

FINAL REPORT

Further Examining the Role of Cohesive Sediments in Munitions
Mobility through Additional Infield Deployment of Smart Munitions
and Application of a SERDP-developed Penetrometer

SERDP Project MR20-1480

JUNE 2022

Arthur C. Trembanis
Carter DuVal
University of Delaware

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List of Acronyms

DNREC: Delaware Department of Natural Resources and Environmental Control
DOD: Department of Defense
DSPSU: Delaware State Police SCUBA Unit
FUDS: Formerly-Used Defense Site
GPS: Global Position Systems
IMU: Inertial Motion Unit
MEC: Munitions and Explosives of Concern
MLLW: Mean Lower-Low Water
MR: Munitions Response
MRS: Munitions Response Site
PMES: Phase-Measuring Echo Sounder
QSBC: Quasi-Static Bearing Capacity
RTK: Real-Time Kinematic
SCUBA: Self-Contained Underwater Breathing Apparatus
SERDP: Strategic Environmental Research and Development Program
UD: University of Delaware
UnMES: Underwater Munitions Expert System
UXO: UneXploded Ordnance
VPS: Vemco Positioning System

1. Abstract

Objectives: While the mechanisms for munitions burial in non-cohesive sediments are well established, be it through scour-burial processes (see ONR mine burial studies) or granular sorting (Calantoni MR-2320), the resistive nature of cohesive sediment to granular erosion reduces the likelihood of granular sorting as a primary mechanism for burial, inhibits scour (Inman and Jenkins, 2002), and may result in other mechanisms for burial not characteristic of non-cohesive sediments (Baeye et al., 2012; Sheremet et al., 2005). This study expands the research on MEC mobility and burial in cohesive sediments by investigating the geotechnical properties of cohesive sediments that contribute to MEC mobility and burial as observed in detailed field experiments in MR-2730.

Technical Approach: Leveraging existing resources and knowledge gained from previous and ongoing SERDP Munitions Response studies, this study couples periodic site-wide geophysical surveying with contemporaneous in-field geotechnical sediment characterization through repetitive sampling and application of a SERDP supported penetrometer (Dr. Nina Stark MR18-1233) at an munitions mobility and burial study site (MR-2730).

Results: Sediment bearing capacity is shown to be an important predictor for surrogate burial in mixed-cohesive or cohesive sediments. A Hertzian contact model introduced here provides a simple method to predict munitions burial due to bearing capacity. This study additionally demonstrates methods to link sediment geotechnical properties such as bearing capacity to sonar classification / surficial sediment distributions maps.

Benefits: Results from this combined effort include better characterization of munitions mobility as influenced by cohesive sediment geotechnical properties, as well as providing an in-field demonstration of the penetrometer technology and methods being refined by MR18-1233. Data from this study contributed significantly to the munitions mobility and burial analysis presented in MR-2730 and assists in the continued development of existing expert system modeling of UXO burial and mobility (e.g. Underwater Munitions Expert System, Rennie MR-2645). The methods and results presented in this study provide additional information pertinent to FUDS site management. Extrapolating subsurface properties based on surficial sediment distributions will reduce the amount of geotechnical sampling required at FUDS sites and allow for modeling of surrogate burial across a wide spatial domain.

2. Executive Summary

2.1. Introduction

There are a number of current and past SERDP studies that have investigated MEC and sediment dynamics to better understand the question of munitions mobility. The majority of these studies have concentrated on MEC in sandy, non-cohesive, coastal settings (e.g. Calantoni SERDP MR-2320, Traykovski MR-2319, Puleo MR-2503), which have provided pertinent information to models (e.g. Rennie MR-2645) in development to assist in the management of FUDS sites. However, a significant data gap was identified in previous SERDP Munitions Response (MR) workshops regarding the behavior of legacy munitions in FUDS sites containing cohesive sediments (SERDP Munitions Mobility and Modeling Workshop, Dec. 8-9, 2015). A review of available FUDS data, compiled by Calantoni (MR-2320) and Puleo (MR-2503), suggested as many as 139 FUDS sites lay partially or wholly in tidally-driven, cohesive sediment environments. To better address this data gap, a SERDP funded study (Trembanis MR-2730) investigated munition mobility and burial in cohesive sediments using acoustically-tracked surrogate munitions. The initial results of MR-2730 indicated that properties of the cohesive sediments were influencing the burial of surrogate munitions, but pertinent geotechnical site characteristics were not yet determined. In combination with MR-2730, this study expands the research on MEC mobility and burial in cohesive sediments through a focused in field study on the geotechnical properties of cohesive sediments that most contribute to the fate of MEC.

2.2. Objectives

The main objective of this study is to better characterize the geotechnical properties of cohesive sediments that contribute to MEC mobility and burial as observed in detailed field experiments in MR-2730. To achieve this objective, this study coupled periodic site-wide geophysical surveying with contemporaneous in-field geotechnical sediment characterization through repetitive sampling and application of a SERDP supported penetrometer (Dr. Nina Stark MR18-1233) at the MR-2730 munitions mobility and burial study sites. This study collaborated with Dr. Nina Stark (MR18-1233), who is currently developing and testing procedures for a sediment penetrometer to better characterize underwater FUDS sites. A second objective of this study is to examine the potential to link surface geophysical properties to sediment geotechnical properties. Extrapolating subsurface properties based on surficial sediment distributions will reduce the amount of geotechnical sampling required to characterize FUDS sites. Finally, data from this study provides additional information pertinent to FUDS site management and assist in the continued development of existing expert system modeling of UXO burial and mobility (e.g. Underwater Munitions Expert System, Rennie MR-2645).

2.3. Technical Approach

This study leveraged existing data from MR-2730 as well as new geophysical and geotechnical sampling collected at the completion of the final field experiment of MR-2730. Existing geophysical survey data, sediment samples, and hydrodynamics and observations of surrogate mobility and burial were combined with new sediment samples, geotechnical measurements, and geophysical surveying over both field sites used in MR-2730 (Figure 2.1). Geotechnical measurements were provided by Stark (MR18-1233) using a freefall drop penetrometer at

predetermined sites. The geotechnical data were used to test scour burial and burial by settling models. The scour burial model was adapted from mine burial models developed for non-cohesive sediments (Traykovski et al., 2007; Trembanis et al., 2007; Whitehouse, 1998) and modified for use in cohesive sediments. The burial by settling model introduced in this study is based on the bearing capacity of the soil as related to the freefall penetrometer measurements. Geophysical survey data and geotechnical sampling were combined through image classification to examine the potential to link sediment geotechnical properties to surficial sediment distribution maps. The objective for MR20-1480 was to synthesize the new and existing data to provide better characterization of the near-bed processes and sediment characteristics that contributed to the burial of surrogates observed in MR-2730

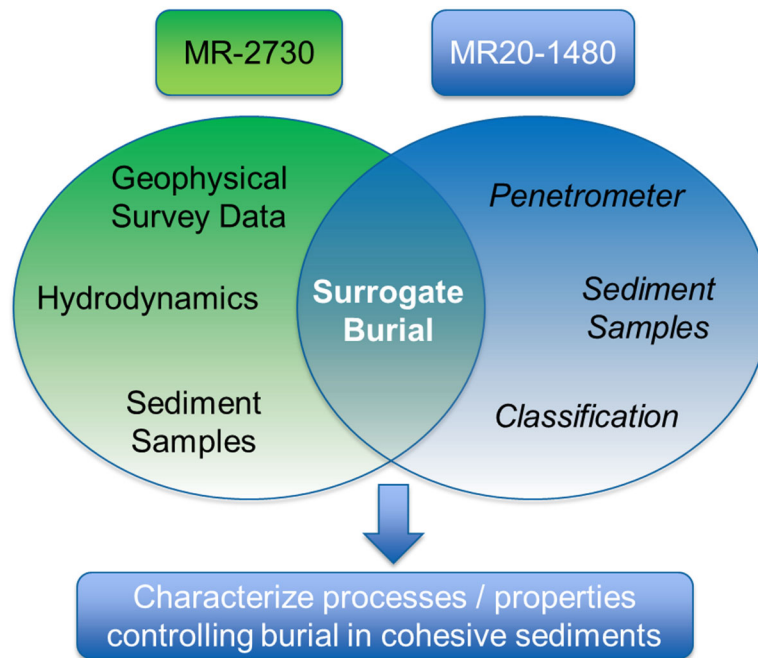


Figure 2.1: SERDP MR20-1480 overview and relationship to MR-2730.

2.4. Results and Discussion

Geotechnical analysis supported the observations of surrogate burial in the MR-2730 field experiments. Penetrometer measurements in and around study Sites 1 and 2 were showed very tight clustering at each site, suggesting little variation in sediment properties within and around each study site (Figure 2.2). Site 1 showed considerably higher quasi-static bearing capacity (QSBC), with penetrometer measurements ranging between 30-60 kPa at only 15-25 cm depth. In comparison, the penetration depth was much greater at Site 2, exceeding 70 cm in some measurements with QSBC below 13 kPa. The measureable difference in QSBC and penetration depth between Sites 1 and 2, located only 1 km apart, indicates that the difference in site sediment properties contributed to the difference in surrogate burial depths observed in MR-2730.

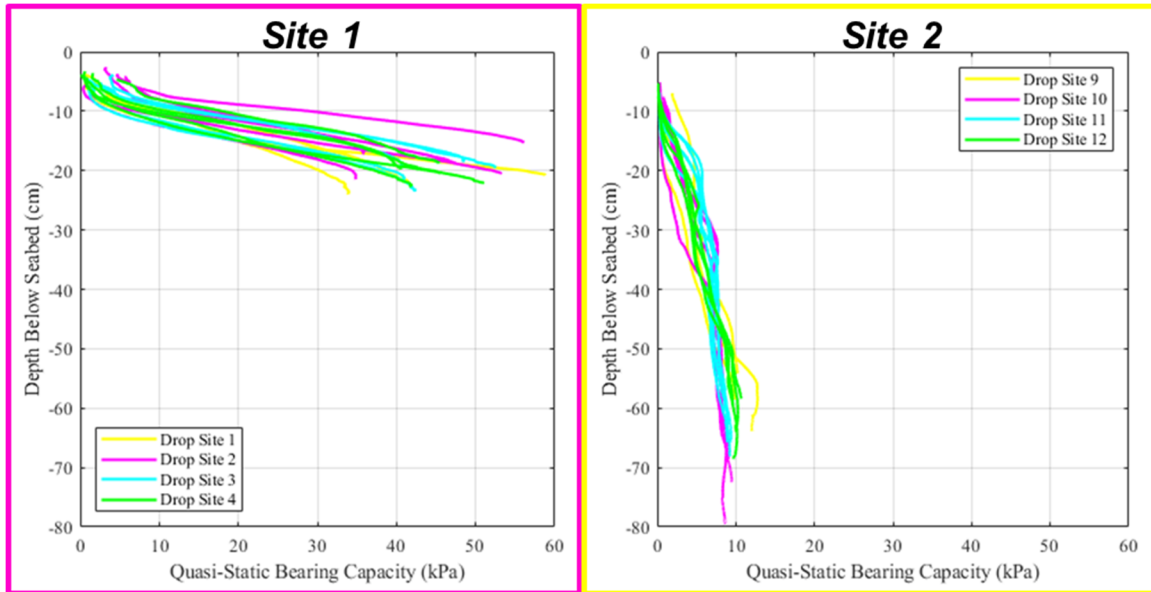


Figure 2.2: Penetrometer results for MR-2730 field sites showing quasi-static bearing capacity (QSBC) vs. penetration depth. Note the difference in QSBC and penetration depth between the two field sites.

Scour burial and settling models were run using *in situ* hydrodynamics from four MR-2730 field experiments and geotechnical analysis from MR20-1480 (Figure 2.3). The results for both scour and settling models were compared to the reported burial depth for each surrogate type. The scour models developed for non-cohesive sediments agreed reasonably well with field observations in the muddy sand sediment of Site 1 when adapted to account for mixed-cohesive sediments in this study. The Hertzian contact model implemented in this study for surrogate settling due to bearing capacity also agreed well with the burial depth of the surrogates at both Site 1 and 2 in absence of high-energy forcing. Neither model closely predicted surrogate burial at Site 2 with storm events, where surrogates buried significantly deeper than scour burial and bearing capacity predicted. This enhanced burial is likely related to additional fluidization of the soft sandy muds in Site 2 during storm events. Future investigations are required to better understand the burial depth of surrogates due to bed fluidization in cohesive sediments. Existing models for fluid mud layer thickness under waves (see Soltanpour et al., 2009) and may be adapted for application with munitions burial in soft muds.

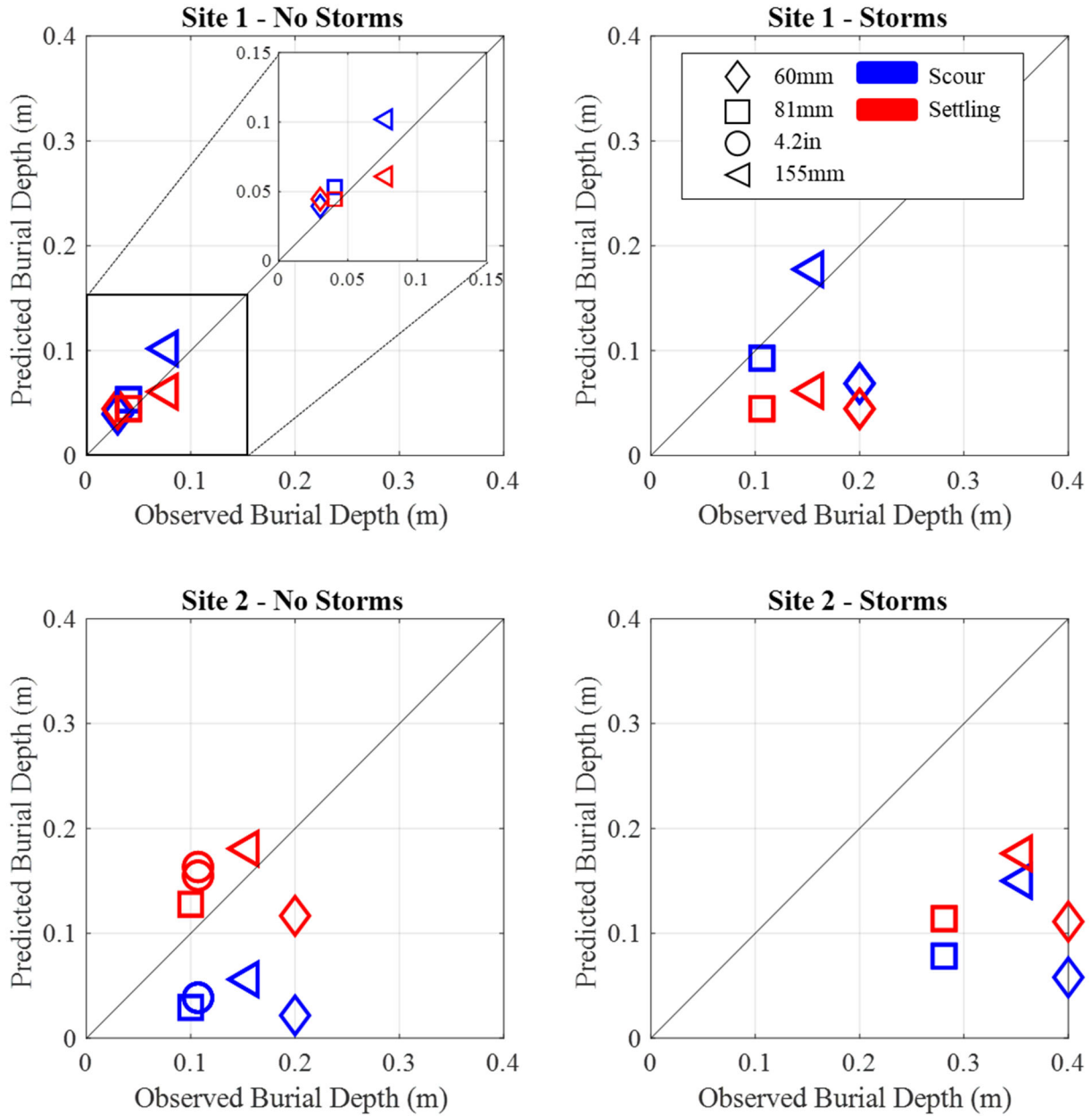


Figure 2.3: Model performance comparison for the four field experiments listed by site and storm activity. Plots are presented in the same scale. Site 1 – No Storm shows inset with close-up of model results where limited burial was observed. All observed burial depths are estimated from diver reports.

Sonar collected with an Edgetech 6205 Phase-Measuring Echo Sounder (PMES) was segmented using a Maximum Likelihood Supervised Classification in ESRI ArcMap 10.4 (Figure 2.4). To determine whether the segmented image could be classified using sediment samples, the non-segmented sonar mosaic pixel values were extracted and compared to the median grain size (d_{50}) and sand / mud fraction of each sample. A moderate correlation was found between sonar imagery and sand fraction ($r^2=0.55$), where higher sand fractions correlated to higher sonar backscatter. The segmented raster values at each sample location were then extracted and compared to the sand and mud fraction of each sample. The results indicate a good agreement between sand / mud fraction and sonar mosaic classes.

Distinct patterns were also found comparing shallow subsurface geotechnical properties to surface sediment samples. Maximum QSBC decreased as the sediment mud fraction increased, with a strong inflection point at 20% mud content. Penetration depth was found to increase with decreasing d50. Another strong inflection point was found around 63 microns, which corresponds to the sand – mud interface in traditional sediment grain size analysis.

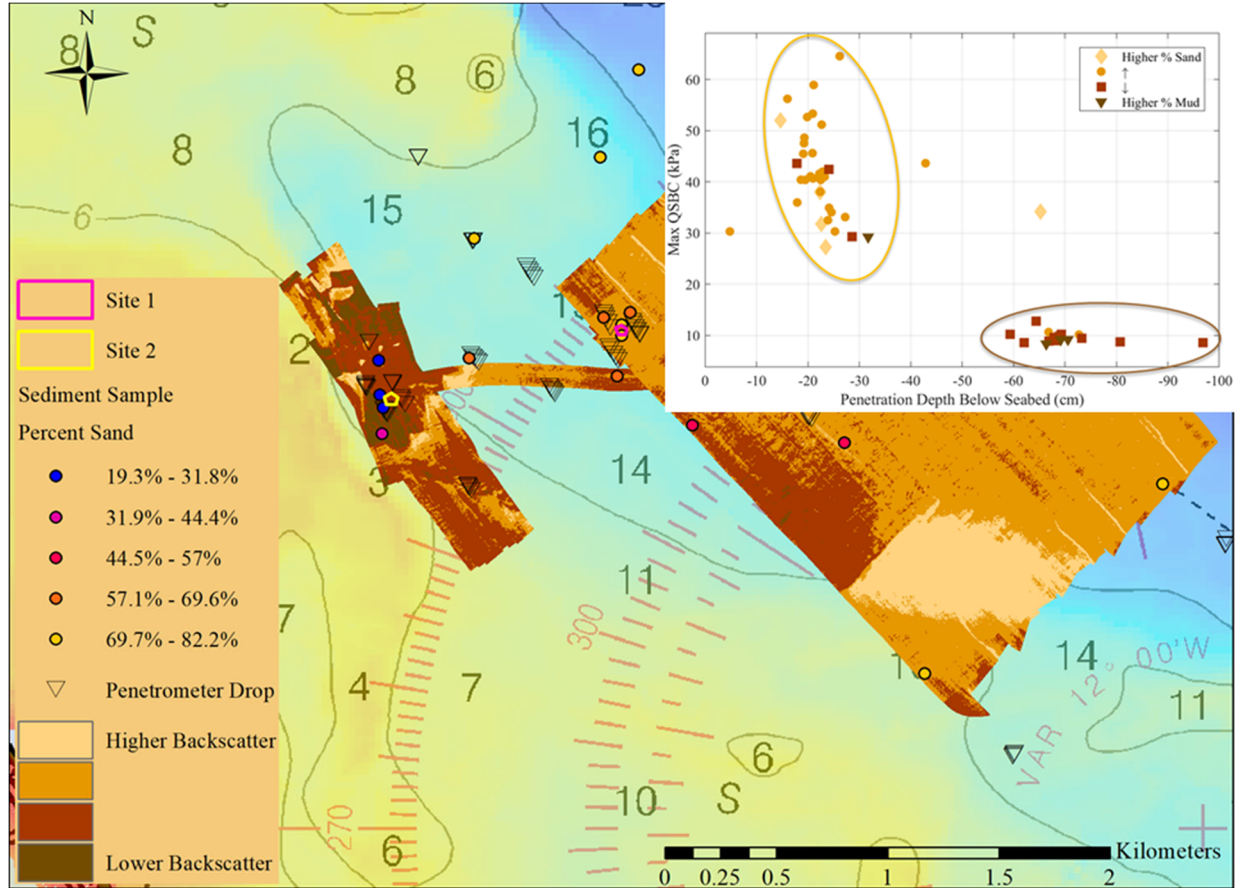


Figure 2.4: Segmented mosaic for composite sonar imagery using an ESRI ArcGIS supervised classification. Inset: Penetrometer measurements compared to sonar mosaic classification results. Note the 2 distinct groups reflecting higher percent sands (e.g. Site 1) and higher percent muds (e.g. Site 2).

Since both the sonar backscatter and geotechnical properties could be linked to the surface sediment samples, a geotechnical classification was attempted (Figure 2.4 inset). The sediment classes, as defined by sand/mud fraction, were extracted at overlapping penetrometer sample locations. Much like the penetrometer results from Sites 1 and 2, there are 2 distinct groups. The first group (upper left) is composed of 87.9% of samples in the higher percent of sand classes and is characterized by higher measured QSBC and shallower penetration depth. The second group (lower right) contains 87.5% of samples in the higher percent mud classes and is characterized by lower measured QSBC and higher penetration depth. Thus, the distinct clustering of samples by shallow subsurface geotechnical properties is strongly related to the surface sediment geophysical classification.

2.5. Implications for Future Research and Benefits

The objective of this study was to provide further analysis on the properties of cohesive sediments that influence MEC burial and mobility. By leveraging existing data from MR-2730 and collecting new geotechnical measurements in collaboration with MR18-1233 (Stark), this study identified sediment bearing capacity is an important predictor for surrogate burial. Further, we adapted and tested an scour burial model developed for non-cohesive sediments, and compared the model to a new bearing capacity / settling model developed for this study. Finally, we continued the investigation into geotechnical site classification based on the work of Stark et al., (2016) and found it a viable option for future FUDs site characterization. Data from this study contributed significantly to the munitions mobility and burial analysis presented in MR-2730 and assists in the continued development of existing expert system modeling of UXO burial and mobility (e.g. Underwater Munitions Expert System, Rennie MR-2645).

3. Objective

The detection, monitoring, and mitigation of munitions and explosives of concern (MEC) remains a topic of interest in coastal and underwater sites. Formerly-used defense sites (FUDS) span a wide-range environmental characteristics and histories, which contribute uniquely to the fate of MEC in individual FUDS sites. The interplay between historical and current physical forcing (e.g. wave and currents), sedimentology (e.g. cohesive vs. non-cohesive), and MEC type is at the center the underwater MEC question. As such, there is a defined need for better characterization of FUDS sites, focusing on, but not limited to, the interactions between sediment dynamics and MEC.

There are a number of current and past SERDP studies that have investigated MEC and sediment dynamics to better understand the question of monitions mobility. The majority of these studies have concentrated on MEC in sandy, non-cohesive, coastal settings (e.g. Calantoni SERDP MR-2320, Traykovski MR-2319, Puleo MR-2503), which have provided pertinent information to models (e.g. Rennie MR-2645) in development to assist in the management of FUDS sites. However, a significant data gap was identified in previous SERDP Munitions Response (MR) workshops regarding the behavior of legacy munitions in FUDS sites containing cohesive sediments (SERDP Munitions Mobility and Modeling Workshop, Dec. 8-9, 2015). A review of available FUDS data, compiled by Calantoni (MR-2320) and Puleo (MR-2503), suggested as many as 139 FUDS sites lay partially or wholly in tidally-driven, cohesive sediment environments. To better address this data gap, a SERDP funded study (Trembanis MR-2730) investigated munition mobility and burial in cohesive sediments using acoustically-tracked surrogate munitions. The initial results of MR-2730 indicated that properties of the cohesive sediments were influencing the burial of surrogate munitions, but pertinent geotechnical site characteristics were not yet determined. In combination with MR-2730, this study expands the research on MEC mobility and burial in cohesive sediments through a focused in field study on the geotechnical properties of cohesive sediments that most contribute to the fate of MEC.

The main objective of this study is to better characterize the geotechnical properties of cohesive sediments that contribute to MEC mobility and burial as observed in detailed field experiments in MR-2730. To achieve this objective, this study coupled periodic site-wide geophysical surveying with contemporaneous in-field geotechnical sediment characterization through repetitive sampling and application of a SERDP supported penetrometer (Dr. Nina Stark MR18-1233) at the MR-2730 munitions mobility and burial study sites. This study collaborated with Dr. Nina Stark (MR18-1233), who is currently developing and testing procedures for a sediment penetrometer to better characterize underwater FUDS sites. A second objective of this study is to examine the potential to link surface geophysical properties to sediment geotechnical properties. Extrapolating subsurface properties based on surficial sediment distributions will reduce the amount of geotechnical sampling required to characterize FUDS sites. Finally, data from this study provides additional information pertinent to FUDS site management and assist in the continued development of existing expert system modeling of UXO burial and mobility (e.g. Underwater Munitions Expert System, Rennie MR-2645).

4. Technical Approach

4.1. Background

In support of SERDP Munitions Response Statement of Need 17-01, MR-2730 initiated field investigations munitions mobility in cohesive sediment environments in FY2017. The primary objectives of MR-2730 were to: 1) monitor the mobility and behavior of sensor-integrated surrogate munitions in muddy environments using a high-accuracy acoustic positioning system, 2) observe surrogate munition response to hydrodynamic forcing through *in situ* hydrodynamics and sonar imagery, and 3) monitor morphological site changes through repetitive geophysical site surveying and benthic sediment sampling. A detailed description of the MR-2730 study is available in the MR-2730 Final Report to SERDP. A short summary of the study, as related to this project, is presented here.

Using a shallow estuarine site in the Delaware Bay, MR-2730 monitored the mobility and behavior of sensor-integrated surrogate munitions. Three munition types were selected as surrogates: 60mm mortars, 81mm mortars, and 155mm artillery shells. An additional surrogate type, 4.2-inch mortars, was added later to the study. Surrogates were monitored for changes in mobility and burial using a Vemco (Innovasea) VPS acoustic tracking system and inertial motion units (IMU). Time-series acoustic imagery and hydrodynamic sensors were also deployed to characterize MEC response to varied (e.g. storm vs. fair-weather) hydrodynamic conditions. A series of repetitive surveys were conducted using a hull-mounted, high-resolution phase-measuring bathymetric sonar and autonomous underwater vehicle (AUV) equipped with a magnetometer. In total, four deployments of the VPS array and surrogate munitions were conducted from 2017-2019 at two separate sites located in the lower Delaware Bay (Figure 4.1). The area of Site 1, situated in 4.5 m MLLW depth, was predominantly poorly sorted, fine muddy sand, with 60-75% sand and 25-40% muds. The area of Site 2, situated 1 km in shore of Site 1 and in 3.5 m MLLW depth, was predominantly poorly sorted sandy mud, with 15-40% sand and 60-85% muds. Two deployments occurred at Site 1 from 2 Nov - 4 Dec 2017 and 9 Feb - 11 Apr 2018. An additional two deployments were conducted at Site 2 from 29 Aug - 19 Nov 2018 and 27 Mar - 20 May 2019.

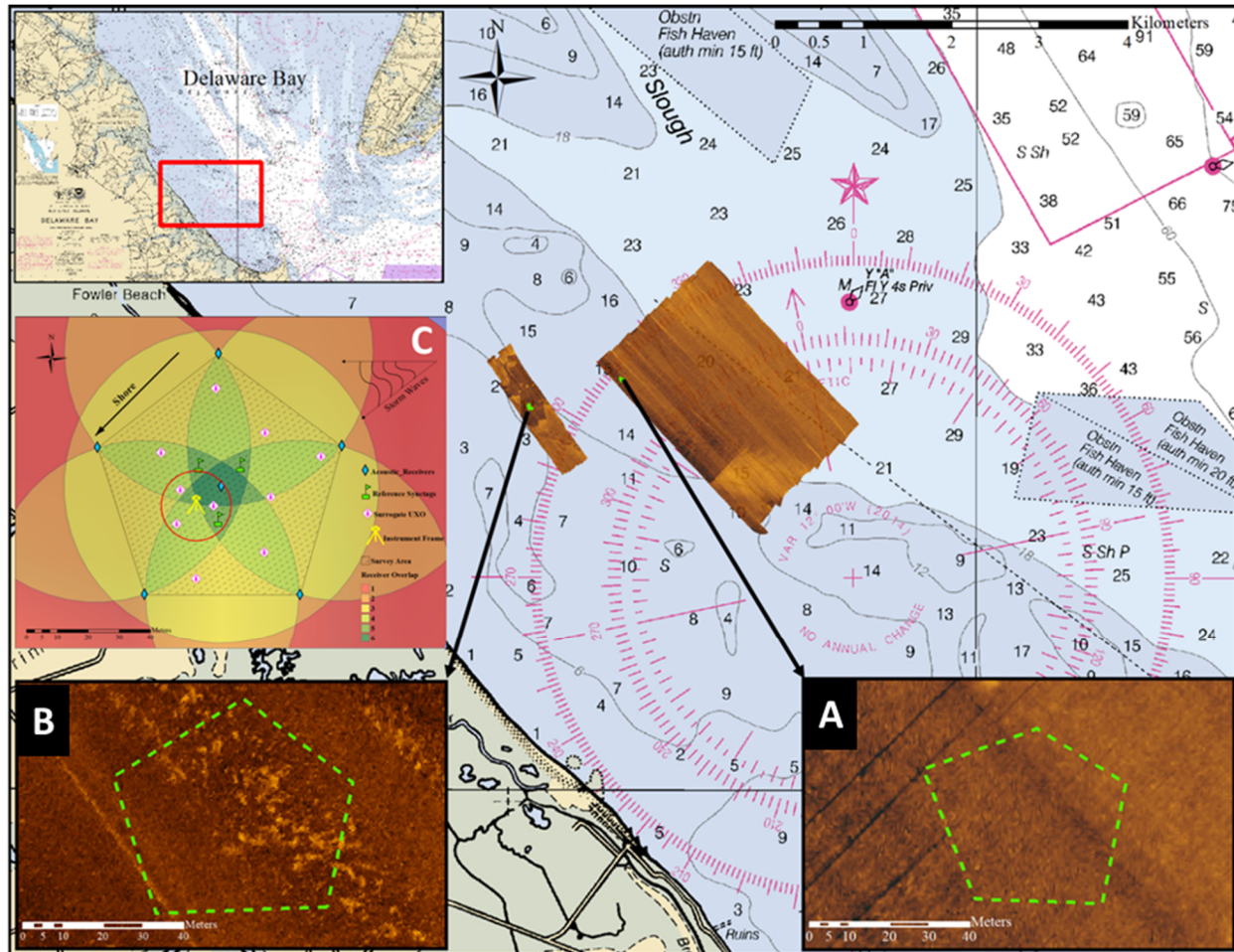


Figure 4.1: MR-2730 field experiment sites and surrounding area of the lower Delaware Bay, USA. Site 1 (A) was situated in muddy sands, while Site 2 (b) was situated in soft sandy mud. An idealized VPS array diagram (C) illustrates the field setup for each deployment.

Surrogate burial was consistently observed over the course of the four deployments. Divers from the Delaware State Police Scuba Unit (DSPSU), who assisted MR-2730, reported the depth of burial as precisely as possible given little to no visibility. Consistent among reports was the change from the stiff muddy sands of Site 1 to the soft sandy muds of Site 2 and the difference in burial depth at each site. The overall status of the surrogates at the end of their respective deployments are shown in Figure 4.2. The comparative figure highlights the differences in burial between Site 1 and 2, despite similar forcing conditions. For instance, with no storm events, surrogates were only partially buried in Site 1, but almost completely buried in Site 2. With storm events, the surrogates at Site 1 were mostly buried or exposed in scour pits, while in Site 2, they were buried with 20-30 cm of overburden. Given extensive burial, no large-scale horizontal mobility was observed during MR-2730, although during storms, particularly nor'easter Toby in March 2018, limited motion was recorded in the internal IMU of 60mm and 81mm surrogates. Using the VPS acoustic tracking, the final displacement of the surrogate was estimated at only 0.25 m from initial placement.

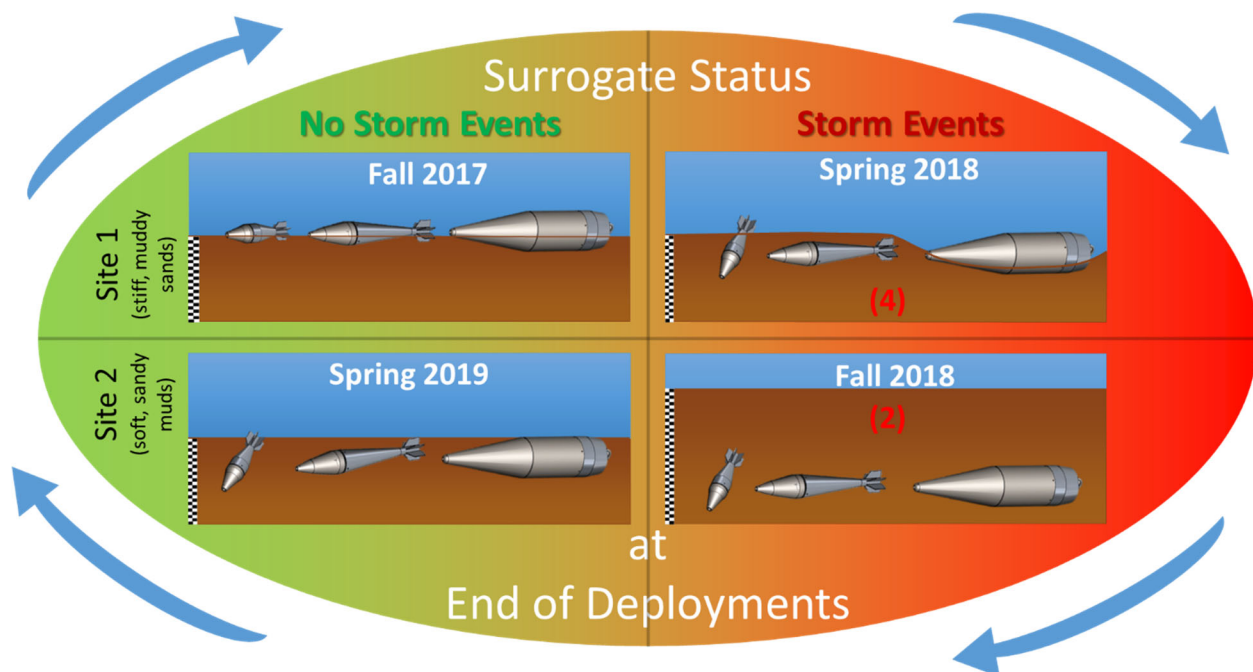


Figure 4.2: Comparative diagram of surrogate status for each of the four field experiments conducted by MR-2730. Note the difference in burial depth between Site 1 (top) and Site 2 (bottom) deployments under similar conditions and the difference between burial depth at the same site when storms (right) or no storms (left) were observed.

While MR-2730 provided new observations of munitions burial in cohesive sediments, the characteristics of cohesive sediments that contribute to burial and the mechanisms for burial in cohesive sediments were not fully identified through the MR-2730 field experiments. Parallels may exist with MEC mobility and burial in non-cohesive sediments, where the interaction between objects and the seabed occur in more predictable manners (see Calantoni MR-2320; Traykovski and Austin, 2017). However, there are fundamental differences between erosion and transport between cohesive and non-cohesive sediments that hamper direct translation.

In non-cohesive sediment, the initiation of sediment motion occurs on the granular level, which defines the processes controlling munitions mobility and burial. For instance, turbulence around seabed objects scours sediment away from the objects, forming pits that may eventually infill and bury object. This behavior was thoroughly characterized and modeled in recent mine burial studies (Traykovski et al., 2007; Trembanis et al., 2007; Catano-Lopera and Garcia, 2006). As well, there is work suggesting that highly energetic events may create a granular sorting effect, where objects denser than the surrounding mobilized sediment will sink to a depth where sediment is not mobile; this may result in MEC burial to depths lower than typically observed through scour processes (Calantoni MR-2320; see also Klammler et al., 2019; Calantoni and Thaxton, 2008).

Cohesive sediments conform to different transport regimes than non-cohesive particles. The cohesive forces linking particles typically requires higher energy to initiate erosion, which occurs as conglomerate “floculate” particles, or even as fluidized mobile mud beds, rather than individual grains. Characteristics such as sand-silt-clay composition, water content, compaction, and bulk density may influence the stresses needed to initiate erosion and transport (Jacobs et al.,

2011; Van Prooijen and Winterwerp, 2010). Thus, mechanisms for burial such as granular sorting are unlikely in theory. Likewise, less scour is anticipated in cohesive sediments than in non-cohesive sediments at an equivalent flow velocity and duration. However, scour pits were observed by both divers and in sonar imagery around 155mm surrogates during MR-2730 field experiments, but only in the muddy sands of Site 1 and not the softer sandy muds of Site 2.

Given the comparatively higher threshold for erosion of cohesive sediments, the mechanisms for MEC mobility and burial likely differ than those in non-cohesive sediments, although the characteristics of MEC (e.g. density) that are predictive of burial or mobility in non-cohesive sediments may remain important in cohesive settings. For example, under increasing wave height, mud layer thickness has been shown to increase (Soltanpour et al., 2009), with a corresponding increase in water content and decrease in sediment bulk density (Sahin et al., 2012). Much as with granular sorting, denser objects should in theory sink through the fluidized mud until reaching a denser or stiffer mud layer. Even in absence of substantive wave forcing, burial would be expected for objects if the object density sufficiently exceeded the sediment bearing capacity; the bed will undergo plastic deformation, allowing the object to effectively sink into the sediment over time (Richardson et al., 2001). Conversely, in stiff or compacted muds with higher bearing capacity, burial would be inhibited. For instance, mines in stiff muds were found to only undergo slight scour and partial burial (Inman and Jenkins, 2002). There, impact burial was observed to be the largest contributor to mine burial, not subsequent hydrodynamics.

Thus, while the mechanisms for munitions burial in non-cohesive sediments are well established, be it through scour-burial processes (Traykovski et al., 2007) or granular sorting (Calantoni MR-2320), the resistive nature of cohesive sediment to granular erosion reduces the likelihood of granular sorting as a primary mechanism for burial, inhibits scour (Inman and Jenkins, 2002), and may result in other mechanisms for burial not characteristic of non-cohesive sediments (Baeye et al., 2012; Sheremet et al., 2005). As identified in MR-2730 Final Report, and as will be shown below, the rheology of cohesive sediments may be a key predictor of object burial.

4.2. Methods

The technical approach of MR20-1480 was to leverage the existing data from MR-2730 as well as conduct new geophysical and geotechnical sampling concurrent with the final field experiment planned for MR-2730. Existing geophysical survey data, sediment samples, and hydrodynamics and observations of surrogate mobility and burial were combined with new sediment samples, geotechnical measurements, and geophysical surveying over both field sites used in MR-2730 (Figure 4.3). Geotechnical measurements were provided by Dr. Stark (MR18-1233) and her team using a freefall drop penetrometer at predetermined sites (Section 4.2.3). The geotechnical data were used to test various object burial models adapted for cohesive sediments (Section 4.2.4.) Geophysical survey data and geotechnical sampling were combined through image classification to examine the potential to link sediment geotechnical properties to surficial sediment distribution maps (Section 4.2.5). The objective for MR20-1480 was to synthesize the new and existing data to provide better characterization of the near-bed processes and sediment characteristics that contributed to the burial of surrogates observed in MR-2730

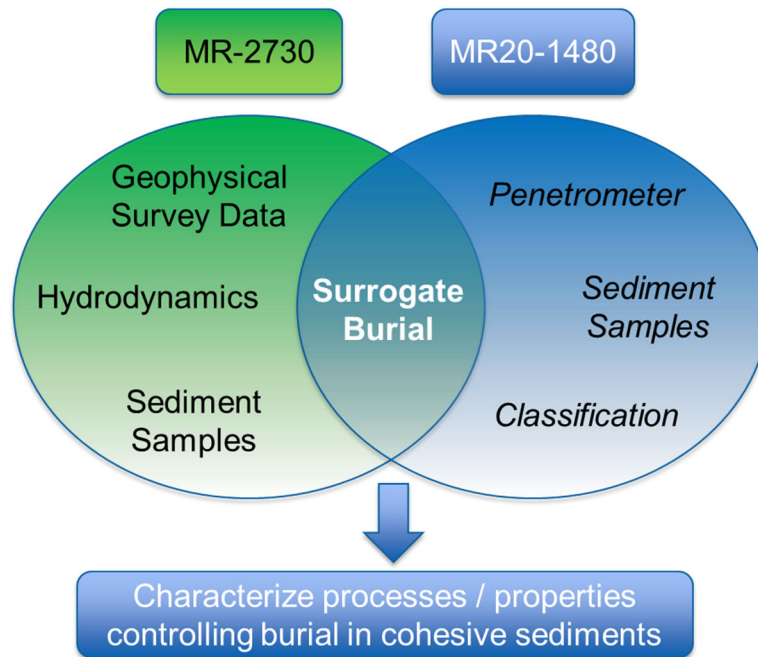


Figure 4.3: SERDP MR20-1480 overview and relationship to MR-2730.

4.2.1. Spring 2019 Deployment

MR20-1480 operations were conducted at the end of the final MR-2730 field experiment in May 2019. The experiment was conducted as Site 2 (soft, sandy mud site), and comprised a suite of hydrodynamic sensors, VPS acoustic tracking system, and 11 surrogate munitions. Instruments and surrogates were deployed on Mar 27-28, 2019, with the VPS and hydrodynamic sensors recovered on May 20, 2019. Only 2 of the 11 surrogates were recovered at that time, with the final 9 surrogates unable to be recovered until Aug 19, 2019 due to conditions and diver availability. A detailed description of the field experiment is outlined in Section 4.2.6.2 of the MR-2730 Final Report.

4.2.2. Geophysical Survey

Geophysical surveys were conducted at the deployment on Mar 27, 2019 and before the recovery on May 9, 2019 with University of Delaware's *R/V Joanne Daiber*. The *Daiber* was fitted with an Edgetech 6205 Phase-Measuring Echo Sounder (PMES), which collects simultaneous dual-frequency side-scan sonar at 230 and 550 kHz, and bathymetry on the 550 kHz frequency (Figure 4.4). The PMES uses a Coda Octopus F190R+ inertial motion unit coupled with RTK/PPK GPS to record vessel attitude (heading, pitch, roll, and heave) and horizontal position accuracy of 10 cm or less. While the Mar. 27 survey focused on Site 2 and the surrounding area, both Sites 1 and 2 were surveying with the PMES on May 9, 2019. An additional 9 surveys were also available from MR-2730 ranging from 2017 to 2019 (Table 4.1). Complete site acoustic backscatter and bathymetry map products were generated for each survey using Chesapeake Technologies, Inc. SonarWiz.



Figure 4.4: University of Delaware R/V Joanne Daiber equipped with Edgetech 6205 Phase-measuring Echo Sounder.

Table 4.1: PMES Survey dates and area.

Survey Dates	Site 1	Site 2	Surrounding Area
18-Oct-17	X		X
19-Oct-17	X		
2-Nov-17	X		
6-Mar-18	X		
10-Jul-18	X	X	X
11-Jul-18			X
27-Aug-18	X	X	
7-Nov-18		X	
27-Mar-19		X	
28-Mar-19		X	
9-May-19	X	X	

4.2.3. Geotechnical Sampling

Geotechnical characterization consisted of targeted surficial sediment sampling, gravity core, and penetrometer measurements, while leveraging previously collected sediments samples, shallow core samples, and shear vane analysis. The main sampling efforts of MR20-1480 were conducted on May 14-15, 2019. Using the MR-2730 sonar imagery and publically-available Roxan seabed classification data (DNREC 2004), twenty-three sampling locations were identified for sediment sampling and penetrometer measurements (Figure 4.5).

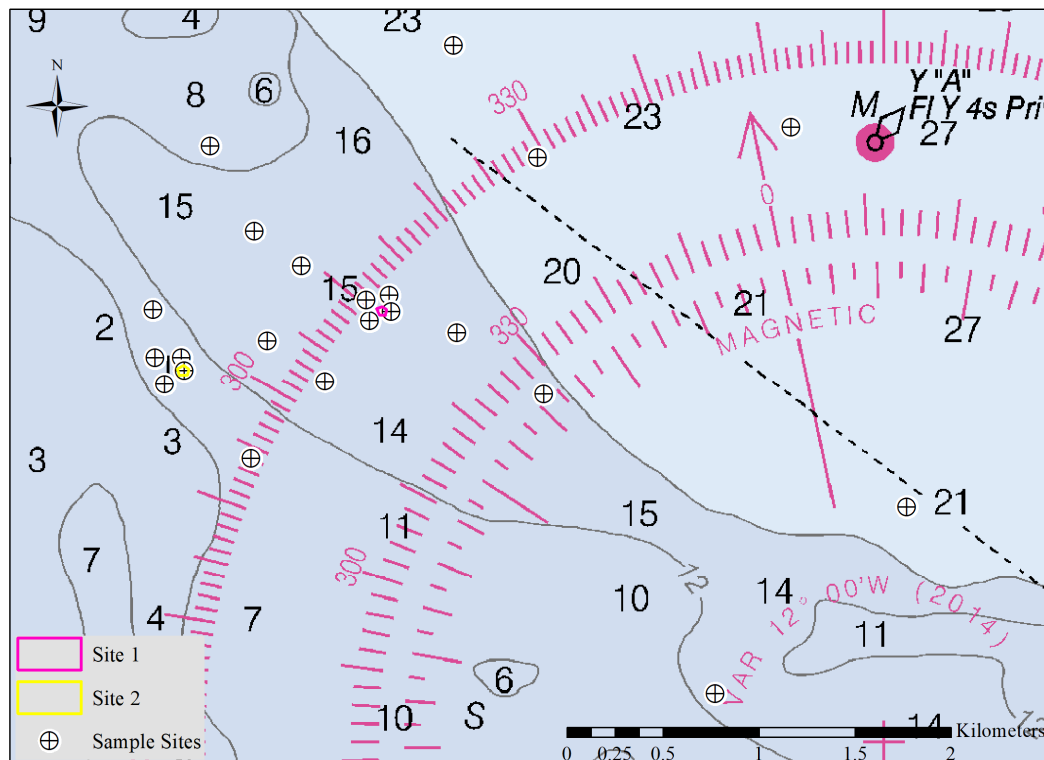


Figure 4.5: Locations for surface grab sediment sampling and penetrometer measurements.

Penetrometer measurements were collected by Dr. Nina Stark (MR18-1233) and her team using a BlueDrop portable free-fall drop penetrometer (Figure 4.6a; see also Stark et al., 2016). Five drops were made at each sample location. Additionally, two static pore pressure tests were conducted at each MR-2730 study site. The penetrometer was dropped within the site and left in the sediment for a minimum of 30 min per test. Two gravity cores (1 at each site) were also collected to assist the penetrometer geotechnical characterization (Figure 4.6b). The penetrometer data was analyzed by Dr. Stark's team, which provided MR20-1480 with profiles of penetration depth (m), velocity (m/s), deceleration (g), and quasi-static bearing capacity (kPa) at each sample location.

Surface sediment samples were collected at the 23 sample locations using a modified Young's sediment grab sampler. Two samples were extracted at each location, and two 100mL samples were collected from each grab. A 20 gram portion was sub-sampled and processed using a standard grain size analysis by sieve (for sand fraction) and pipette (for mud fraction) methods at

$\frac{1}{2}$ phi intervals. The data was collated and statistical analysis conducted using GRADISTAT version 9.1 (Blott and Pye, 2001).

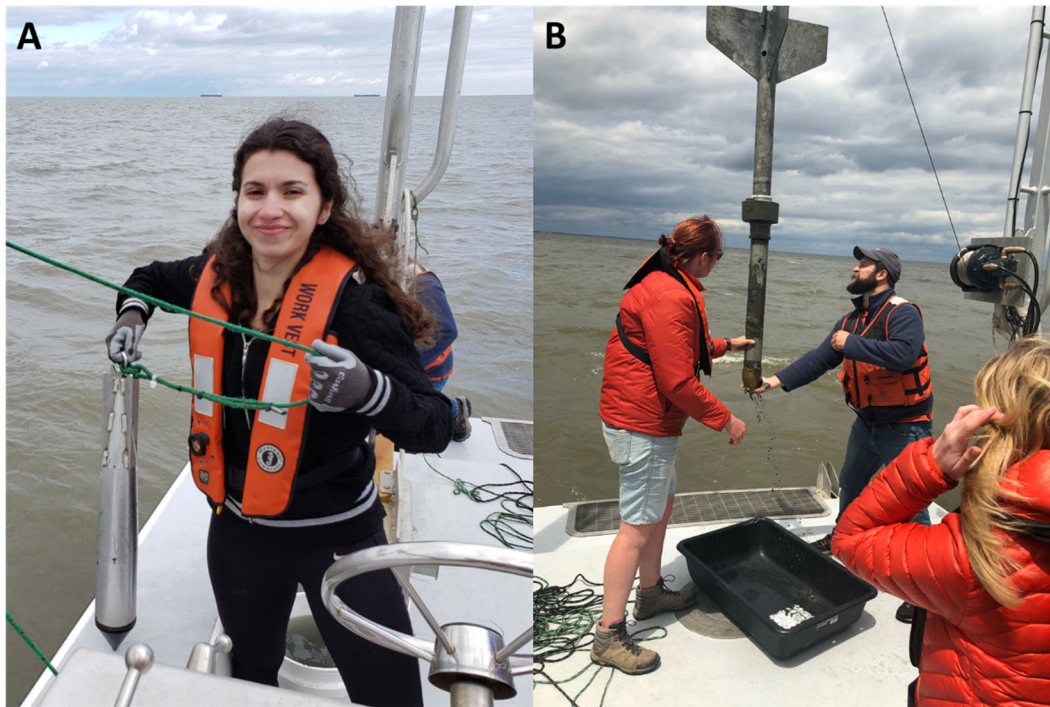


Figure 4.6: Geotechnical site characterization was provided by Dr. Nina Stark (MR18-1233) and her team. Data was collected with a portable freefall penetrometer (a), and ground-truthed with sediment samples and gravity cores (b).

In addition to the MR20-1480 field samples, sediment grab samples, short core, and shear vane analysis were available from MR-2730. Between the two studies, 63 total surface sediment samples were collected in the study area and the surrounding Broadkill Slough, with 37 fully processed. Additionally, four 30-cm short-cores were collected at four separate locations using a HAPS corer (Figure 4.7). Two cores were collected at each location. The first core was subjected to shear vane analysis immediately after collection. A standard 5 cm spade was used for the shear vane analysis. Measurements were collected in 5 cm vertical sections. Each 5 cm section was divided into four quadrants, and each quadrant measured using a calibrated shear vane. A single shear strength was averaged over the 4 quadrants for each 5 cm vertical section. The 2018 shear vane measurements were leveraged by Dr. Stark's team for additional ground-truthing of penetrometer analysis.

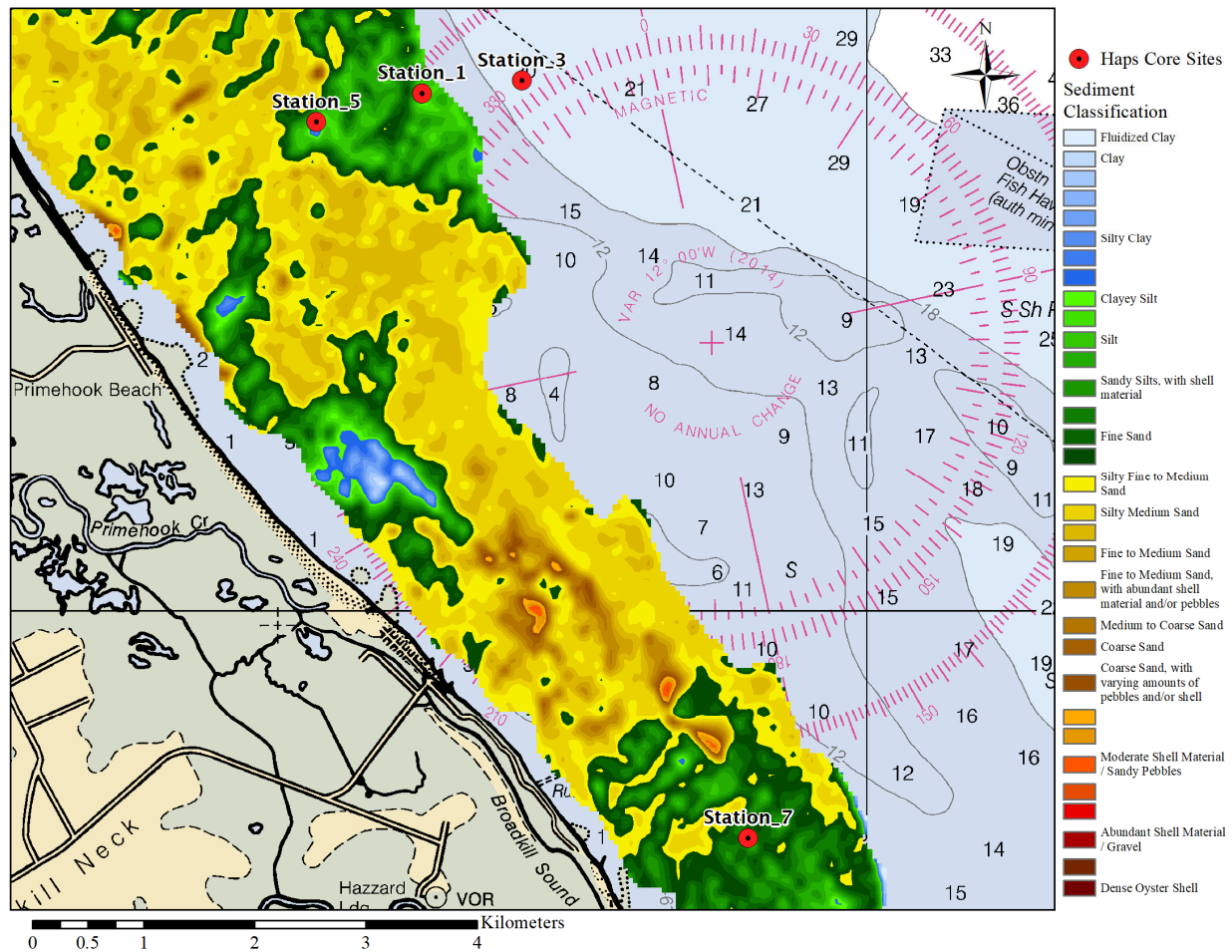


Figure 4.7: Locations for HAPS core samples collected in July 2018 overlaying 2004 Roxan seabed classification data (DNREC 2004).

4.2.4. Object Burial Models

As identified in Section 4.1, the likely mechanisms for burial in cohesive sediments are impact burial, settling (either at initial deposition or later by fluidization of the muds), and, to a lesser degree, scour burial. As the surrogates in this study were set on the seafloor, impact burial can be ruled out. This leaves scour burial and burial by settling. For scour burial, extensive work was conducted with seabed mines to model scour burial in non-cohesive sediments (Traykovski et al., 2007; Trembanis et al., 2007; Whitehouse, 1998) and adapted here for use in cohesive sediments. With burial by settling, a new model is introduced based on the bearing capacity of the soil as related to the freefall penetrometer measurements.

4.2.4.1. Scour Burial Model

Using the Whitehouse et al. (2000) modified Shields parameter for mixed sediments (see MR-2730 Final Report Section 5.2.2.2), we adapted the mine scour burial model developed by Trembanis et al., (2007) (adapted from Whitehouse 1998 for application in wave oscillatory flow) for applications in cohesive sediments. To simplify the problem, we assumed a cylindrical

shape for the surrogates, with the diameter, weight, and length of the cylinder consistent with the surrogates. For this model, the time-dependent scour of a cylinder is given by the equation,

$$S(t) = S_{eq} \left[1 - \exp \left(-\frac{t}{T_x} \right)^{P_m} \right]$$

where S_{eq} is the equilibrium scour depth relative to the far-field seabed, t is time, T_x is the time scale of the scour process and P_m is a fitting coefficient related to the object's geometry. A value of $P_m = 0.6$ was found to be a good fit for short cylinders by several studies (Demir and Garcia, 2007; Trembanis et al., 2007; Whitehouse, 1998). The time scale of the scour process T_x is related to the far-field (i.e. not influenced by the object) Shields parameter (modified using the Whitehouse et al., 2000 method) for sediment motion and is given by the equation,

$$T_x = M \theta_{sed}^N D^2 [g(s_{sed} - 1) d_{sed}^3]^{-0.5}$$

where M and N are empirical coefficients defined by Whitehouse (1998) as 0.095 and -2.02 respectively, D is the object diameter, s the specific gravity of sand, and d the median grain size. S_{eq} is related to the far field Shields parameters and calculated as,

$$S_{eq} \begin{cases} 0 & \text{for } (\theta/\theta_{cr})^{1/2} < 0.75 \\ 1.15D[2(\theta/\theta_{cr})^{1/2} - 1.5] & \text{for } 0.75 \leq (\theta/\theta_{cr})^{1/2} < 1.25 \\ 1.15D & \text{for } (\theta/\theta_{cr})^{1/2} \geq 1.25 \end{cases}$$

The maximum burial is represented as a percentage of the surrogate diameter by the equation,

$$\%Burial = 100 \left(\frac{S_{max}}{D} \right)$$

The model was run for each surrogate type over the four deployments.

4.2.4.1. Bearing Capacity Model

As noted in previous mine burial studies, the bearing capacity of muds may be a primary predictor of burial depth for mine-like objects (Richardson et al., 2001). If the force exerted on the seabed by the surrogates is greater than the sediment bearing capacity, the surrogates should sink into the sediment. To test this, we modeled the force exerted on the seabed by the surrogate munitions. The penetrometer data provided QSBC profiles for the sediment at Sites 1 and 2. QSBC estimates the load capacity of the sediment before failure under a threshold pressure. The surrogate pressure is calculated from the total weight from gravitation forcing minus buoyant forces. If the weight of the surrogates exceeds the sediment bearing capacity, we would assume shearing or compressive failure of the sediment, resulting in the surrogates “sinking” into the seabed.

To simplify the problem, we assumed a cylindrical shape for the surrogates, with the diameter, weight, and length of the cylinder consistent with the surrogates. Pressure along a cylinder varies as:

$$P(\varphi) = P_{max} * \cos(\varphi)$$

Where ϕ is the contact angle of the half surface, and P_{max} is calculated by:

$$P_{max} = \frac{4F}{LD} * \left[\frac{1 - \cos(\phi_0)}{2\phi_0 - \sin(2\phi_0)} \right]$$

Where F = force, L = length of the cylinder, D = diameter of the cylinder, and ϕ_0 is the half contact angle (from the centerline to the surface). To estimate ϕ_0 , we assume a simple Hertzian contact problem between a rigid cylinder and an elastic surface. This assumes a rectangular contact surface of deformation between the cylinder and the surface. The half-width of the rectangular contact area is calculated by:

$$\beta = \text{sqrt} \left[\frac{4F \left(\left(\frac{1 - \nu_{sed}^2}{E_{sed}} \right) + \left(\frac{1 - \nu_{obj}^2}{E_{obj}} \right) \right)}{\pi L \left(\frac{1}{r_{sed}} + \frac{1}{r_{obj}} \right)} \right]$$

Where ν is Poisson's ratio for the object material (i.e. steel) and sediment, E is the elastic modulus for the object and sediment, and r is the radius of the object and sediment (in this case, we assume the surface is a cylinder of infinite radius). Without direct measurements, we used published values for Poisson's ratio and elastic modulus of sediments (Obrzud and Truty, 2012; Hamilton, 1979; Hamilton, 1971). Poisson's ratio and the elastic modulus was estimated for silty sands with medium stiffness for Site 1 and soft silts and clays for Site 2. The half-rectangular contact surface is converted to the radial surface of the object to estimate ϕ_0 . This is then used to calculate the pressure exerted on the seabed by the object.

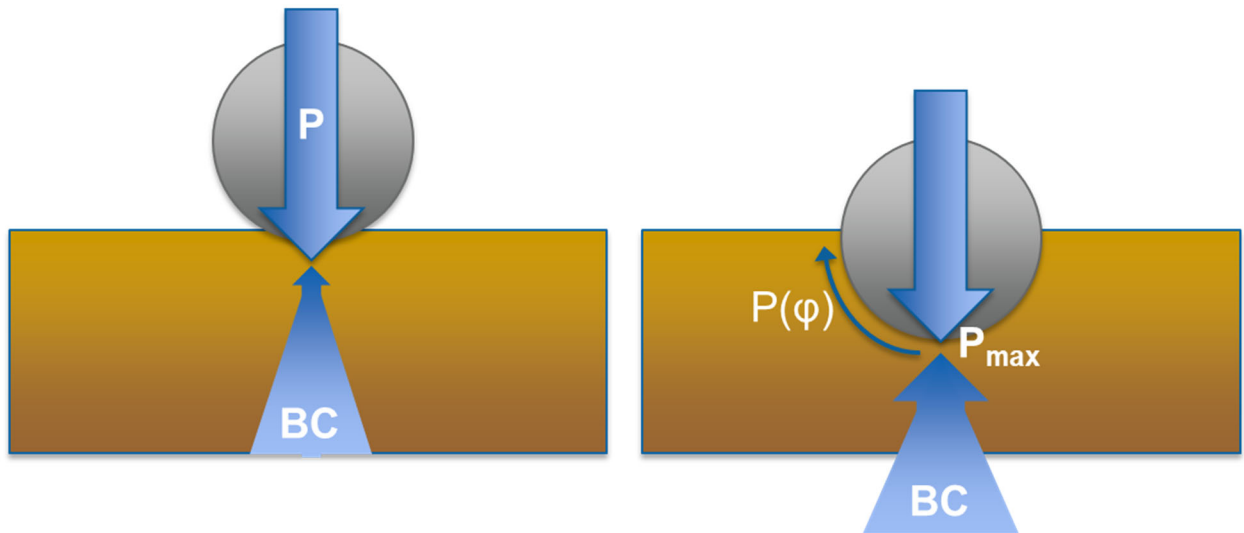


Figure 4.8: Conceptual diagram of burial due to bearing capacity. If the pressure exerted by the object exceeds the bearing capacity of the sediment, the object will sink until the sediment can support the weight of the object.

The model was run for each surrogate and compared to the QSBC profiles for each penetrometer sample. Maximum burial depth, estimated at the leading edge of the surrogate surface, is estimated at the depth where $QSBC \geq P_{max}$, or the depth at which the sediment bearing capacity exceed the pressure exerted by the object (Figure 4.8).

4.2.5. Geophysical & Geotechnical Classification

Geophysical survey data and geotechnical sampling were combined through image classification to examine the potential to link sediment geotechnical properties to surficial sediment distribution maps. A conceptual workflow (Figure 4.9) was developed building off of methods used by Stark et al., (2016). Sonar collected by the PMES was used to classify sediment distributions at the field sites. Sediment samples provided ground-truthing for image segmentation. All 11 sonar data sets were mosaicked using Chesapeake Technologies Inc., SonarWiz. Identical gain settings were applied to each, and mosaics were exported with the same settings and color map. Mosaics were classified using ESRI ArcGIS 10.4. To establish a baseline, a composite mosaic was created from all of the sonar surveys. The composite mosaic was then classified using an unsupervised Iso Cluster classification. The Iso Cluster classification was then used to inform a Maximum Likelihood supervised classification. The results were compared to the processed sediment samples. The classified raster values at each sample location were extracted and compared to the sand and mud fraction of each sample. Using a similar method, sediment samples were compared to collocated penetrometer profiles.

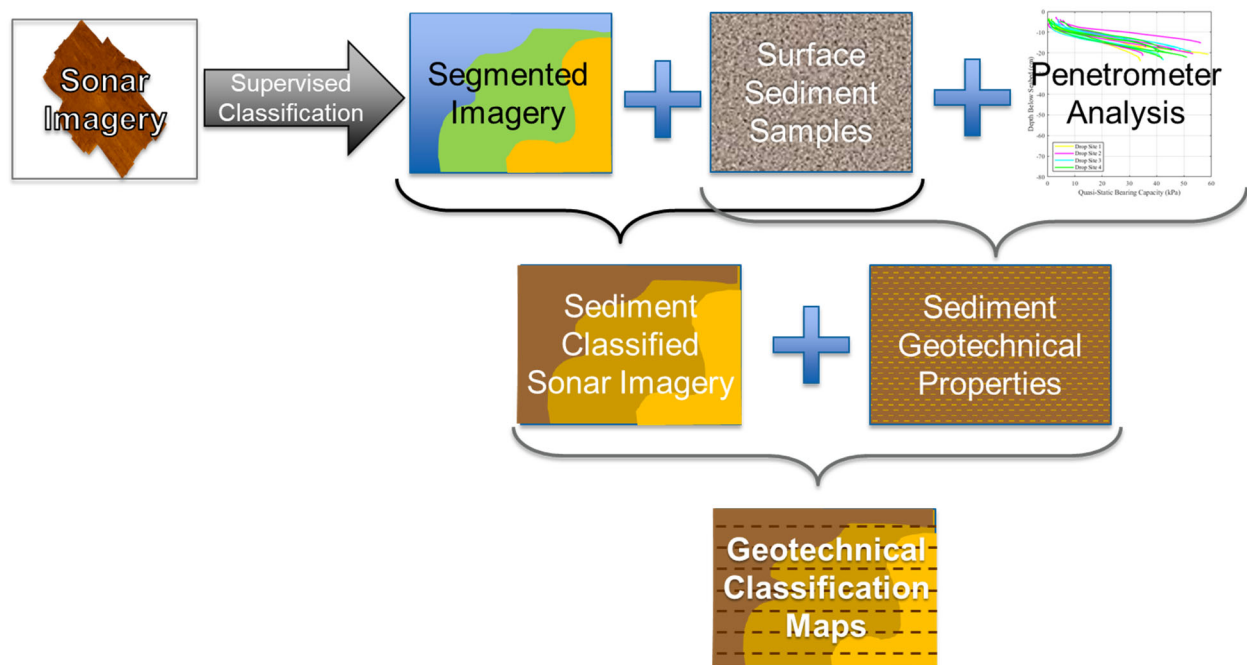


Figure 4.9: Conceptual workflow to combine geophysical survey data with geotechnical characterization to produce geotechnical classification maps linking shallow subsurface geotechnical properties with surficial sediment distribution.

The ability to create a classified geotechnical map would be determined by whether backscatter, surficial sediment, and shallow subsurface geotechnical properties are correlated. For instance, if a strong correlation exists between backscatter intensity and grain size or sand / mud fraction, then a classified sediment distribution map can be produced. This is a fairly common practice in the marine geophysics (Brown et al., 2011) and the basis of many seabed classification systems (e.g. Roxan) or software (e.g. Geocoder). Similarly, if quasi-static bearing capacity (QSBC) and/or penetration depth are correlated to grain size and sand / mud fraction, then a relationship can be established between surface sediments and shallow geotechnical properties. Stark et al. (2016) showed that such a relationship could be determined from the BlueDrop penetrometer profiles and surface sediment samples. Should the relationships between backscatter, sediment size / fraction, and geotechnical properties overlap (e.g. backscatter $\propto$ sediment grain size $\propto$ QSBC), the sediment classified sonar maps and sediment geotechnical properties may be linked to produce a geotechnical classified sonar map.

5. Results and Discussion

5.1. Geotechnical Results

Processed sediment samples show a wide distribution of mixed cohesive sediments in and around the MR-2730 study sites (see Figure 5.1). The area of Site 1 was predominantly poorly sorted, fine silty sands, with 60-75% sand and 25-40% muds (silts and clays). The area of Site 2 was predominantly poorly sorted sandy silts, with 15-40% sand and 60-85% muds. The differing composition of the site sediments was also reflected in the 2018 shear vane analysis (Table 5.1). The first 5 cm of Site 1 (Station 1) was a soft muddy sand with high water content, but overlaid a stiff, compacted muddy sand found 5-15 cm deep. The layer was so stiff as to prevent deeper sampling by the HAPS corer, which is otherwise capable coring to 30 cm depth. At Site 2 (Station 5), the core sample was comprised of soft sand muds from 0-30 cm with shear strengths 2-4x less than corresponding depths at Site 1.

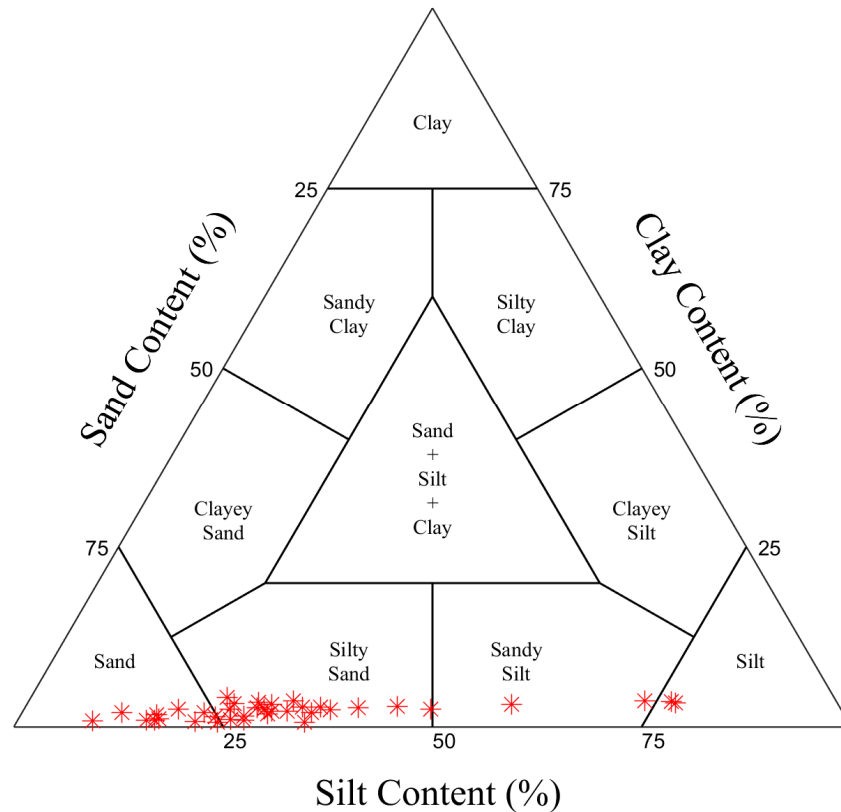


Figure 5.1: Shepard (1954) sediment ternary diagram for sediment samples from MR-2730 field sites and wider Broadkill Slough region.

Table 5.1: Shear-vane measurements for HAPS core samples collected in July 2018.

HAPS Core Shear Vane Analysis							
(Avg. kPa of 4 measurements per 5cm bin)							
Core Site	0-5cm	5-10cm	10-15cm	15-20cm	20-25cm	25-30cm	Description
Station1	8.25	42.25	41.75	NA	NA	NA	soft muddy sand overlaying stiff muddy sand
Station3	7.75	40	31.75	24	NA	NA	soft muddy sand overlaying stiff muddy sand
Station5	3.5	5.75	2.25	6.25	10	6.5	soft sandy mud
Station7	10.25	17.75	35.5	34	NA	NA	soft muddy sand overlaying stiff muddy sand

The 2019 penetrometer analysis was conducted by Dr. Stark's team and the results provided to the MR20-1480. The penetrometer results supported the observations of the DSPSU divers, sediment sampling, and shear vane analysis. Four penetrometer sample sites in and around Study Site 1 and 2 were selected for and compared (Figure 5.2). Both groups showed very tight clustering at each site, suggesting little variation in sediment properties within and around each study site. Site 1 showed considerably higher quasi-static bearing capacity (QSBC), with penetrometer measurements ranging between 30-60 kPa at only 15-25 cm depth. Like the HAPS corer, penetration depth was limited by the stiff muddy sands. In comparison, the penetration depth was much greater at Site 2, exceeding 70 cm in some measurements. The QSBC at Site 2 maxed out only 8-12 kPa at depths of 60-80 cm. The surrounding region was consistent with the measurements of Site 1 except for the shallower shoals. Two sites were sampled on the flanks of sandy shoals to the NW and SE of the field sites. The penetrometer measured QSBC between 183 – 272 kPa and penetration depths of only 4-7 cm at these sites. The sediments in Site 1 and 2 were therefore much softer, which likely contributed to the surrogate burial seen in MR-2730.

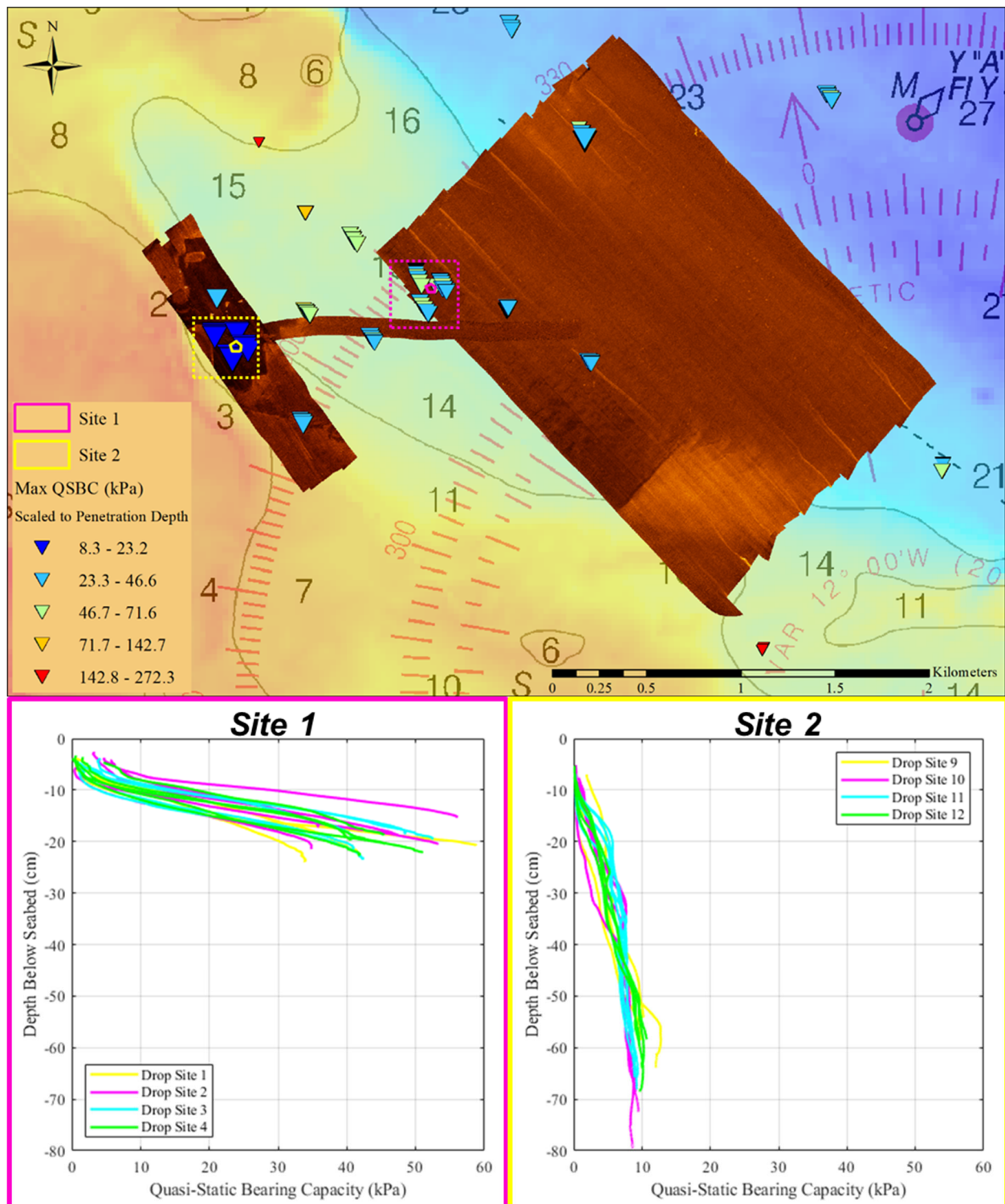


Figure 5.2: Penetrometer results for MR-2730 field sites and surrounding Broadkill Slough (top) showing quasi-static bearing capacity (QSBC) scaled to penetration depth (deeper penetration = larger symbol). The samples in and around Site 1 and Site 2 are shown below. Note the difference in QSBC and penetration depth between the two field sites.

5.2. Burial and Modeling

5.2.1. Observed Burial

The measureable difference in QSBC and penetration depth between Sites 1 and 2, located only 1 km apart, indicates that the difference in site sediment properties contributed to the difference in surrogate burial depths observed in MR-2730. The status of the surrogates at the end of their respective deployments are shown in Figure 5.3, represented by the average relative density ($\rho_{obj}/\rho_{seawater}$) of each surrogate type by deployment versus the relative burial depth (burial depth/object diameter) estimated from diver reports. Depth is reported as the deepest portion of the surrogate below the sediment surface and takes into account pitch and orientation. Two deployments occurred at each study site, of which one deployment at each site experienced low – moderate forcing and the other deployment high forcing through extra-tropical cyclones and other wave events. The plot highlights the differences in burial between Site 1 and 2, despite similar forcing conditions. For instance, with no storm events, surrogates were only partially buried in Site 1, but almost completely buried in Site 2. With storm events, the surrogates at Site 1 were mostly buried or exposed in scour pits, while in Site 2, they were buried 20-30 cm deep. It should be noted that the average density of the 81mm and 155mm surrogates did vary slightly (<5% and <9% respectively) between deployments due to reconfiguration of the internal electronics and ballasting to improve IMU battery life and performance, which may explain some of the variation in burial between Site 1 and 2. However, the 60mm mortar surrogates remained consistent across deployments and the patterns in 60mm burial behavior was consistent with difference observed in burial between sites with the 81mm and 155mm surrogates.

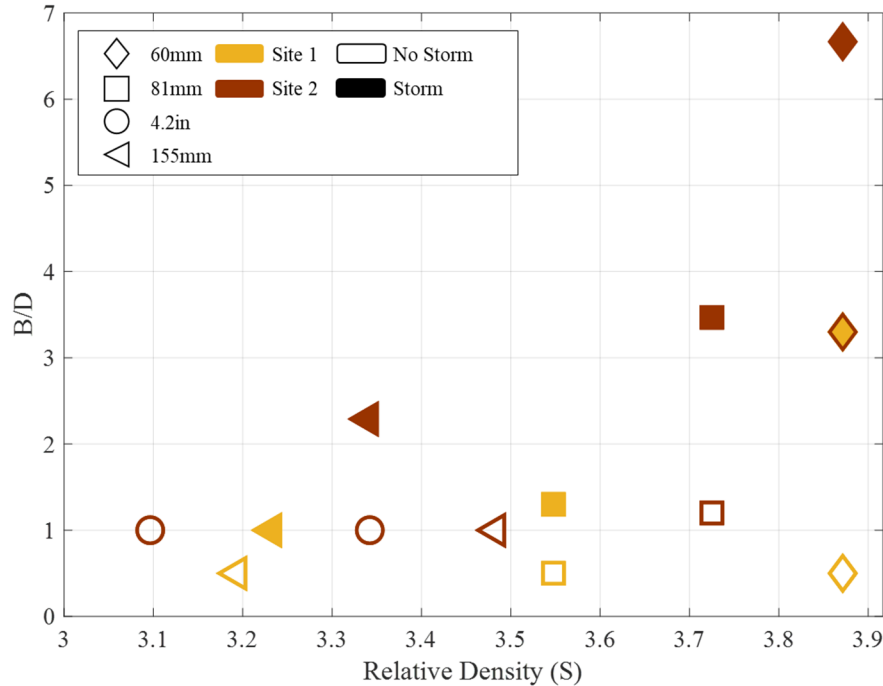


Figure 5.3: Comparative diagram of surrogate status for each of the four field deployments shown as the ratio of the burial depth (B) to the surrogate diameter (D) and plotted against the relative density of the surrogates ($\rho_{obj}/\rho_{seawater}$). Note that the 60mm mortars were reported as buried in a near vertical orientation, and the burial depth is estimated at the deepest portion of each surrogate.

5.2.2. Burial Model Comparison

Scour burial and settling models were run for all four deployments using *in situ* hydrodynamics from MR-2730 and geotechnical analysis from MR20-1480 (Figure 5.4). The results for both scour and settling models were compared to the reported burial depth for each surrogate type.

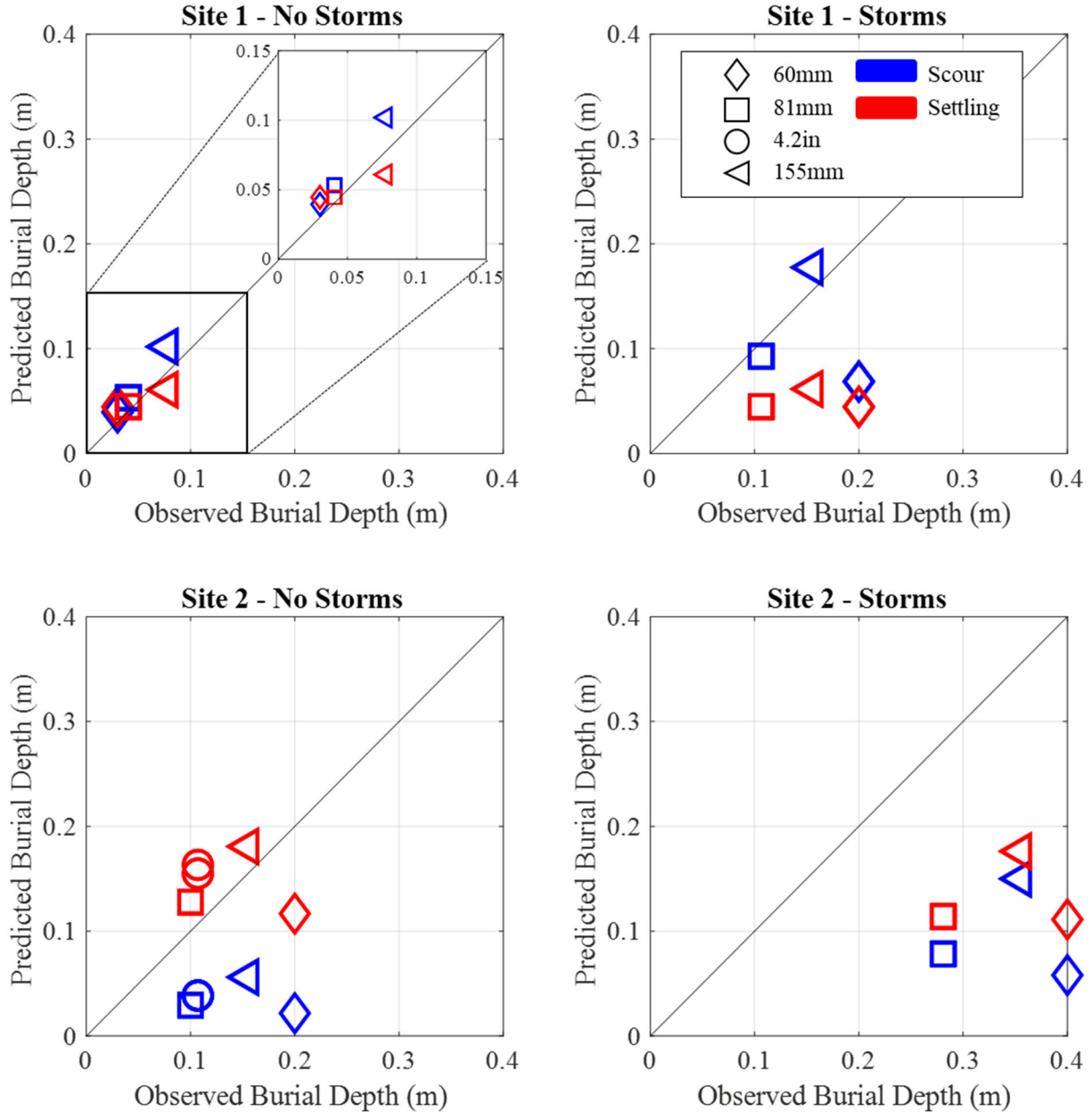


Figure 5.4: Model performance comparison for the four field experiments listed by site and storm activity. Plots are presented in the same scale. Site 1 – No Storm shows inset with close-up of model results where limited burial was observed. All observed burial depths are estimated from diver reports.

Model performance varied between field site and conditions (i.e. storm vs no storm). In Site 1 with no storm events recorded (Fall 2017), the scour model closely predicted the observed scour burial for all surrogate types. The scour model also agreed well with the Site 1 deployment when

storms were observed (Spring 2018). Both the 155mm and 81mm surrogate burial depth were closely predicted by the scour model. While the observed burial depth for the 60mm mortar (when reported at as the deepest part of the surrogate below the sediment surface) was much deeper than the scour model prediction, the 60mm surrogates were reported to be pitched in a near vertical orientation with only the fins partly exposed. The scour model assumes a cylindrical shape burying on an even keel, and therefore, deviates from observations where the surrogates pitched downwards. If viewed as percent burial rather than burial depth, the scour model predicts 100-115% scour burial for all of the surrogates in Site 1 with storms. The 60mm were nearly 100% buried. It also notable that the 155mm were not completely covered by sediment, but lay recessed below the far-field seabed in large open scour pits observed by both divers and in sonar imagery (Figure 5.5). This evidence of scour pits around the 155mm surrogates indicates scour burial was the primary burial mechanism at Site 1 during storms and is supported by the scour model. At Site 2, the scour model significantly deviates from the reported burial depth of the surrogates. During these deployments (Fall 2018 and Spring 2019), no scour pits were observed by diver or in sonar, which further indicates that other mechanisms may have contributed to surrogate burial.

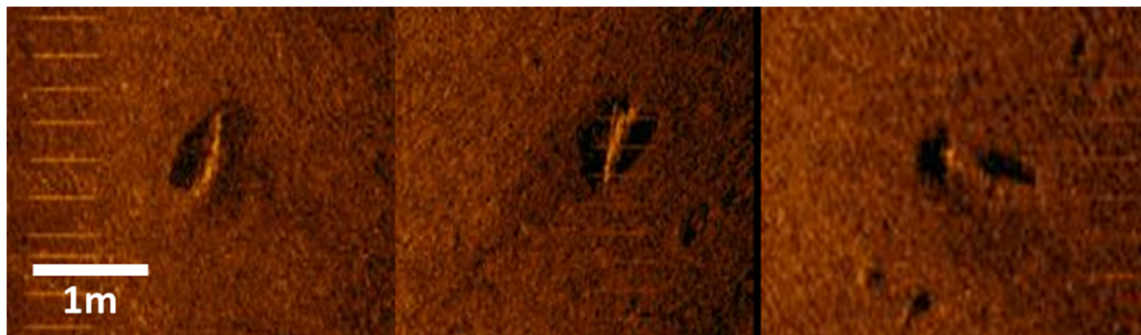


Figure 5.5: Side-scan sonar images from a Teledyne Gavia Autonomous Underwater Vehicle showing the 155mm surrogates after the Spring 2018 deployment when 4 nor'easters passed over the site. Note the acoustic shadows indicate the surrogates are laying in scour pits.

The settling model performed best in conditions where no storms were recorded. For example, the settling model predicted that the 155mm surrogates should sink to an average depth of 6.1 cm at Site 1 and 17.9 cm at Site 2, or 40% and 116% buried respectively, given no other force but the weight of the surrogate. This agrees well with observations. When storm events occurred at both sites, the settling model, which does not account for outside forcing, unsurprisingly deviates from observations. There is also a slight deviation between estimated depth and observed depth for the 60mm mortars, which buried in near vertical orientations throughout the latter 3 deployments. Like the scour model, the settling model assumes a cylindrical object settling on an even keel and does not account for increased drag caused by complex shapes such as tail fins. Regardless, the estimated surrogate settling depth due to the sediment bearing capacity does generally agree well with diver observations for the Fall 2017 and Spring 2019 deployments (no storms). These results indicate that the weight and shape of the surrogate and bearing capacity of the sediment may be a controlling factor in MEC burial in cohesive sediments, supporting previous observations of mine-burial studies (see Richardson et al., 2001).

Neither model closely predicted surrogate burial at Site 2 with storm events (Fall 2018). Surrogates buried significantly deeper than scour burial and bearing capacity predicted. This

enhanced burial is likely related to additional fluidization of the soft sandy muds in Site 2 during storm events. Increasing waves are known increase water flux into soft muds, causing a dilation of the sediments, fluidization, and associated reduction of the bulk density (Sahin et al., 2012; Soltanpour et al., 2009). The decrease in bulk density would therefore cause a corresponding drop in the bearing capacity, allowing the surrogates to settle further into the sediment. Following the storms, after wave energy decreases, the sediment would undergo settling and consolidation (Sahin et al., 2012). This process is similar to the bed fluidization and granular sorting mechanisms reported by Klammler et al., (2019). Future investigations are required to better understand the burial depth of surrogates due to bed fluidization in cohesive sediments. Existing models for fluid mud layer thickness under waves (see Soltanpour et al., 2009) may be adapted for application with munitions burial in soft muds.

5.3. Geotechnical Classification

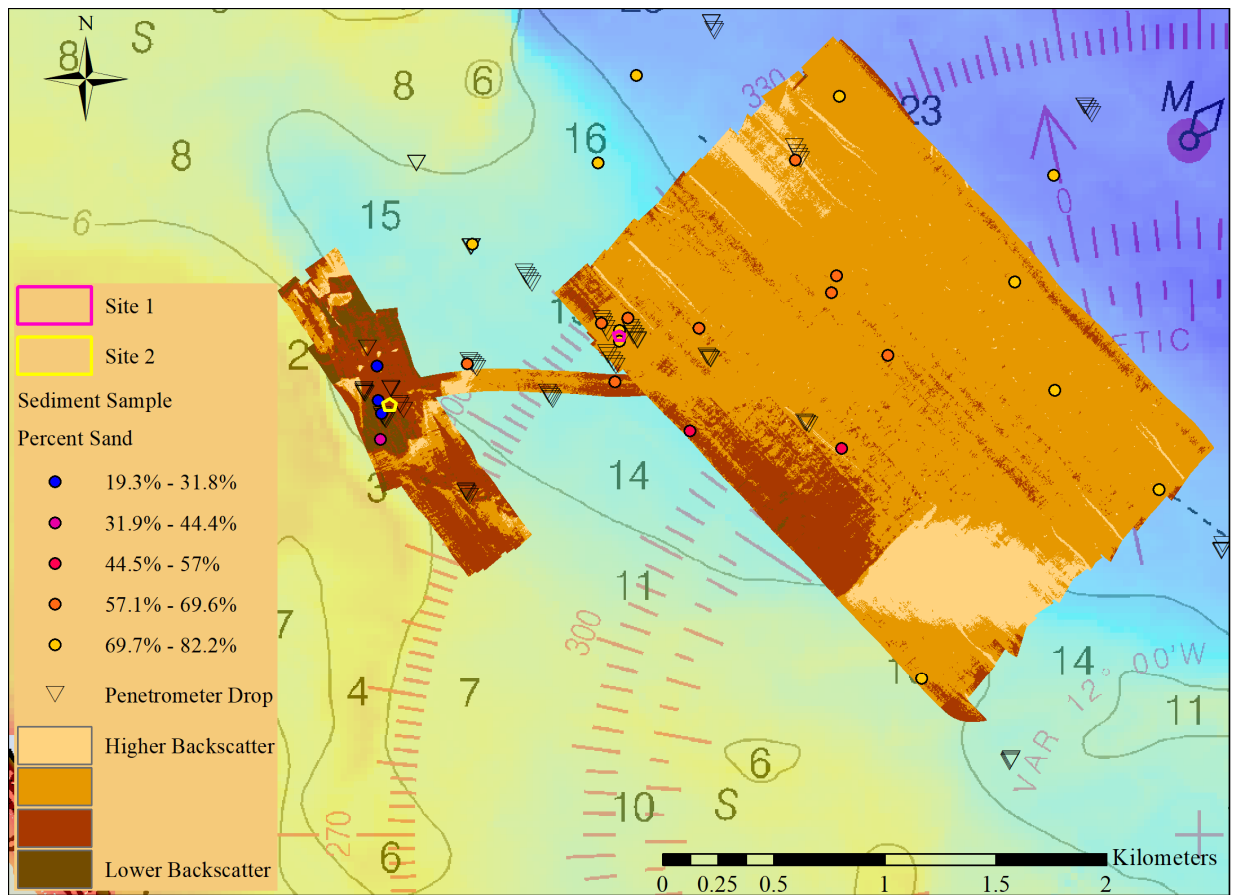


Figure 5.6: Segmented mosaic for composite sonar imagery using an ESRI ArcGIS supervised classification. Sediment samples, showing percent sand, and penetrometer sample locations are overlaid.

Sonar collected by the PMES was used to classify sediment distributions at the MR-2730 field sites. A composite mosaic was created from all of the available sonar surveys (see Figure 5.2 top). Following the workflow outlined in Section 4.2.5, the composite mosaic was segmented using an unsupervised Iso Cluster classification. The Iso Cluster classification returned 4 separate classes. These classes were then used to inform a Maximum Likelihood supervised classification (Figure 5.6).

To determine whether the segmented image could be classified using sediment samples, the non-segmented sonar mosaic pixel values were extracted and compared to the d50 and sand / mud fraction of each sample. This would determine whether a relationship existed between the sonar backscatter and sediment samples. A weak correlation was found between the sonar imagery and sediment d50 ($r^2=0.07$). A moderate correlation was found between sonar imagery and sand fraction ($r^2=0.55$), where higher sand fractions correlated to higher sonar backscatter. The segmented raster values at each sample location were then extracted and compared to the sand and mud fraction of each sample. The results indicate a good agreement between sand / mud fraction and sonar mosaic classes (Figure 5.7).

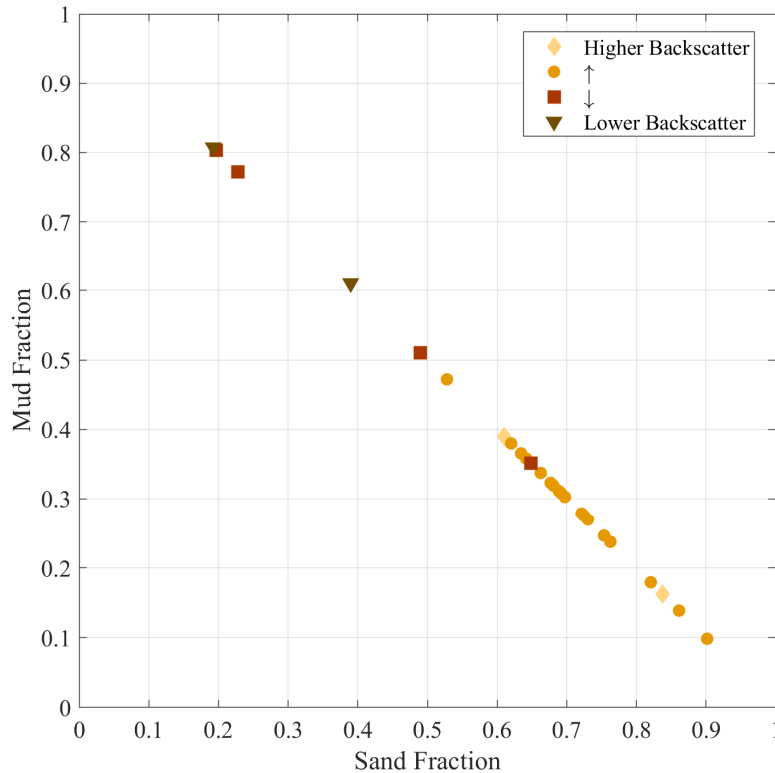


Figure 5.7: Segmented sonar mosaic classes compared to sand and mud fraction. The results show strong agreement between backscatter intensity and sand / mud fraction.

The penetrometer measurements, specifically QSBC and penetration depth, were then compared to sediment samples to determine whether subsurface geotechnical properties correlated to surficial sediments. Using similar methods to those described by Stark et al. (2016), distinct patterns were found between max QSBC and mud content, and penetration depth and d50 (Figure 5.8). Maximum QSBC decreased as the sediment mud fraction increased, with a strong inflection point at 20% mud content. It is notable that Whitehouse et al., (2000) found a strong increase in critical shear stress for mixed-cohesive sediments with 20% or higher mud content. This indicates that 20% mud threshold may strongly influence the properties of mixed-cohesive sediments, including QSBC and shear strength. Penetration depth was found to increase with decreasing d50. Another strong inflection point was found around 63 microns, which corresponds to the sand – mud interface in traditional sediment grain size analysis. Similar

results were found by Stark et al., (2016) in their study of Arctic nearshore marine sediments (see specifically Starke et al., 2016 Figure 12).

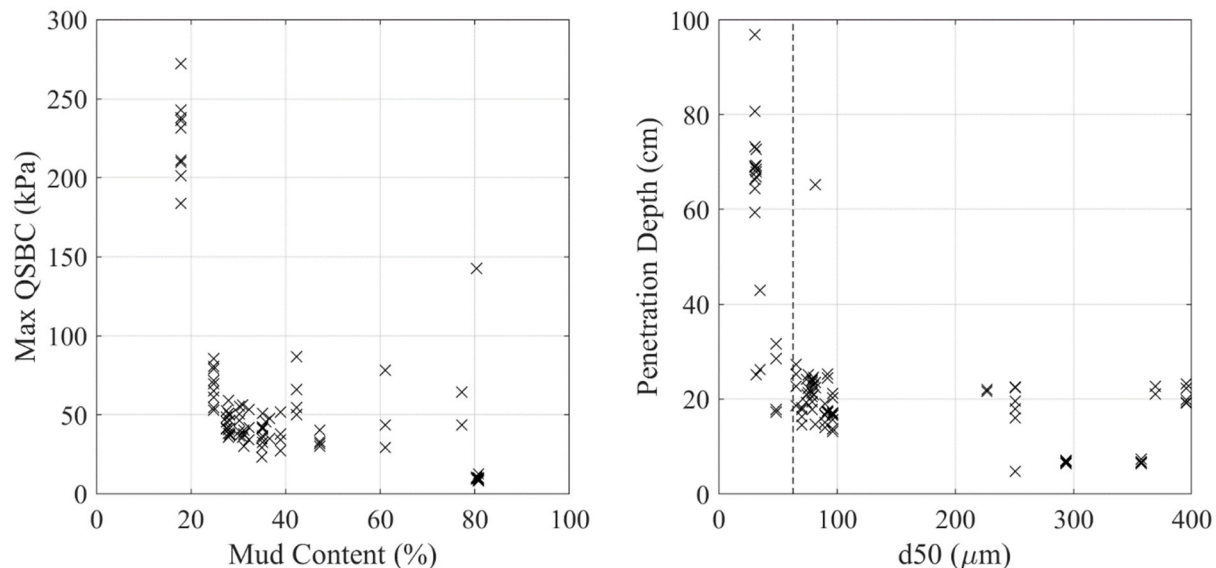


Figure 5.8: Comparison of surface sediment properties and geotechnical properties at sampling sites for MR-2730 and MR20-1480. Max QSBC is shown to decrease in sediments with >20% mud fraction, while penetrometer depth increased in sediments with $d_{50} < 63$ microns (sand-mud interface).

Since both the sonar backscatter and geotechnical properties could be linked to the surface sediment samples, a geotechnical classification was attempted. The sediment classes, as defined by sand/mud fraction, were extracted at overlapping penetrometer sample locations. The “classified” penetrometer results are shown in Figure 5.9. Much like the penetrometer results from Sites 1 and 2, there are 2 distinct groups. The first group (upper left) is composed of 87.9% of samples in the higher percent of sand classes and is characterized by higher measured QSBC and shallower penetration depth. The second group (lower right) contains 87.5% of samples in the higher percent mud classes and is characterized by lower measured QSBC and higher penetration depth. Thus, the distinct clustering of samples by shallow subsurface geotechnical properties is strongly related to the surface sediment geophysical classification.

This process was repeated for each individual sonar survey shown in Table 4.1, with specific focus on surveys conducted at the beginning and end of each field experiment. The results, which are shown in the MR-2370 Final Report, were combined with threshold of motion calculations to determine the impact that storm events had on the field sites. The method presented here are easily repeatable for any future investigation at FUDS sites.

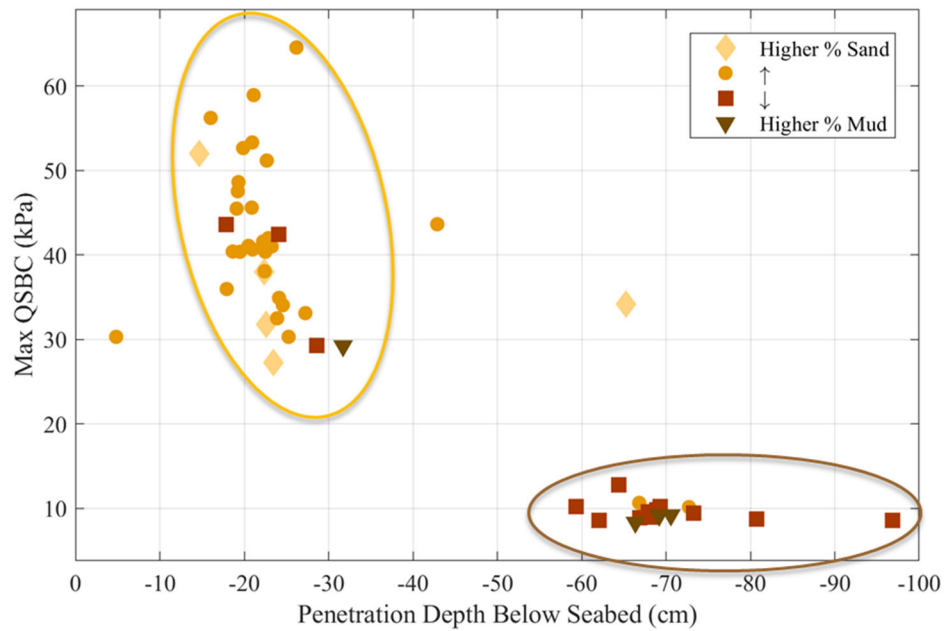


Figure 5.9: Penetrometer measurements compared to sonar mosaic classification results. Note the 2 distinct groups reflecting higher percent sands (e.g. Site 1) and higher percent muds (e.g. Site 2).

6. Conclusions and Implications for Future Research/Implementation

The objective of this study was to provide further analysis on the properties of cohesive sediments that influence MEC burial and mobility. By leveraging existing data from MR-2730 and collecting new geotechnical measurements in collaboration with MR18-1233 (Stark), we identified that sediment bearing capacity is an important predictor for surrogate burial. Further, we adapted and tested an scour burial model developed for non-cohesive sediments, and compared the model to a new bearing capacity / settling model developed for this study. Finally, we continued the investigation into geotechnical site classification based on the work of Stark et al., (2016) and found it a viable option for future FUDS site characterization. Data from this study contributed significantly to the munitions mobility and burial analysis presented in MR-2730 and assists in the continued development of existing expert system modeling of UXO burial and mobility (e.g. Underwater Munitions Expert System, Rennie MR-2645).

The scour models developed for non-cohesive sediments agreed reasonably well with field observations in the muddy sand sediment of Site 1 when adapted to account for mixed-cohesive sediments in this study. The Hertzian contact model implemented in this study for surrogate settling due to bearing capacity also agreed well with the burial depth of the surrogates at both Site 1 and 2 in absence of high-energy forcing. This model currently does not incorporate a temporal component or frictional effects, and would benefit from time-series observations of munitions settling. Future investigations are also required to better understand the burial depth of surrogates due to bed fluidization in cohesive sediments. Existing models for fluid mud layer thickness under waves (see Soltanpour et al., 2009) and may be adapted for application with munitions burial in soft muds. Impact burial should also be a topic for further investigation. As many MEC were likely deposited on the seabed via live-fire exercises or dumping. Previous mine-burial studies noted that impact burial was the largest contributor to mine burial in stiff muds, not subsequent burial processes (Inman and Jenkins, 2002). In soft muds, the forces exerted by impact would greatly exceed the bearing capacity of the sediment and result in burial deeper than observed in this study. It is unclear whether any subsequent processes could contribute re-exposure or further object burial. Therefore, impact burial for MEC in cohesive sediments should be a topic of future research.

The strong agreement between penetrometer measurements and geophysical classification indicates a “geotechnical classification” mapping approach is a viable method for FUDS site classification and warrants further investigation. The ability to tie sediment geotechnical properties such as bearing capacity to sonar classification / surficial sediment distributions maps, as demonstrated in this study, has wide-ranging implications for FUDS site management. A natural extension of this method is to classify areas of FUDS sites by the geotechnical properties that influence burial mechanism, burial depth, and mobility, and use the classified maps for predictive burial and mobility models tailored the individual FUDS site. As the process for a geotechnical classification method becomes more refined, geotechnical site classification should be incorporated into site management practices and made available for ongoing numerical and probabilistic site models.

7. Literature Cited

- Baeye, M., Fettweis, M., Legrand, S., Dupont, Y., and V. Van Lanker, 2012. Mine burial in the seabed of high-turbidity area- findings of a first experiment. *Continental Shelf Research* 43, pp. 107-119.
- Blott, S.J. and Pye, K. 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surf. Process. Landforms*, 26: 1237-1248.doi:10.1002/esp.261
- Brown, C.J., Smith, S.J., Lawton, P. and Anderson, J.T., 2011. Benthic habitat mapping: A review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. *Estuarine, Coastal and Shelf Science*, 92(3), pp. 502-520.
- Calantoni, J., and C.S. Thaxton. 2008. Simple power law for transport ratio with bimodal distributions of coarse sediments under waves. *J. of Geophys. Res.*, 113, C03003, doi:10.1029/2007JC004237.
- Cataño-Lopera, Y. A., Demir, S. T., and M. H. García, 2007. Self-burial of short cylinders under oscillatory flows and combined waves plus currents. *IEEE J. Ocean. Eng.*, 32(1), pp. 191–203.
- Cataño-Lopera, Y. A., and M. H. García, 2006. Burial of Short cylinders Induced by Scour under Combined Waves and Currents. *J. Waterway, Port, Coast, Ocean Eng.* 132, 439-449.
- Demir, S.T., García, M.H., 2007. Experimental studies on Burial of finite length cylinders under oscillatory flow. *J. Waterw. Port. Coast Ocean Eng.* ASCE 133 (2), 117–124.
- Inman, D. L. and S.A. Jenkins, 2002. Scour and Burial of Bottom Mines: a Primer for Fleet Use. SIO Reference, Scripps Institution of Oceanography, University of California, San Diego, La Jolla.
- Jacobs, W., Le Hir, P., Van Kesteren, D., and P. Cann. 2011. Erosion threshold of sand-mud mixtures. *Cont. Shelf Res.* 31, S14-S25.
- Jenkins, S.A., Inman, D.L., Richardson, M.D., Weaver, T.F, and J. Wasyl. 2007. Scour and Burial Mechanics of Objects in the Nearshore. *IEEE Journal of Oceanic Engineering*, 32 (1), 78-90.
- Klammler, H., Sheremet, A., and J. Calantoni. 2019. Seafloor Burial of Surrogate Unexploded Ordnance by Wave-Induced Sediment Instability. *IEEE J. Ocean Eng.* DOI: 10.1109/JOE.2019.2919356
- Obrzud R. & Truty, A. THE HARDENING SOIL MODEL - A PRACTICAL GUIDEBOOK Z Soil. PC 100701 report, revised 31.01.2012.
- Rennie, S.E. 2017. Underwater munitions expert system to predict mobility and burial. Final Report Strategic Environmental Research Development Program MR-2227.
- Rennie, S.E., Brandt, A., and C.T. Friedrichs. 2017. Initiation of motion and scour burial of objects underwater. *Ocean Engineering*, 131, 282-294.
- Richardson, M., Valent, P., Briggs, K., Bradley, J., and S. Griffin. 2001. NRL Mine Burial Experiments. Proc. 2nd Austr.-Amer. Joint Conf. Technol. Mine Countermeasures, Sydney, Australia, Mar. 27–29, 2001.

- Sahin, C., I. Safak, A. Sheremet, and A. J. Mehta. 2012. Observations on cohesive bed reworking by waves: Atchafalaya Shelf, Louisiana, J. Geophys. Res., 117, C09025, doi:10.1029/2011JC007821.
- SERPD Final Report, 2013. SERDP/Office of Naval Research Workshop on Acoustic Detection and Classification of MEC in the Underwater Environment, Sept. 2013.
- SERPD Draft Report, 2014. Program Review for Burial and Mobility Modeling of Munitions in the Underwater Environment. Draft Version 1.2, 15 Oct. 2014.
- Sheremet, A., Mehta, A.J., Liu, B., and G.W. Stone, 2005. Wave-sediment interaction on a muddy inner shelf during Hurricane Claudette. *Estuarine, Coastal and Shelf Science* 63, pp. 225-233.
- Soltanpour, M., Haghshenas, S.A., and A.J. Mehta, 2009. Fluidized Mud-Wave Interaction under Regular and Irregular Waves. *Journal of Coastal Research* 25 (3), pp. 616-626.
- Stark, N., Radosavljevic, B., Quinn, B., and H. Lantuit. 2016. Application of portable free-fall penetrometer for geotechnical investigation of Arctic nearshore zone. *Can. Geotech. J.* 54: 31–49, dx.doi.org/10.1139/cgj-2016-0087
- Traykovski, P. and T. Austin. 2017. Continuous monitoring of mobility, burial and re-exposure of underwater munitions in energetic near-shore environments. Final Report Strategic Environmental Research and Development Program (SERDP) Project MR-2319.
- Traykovski, P., Richardson, M.D., Mayer, L.A., and J.D. Irish, 2007. Mine Burial Experiments at Martha's Vineyard Coastal Observatory. *IEEE Journal of Oceanic Engineering* 32(1), pp. 150-166.
- Trembanis, A.C., Friedrichs, C.T., Richardson, M.D., Traykovski, P., Howd, P.A., Elmore, P.A. and Wever, T. F., 2007. Predicting seabed burial of cylinders by wave-induced scour: application to the sandy inner shelf off Florida and Massachusetts. *IEEE Journal of Oceanic Engineering* 32(1), pp 167-183.
- Van Prooijen, B. C., and J. C. Winterwerp (2010), A stochastic formulation for erosion of cohesive sediments, J. Geophys. Res., 115, C01005, doi:10.1029/2008JC005189
- Whitehouse, R.J.S., Soulsby, R.L., Roberts, W. and Mitchener, H.J., 2000. Dynamics of estuarine muds.
- Wilson, B.D., Madsen, J.A., Fox, D., Simpson, P., Moore, J., Bruce, D., and D.B. Carter, 2010. Delaware Bay Benthic Mapping Project: Mapping the Distribution of Bottom Sediments, Key Habitats, and Sub-bottom Imaging in Delaware Bay and River. Delaware Department of Natural Resources and Environmental Control. Access at: http://www.dnrec.delaware.gov/coastal/Documents/Benthic%20Mapping/Benthic_Mapping_Presentation.pdf

Appendix A

A.1. Sediment Samples

Sediment samples were collected using a modified Young's sediment grab sampler. Two 100mL samples were collected from each grab. A 20 gram portion was sub-sampled and processed using a standard grain size analysis by sieve (for sand fraction) and pipette (for mud fraction) methods at $\frac{1}{2}$ phi intervals. The data was collated and statistical analysis conducted using GRADISTAT version 9.1 (Blott and Pye, 2001). Please see Blott and Pye (2001) for more details of GRADISTAT and the tabulated data products provided below.

Table A.1: Sediment sample grain size analysis and statistics.

SAMPLE	20170706 Sample 1	20170706 Sample 2	20170706 Sample 3	20170706 Sample 4	20170706 Sample 5	20170706 Sample 6
LAT	38.86228333	38.87471667	38.88073333	38.89145	38.88205	38.87235
LON	-75.19713333	-75.19906667	-75.21795	-75.20651667	-75.19041667	-75.17783333
SIEVING ERROR	-0.4%	3.2%	1.0%	2.5%	2.1%	2.9%
SAMPLE TYPE	Unimodal, Poorly Sorted	Bimodal, Poorly Sorted	Bimodal, Poorly Sorted	Unimodal, Poorly Sorted	Bimodal, Poorly Sorted	Bimodal, Poorly Sorted
TEXTURAL GROUP	Muddy Sand	Muddy Sand	Muddy Sand	Muddy Sand	Muddy Sand	Muddy Sand
SEDIMENT NAME	Very Coarse Silty Medium Sand	Coarse Silty Very Fine Sand	Very Coarse Silty Medium Sand	Very Coarse Silty Very Fine Sand	Coarse Silty Very Fine Sand	Very Coarse Silty Very Fine Sand
ARITH MEAN MICRON	370.6	94.37	255.3	102.9	116.3	92.96
ARITH SORTING MICRON	223.8	109.2	178.5	162.5	150.3	116.9
ARITH SKEWNESS MICRON	1.492	7.449	0.595	6.041	6.330	6.816
ARITH KURTOSIS MICRON	9.971	84.58	5.317	46.59	54.47	67.01
GEOM MEAN MICRON	239.9	57.26	150.2	57.10	67.69	56.10
GEOM SORTING MICRON	3.857	3.181	3.880	3.100	3.297	3.081
GEOM SKEWNESS MICRON	-2.346	-1.385	-1.607	-0.918	-1.325	-1.333
GEOM KURTOSIS MICRON	8.031	5.136	5.368	4.890	5.390	5.331
LOG MEAN PHI	2.059	4.112	2.661	4.108	3.798	4.138
LOG SORTING PHI	1.947	1.662	1.867	0.620	1.663	1.615
LOG SKEWNESS PHI	2.346	1.347	1.510	0.836	1.090	1.277
LOG KURTOSIS PHI	8.031	5.111	5.052	4.796	5.104	5.289
FW MEAN MICRON	318.1	59.59	188.1	58.07	69.17	56.99
FW SORTING MICRON	2.621	2.869	3.067	2.803	2.940	2.744
FW SKEWNESS MICRON	-0.589	-0.504	-0.626	-0.418	-0.443	-0.529
FW KURTOSIS MICRON	3.748	1.560	1.049	1.736	1.465	1.834
FW MEAN PHI	1.652	4.069	2.411	4.106	3.854	4.133
FW SORTING PHI	1.390	1.521	1.617	1.487	1.556	1.456
FW SKEWNESS PHI	0.589	0.504	0.626	0.418	0.443	0.529
FW KURTOSIS PHI	3.748	1.560	1.049	1.736	1.465	1.834
FW MEAN	Medium Sand	Very Coarse Silt	Fine Sand	Very Coarse Silt	Very Fine Sand	Very Coarse Silt
FW SORTING	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted

FW SKEWNESS	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed
SAMPLE	20170706 Sample 1	20170706 Sample 2	20170706 Sample 3	20170706 Sample 4	20170706 Sample 5	20170706 Sample 6
FW KURTOSIS	Extremely Leptokurtic	Very Leptokurtic	Mesokurtic	Very Leptokurtic	Leptokurtic	Very Leptokurtic
MODE 1 MICRON	427.5	94.00	427.5	94.00	94.00	94.00
MODE 2 MICRON		27.00	94.00		19.00	19.00
MODE 3 MICRON						
MODE 1 PHI	1.247	3.494	1.247	3.494	3.494	3.494
MODE 2 PHI		5.236	3.494		5.736	5.736
MODE 3 PHI						
D10 MICRON	35.54	11.18	23.94	11.22	17.12	10.98
D50 MICRON	370.5	79.92	275.4	75.69	91.87	77.95
D90 MICRON	578.4	160.7	471.0	124.4	194.1	122.9
D90 Div D10 MICRON	16.28	14.38	19.67	11.08	11.34	11.19
D90 Sub D10 MICRON	542.9	149.5	447.1	113.1	176.9	111.9
D75 Div D25 MICRON	1.666	2.857	4.723	2.631	2.857	2.355
D75 Sub D25 MICRON	182.5	72.34	310.9	64.00	92.38	59.62
D10 PHI	0.790	2.637	1.086	3.007	2.365	3.024
D50 PHI	1.433	3.645	1.860	3.724	3.444	3.681
D90 PHI	4.815	6.483	5.384	6.477	5.868	6.509
D90 Div D10 PHI	6.096	2.458	4.957	2.154	2.481	2.152
D90 Sub D10 PHI	4.025	3.846	4.298	3.470	3.503	3.484
D75 Div D25 PHI	1.651	1.478	2.668	1.426	1.538	1.378
D75 Sub D25 PHI	0.736	1.514	2.240	1.396	1.515	1.235
PER GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER SAND	86.1%	68.1%	82.8%	65.0%	71.8%	68.8%
PER MUD	13.9%	31.9%	17.2%	35.0%	28.2%	31.2%
PER V COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER MEDIUM GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER FINE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER V FINE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER V COARSE SAND	1.3%	0.4%	0.9%	1.0%	1.6%	0.4%
PER COARSE SAND	12.8%	0.7%	4.1%	1.8%	1.1%	1.4%
PER MEDIUM SAND	67.9%	1.3%	51.2%	2.7%	2.2%	1.8%
PER FINE SAND	2.6%	13.7%	7.7%	4.1%	27.4%	4.8%
PER V FINE SAND	1.5%	51.8%	18.9%	55.4%	39.5%	60.3%
PER V COARSE SILT	4.6%	9.9%	5.5%	13.7%	8.9%	10.1%
PER COARSE SILT	3.0%	10.1%	5.1%	9.6%	11.1%	8.7%
PER MEDIUM SILT	0.7%	4.0%	2.1%	3.6%	2.0%	4.6%
PER FINE SILT	2.0%	2.9%	1.7%	4.3%	2.8%	3.2%
PER V FINE SILT	1.5%	2.8%	1.9%	3.1%	1.9%	2.7%

PER CLAY	2.0%	2.2%	0.9%	0.6%	1.5%	1.8%	
SAMPLE	20171018 Sample 1	20171018 Sample 3	20171018 Sample 4	20171018 Sample 5	20171018 Sample 6	20171018 Sample 10	20171018 Sample 11
LAT	38.8733	38.88526667	38.8777	38.86926667	38.86321667	38.87925	38.88255
LON	-75.19036667	-75.20158333	-75.19246667	-75.18493333	-75.19563333	-75.2207	-75.21415
SIEVING ERROR	1.7%	0.8%	0.5%	5.4%	-1.5%	1.0%	2.3%
SAMPLE TYPE	Unimodal, Poorly Sorted	Unimodal, Poorly Sorted	Unimodal, Poorly Sorted	Bimodal, Very Poorly Sorted	Unimodal, Poorly Sorted	Trimodal, Poorly Sorted	Unimodal, Poorly Sorted
TEXTURAL GROUP	Muddy Sand	Muddy Sand	Muddy Sand	Muddy Sand	Sand	Muddy Sand	Muddy Sand
SEDIMENT NAME	Very Coarse Silty Very Fine Sand	Very Coarse Silty Very Fine Sand	Very Coarse Silty Very Fine Sand	Very Coarse Silty Very Fine Sand	Poorly Sorted Coarse Sand	Coarse Silty Very Fine Sand	Very Coarse Silty Very Fine Sand
ARITH MEAN MICRON	154.1	121.5	115.1	102.2	541.1	133.7	80.53
ARITH SORTING MICRON	234.3	174.0	136.4	125.6	313.7	148.7	66.73
ARITH SKEWNESS MICRON	4.476	5.942	7.318	6.053	0.914	4.633	9.372
ARITH KURTOSIS MICRON	24.73	45.07	69.74	59.23	5.000	36.63	163.7
GEOM MEAN MICRON	77.52	63.41	78.57	49.10	374.5	77.61	53.92
GEOM SORTING MICRON	3.787	3.873	2.624	4.648	3.303	3.333	2.921
GEOM SKEWNESS MICRON	-1.217	-1.344	-1.853	-1.251	-2.527	-1.200	-1.714
GEOM KURTOSIS MICRON	5.250	4.943	9.270	3.826	9.700	4.821	5.352
LOG MEAN PHI	3.571	3.790	3.598	3.818	1.411	3.671	4.192
LOG SORTING PHI	1.836	1.844	1.320	1.990	1.711	1.724	1.536
LOG SKEWNESS PHI	1.017	1.067	1.397	0.796	2.518	1.157	1.638
LOG KURTOSIS PHI	5.104	4.902	8.433	4.143	9.647	4.747	5.296
FW MEAN MICRON	85.71	74.47	89.71	68.26	486.8	80.15	55.73
FW SORTING MICRON	3.198	3.230	2.008	4.466	2.309	3.182	2.575
FW SKEWNESS MICRON	-0.307	-0.363	-0.176	-0.209	-0.377	-0.315	-0.677
FW KURTOSIS MICRON	2.210	1.877	1.481	2.202	2.704	1.747	2.322
FW MEAN PHI	3.544	3.747	3.479	3.873	1.039	3.641	4.165
FW SORTING PHI	1.677	1.692	1.006	2.159	1.208	1.670	1.365
FW SKEWNESS PHI	0.307	0.363	0.176	0.209	0.377	0.315	0.677
FW KURTOSIS PHI	2.210	1.877	1.481	2.202	2.704	1.747	2.322
FW MEAN	Very Fine Sand	Very Fine Sand	Very Fine Sand	Very Fine Sand	Medium Sand	Very Fine Sand	Very Coarse Silt
FW SORTING	Poorly Sorted	Poorly Sorted	Poorly Sorted	Very Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted

FW SKEWNESS	Very Fine Skewed	Very Fine Skewed	Fine Skewed	Fine Skewed	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed
SAMPLE	20171018 Sample 1	20171018 Sample 3	20171018 Sample 4	20171018 Sample 5	20171018 Sample 6	20171018 Sample 10	20171018 Sample 11
FW KURTOSIS	Very Leptokurtic	Very Leptokurtic	Leptokurtic	Very Leptokurtic	Very Leptokurtic	Very Leptokurtic	Very Leptokurtic
MODE 1 MICRON	152.5	94.00	94.00	94.00	605.0	94.00	94.00
MODE 2 MICRON				19.00		215.0	
MODE 3 MICRON						19.00	
MODE 1 PHI	2.737	3.494	3.494	3.494	0.747	3.494	3.494
MODE 2 PHI				5.736		2.237	
MODE 3 PHI						5.736	
D10 MICRON	16.32	12.21	37.00	9.347	66.23	15.75	8.698
D50 MICRON	104.3	92.02	91.12	90.22	503.8	96.54	79.33
D90 MICRON	242.9	218.9	176.4	246.5	892.7	249.8	117.3
D90 Div D10 MICRON	14.88	17.93	4.769	26.37	13.48	15.86	13.49
D90 Sub D10 MICRON	226.6	206.7	139.4	237.2	826.4	234.0	108.6
D75 Div D25 MICRON	2.454	2.677	2.118	3.237	1.802	2.625	1.822
D75 Sub D25 MICRON	93.69	90.81	70.46	100.3	300.9	102.7	45.70
D10 PHI	2.042	2.191	2.503	2.020	0.164	2.001	3.091
D50 PHI	3.261	3.442	3.456	3.470	0.989	3.373	3.656
D90 PHI	5.937	6.356	4.757	6.741	3.916	5.988	6.845
D90 Div D10 PHI	2.908	2.900	1.900	3.337	23.91	2.992	2.214
D90 Sub D10 PHI	3.896	4.164	2.254	4.721	3.753	3.987	3.754
D75 Div D25 PHI	1.487	1.510	1.373	1.609	2.505	1.537	1.262
D75 Sub D25 PHI	1.295	1.420	1.082	1.695	0.850	1.392	0.865
PER GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER SAND	76.3%	73.0%	75.4%	69.7%	90.2%	75.3%	73.6%
PER MUD	23.7%	27.0%	24.6%	30.3%	9.8%	24.7%	26.4%
PER V COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER MEDIUM GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER FINE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER V FINE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER V COARSE SAND	3.4%	3.0%	1.3%	5.7%	4.6%	0.6%	0.3%
PER COARSE SAND	2.3%	1.1%	0.8%	0.9%	46.0%	1.7%	0.4%
PER MEDIUM SAND	3.7%	2.2%	1.6%	3.3%	36.7%	7.6%	0.6%
PER FINE SAND	31.2%	25.2%	24.7%	22.4%	1.2%	24.8%	2.3%
PER V FINE SAND	35.7%	41.6%	46.8%	37.5%	1.6%	40.5%	70.1%
PER V COARSE SILT	8.2%	8.6%	16.0%	10.2%	3.2%	6.0%	6.3%
PER COARSE SILT	5.8%	7.3%	3.6%	7.3%	2.9%	8.8%	6.3%
PER MEDIUM SILT	2.8%	3.0%	1.4%	3.8%	1.5%	3.8%	4.5%
PER FINE SILT	2.8%	3.0%	1.4%	3.6%	0.8%	2.7%	4.6%
PER V FINE SILT	2.2%	2.6%	1.5%	2.8%	0.6%	2.1%	3.7%

PER CLAY	2.0%	2.5%	0.6%	2.6%	0.8%	1.4%	1.0%
SAMPLE	20171019 Sample 12	20171207 North	20171207 Center A	20171207 SA	20180306 Site 1	20180306 Site 2	20180306 Site 3
LAT	38.87603333	38.875732	38.875513	38.8753	38.88611667	38.8729	38.87625
LON	-75.21398333	-75.213027	-75.21305	-75.213024	-75.21215	-75.22561667	-75.21258333
SIEVING ERROR	1.4%	-6.6%	4.6%	-1.5%	0.6%	2.5%	1.5%
SAMPLE TYPE	Bimodal, Very Poorly Sorted	Bimodal, Very Poorly Sorted	Bimodal, Poorly Sorted	Bimodal, Very Poorly Sorted	Trimodal, Very Poorly Sorted	Unimodal, Poorly Sorted	Bimodal, Poorly Sorted
TEXTURAL GROUP	Muddy Sand	Muddy Sand	Muddy Sand	Muddy Sand	Muddy Sand	Sandy Mud	Muddy Sand
SEDIMENT NAME	Very Coarse Silty Medium Sand	Very Coarse Silty Coarse Sand	Very Coarse Silty Very Fine Sand	Coarse Silty Coarse Sand	Very Coarse Silty Medium Sand	Very Fine Sandy Very Coarse Silt	Very Coarse Silty Very Fine Sand
ARITH MEAN MICRON	195.1	357.9	125.7	362.5	285.1	44.97	82.95
ARITH SORTING MICRON	187.0	271.0	201.3	270.9	299.1	69.63	106.1
ARITH SKEWNESS MICRON	2.576	0.085	4.542	0.054	1.786	10.21	8.977
ARITH KURTOSIS MICRON	17.41	2.384	27.35	2.405	7.437	158.1	109.8
GEOM MEAN MICRON	90.48	153.7	59.10	156.3	119.4	24.64	49.40
GEOM SORTING MICRON	4.958	6.123	3.841	6.148	5.312	3.259	3.261
GEOM SKEWNESS MICRON	-1.092	-1.195	-0.905	-1.218	-0.955	-0.664	-1.403
GEOM KURTOSIS MICRON	3.333	3.266	4.362	3.339	3.231	3.091	4.883
LOG MEAN PHI	3.430	2.673	4.036	2.648	2.924	5.343	4.321
LOG SORTING PHI	2.285	2.589	1.920	2.594	2.289	1.705	1.698
LOG SKEWNESS PHI	1.078	1.197	0.834	1.220	0.875	0.664	1.355
LOG KURTOSIS PHI	3.325	3.273	4.330	3.350	3.027	3.091	4.879
FW MEAN MICRON	114.8	171.6	59.21	173.2	145.4	24.31	53.28
FW SORTING MICRON	4.290	5.392	3.553	5.524	4.799	3.297	2.866
FW SKEWNESS MICRON	-0.837	-0.725	-0.360	-0.761	-0.455	-0.352	-0.599
FW KURTOSIS MICRON	0.978	0.930	1.950	0.936	1.003	1.129	1.524
FW MEAN PHI	3.123	2.543	4.078	2.530	2.782	5.362	4.230
FW SORTING PHI	2.101	2.431	1.829	2.466	2.263	1.721	1.519
FW SKEWNESS PHI	0.837	0.725	0.360	0.761	0.455	0.352	0.599
FW KURTOSIS PHI	0.978	0.930	1.950	0.936	1.003	1.129	1.524
FW MEAN	Very Fine Sand	Fine Sand	Very Coarse Silt	Fine Sand	Fine Sand	Coarse Silt	Very Coarse Silt
FW SORTING	Very Poorly Sorted	Very Poorly Sorted	Poorly Sorted	Very Poorly Sorted	Very Poorly Sorted	Poorly Sorted	Poorly Sorted

FW SKEWNESS	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed
SAMPLE	20171019 Sample 12	20171207 North	20171207 Center A	20171207 SA	20180306 Site 1	20180306 Site 2	20180306 Site 3
FW KURTOSIS	Mesokurtic	Mesokurtic	Very Leptokurtic	Mesokurtic	Mesokurtic	Leptokurtic	Very Leptokurtic
MODE 1 MICRON	302.5	605.0	94.00	605.0	427.5	54.00	94.00
MODE 2 MICRON	94.00	302.5	19.00	302.5	94.00		19.00
MODE 3 MICRON					19.00		
MODE 1 PHI	1.747	0.747	3.494	0.747	1.247	4.231	3.494
MODE 2 PHI	3.494	1.747	5.736	1.747	3.494		5.736
MODE 3 PHI					5.736		
D10 MICRON	7.273	7.896	8.703	9.856	12.25	3.608	7.912
D50 MICRON	250.6	369.2	80.14	395.3	226.8	31.94	74.57
D90 MICRON	341.3	666.8	225.9	667.6	655.2	89.75	120.5
D90 Div D10 MICRON	46.93	84.44	25.95	67.74	53.50	24.88	15.24
D90 Sub D10 MICRON	334.0	658.9	217.2	657.8	643.0	86.14	112.6
D75 Div D25 MICRON	7.733	11.45	2.929	11.69	8.542	4.075	2.883
D75 Sub D25 MICRON	264.7	540.5	74.34	543.3	393.6	42.53	65.75
D10 PHI	1.551	0.585	2.146	0.583	0.610	3.478	3.052
D50 PHI	1.996	1.437	3.641	1.339	2.140	4.969	3.745
D90 PHI	7.103	6.985	6.844	6.665	6.351	8.115	6.982
D90 Div D10 PHI	4.580	11.95	3.189	11.43	10.41	2.333	2.287
D90 Sub D10 PHI	5.552	6.400	4.698	6.082	5.741	4.637	3.929
D75 Div D25 PHI	2.718	5.653	1.493	5.722	3.655	1.488	1.461
D75 Sub D25 PHI	2.951	3.517	1.550	3.547	3.095	2.027	1.527
PER GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER SAND	69.1%	72.1%	67.7%	72.5%	72.1%	19.7%	64.2%
PER MUD	30.9%	27.9%	32.3%	27.5%	27.9%	80.3%	35.8%
PER V COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER MEDIUM GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER FINE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER V FINE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER V COARSE SAND	1.0%	0.7%	1.6%	0.7%	3.9%	0.1%	0.5%
PER COARSE SAND	2.6%	45.7%	3.9%	46.5%	15.1%	0.4%	0.5%
PER MEDIUM SAND	46.7%	17.4%	4.1%	17.7%	29.2%	0.4%	1.1%
PER FINE SAND	0.7%	0.4%	8.0%	0.4%	7.6%	0.4%	4.8%
PER V FINE SAND	18.1%	7.9%	50.1%	7.2%	16.4%	18.3%	57.2%
PER V COARSE SILT	8.8%	9.4%	9.9%	7.2%	10.0%	31.1%	12.6%
PER COARSE SILT	8.1%	5.3%	8.9%	7.3%	6.7%	22.8%	9.2%
PER MEDIUM SILT	3.6%	3.2%	4.1%	4.4%	3.2%	8.1%	4.0%
PER FINE SILT	3.5%	3.1%	3.6%	2.2%	4.0%	7.5%	3.3%
PER V FINE SILT	3.5%	3.7%	2.6%	2.2%	3.1%	7.3%	4.0%

PER CLAY	3.4%	3.2%	3.1%	4.1%	0.9%	3.5%	2.7%
SAMPLE	20180306 Site 4	20180306 Site 5	20180828 Site 3 S1	20180828 Site 3 S2	20190515 Site 2 sa	20190515 Site 5 sb	20190515 Site 10sa
LAT	38.87728333	38.86155	38.87131	38.87333	38.876029	38.87796333	38.872354
LON	-75.202	-75.19728333	-75.22549	-75.227	-75.213983	-75.20171683	-75.22542967
SIEVING ERROR	3.8%	0.1%	1.4%	1.1%	1.8%	2.4%	3.1%
SAMPLE TYPE	Bimodal, Poorly Sorted	Unimodal, Poorly Sorted	Bimodal, Poorly Sorted	Trimodal, Very Poorly Sorted	Trimodal, Poorly Sorted	Bimodal, Poorly Sorted	Bimodal, Poorly Sorted
TEXTURAL GROUP	Muddy Sand	Muddy Sand	Sandy Mud	Muddy Sand	Muddy Sand	Muddy Sand	Sandy Mud
SEDIMENT NAME	Very Coarse Silty Very Fine Sand	Very Coarse Silty Medium Sand	Very Fine Sandy Very Coarse Silt	Very Coarse Silty Medium Sand	Coarse Silty Very Fine Sand	Very Coarse Silty Very Fine Sand	Very Fine Sandy Very Coarse Silt
ARITH MEAN MICRON	146.5	348.8	69.66	382.8	83.50	84.59	41.85
ARITH SORTING MICRON	269.9	226.9	98.34	405.9	111.8	118.3	46.63
ARITH SKEWNESS MICRON	3.821	0.995	8.222	1.570	8.214	8.063	9.249
ARITH KURTOSIS MICRON	18.05	7.163	104.5	4.910	94.22	87.97	200.1
GEOM MEAN MICRON	56.39	203.4	39.35	145.1	46.79	47.12	25.57
GEOM SORTING MICRON	4.326	4.361	3.208	6.832	3.429	3.457	2.955
GEOM SKEWNESS MICRON	-0.612	-1.836	-0.929	-1.314	-1.136	-1.222	-0.791
GEOM KURTOSIS MICRON	3.845	5.488	4.234	3.975	3.956	4.460	3.383
LOG MEAN PHI	4.009	2.298	4.668	2.157	4.398	4.322	5.290
LOG SORTING PHI	2.053	2.125	1.682	2.128	1.771	1.760	1.563
LOG SKEWNESS PHI	0.439	1.836	0.929	1.253	1.089	1.026	0.791
LOG KURTOSIS PHI	3.741	5.488	4.234	4.408	3.947	4.438	3.383
FW MEAN MICRON	55.75	200.1	43.36	261.2	50.35	51.13	26.71
FW SORTING MICRON	3.801	3.815	3.036	4.361	3.016	3.007	2.953
FW SKEWNESS MICRON	-0.326	-0.728	-0.279	-0.292	-0.590	-0.552	-0.272
FW KURTOSIS MICRON	1.875	3.457	1.317	1.321	1.218	1.353	1.195
FW MEAN PHI	4.165	2.321	4.528	1.937	4.312	4.290	5.226
FW SORTING PHI	1.926	1.932	1.602	2.125	1.593	1.588	1.562
FW SKEWNESS PHI	0.326	0.728	0.279	0.292	0.590	0.552	0.272
FW KURTOSIS PHI	1.875	3.457	1.317	1.321	1.218	1.353	1.195
FW MEAN	Very Coarse Silt	Fine Sand	Very Coarse Silt	Medium Sand	Very Coarse Silt	Very Coarse Silt	Coarse Silt
FW SORTING	Poorly Sorted	Poorly Sorted	Poorly Sorted	Very Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted

FW SKEWNESS	Very Fine Skewed	Very Fine Skewed	Fine Skewed	Fine Skewed	Very Fine Skewed	Very Fine Skewed	Fine Skewed
SAMPLE	20180306 Site 4	20180306 Site 5	20180828 Site 3 S1	20180828 Site 3 S2	20190515 Site 2 sa	20190515 Site 5 sb	20190515 Site 10sa
FW KURTOSIS	Very Leptokurtic	Extremely Leptokurtic	Leptokurtic	Leptokurtic	Leptokurtic	Leptokurtic	Leptokurtic
MODE 1 MICRON	94.00	427.5	94.00	427.5	94.00	94.00	54.00
MODE 2 MICRON	27.00		215.0	38.50	19.00	27.00	19.00
MODE 3 MICRON				19.00	38.50		
MODE 1 PHI	3.494	1.247	3.494	1.247	3.494	3.494	4.231
MODE 2 PHI	5.236		2.237	4.720	5.736	5.236	5.736
MODE 3 PHI				5.736	4.720		
D10 MICRON	7.116	19.24	9.002	26.15	5.826	7.942	5.095
D50 MICRON	78.63	357.6	48.87	320.6	74.20	73.44	30.93
D90 MICRON	399.7	589.9	119.2	1453.0	121.2	123.2	88.35
D90 Div D10 MICRON	56.17	30.66	13.24	55.57	20.80	15.51	17.34
D90 Sub D10 MICRON	392.6	570.6	110.2	1426.9	115.4	115.3	83.25
D75 Div D25 MICRON	3.328	1.786	3.739	5.090	3.831	3.381	3.570
D75 Sub D25 MICRON	77.52	199.9	62.51	494.5	74.51	71.46	40.05
D10 PHI	1.323	0.761	3.069	-0.539	3.045	3.021	3.501
D50 PHI	3.669	1.484	4.355	1.641	3.752	3.767	5.015
D90 PHI	7.135	5.700	6.796	5.257	7.423	6.976	7.617
D90 Div D10 PHI	5.393	7.485	2.214	-9.752	2.438	2.309	2.176
D90 Sub D10 PHI	5.812	4.938	3.727	5.796	4.379	3.955	4.116
D75 Div D25 PHI	1.547	1.735	1.536	4.353	1.585	1.532	1.440
D75 Sub D25 PHI	1.734	0.836	1.903	2.348	1.938	1.758	1.836
PER GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER SAND	66.3%	82.1%	39.0%	83.8%	63.5%	62.0%	19.3%
PER MUD	33.7%	17.9%	61.0%	16.2%	36.5%	38.0%	80.7%
PER V COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER MEDIUM GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER FINE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER V FINE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER V COARSE SAND	4.1%	0.8%	0.2%	14.3%	0.5%	1.3%	0.0%
PER COARSE SAND	4.4%	14.2%	0.5%	16.8%	0.6%	0.7%	0.1%
PER MEDIUM SAND	3.6%	61.3%	1.8%	27.3%	1.7%	1.5%	0.3%
PER FINE SAND	4.2%	2.4%	5.4%	16.1%	4.7%	5.4%	0.4%
PER V FINE SAND	50.0%	3.3%	31.1%	9.2%	56.0%	53.1%	18.4%
PER V COARSE SILT	9.6%	4.6%	27.5%	5.0%	9.5%	12.3%	30.4%
PER COARSE SILT	9.1%	4.5%	17.7%	4.7%	10.9%	9.9%	25.3%
PER MEDIUM SILT	4.4%	2.2%	7.0%	1.9%	3.7%	5.9%	10.7%
PER FINE SILT	5.1%	2.9%	1.5%	2.0%	5.7%	4.0%	6.9%
PER V FINE SILT	3.4%	2.1%	4.1%	1.7%	4.8%	3.2%	4.1%

PER CLAY	2.2%	1.7%	3.1%	0.9%	2.0%	2.7%	3.3%
SAMPLE	20190515 Site 7 sa	20190514 Site 13 sa	20190514 Site 16 sa	20190515 Site 18 sa	20190515 Site 19 sb	20190515 Site 20 sa	
LAT	38.874388	38.87428067	38.88252052	38.87094757	38.88265632	38.87164263	
LON	-75.22097133	-75.22566067	-75.22361227	-75.20146883	-75.20386603	-75.20937352	
SIEVING ERROR	3.1%	0.7%	-0.2%	3.6%	2.8%	0.8%	
SAMPLE TYPE	Bimodal, Poorly Sorted	Trimodal, Poorly Sorted	Unimodal, Poorly Sorted	Bimodal, Poorly Sorted	Polymodal, Very Poorly Sorted	Bimodal, Poorly Sorted	
TEXTURAL GROUP	Muddy Sand	Sandy Mud	Muddy Sand	Muddy Sand	Muddy Sand	Sandy Mud	
SEDIMENT NAME	Very Coarse Silty Very Fine Sand	Very Fine Sandy Very Coarse Silt	Very Coarse Silty Medium Sand	Very Coarse Silty Very Fine Sand	Very Coarse Silty Very Fine Sand	Very Fine Sandy Very Coarse Silt	
ARITH MEAN MICRON	90.72	43.52	288.6	101.2	156.9	104.3	
ARITH SORTING MICRON	143.9	45.42	169.8	182.3	265.9	192.7	
ARITH SKEWNESS MICRON	6.525	11.03	0.247	5.170	3.728	5.173	
ARITH KURTOSIS MICRON	57.02	299.6	4.648	34.73	18.02	34.39	
GEOM MEAN MICRON	45.63	25.10	178.6	44.44	58.47	43.63	
GEOM SORTING MICRON	3.670	3.317	3.967	3.886	4.809	4.035	
GEOM SKEWNESS MICRON	-0.946	-0.828	-1.909	-0.621	-0.636	-0.521	
GEOM KURTOSIS MICRON	4.014	2.779	5.775	3.645	3.278	3.434	
LOG MEAN PHI	4.357	5.316	2.486	4.444	3.942	4.424	
LOG SORTING PHI	1.846	1.730	1.988	1.946	2.199	1.988	
LOG SKEWNESS PHI	0.756	0.828	1.909	0.541	0.511	0.377	
LOG KURTOSIS PHI	3.981	2.779	5.775	3.626	3.208	3.380	
FW MEAN MICRON	50.30	25.00	185.3	44.94	66.74	45.48	
FW SORTING MICRON	3.241	3.450	3.503	3.736	4.618	3.842	
FW SKEWNESS MICRON	-0.441	-0.407	-0.679	-0.380	-0.208	-0.272	
FW KURTOSIS MICRON	1.360	1.058	2.675	1.411	1.451	1.308	
FW MEAN PHI	4.313	5.322	2.432	4.476	3.905	4.459	
FW SORTING PHI	1.697	1.787	1.809	1.902	2.207	1.942	
FW SKEWNESS PHI	0.441	0.407	0.679	0.380	0.208	0.272	
FW KURTOSIS PHI	1.360	1.058	2.675	1.411	1.451	1.308	
FW MEAN	Very Coarse Silt	Coarse Silt	Fine Sand	Very Coarse Silt	Very Fine Sand	Very Coarse Silt	
FW SORTING	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Very Poorly Sorted	Poorly Sorted	

FW SKEWNESS	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed	Very Fine Skewed	Fine Skewed	Fine Skewed
SAMPLE	20190515 Site 7 sa	20190514 Site 13 sa	20190514 Site 16 sa	20190515 Site 18 sa	20190515 Site 19 sb	20190515 Site 20 sa
FW KURTOSIS	Leptokurtic	Mesokurtic	Very Leptokurtic	Leptokurtic	Leptokurtic	Leptokurtic
MODE 1 MICRON	94.00	54.00	302.5	94.00	94.00	94.00
MODE 2 MICRON	19.00	19.00		19.00	38.50	6.000
MODE 3 MICRON		3.000			19.00	
MODE 1 PHI	3.494	4.231	1.747	3.494	3.494	3.494
MODE 2 PHI	5.736	5.736		5.736	4.720	7.466
MODE 3 PHI		8.466			5.736	
D10 MICRON	6.703	3.361	20.49	5.746	6.232	6.009
D50 MICRON	70.28	35.19	293.8	65.69	81.76	60.28
D90 MICRON	135.5	93.13	478.3	132.0	410.0	188.2
D90 Div D10 MICRON	20.21	27.71	23.34	22.97	65.78	31.32
D90 Sub D10 MICRON	128.7	89.77	457.8	126.2	403.7	182.2
D75 Div D25 MICRON	3.832	4.524	2.032	4.274	4.944	4.696
D75 Sub D25 MICRON	74.97	46.78	201.8	75.46	124.7	82.50
D10 PHI	2.884	3.425	1.064	2.922	1.286	2.410
D50 PHI	3.831	4.829	1.767	3.928	3.612	4.052
D90 PHI	7.221	8.217	5.609	7.443	7.326	7.379
D90 Div D10 PHI	2.504	2.399	5.272	2.548	5.695	3.062
D90 Sub D10 PHI	4.337	4.792	4.545	4.521	6.040	4.969
D75 Div D25 PHI	1.587	1.537	1.768	1.627	1.861	1.686
D75 Sub D25 PHI	1.938	2.178	1.023	2.096	2.306	2.232
PER GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER SAND	57.6%	22.8%	82.2%	52.8%	61.0%	49.0%
PER MUD	42.4%	77.2%	17.8%	47.2%	39.0%	51.0%
PER V COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER COARSE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER MEDIUM GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER FINE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER V FINE GRAVEL	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PER V COARSE SAND	1.5%	0.0%	0.1%	1.4%	4.2%	2.1%
PER COARSE SAND	1.4%	0.1%	6.3%	2.8%	3.6%	2.1%
PER MEDIUM SAND	2.5%	0.1%	57.1%	2.8%	6.9%	3.8%
PER FINE SAND	5.4%	0.5%	16.2%	3.4%	17.7%	8.8%
PER V FINE SAND	46.8%	22.1%	2.5%	42.5%	28.7%	32.2%
PER V COARSE SILT	14.8%	31.4%	5.0%	17.0%	14.1%	18.3%
PER COARSE SILT	11.5%	19.1%	4.0%	12.3%	8.9%	14.5%
PER MEDIUM SILT	4.8%	7.5%	2.2%	5.3%	4.7%	5.7%
PER FINE SILT	5.3%	7.4%	2.8%	5.9%	3.9%	6.4%
PER V FINE SILT	3.3%	8.2%	2.6%	3.9%	5.0%	3.5%

PER CLAY	2.6%	3.6%	1.1%	2.8%	2.4%	2.5%
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A.2. Penetrometer Results

Table A.2: BlueDrop Free Fall Penetrometer results by drop

Drop	Lat	Lon	Minimum Velocity (m/s)	Minimum Velocity Depth (cm)	Maximum Deceleration (g)	Maximum Deceleration Depth (cm)	Maximum QSBC (kPa)	Maximum QSBC Depth (cm)
'1-2'	38.875608	-75.212745	0.0294	-21.12	23.02	-20.00	58.91	-20.80
'1-3'	38.875475	-75.212314	0.0284	-24.58	13.98	-22.15	34.04	-23.69
'1-4'	38.875351	-75.212084	0.0494	-22.25	16.26	-20.81	41.58	-21.91
'10-1'	38.872292	-75.225410	0.0242	-69.19	3.57	-50.48	9.16	-67.36
'10-2'	38.872230	-75.225356	0.0258	-80.76	3.77	-66.38	8.73	-66.83
'10-3'	38.872149	-75.225291	0.0188	-66.37	3.52	-54.55	8.31	-56.97
'10-4'	38.872102	-75.225239	0.0187	-73.29	3.59	-68.58	9.42	-72.07
'10-5'	38.872058	-75.225189	0.0163	-96.85	3.58	-80.75	8.59	-95.49
'11-1'	38.873334	-75.226348	0.0216	-62.09	3.41	-40.40	8.53	-59.53
'11-2'	38.873261	-75.226359	0.0150	-70.58	3.67	-64.27	9.19	-67.08
'11-3'	38.873213	-75.226343	0.0165	-66.86	3.60	-58.83	8.86	-65.42
'11-4'	38.873174	-75.226322	0.0220	-68.45	3.69	-60.57	8.98	-62.37
'11-5'	38.873139	-75.226284	0.0208	-68.53	3.75	-61.80	9.37	-65.07
'12-1'	38.873382	-75.224970	0.0147	-66.82	4.47	-58.27	10.63	-58.39
'12-2'	38.873374	-75.224963	0.0201	-72.72	4.26	-63.23	10.13	-64.26
'12-3'	38.873365	-75.224951	0.0072	-25.16	51.72	-24.94	142.72	-25.10
'12-4'	38.873333	-75.224914	0.0295	-67.89	4.02	-57.19	9.59	-59.61
'12-5'	38.873332	-75.224915	0.0171	-69.27	4.33	-58.51	10.23	-60.90
'13-4'	38.874996	-75.226164	0.0273	-26.18	26.64	-24.42	64.53	-25.44
'13-5'	38.874996	-75.226158	0.0151	-42.89	17.41	-41.27	43.62	-42.35
'15-2'	38.879118	-75.220774	0.0205	-13.22	33.06	-11.82	79.28	-12.52
'15-3'	38.879124	-75.220757	0.0245	-16.87	26.90	-15.50	65.17	-16.05
'15-4'	38.879126	-75.220749	0.0259	-13.76	33.90	-13.11	85.72	-13.28
'15-5'	38.879127	-75.220738	0.0206	-13.67	34.05	-12.24	80.57	-12.63
'16-1'	38.882519	-75.223613	0.0250	-6.36	54.11	-5.60	272.26	-4.17
'16-2'	38.882517	-75.223612	0.0201	-7.12	51.95	-5.96	211.06	-5.08
'16-3'	38.882518	-75.223616	0.0299	-6.61	58.15	-6.07	236.54	-4.93
'16-4'	38.882524	-75.223610	0.0441	-6.40	55.98	-5.78	242.79	-4.17
'16-5'	38.882524	-75.223610	0.0287	-6.94	54.22	-6.23	209.74	-5.00
'17-1'	38.874671	-75.208483	4.1217	-4.82	33.10	-26.15	30.29	-24.70
'17-2'	38.874614	-75.208391	0.0185	-22.50	15.60	-21.18	40.36	-21.90
'17-3'	38.874572	-75.208322	0.0206	-19.50	16.36	-17.56	40.36	-18.78
'17-4'	38.874533	-75.208264	0.0351	-22.42	15.27	-20.78	38.05	-21.50
'18-1'	38.871992	-75.203399	0.0307	-22.64	13.10	-20.29	31.79	-20.83
'18-2'	38.871958	-75.203306	0.0340	-25.26	12.04	-22.20	30.29	-24.70

'18-3'	38.871940	-75.203278	0.0320	-27.25	13.10	-24.99	33.10	-26.15
'18-4'	38.871877	-75.203177	0.0219	-18.64	16.78	-15.80	40.39	-17.71
'19-1'	38.883188	-75.203947	0.0191	-14.64	21.48	-12.96	51.97	-13.80
'19-3'	38.882937	-75.203801	0.0126	-23.48	11.64	-19.46	27.26	-19.46
'19-4'	38.882808	-75.203708	0.0519	-22.41	15.35	-20.59	38.02	-21.67
'19-5'	38.882678	-75.203618	0.0426	-65.24	13.53	-63.75	34.13	-64.32
'2-1'	38.876198	-75.213966	0.0228	-17.92	14.46	-16.10	35.95	-17.15
'2-2'	38.876082	-75.213922	0.0318	-16.02	22.77	-14.71	56.20	-15.30
'2-3'	38.875958	-75.213852	0.0212	-24.13	15.03	-20.13	34.90	-21.45
'2-4'	38.875808	-75.213753	0.0264	-19.24	18.68	-17.93	47.52	-18.76
'2-5'	38.875606	-75.213612	0.0247	-20.94	20.93	-19.94	53.30	-20.60
'20-1'	38.888238	-75.208261	0.0335	-21.34	14.68	-18.44	35.05	-19.74
'20-2'	38.888224	-75.208256	0.0286	-25.19	9.22	-22.78	23.15	-24.76
'20-3'	38.888211	-75.208250	0.0136	-22.26	11.48	-19.37	29.43	-21.54
'20-4'	38.887980	-75.208130	0.0180	-21.60	14.50	-19.40	35.68	-20.57
'20-5'	38.887886	-75.208076	0.0481	-21.96	14.49	-20.98	38.48	-21.69
'21-1'	38.884857	-75.188800	0.0159	-17.47	14.82	-15.78	37.24	-16.84
'21-2'	38.884840	-75.188776	0.0264	-25.25	16.79	-23.78	41.74	-24.25
'21-3'	38.884744	-75.188666	0.0277	-17.27	18.31	-15.81	46.57	-16.68
'21-4'	38.884621	-75.188537	0.0389	-17.18	16.73	-16.84	49.59	-16.99
'21-5'	38.884506	-75.188438	0.0344	-24.51	14.34	-23.36	37.71	-24.10
'22-1'	38.867014	-75.181628	0.0331	-15.10	14.55	-14.27	39.41	-14.87
'22-2'	38.866775	-75.181662	0.0182	-13.96	14.43	-12.45	36.60	-13.50
'22-3'	38.866763	-75.181667	0.0417	-19.00	19.64	-15.82	46.50	-17.40
'22-4'	38.866743	-75.181678	0.0353	-16.74	23.11	-15.22	55.34	-15.22
'22-5'	38.866742	-75.181679	0.0244	-16.60	20.03	-15.46	50.68	-15.98
'23-1'	38.858285	-75.192617	0.0506	-6.57	49.70	-5.56	231.43	-5.10
'23-2'	38.858249	-75.192647	0.0203	-6.84	54.87	-6.26	201.46	-5.86
'23-3'	38.858202	-75.192679	0.0813	-6.38	55.41	-5.76	238.21	-5.18
'23-4'	38.858160	-75.192720	0.0412	-7.30	59.84	-6.74	183.64	-6.61
'3-1'	38.874821	-75.213703	0.0212	-23.26	17.28	-20.57	40.99	-21.46
'3-2'	38.874705	-75.213611	0.0237	-19.87	20.85	-18.29	52.64	-19.51
'3-3'	38.874511	-75.213443	0.0367	-19.32	20.09	-17.44	48.60	-18.57
'3-4'	38.874385	-75.213327	0.0179	-20.50	16.99	-18.18	41.05	-19.38
'3-5'	38.874272	-75.213208	0.0244	-24.06	17.32	-21.58	42.45	-23.28
'4-1'	38.875856	-75.212492	0.0240	-20.89	17.56	-20.04	45.58	-20.45
'4-2'	38.875737	-75.212412	0.0310	-21.00	16.91	-17.79	40.64	-19.79
'4-3'	38.875603	-75.212318	0.0234	-22.67	20.30	-21.27	51.15	-22.09
'4-4'	38.875477	-75.212223	0.0292	-22.87	16.50	-21.16	41.97	-22.51
'4-5'	38.875308	-75.212097	0.0212	-19.10	17.49	-18.27	45.47	-18.67
'5-1'	38.878110	-75.217994	0.0191	-15.60	28.12	-14.55	69.54	-15.17
'5-2'	38.877969	-75.217896	0.0338	-21.14	22.14	-19.77	54.64	-20.60

'5-3'	38.877861	-75.217812	0.0192	-16.54	25.13	-14.72	61.20	-16.01
'5-4'	38.877733	-75.217711	0.0207	-17.13	29.34	-16.03	71.61	-16.35
'5-5'	38.877624	-75.217592	0.0219	-20.27	21.52	-18.57	52.94	-19.86
'6-1'	38.873211	-75.216794	0.0360	-23.91	13.34	-21.52	32.49	-22.37
'6-2'	38.873100	-75.216694	0.0248	-23.45	15.63	-22.44	41.34	-23.09
'6-3'	38.873021	-75.216629	0.0208	-17.82	21.27	-15.67	50.95	-17.31
'6-4'	38.872953	-75.216573	0.0255	-21.28	14.95	-19.09	36.80	-20.29
'6-5'	38.872882	-75.216509	0.0301	-19.48	17.28	-17.68	41.85	-17.79
'7-1'	38.874496	-75.220868	0.0182	-14.57	34.02	-13.83	86.72	-14.09
'7-2'	38.874409	-75.220763	0.0247	-18.26	20.89	-16.39	50.18	-17.28
'7-3'	38.874345	-75.220666	0.0315	-16.34	27.19	-14.98	66.04	-15.53
'7-4'	38.874246	-75.220553	0.0196	-16.34	27.19	-14.98	66.04	-15.53
'7-5'	38.874186	-75.220454	0.0237	-17.79	23.30	-15.45	54.52	-16.15
'8-1'	38.869205	-75.221058	0.0373	-17.86	17.11	-16.74	43.57	-17.34
'8-2'	38.869148	-75.221019	0.0322	-17.25	29.59	-16.50	78.17	-17.08
'8-3'	38.869086	-75.220954	0.0269	-28.57	13.12	-20.18	29.25	-20.18
'8-5'	38.868963	-75.220854	0.0500	-31.72	10.79	-30.47	29.21	-31.22
'9-1'	38.872742	-75.224520	0.0177	-68.88	4.22	-56.77	9.84	-58.53
'9-2'	38.872661	-75.224454	0.0178	-59.33	4.13	-52.84	10.16	-54.08
'9-5'	38.872482	-75.224270	0.0190	-64.38	5.39	-55.91	12.74	-58.37

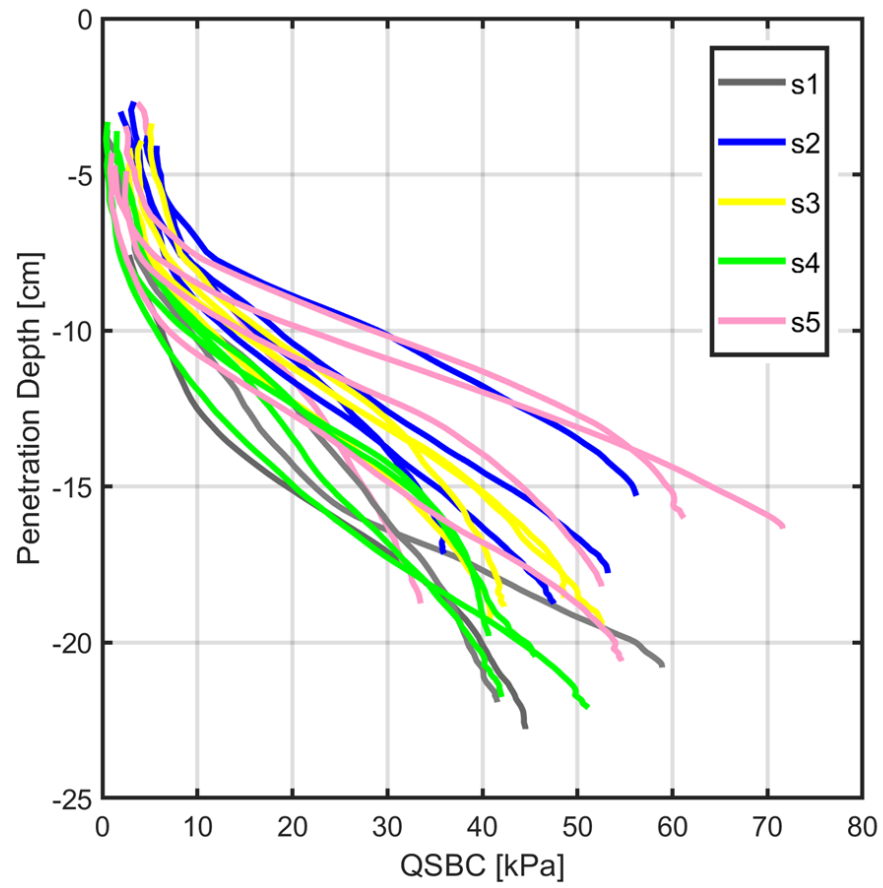


Figure A.1: BlueDrop penetrometer measurements around MR-2730 Field Site 1

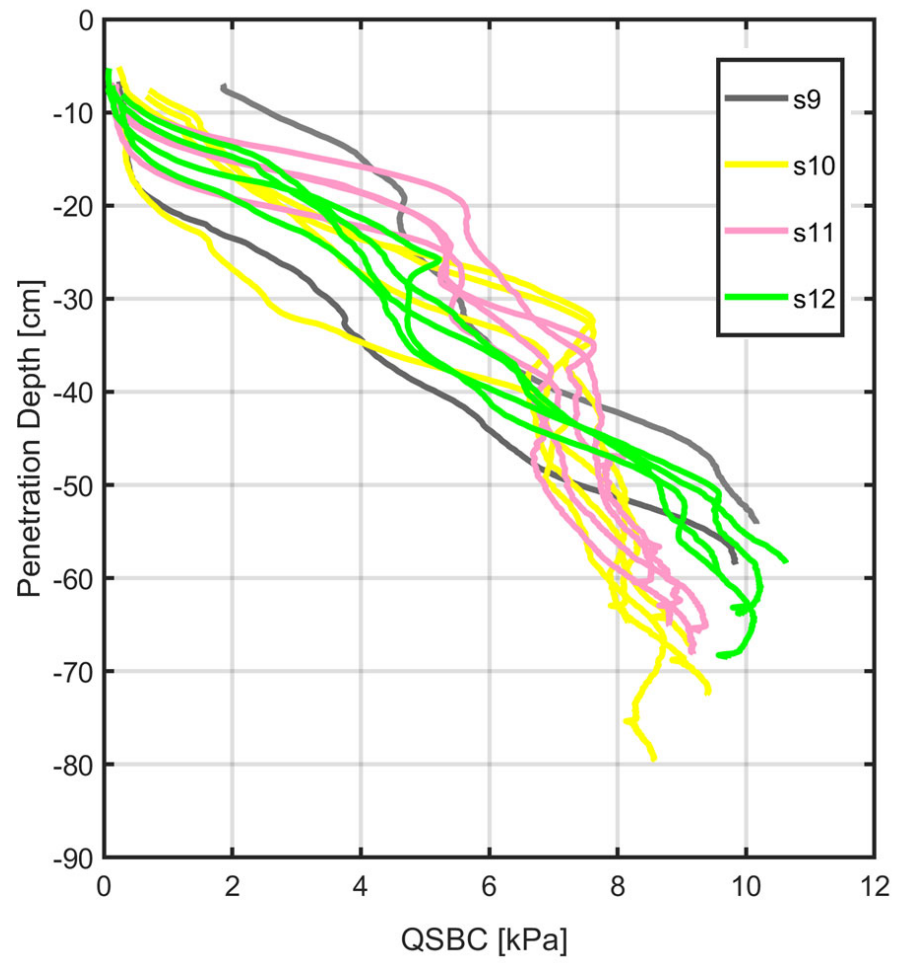


Figure A.2: BlueDrop penetrometer measurements around MR-2730 Field Site 2

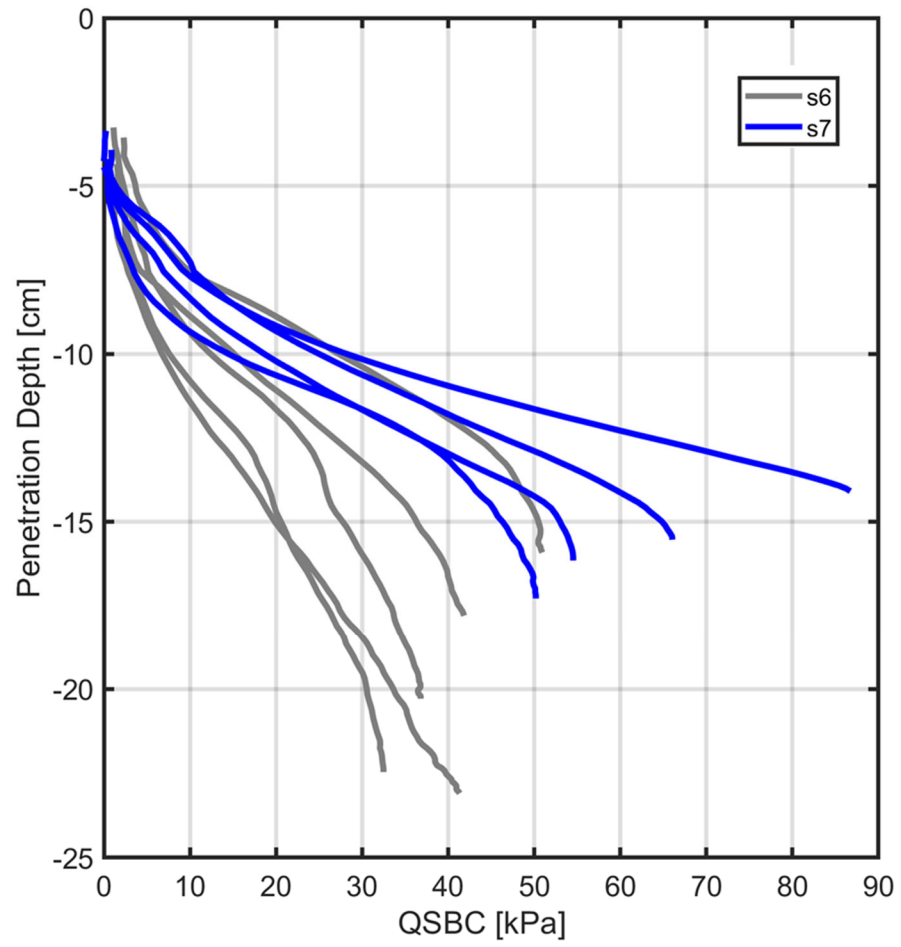


Figure A.3: BlueDrop penetrometer measurements between MR-2730 Field Sites 1 and 2.

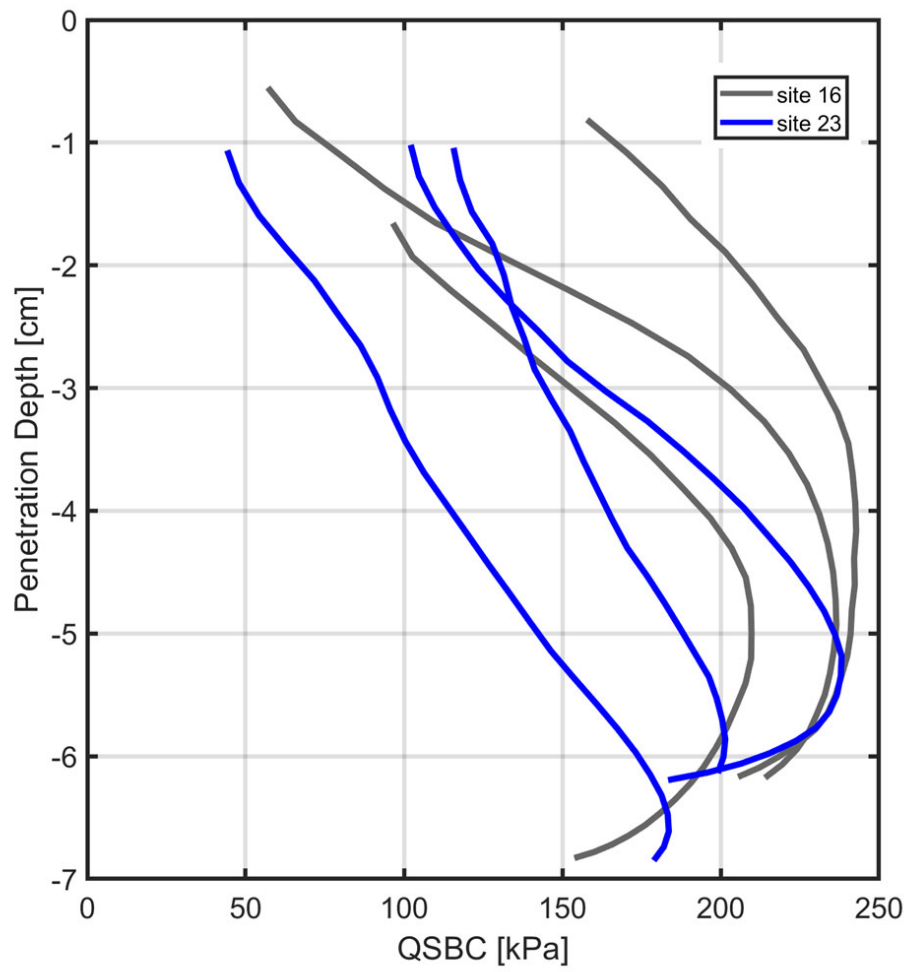


Figure A.4: BlueDrop penetrometer measurements in high % sand sites.

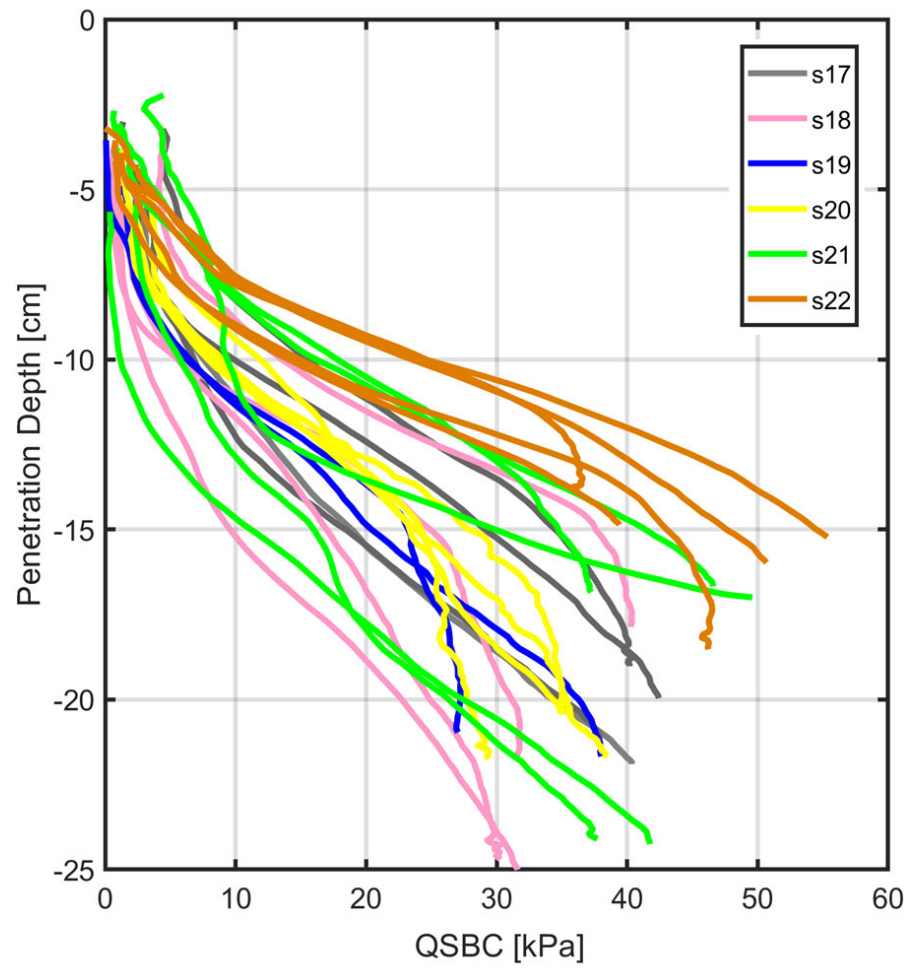


Figure A.5: BlueDrop penetrometer measurements in general region around MR-2730 Field Sites.