EXECUTIVE SUMMARY

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

SERDP Project MR18-1233

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1.0 INTRODUCTION

Geomechanical properties of seafloor surface sediments and sediment layers affect the characterization, assessment, and management of submerged munitions sites. Some of the aspects affected include: 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 (Figure 1).

![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]

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 (FFPs) 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 MR18-1233 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 UXO site characterization be directly inferred from PFFP 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 PFFPs?
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.

2.0 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 (see Figure 1).

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 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 Munitions Response program area 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 used to estimate munition burial depth at impact. PFFP characterization, therefore, aids in assessment of risks of munition exposure or burial related to the sediment’s geomechanical behavior and layering.

3.0 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 database based on relevance to the project goals. The data sets provided a wider range of environmental conditions. The included data were from two additional sites in Virginia (Piankatank River and James River); Sydney Harbour in 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 ten 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 one minute per deployment in coastal water depths). Additional sites featured at least ten 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 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 meter [m]). Depth intervals of 1–10 centimeters (cm) were subsampled and tested, with 1-cm increments typically being applied in the top 10 cm of the sediment cores.

The goal of the analysis and synthesis of the collected field and laboratory data was to answer the research questions, and by doing so, test 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.
4.0 RESULTS AND DISCUSSION

4.1 CORRELATE PFFP MEASUREMENTS WITH GEOMECHANICAL PROPERTIES AND THE DEVELOPMENT OF RELATIONSHIPS

Simple and rugged PFFP that can be rapidly deployed 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 and can, more specifically, 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 cohesionless and cohesive sediments. From further literature review and as shown in Figure 2, 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 expresses porosity. 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.

![Flow Chart](image)

**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 per second [cm/s] in line with standard CPT testing; Lunne 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 previous studies (e.g., Aubeny and Shi 2006). Strain rate effects were found negligible. Therefore, it was tested if similarly agreeable estimates of undrained shear strength could be derived when omitting the strain rate correction (Figure 3). 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 kilopascals (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. Two conference papers (Kiptoo et al. 2019a and b), a conference presentation at the Ocean Sciences Meeting (Kiptoo et al. 2020), and a journal manuscript (Kiptoo et al., in prep. [a]) resulted from these findings.

Figure 3. 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])*
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 $s_u \leq 1.5$ 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 Ocean Sciences Meeting (Stark et al. 2020a) and a journal manuscript (Kiptoo et al., in prep. [b]) resulted from this.

In line with the variations in undrained shear strength measured at the different sites (Figure 3), 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 (Figure 2). A journal manuscript is in preparation based on these results (Stark et al., in prep.). 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.

4.2 DIFFERENCES IN GEOMECHANICAL PROPERTIES OF DIFFERENT SEAFLOOR SURFACE LAYERS

The PFFP results identified significant variations in undrained shear strength (Figure 3), 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 $\leq 10–30$ 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).

4.3 IMPACT ON CURRENT SURVEYING AND MONITORING METHODS

Undrained shear strength varied significantly within the uppermost meter of the seabed surface. This directly impacts 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 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.
4.4 NOVEL PFFP DATA ANALYSIS AND DEPLOYMENT FRAMEWORK FOR
PFFP SITE ASSESSMENT

PFFP deployments were performed along gridded transects to cover a previously unsampled riverbed area in the Potomac River near Blossom Point, Maryland. Within <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. 2019c) and were also distinguishable regarding chirp sonar backscatter intensity (Jaber et al., 2020). 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 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.

5.0 IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

The key findings of this project include the following:

- 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 4. As indicated, 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 soil type is available from geological maps or pre-existing data, sediment samples, or can be inferred from remote sensing techniques 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 and fine gravel with negligible amounts of fines) and cohesive sediments including clays, muds, and mixed grain sizes that exhibit a cohesive soil behavior.
Figure 4. Flow Chart of Proposed PFFP Data Analysis Framework.

Solid arrows refer to high confidence relationships. 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.

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-grained 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 over-consolidated 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 and Stark (2017) suggest pathways to distinguish these groups from PFFP data. Kiptoo et al. (2020) and Kiptoo et al. (In prep. [a]) provide detailed guidelines to derive undrained shear strengths of very soft muds with water contents at or beyond the liquid limit. Stark et al. (2020b) discuss the role of soil drag. 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 over-consolidated 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 4 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 (Figure 4 bottom line) can be used for further assessment of relevant parameters for remote sensing or erosional processes (e.g., Figure 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 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.

6.0 LITERATURE CITED


