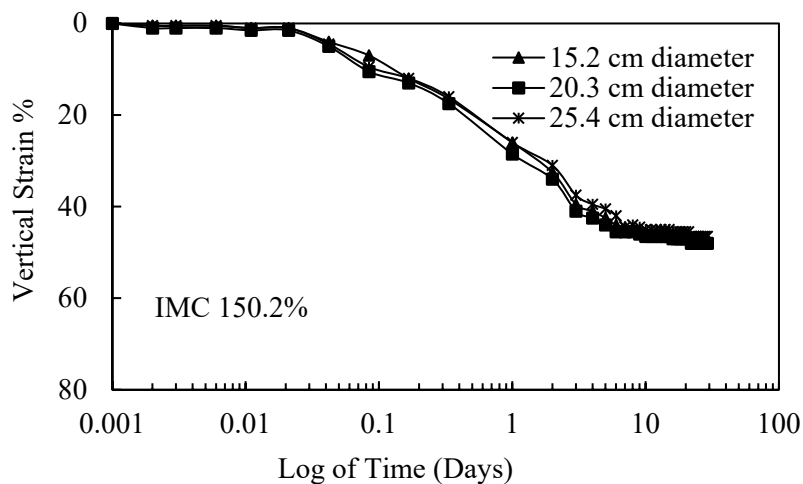
To determine the diameter effect of the settlement column, three acrylic cylinders with diameters of 15.2 cm (6 inch), 20.3 cm (8 inch), and 25.4 cm (10 inches), respectively, were used to conduct the self-weight consolidation tests. The columns were constructed from new, smooth, and clean acrylic tubing [32], minimizing the friction between slurry and sidewall. Figure 6(a-c) represents percent vertical strain against logarithmic time for the three sets of self-weight consolidation tests, in which the slurry samples had an initial moisture content of 210.1%, 180.3%, and 150.2%, respectively. On average, each test spent 28 days before ending up taking any slurry settlement readings. Settlement results from the three tests with different cylinder diameters showed that no significant differences were found among the three-diameter settling column tests. It could be concluded that any acrylic cylinders with a diameter equal to or greater than 15.2 cm (6 inch) would have a negligible frictional effect on the final consolidation settlement.



6(a)



6(b)



6(c)

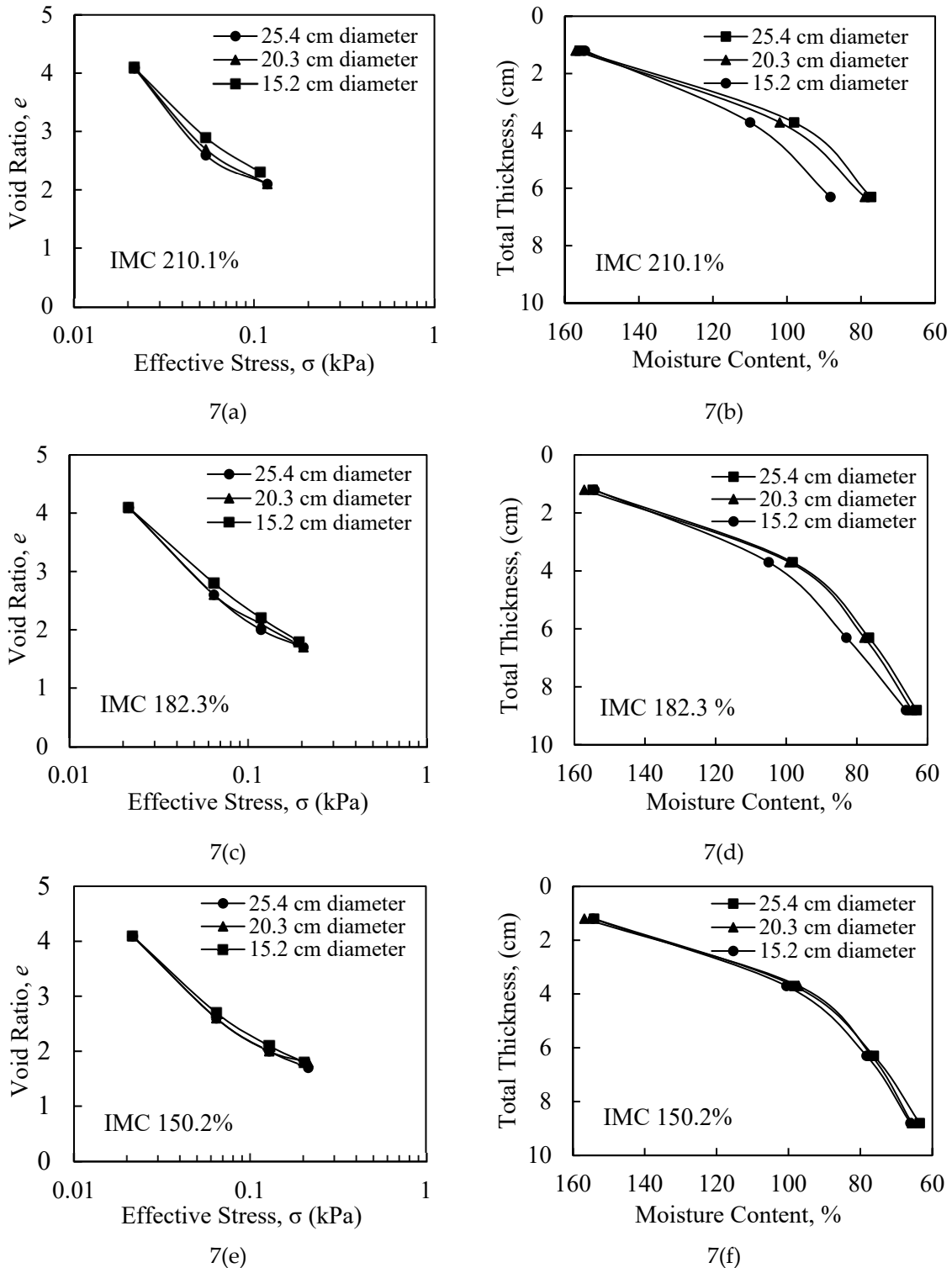
*IMC = Initial Moisture Content of soil sample.

Figure 6. (a-c) Logarithm of time vs. vertical strain of the settlement column tests with initial moisture contents of 210.1%, 180.3%, and 150.2%, respectively.

6.2. Consolidation Properties of the Slurries from the Self-Weight Tests

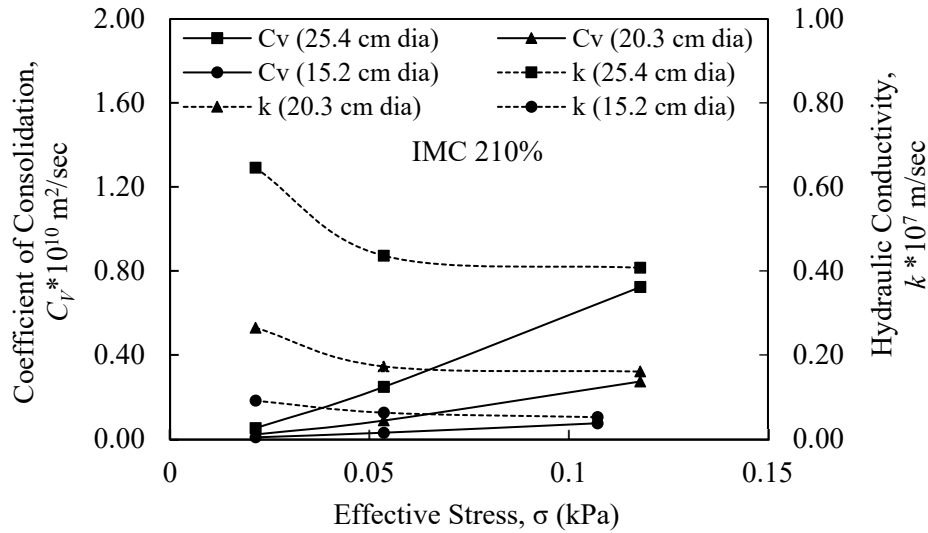
For the completed settling column/self-weight consolidation tests, the plots of void ratio versus effective stress on a semi-log scale were illustrated in Figure 7(a, c, e) for the slurry samples with moisture contents of 210.1%, 180.3%, and 150.2%, respectively. At each data point shown on a single plot, the results were derived from a one-inch-thick layer of the slurry specimen extracted at a particular depth within the test cylinder. Figure 7(b, d, f) represents the plots of the total thickness of the settled slurry soils versus moisture content of each set of settling column test. In the settling columns, total thickness of the settled slurry was measured from water/soil interface to the bottom, and the measured moisture content of each layer of the consolidated slurry was presented in Figure 7(b, d, f). The effective stresses in each test were determined by considering the buoyancy weight of the soils within every layer. The void ratio vs. effective stress curves for dredged/marsh soils demonstrates a distinct behavior, attributed to the intricate nature of the soil composition and the dredging process. The curves show higher initial void ratios at lower effective stresses, followed by a quick decrease as effective stress increases, indicating the gradual densification of the soil.

As shown in Figure 8, values of the measured coefficient of consolidation, c_v , from the settling column tests of the dredged soils at the No-Name Bayou marsh creation site in coastal Louisiana, ranged from 4×10^{-10} m²/s to 1.1×10^{-8} m²/s. Figure 8(a-c) presents the c_v versus effective stress plots of the three sets of settling column tests. It is identified that c_v increased with the increase in effective stress for all the specimens. Azimi [7] measured c_v of dredged material obtained from the Savannah River in North Carolina, and it ranged from 9.8×10^{-11} m²/s to 1.1×10^{-10} m²/s, similar to those values presented in this paper. The c_v values for the bentonite-ZVI mixed

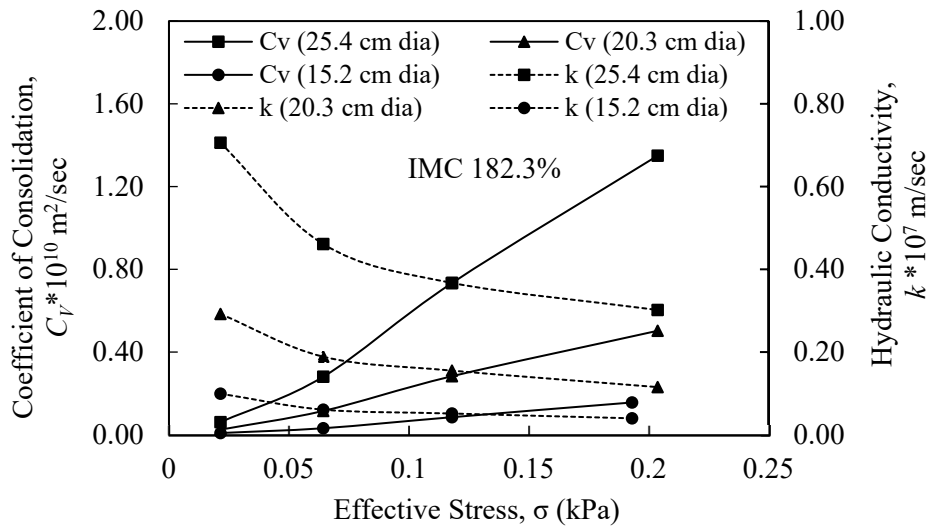


*IMC = Initial Moisture Content of soil sample

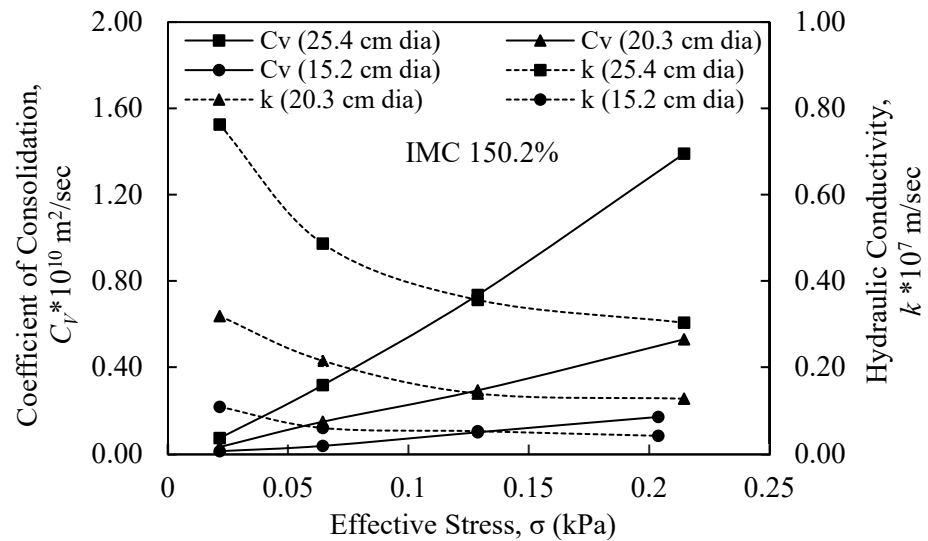
Figure 7. (a, c, e) Effective stress vs. void ratio plots of the soil samples with initial water contents of 210.1 %, 180.3% and 150.2%. (b, d, f) Moisture content vs. thickness of soil specimens with initial water contents of 210.1 %, 180.3% and 150.2%.



8(a)



8(b)



8(c)

*IMC = Initial moisture content of a soil sample.

Figure 8. (a-c) Effective stress vs. coefficient of consolidation C_v and hydraulic conductivity, k of the soil samples for initial water contents of 210.1 %, 180.3% and 150.2%, respectively.

slurry sand ranged from 1.9×10^{-6} m²/s to 5.0×10^{-5} m²/s, which are higher than those typically reported for pure clay samples and lower than those typically for pure sand specimens' samples [33,34].

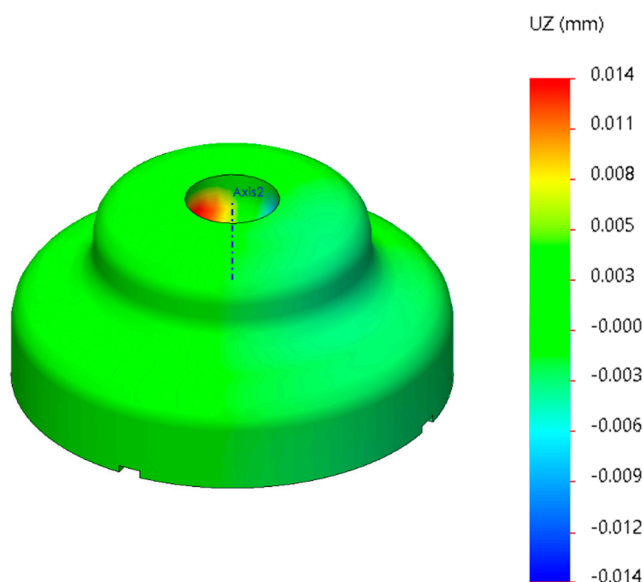
To determine the hydraulic conductivity (k) from the coefficient of consolidation (C_v) we used the relation $C_v = -k/\gamma_f (1 + e_0)/a_v$ where, e_0 is the initial void ratio, a_v is the coefficient of compressibility and the γ_f is the unit weight of water. The hydraulic conductivity values of the slurry samples from the settling column tests, k , ranged from 9.1×10^{-6} m/s to 1.1×10^{-5} m/s for the slurries made from the dredged soils at No-Name Bayou Marsh Creation site in coastal Louisiana (Figure 8(a-c)). The test results showed that the hydraulic conductivities decreased due to the increase in effective stress. The hydraulic conductivity was higher for the test cylinder with larger diameters and gradually decreased with the decrease in cylinder diameter. It indicates that the pore water was decapitated more quickly from the soil matrix in the test cylinders with larger diameters. According to Pane et al. [35], the consolidation duration depends on the soil's hydraulic conductivity. The higher the hydraulic conductivity, the lower the consolidation duration of time and vice versa for the case of lower hydraulic conductivity. Azimi [7] measured k values of dredged material obtained from Savannah River in North Carolina, and they ranged from 8.9×10^{-6} m/s to 1.0×10^{-5} m/s. Castelbaum and Shackelford [36] had k values of sand samples mixed with bentonite slurry, which ranged from 2.4×10^{-9} m/s to 6.8×10^{-6} m/s. k values from Sample and Shackelford [33] for bentonite-ZVI slurry mixed sand specimens were ranged from 3.4×10^{-9} m/s to 1.9×10^{-8} m/s. Therefore, the range of k values from the settling column tests presented in this study is similar to the measured values by Azimi [7], falls at the higher end of the range provided by Castelbaum and Shackelford [36], and is almost close to the measured values by Sample and Shackelford [33]. Though the previous studies were on different soil types, the estimated coefficients of consolidation and hydraulic conductivities in this study followed a similar trend.

6.3. Deflections of the Dial Caps Themselves

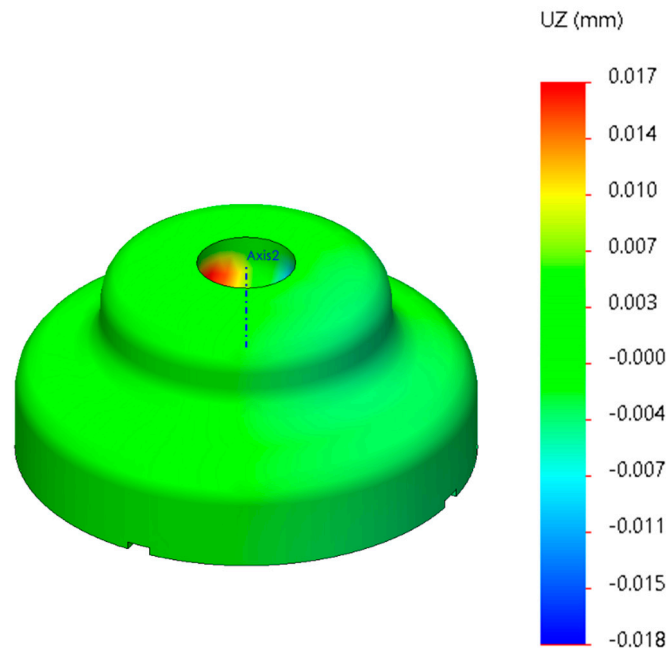
The 3D-printed dial caps are significantly lighter than their stainless-steel counterparts. However, they must remain sufficiently rigid and stiff relative to the soil specimen. Before these 3D-printed caps can reliably replace the stainless-steel ones, their own deformation—particularly the vertical displacement under standard consolidation pressures—must be minimal compared to the consolidation settlement of a one-inch marsh soil sample. In this study, the vertical deformation of the 3D-printed dial caps was investigated both experimentally and numerically. In the experimental program, conventional consolidation pressures were applied to a dial cap using the same loading frame setup. However, the one-inch-thick consolidation soil sample below the dial cap was replaced by the same-size cylindrical iron weight. Therefore, during any loading stage, the measured vertical displacements on the top of the dial cap could be reasonably considered the displacements of the dial cap itself. Numerical modeling was performed using the FEM-based commercial software package SolidWorks. The dial cap displacements from the above-mentioned studies were compared with the consolidation displacements measured in the consolidation process, and it was found that the vertical deformation of the 3D-printed dial cap was less than 1% of the consolidation settlements of the slurry sample subjected to a consolidation pressure of 214.50 kPa (2 TSF) measured at the end of time period of 24 hours.

For the 3D printed dial caps, special alloy called Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) were employed. After applying a load of 214.50 kPa (2 TSF), vertical displacements of the PLA, ABS and conventional stainless-steel dial caps were measured at 0.026, 0.031 and 0.002 mm, respectively. Numerical results with finite element analyses came up at 0.014 mm, 0.017 mm and 0.001 mm, respectively, using the Solid-Works software, as shown in Figure 9(a-

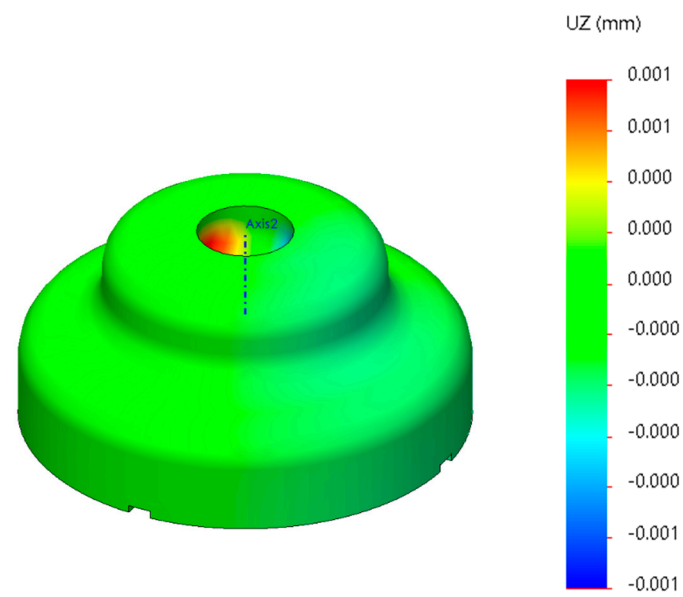
c). Displacement distributions shown with the same color for the PLA and ABS dial caps in Figure 9(a, b) indicated that the 3D-printed dial caps behaved nearly as a rigid body, which was similar to the deformed body of the conventional steel dial cap when they were subjected to the load of 214.50 kPa (2 TSF). The comparisons between the experimental and numerical results of the deflections were presented in Figure 9(d). For the slurry consolidation tests, a 24-hour consolidation settlement could reach 50% of the original sample depth (25.4 mm) at 1 TSF [9], so the error was less than about 0.2% for each printed dial cap, which is surely acceptable. Based on the information gathered from literature review, we selected specific mechanical properties for the materials we used in our finite element analyses. For the PLA material, we considered an elastic modulus of 3500 MPa, a yield strength of 70 MPa, and a Poisson's ratio of 0.36, as reported by Lay et al. [37] and Torres et al. [38]. Similarly, for the ABS material, we adopted an elastic modulus of 1960 MPa, a yield strength of 30.3 MPa, and a Poisson's ratio of 0.39, which were drawn from research by Saenz et al. [40] and Cantrell et al. [39]. Regarding the default mechanical properties for stainless steel in SolidWorks software, we utilized an elastic modulus of 193 GPa, a yield strength of 415 MPa, and a Poisson's ratio of 0.3. Furthermore, the inner diameter of the oedometer dial ring was 63.5 mm, and its height measured at 25.4 mm.



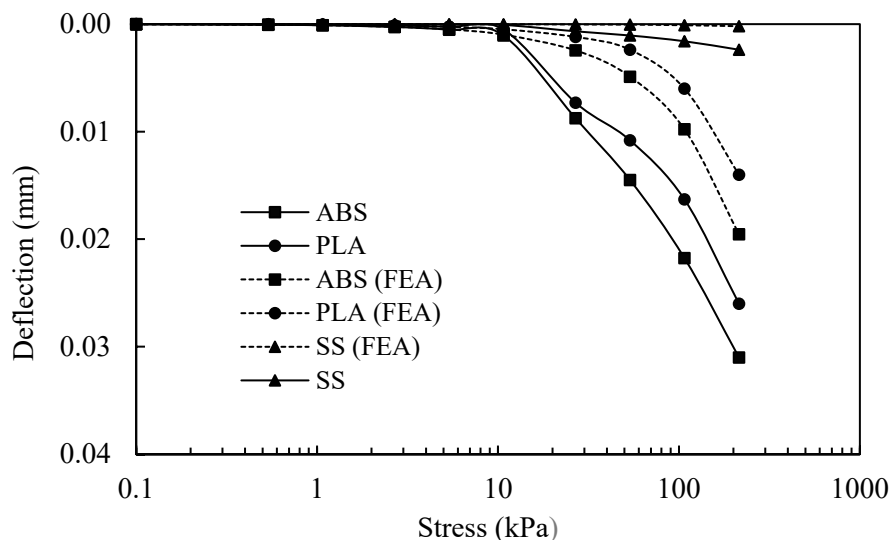
9(a)



9(b)



9(c)



9(d)

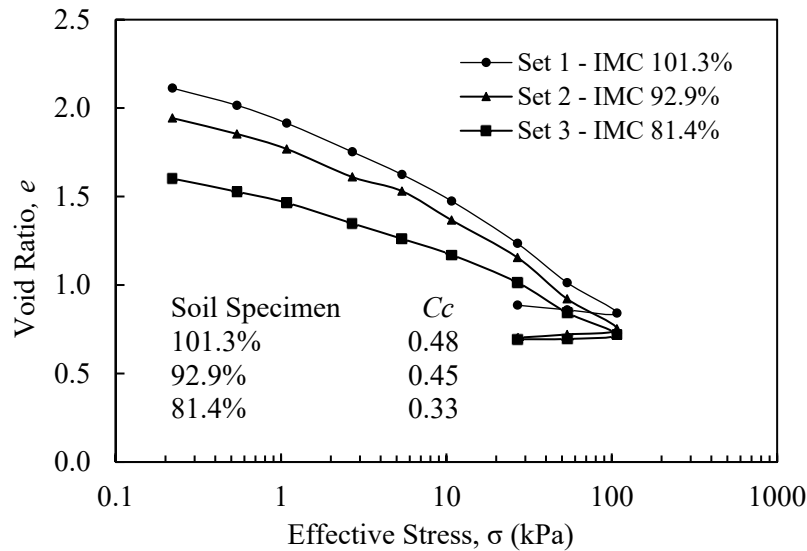
*UZ = Deflection in the vertical direction.

Figure 9. (a-c) Finite element analysis of dial caps (a. PLA, b. ABS, c. Stainless-Steel) using SOLID WORKS software, (d) Stress vs. deflection plots of the dial caps of the oedometer consolidation tests.

6.4. Analyses of Consolidation Data from the Modified Oedometer Tests Using the 3D Printed Dial Caps

The consolidation properties were determined using Method B of ASTM 2435 standard [5]. The 3D printed dial caps, which came up with a seating load of 0.21 kPa (0.002 TSF), including the weight of the porous stone, were utilized successfully to test the soil specimen with a moisture content of 101.3% [9]. Similarly, two other soil specimens with moisture contents of 92.9% and 82.4% were also tested effectively. The resulting void ratio versus effective stress curves from the modified oedometer tests using these 3D-printed dial caps are illustrated in Figure 10 [9]. The curves exhibited similar patterns, and the ultimate void ratios of the three consolidated soil specimens were nearly identical, all falling below 1.0 after applying a load of 107.25 kPa (1 TSF). This load induced significant consolidation deformation, with all tested specimens experiencing vertical strains of approximately 50%, which indicated that a large consolidation deformation happened. According to Apu et al. [41], Sarker et al. [42], Apu & Wang [43], and Apu & Wang [9], the compression index (c_c) of Louisiana marsh soils along the coastal line typically ranged from 0.16 to 2.86. The lab experiments on the three soil specimens resulted in compression indices falling within the range from 0.33 to 0.48, as depicted in Figure 10. These values are reasonable and consistent with the established literature.

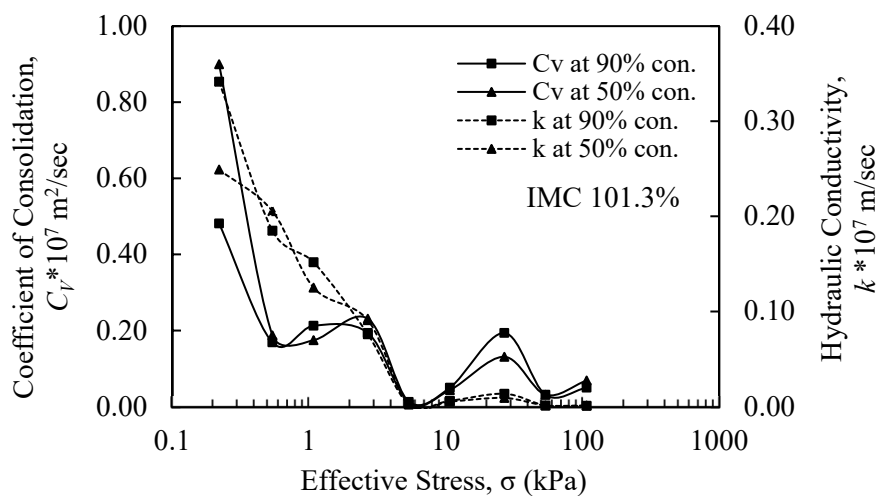
The coefficients of consolidation, c_v , determined through the modified oedometer tests, were displayed in a range between 1.0×10^{-8} m²/s and 9.6×10^{-8} m²/s, as indicated in Figure 11(a-c). It is noteworthy that there was an observed decrease in c_v with the increasing effective stress. However, a significant drop in c_v was noted after applying a load of 1.07 kPa (0.01 TSF) [9]. Holtz [44] reported that values of c_v scattered in the range from 4.0×10^{-9} m²/s to 7.0×10^{-9} m²/s for the clayey soils in Mexico City, which closely resembled the c_v values observed in the dredged soils at the No-Name Bayou marsh creation site in coastal Louisiana. On the other hand, for Ottawa sand mixed with 15% silt, c_v values ranged from 4.4×10^{-4} m²/s to 1.2×10^{-3} m²/s when subjected to consolidation in triaxial tests, and from 6.2×10^{-4} m²/s to 2.7×10^{-3} m²/s when consolidated in oedometer tests, as outlined by Carraro et al. [45]. Furthermore, for foundry sand mixed with 15% non-plastic silt, Thevanayagam et al. [46] reported that c_v values spanned from 3.5×10^{-4} m²/s to 1.7×10^{-3} m²/s.



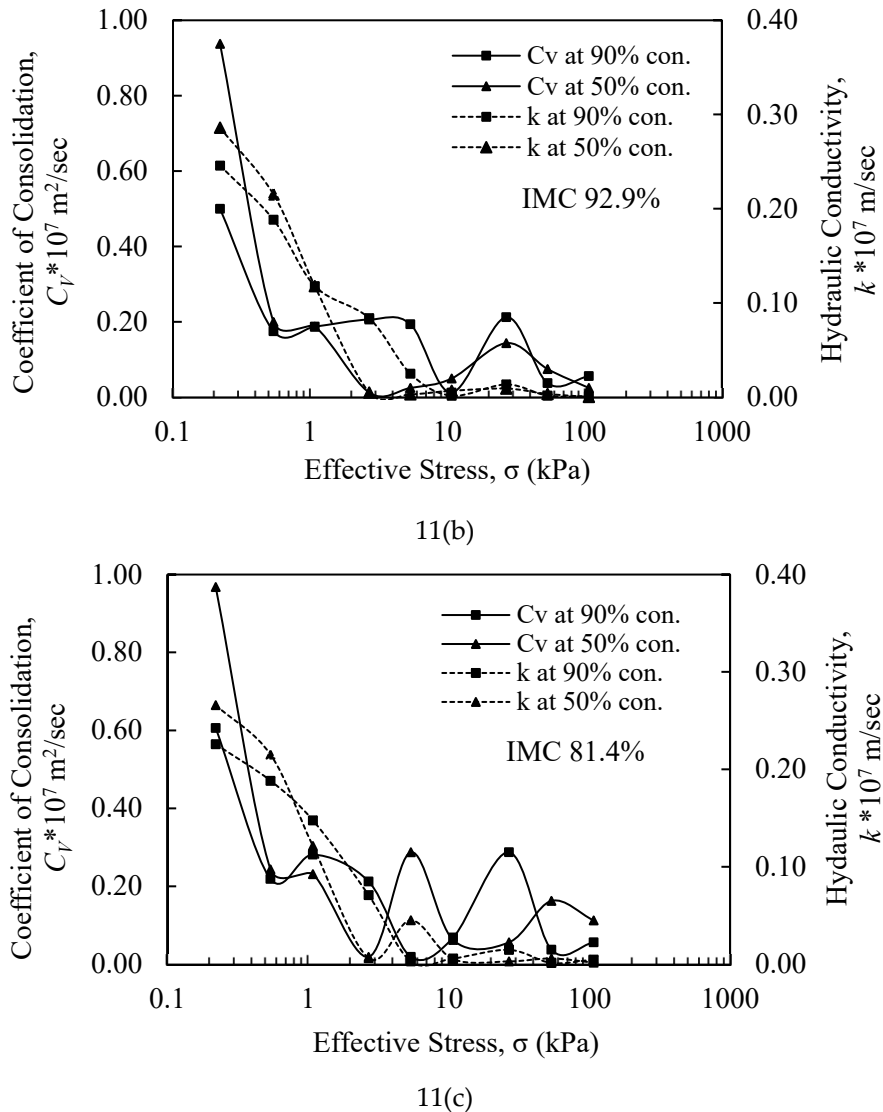
*IMC = Initial moisture content of a soil sample.

Figure 10. Effective stress vs void ratio curves of the soil samples with moisture contents of 101.30%, 92.90% or 81.40% using the modified oedometer.

ASTM D2435 [5] provided a procedure for calculating hydraulic conductivity (k) based on results from a oedometer consolidation test. This method encompasses determination of void ratio and coefficient of consolidation, and utilization of the time factor for the degree of consolidation, with the initial and final thicknesses of the soil specimen integrated in the analyses process. In the specific case of the modified oedometer tests conducted for the soil samples taken at the No-Name Bayou marsh creation site in coastal Louisiana, it was observed that the hydraulic conductivity (k) of dredged soils decreased significantly after subjecting them to a load of 1.07 kPa (0.01 TSF). The hydraulic conductivity values recorded ranged from 1.1×10^{-9} m/s to 3.5×10^{-8} m/s in Figure 11(a-c) [9]. Comparatively, Li et al. [47] reported the hydraulic conductivity values for highly lean clay in the range between 3.3×10^{-7} m/s and 1.2×10^{-6} m/s, while Moozhikkal et al. [48] found the hydraulic conductivity values for Bombay marine clay ranging from 1.0×10^{-10} m/s to 1.9×10^{-8} m/s. These findings are consistent with the hydraulic conductivity values obtained in the present study.



11(a)

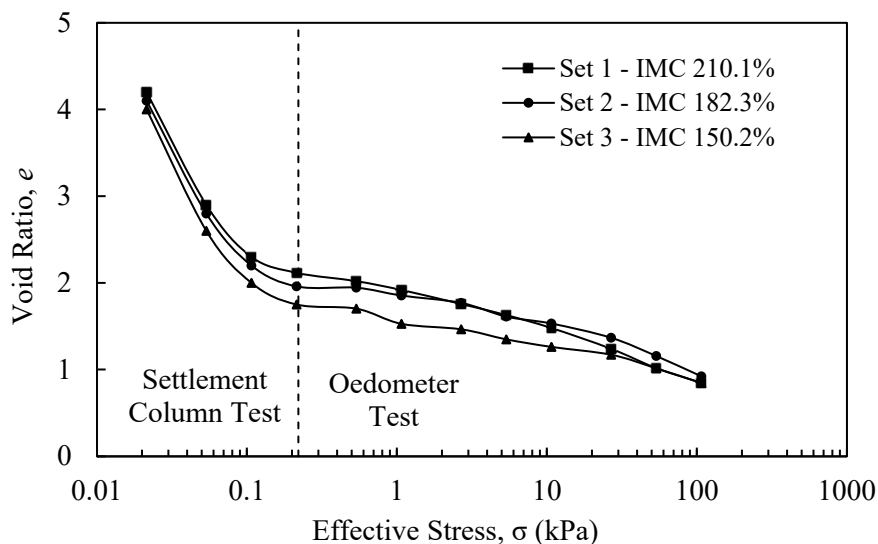


*IMC = Initial moisture content of a soil sample.

Figure 11. (a-c) Effective stress vs. coefficient of consolidation C_v and hydraulic conductivity k of the soil sample having a moisture content of 101.3%, 92.9% or 81.4% using the modified oedometer.

6.5. The Combined Profile of Void Ratio Verses Effective Stress

As mentioned earlier in this paper, the void ratio variations from the settling column tests and modified oedometer tests were combined and plotted against the effective stresses (Figure 12). The void ratios resulting from the three settling column tests at the same effective stresses and the same initial moisture contents were averaged and combined with the test results obtained from the modified oedometer tests. The plotted curves covered effective pressures ranging from 0.02 kPa (0.0002 TSF) to 107.25 kPa (1 TSF). In Figure 12, the three combined void ratio vs. effective stress curves were presented using the laboratory test data and marked as sets 1, 2, and 3. It is clear from the deflection analysis that the 3D-printed dial cap could take a load of 214.50 kPa (2 TSF) without generating a significant deflection. Based on the study, we may draw the conclusion that a 3D-printed dial cap instead of a stainless-steel dial cap could be utilized for the oedometer consolidation tests.



*IMC = Initial moisture content of a soil sample.

Figure 12. Effective stress vs. void ratio of the combined settling column and modified oedometer tests.

After reviewing the combined void ratio vs. effective stress curves, we observed that the void ratio decreases more quickly in the settling column test portion than in the modified oedometer test portion. It indicates that the consolidation process is highly nonlinear for the dredged soils with high water contents.

7. Concluding Remarks

Use of the 3D-printed dial caps for the conventional 1-D oedometer test could significantly reduce the seating pressure from 1.07 kPa (0.01 TSF) to 0.21 kPa (0.002 TSF). And thus, the much lighter dial cap could make 1-D conventional oedometer test handle a slurry sample with a water content as high as around 100%. A small-scale settling column self-weight consolidation test and a modified 1-D oedometer test could be combined effectively to conduct consolidation tests for soil slurries with an extremely high moisture content. The procedures presented in this study may provide reliable and tangible consolidation test results of dredged soils for marsh creation projects in coastal Louisiana. The research outcome is very promising for the combination of the modified 1-D conventional oedometer test and small-scale settling column test. By reviewing the settling column test results, it may be recommended that an acrylic plexiglass cylinder with a diameter of six inches or greater could be used for the small-scale settling column test. The wall friction among the three diameter cylinders used in this study is negligible for final settlement. With regard to the hydraulic conductivity and consolidation coefficient in the settling column tests, a cylinder with a greater diameter might give more accurate results. More research needs to be done before a quantitative recommendation is made.

Funding: The research presented in this paper was supported by Louisiana Sea Grant (Grant number: 32-4116-40359). Corresponding author Jay X. Wang has received research grant supports from the funding agency.

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

Author Contributions: All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Omar Shahrear Apu and Jay X. Wang. The first draft of the manuscript was written by the first author and the second author reviewed, commented and revised the manuscript. The two authors read and approved the final manuscript.

Data Availability: Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The research presented in this paper was sponsored by the Coastal Protection and Restoration Authority of Louisiana (CPRA). We are thankful to Dr. David Hall and Dr. Kelly Crittenden for their support and assistance in drawing and printing the dial cap. Support and assistance from Mr. Jacques Boudreaux and Mr. Russ Joffrion are gratefully acknowledged. We are thankful to Ardaman & Associates, Inc. for supplying the dredged soil samples from the No-Name Bayou swamp production site.

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