WORKSHOP REPORT

SERDP Workshop on UXO Mobility, Burial, and Exposure Processes: Discussion for a Demonstration Project

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July 2023

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**					
1. REPORT DATE *(DD-MM-YYYY)* 15-06-2023		**2. REPORT TYPE** White Paper			**3. DATES COVERED** *(From - To)* Apr – June 2023
4. TITLE AND SUBTITLE SERDP Workshop on UXO Mobility, Burial, and Exposure Processes: Discussion for a Demonstration Project					**5a. CONTRACT NUMBER** W912HQ20C0050
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Jack A. Puleo; Joe Calantoni					**5d. PROJECT NUMBER** MR20-1094
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Delaware, Newark, DE 19716, Naval Research Laboratory					**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Strategic Environmental Researc 4800 Mark Center Drive Suite 16F Alexandria, VA 22350					**10. SPONSOR/MONITOR'S ACRONYM(S)**
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION / AVAILABILITY STATEMENT **Approved for public release; distribution is unlimited**					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT (see below)					
15. SUBJECT TERMS UXO, nearshore, burial, migration, exposure					
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Jack A. Puleo
a. REPORT UU	**b. ABSTRACT** UU	**c. THIS PAGE** UU		42	**19b. TELEPHONE NUMBER** *(include area code)* 302-831-2442

14. ABSTRACT

SERDP and ESTCP support numerous researchers investigating munitions processes in the underwater environment. SERDP funded a Munitions Response in the Underwater Environment workshop at the University of Delaware from April 11 – 13, 2023. Researchers gave presentations on the state of knowledge of munitions mobility, burial, and exhumation (MBE). Subsequent breakout sessions focused on knowledge gaps, modeling capabilities, and the concept of a demonstration project.

An extensive unified model of hydrodynamics, sediment transport, morphology, geotechnical characteristics, and munitions MBE presently does not exist. Results from disparate SERDP-funded research must now be combined to yield an operational tool for site management. The research team shall create a plan of action that results in the "best" munitions MBE model under the constraint of not having perfect inputs, antecedent conditions, or theoretical understanding. The major workshop goal was to chart future SERDP/ESTCP munitions MBE research that leads to an operational model for wave-dominated, sandy, nearshore environments. The goal should include the rough framework for a demonstration project related to the MBE model. Discussion and feedback were distilled into three categories.

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

EXECUTIVE SUMMARY

SERDP and ESTCP support numerous researchers investigating munitions processes in the underwater environment. SERDP sponsored a workshop for Munitions Response in the Underwater Environment at the University of Delaware from April 11 – 13, 2023. Researchers gave presentations on the state of knowledge of munitions mobility, burial, and exhumation (MBE). Subsequent breakout sessions focused on knowledge gaps, modeling capabilities, and the concept of a demonstration project.

An extensive, unified model of hydrodynamics, sediment transport, morphology, geotechnical characteristics, and munitions MBE presently does not exist. Results from disparate SERDP-funded research must now be combined to yield an operational capability for site management. The research team shall create a plan of action that results in the "best" munitions MBE model under the constraint of not having perfect inputs, antecedent conditions, or theoretical understanding. The major workshop goal was to chart future SERDP/ESTCP munitions MBE research and development that will result in the demonstration of an operational capability for wave-dominated, sandy, nearshore environments. Discussion and feedback were distilled into three categories:

<u>Processes</u>: Burial is the expected default condition with morphodynamics being the main driver for exposure and gravity and flow convergences driving migration. Thus, an identification of "initial munition condition" is needed, or must be hypothesized, for munitions with at least partial exposure. Short- and long-term measurements of munitions MBE are needed to fully understand the problem. Researchers should focus on munitions in the intermediate density range $2.5 < SG < 4$, where SG is specific gravity. Liquefaction and momentary bed destabilization are the main mechanisms affecting MBE that still require more understanding and simplified criteria based on easily modeled or measured parameters.

<u>Models</u>: Adequate laboratory and field data exist to validate high resolution models and assist in training probabilistic models (e.g. UnMES). Validated high resolution models should be used, when possible, to generate data sets over a wide parameter space creating additional training data. UnMES parameter resolution needs improvement, and simulation results can be used to identify the most important parameters in ranked order. The operational version of UnMES must be user friendly and require minimal training and expertise for successful operation by contractors or other personnel under the direction of a site manager.

<u>Demonstration site</u>: Several candidate sites will need to be vetted. Site characteristics, suitability, access, and other parameters will be identified with the final site selected via scoring rubric. Early and regular interaction with USACE, NAVFAC and the manager(s) of the selected site must occur. Their involvement is critical to understand needs and data collection capacity. Deployment and testing procedures will be determined following site selection.

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LIST OF ACRONYMS

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
CFD	Computational Fluid Dynamics
DOD	Department of Defense
DOF	Degrees Of Freedom
ESTCP	Environmental Security Technology Certification Program
FL	Florida
FUDS	Formerly Used Defense Sites
MBE	Migration, Burial, and Exposure
MR	Munitions Response
MRL	Munitions Response Library
MRS	Munitions Response Sites
MRUE	Munitions Response in the Underwater Environment
MVCO	Martha's Vineyard Coastal Observatory
NAVFAC	Naval Facilities Engineering Systems Command
NC	North Carolina
NRL	Naval Research Laboratory
PMM	Pressure Mapped Munition
PS	Pressure Stick
Q	Quarter
RMSE	Root Mean Square Error
SERDP	Strategic Environmental Research and Development Program
UnMES	Underwater Munitions Expert System

US	United States
USACE	United States Army Corps of Engineers
UXO	Unexploded Ordnance
VA	Virginia

LIST OF VARIABLES

Δdx_{fi}, Δdy_{fi}	Munition migration distance in the cross-shore (x) and alongshore (y) direction
$\rho_{munition}$	Bulk density of a munition
ρ_{water}	Density of water
P_g	Gauge pressure
S_{crit}	Critical Sleath parameter
S_{PMM}	Sleath parameter quantified with PMM data
S_{wave}	Sleath parameter quantified with wave data
SG	Specific Gravity
x_f , y_f	Initial cross-shore (x) and alongshore (y) position of a munition
z	Vertical coordinate; positive up

1.0 INTRODUCTION

1.1 BACKGROUND AND PROBLEM STATEMENT

An unknown quantity of unexploded ordnance (UXO; also referred to as munitions) exists on coastal seafloors worldwide, including over 400 formerly used defense sites (FUDS) in the US (SERDP, 2010). Geolocation and remediation of UXO are crucial for safety reasons, as shallow coastal regions are used for recreational activities. Understanding UXO mobility, burial, and exposure (MBE hereafter), in relation to the environmental conditions is fundamental for UXO localization and determining if UXO pose a threat to human receptors (MacDonald and United States, 2004). Probabilistic predictive models of mobility exist (Rennie, 2017) but require additional data to improve the range of applicable conditions. Field observations of munition mobility are scarce (Calantoni et al., 2014; Cristaudo et al., 2023; Traykovski, 2020; Traykovski and Austin, 2017). Thus, additional field data may be needed to improve predictive models of initiation of motion and long-term munitions migration.

The coastal region (Figure 1) extends from offshore where wave orbital motion rarely intersects the seafloor into the surf zone. The nearshore zone is subdivided into the shoaling and surf zone regions. The shoaling region is where decreasing water depth causes wave celerity to decrease leading to a corresponding increase in wave height to conserve cross-shore directed energy flux. Eventually the wave steepness exceeds a threshold leading to wave breaking and bore generation at the edge of the surf zone. Bores may reform into waves depending on the dissipative nature of the cross-shore bathymetric profile. Ultimately, bores are captured by subsequent bores or they collapse on the foreshore (also called beach face), initiating swash motion in the swash zone.

Flows offshore of the swash zone, but within the surf zone, tend to be skewed-asymmetric with a larger onshore-directed velocity for less than half of the of the wave period compared to a longer duration offshore-directed velocity of weaker amplitude. The skewed nature leads to steeper front faces of waves with shallower sloping rear faces. The impact on the velocity is a rapid transition from offshore-directed to onshore-directed flows potentially leading to large onshore-directed pressure gradients near the bed and into the sediment matrix (Anderson et al., 2017). Incident wave-band transport of water towards the beach above the wave troughs is typically balanced by offshore directed mean currents. Flows within the swash zone are not strictly oscillatory like their surf zone counterparts. Instead they consist of distinct onshore-directed and offshore-directed flow phases. Velocity magnitudes may exceed 3 m/s for depths rapidly increasing from shallow or non-existent to over 1 m (see Chardon-Maldonado et al., 2016). Uprush motion, following bore collapse, is controlled by gravity and friction at the bed; the two processes acting in opposition to the flow direction. Uprush motion of the leading edge eventually slows to zero. The fluid then accelerates downslope as backwash where the flow is controlled again by gravity and friction; the two processes acting in opposition to *each other* to drive the flow. Eventually backwash flow decelerates when the fluid thins considerably and friction dominates gravitational forces.

Hydrodynamic forcing over a mobile bed leads to sediment transport if the initiation of motion criterion is exceeded. Bed shear stresses and pressure gradients in the surf and swash zones are often sufficient to initiate sediment motion (e.g. Masselink and Puleo, 2006). Cross-shore and alongshore gradients in sediment transport cause bed elevation changes resulting from sediment continuity. The most obvious manifestation of morphodynamics on beaches are sandbars and berms. These features are not static, and they may erode or accrete quickly and/or migrate onshore or offshore (Wright and Short, 1984). Morphodynamics are of interest to the study of MBE because variations can lead to the covering, or more importantly, the uncovering of munitions exposing them to active hydrodynamics. Much like sediment, munitions have associated initiation of motion criteria (e.g. Rennie et al., 2017) and physical/empirical relations that should govern migration and burial (Cristaudo et al., 2023; Friedrichs et al., 2016). These criteria and laws are not fully defined leading to difficulty in predictive schemes for developers and potentially the subsequent use of tools by site managers.

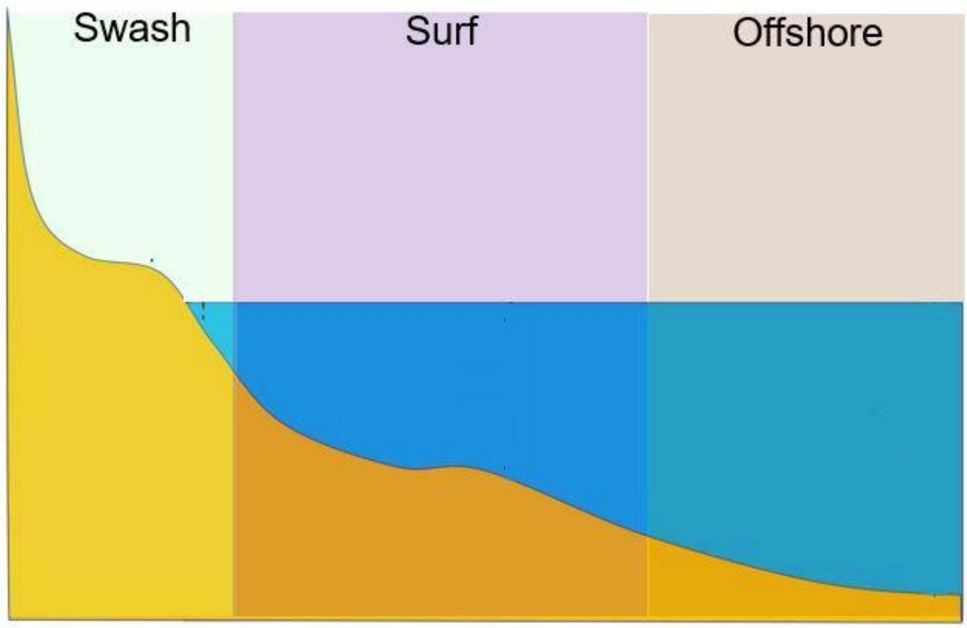

Figure 1. Cross-shore profile of an intermediate to steep beach showing the offshore, surf, and swash zones.

1.2 SERDP MUNITIONS IN THE UNDERWATER ENVIRONMENT – RESEARCH GOALS

The SERDP/ESTCP Munitions Response in Underwater Environments (MRUE) effort seeks to understand and predict behavior of munitions in underwater environments, development and demonstration of technologies for geophysical site characterization, site and munitions survey and management techniques, and cost-effective recovery and disposal methods. Here, we focus on the understanding and prediction of munitions MBE in underwater environments. Underwater environments and processes of interest consist of lakes, rivers, estuaries and muddy environments, open ocean coastlines consisting of rocky, sandy, cobble, coral, and/or frozen beaches, and anthropogenic effects including propeller wash and ship wake in ports and channels, and trawling and dredging aspects. We recognize the importance of all of these underwater environments, but here we focus on wave-dominated, sandy, nearshore environments. A narrowing of the goals and field site is necessary to make the problem more tractable and enable an eventual directed demonstration project with defined purpose and performance metrics.

SERDP and other Department of Defense (DOD)-funded researchers have previously worked on mine burial and mobility (e.g. Bradley et al., 2007; Elmore et al., 2007). Over the last roughly 20 years, researchers have shifted from mines to the munitions (smaller objects) MBE problem in an effort to improve understanding and prediction. Early work focused on a Vortex Lattice Scour and Burial Model that was validated during a demonstration project at Duck, NC (Wilson et al., 2008). Munitions migration was predicted with skill exceeding 0.8 and reported as "good". Subsequent work focused on detailed (1) measurements of flows around proud and partially buried munitions in oscillatory conditions (Cantano-Lopera et al., 2011, 2007; Catano-Lopera and Garcia, 2006); (2) measurements of MBE in small-scale (Cristaudo et al., 2023; Gross and Puleo, 2019) and large-scale laboratory conditions (Bruder et al., 2018; Cristaudo and Puleo, 2020); (3) field measurements of forcing conditions and MBE (Calantoni, 2014; Cristaudo et al., 2023; Traykovski and Austin, 2017). Other measurements were collated into simple predictive equations for burial (Friedrichs et al., 2016) and initiation of motion (Rennie et al., 2017). Additionally, measurements have been used to initiate an expert system (neural network) for MBE (UnMES; Rennie, 2017) and a subsequent munitions response library (Penko; MR21-5207). Measurements have been supplemented with highly resolved numerical models of flow, scour, seepage, and MBE (Hsu et al., 2023; Song et al., 2022).

The MRUE program has steadily climbed the time/value curve (Figure 2) since inception. The program may be on the right side of the best value cut off suggesting that excessive support for continued basic research becomes increasingly unwarranted. Thus, the MRUE program is now at a time where the existence of sufficient quantities of data and predictive capabilities suggest a transition to a useable tool for site managers is needed.

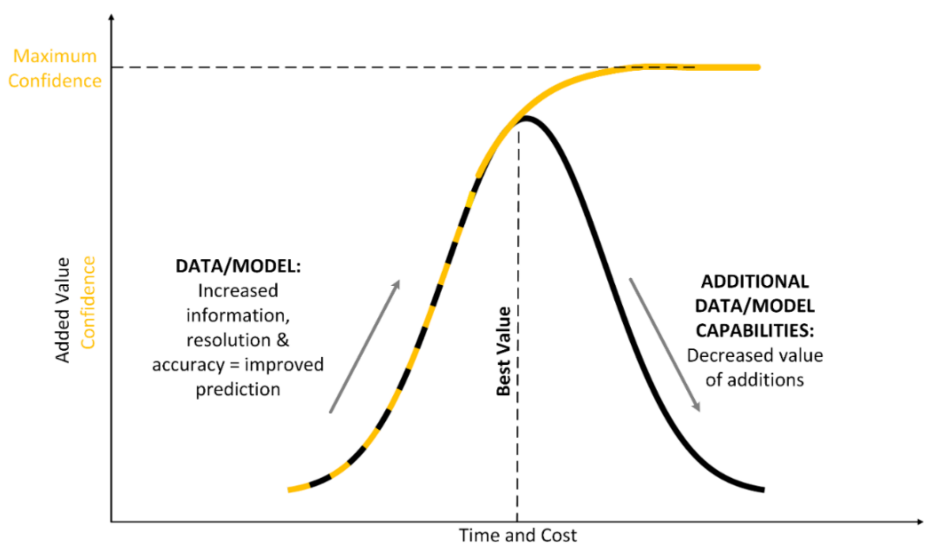

Figure 2. Schematic showing added value and model confidence as a function of time and cost.

1.3 SERDP WORKSHOP OBJECTIVE

A unified model of hydrodynamics, sediment transport, morphology, geotechnical characteristics, and munitions MBE presently does not exist. SERDP researchers have worked diligently on individual projects and efforts to understand better munitions MBE. SERDP researchers must now come together as a research team to create a plan of action that results in the “best” munitions MBE model under the constraint of not having perfect inputs, antecedent conditions, or theoretical understanding. The major workshop objective is a **focused goal for future SERDP/ESTCP munitions MBE research** that leads to an “end point” of a functional MBE operational model for wave-dominated, sandy, coastal environments. The objective will include the rough framework for a demonstration project related to the MBE model.

2.0 PRESENTATIONS ON PRESENT KNOWLEDGE

2.1 PULEO – INTRODUCTION AND RELATIONSHIP TO SERDP GOALS

SERDP researchers have reached a nexus where knowledge, available data, and understanding are at a level where future focus should be aimed towards a validated product for operational capability. There is agreement that a developed tool will always have imperfect inputs, thus requiring a probabilistic approach to the problem of MBE (Figure 3). Indeed, Bayesian network approaches have shown skill in predicting MBE in offshore environments (Rennie, 2017), and compilation of varied data sets has provided simplified empirical relationship for MBE under different hydrodynamic forcing conditions (Friedrichs et al., 2016). Yet, it is clear that MBE predictions are hampered by unknown unknowns and known unknowns. Known unknowns include: how a UXO was delivered to its present location; the time history of associated MBE processes; and munitions characteristics, including orientation, burial depth, level of corrosion and encrustation, and level of intactness. One exception may be that burial is the default condition for munitions located in nearshore environments, with the assumption being that local scour processes and morphodynamics time scales are sufficient for burial. Predictions may also be hampered by imperfect knowns such as bottom type and geotechnical characteristics, morphodynamics, rate of erosion/ accretion, and hydrodynamic setting. In terms of hydrodynamics, the main interest is likely associated with energetic conditions sufficient to mobilize a proud munition, or conditions more likely lead to morphodynamics sufficient to expose a previously buried munition, enabling it to be acted upon by the energetic hydrodynamics. These imperfections can be improved with inferences from lab and field data collections and detailed numerical modeling.

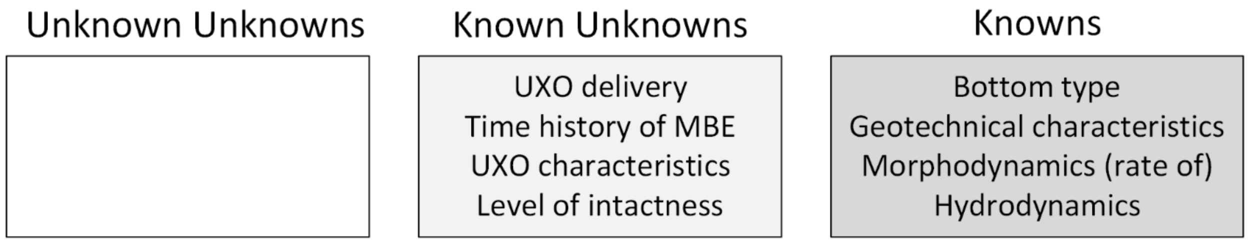

Figure 3. Unknowns and knowns related to munitions MBE in open coast environments.

2.2 HSU - MODELING SEABED RESPONSE AND BURIAL DYNAMICS IN A TWO-PHASE MODEL FRAMEWORK

A high fidelity Eulerian two-phase model, SedFoam, has been developed to simulate mobility and burial dynamics of UXO under waves and currents (MR-1478). SedFoam resolves the full dynamics of sediment transport without the need to artificially separate transport into bedload and suspended load layers by solving the mass and momentum equations for the water phase and fluid phase with closure on turbulence, particle stresses and interphase momentum coupling. Since fall 2022, SedFoam has been extended on several fronts, including a refined elastic-plastic closure of particle stress, implementation of UXO-sediment-fluid interaction with six degrees of freedom (6DoF), preliminary simulations of mobility and scour burial of objects driven by waves, and an evaluation of the most computationally efficient turbulence closure to simulate vortices around an object.

A key effort is to evaluate SedFoam capability to simulate mobility and burial of munitions. First, SedFoam was benchmarked with the simulation results of a comprehensive laboratory experiment of scour around a vertical pile driven by waves. Results suggest the most viable approach for simulating munition mobility and burial dynamics is the Reynolds-averaged formulation based on an advanced turbulent closure scheme. However, a fine mesh to resolve vortices around the munition is still needed. Second, an optimum model domain and numerical stability were improved based on a series of idealized and computationally efficient 2D cylinder simulations. Simulation results reproduce the expected behavior that a lower density object driven by an oscillatory flow tends to be mobile, while a higher density object tends to bury. However, results also indicate that the response of the munition also depends on the soil strength as controlled by the dilatancy parameters.

Selected 2D cylinder simulations have been extended for complete 3D simulations of a short cylinder, driven by oscillatory flow similar to existing laboratory experiment (Figure 4). Preliminary results show similar sensitivity to object density. More extensive model validations with available laboratory experimental data are underway. A specific simulation plan aimed at completing an extensive model validation for munition burial dynamics and to fill the data gaps in the probabilistic model is proposed.

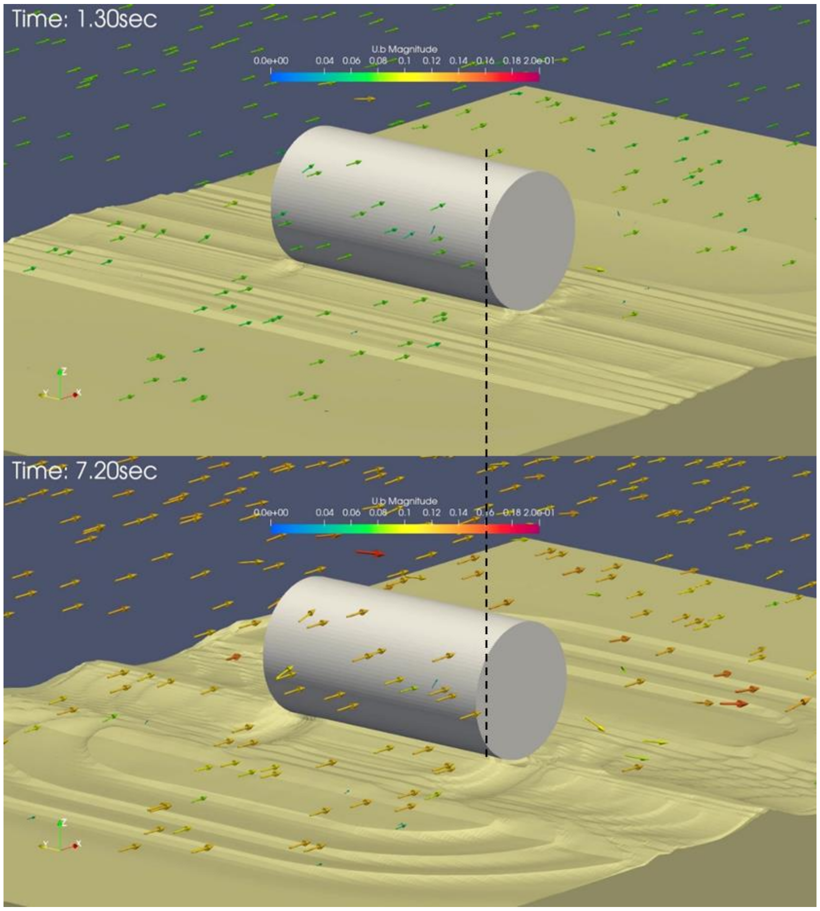

Figure 4. SedFoam simulation of the mobility and scour burial of a 3D short cylinder driven by an oscillatory flow, with cylinder density of $2300\ kg/m^3$ *and diameter 0.1 m. The black-dashed line helps to identify the location of the cylinder. The oscillatory flow is of velocity amplitude 0.2 m/s and wave period 3 s. The bed consists of 0.25 mm diameter sand.*

2.3 LIU - MODELING OF THE FLOW-OBJECT-SEDIMENT SYSTEM: CAPABILITIES, LIMITATIONS, AND INSIGHTS

UXOs in the underwater environment can be conceptualized as a flow-object-sediment system, whose dynamics are controlled by multiple processes (waves and currents, rigid body dynamics, and soil mechanics) at multiple scales (from grain to regional). The computational modeling of such a complex system, though challenging, has advanced to a state that computer models can generate useful results and insights to inform munition response and remediation decisions. The SERDP MR program has supported the development and implementation of several modeling efforts (Figure 5). In general, these models belong to physics-based models (e.g. ibScourFoam, SedFoam, Delft3D), data-driven models (e.g. regression models based on laboratory and field data), or hybrid models (e.g. UnMES). The MR research community has the consensus that currently there is no physics-based model capable of simulating and predicting the dynamics of the coupled system at all temporal and spatial scales. UnMES, an expert system that is trained on data and rules embedding the underlying physics, is the most viable approach for operational use. Within UnMES, currently there are numerous components which are based on assumptions or simply placeholders. All other models, especially high-fidelity, physics-based models, should support UnMES with needed results and data. The parameter space for the flow-object-sediment system is vast, and the "curse of dimensionality" is the most significant challenge for MR research. Models, in conjunction with laboratory and field experiments, can partially alleviate the problem with well-designed and targeted computational experiments.

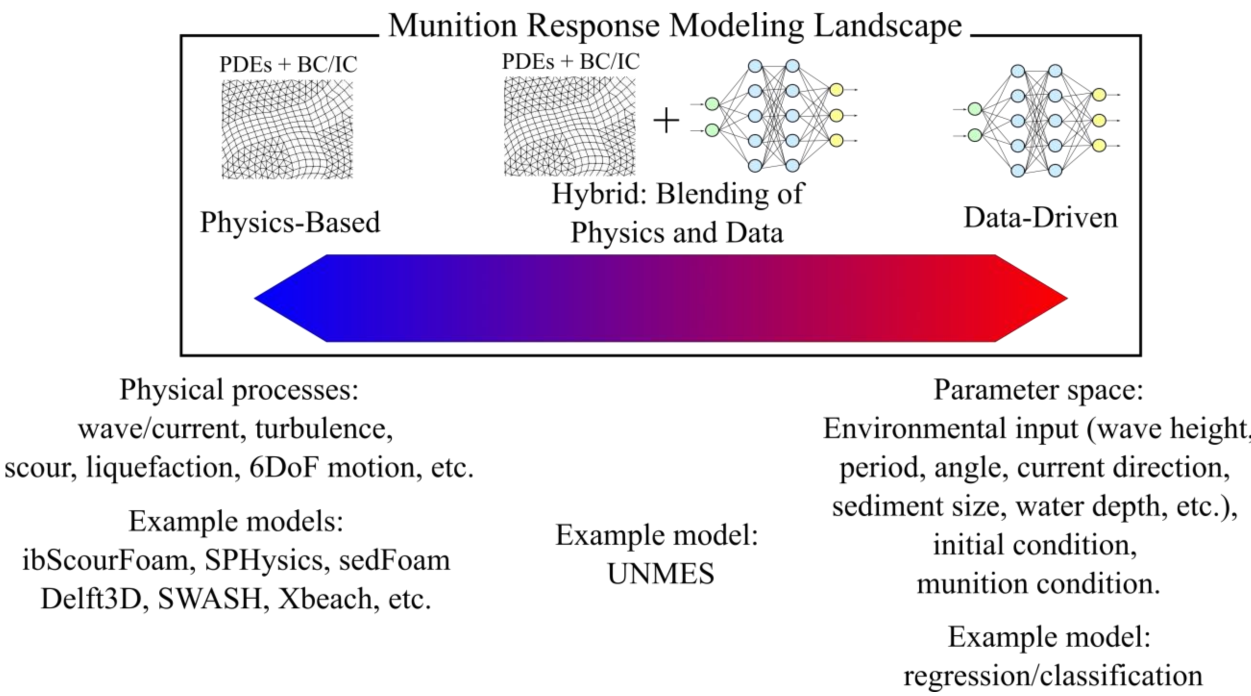

Figure 5. Modeling landscape for the Munition Response program.

2.4 PULEO - OBSERVATIONS OF MUNITIONS MBE IN THE INNER-SURF AND SWASH ZONES

Inner surf and swash zone measurements of hydrodynamics and munitions MBE were collected from laboratory and field settings (Cristaudo et al., 2023; Cristaudo and Puleo, 2020). Laboratory studies consisted of a dam-break scenario in a 30 m long wave flume and irregular waves in a 120 m long wave flume. The dam break enables near prototype swash zone velocities in an otherwise scaled apparatus. Only spherical surrogates (mimicking BLU 61) were tested. A moment balance was applied to derive two data-driven relationships to: 1) predict moments from the cross-shore flow velocity with predictions confined within a factor of two; 2) predict upslope or downslope migration from the moment. Fitting coefficients for the upslope and downslope relationships vary as a function of density, initial position, and burial. A quadratic fit was sought to relate a dimensionless moment group with the dimensionless velocity group. A unique set of fitting coefficients provided predicted moments confined within a factor 2, when compared with the corresponding observations. Thus, the moment prediction was considered partially successful due to the identification of a single relationship. However, the variability in the observed munitions mobility made finding a unique set of coefficients for a single migration formula challenging. Similar challenges occurred when data were parsed into net upslope or net downslope dimensionless migration. These results, for what are expected to be repeatable forcing conditions, highlight the need for probability descriptions of munitions MBE.

The large-scale study consisted of numerous test cases with increasing wave energy and/or water levels. Over 150 surrogates of various densities were deployed across the beach profile. Data from the study (conducted summer 2022) are still being analyzed. However, preliminary data from the more energetic conditions indicate that surrogates ($2 < SG < 4$) either remained and scoured in place (more dense munitions) or migrated offshore (less dense munitions). Other large-scale laboratory efforts for a variety of surrogate munitions densities suggest offshore motion is the dominant transport direction (Bruder et al., 2018). These findings further indicate that rare conditions may be necessary to cause onshore migration into the swash zone.

A field study was also conducted to investigate long-term behavior of eight varieties of UXO surrogates (Figure 6; Cristaudo et al., 2023). Of the 129 observations, 56% were mobilized, of which 76% were directed offshore (negative Δdx_{fi}). Burial/exposure was mostly related to far-field beach accretion/erosion (67%). However, scouring processes were also observed. Data showed that migration is likely a short-term process, and most munitions will ultimately scour into a mobile bed.

2.5 FOSTER - THE DETAILS OF MUNITION MOBILITY

The causes of munition mobility in nearshore regions are not well understood phenomena. In situ measurements of position, burial, orientation, and the local flow field are complicated by the high energy nature of the surf and swash zones. The pressure mapped munition (PMM), a self-contained, Lagrangian instrument representative of 105-155 mm shells, has been developed to autonomously measure the surface pressure and attitude around munitions and determine positional state changes. A second instrument, the Pressure Stick (PS), has also been developed to measure vertical pressure gradients to characterize the presence of momentary bed destabilization events that can also factor into positional state changes of munitions. These instruments were deployed at Wallis Sands Beach, a medium sloping, sandy beach in New Hampshire, with a relatively uniform alongshore profile, from October 26-27, 2021 during a large nor'easter.

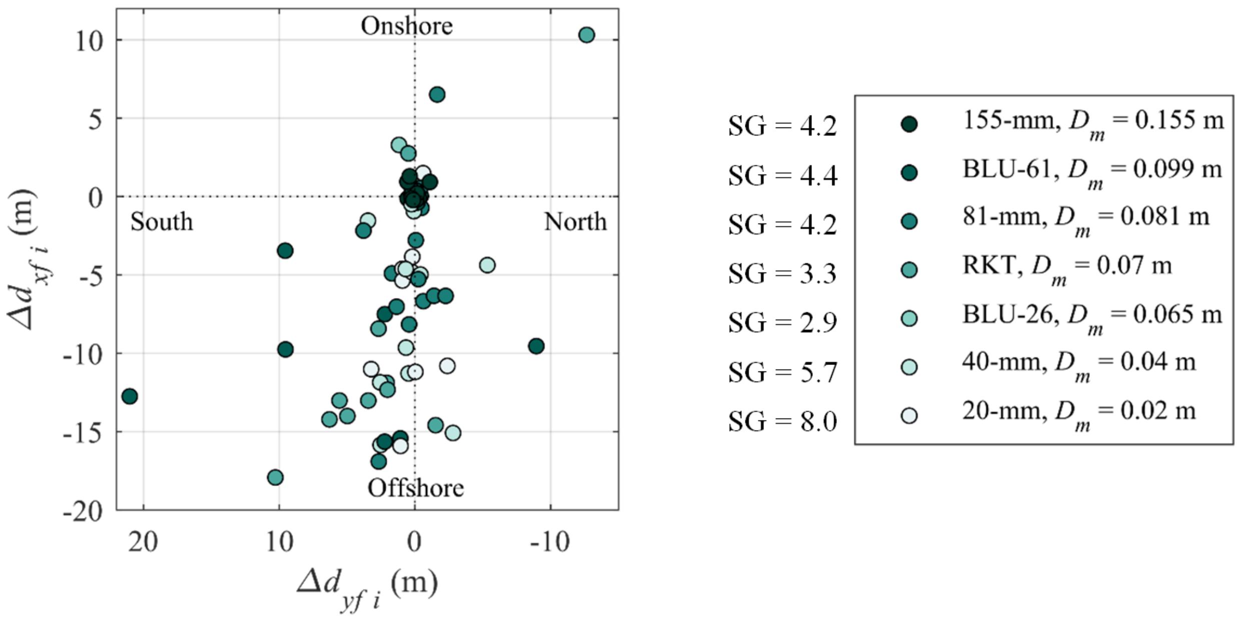

Figure 6. Long term deployed munitions migration observations, with distances Δdx_{fi} and Δdy_{fi} from initial (x_f,y_f) position (Cristaudo et al., 2023).

Positional state of the PMM is inferred based on changes in attitude and on characterizations of the surface pressure variability, where transport occurs when the PMM is rolling multiple times about its long axis at more than 360˚/s. Figure 7 shows a transport event where the PMM rolls once in reaction to a wave (Event 4.2) and provides the hydrodynamic conditions for this event. The slices A-F show a wave drawdown that leads to PMM motion. At A, the pressure is highest, and the pressure around the PMM and PS is hydrostatic. In B-D, $(\partial Pg/\partial z)_{PMM}$ increases above 2, and $(\partial Pg/\partial x)_{PMM}$ increases to about 1.5. These findings imply that upward and offshore-directed pressure gradients exist around the PMM. At the same time, $(\partial Pg/\partial z)_{PS}$ between PS sensors 5 – 4 and 7 – 6 increase until they exceed $(\partial Pg/\partial z)_{crit}$, implying that the vertical pressure gradients are large enough to induce momentary liquefaction within the bed. At E with the oncoming bore, S_{wave}, and S_{PMM} both reach S_{crit} implying that the horizontal forcing due to waves and the presence of the PMM are both large enough to destabilize the PMM. Consequently, at E, the PMM rolls offshore ($\theta \approx 350˚$) then rolls back onshore ($\theta \approx -100˚$). As shown, resolving the full pressure field around munitions can be used to determine and potentially predict the positional state of munitions in the nearshore.

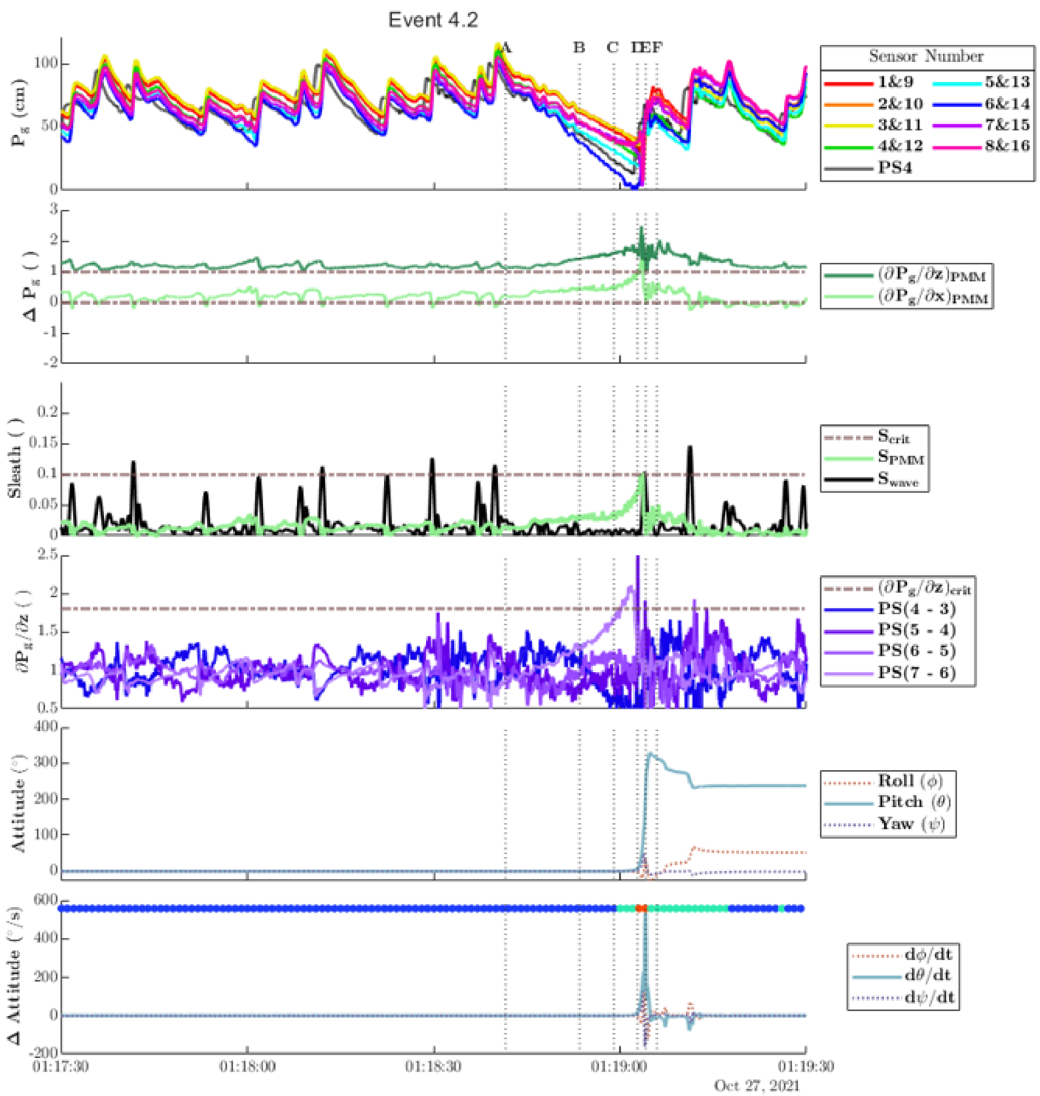

Figure 7. Event 4.2 transport. Dotted lines labeled A-F indicate noteworthy instances within the time series and are used for in-text reference. Panel 1 shows the gauge pressure, P_g, for the PMM sensor pairs and PS4. Panel 2 shows the vertical and horizontal pressure gradients on the PMM surface in dark and light green, respectively. Panel 3 shows the Sleath parameter with the wave and PMM contributions to the mobilization forces indicated with black and light green lines, respectively. The critical Sleath parameter, $S_{crit} = 0.1$, is indicated by the horizontal line. Panel 4 shows the critical value for sediment liquefaction from Mory et al. (2007) and the vertical pressure gradient between the PS sensors plotted in shades of purple, with darker shades indicating sensor pairs that are higher in the bed. Panel 5 shows the attitude time series for roll, pitch, and yaw. Panel 6 shows the Δ attitude time series for each axis of motion; above are points that represent the most active positional state of the PMM during 1 s intervals. Blue points indicate when the PMM is proud, green points indicate when the PMM is wobbling, and red points when the PMM is being transported.

2.6 TRAYKOVSKI - TRANSITIONING FROM PHASE RESOLVED (SWASH) TO PHASE AVERAGED MODELS WITH MORPHOLOGY (XBEACH) FOR UXO MOBILITY AND BURIAL

Results were presented from a parameterized munition mobility and burial model that has been calibrated based on observations from MVCO in 2014 and 2018. The model uses either wave phase resolved output from a coastal hydrodynamics model (such as SWASH) or phase averaged output from a model (such as Xbeach) and produces munition migration and burial depth results. The advantage of the phase averaged model is that it also simulates the morphodynamic change of the nearshore region, including sand bar migration.

Results from a 2018 deployment at Long Point Wildlife Refuge and simulations with maximum wave height of 3.5 m are shown (Figure 8) (Traykovski, 2020). Surrogate munitions (0.75 m long, 0.15 m in diameter, *SG* = 2.3 to 3) were deployed in 3.5 to 4.5 m water depth. Measurements showed little migration of the surrogate munitions and deep burial, up to 1.5 m, due to a sand bar that formed and migrated offshore during the storm, with a final location centered approximately on the location of munition deployment. This location is roughly consistent with the outer edge of the surf zone based on a wave breaking index (wave height/ water depth) of one (Battjes, 1975). At the breaking location, strong offshore return flows subside leading to a balance between onshore forcing of munition migration by wave skewness and asymmetry and offshore forcing by mean currents.

XBeach simulations predicted offshore sand bar migration, with a final location that is slightly farther offshore than the measurements (Figure 8A). The mobility and burial simulation results show no migration for the *SG* = 2.6 munitions and deep burial of the munitions that had initial locations under the final location of the sand bar, consistent with the observations (Figure 8B). The simulation results with *SG* = 2.2 munitions with initial locations closer to the beach (distance offshore = 100 and 150 m, corresponding to 3 and 4 m water depth) show offshore migration followed by onshore migration (Figure 8C). This simulation result was not observed in the measurements, suggesting additional tuning of initiation of motion parameters is required. The *SG* = 2.2 munitions with initial locations farther from the beach were buried by sandbar migration.

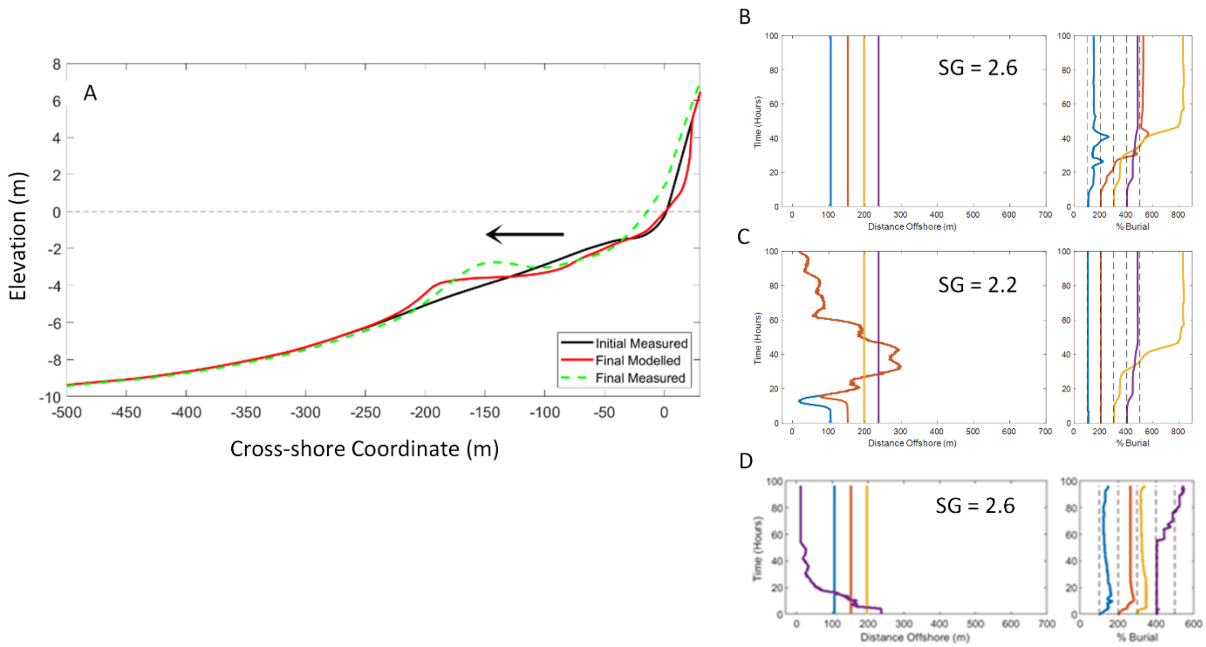

Figure 8. Results and simulations of the 2014 and 2018 Long Point Wildlife Refuge deployment. A) Measured and predicted sandbar migration. B, C) Migration and percent burial predictions of different density proud munitions with different initial cross-shore locations from the 2018 deployment. D) Migration and percent burial predictions of different density proud munitions with different initial cross-shore locations from the 2014 deployment.

In a separate deployment in 2014, with similar density surrogate munitions, onshore migration of the munitions up to 120 m was observed in response to forcing by smaller waves than the 2018 deployment, with height of 2.5 m. The conditions led to a breaking location onshore of the deployment location and subsequent onshore migration. The Xbeach based model forced with the 2014 boundary conditions and with the same UXO parameters as the 2018 simulations produced onshore migration of UXO deployed in the offshore part of the domain and deep burial due to accretion near the beach (Figure 8D). The ability of the model to produce hindcasts consistent with measurements from two different deployments for some UXO density classes suggests potential for using this approach as a basis for seeding statistical models.

2.7 PENKO / SIMEONOV - MUNITIONS RESPONSE LIBRARY FOR SITE MANAGEMENT

The Munitions Response Library (MRL) addresses the availability of capabilities developed and transitioned through SERDP and ESTCP, respectively, to the managers of munitions response sites (MRS) or formerly used defense sites (FUDS). The MRL includes a back end that addresses the responsibilities and procedures for the validation, control, and application of submissions, and a web-based front end that will query and run models on an internal Naval Research Laboratory (NRL) server and export the requested information to users. The design framework of the MRL

(Figure 9) allows the user to input time and region of interest, as well as sediment and munitions information, on the front-end website. The MRL then extracts the hydrodynamic information needed to compute the seafloor boundary layer information and run UnMES. Presently, the website provides useful environmental information in a graphical format to the user. The demonstration MRL includes the application of publicly available hindcasted wave and current information to provide estimates of seabed and munitions dynamics at a specific location over a given time period (Figure 10). With the continual feedback from users, the goal of the MRL will be a community standard set of tools providing environmental information to facilitate decisions for site and resource management.

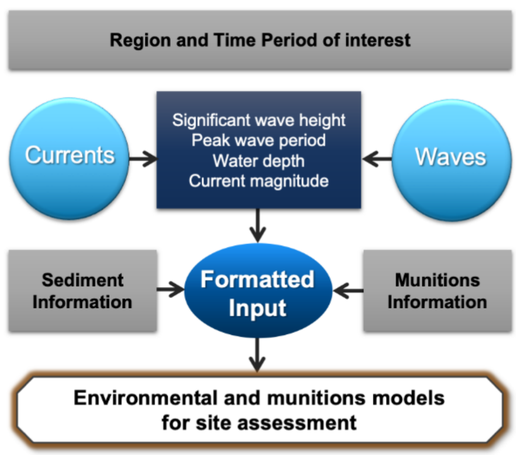

Figure 9. General framework of the MRL. User inputs are indicated by the grey boxes. The hydrodynamic and sediment information are formatted and used to drive sediment and munitions models (e.g. UnMES).

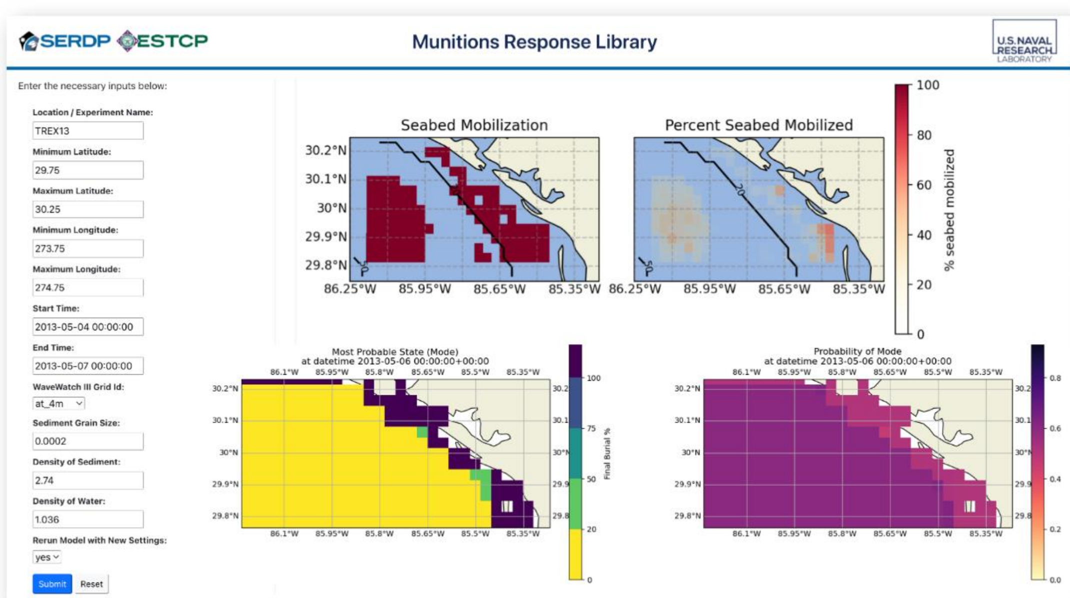

Figure 10. Example output from the initial demonstration of the MRL. The user inputs a maximum and minimum latitude and longitude and a time period of interest, as well as sediment and munitions information. After clicking "Submit," the MRL gathers publicly available wave and current information, calculates the bottom sediment and hydrodynamics and displays the response of munitions as predicted by UnMES.

2.8 DUVAL - MUNITIONS MOBILITY AND BURIAL MANUAL

A primary objective of the MR program at SERDP & ESTCP is to transition the findings and predictive capabilities developed by munitions MBE studies to Munitions Response Site (MRS) management. The collective knowledge of munitions MBE is maturing to the point where we can now apply the science of munitions phenomenology to real world scenarios. Proper documentation, maintenance, and distribution will be a critical factor in transitioning munitions MBE tools to MRS. The MRL is already under development to provide a mechanism for accreditation, maintenance, and dissemination of munitions MBE findings and predictive capabilities, but thorough documentation is required to apply the tools of the MRL to MRS. More specifically, a living document that grows as the research and application of munitions MBE evolves is necessary to address MRS needs. This document, the Munition Mobility and Burial Manual, will serve as a "cookbook" by documenting the application of the munitions MBE tools and the data and parameters of MRS to arrive at management strategies for MRS (Figure 11). As the Manual grows, researchers will continually need to evaluate what data are fundamentally required to predict munitions MBE and at what level of fidelity to conditions is necessary to meet regulatory standards. Since MRS data are not always available or cost effective to obtain, the Manual should provide insight into what parameters are essential for predictions to meet regulatory standards, thereby allowing MRS managers to prioritize efforts to address those parameters. Continuing open lines of communication between researchers and MRS managers is critical to maintaining the Munitions Mobility and Burial Manual and ensuring the successful transition of the munitions MBE program

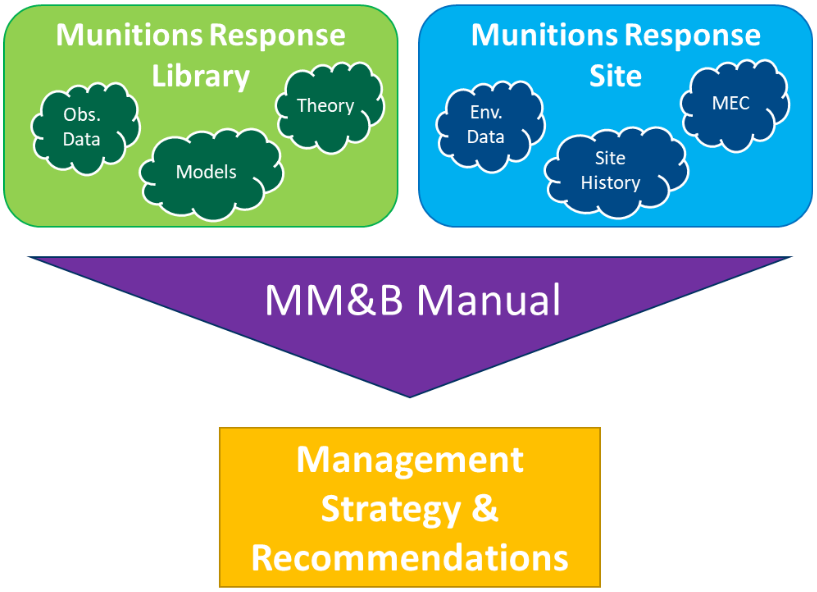

Figure 11. The Munitions Mobility and Burial Manual will provide documentation and examples on how to use the tools of the Munitions Response Library and the data and conditions present at Munitions Response Sites to arrive at management strategies and recommendations.

3.0 BREAKOUT DISCUSSION

3.1 BREAKOUT 1 - WHAT KEY PROCESSES ARE MISSING FROM A BETTER UNDERSTANDING OF MUNITIONS MBE?

Researchers were presented with this prompt to help understand what key knowledge gaps may still exist. Discussions revolved around the numerous environments, mentioned previously, that still require improved understanding. However, it was decided that open-coast, sandy, wave-dominated environments are where MBE processes may be most dynamic and where receptor contact is more likely.

Subsequent discussion focused on time scales of processes. A key point is what represents the "initial" condition of a munition and the ability to predict subsequent MBE. For example, is the initial condition / time scale related to the day the munition was delivered to the seafloor (e.g. day 1), related to some reset event (e.g. storm), or merely "now" being the day from which a prediction is meant to be made. Answers to the preceding depend highly on the morphodynamic time scale in the area of interest vs. the mobility / burial time scale. One suggestion was to use a mapping of a region of interest to set the initial condition. Concerns were raised as to the cost associated with this type of mapping. Following any initial condition used, researchers sought to understand the concept of long-time scale equilibrium, where long would need to be defined in terms of background processes. For example, if the munition is exposed to hydrodynamics and is mobile, will convergence forcing cause it to migrate towards a sand bar or remain near the beach step? For horizontally stationary munitions, at what depth in the sea bed do they reside? The answer is likely related to antecedent conditions, time, morphodynamics, scour, and liquefaction. For mobility and burial understanding the limits on density, liquefaction, and burial depth are key.

The final aspect of breakout #1 focused on processes:

1) Most attention for MBE has focused on the mobility and burial aspect rather than the exposure aspect. An issue with this mindset is that most munitions in natural coastal environments are likely buried such that there is no opportunity for mobility unless they become exposed. Researchers discussed the importance of munitions density for mobility and burial. Several bulk density ranges (using specific gravity, $SG = \frac{\rho_{munition}}{\rho_{water}}$, where ρ represents density) were suggested. Low density munitions ($SG < 2.5$) are likely to be highly mobile and unlikely to bury. Medium density munitions ($2.5 < SG < 3$) are in a range where burial and mobility are the most difficult to determine because the density is near that of sand. High density munitions ($SG > 3$) are most likely in a buried state due to difficulty in mobilization and settling under scour processes. Most of the munitions in the SERDP standardized target repository have bulk densities in the high-density range. The preceding concepts on the importance of density lead to a discussion of density variation. That is, is density variation over time important to consider? Proud or partially proud munitions in a sandy, wave-dominated environment may bury quickly due to prevailing forcing. Is a buried munition likely to undergo significant degradation over time?

2) Given the expected propensity of burial, discussions continued with competing aspects of burial and mobility processes. Researchers identified liquefaction, the depth of liquified sediments, and the time history of the strength of the bed profiles in relation to munition density ranges as a critical gap in understanding. It was discussed that saturation/gas content and the understanding of 3D dissipation/diffusion of pressure is important and not straightforward to solve/investigate/measure. A probabilistic framework for liquefaction may also be needed. Researchers expressed that there is still a lack of understanding of when and how long momentary liquefaction or significant reduction of effective stress occurs and how it relates to actual sediment transport or response of a munition. For example, most momentary liquefaction events are short (< 1 s). Is this time period long enough to allow a munition to sink to a significant depth (liquified depth?)

Liquefaction is an area that still requires fundamental research. Two pathways are suggested: 1) Understanding how momentary liquefaction relates to geotechnical and easily measured hydrodynamic properties; and 2) How does the transition from non-liquefied to near-liquefied (loss of strength and effective stresses) to fully liquefied interact with different types of munitions. These findings will help to improve predictions and may lead to development of tools (Foster; MR-2371) to further quantify liquefaction or momentary bed destabilization. Researchers stressed that measurements alone are not sufficient. The potential for liquefaction should be related to sediment bed geotechnical properties and hydrodynamic conditions, particularly the role of large individual waves, rather than time-dominated mild conditions. Along these lines, researchers expressed interest in predicting these processes specifically in the inner surf and swash zones and any potential for *onshore* munitions migration.

3) A final aspect of processes revolved around the importance of mobility. Researchers asked how large of a problem is munitions mobility? Is the science and understanding seeking to solve a problem with extremely low probability? For mobile munitions, there is still a gap in knowledge as to how far the munition may migrate, which direction (offshore, onshore, alongshore), and any uncertainty in predictions of the migration. It is imagined that the cone of uncertainty (position as a function of time) for known mobile munitions is large. An approach to investigating the uncertainty is to gather repeated measurements under the same forcing and initial conditions; a process that appears straightforward, but is rather difficult given “small” initial variations can lead to large differences in final conditions. Thus, researchers may seek to generate a list of observations that did not match expectations based on prevailing conditions. Underlying the question of the importance of mobility is the expectation that only a small minority of munitions have low density ($SG < 2.5$), which are most likely to be highly mobile.

<u>Synthesis</u>: Discussion items from Breakout #1 are synthesized as follows:

- There is a wide variety of environments of interest. Not all can be investigated in detail. A demonstration effort will focus on open-coast, sandy, wave-dominated environments.

- Researchers need to define “present state” for determining an initial condition. That condition is likely buried. There is an expectation that sensor technology will be able to provide maps of geolocated munitions or munitions-like objects along with estimates of burial depths.

- Morphodynamic models are imperfect in quantifying magnitudes of change. Predicting the position time history of morphologic features (when migrated; to where) vs. magnitude will need to be sufficient. SERDP funding is not aimed at supporting development or validation / calibration of morphodynamic models.

- Liquefaction and momentary bed destabilization are order one processes related to munitions burial. Quantifying this process using a simplified approach based on sediment characteristics and hydrodynamic forcing conditions, is needed to improve MBE predictions (Klammler et al., 2021; Pessanha et al., 2023).

- Available laboratory, numerical, and field data of MBE should be collated and related to commonly used forcing parameters. The parameters shall then be ranked in order of importance to MBE.

3.2 BREAKOUT 2 - WHAT COMPUTATIONAL EFFORTS ARE NEEDED TO FINALIZE A SIMPLIFIED MBE MODEL APPROPRIATE FOR MANAGER DECISIONS?

Researchers were presented with this prompt to help identify the computational efforts needed for an operational tool. Discussion and responses were grouped into three key topic areas; the first two were focused on detailed numerical predictions:

1) Model time and space scales: Researchers discussed the need to link across model scales in space and time using nested approaches. This need will manifest mostly through sophisticated computational fluid dynamics models (CFD) and those containing modules for morphodynamics and geotechnical aspects. Most detailed models, and even probabilistic models (and associated validation data), are short-term (minutes to days). There is less knowledge on model skill for long-term response. Regardless, even short-term processes are relevant, including the "level of extreme" needed for significant mobility (e.g. time rate of change of wave height or wave period), and the importance of model ramp-up conditions; mostly for exposed or partially exposed munitions. Finally, researchers discussed the general difficulty to model onshore munition migration in the surf and swash zones.

2) Model validation: SERDP researchers have various data sets for model validation, but more data may be required. Any future data collection should be tightly coupled with modeling efforts ensuring the measurements comport with modeling needs to answer specific questions related to MBE. Quality checks / uncertainty bars are needed for validation data so that information can eventually be fed into probability descriptions. At this stage, it is well known that hydrodynamic prediction skill is well ahead of the ability of researchers to predict morphodynamics. Hence, the previous discussion to avoid the need for predicting the magnitude of morphodynamics.

Model validation can occur through quantification, such as root mean square errors (RMSE) or skill scores, such as Brier or Wilmott (Brier, 1950; Wilmott, 1981). A validated model must be checked for sensitivity in output to a range of input parameters from a testing matrix. Monte Carlo simulations may also be needed to expand the parameter space. An additional aspect to address in model validation is the development of simplified parameterizations for liquefaction, such as the degree of liquefaction (Klammler et al., 2021). This aspect is necessary because an operational model must be simple and run quickly on standard computational hardware. Detailed hydrodynamic–sediment interaction models, including geotechnical variability, are outside the scope of a simple operational model.

3) Models and operational tool use: The third topic area focused on model usage. There is a need for model simulations to focus on limits of burial and thresholds for initiation of motion. Machine learning and hybrid approaches can be employed to refine the research and identify the most important parameters. Validated models can subsequently serve as data generators. Models can be used to generate data across a wide parameter space to provide and improve inputs to probabilistic models (those likely to be used by site managers). An example is to test models with varying levels of initial burial to determine the impact on final burial condition. Model output of morphodynamics may serve as a prompt to site managers to conduct a survey. SERDP has funded development of new technologies to efficiently conduct bathymetric surveys of the near shore using robotic vehicles (Francis and Traykovski, 2021; Traykovski, 2020). CFD and morphodynamic models should be designed and used by forcing with data/parameters that are easily obtained by site managers. Finally, the most likely probabilistic model to be used is UnMES. The overall layout of UnMES was deemed appropriate. However, UnMES should be improved by a) including more training for impact burial, liquefaction, and swash zone processes; and b) increasing resolution of the important parameters. For example, changing the state of migration from "stay", "near", and "far" to a sequence of distance ranges.

<u>Synthesis</u>: Discussion items from Breakout #2 are synthesized as follows:

- Modelers and experimentalists must work together to identify key needs for model validation.

- Researchers need to bridge CFD, morphodynamics, and simple parameterized models providing training data over a broad parameter space to UnMES. In this way, high fidelity, validated models become data generators for probabilistic models.

- Model simulations should focus on density ranges $2.5 < SG < 3$, where the munitions response is least understood. Simulations must focus on short-term *and* long-term response of munitions.

- Research must understand site manager capacity for data collection and ensure model simulations can be conducted with the more restricted boundary and forcing conditions.

- UnMES model parameters are largely appropriate. However, UnMES requires additional training and parameter resolution.

3.3 BREAKOUT 3 - CONCEPTUAL DESIGN FOR GROUP DEMONSTRATION PROJECT

Researchers were presented with this prompt to help identify concepts around an eventual demonstration project. It was decided quickly that a large-scale laboratory study would not be sufficient for demonstration. The researchers focused solely on the potential for a field effort. There was again agreement on an open-coast, sandy, wave-dominated environment with a preference for a site with weak alongshore gradients. Eventually, a few live sites should be identified as potential candidates with pros/cons classified for each. Several candidate sites were already mentioned: Camp Lejeune, NC; Flamenco Beach, Puerto Rico; Wallops Island, VA, and Fort Pierce, FL. Some arguments were made for multiple sites, starting out at a "simple" site, and then transitioning to a more complicated site; perhaps with significant alongshore variability. Regardless of the eventual selected site, there is a preference for: a) being adjacent to a live site to obtain manager buy-in and testing under actual scenarios; b) variability in wave intensity (calm and storm periods); and c) a moderate tide range to help facilitate sensor placement. Researchers will need to work with site managers in the demonstration formulation including for site logistics, ease of access, and rapid deployments, and the site must be seeded with long-term surrogate and/or inert munitions. A quality assurance of data will be needed. Initially researchers should plan to run CFD, morphodynamics, and UnMES models in advance of any testing to provide preliminary expectations based on historical forcing. Subsequently, researchers should be prepared to run blind models with only available hydrodynamic boundary conditions and other information readily available to a site manager. Those predictions will be tested / scored with observation of UXO mobility and burial.

Synthesis: Discussion items from Breakout #3 are synthesized as follows:

- A final site must be selected from a group of candidate sites so managers can be incorporated from the outset of the planning. Andy Schwartz (USACE) and Bryan Harre (NAVFAC) can help facilitate site manager interactions.

- Researchers must have functional CFD, morphodynamics, and UnMES versions ready for prediction and comparison to specified performance metrics.

- Subsequent group meetings will be needed to identify scope and objectives.

3.4 BREAKOUT 4 – DEMONSTRATION PROJECT

More general discussion on a potential demonstration project and MBE processes occurred in Breakout #4 after researchers had time to digest materials from Breakouts #1-3. Key items are:

Site selection: A demonstration should occur adjacent to a managed site because of the immediate relevance of the results and will simplify approval of seeded munitions. Using an operational range may allow for the demonstration to be incorporated into an ongoing remedial effort. In that sense, the remediation site manager would serve as the demonstration site manager. Any potential demonstration will require an establishment of the horizontal limits of interest (offshore and alongshore).

Field effort: Researchers agreed that surrogates would need to be deployed at the field sites in several different scenarios. Some surrogates should be considered long-term, where they remain at the site for 12 to 18 months. Others should be placed in a rapid-response fashion prior to an energetic event. There was no consensus at this time on the number of surrogates or the number of cross-shore or alongshore arrays. Surrogate layout will be determined after site selection. There was discussion on the need to study low density munitions MBE. However, munitions at field sites are rarely in this density range. Thus, ignoring low density munitions would simplify the demonstration plan parameter space. In addition, alterations to bulk density (e.g. corrosion) is a slow process and may not change the bulk density significantly, implying it is not an order one process. Thus, the final munitions density range will be determined after site selection. Regardless of the munitions surrogates chosen, researchers must have a robust plan for periodic geolocation. Every surrogate should be fitted with a long-term acoustic pinger and there must be reference posts for diver measurements. The demonstration project shall be designed such that SERDP researchers are also able to collect the routine data (e.g. acoustic Doppler velocimeter, water level, wave statistics, pressure) that could be used to further enhance process understanding and model parameterization.

Models use: Part of the development is to upgrade UnMES, but it must be functional prior to the actual demonstration. To that end, UnMES researchers must identify what is needed from experimentalists, must include the surf and swash zones in model training, must increase parameter resolution, and must develop a set of milestones of completion prior to demonstration plan development. UnMES enhancement also requires determination of the output needed from the high resolution CFD models. Liquefaction and momentary bed destabilization are difficult to obtain in situ. The models must help assist in developing proxies based on easily quantified hydrodynamic or pressure parameters.

Site managers will need to be informed as to the minimum set of inputs needed to run a particular model. It must be kept in mind that site managers will not have the capacity to conduct a large-scale field effort. Models inputs are expected to be minimal and of coarse resolution. So, it behooves researchers to identify the top parameters (no more than five) that a site manager would need to successfully run a particular simulation. Site manager education and feedback must start early in the process. The models would need to be arranged with the understanding that the inputs would be limited.

4.0 SUMMARY

4.1 PRIORITY RECOMMENDATIONS

MRUE SERDP researchers should work together to develop an ESTCP demonstration plan for testing of CFD, morphodynamics, and UnMES models of munitions MBE. A focus on open-coast, sandy, wave-dominated environments was identified based on likely migration and potential for receptor contact.

Demonstration site: Several candidate sites will be considered. Site characteristics, suitability, access and other parameters will be identified. Then, a rubric will be developed to select the site for actual demonstration. Regardless of site location, USACE and NAVFAC colleagues will facilitate discussion with site managers who must be included early in the process. Their involvement is critical to understand needs and data collection capacity. Deployment and testing procedures will be determined following site identification.

Processes: An identification of "initial munition condition" is needed especially when the default condition is assumed to be buried. Short- and long-term measurements of munitions MBE are needed to fully track the problem. In doing so, researchers should focus on munitions in the intermediate density range of $2.5 < SG < 3$. Liquefaction and momentary bed destabilization are the main mechanisms affecting MBE that still require more understanding and simplified criteria based on easily modeled or measured parameters.

Models: Adequate laboratory and field data exist to validate high resolution models and assist in training UnMES. Modelers and experimentalists need to work together to determine any additional needs for model validation. Validated high resolution models should be used to generate additional data sets over a wide parameter space creating training data for UnMES. Of course, there is a limit on the number and range of simulations to be performed due to computational expense. UnMES already contains identified important parameters, but the parameter resolution needs improvement. Results from UnMES can be used to identify the most important parameters in ranked order to assist in future data collection. Soon, MRUE SERDP researchers will need an UnMES version that is ready for prediction at the chosen site for comparison to performance metrics. The operational version of UnMES must be user friendly and require minimal training and expertise for successful operation by contractors or other personnel under the direction of the site manager.

4.2 SUGGESTED SCHEDULE OF ACTIVITIES

The schedule of activities is presented in a Gantt chart (Figure 12), where gray shading indicates quarters of expected activity. If funded we anticipate a project starting in Q3 of 2024.

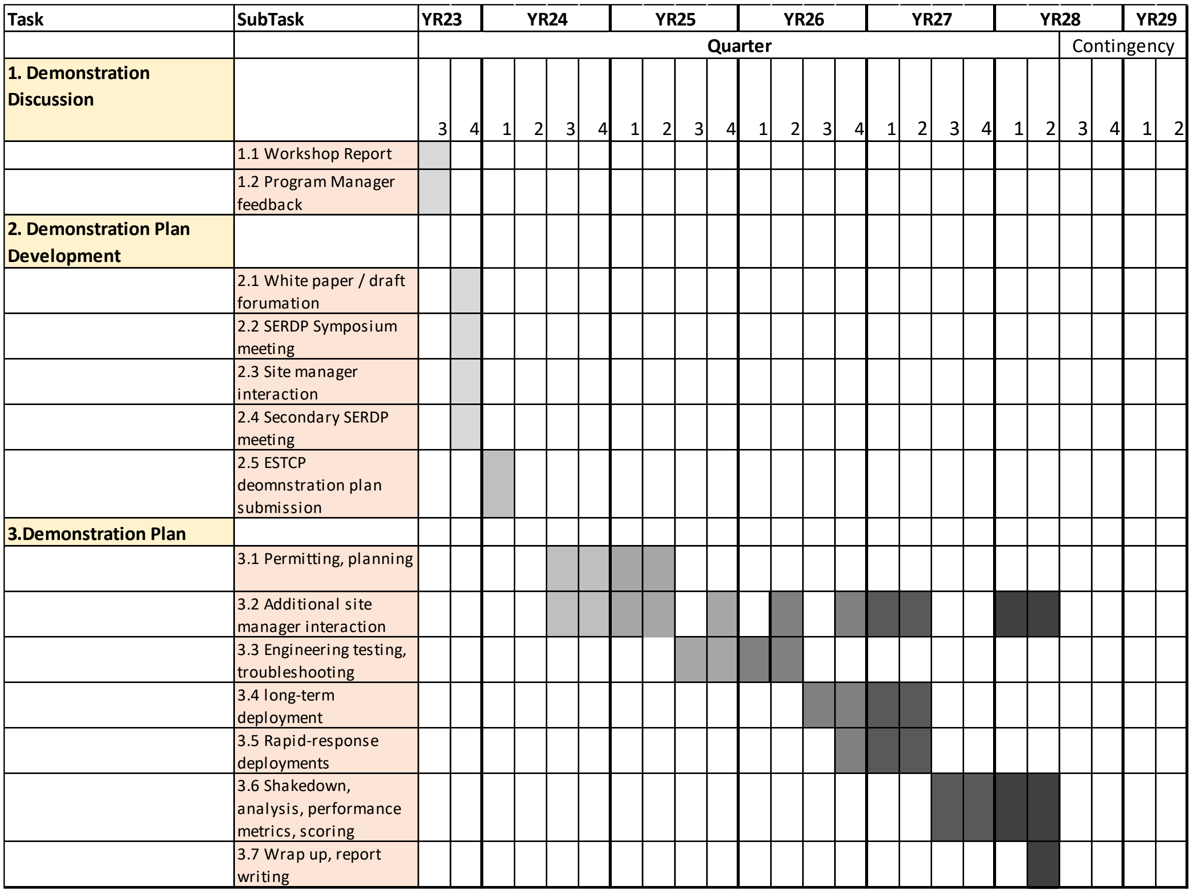

Figure 12. Gantt chart of demonstration activities.

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6. APPENDICES

6.1 WORKSHOP AGENDA

April 11, 2023		
Time	**Item Description**	**Speakers**
1800-	Ice breaker get together at Puleo Home Heavy hors d'oeuvres 2 Rossiter Circle, Newark, DE (see map) cell: 302-339-0343	N/A

April 12, 2023		
Time	**Item Description**	**Speakers**
0830	Breakfast	N/A
0900	Welcome	David Bradley
0910-0930	Introduction, history, workshop goals	Jack Puleo
0930-0945	Modeling seabed response and burial dynamics in a two-phase model framework	Tom Hsu
0945-1000	Modeling of the Flow-Object-Sediment System: Capabilities, Limitations, and Insights	Xiaofeng Liu
1015-1030	Observations of Munitions MBE in the Inner-Surf and Swash Zones	Jack Puleo
1030-1045	Break	
1045-1100	The details of munition mobility	Diane Foster
1100-1115	Transitioning from phase resolved (Swash) to phase averaged models with morphology (Xbeach) for UXO mobility and burial	Peter Traykovski
1115-1130	Update on the Munitions Response Library	Julian Simeonov
1130-1145	Munitions Mobility and Burial Manual	Carter DuVal
1145-1200	Operational requirements for munitions mobility	Bryan Harre
1200-1300	Lunch	All
1300-1400	Breakout #1: What key processes are missing from a better understanding of munitions MBE?	All
1400-1430	Breakout group dissemination	Led by: Mike Richardson

1430-1530	Breakout #2 What computational efforts are needed to finalize a simplified MBE model appropriate for manager decisions?	
1530-1545	Break	
1545-1615	Breakout group dissemination	Led by: Joe Calantoni
1615-1715	Breakout #3 Conceptual design for group demonstration project	All
1715-1745	Breakout group dissemination	Led by: Jack Puleo
1745-	Dinner	All
April 13, 2023		
Time	**Item Description**	**Speakers**
0830	Breakfast	NA
0900	Wrap up from Day 1	Jack Puleo
0930-1000	Discussion and feedback	Led by: David Bradley, Mike Richardson, and/or Mike Tuley
1000-1100	Breakout groups – Demo project A) Model team B) Data collection	All
1100-1130	Breakout group dissemination Next steps	Led by: Joe Calantoni and Jack Puleo
1130	Adjourn	

6.2 WORKSHOP ATTENDEE LIST

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6.3 BRYAN HARRE - MUNITIONS RESPONSE SITE MANAGEMENT ISSUES PERTAINING TO UNDERWATER MUNITIONS MOBILITY

Introduction

Military munitions are found in certain underwater locations resulting from historic disposal activities and as a result of live fire training, testing, and other operations (Beck et al., 2018). Projectiles and other munitions that remain functional in the underwater environment pose an explosive hazard that can potentially migrate, allowing personnel to encounter these munitions. The management of this explosive hazard is complex and depends on site-specific considerations such as munitions type, the marine environment, the potential for mobility, and how personnel encounter and interact with the munitions. The purpose of this whitepaper is to summarize some of the site management issues regarding munitions mobility in underwater environments.

Common MR Underwater Site Types

Munitions manufacture, training, and disposal has resulted in releases of MEC into the environment. Table 1 provides a short summary of some typical Munitions Response Site types and the potential categories of MEC that may have been released (NAVFAC MR RI/FS Guidance, 2019). Underwater munitions response site types can consist of locations in bays and harbors where munitions were loaded or transferred onto ships or barges. Firing fan locations on land may extend out into the sea and adjacent waterways such as rivers and lakes resulting in munitions being released into these waterways and coastal zones. Targets on water ranges can consist of stationary targets or moving targets with varied impact area sizes. Due to the varied nature of warfare and the industrial operations to support national defense, munitions can be found in ponds, lakes, rivers, bays, harbors, coastal areas adjacent to land, and in the ocean.

Table 1. Summary of Typical Munitions and Possible MEC Present at MRSs

MRS TYPE	TYPICAL MUNITIONS USED	POSSIBLE CATEGORIES OF MEC
Small arms range	Small arms ammunition*	None
Grenade range	Hand and rifle grenades	UXO, DMM, MC
Artillery range	Medium and large caliber projectiles	UXO, DMM, MC
Bombing range	Bombs (including sub-munitions), medium and large caliber projectiles, rockets, guided missiles	UXO, DMM, MC
Air-to-Ground	Projectiles, rockets, guided missiles	UXO, DMM, MC
Ground-to-ground	Rockets and guided missiles	UXO, DMM, MC
Multi-use range	Small arms ammunition, projectiles, grenades, rockets, bombs	UXO, DMM, MC
Training/maneuver area	Small arms ammunition, signals, trip flares, other training devices	UXO, DMM, MC
Open burn/open detonation (OB/OD) area	Any and all types of military munitions. Varies based on munitions stored/used at a given facility or location and/or permit allowance	UXO, DMM, MC
Munitions manufacturing facility	The types of munitions manufactured at the facility, test ranges for lot acceptance testing, explosive residues and pellets in buildings and facility infrastructure, manufacturing rejects, test items, explosives in soils at concentrations high enough to pose an explosive hazard, groundwater (GW) contamination	UXO, DMM, MC
Storage area/transfer point	Various unused military munitions	DMM, MC
Firing point	Various unused military munitions	DMM, MC
Burial pit	Various unused military munitions	DMM, MC

*Ammunition without projectiles that contain explosives (other than tracers), that is .50 caliber or smaller, or for shotguns.

Potential Receptors

The potential receptors at a MR site vary by site and are site specific. For underwater MR sites there are some general types of receptors that may encounter the MEC, depending upon actual site conditions. These include the following:

- Recreational users – Recreational activities that may come in contact with the underwater munitions include beachgoers, swimmers, and souvenir collectors using metal detectors. Recreational boaters may deploy anchors that can come in contact with the subsurface

MEC. Recreational fishing, such as clam digging may also result in a potential complete exposure pathway.

- Commercial Fisherman – The use of scraping or penetrating dredges for the collection of bivalves may result in the collection of MEC. In addition, traps and other bottom gear can come in contact with the MEC in the subsurface.

- Dredging personnel – Maintenance dredging personnel can encounter MEC when operating in areas where MEC has been deposited in the subsurface. This can include areas along piers, transfer points and channels. In addition, borrow areas contaminated with MEC have been used for beach replenishment.

- Construction personnel – Construction and maintenance of structures in the various waterways may also result in exposure to MEC. This can include such things as the construction and maintenance of bridges, piers, pilings, and seawalls.

- Divers – Commercial divers employed to support construction efforts may be exposed to MEC. Subsistence divers (tribal) may also harvest seafood in the tidal zone and subtidal region. Recreational diving can also be a complete exposure pathway.

- Fisheries and Wildlife Management personnel – Personnel assigned to manage wildlife areas may encounter MEC in performance of their management duties.

Physical and Biological Processes Affecting Munitions Mobility in Underwater Environments

The physical and biological processes that may affect MEC fate and transport in underwater environments will be site specific. Some general considerations include;

- Wave Climate- Exposure to waves and the dynamics of the nearshore environment
- Winds - Wind strength and the generation of waves and currents
- Currents – Oceanic, longshore and wind driven
- Tidal range and strength of tidal currents
- Sediment supply and its transport
- Bottom type- bedrock, mud, gravel, sand, and coral
- Riverine variability – Runoff/freshwater discharge, density distributions, and suspended-sediment concentrations.
- Estuarine variability - The drainage-basin size, water-surface size, and water-marsh ratio
- Biological growth – Encrustation and growth nearby munitions

CERCLA Phase Goals and Munitions Mobility Considerations

The mobility of munitions can impact the planning and execution of the CERCLA assessment and cleanup of a MR site. If the munitions are not mobile, then the traditional Remedial Investigation to determine the nature and extent of the MEC would most likely be warranted. Cleanup of the site would then be performed in the Remedial Action phase. If however, the munitions are mobile, the management of the site might require more time critical remediation efforts (e.g. time critical removal action or a non-time critical removal action), since the munitions mobility can invalidate the data collected. This would allow for the detection and removal of the munitions to be performed as closely as possible to minimize the impacts of the item's mobility.
The depth of burial will also influence the decision on what type of detection technology to use to assess the site and perform any removals of the MEC. The mobility of a MEC item could also impact the selection of the remedy (e.g. implementation of institutional controls versus removal) and the long-term management decisions of the site.

Site Manager Questions and Concerns Regarding Munitions Mobility

After considering the site types, the receptors, the physical processes that may influence the mobility and the planning and execution of a CERCLA cleanup of a MR site, a list of potential questions a site manager might have includes:

- What are the environmental conditions that can induce mobility at my site?
- Are there areas where people can be exposed to the munitions?
- Are there extreme weather events such as hurricanes or typhoons that can mobilize the munitions?
- How confident can I be that the munitions are moving or not moving?
- Are there areas where the munitions are collecting over time?
- Can the munitions move from the offshore areas to the beach or surfzone?
- Is there a depth of burial that can be expected based upon my site conditions and does this vary across the site?
- How confident can I be in the depth of burial estimates?
- How much site specific data do I need to estimate whether an item is moving or not?
- For munitions released into a river or an area with longshore currents, can you tell me if the munitions are still there or have they moved downstream or further along the shore?
- At a coral reef MR site, do the munitions move toward the awa channels?
- Can munitions be expected to migrate and be found onshore (i.e. into housing areas) by earthquake generated tidal waves/tsunami?

- At a coral reef MR site where coral growth has embedded portions of DMM piles, is there potential for migration from the tidal wave/tsunami?
- Is there a tidal wave/tsunami size and force range for the breakaway of munitions from the coral reef?
- How does propwash effect the mobility of munitions items?
- What are the strengths and weaknesses in the mobility analysis?
- What is the depth of closure for the different munitions types?
- How can I mitigate the potential explosive hazard and protect human receptors in the interim prior to the Remedial Action phase?

Summary

Military munitions can be found in certain underwater locations resulting from historic disposal activities and as a result of live fire training, testing, and other operations. In order to assess and manage the release of the MEC, a number of questions will need to be answered regarding the potential mobility of the munitions.