

FINAL REPORT

Improved Penetrometer Performance in Stratified Sediment for
Cost-Effective Characterization, Monitoring and Management of
Submerged Munitions Sites

SERDP Project MR18-1233

JUNE 2020

Nina Stark
Virginia Tech

Grace M. Massey
Carl T. Friedrichs
Virginia Institute of Marine Sciences

Distribution Statement A

This document has been cleared for public release



Page Intentionally Left Blank

This report was prepared under contract to the Department of Defense Strategic Environmental Research and Development Program (SERDP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

Page Intentionally Left Blank

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 01-06-2020		2. REPORT TYPE SERDP Final Report		3. DATES COVERED (From - To) June 2018 - June 2020	
4. TITLE AND SUBTITLE Improved Penetrometer Performance in Stratified Sediment for Cost-Effective Characterization, Monitoring, and Management of Submerged Munitions Sites				5a. CONTRACT NUMBER W912HQ-18-C-0034	
				5b. GRANT NUMBER N/A	
				5c. PROGRAM ELEMENT NUMBER N/A	
6. AUTHOR(S) Nina Stark, Grace M. Massey, Carl T. Friedrichs				5d. PROJECT NUMBER MR18-1233	
				5e. TASK NUMBER N/A	
				5f. WORK UNIT NUMBER N/A	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Virginia Tech, Charles E. Via, Jr., Department of Civil & Environmental Engineering, Blacksburg, VA 24060, ninas@vt.edu				8. PERFORMING ORGANIZATION REPORT NUMBER MR18-1233	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Strategic Environmental Research and Development Program 4800 Mark Center Drive, Suite 16F16, Alexandria, VA 22350-3605				10. SPONSOR/MONITOR'S ACRONYM(S) SERDP	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) MR18-1233	
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Geomechanical properties of seafloor surface sediment layers affect the characterization, assessment, and management of submerged munitions sites in multiple aspects. The overarching goal of project MR 18-1233 is the development and proof of concept of an improved framework for the deployment and data analysis of a portable free fall penetrometer (PFFP) in stratified sediments to assist with a cost-effective and rapid characterization, monitoring, and management of submerged munitions sites. The research strategy included field surveys, laboratory testing, data analysis and correlation, and the development of a novel investigation framework. The key findings of this project are: 1) Current methods of PFFP data analysis were improved and validated. Undrained shear strength can be estimated from PFFP for muddy seafloor sediments. Friction angles and relative density can be derived from PFFP for sandy seafloor sediments. 2) Significant variations in geomechanical properties within uppermost seabed surface layers were identified even without significant changes in sediment type. The results suggested that uppermost seabed surface layers may exhibit more suspension-like behavior than soil behavior depending on the water content. 3) The variability in geomechanical properties is of relevance to UXO site assessment and monitoring. 4) A novel PFFP deployment and analysis strategy was formulated that enables a rapid and cost-effective characterization of the upper meter of the seabed surface. The results provide a new insight into effects of geomechanical seabed soil layers on the interpretation of remotely sensed UXO site monitoring methods and UXO risk assessment.					
15. SUBJECT TERMS portable free fall penetrometer; seafloor surface layering; geomechanical properties; data analysis framework					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 38	19a. NAME OF RESPONSIBLE PERSON Nina Stark
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 540-231-7152

Page Intentionally Left Blank

Table of Contents

Abstract	1
Executive Summary	2
<i>Introduction</i>	2
<i>Objectives</i>	3
<i>Technical Approach</i>	3
<i>Results and Discussion</i>	4
a) <i>Correlate PFFP measurements with geomechanical properties and the development of relationships</i>	4
b) <i>Differences in geomechanical properties of different seafloor surface layers</i>	7
c) <i>Impact on current surveying and monitoring methods</i>	7
d) <i>Novel PFFP data analysis and deployment framework for PFFP site assessment</i>	7
<i>Implications for Future Research and Benefits</i>	8
Objective	10
Background	11
Materials & Methods	11
Results & Discussion	13
a) <i>Correlate PFFP measurements with geomechanical properties and the development of relationships</i>	13
b) <i>Differences in geomechanical properties of different seafloor surface layers</i>	16
c) <i>Impact on current surveying and monitoring methods</i>	17
d) <i>Novel PFFP data analysis and deployment framework for PFFP site assessment</i>	17
Conclusions & Implications for Future Research/Implementation	18
Literature Cited	21
Appendices	25
A. Supporting data	25
B. List of Scientific/Technical Publications	25
C. Supporting Materials	27

List of Tables

N/A

List of Figures

Figure E1. Conceptual sketch of potential issues for UXO site assessment and management associated with variations of geomechanical properties and layering of seafloor surface sediments.....	2
Figure E2. Flow chart providing overview over theoretical and empirical relationships between geomechanical properties and PFFP measurements based on literature.....	5
Figure E3. Estimated undrained shear strength from PFFP profiles without application of strain rate correction for ten muddy sites. Vane shear results are shown as dots. (Kiptoo et al., in prep. a).....	6
Figure E4. Flow chart of proposed PFFP data analysis framework. Solid arrows refer to high confidence relationship. Dashed arrows refer to available relations with need for further improvement regarding broader grain size distributions. The resulting properties can be further related as shown in Figure E2.....	8
Figure 1. Conceptual sketch of potential issues for UXO site assessment and management associated with variations of geomechanical properties and layering of seafloor surface sediments.....	10
Figure 2. Flow chart providing overview over theoretical and empirical relationships between geomechanical properties and PFFP measurements based on literature.....	13
Figure 3. Undrained shear strength estimated from PFFP deployments at Indian Creek with a logarithmic (left) and power law strain rate correction (right). The different lines express results for different strain rate factors k and β , respectively, and for the shown cone factors N_k . The black dots indicate vane shear results. (Kiptoo et al., in prep. a).....	14
Figure 4. Estimated undrained shear strength from PFFP profiles without application of strain rate correction for ten muddy sites. Vane shear results are shown as dots. (Kiptoo et al., in prep. a).....	15
Figure 5. Erodibility in terms of eroded mass per critical shear stress for sediment samples from the visited sites determined using a Gust microcosm apparatus.....	16
Figure 6. Porosity versus wet bulk density of muddy sediments from the York River and from the literature	16
Figure 7. Stratification shown in X-ray imaging of a gravity core and a box core. Please note that intensity units between these cores should not be directly and quantitatively compared due to differences in core shape (round vs rectangular).....	17
Figure 8. Flow chart of proposed PFFP data analysis framework. Solid arrows refer to high confidence relationship. Dashed arrows refer to available relations with need for further improvement regarding broader grain size distributions. The resulting properties can be further related as shown in Figure 2.....	19

List of Acronyms

ADCP	Acoustic Doppler Current Profiler
CB	Clay Bank
CPT	Cone Penetration Test
CTD	Conductivity-Temperature-Depth
FFP	Free Fall Penetrometer
MR	Munition Response
PFFP	Portable Free Fall Penetrometer
PI	Primary Investigator
SERDP	Strategic Environmental Research and Development Program
SON	Statement of Need
UXO	Unexploded Ordnance
VIMS	Virginia Institute of Marine Sciences
VT	Virginia Tech

Keywords

portable free fall penetrometer; seafloor surface layering; geomechanical properties; data analysis framework

Acknowledgments

The investigators would like to acknowledge constructive feedback and support from the SERDP team during this project. Furthermore, the investigators would like to thank the group of graduate students from Virginia Tech and from the Virginia Institute of Marine Science for their dedication and contributions to data collection, data analysis, and dissemination of results, namely Dennis Kiptoo and Cristin Wright, and the Coastal Geotechnics graduate student team from Virginia Tech and the graduate and undergraduate student team and staff from the Coastal Hydrodynamics and Sediment Dynamics from the Virginia Institute of Marine Science. The investigators acknowledge Bernardo Castellanos for his assistance and feedback regarding geotechnical laboratory testing. Also, the investigators would like to thank other SERDP MR PIs who provided constructive feedback and/or opportunities for collaborations, particularly Joe Calantoni, Art Trembanis, and Carter Duval should be mentioned.

Abstract

Introduction & Objectives. Geomechanical properties of seafloor surface sediment layers affect the characterization, assessment, and management of submerged munitions sites in multiple aspects including: sinkage and burial of unexploded ordnances (UXO), exposure or capping of UXOs through sediment transport processes, and interpretation of remote sensing (e.g., acoustic and electromagnetic) surveying methods. Traditional methods of seafloor sampling or cone penetration testing (CPT) are either time- and cost-intensive or do not provide the required sensitivity to sample sediments in the uppermost surface accurately. Free fall penetrometers (FFP) have been introduced as a cost- and time-effective method to assess the geomechanical properties of seabed surface properties and have been specifically suggested for UXO characterization. The overarching goal of project MR 18-1233 is the development and proof of concept of an improved framework for the deployment and data analysis of a portable free fall penetrometer (PFFP) in stratified sediments to assist with a cost-effective and rapid characterization, monitoring, and management of submerged munitions sites.

Technical Approach. The following research questions were identified as essential to achieve this goal: 1) What are the typical differences in geomechanical properties (such as sediment strength, erodibility, and permeability) between surficial seafloor layers in sandy and muddy environments, respectively? 2) Can key geomechanical properties for UXO site characterization be directly inferred from portable free fall penetrometer results? 3) Which potential uncertainties of current UXO site characterization and monitoring methods resulting from surficial seafloor stratification can be addressed by an advanced use of PFFP? The research strategy included field surveys in areas of varying sediment types and environmental conditions, laboratory testing (sedimentology and geomechanics), data analysis and correlation, and the development and proof of concept of a novel investigation framework. Seven main field sites were tested during this experiment and were complemented by additional measurements obtained through collaborative efforts.

Key Results. The key findings of this project include: 1) Current methods of PFFP data analysis were improved and validated. It was found that undrained shear strength can be estimated from PFFP for muddy seafloor sediments and that friction angles and relative density can be derived from PFFP for sandy seafloor sediments. 2) Significant variations in geomechanical properties within uppermost seabed surface layers were identified even without significant changes in sediment type. The results even suggested that uppermost seabed surface layers may exhibit more suspension-like behavior than soil behavior depending on the water content. 3) The variability in geomechanical properties is of relevance to UXO site assessment and monitoring. 4) A novel PFFP deployment and analysis strategy was formulated that enables a rapid and cost-effective characterization of the upper meter of the seabed surface.

Benefits. The results provide a new insight into effects of geomechanical seabed soil layers on the interpretation of remotely sensed UXO site monitoring methods and UXO risk assessment. The derived relationships improve PFFP data analysis and interpretation for geomechanical characterization of subaquatic sites. The developed PFFP deployment and analysis framework can provide rapid, site-specific insights into spatial and sediment-depth dependent variations in geomechanical properties.

Executive Summary

Introduction

Geomechanical properties of seafloor surface sediments and sediment layers affect the characterization, assessment, and management of submerged munitions sites in multiple aspects including: sinkage and burial of unexploded ordnances (UXO), exposure or capping of UXOs through sediment transport processes, and interpretation of remote sensing (e.g., acoustic and electromagnetic) surveying methods (Fig. E1). Traditional methods of seafloor sampling or cone penetration testing (CPT) are either time- and cost-intensive or do not provide the required sensitivity to sample sediments in the uppermost surface accurately (e.g., Blomqvist 1991; Lunne 2012). Free fall penetrometers (FFP) have been introduced as a cost- and time-effective method to assess the geomechanical properties of seabed surface properties and have been specifically suggested for UXO characterization (Mulhearn 2002; Wilkens 2003; Richardson and Valent 2004; Stoll et al. 2007; Zhang et al. 2007; Abelev et al. 2009; Stark and Wever 2009). However, limitations in data analysis have been identified that still restrict the direct application of FFP for UXO site assessment (Stoll et al. 2007; Abelev et al. 2009; Stark and Wever 2009; Stark et al. 2012; Chow et al. 2017). The overarching goal of project MR 18-1233 is the development and proof of concept of an improved framework for the deployment and data analysis of a portable free fall penetrometer (PFFP) in stratified sediments to assist with a cost-effective and rapid characterization, monitoring, and management of submerged munitions sites. The following research questions were identified essential to achieve this goal: 1) What are the typical differences in geomechanical properties (such as sediment strength, erodibility, and permeability) between surficial seafloor layers in sandy and muddy environments, respectively? 2) Can key geomechanical properties for unexploded ordnances (UXO) site characterization be directly inferred from portable free fall penetrometer results? 3) Which potential uncertainties of current UXO site characterization and monitoring methods resulting from surficial seafloor stratification can be addressed by an advanced use of portable free fall penetrometers? The research strategy included field surveys in areas of varying sediment types and environmental conditions, laboratory

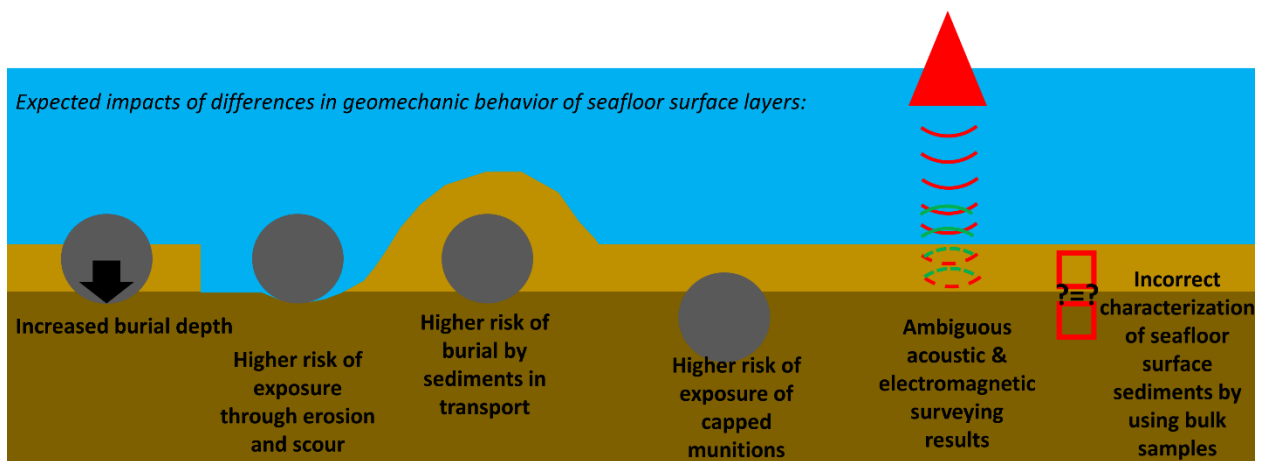


Figure E1. Conceptual sketch of potential issues for UXO site assessment and management associated with variations of geomechanical properties and layering of seafloor surface sediments.

testing (sedimentology and geomechanics), data analysis and correlation, and the development and proof of concept of a novel investigation framework.

Objectives

Sediment stratification at the uppermost surface of subaqueous sediments can vary in dimensions, physical characteristics, and behavior. The top layer often exhibits lower density and strength, and higher erodibility and mobility. This impacts munition deposition, burial depth, and stability, as well as most surveying methods, and can lead to significant issues with munition detection, monitoring, and munition site management (Fig. E1).

Portable free fall penetrometers (PFFPs) have been shown to be a cost-effective tool to characterize a munitions site. However, the calibration process previously used tends to blur interpretation of the data within seabed sediment strata. The key hypotheses of this project were:

1. Seafloor surface layers can exhibit significant differences in geomechanical properties, impacting current UXO site surveying and monitoring, as well as UXO burial/exposure risk assessment.
2. PFFP data analysis methods can be advanced to help to assess relevant geomechanical properties at UXO sites, and particularly at sites featuring surficial seabed stratification, in a rapid and cost-effective manner by complementing and supporting current methodologies.

These research hypotheses are directly in line with one of the objectives of the Statement of Need (SON) MRSON-18-C1: the improvement of the current knowledge of environmental conditions, specifically, sediment characteristics, of underwater sites that impact the performance of sensors and systems to detect and classify buried and proud munitions. In this project, a novel investigation framework was developed and initially tested. This framework enables MR investigators to conduct a rapid and cost-effective PFFP site characterization of seafloor surface layering. This PFFP characterization provides information that helps assess potential uncertainties when using acoustic/visual seafloor inspection, that can be used to estimate munition burial depth at impact, and, therefore, that aids in assessment of risks of munition exposure or burial related to the sediment's geomechanical behavior and layering.

Technical Approach

The research strategy of this project included four main parts: 1) The collection of a comprehensive set of field measurements and sediment sampling from locations of varying environmental conditions; 2) a detailed geotechnical and sedimentological characterization of sediments from all tested field sites based on laboratory testing; 3) data analysis and synthesis towards addressing the stated research questions and hypotheses; and 4) the development of a novel investigation framework using PFFP and a field demonstration.

Field testing sites included seven areas in the Pamunkey-York River tidal system (hereafter termed York River), which feeds into the Chesapeake Bay. Seafloor sediments were predominantly muddy at four of these sites and predominantly sandy at the remaining three sites. Salinity and flow conditions varied between most sites. These sites were chosen for their differences in environmental conditions while still being located conveniently close to each other. Additional data sets were integrated into this data base based on relevance to the project goals. They provided a wider range of environmental conditions. This included two additional sites in Virginia (Piankatank River and James River), Sydney Harbour, Nova Scotia, Canada, and sites in Delaware Bay. Most of these data collections were in collaboration with other SERDP investigators. Furthermore, some locations in the York River were revisited with diver support

based on feedback during the In-Progress Review meeting. All seven York sites were investigated using a consistent testing program with: more than 10 PFFP deployments per site using the PFFP *BlueDrop*; sediment sampling/coring using box coring, Ponar grab sampling, gravity coring (muddy sites), vibrocoring (sandy sites), and/or diver push cores for chosen sites; acoustic measurements using an acoustic Doppler current profiler (ADCP) for assessment of flow conditions, chirp sonar, and in some locations rotary side scan sonar imaging; and, conductivity-temperature-depth (CTD) measurements. The *BlueDrop* PFFP was chosen for its ruggedness and suitability for deployment in most environmental conditions and its speed of deployment (about 1 minute per deployment in coastal water depths). Additional sites featured at least 10 PFFP deployments, the collection of sediment samples, and some acoustic seabed surveying.

All sediment samples collected at the main sites of this project were analyzed in great detail through sedimentological (grain size, bulk density, organic content, X-ray imaging, and erodibility measurements) and geotechnical (friction angles, cohesion, undrained shear strength, state of consolidation, void ratios) laboratory testing. The cores enabled an analysis to a sediment depth equaling the penetration depth of the PFFP (~ 1 m). Depth intervals of 1 – 10 cm were subsampled and tested, with 1 cm increments typically being applied in the top 10 cm of the sediment cores.

The analysis and synthesis of the collected field and laboratory data was committed to answering the research questions stated, and by doing so, testing the project's key hypotheses. Firstly, PFFP measurements were correlated to the geomechanical properties derived from the sediment sampling and laboratory testing, and those correlations were used towards the development of relationships to estimate geomechanical properties from PFFP measurements. Special attention was given to deriving undrained shear strength. Secondly, sediment properties were evaluated along vertical profiles into the bed with special attention to changes with sediment depth (layering). Finally, a discussion was provided regarding impacts on surveying and monitoring strategies that arise from the variations in geomechanical properties between the different layers and soil conditions.

This project concluded with the development of a novel investigation framework and strategy for utilizing PFFP for rapid and cost-efficient UXO site characterization. A strategy was developed based on the results from the previous tasks, and was demonstrated through a proof-of-concept field study conducted in the Potomac River, Maryland, in 2019.

Results and Discussion

a) Correlate PFFP measurements with geomechanical properties and the development of relationships

PFFP featuring a simplicity and ruggedness to be deployed rapidly in varying environmental conditions and from different types of deployment platforms often offer only measurements of acceleration and pore pressure with time. Based on existing literature, it was hypothesized that a better correlation between geomechanical properties and PFFP measurements can be achieved if the data analysis strategy is adjusted to different soil types. More specifically, it is suggested to differentiate between cohesionless, cohesive, and mixed sediments. It is expected that mixed sediments will collapse towards an either cohesionless or cohesive behavior depending on the specific mixtures. Therefore, special attention was given to the cohesionless and cohesive sediments. From further literature review, it was determined that for cohesionless sediment, a correlation to friction angle and relative density should be sought, where friction angle is expected to be related to erosional parameters and relative density is expressing porosity (Fig. E2). For

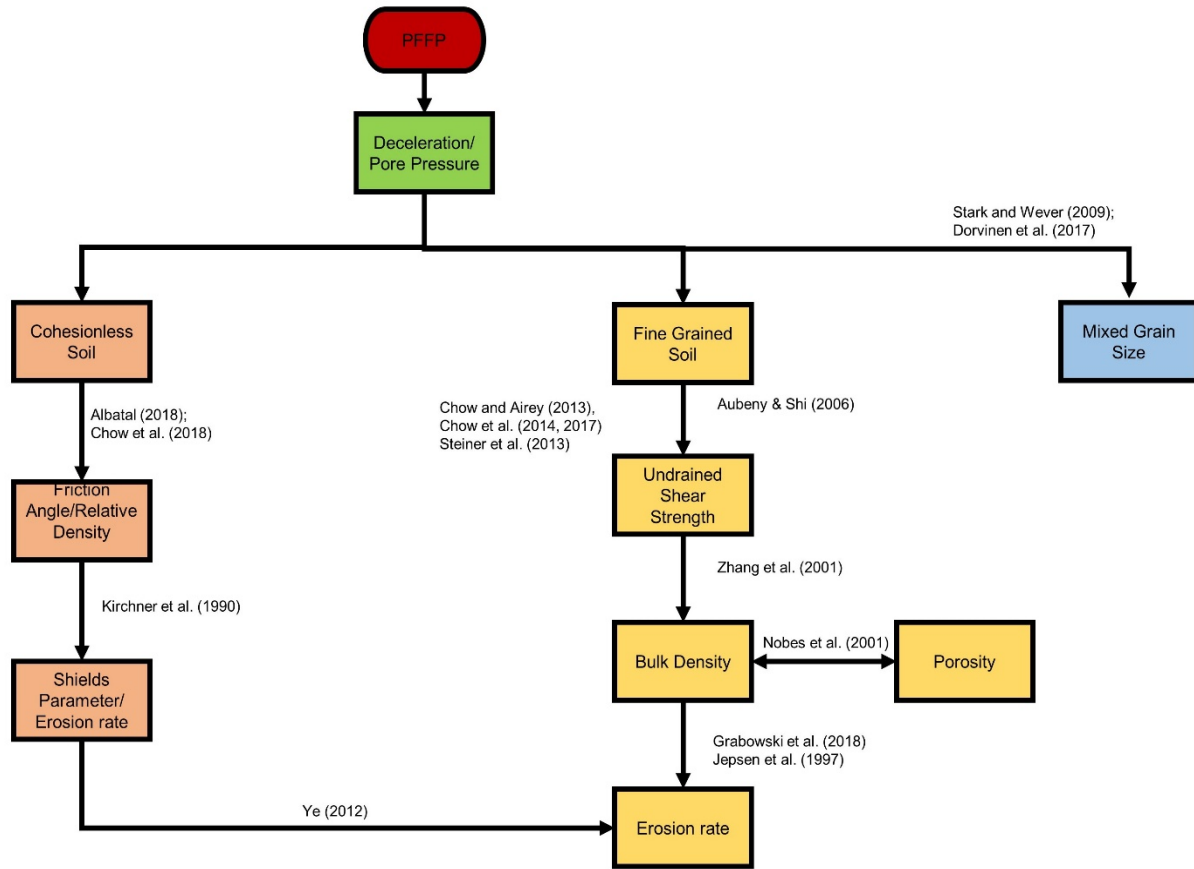


Figure E2. Flow chart providing overview over theoretical and empirical relationships between geomechanical properties and PFFP measurements based on literature.

cohesive sediments, it is proposed to estimate undrained shear strength, which is expected to be related to bulk density which, in turn, is related to erosional parameters as well as porosity (Fig. E2).

The collected data set allowed a significant step towards a confident derivation of undrained shear strength from the acceleration measurements. The conceptual method, as suggested by, e.g., Dayal and Allen (1973), Aubeny and Shi (2006), or Stoll et al. (2007), was tested. This method includes the following major steps: 1) Derive the total resistance force from the measured deceleration during impact and the known buoyant weight of the probe using Newton's Law; 2) Calculate the associated stress from the resistance force using the projected surface area of the nose cone of the probe; 3) Apply a strain rate correction to simulate the stresses for a chosen constant penetration velocity (usually 2 cm/s in line with standard CPT testing; Lunne et al. 2012); and 4) Apply an empirical cone factor to account for the shearing principle of using a conical penetrator. Different strain rate correction methods were tested, and strain rate and cone factor correction factors were determined iteratively based on comparison to laboratory vane shear results. The results suggested that the undrained shear strength can be successfully determined from the PFFP results with cone factors in ranges as reported by other studies before (e.g., Aubeny and Shi 2006). Strain rate effects were found approximately negligible. Therefore, it was tested if

similarly agreeable estimates of undrained shear strength could be derived when omitting the strain rate correction (Fig. E3). The results confirmed that no strain rate correction is needed for this type of PFFP for muddy sediments with an undrained shear strength of 1-10 kPa, simplifying the data processing method by omitting the need to estimate one of two empirical factors. It was also found that a cone factor of $N_k=12$ represents a good first estimate with N_k varying in a similar range and with similar behavior as for traditional CPT. A conference paper (Kiptoo et al. 2019), a conference presentation at the Ocean Sciences Meeting (Kiptoo et al. 2020), and a journal manuscript (Kiptoo et al., in preparation a) resulted from these findings.

A significant mismatch between the undrained shear strength determined by the PFFP and the vane shear was noted in the uppermost sediment layers (undrained shear strength $s_u \lesssim 1.5$ kPa). The vane shear appeared unable to record the softness of the seabed sediments as suggested by the PFFP. This was further confirmed through the extraction of diver push cores, as well as the analysis of water content and bulk density in which these sediments were found to have water contents above the liquid limit, suggesting a liquid-like response and no plastic behavior. The issue was further investigated using rheological testing of the samples. Preliminary results suggest that these top layers can be better described by their rheological behavior than through traditional soil behavior (i.e., viscosity could be reported from the penetrometer results). A presentation at the

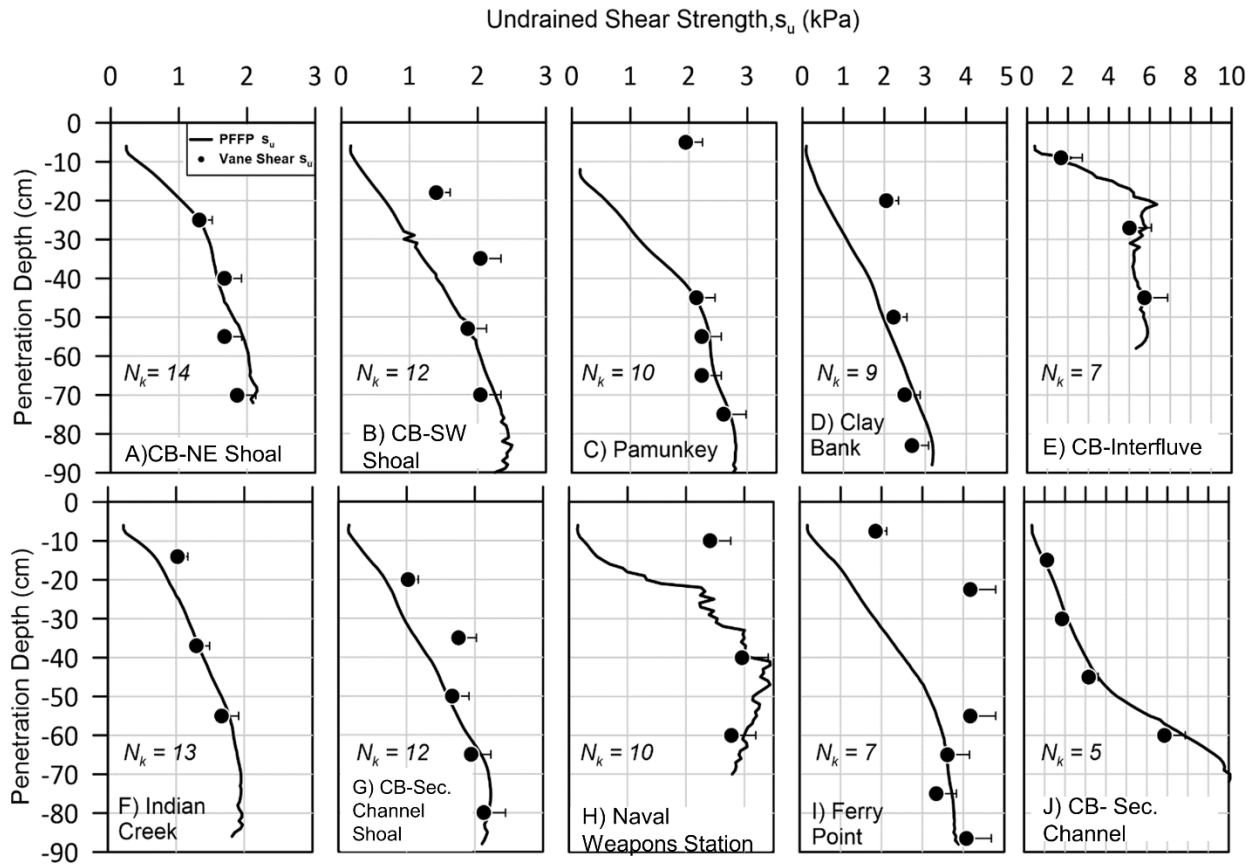


Figure E3. Estimated undrained shear strength from PFFP profiles without application of strain rate correction for ten muddy sites. Vane shear results are shown as dots. (Kiptoo et al., in prep. a)

Ocean Sciences Meeting (Stark et al. 2020) and a journal manuscript (Kiptoo et al., in preparation b) resulted from this.

In line with the variations in undrained shear strength measured at the different sites (Fig. E3), differences in erodibility, sedimentology, and other geomechanical properties were observed, enabling the testing, and if needed, adjustment of existing correlations that were previously identified from the literature (Fig. E2). A journal manuscript is in preparation based on these results (Stark et al., in preparation). PFFP tests at sandy sites were analyzed based on the method suggested by Albatal et al. (2020) and achieved agreeable results regarding friction angles and relative density.

b) Differences in geomechanical properties of different seafloor surface layers

The PFFP results identified significant variations in undrained shear strength (Fig. E3), friction angle, and relative density with sediment depth within the upper meter of the seabed surface. Such differences were so severe in some cases that top layers (sediment depth $\leq 10\text{-}30$ cm) may be better described in terms of rheology (i.e., plastic or liquid flow) rather than soil behavior (with shear strength). This observation was also confirmed from carefully extracted diver cores and box cores. Furthermore, related geomechanical properties such as erodibility and porosity varied as well with the observed variations in undrained shear strength, friction angle, and relative density. Neither gravity cores nor vibrocores were able to sample the soft seabed surface. It follows that seafloor surface layers can exhibit significant differences in geomechanical properties, impacting current UXO site surveying and monitoring, as well as UXO burial/exposure risk assessment (hypothesis 1).

c) Impact on current surveying and monitoring methods

Undrained shear strength varied significantly within the uppermost meter of the seabed surface. This impacts directly UXO stability and burial. Particularly, the soft seabed surface sediments ($s_u < 2$ kPa) will unlikely be able to support a UXO, leading to sinking towards deeper sediment depths. Similarly, differences were noted in erodibility, leading to potentially strong variations regarding scour or capping through sediment transport processes. By ignoring the differences in these properties at the seabed surface, sinking will likely be underestimated, and scour and capping may be predicted incorrectly. Variations in soil porosity, water content, and bulk density were related to the PFFP measurements and also showed significant variations for the different sites and with sediment depth. This means that assuming a constant porosity for a certain general sediment types with depth or just by soil type will lead to biased interpretations of acoustic penetration depth and backscatter in the interpretation of acoustic surveying tools.

d) Novel PFFP data analysis and deployment framework for PFFP site assessment

PFFP deployments were performed along gridded transects to cover a previously unsampled river bed area in the Potomac River near Blossom Point, MD. Within less than 12 hours, the PFFP deployments and initial analysis were carried out. The latter suggested the presence of four different sediment type groups in the tested area. The four groups were confirmed by sediment sampling and laboratory analysis (Kiptoo et al. 2019) and were also distinguishable regarding chirp sonar backscatter intensity (Jaber et al., submitted). Therefore, the PFFP deployment framework was found successful regarding a rapid and cost-efficient seafloor surface (< 1 m) assessment

targeting geomechanical properties and stratification. The relationships identified in this study enable the derivation of geomechanical properties relevant to UXO site surveying, monitoring, and assessment. The results suggested that remote sensing techniques would likely benefit from calibration using the geomechanical seabed profiles. Therefore, key hypothesis 2 of this project (see section 2) was confirmed: PFFP data analysis methods can be advanced to help to assess relevant geomechanical properties at UXO sites, and particularly sites featuring surficial seabed stratification, in a rapid and cost-effective manner by complementing and supporting current methodologies.

Implications for Future Research and Benefits

The key findings of this project include:

- Current methods of PFFP data analysis were improved and validated. It was found that undrained shear strength can be estimated from PFFP for muddy seafloor sediments and that friction angles and relative density can be derived from PFFP for sandy seafloor sediments.
- Significant variations in geomechanical properties within uppermost seabed surface layers were identified even without significant changes in sediment type. The results suggested that uppermost seabed surface layers may exhibit more fluid-like behavior than soil behavior depending on the water content.
- The variability in geomechanical properties is of relevance to UXO site assessment and monitoring.
- A novel PFFP deployment and analysis strategy was formulated that enables a rapid and cost-effective characterization of the upper meter of the seabed surface.

The PFFP analysis strategy derived from this project is summarized in Figure E4. This considers that the PFFP raw data includes acceleration/deceleration measurements and possibly pore

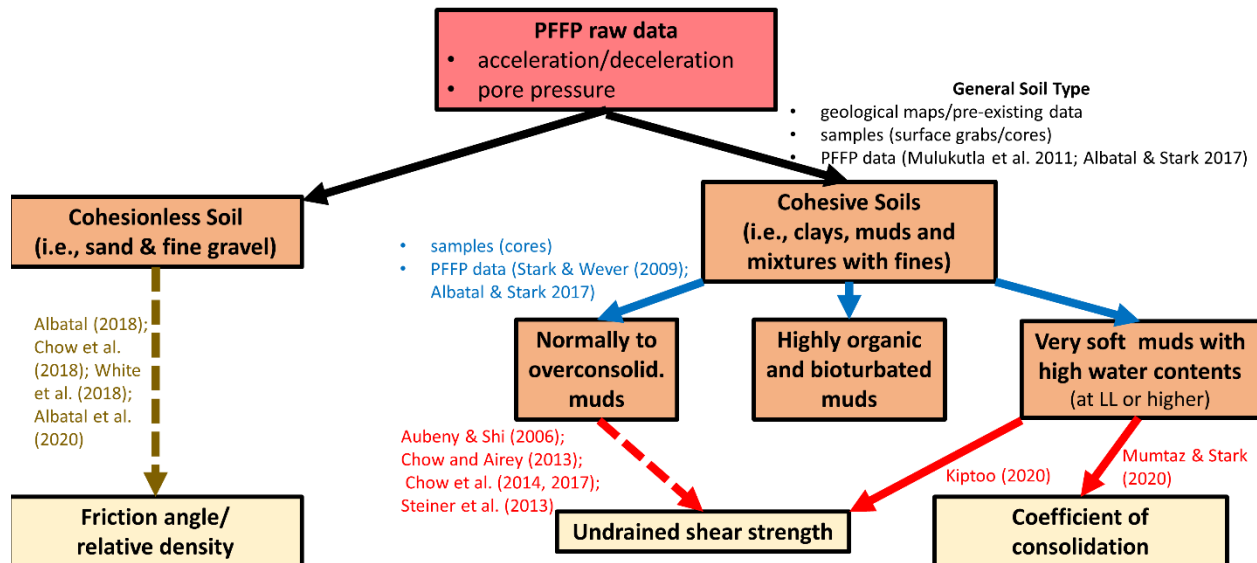


Figure E4. Flow chart of proposed PFFP data analysis framework. Solid arrows refer to high confidence relationship. Dashed arrows refer to available relations with need for further improvement regarding broader grain size distributions. The resulting properties can be further related as shown in Figure E2.

pressure measurements in line with the PFFP used in this study as well as modern PFFP capabilities. Furthermore, it is assumed that general information on soil type are available from geological maps or pre-existing data, sediment samples, and/or can be inferred from remote sensing techniques and/or PFFP data. Mulukutla et al. (2011) introduced the firmness factor derived from PFFP data and demonstrated its correlation to sediment types. Albatal and Stark (2017) proposed a combined use of deceleration and pore pressure data collected by a PFFP to assess general sediment type. Key categories for the recommended PFFP data analysis are cohesionless (i.e., sand & fine gravel with negligible amounts of fines) and cohesive sediments including clays, muds, and mixed grain sizes that exhibit a cohesive soil behavior.

Chow et al. (2018) and White et al. (2018) provided a theoretical approach supported by controlled laboratory tests and validation from synthetic PFFP deployments to derive friction angles and relative density of sands from PFFP. Albatal (2018) and Albatal et al. (2020) demonstrated how friction angles and relative density of sands can be derived directly from PFFP data. The same approach was also successfully tested using data collected within this project. However, the validation of these methods has been limited to fine to medium quartz sands so far. It is expected that calibration factors may vary with coarser sediments, different grain shapes, and mineralogy.

Cohesive sediments require further distinction: normally to overconsolidated muds, highly organic and bioturbated muds, and very soft muds with high water contents at or beyond the liquid limit. Stark and Wever (2009) as well as Albatal & Stark (2017) suggest pathways to distinguish these groups from PFFP data. Kiptoo (2020) and Kiptoo et al. (in prep.) provide detailed guidelines to derive undrained shear strengths of very soft muds with water contents at or beyond the liquid limit. Additionally, Mumtaz and Stark (2020) provide a pathway to estimate the coefficient of consolidation from PFFP pore pressure recordings for very soft muds. For normally to overconsolidated muds, multiple approaches to derive undrained shear strength for PFFP have been presented in the literature. Issues arise associated with a broad variety of grain size distributions. This has not been discussed beyond a clear dependence of the measurements on grain size distributions (i.e., fines content versus sand content) (e.g., Stark et al. 2017). Little knowledge is available to-date regarding how to address high contents of organics, bioturbation, or other effects from benthic organisms.

The framework summarized in Figure E4 offers soil-specific pathways for PFFP data analysis with options of using PFFP data only or integrating data available from soil sampling or other geological information. Geotechnical parameters as listed as results of PFFP data analysis (Fig. E4 bottom line) can be used for further assessment of relevant parameters for remote sensing or erosional processes (e.g., Fig. E2).

Remaining research questions resulting from this work are related to effects of biogenic processes on geomechanical seabed properties, the actual correlation of geomechanical properties to remote sensing techniques, the assessment of seabed liquefaction from wave forcing, and the integration of geomechanical properties into UXO site risk assessment. Furthermore, the proposed framework is currently limited by a lack of calibration and validation for diverse cohesionless sediments, mixed grain size distributions, and organic and bioturbated muds.

Objective

Sediment stratification at the uppermost surface of subaqueous sediments can vary in dimensions, physical characteristics, and behavior. The top layer often exhibits lower density and strength, and higher erodibility and mobility. This impacts munition deposition, burial depth, and stability, as well as most surveying methods, and can lead to significant issues with munition detection, monitoring, and munition site management (Fig. 1).

Portable free fall penetrometers (PFFPs) have been shown to be a cost-effective tool to characterize a munitions site. However, the calibration process previously used tends to blur interpretation of the data within seabed sediment strata. The key hypotheses of this project were:

1. Seafloor surface layers can exhibit significant differences in geomechanical properties, impacting current UXO site surveying and monitoring, as well as UXO burial/exposure risk assessment.
2. PFFP data analysis methods can be advanced to help to assess relevant geomechanical properties at UXO sites, and particularly at sites featuring surficial seabed stratification, in a rapid and cost-effective manner by complementing and supporting current methodologies.

These research hypotheses are directly in line with one of the objectives of the Statement of Need (SON) MRSON-18-C1: the improvement of the current knowledge of environmental conditions, specifically, sediment characteristics, of underwater sites that impact the performance of sensors and systems to detect and classify buried and proud munitions. In this project, a novel investigation framework was developed and initially tested. This framework enables MR investigators to conduct a rapid and cost-effective PFFP site characterization of seafloor surface layering. This PFFP characterization provides information that helps assess potential uncertainties when using acoustic/visual seafloor inspection, that can be used to estimate munition burial depth at impact, and, therefore, that aids in assessment of risks of munition exposure or burial related to the sediment's geomechanical behavior and layering.

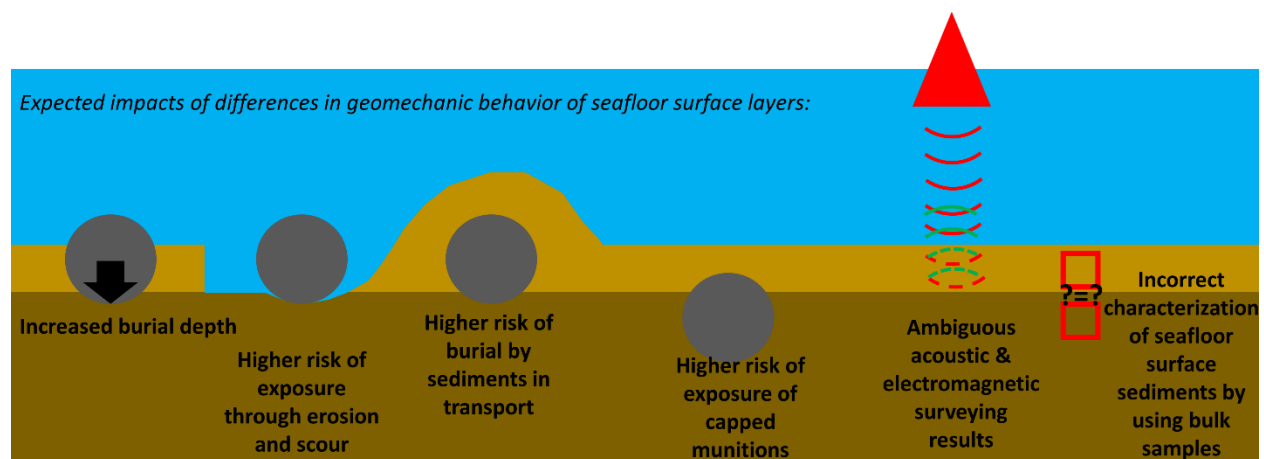


Figure 1. Conceptual sketch of potential issues for UXO site assessment and management associated with variations of geomechanical properties and layering of seafloor surface sediments.

Background

Sediment layers in the uppermost seafloor may be associated with mobile strata, which are generally involved in the local sediment dynamics (e.g., Flores and Sleath 1998), armoring, or selective transport (e.g., Dietrich et al. 1989), as well as freshly deposited sediments (e.g., Woodruff et al. 2001). The uppermost seafloor layer may also be altered by benthic lifeforms, creating possibly stiff layers, or loosening up sediments through burrowing and other activities (e.g., Boudreau and Jorgensen 2001). Additionally, biogeochemical or geochemical processes may alter sediment properties, being well reflected in the complex effect of organic matter on sediment strength (e.g., Ekwue 1990). The resulting changes in the sediment properties in the uppermost seafloor layers impact sediment transport, rates of scour, sediment strength, as well as acoustic penetration into the sediment (Stoll 1977; Sumer et al. 1992; Terzaghi et al. 1996; Van Rijn 2007). Thus, it can be hypothesized that geomechanical properties can vary significantly in the uppermost seabed surface sediments, and that this affects current UXO site characterization, monitoring, and risk assessment.

Portable free fall penetrometers have been utilized as a cost- and time-effective technique to investigate, and characterize seafloor surface sediments (Dayal and Allen 1973; Chari et al. 1981; Dayal 1981; Aubeny and Shi 2006; Stoll et al. 2007; Stark and Wever 2009). PFFPs have also been investigated as a tool for sediment characterization for mine burial prediction (Preston et al. 1999; Mulhearn 2002; Abelev et al. 2009). Stark and Wever (2009) compared the penetrometer deceleration-sediment depth profiles to sediment cores, and they were able to correlate different gradients of penetrometer deceleration to layers of different sediments, organic content, as well as to traces of gas in the sediment. Stark et al. (2014) found a distinct difference in PFFP profiles associated with tube worm activity. Stark and Kopf (2011) documented that the formation of a soft mobile sediment top layer associated with wave forcing in a wave channel was reflected in PFFP results, and Stark et al. (2011) concluded that tidal currents impact the formation and geotechnical appearance of a soft sediment top layer. Stark and Ghose Hajra (2016) demonstrated that laboratory settling and consolidation experiments are not reflective of the in-situ seafloor stratification, and that this can lead to potential issues for all applications relying on a proper characterization of seafloor surface sediments. Lucking et al. (2017) observed a correlation between sediment grain size, strength, and bulk density to the sediment resistance force acting against a PFFP and the recorded pore pressure signature. Bilici et al. (2019) documented the relation between PFFP results and sediment erodibility measurements. Nevertheless, no consistent data base of co-located PFFP data, physical sediment sampling for detailed geotechnical and sedimentological sediment characterization, and environmental data has been assembled yet that covers a sufficient variability of different environmental conditions and sediment types to develop a rapid PFFP survey and data analysis framework to enhance the use of PFFP for UXO site characterization and management.

Materials & Methods

The research strategy of this project included four main parts: 1) The collection of a comprehensive set of field measurements and sediment sampling from locations of varying environmental conditions; 2) a detailed geotechnical and sedimentological characterization of sediments from all tested field sites based on laboratory testing; 3) data analysis and synthesis towards addressing the stated research questions and hypotheses; and 4) the development of a novel investigation framework using PFFP and a field demonstration.

Field testing sites included seven areas in the Pamunkey-York River tidal system (hereafter termed York River), which feeds into the Chesapeake Bay. Seafloor sediments were predominantly muddy at four of these sites and predominantly sandy at the remaining three sites. Salinity and flow conditions varied between most sites. These sites were chosen for their differences in environmental conditions while still being located conveniently close to each other. Additional data sets were integrated into this data base based on relevance to the project goals. They provided a wider range of environmental conditions. This included two additional sites in Virginia (Piankatank River and James River), Sydney Harbour, Nova Scotia, Canada, and sites in Delaware Bay. Most of these data collections were in collaboration with other SERDP investigators. Furthermore, some locations in the York River were revisited with diver support based on feedback during the In-Progress Review meeting. All seven York sites were investigated using a consistent testing program with: more than 10 PFFP deployments per site using the PFFP *BlueDrop*; sediment sampling/coring using box coring, Ponar grab sampling, gravity coring (muddy sites), vibrocoring (sandy sites), and/or diver push cores for chosen sites; acoustic measurements using an acoustic Doppler current profiler (ADCP) for assessment of flow conditions, chirp sonar, and in some locations rotary side scan sonar imaging; and, conductivity-temperature-depth (CTD) measurements. The *BlueDrop* PFFP was chosen for its ruggedness and suitability for deployment in most environmental conditions and its speed of deployment (about 1 minute per deployment in coastal water depths). Additional sites featured at least 10 PFFP deployments, the collection of sediment samples, and some acoustic seabed surveying.

All sediment samples collected at the main sites of this project were analyzed in great detail through sedimentological (grain size, bulk density, organic content, X-ray imaging, and erodibility measurements) and geotechnical (friction angles, cohesion, undrained shear strength, state of consolidation, void ratios) laboratory testing. The cores enabled an analysis to a sediment depth equaling the penetration depth of the PFFP (~ 1 m). Depth intervals of 1 – 10 cm were subsampled and tested, with 1 cm increments typically being applied in the top 10 cm of the sediment cores.

The analysis and synthesis of the collected field and laboratory data was committed to answering the research questions stated in the previous section, and by doing so, testing the project's key hypotheses. Firstly, PFFP measurements were correlated to the geomechanical properties derived from the sediment sampling and laboratory testing, and those correlations were used towards the development of relationships to estimate geomechanical properties from PFFP measurements. Special attention was given to deriving undrained shear strength. Secondly, sediment properties were evaluated along vertical profiles into the bed with special attention to changes with sediment depth (layering). Finally, a discussion was provided regarding impacts on surveying and monitoring strategies that arise from the variations in geomechanical properties between the different layers and soil conditions.

This project concluded with the development of a novel investigation framework and strategy for utilizing PFFP for rapid and cost-efficient UXO site characterization. A strategy was developed based on the results from the previous tasks, and was demonstrated through a proof-of-concept field study conducted in the Potomac River, Maryland, in 2019.

Results have been disseminated to the research community through multiple conference papers and presentations in 2019 and 2020, and refereed journal contributions are in preparation (see appendix B). Project updates have been disseminated to the public through the PI's blog as well as Twitter contributions.

Results & Discussion

a) Correlate PFFP measurements with geomechanical properties and the development of relationships

PFFP featuring a simplicity and ruggedness to be deployed rapidly in varying environmental conditions and from different types of deployment platforms often offer only measurements of acceleration and pore pressure with time. Based on existing literature, it was hypothesized that a better correlation between geomechanical properties and PFFP measurements can be achieved if the data analysis strategy is adjusted to different sediment types. More specifically, it is suggested to differentiate between cohesionless, cohesive, and mixed sediments. It is expected that mixed sediments will collapse towards an either cohesionless or cohesive behavior depending on the specific mixtures. Therefore, special attention was given to the cohesionless and cohesive sediments. From further literature review, it was determined that for cohesionless sediment, a correlation to friction angle and relative density should be sought, where friction angle is expected to be related to erosional parameters and relative density is expressing porosity (Fig. 2). For cohesive sediments, it is proposed to estimate undrained shear strength, which is expected to be related to bulk density which, in turn, is related to erosional parameters as well as porosity (Fig. 2).

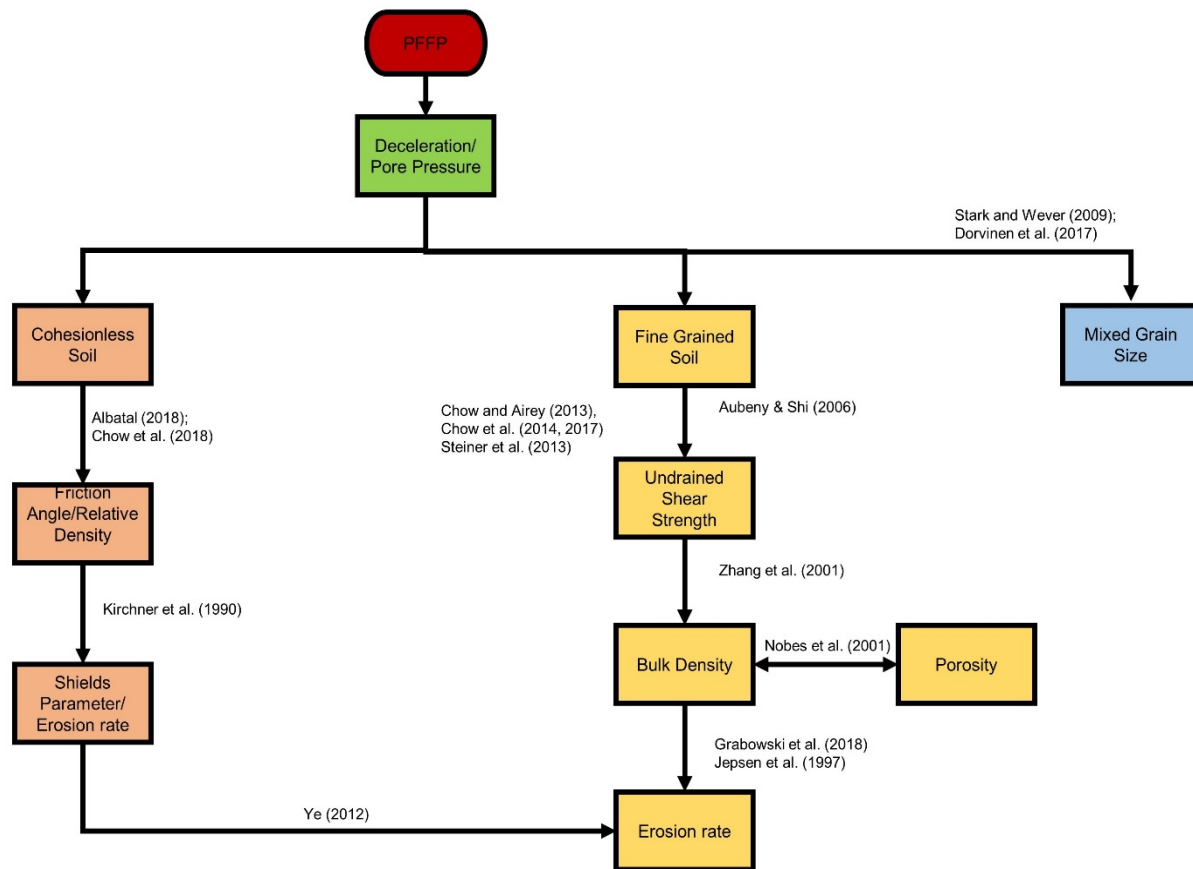


Figure 2. Flow chart providing overview over theoretical and empirical relationships between geomechanical properties and PFFP measurements based on literature.

The collected data set allowed a significant step towards a confident derivation of undrained shear strength from the acceleration measurements. The conceptual method, as suggested by, e.g., Dayal and Allen (1973), Aubeny and Shi (2006), or Stoll et al. (2007), was tested. This method includes the following major steps: 1) Derive the total resistance force from the measured deceleration during impact and the known buoyant weight of the probe using Newton's Law; 2) Calculate the associated stress from the resistance force using the projected surface area of the nose cone of the probe; 3) Apply a strain rate correction to simulate the stresses for a chosen constant penetration velocity (usually 2 cm/s in line with standard CPT testing; Lunne et al. 2012); and 4) Apply an empirical cone factor to account for the shearing principle of using a conical penetrator. Different strain rate correction methods were tested, and strain rate and cone factor correction factors were determined iteratively based on comparison to laboratory vane shear results (Fig. 3). The results suggested that the undrained shear strength could be successfully determined from the PFFP results with cone factors in ranges as reported by other studies before (e.g., Aubeny and Shi 2006). Strain rate effects were found approximately negligible. Therefore, it was tested if similarly agreeable estimates of undrained shear strength could be derived when omitting the strain rate correction (Fig. 4). The results confirmed that no strain rate correction is needed for this type of PFFP for muddy sediments with an undrained shear strength of 1-10 kPa, simplifying the data processing method by omitting the need to estimate one of two empirical factors. It was also found that a cone factor of $N_k=12$ represents a good first estimate with N_k varying in a similar range and with similar behavior as for traditional CPT. A conference paper (Kiptoo et al. 2019), a conference presentation at the Ocean Sciences Meeting (Kiptoo et al. 2020), and a journal manuscript (Kiptoo et al., in preparation a) resulted from these findings.

A significant mismatch between the undrained shear strength determined by the PFFP and the vane shear was noted in the uppermost sediment layers (undrained shear strength $s_u \lesssim 1.5$ kPa). The vane shear appeared unable to record the softness of the seabed sediments as suggested

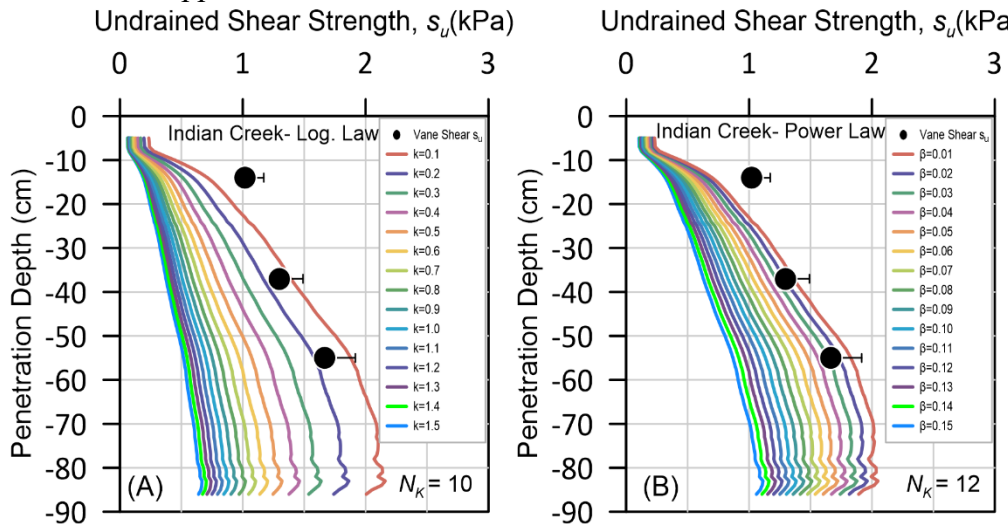


Figure 3. Undrained shear strength estimated from PFFP deployments at Indian Creek with a logarithmic (left) and power law strain rate correction (right). The different lines express results for different strain rate factors k and β , respectively, and for the shown cone factors N_k . The black dots indicate vane shear results. (Kiptoo et al., in prep. a)

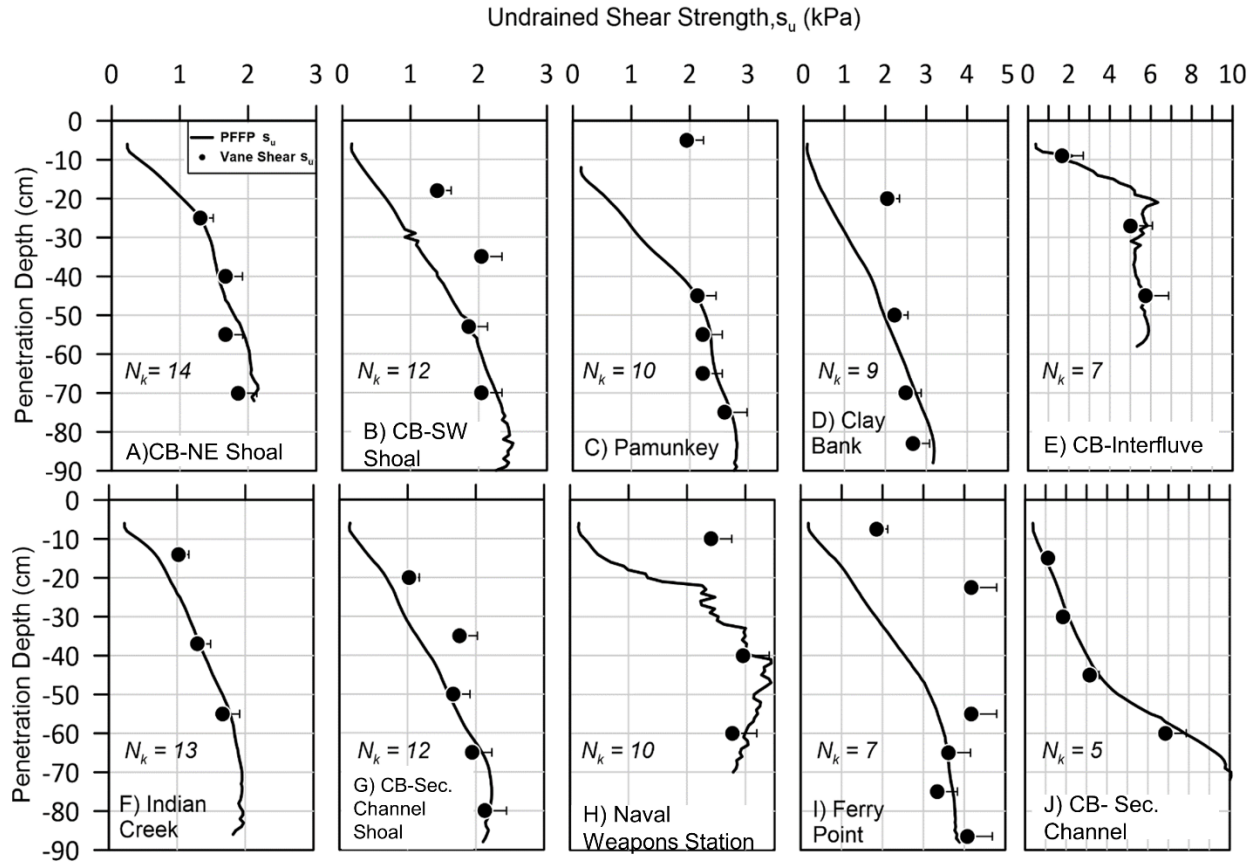


Figure 4. Estimated undrained shear strength from PFFP profiles without application of strain rate correction for ten muddy sites. Vane shear results are shown as dots. (Kiptoo et al., in prep. a)

by the PFFP. This was further confirmed through the extraction of diver push cores, as well as the analysis of water content and bulk density in which these sediments were found to have water contents above the liquid limit, suggesting a liquid-like response and no plastic behavior. The issue was further investigated using rheological testing of the samples. Preliminary results suggest that these top layers can be better described by their rheological behavior than through traditional soil behavior (i.e., viscosity could be reported from the penetrometer results). A presentation at the Ocean Sciences Meeting (Stark et al. 2020) and a journal manuscript (Kiptoo et al., in preparation b) resulted from this.

In line with the variations in undrained shear strength measured at the different sites (Fig. 4), differences in erodibility, sedimentology, and other geomechanical properties were observed (Fig. 5), enabling the testing, and if needed, adjustment of existing correlations that were previously identified from the literature (Figs. 2 and 6). A journal manuscript is in preparation based on these results (Stark et al., in preparation). PFFP tests at sandy sites were analyzed based on the method suggested by Albatal et al. (2020) and achieved agreeable results regarding friction angles and relative density.

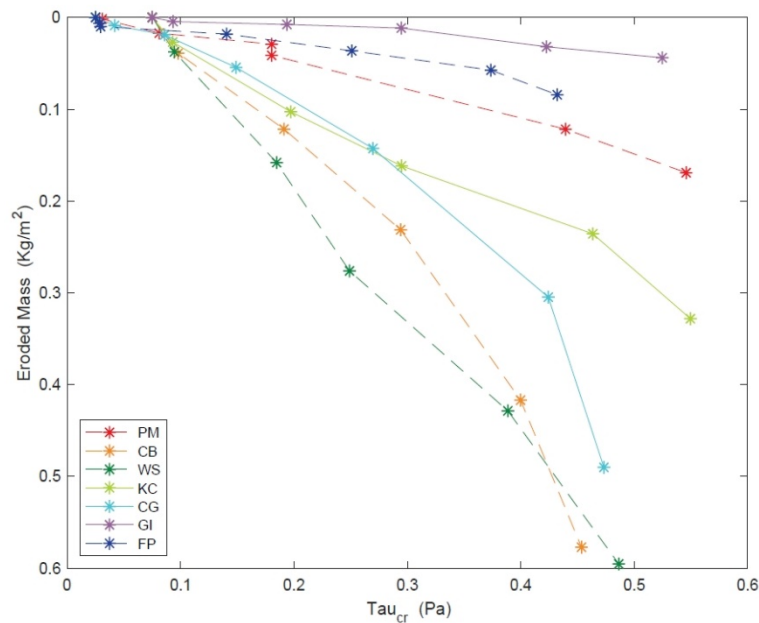


Figure 5. Erodibility in terms of eroded mass per critical shear stress for sediment samples from the visited sites determined using a Gust microcosm apparatus.

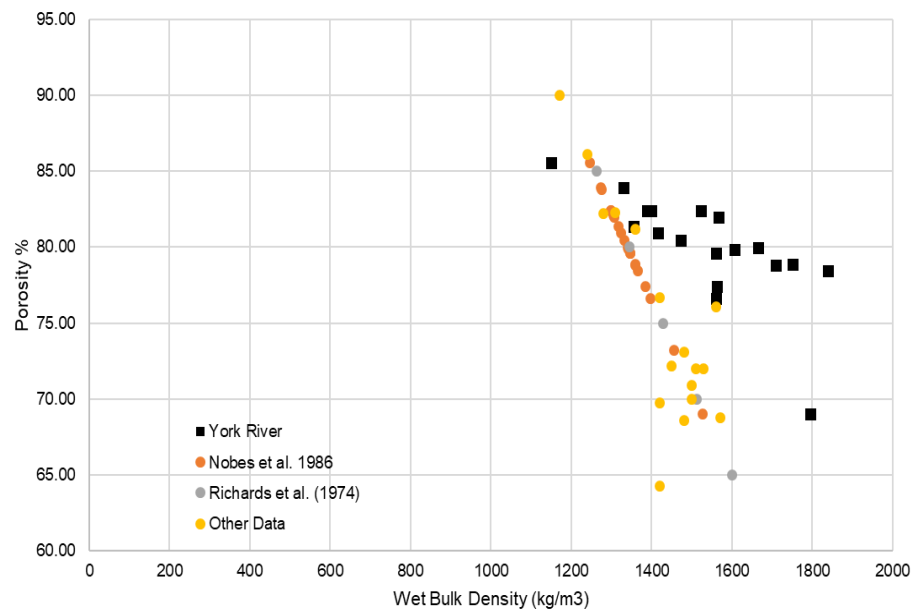


Figure 6. Porosity versus wet bulk density of muddy sediments from the York River and from the literature.

b) Differences in geomechanical properties of different seafloor surface layers

The PFFP results identified significant variations in undrained shear strength (Fig. 4), friction angle, and relative density with sediment depth within the upper meter of the seabed surface. Such

differences were so severe in some cases that top layers (sediment depth $\leq 10\text{-}30\text{ cm}$) may be better described in terms of rheology (i.e., plastic or liquid flow) rather than soil behavior (with shear strength). This observation was also confirmed from carefully extracted diver cores and box cores (Fig. 7). Furthermore, related geomechanical properties such as erodibility and porosity varied as well with the observed variations in undrained shear strength, friction angle, and relative density (Figs. 5 and 6). Neither gravity cores nor vibrocores were able to sample the soft seabed surface. It follows that seafloor surface layers can exhibit significant differences in geomechanical properties, impacting current UXO site surveying and monitoring, as well as UXO burial/exposure risk assessment (hypothesis 1).

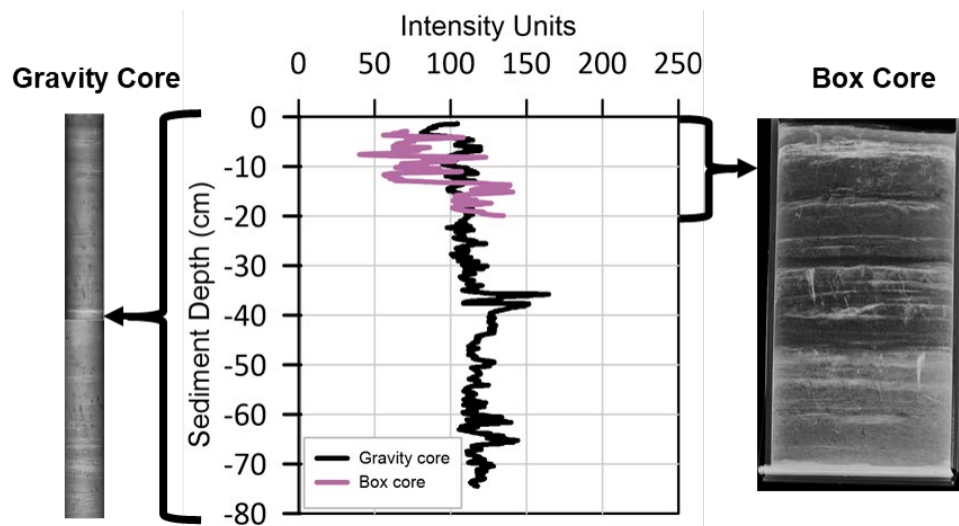


Figure 7. Stratification shown in X-ray imaging of a gravity core and a box core. Please note that intensity units between these cores should not be directly and quantitatively compared due to differences in core shape (round vs rectangular).

c) Impact on current surveying and monitoring methods

Undrained shear strength varied significantly within the uppermost meter of the seabed surface. This impacts directly UXO stability and burial. Particularly, the soft seabed surface sediments ($s_u < 2\text{ kPa}$) will unlikely be able to support a UXO, leading to sinking towards deeper sediment depths. Similarly, differences were noted in erodibility, leading to potentially strong variations regarding scour or capping through sediment transport processes. By ignoring the differences in these properties at the seabed surface, sinking will likely be underestimated, and scour and capping may be predicted incorrectly. Variations in soil porosity, water content, and bulk density were related to the PFFP measurements and also showed significant variations for the different sites and with sediment depth. This means that assuming a constant porosity for a certain general sediment types with depth or just by soil type will lead to biased interpretations of acoustic penetration depth and backscatter in the interpretation of acoustic surveying tools.

d) Novel PFFP data analysis and deployment framework for PFFP site assessment

PFFP deployments were performed along gridded transects to cover a previously unsampled river bed area in the Potomac River near Blossom Point, MD. Within less than 12 hours, the PFFP

deployments and initial analysis were carried out. The latter suggested the presence of four different sediment type groups in the tested area. The four groups were confirmed by sediment sampling and laboratory analysis (Kiptoo et al. 2019) and were also distinguishable regarding chirp sonar backscatter intensity (Jaber et al., submitted). Therefore, the PFFP deployment framework was found successful regarding a rapid and cost-efficient seafloor surface (< 1 m) assessment targeting geomechanical properties and stratification. The relationships identified in this study enable the derivation of geomechanical properties relevant to UXO site surveying, monitoring, and assessment. The results suggested that remote sensing techniques would likely benefit from calibration using the geomechanical seabed profiles. Therefore, key hypothesis 2 of this project (see section 2) was confirmed: PFFP data analysis methods can be advanced to help to assess relevant geomechanical properties at UXO sites, and particularly sites featuring surficial seabed stratification, in a rapid and cost-effective manner by complementing and supporting current methodologies.

Conclusions & Implications for Future Research/Implementation

The key findings of this project include:

- Current methods of PFFP data analysis were improved and validated. It was found that undrained shear strength can be estimated from PFFP for muddy seafloor sediments and that friction angles and relative density can be derived from PFFP for sandy seafloor sediments.
- Significant variations in geomechanical properties within uppermost seabed surface layers were identified even without significant changes in sediment type. The results suggested that uppermost seabed surface layers may exhibit more fluid-like behavior than soil behavior depending on the water content.
- The variability in geomechanical properties is of relevance to UXO site assessment and monitoring.
- A novel PFFP deployment and analysis strategy was formulated that enables a rapid and cost-effective characterization of the upper meter of the seabed surface.

The PFFP analysis strategy derived from this project is summarized in Figure 8. This considers that the PFFP raw data includes acceleration/deceleration measurements and possibly pore pressure measurements in line with the PFFP used in this study as well as modern PFFP capabilities. Furthermore, it is assumed that general information on sediment type are available from geological maps or pre-existing data, soil samples, and/or can be inferred from remote sensing techniques and/or PFFP data. Mulukutla et al. (2011) introduced the firmness factor derived from PFFP data and demonstrated its correlation to soil types. Albatal and Stark (2017) proposed a combined use of deceleration and pore pressure data collected by a PFFP to assess general soil type. Key categories for the recommended PFFP data analysis are cohesionless (i.e., sand & fine gravel with negligible amounts of fines) and cohesive sediments including clays, muds, and mixed grain sizes that exhibit a cohesive soil behavior. Here, it should be noted that PFFP are generally not recommended for gravelly sites due to limited penetration depths. It should

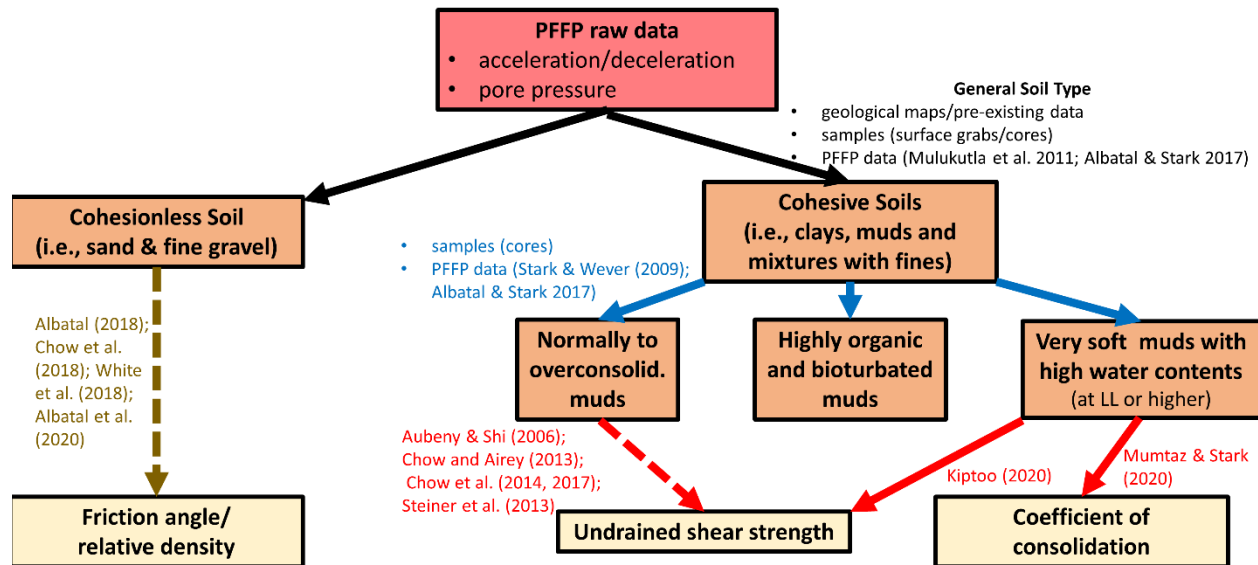


Figure 8. Flow chart of proposed PFFP data analysis framework. Solid arrows refer to high confidence relationship. Dashed arrows refer to available relations with need for further improvement regarding broader grain size distributions. The resulting properties can be further related as shown in Figure 2.

also be noted that only fully saturated sediments are considered here. Those may include sediments with small gas contents that do not affect strength by introducing apparent cohesion.

Chow et al. (2018) and White et al. (2018) provided a theoretical approach supported by controlled laboratory tests and validation from synthetic PFFP deployments to derive friction angles and relative density of sandy soils from PFFP. Albatal (2018) and Albatal et al. (2020) demonstrated how friction angles and relative density of sands can be derived directly from PFFP data. The same approach was also successfully tested using data collected within this project. However, the validation of these methods has been limited to fine to medium quartz sands so far. It is expected that calibration factors may vary with coarser sediments, different grain shapes, and mineralogy.

Cohesive sediments require further distinction: normally to overconsolidated muds, highly organic and bioturbated muds, and very soft muds with high water contents at or beyond the liquid limit. Stark and Wever (2009) as well as Albatal & Stark (2017) suggest pathways to distinguish these groups from PFFP data. Kiptoo (2020) and Kiptoo et al. (in prep.) provide detailed guidelines to derive undrained shear strengths of very soft muds with water contents at or beyond the liquid limit. Additionally, Mumtaz and Stark (2020) provide a pathway to estimate the coefficient of consolidation from PFFP pore pressure recordings for very soft muds. For normally to overconsolidated muds, multiple approaches to derive undrained shear strength for PFFP have been presented in the literature. Issues arise associated with a broad variety of grain size distributions. This has not been discussed beyond a clear dependence of the measurements on grain size distributions (i.e., fines content versus sand content) (e.g., Stark et al. 2017). Little knowledge is available to-date regarding how to address high contents of organics, bioturbation, or other effects from benthic organisms.

The framework summarized in Figure 8 offers sediment-specific pathways for PFFP data analysis with options of using PFFP data only or integrating data available from sediment sampling or other geological information. Geotechnical parameters as listed as results of PFFP data analysis (Fig. 8 bottom line) can be used for further assessment of relevant parameters for remote sensing or erosional processes (e.g., Fig. 2).

Remaining research questions resulting from this work are related to effects of biogenic processes on geomechanical seabed properties, the actual correlation of geomechanical properties to remote sensing techniques, the assessment of seabed liquefaction during wave forcing, and the integration of geomechanical properties into UXO site risk assessment. This will require further data collection and analysis. Furthermore, the proposed framework is currently limited by a lack of calibration and validation for diverse cohesionless sediments, mixed grain size distributions, and organic and bioturbated muds. This will be improved from additional processing of data from this project, complementary data that becomes available, but will likely still need additional data collection.

Literature Cited

- Abelev, A., Tubbs, K., & Valent, P. (2009). Numerical investigation of dynamic free-fall penetrometers in soft cohesive marine sediments using a finite difference approach. In *OCEANS 2009*, 1-10.
- Albatal, A. H. A. (2018). *Advancement of using portable free fall penetrometers for geotechnical site characterization of energetic sandy nearshore areas* (Doctoral dissertation, Virginia Tech).
- Albatal, A., Stark, N., & Castellanos, B. (2020). Estimating in situ relative density and friction angle of nearshore sand from portable free-fall penetrometer tests. *Canadian Geotechnical Journal*, 57(1), 17-31.
- Aubeny, C. P., & Shi, H. (2006). Interpretation of impact penetration measurements in soft clays. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(6), 770-777.
- Bilici, C., Stark, N., Friedrichs, C. T., & Massey, G. M. (2019). Coupled sedimentological and geotechnical data analysis of surficial sediment layer characteristics in a tidal estuary. *Geo-Marine Letters*, 39(3), 175-189.
- Blomqvist, S. (1991). Quantitative sampling of soft-bottom sediments: problems and solutions. *Marine Ecology Progress Series*, 72(3), 295-304.
- Boudreau, B. P., & Jorgensen, B. B. (Eds.). (2001). *The benthic boundary layer: Transport processes and biogeochemistry*. Oxford University Press.
- Chari, T., Smith, W., & Chaudhuri, S. (1981). Development of the free-fall penetrometer. In *OCEANS 81*, 678-682.
- Chow, S. H., & Airey, D. W. (2013). Soil strength characterisation using free-falling penetrometers. *Géotechnique*, 63(13), 1131-1143.
- Chow, S. H., O'loughlin, C. D., & Randolph, M. F. (2014). Soil strength estimation and pore pressure dissipation for free-fall piezocone in soft clay. *Géotechnique*, 64(10), 817-827.
- Chow, S. H., O'Loughlin, C. D., White, D. J., & Randolph, M. F. (2017). An extended interpretation of the free-fall piezocone test in clay. *Géotechnique*, 67(12), 1090-1103.
- Chow, S. H., Bienen, B., & Randolph, M. F. (2018, June). Rapid penetration of piezocones in sand. In *Proceedings of the 4th International Symposium on Cone Penetration Testing (CPT'18), Delft*, 213-219.
- Dayal, U., & Allen, J. H. (1973). Instrumented impact cone penetrometer. *Canadian Geotechnical Journal*, 10(3), 397-409.
- Dayal, U. (1981). Analysis of free-fall penetrometer data. In *OCEANS 81*, 683-687.
- Dietrich, W. E., Kirchner, J. W., Ikeda, H., & Iseya, F. (1989). Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. *Nature*, 340(6230), 215-217.

- Ekvwue, E. I. (1990). Organic-matter effects on soil strength properties. *Soil and Tillage Research*, 16(3), 289-297.
- Flores, N. Z., & Sleath, J. F. (1998). Mobile layer in oscillatory sheet flow. *Journal of Geophysical Research: Oceans*, 103(C6), 12783-12793.
- Jaber, R., Kiptoo, D.K., Stark, N., Jafari, N., Ravichandran, N. Towards combined use of chirp sonar and portable penetrometer results at the Potomac River. In review for: *International Symposium on Frontiers in Offshore Geotechnics*, Austin, Texas, USA, 16-19 August 2020.
- Kiptoo, D., Stark, N., Massey, G., Wright, C., and Friedrichs, C.T. (2018). In-situ Geotechnical and Sedimentological Investigation of Stratified Sediment in the York River, Virginia. Abstract #EP31E-2393. *AGU Fall Meeting 2018*, December 10-14, 2018, Washington, DC
- Kiptoo, D. K., Stark, N., Albatal, A., & Bilici, C. (2019). Uppermost Subaqueous Soil Variability in Front of the Situk River Inlet, Alaska, from Portable Free Fall Penetrometer. In *Geo-Congress 2019: Engineering Geology, Site Characterization, and Geophysics*, Philadelphia, USA, 24-27 March 2019.
- Kiptoo, D., Stark, N., Massey, G., Wright, C., & Friedrichs, C. (2019). Geotechnical site investigation of a soft clay surface layer in the Pamunkey River, Virginia. *Coastal Sediments 2019*, 27-31 May 2019, St. Pete, FL, USA.
- Kiptoo, D., Stark, N., Massey, G., Wright, C., & Friedrichs, C. (2019). Rapid geotechnical characterization of seafloor sediments at the Potomac River, Maryland, using a novel assessment framework based on portable free fall penetrometer measurements. *SERDP/ESTCP Symposium 2018*, December 3-5, 2019, Washington, DC.
- Kiptoo, D., Stark, N., Massey, G., Wright, C., & Friedrichs, C. T. (2020). Strain Rate Effects in Soft Estuarine Soils using Portable Free Fall Penetrometers. In *Ocean Sciences Meeting 2020*. <https://agu.confex.com/agu/osm20/meetingapp.cgi/Paper/639612>
- Kiptoo, D.K., Stark, N., Massey, G., Wright, C., & Friedrichs, C. Derivation of undrained shear strength in fine grained estuarine soils from a portable free fall penetrometer. In preparation for publication in: *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, [90% complete]
- Kiptoo, D.K., Stark, N., Bortner, M. Rheology versus soil behavior – interpretation of the resistance of very soft estuarine soils. In preparation for publication in: *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, [50% complete]
- Kirchner, J. W., Dietrich, W. E., Iseya, F., & Ikeda, H. (1990). The variability of critical shear stress, friction angle, and grain protrusion in water-worked sediments. *Sedimentology*, 37(4), 647-672.
- Lunne, T. (2012). The Fourth James K. Mitchell Lecture: The CPT in offshore soil investigations-a historic perspective. *Geomechanics and Geoengineering*, 7(2), 75-101.

Mulhearn, P. J. (2002). *Influences of penetrometer probe tip geometry on bearing strength estimates for mine burial prediction* (No. DSTO-TR-1285). DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION CANBERRA (AUSTRALIA).

Preston, J. M., Collins, W. T., Mosher, D. C., Poeckert, R. H., & Kuwahara, R. H. (1999). The strength of correlations between geotechnical variables and acoustic classifications. In *OCEANS'99 MTS/IEEE. Riding the Crest into the 21st Century*, 3, 1123-1128.

Richardson, M. D., & Valent, P. J. (2004). *Mine Burial Prediction: A Cooperative NRL/ONR Study*. NAVAL RESEARCH LAB STENNIS DETACHMENT STENNIS SPACE CENTER MS MARINE GEOSCIENCES DIV.

Steiner, A., Kopf, A. J., L'Heureux, J. S., Kreiter, S., Stegmann, S., Haflidason, H., & Moerz, T. (2014). In situ dynamic piezocone penetrometer tests in natural clayey soils—a reappraisal of strain-rate corrections. *Canadian Geotechnical Journal*, 51(3), 272-288.

Stark, N., & Wever, T. F. (2009). Unraveling subtle details of expendable bottom penetrometer (XBP) deceleration profiles. *Geo-Marine Letters*, 29(1), 39-45.

Stark, N., & Kopf, A. (2011). Geotechnical investigations of sediment remobilization processes using a dynamic penetrometer. In *Proceedings of MTS/IEEE Oceans '11*, 19-22 September 2011 in Kona, Hawaii.

Stark, N., Hanff, H., Svenson, C., Ernstsén, V. B., Lefebvre, A., Winter, C., & Kopf, A. (2011). Coupled penetrometer, MBES and ADCP assessments of tidal variations in surface sediment layer characteristics along active subaqueous dunes, Danish Wadden Sea. *Geo-Marine Letters*, 31(4), 249-258.

Stark, N., Wilkens, R., Ernstsén, V. B., Lambers-Huesmann, M., Stegmann, S., & Kopf, A. (2012). Geotechnical properties of sandy seafloors and the consequences for dynamic penetrometer interpretations: quartz sand versus carbonate sand. *Geotechnical and Geological Engineering*, 30(1), 1-14.

Stark N, Staelens P, Hay AE, Hatcher B, Kopf A (2014). Geotechnical investigation of coastal areas with difficult access using portable free-fall penetrometers. In *Proceedings of the CPT'14 conference 2014*, 12-14 May 2014 in Las Vegas, Nevada.

Stark, N., & Ghose Hajra, M. (2016). Field and laboratory characterization of native coastal deposits using a portable free-fall penetrometer and settling column tests. In *Proceedings of the ASCE G-I Geo-Chicago 2016: Sustainability, Energy, and the Geoenvironment*. August 14-18, 2016, Chicago, IL. doi: 10.1061/9780784480168.045

Stark, N., Radosavljevic, B., Quinn, B., & Lantuit, H. (2017). Application of portable free-fall penetrometer for geotechnical investigation of Arctic nearshore zone. *Canadian Geotechnical Journal*, 54(1), 31-46.

Stark, N., Kiptoo, D., Massey, G., Wright, C., and Friedrichs, C.T. (2018). Improved penetrometer performance in stratified sediment for cost-effective characterization, monitoring

and management of submerged munitions sites. *SERDP/ESTCP Symposium 2018*, November 27-29, 2018, Washington, DC.

Stark, N., Kiptoo, D., Massey, G., Wright, C., & Friedrichs, C. (2019). Improved Penetrometer Performance in Stratified Sediment for Cost-Effective Characterization, Monitoring and Management of Submerged Munitions Sites. *SERDP/ESTCP Symposium 2018*, December 3-5, 2019, Washington, DC.

Stark, N., Kiptoo, D., Bilici, C., Massey, G., Wright, C., & Friedrichs, C. T. (2020). Geotechnical Investigation of Fine-Grained Top Layer Stratification in the York Estuary, Virginia. In *Ocean Sciences Meeting 2020*. AGU.
<https://agu.confex.com/agu/osm20/meetingapp.cgi/Paper/640338>

Stark, N., Kiptoo, D., Brilli, N., & Jaber, R. Portable free fall penetrometer measurements: shear resistance versus drag resistance. In review for: *International Symposium on Frontiers in Offshore Geotechnics*, Austin, Texas, USA, 16-19 August 2020.

Stark, N., Kiptoo, D.K., Massey, G., Wright, C., & Friedrichs, C. Variations in geomechanical properties and sediment stratification in the York River estuary, Virginia. In preparation for publication in: *Geo-Marine Letters* [50% complete]

Stoll, R. D. (1977). Acoustic waves in ocean sediments. *Geophysics*, 42(4), 715-725.

Stoll, R. D., Sun, Y. F., & Bitte, I. (2007). Seafloor properties from penetrometer tests. *IEEE Journal of Oceanic Engineering*, 32(1), 57-63.

Sumer, B. M., Fredsøe, J., & Christiansen, N. (1992). Scour around vertical pile in waves. *Journal of waterway, port, coastal, and ocean engineering*, 118(1), 15-31.

Terzaghi, K., Peck, R. B., & Mesri, G. (1996). *Soil mechanics in engineering practice*. John Wiley & Sons.

Van Rijn, L. C. (2007). Unified view of sediment transport by currents and waves. I: Initiation of motion, bed roughness, and bed-load transport. *Journal of Hydraulic Engineering*, 133(6), 649-667.

Wilkens, R. H. (2003). *The Role of Variability in Mine Burial Prediction*. HAWAII UNIV HONOLULU INST OF GEOPHYSICS AND PLANETOLOGY.

Zhang, B., Zhao, Q. G., Horn, R., & Baumgartl, T. (2001). Shear strength of surface soil as affected by soil bulk density and soil water content. *Soil and tillage research*, 59(3-4), 97-106.

Zhang, Q., Al-Nuaimy, W., & Huang, Y. (2007). Detection of deeply buried UXO using CPT magnetometers. *IEEE transactions on geoscience and remote sensing*, 45(2), 410-417.

Appendices

A. Supporting data

All geotechnical data collected and processed data utilized for publications are published through the *VTechWorks* data repository. The data set is accessible through:

Kiptoo, D., Stark, N., Massey, G., Wright, C., & Friedrichs, C. (2020). *In-situ geotechnical characterization of soft estuarine surficial sediments using a portable free fall penetrometer [Data]*. University Libraries, Virginia Tech. <https://doi.org/10.7294/YZRV-QJ06>

Sedimentological and environmental data are additionally available in two data reports (for the York River and the Potomac River, respectively) through the William & Mary University ScholarWorks data repository. The data set is accessible through:

Massey, Grace M.; Wright, Cristin L.; Friedrichs, Carl T.; Stark, Nina; and Kiptoo, Dennis, "VIMS 2019 York River Estuary Data in Support of: Improved Penetrometer Performance in Stratified Sediment for Cost-Effective Characterization, Monitoring and Management of Submerged Munitions Sites (SERDP project: MR18-1233)" (2020). Virginia Institute of Marine Science, College of William and Mary. <https://doi.org/10.25773/2rze-fg21>

Massey, Grace M.; Wright, Cristin L.; Friedrichs, Carl T.; Stark, Nina; and Kiptoo, Dennis, "VIMS 2019 Potomac River Estuary Data in Support of: Improved Penetrometer Performance in Stratified Sediment for Cost-Effective Characterization, Monitoring and Management of Submerged Munitions Sites (SERDP project: MR18-1233)" (2020). Virginia Institute of Marine Science, College of William and Mary. <https://doi.org/10.25773/hg68-xf88>

B. List of Scientific/Technical Publications

Refereed journal contributions

Kiptoo, D.K., Stark, N., Massey, G., Wright, C., & Friedrichs, C. Derivation of undrained shear strength in fine grained estuarine soils from a portable free fall penetrometer. In preparation (a) for publication in: *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, [90% complete]

Stark, N., Kiptoo, D.K., Massey, G., Wright, C., & Friedrichs, C. Variations in geomechanical properties and sediment stratification in the York River estuary, Virginia. In preparation for publication in: *Geo-Marine Letters* [50% complete]

Kiptoo, D.K., Stark, N., Bortner, M. Rheology versus soil behavior – interpretation of the resistance of very soft estuarine soils. In preparation (b) for publication in: *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, [50% complete]

Refereed conference articles

Kiptoo, D. K., Stark, N., *Albatal, A., & Bilici, C. (2019). Uppermost Subaqueous Soil Variability in Front of the Situk River Inlet, Alaska, from Portable Free Fall Penetrometer. In *Geo-Congress 2019: Engineering Geology, Site Characterization, and Geophysics*, Philadelphia, USA, 24-27 March 2019.

Jaber, R., Kiptoo, D.K., Stark, N., Jafari, N., Ravichandran, N. Towards combined use of chirp sonar and portable penetrometer results at the Potomac River. In review for: *International Symposium on Frontiers in Offshore Geotechnics*, Austin, Texas, USA, 16-19 August 2020.

Stark, N., Kiptoo, D., Brilli, N., & Jaber, R. Portable free fall penetrometer measurements: shear resistance versus drag resistance. In review for: *International Symposium on Frontiers in Offshore Geotechnics*, Austin, Texas, USA, 16-19 August 2020.

Conference presentations

Kiptoo, D., Stark, N., Massey, G., Wright, C., & Friedrichs, C. T. (2020). Strain Rate Effects in Soft Estuarine Soils using Portable Free Fall Penetrometers. In *Ocean Sciences Meeting 2020*. Abstract # MG42A-04.

Stark, N., Kiptoo, D., Bilici, C., Massey, G., Wright, C., & Friedrichs, C. T. (2020). Geotechnical Investigation of Fine-Grained Top Layer Stratification in the York Estuary, Virginia. In *Ocean Sciences Meeting 2020*. AGU. Abstract # MG52A-02.

Stark, N., Kiptoo, D., Massey, G., Wright, C., & Friedrichs, C. (2019). Improved Penetrometer Performance in Stratified Sediment for Cost-Effective Characterization, Monitoring and Management of Submerged Munitions Sites. *SERDP/ESTCP Symposium 2018*, December 3-5, 2019, Washington, DC.

Kiptoo, D., Stark, N., Massey, G., Wright, C., & Friedrichs, C. (2019). Geotechnical site investigation of a soft clay surface layer in the Pamunkey River, Virginia. *Coastal Sediments 2019*, 27-31 May 2019, St. Pete, FL, USA.

Conference posters and abstracts

Wright, C., Massey, G., & Friedrichs, C. T. (2020). Exploratory Statistical Analysis of Controls on Sediment Bed Erodibility in a Partially-Mixed Estuary. In *Ocean Sciences Meeting 2020*. AGU. Abstract # MG34A-2203.

Kiptoo, D., Stark, N., Massey, G., Wright, C., & Friedrichs, C. (2019). Rapid geotechnical characterization of seafloor sediments at the Potomac River, Maryland, using a novel assessment framework based on portable free fall penetrometer measurements. *SERDP/ESTCP Symposium 2018*, December 3-5, 2019, Washington, DC.

Kiptoo, D., Stark, N., Massey, G., Wright, C., and Friedrichs, C.T. (2018). In-situ Geotechnical and Sedimentological Investigation of Stratified Sediment in the York River, Virginia. Abstract #EP31E-2393. *AGU Fall Meeting 2018*, December 10-14, 2018, Washington, DC

Stark, N., Kiptoo, D., Massey, G., Wright, C., and Friedrichs, C.T. (2018). Improved penetrometer performance in stratified sediment for cost-effective characterization, monitoring and management of submerged munitions sites. *SERDP/ESTCP Symposium 2018*, November 27-29, 2018, Washington, DC.

Thesis

Kiptoo, D. (2020). *Deriving shear strength from portable free fall penetrometer measurements in soft estuarine sediments*. MS thesis in preparation for submission to: Virginia Tech, Charles E. Via, Jr., Department of Civil and Environmental Engineering.

Wright, C.L. (2020). *Controls on estuarine sediment bed erodibility*. MS thesis in preparation for submission to: Virginia Institute of Marine Science, Department of Physical Sciences.

C. Supporting Materials

N/A