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Improved Assessment of Estuarine Soils via Nuclear Magnetic Resonance (NMR)

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ABSTRACT: The US Army Corps of Engineers (USACE) seeks to beneficially use 70% of sediment dredged, which equates to approximately 107 to 161 million cubic meters annually. During navigation channel maintenance events, historically, dredged material was disposed offshore or within confined disposal facilities, which removes sediment from coastal systems that are at-risk of converting to open-water due to natural and anthropogenic disturbances. An option to beneficially use dredged material (BUDM) is to supplement platform elevation on degraded marshes, bolstering the long-term stability of natural infrastructure against coastal forcings. Coastal wetlands contribute significantly to protecting coastal infrastructure and populations, providing ecosystem services such as water quality and habitat. These wetland environments are highly contingent on the platform elevation in relation to the tidal frame, so it is imperative to predict settlement within the foundation and dredged material.

The USACE-Philadelphia District is considering a BUDM within the Edwin B. Forsythe National Wildlife Refuge during an upcoming New Jersey Intracoastal Waterway maintenance event. Elevations within the eastern pool of the refuge are insufficient to support the desired habitat, so planners intend to elevate portions of the refuge with dredged material. The refuge is in the back-bay of New Jersey, which has a foundation composed of soft, estuarine deposits that are easily prone to disturbance and generate large degrees of uncertainty during laboratory tests. Thus, to accurately determine soil characteristics and sub-stratification, an in-situ investigation was conducted, combining traditional geotechnical procedures (vibracore and laboratory tests) with in-situ nuclear magnetic resonance (NMR) logging. The combination allowed for the verification of NMR methods to assess moisture content, porosity, and hydraulic conductivity profiles within a wetland environment. Lessons learned from this case study are being implemented in multiple BUDM projects across the United States to improve spatial and temporal soil assessments, which improve modeling abilities.

KEYWORDS: NMR, Vibracore, Beneficial Use of Dredged Material, Wetlands, In-situ, Soft-Soils.

1 INTRODUCTION

To facilitate an ever-growing cargo fleet and ever-enlarging ship capacity, port authorities and waterway managers must dredge more now than ever before, and there has been a trend to use this material beneficially. Specifically, the US Army Corps of Engineers (USACE) maintains over 400 major ports, and 40,000 km of federal waterways, resulting in >190 million cubic meters of dredged material annually. The USACE has the goal to beneficially use 70% of this, equating to 130 million cubic meters of sediment. An ideal use for much of this material is to bolster at-risk coastal wetlands, which have faced serious declines over the past century.

Wetland function (i.e., health) is primarily controlled by wetland surface elevation with respect to water level, and both wetland soils and dredged material can undergo large deformations (i.e., consolidation) so it is imperative to accurately predict this (Morris et al. 2021; Jafari et al., 2024; Harris et al., 2025a). However, wetland soils are notoriously difficult to test due to sample disturbance of the soft materials during collection and transport (Jafari et al. 2018), so in-situ geotechnical methods are a great solution. The key variables to determine from in-situ tests are the magnitude and time-rate of consolidation

Nuclear magnetic resonance (NMR) logging has been used for decades in the oil and gas and water monitoring industries to determine soil porosities and hydraulic conductivities. However, it is relatively unknown in the geotechnical world. To determine its efficacy for coastal restoration projects, NMR soundings were added to a suite of standard geotechnical tests at a future coastal restoration site to compare and evaluate results.

2 METHODOLOGY

2.1 *Overview*

In April 2025, a subsurface soil investigation was conducted across two anticipated dredged material placement areas. Methods consisted of co-located vibracores used to determine index properties and perform 1 dimension consolidation tests, and NMR soundings (Figure 1).

2.2 *Location*

The Edwin B. Forsythe National Wildlife Refuge is in central coastal New Jersey, US. The refuge comprises natural salt marsh and impounded salt marsh, both of which serve as critical habitat for migratory waterfowl. Our study focuses on the East Pool of the marsh that was impounded in the 20th century. Tidal gates control the tidal range (0.15 to 0.2 m), allowing refuge managers to optimize soil conditions for various bird species throughout the year. However, the elevations in the site are decreasing due to the lack of natural mineral sediment deposition and the low tidal ranges which have changed the hydroperiod of the remaining marsh platforms. Much of the site is now open-water habitat with native salt marsh species occupying elevations from 0.2 to 0.3 m relative to the North American Vertical Datum of 1988 (NAVD88), which is equivalent to local mean sea level. At elevations greater than 0.3 m NAVD88, the invasive reed *Phragmites* is common. To support the degrading marsh environment in the pool, the US

Army Corps of Engineers plans to beneficially place dredged material from an adjacent waterway.

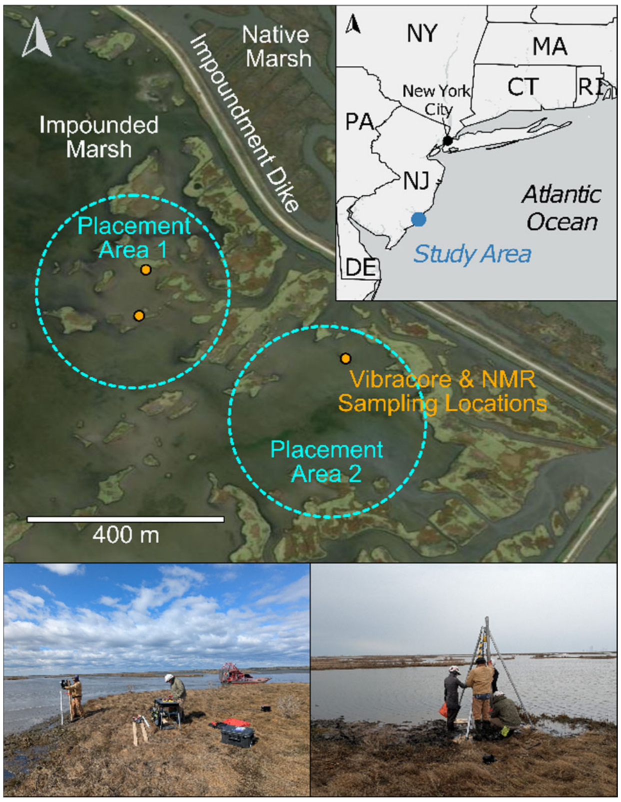

Figure 1. Study Location showing test locations within anticipated placement area.

2.3 *In-Situ Methods*

NMR logging directly measures fluid hydrogen in groundwater. The measurement is conducted with a downhole probe containing magnets that polarize the fluid hydrogen, creating a net nuclear magnetization. During a measurement, coils within the probe transmit radio-frequency electromagnetic (EM) pulses to excite the hydrogen magnetization and measure its response. The measured NMR signal has an initial detected amplitude and decays over time. The signal amplitude and decay rate provide information about the in-situ hydrogeologic properties of the investigated volume. The initial amplitude is proportional to the quantity of fluid hydrogen present and therefore provides a measure of the volumetric water content and, if the formation is fully saturated, the porosity. The decay time of the signal (T_2) decreases as the number of interactions between the fluid and pore walls increases, thereby providing an indicator of pore size distribution: shorter T_2 times indicate that water is contained in smaller pores (or bound in clays) and longer T_2 times indicate that water is contained in larger pores.

In total, three (3) NMR logs were performed within a 5.08 cm (2 inch) polyvinyl chloride tube down to an approximate depth of 3-m below ground surface at three sites (Figure 1). However, data is shown down to 2.5-m for comparison purposes. In saturated conditions, the volumetric water content measured from the NMR is equal to the porosity and from porosity, void ratio profiles were determined via the following equation:

$$e = \frac{\varphi}{1-\varphi} \qquad (1)$$

where e is void ratio and φ is porosity. Hydraulic conductivities were determined from the NMR using the following equation:

$$K_{TC} = C_{TC}\varphi^{M}\left(\frac{FFI}{BVI}\right)^{2}$$

This Timur-Coates equation (K_{TC}) is based on the total porosity (φ) and ratio of the "free-fluid index" (*FFI*), which is the estimated mobile water, and bulk-volume-irreducible" (*BVI*), which is the estimated bound water. The coefficient () and exponent M are empirical factors adjusted for lithologies. For these analyses, the sediments were considered unconsolidated (Knight et al., 2016).

2.4 *Sediment Collection and Analysis*

Vibracores were collected using a motorized vibrating head clamped to a 3m (10 ft) thin walled 7.6 cm (3 inch) diameter aluminum irrigation pipe at three locations across the proposed dredged material placement site (Figure 1). At each sampling location, two cores were collected within 0.5 m of each other, allowing one core to be rapidly opened, photographed, described, and subsamples collected for grain size analysis via laser diffraction particle size analysis and water content and organic content via LOI. The second core was kept undisturbed for 1-D consolidation testing, Atterberg Limits, and specific gravity, *Gs*, within the laboratory. Sediment descriptions were used to identify core sections for 1-D consolidation testing. Void ratios, e, were determined from the gravimetric water contents via the following formula:

$$Se = wGs \qquad (3)$$

Where *S* is saturation and *Gs* is specific gravity determined via ASTM.

3 RESULTS AND DISCUSSION

Figure 2 shows a processed NMR log. The leftmost panel shows the decay time distribution, with energy at shorter times indicating water in smaller pores and energy at longer times indicating water in larger pores. The middle panel shows the volumetric water content, with subfractions indicating water in larger pores, i.e., more mobile (dark blue), water in smaller pores, typically capillary-bound (light blue), and water bound in clays (light brown). In this log, the overall water content, as well as the subfraction of large-pore water, both peak at around 0.4m below the ground surface. The right panel shows residual noise, which is uniformly excellent this this log.

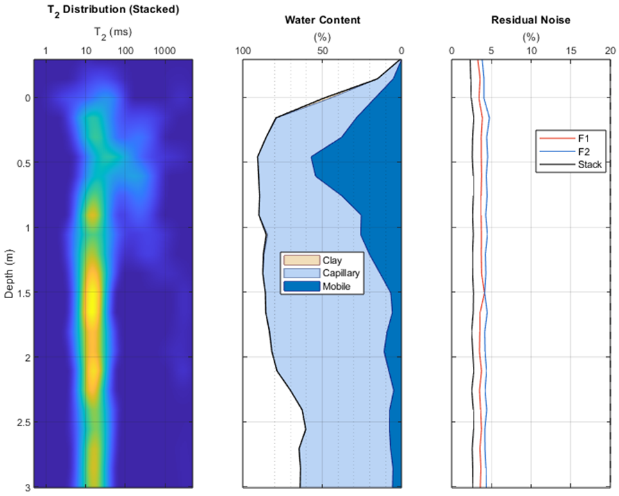

Figure 2. Example NMR plot of T2 distribution, volumetric water content, hydraulic conductivity, and residual noise.

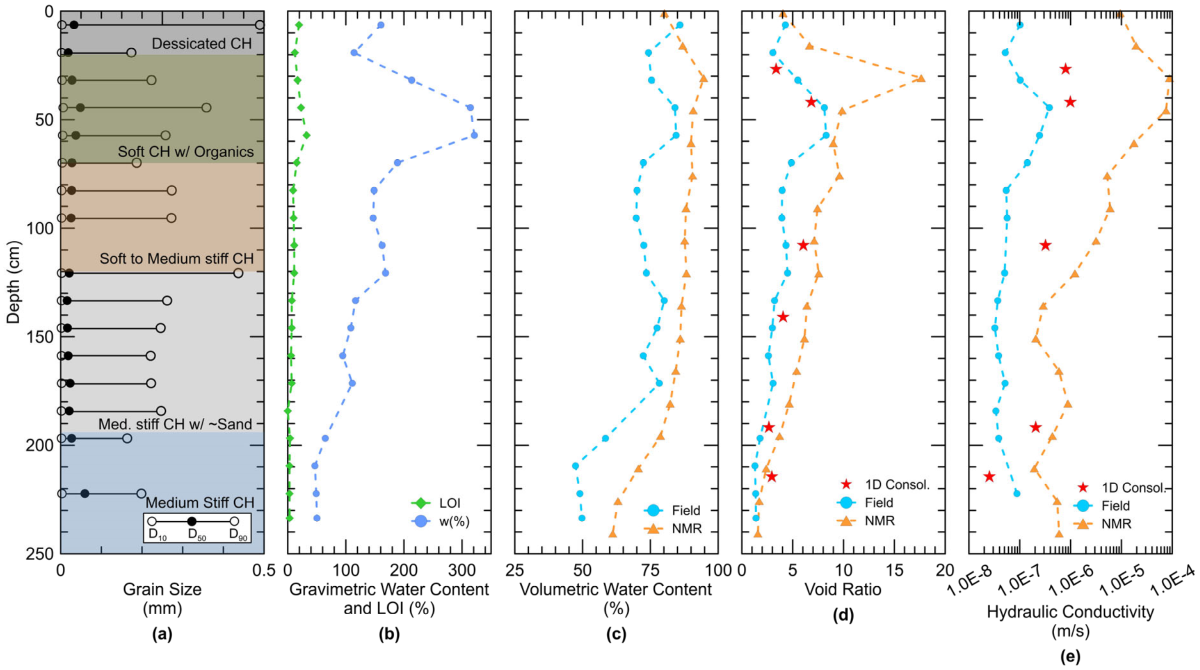

FIGURE 3. Subsurface data from Site 2 showing (a) grain size (D_{10}, D_{50}, D_{90}), (b) Gravimetric Water Content and Organic Content (LOI), (c) Volumetric water content from field samples and NMR, (d) void ratios from field samples, 1D Consolidation tests, and NMR, and (e) hydraulic conductivities from field samples, 1D Consolidation tests, and NMR.

The general subsurface stratigraphy across the site comprised a 21-cm thick surficial layer of high plasticity clay (CH) with approximate gravimetric water contents and organic contents of 145% and 13%. This layer was underlain by a more compressible 47-cm thick clay layer that exhibited higher *w(%)* and *LOI* values at 247% and 19%. Below this was a 59-cm thick clay layer with increased stiffness and lower *w(%)* and *LOI* of 143% and 9%, respectively. The sediment continued to increase in stiffness and decreases in w(%) at 102% and 6%. The final layer encountered was the stiffest, comprising a medium stiff CH with *w(%)* <50% and <4% organics.

Volumetric water contents measured from the NMR compared well to the values determined from the field samples. Values showed distinct peaks (84% and 94% for field and NMR respectively) within the soft CH layer underneath the desiccated top layer and proceeded to decrease with depth. Since field samples were not directly measured but approximated using bulk densities determined from the consolidation tests, it is possible that the NMR and field values could be closer if more soil bulk density measurements were collected.

Void ratios determined from the field samples (using equation 3) compared well with void ratios provided from the consolidation tests. As with the volumetric water contents, void ratios peaked within the organic-rich layer directly below the desiccated surface layer and proceeded to decrease with depth. Void ratios determined via the NMR (using equation 1) exhibited a value of over 15 within this soft clay layer, which is much higher than typically expected. Standard geotechnical reports rarely show void ratios above 3 to 5 for soft, organic clays, while coastal geotechnical reports can report up to nearly 10 (Terzaghi et al. 1996; Harris et al. 2025b). However, the authors believe that despite this site being routinely inundated, the soil may not have been completely saturated leading to an unnaturally high void ratio estimation from the NMR at ~30-cm. However, once below a depth of 50-cm, NMR measurements compared well with field and consolidation values.

Hydraulic conductivities from the consolidation tests were back calculated using volume compressibility and Mv and this method has been documented to be off as much as an order of magnitude when compared to directly measured values (Tavenas et al., 1983; Jafari et al. 2019). Thus, the field and NMR derived hydraulic conductivities are acceptable, being approximately within an order of magnitude of each other. In addition, Harris et al. 2025 has shown that overall magnitudes of consolidation (determined via void ratio and compression index) are more important to the overall outcome of the wetland restoration that the rate of consolidation (determined via hydraulic conductivities) so this deviation is acceptable.

4 CONCLUSIONS

This study applied the NMR technique alongside more traditional geotechnical methods to determine consolidation parameters of a future wetland restoration project. The final wetland surface elevation with respect to water level is the dominate controlling factor behind future project success so it is imperative to accurately model consolidation of the dredged material and foundation material. Below a depth of 50-cm, the NMR provided comparable data against field and laboratory measurements for both the void ratio and hydraulic conductivity measurements showing the potential benefits that NMR can offer in coastal restoration efforts. However, additional work is required to determine the overall benefit it can offer when compared to traditional laboratory methods.

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