FINAL REPORT

Second Workshop on Burial and Mobility Modeling of Munitions in the Underwater Environment (2015)

SERDP Munitions Response

MARCH 2017

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Executive Summary

The Strategic Environmental Research and Development Program (SERDP) hosted the second workshop on "Burial and Mobility Modeling of Munitions in the Underwater Environment" on 8-9 December 2015, at the Kossiakoff Center at the Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland. The purpose of the workshop was to enable SERDP project teams to: 1) collaboratively share research progress with peers; 2) identify data gaps and coordinate data sharing to seamlessly integrate field and laboratory observations with modeling efforts; 3) define a suite of surrogate munitions of interest and outline best practices for fabrication, deployment/recovery, and tracking, including the use of smart munitions; and 4) clearly state the product expected to culminate from all relevant project efforts. The workshop agenda, a list of participants, and summaries of current SERDP Munitions Response projects related UXO burial, migration, and re-emergence are presented in the appendices.

Central to the underwater munitions response (MR) program is the development of a probabilistic expert system to predict burial, migration, and re-emergence of UXO in coastal, estuarine, freshwater, and riverine environments. The laboratory and field experiments are designed to provide data and validated models that are components of the Underwater Munitions Expert System (UnMES). Field experiments described include those in the swash zone, surf zone with breaking waves, and other shallow-water areas where wave and currents interact with the seafloor. Experiments include simultaneous measurements of nearbed forcing, sediment transport, and munitions mobility. The objectives are to develop physics-based, force-balance models, focusing on a first-order approximation with empirically-determined parameters that predict dominant patterns of UXO behavior. The completed and planned field experiments are complimented by ongoing laboratory experiments where wave and current forcing is better controlled. Laboratory experiments often suffer from issues associated with scaling and the inability to recreate complexities associated with natural environmental conditions; however, laboratory observations do provide detailed and repeatable data for well-controlled conditions where field experimental data is nonexistent. Previous laboratory and field experiments on objects similar in size and density to UXO have also been compiled from the literature to provide simple parameterized models to predict UXO initiation of motion and burial. Data compilations from the literature and from current experiments have allowed us to identify data gaps and inconsistencies and provide a guide to future experiments and model development.

The focus of the current version of UnMES is on wave and current dominated environments where sediments are non-cohesive sands. In these environments larger UXO with densities greater than 2500 kg/m^3 tend to bury by scour or are buried by migrating sand dunes. UXO with densities less than 2000 kg/m^3 tend to migrate under strong currents and wave energy associated with storms. Simplified parameterized models are well developed for hydrodynamic-object interactions describing scour burial and onset of motion; further modeling development is needed to quantify bedform interaction and migration distances. In addition, more emphasis on long-term, time-dependent studies and the effects of extreme events are needed. Additional data and modeling are required for softer cohesive sediments where impact burial dominates, active areas of deposition and accretion, rock outcrops, and coral reefs.

Planning for demonstrations of munitions burial and mobility modeling in the underwater environments is in the very early stages of development and requires engagement with stakeholders, site managers, and regulators to align the recent scientific and technology advances with critical underwater remediation requirements. A small representative suite of surrogate munitions was identified and many are now available as CAD drawings or as certified inert munitions. The development of smart munitions, UXO that are enhanced with sensors to collect data on migration and burial, has been accomplished by several investigators. Techniques such as passive tethers, acoustic pingers, and embedded inertial measurement units have been tested. Additional methods for tracking UXO, especially in dynamic environments such as the surf zone are being developed as part of the SERDP program.

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Acronyms

ATC – Aberdeen Testing Center

CFD - Computational Fluid Dynamics (Models)
CAD – Computer Aided Design (drawings)

DNS – Direct Numerical Simulation

ESTCP – Environmental Security Technology Certification Program

GPS – Global Positioning System

IMPACT35 – 3D rigid body impact burial prediction model
IMU – Inertial Measurement Unit
IGW - Infragravity Waves

LED - Light-emitting diodes

MR – Munitions Response

NAVFAC – Naval Facilities Engineering Command
NMSE - Nonlinear Mild-Slope Equation
NOAA – National Oceanic and Atmospheric Administration
NRL – Naval Research Laboratory

PI – Principal Investigator
PIV- Particle Image Velocimetry
PMRF – Pacific Missile Range Facility

RAS – Risk Assessment System
RFID - Radio Frequency Identification

SERDP – Strategic Environmental Research and Development Program
STRIKE35 – Bomb Maneuvering Model for Obstacle Clearance
SWAN – Simulating WAves Nearshore (Model)
SWASH – Simulating WAves till SHore

UnMES – Underwater Munitions Expert System
USACE – United States Army Corps of Engineers
USBL – Ultra-short Baseline
UXO – Unexploded Ordnance

Preface

The Strategic Environmental Research and Development Program (SERDP) hosted the second workshop on "Burial and Mobility Modeling of Munitions in the Underwater Environment" on 8-9 December 2015, in the Kossiakoff Center at the Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland. The purpose of the workshop was to enable SERDP project teams to 1) collaboratively share research progress with peers; 2) identify data gaps and coordinate data sharing to seamlessly integrate field and laboratory observations with modeling efforts; 3) define a suite of surrogate munitions of interest and outline best practices for fabrication, deployment/recovery, and tracking, including the use of smart munitions; and 4) clearly state the product expected to culminate from all relevant project efforts. A list of the 21 attendees representing 12 institutions is presented in Appendix B. Their participation was greatly appreciated.

The strategy for achieving the program review objectives was developed by the coordinating committee led by Dr. Joseph Calantoni (Naval Research Laboratory) and Dr. Sarah Rennie (Applied Physics Laboratory, Johns Hopkins University) with assistance from Dr. Herbert Nelson (SERDP) and Dr. Michael Richardson (Institute for Defense Analyses). The report was written and compiled by the members of the coordinating committee along with comments and revisions provided by all program review participants. Ms. Natalia Koroleva (SERDP Munitions Response Program Support Office) acted as the organizer for the workshop and her notes from the meeting provided the basis for much of the content contained in the report. The workshop was supported by SERDP/ESTCP Director, Dr. Anne Andrews and Munitions Response Program Manager, Dr. Herbert Nelson.

1. Introduction and Objectives of Workshop

The Strategic Environmental Research and Development Program (SERDP) hosted a workshop on "Burial and Mobility Modeling of Munitions in the Underwater Environment" from 8-9 December 2015, at the Kossiakoff Center at the Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland. The purpose of the program review was to enable SERDP project teams to 1) collaboratively share research progress with peers; 2) identify data gaps and coordinate data sharing to seamlessly integrate field and laboratory observations with modeling efforts; 3) define a suite of surrogate munitions of interest and outline best practices for fabrication, deployment/recovery, and tracking, including the use of Smart munitions; and 4) clearly state the product expected to culminate from all relevant project efforts. A list of the 21 attendees representing 12 institutions is presented in Appendix B. Their participation was greatly appreciated.

The workshop consisted of presentations by principal investigators supported by SERDP's Munitions Response (MR) program on the first day (see Appendices C through I), followed by general discussions covering the following technical issues: 1) identifying needs for integration of field and laboratory observations with modeling requirements; 2) addressing gaps in field and laboratory data collections; 3) discussing how to exploit data collection methods to improve discretization of model input parameters; and 4) defining a pathway forward for process-based models in the Underwater Munitions Expert System (UnMES) including gaps in physics or methods to handle extreme events. On the second day of the workshop, group discussion centered on surrogate and smart munitions. Discussion focused on determining the appropriate suite of munitions size, shape, and density and the best methods/practices for developing, fabricating and sharing surrogate munitions. Similarities and differences between munitions used in mobility and burial studies versus the requirements for detection and classification using acoustic, magnetic and electromagnetic sensors were identified. Methods to monitor movement and migration of UXO using smart munitions were compiled. Potential UnMES demonstrations and requirement for upgrades and improvements to UnMES completed the final afternoon discussions.

2. Summary of the Presentations

Dr. Joe Calantoni (NRL) provided a short introduction to the workshop which included participant introductions, a discussion of the workshop schedule, and presentation of workshop objectives (see Section 1). The adoption of common formats to facilitate data distribution along with a data repository to encourage collaboration were suggested. Standardized CAD drawings for munitions fabrication was proposed. The following questions for the UnMES discussions were proposed.

1) Will UnMES provide results that are needed by site managers and regulators?
2) Are all of the relevant sediment-object processes (models) included in UnMES? If not what additional processes should be added?
3) Which core process models require additional study?
4) Does the required environmental input data for UnMES exist, and is it in readily available formats appropriate for use in UnMES?
5) Are the military archives adequate to provide the initial data on types, descriptions, and distribution of UXO as required for the process models in UnMES?
6) Are the discretization intervals for the various nodes in UnMES optimal?

The PIs of ongoing projects were then provided 30 minutes each to summarize research accomplishments and provide plans for continued research. Each PI has provided a summary of those presentations that can be found in Appendices C through I. The presentations will be briefly summarized in the following paragraphs with an emphasis on resultant discussions.

Dr. Jack Puleo (MR-2503) described UXO mobility, migration, and burial experiments planned for the Swash Zone. Large-scale laboratory experiments are proposed jointly at the Aberdeen Testing Center Littoral Warfare Environment in May 2016 and field experiments are proposed for 2017 in a coarse grain steep beach face (Delaware) and medium grained sloping beach face with more intense wave action (New Jersey). UXO surrogates will be instrumented to quantify munitions movement and burial. Simultaneous measurements of near-bed forcing, sediment transport, and munitions mobility will be made to better understand UXO mobility and burial in the Swash Zone. Munitions mobility underwater will be modeled using the governing force balance equations. Dr. Puleo hypothesizes that instantaneous surge force is the main contributor to munitions mobility on the beach face. These experiments compliment field tests conducted by Dr. Calantoni (MR-2320) in a shoaling environment and Dr. Peter Traykoviski (MR-2319) in the breaker zone. Science questions include the following:

1) Will buried munitions on the beach face be exhumed under wave action?
2) Will munitions delivered to the swash zone transport onshore, offshore, alongshore or bury?
3) Will munitions just outside the swash zone transport offshore, enter the swash zone or bury?
4) How important is the surge force for governing munitions mobility on the beach face?
5) Can terms in the force balance be quantified/parameterized providing models with a better indication of munitions mobility?

Dr. Peter Traykovski (MR-2319) described UXO burial and mobility experiments conducted in an energetic tidal shoals environment (Wasque Shoals, 2013-14) and in the surf zone (Long Point near Martha's Vineyard Coastal Observatory, 2014-15). Migration was measured using GPS floats, GPS surveys, and in situ USBL tracking and burial was measured with rotary scanning sonars and during diver recovery operations.

Environmental forcing (wave and currents) was measured using a variety of standard hydrographic instruments mounted on bottom moored platforms. At the Wasque Shoals less dense UXO migrated up to 20 m into the trough of migrating sand waves whereas denser UXO buried in place. All UXO were eventually buried by the migrating dunes, which had amplitudes of 3m and wavelengths up to 100 m. At the Martha's Vineyard surf zone site lower density UXO migrated onshore up to 170 m and came to rest in water depths of 1.0 to 1.5 m. UXO with higher densities (> 2500 kg/m^3) did not migrate and buried in place to sediment depths of 0.5 m. Based on the data, it was concluded that migration of higher density, larger objects only occurs during extreme events. Additional modeling is underway to explain these observations.

Dr. Joe Calantoni (MR-2320) presented the results from a pair of UXO burial and migration experiments in the Gulf of Mexico off Panama City (7.5 m and 20 m water depth) during the passage of an atmospheric front on 5-6 May 2103 and a second set of experiments at the Army Corps of Engineers Field Research Facility at Duck, NC (6-8 m water depths) during a series of intense storms from 26 January to 10 March 2015. The objectives were to validate existing burial and migration models and to develop a new two parameter conceptual model accounting for granular sorting processes. The emphasis of his presentation was on the Duck experiments but all data sets were used for model validation and development. Simultaneous measurements of wave, currents, bathymetry, sediment transport, and the fate of munitions were made at both sites. Sediments were similar at both sites but the Duck site was the higher energy site. UXO ranged from 20 cm to 155 cm diameter munitions. UXO buried or migrated depending on ratio of munitions and sediment density and the ratio of the activity parameter and munitions diameter.

Dr. Marcelo Garcia and Dr. Blake Landry (MR-2410) described a series of laboratory experiments on UXO burial and migration conducted in large flumes at the University of Illinois, Urbana-Champaign. The objectives are to provide detailed laboratory observations and measurements to quantify, parameterize, and model the motion, transport, and fate of munitions under a full range of relevant hydrodynamic conditions (e.g., waves, currents, and combined flows) and substrate characteristics (e.g., sand, gravel, shingles). Recent experiments conducted relate to initiation of motion and transport of UXO on a rigid bed under different flow conditions, angle of emplacement or attack, bed slope, and bed roughness. Experiments on mobile beds are planned for the coming year. Experimental results for initiation of motion are in general agreement with a summary of the literature by Friedrichs (MR-2647); additional variability due to flow angle of attack was quantified. Techniques have been developed to characterize turbulent flow structure around munitions using Particle Image Velocimetry (PIV), and to track UXO motion using optical tracking techniques. The goal of these measurements is to resolve the flow structure and estimate drag forces on the munitions and ultimately help develop relationships to predict initiation of motion and transport of munitions.

Dr. Carl Friedrichs (MR-2224 and MR-2647) provided a literature summary of initiation of motion and scour burial for UXO-like objects. Data from laboratory and field studies supported by SERDP is included. The objective is to provide simple parameterized models for predicting mobility, burial, and re-exposure of underwater munitions that can be used by UnMES (MR-2227). Data compilations showed theoretically and empirically that the near-bed water velocity at UXO threshold of motion is predicted by the object's critical mobility number (proportional to the fluid drag force divided by the object's weight). More recent data has shown the initiation of motion for spheres on a fixed bed is significantly less than for rough objects on mobile beds. The most important single parameter for predicting scour-induced burial is the sediment mobility number (or, equivalently, the sediment Shields parameter). Additional parameterization with the Keulegan-Carpenter number is important under oscillatory wave-driven flow. Future data compilations will concentrate on burial and migration associated with bedform movement, beach slope evolution, and behavior in high-energy regimes such as sheet flow and liquefaction.

Dr. Sarah Rennie (MR-2227) presented an update on the development of a computer-based, probabilistic expert system for predicting UXO mobility and burial in the underwater environment: the Underwater Munitions Expert System (UnMES). This system is based on a Bayesian network structure and incorporates data compilations and modeling described in the previous presentations, with environmental data, and military archives to provide probabilistic predictions for the fate of underwater UXO. The Bayesian network is implemented in Netica™ where variables are represented by probably distributions, thereby incorporating the uncertainty of inputs and models, and providing these probabilistic predictions that represent this combined uncertainty. The structure of UnMES was presented and several examples provided, including UXO burial and mobility in a wave-driven coastal environment.

This presentation was followed by a discussion on how to incorporate data, models, and environmental data into UnMES. The current version of UnMES incorporates physics-based models for scour burial and initiation of motion in wave-dominated, non-cohesive coastal sandy environments. Existing nodes for bedform processes and UXO migration distance are based on statistical information. UXO burial and migration processes such as impact burial, re-exposure by sand-wave migration, shallow-water (swash and wave-breaking zones) forcing, and the effects of extreme events are not as well-known and will be the focus of future model development in follow-on project MR-2645. Sites where the initial UXO distributions are known and adequate environmental data are available are needed for UnMES demonstrations. The ability of software extension GeoNetica™ is being investigated to handle the spatial variations in these inputs.

3. Discussions Related to UnMES (Product Development)

The afternoon began with discussions on future development of UnMES. The following questions were asked, issues discussed, and statements made.

1. How to deal with UXO migration distance prediction if limited to discrete cells? What distance of UXO migration is of concern to remediation site managers?
2. How will time-dependence be integrated into UXO burial and migration? The current UnMES primarily a spatial model.
3. The types of UXO typically found at underwater sites needs further investigation. Field and laboratory experiments should be conducted realistic munition types, sizes and especially bulk densities. Sites with known distributions of UXO are needed for UnMES demonstrations.
4. Improved process models are needed for re-exposure (erosion/accretion), migration distances, and initial burial for high-velocity projectiles, mobile beds during high-energy events, and infrequent events such as hurricanes.
5. The potential to create statistics to define UnMES nodes using a variety of simulations including CFD models was discussed.
6. Methods to collect and model environmental data were discussed.
7. The need to develop smart (instrumented munitions) was discussed. They are being developed by several investigators.
8. What are the effects of anthropomorphic processes such as bottom fishing?

This ended Day 1 of the Second Workshop on Burial and Mobility Modeling of Munitions in the Underwater Environment

4. Discussions Related to UnMES Continued

The workshop continued with a discussion on the optimal discretization intervals for nodes in UnMES. Sarah Rennie divided the question into resolution and fidelity requirements of the end user and the resolution/fidelity expected for realistic situations. The subsequent discussion suggests the importance of getting the end-users involved early in the development process. More effort is needed to define who the end user is and to develop a product to meet their needs. Some form of this question comes up at every SERDP MR underwater workshop. What are the needs of the end users who are responsible for remediation of underwater UXO?

Dr. Alex Sheremet discussed TRIADS, a research model that calculates non-linear shoaling of directional waves (see Appendix I). Although deep-water wave propagation (WAVEWATCH 3 and SWAN) is well known, prediction of intermediate-deep shoaling wave behavior is challenging. Predicting this shoaling wave behavior is important for predicting sediment transport and thus UXO migration and burial in shallow water where waves interact with the seafloor. Alex suggests that TRIADS can be used to propagate deep-water wave data (wave spectrum from NOAA data buoys or deep water models) to generate a database of nearshore wave climatology. The database would be built on deep-water wave spectrum and bathymetric profiles for the experimental or remediation site in question. The TRIADS model potentially represents a high-fidelity alternative to the current, state-of-the-art in shallow water wave modeling (e.g., SWASH).

The next topic was data sharing which included the results from laboratory and field experiments; data on munitions type, shape; and density; and environmental sediment, seafloor, and hydrodynamic data. Although a host platform was suggested for data sharing, it was decided to include detailed data presentations in interim and final SERDP project reports. Discussions for best practices and lessons learned on data sharing will be revisited during the next workshop.

5. Surrogate Munitions

One of the workshop objectives was to define a suite of surrogate munitions of interest for common use among all MR researchers. Another objective was to outline best practices for fabrication, deployment/recovery, and tracking, including the use of SMART munitions. These topics are covered in the next two sections.

Dr. Calantoni (MR-2320) has created (CAD drawings) and fabricated the following surrogate munitions based on combined specs from Army Technical Manuals (e.g., TM 43-0001-27 and TM 43-0001-28):

- 20 mm and 25 mm cartridges (purchased replicas)**
- 40 mm projectile L/70 practice round
- 57 mm (M22) AP drill projectiles
- 60 mm mortar (M-49A4) with inert fuse (M-734)
- 81 mm mortar
- 105 mm projectile
- 4.2 inch mortar
- 155 mm projectile

After much discussion the group defined 8 general categories of UXO that should be included in burial and migration studies.

- Group 1 – 20 mm cartridges
- Group 2 – 5 inch naval round [5 inch X 38 inch, cylindrical]
- Group 3 – 81 mm mortar
- Group 4 – 155 mm projectile
- Group 5 – rockets (2.25 inch, 2.75 inch, 3.5 inch)
- Group 6 – cluster bombs (lacrosse ball)
- Group 7 – shot put
- Group 8 – 100 lb. bomb [no HE represented here]

Jack Puleo reported ATC personnel opined that smaller munitions were common and their behavior had been less studied. It was decided that detailed measurements should be made of these representative munition types to allow CAD drawing to be made. 3D printing is being explored as a more cost effective manufacturing approach.

6. Smart Munitions

Smart munitions include inert munitions that have been modified with onboard sensors to facilitate data gathering. The emphasis of this discussion was on monitoring munitions mobility associated with both burial and large-scale migration. We did not, but should have included discussion of the collection of environmental data with smart munitions associated with burial and migration. SERDP investigators have employed a variety of methods to measure munitions burial and migration. These methods, methods previously used in the mine burial program, commercial systems available to monitor munitions movement, and R&D methods are summarized in the following Table.

Table 6-1. Methods used by SERDP investigators to measure munitions burial and migration.

Sensor Type	Advantages	Disadvantages
Pressure Sensors	cross shore location, time sync to wave phase, scalar, easy to use ($500 will last months to get depths, $1500 2 Hz for 4 weeks)	*requires recovering the object*
Inertial Measurement Unit (IMU)	orientation, rotation, months deployment, threshold for motion ($500 including logger),	*not location, can't integrate when translation occurs*
Ultra-short baseline (USBL) tracking	tethered to object to stay in water column, ~$3000 per	*expensive, bubbles interfere (intermittent breaking ok)*
Tethered Global Positioning System (GPS) (buoy)	Real-time info cell phone tracker ~$500, reduce size/weight for shorter durations	*large and heavy – drag for long endurance*
Radio Frequency Identification (RFID) (WiFi)	centimeter position accuracy in subaerial swash ~$15K (mostly software and sensors), tags are cheap,	*can't be used under salt water*
Flashers with Light-emitting diodes (LED)	Cheap, long-lasting, green preferred (paired with optical filters)	Limited by depth, turbidity, and ambient light, attract fish underwater
Acoustic Pingers	Cheap (~$300 each), simple, well-proven, long duration, good potential for tracking when paired with surveying	No logging or ranging, no receiving capability (one-way), bubbles and multipath degrade, coarse directional resolution
External Imagers (Paint) or , "Structured lighting for underwater"	Georeferenced for land based – can be paired with flashers (or floating targets) ~$2.5K	Underwater is degraded by turbidity; georeferencing is difficult
Passive Buoys	Cheap, well-proven	Drag can be an issue
Acoustics/optics on targets	Acoustics expensive, optics cheap, provides time-dependence of burial	Requires data- logger, only useful for largest targets
Electrical Resistivity Tactile Pads Photo Electric Erosion Pins Particle Image Velocimetry (PIV)	R&D needed	

7. Discussion and Conclusions

Demonstration for the projects supporting burial and mobility modeling is still over the horizon. A number of sites were suggested (Duck NC, mouth of the Chesapeake Bay, Great Lakes, Indian Head, Dahlgren, Lake Erie, and a riverine site), but it was obvious that it was too early to make such a decision. Different environmental processes dominate burial, migration, and re-exposure at these sites. SERDP should work with Navy and Army working groups, site managers, and state regulators to begin the demonstration site selection process. Sites and environmental processes chosen should be based on munitions remediation requirements. SERDP still does not have the required list of remediation sites, UXO present, and dominate environmental conditions. All of this information needs to be used in the site selection process.

Although a substantial amount of data is available from the literature and from field and laboratory experiments, especially for wave and current dominated non-cohesive environments, significant data and modeling gaps exist. Both data and process models are needed for re-exposure (erosion/accretion), migration distances, and initial burial for high-velocity projectiles, liquefaction and fluidization of mobile beds during high-energy events, beach slope evolution, and infrequent extreme events such as hurricanes. Recently approved projects should fill some of these gaps. Time-dependence needs to be integrated into UXO burial and migration predictions, especially over decadal scales.

Optimal discretization intervals for the nodes in UnMES should match the resolution and fidelity that is realistic and satisfies requirements of end users. Tradeoffs with uncertainty, environmental and munitions data availability, and computational complexity need to be considered. Discretization intervals may vary depending on processes being simulated and data availability.

Development of the list of relevant munitions present in the underwater environment needs to be continued. Based on this list, surrogate munitions with appropriate size, shape, and bulk density characteristics may be designed and fabricated. Smart (instrumented) munitions that can be used to measure short-scale movement and long-scale migrations need to be further developed.

Models, databases, and data collection methods that provide environmental inputs such as sediment type and properties, waves and currents, sediment transport, retreating and accreting beaches, and bedform behavior need to be investigated. Characterization of the time-dependence of these data is very important.

Appendix A. Workshop Agenda

INFORMAL WORKSHOP ON BURIAL AND MOBILITY MODELING OF MUNITIONS IN THE UNDERWATER ENVIRONMENT

PRELIMINARY AGENDA

Kossiakoff Center at the Johns Hopkins University Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel, MD 20723-6099

Tuesday 8 December 2015		
0830	Meet and Greet	
0845	Introduction to Workshop and Objectives	Anne Andrews, SERDP
0855	Introduction of Participants	Joe Calantoni, NRL
0900	MR-2503: Quantification of Hydrodynamic Forcing and Burial, Exposure and Mobility of Munitions on the Beach Face	Jack Puleo, University of Delaware
0930	MR-2319: Continuous Monitoring of Mobility, Burial and Re-exposure of Underwater Munitions in Energetic Near-Shore Environments	Peter Traykovski, Woods Hole Oceanographic Institution
1000	MR-2320: Long Time Series Measurements of Munitions Mobility in the Wave-Current Boundary Layer	Joe Calantoni, Naval Research Laboratory
1030	Break	
1045	MR-2410: Large-Scale Laboratory Experiments of Incipient Motion, Transport, and Fate of Underwater Munitions under Waves, Currents, and Combined-Flows	Marcelo Garcia, University of Illinois at Urbana-Champaign
1115	MR-2647: Parameterized Process Models for Underwater Munitions Expert System	Carl Friedrichs, Virginia Institute of Marine Science
1145	MR-2227: Underwater Munitions Expert System to Predict Mobility and Burial	Sarah Rennie, Johns Hopkins University
1215	Lunch – Einstein Bros. (Sandwiches/drinks $10 per person)	
1245	General Group Discussion (Required reading recent MR-2227 report): - Integration of exiting field / laboratory data w/ modeling efforts - Identify / address gaps in field / laboratory data collections - Modify / exploit data collection methods to improve discretization of parameters - Process-based models in UnMES – Gaps in physics? Extreme events?	
1400	Break	
1415	General Group Discussion (continued)	
1530	Adjourn for the day	
1830	Group dinner – walking distance from Homewood Suites	

Wednesday 9 December 2015	
0800	Morning Networking Session
0815	Reflections and unfinished topics from previous day
0830	General Group Discussion (surrogate munitions): - What is the correct suite of munitions? Relevant range of sizes, shapes, densities? - Best practices for developing, fabricating, and sharing surrogate munitions - Where is the intersection of surrogate munitions designed to study mobility with those used by sensor developers?
1000	Break
1015	General Group Discussion (continued): - Discuss / contrast technology for tracking munitions in the field and laboratory - Discuss best practices for field deployment/recovery - SMART munitions
1200	Lunch – Einstein Bros. (Sandwiches/drinks $10 per person)
1230	General Group Discussion (towards the product): - Who are the "end-users"? What is the expected final product of the group? - Identify existing and missing connections among the research
1430	Break
1445	Final Comments and Direction for Workshop Report: - What has changed since the last workshop? - Timeline for finalizing / submitting report
1530	Adjourn

Appendix B. List of Attendees

- Dr. Anne Andrews (SERDP/ESTCP)
- Dr. Andy Anders (US Army Environmental Command)
- Dr. Alan Brandt (Johns Hopkins University Applied Physics Laboratory)
- Dr. Joseph Calantoni (Naval Research Laboratory)
- Dr. Shelley Cazares (Institute for Defense Analyses)
- Dr. Carter DuVal (University of Delaware)
- Dr. Carl Friedrichs (Virginia Institute of Marine Science)
- Dr. Diane Foster (University of New Hampshire)
- Dr. Marcelo Garcia (University of Illinois at Urbana-Champaign)
- Mr. Steve Hurff (NAVFAC)
- Ms. Natalia Koroleva (SERDP/ESTCP Support Office, HydroGeoLogic, Inc.)
- Dr. Blake Landry (University of Illinois)
- Dr. Herbert Nelson (SERDP/ESTCP)
- Dr. Jack Puleo (University of Delaware)
- Dr. Chris Ratto (Johns Hopkins University Applied Physics Laboratory)
- Dr. Sarah Rennie (Johns Hopkins University Applied Physics Laboratory)
- Dr. Michael Richardson (Institute for Defense Analyses)
- Dr. Alexandru Sheremet (University of Florida)
- Mr. Andrew Schwartz (US Army Corps of Engineers)
- Dr. Peter Traykovski (Woods Hole Oceanographic Institute)

Appendix C. MR-2503 Quantification of Hydrodynamic Forcing and Burial Exposure and Mobility of Munitions on the Beach Face. Dr. Jack Puleo (University of Delaware).

The project objectives are to provide quantification of hydrodynamic and sediment transport processes and concurrent time series of munitions mobility (transport, burial, exhumation) occurring in the swash zone. It is hypothesized that the initial impact force from swash flow inundation is a main contributor to munitions mobility. This process is unique to the beach face and does not occur in continually submerged environments. A critical question to be investigated for munitions found on the beach face is: Are munitions transported landward from the inner surf zone or are they exhumed in place as a result of beach erosion? Small- and large-scale laboratory studies are being conducted to determine the forcing and munitions mobility characteristics at high spatial and temporal resolution using a variety of in situ sensors and remote sensing platforms. The large-scale laboratory studies will be conducted jointly with Aberdeen Testing Center (ATC) personnel. A suite of "smart" surrogate munitions ranging from cluster bombs (BLU-26) to 155 mm high explosive projectiles are being developed in coordination with other SERDP-funded investigators. Surrogate orientation and transport will be monitored using inertial motion units (IMU), Wi-fi tracking systems and submerged and aerial imagery. Percent burial and impact forces will be monitored on the larger surrogates using a ring of photocells and accelerometers and load cells, respectively. In situ processes to be collected/estimated, and deemed important for munitions mobility, include: fluid velocity, bed shear stress, turbulence, water depth, momentum flux, sheet flow and suspended sediment concentrations. The Year 1 small-scale laboratory studies have commenced and the large-scale laboratory pilot study is scheduled for May, 2016.

Appendix D. MR-2319 Continuous Monitoring of Mobility, Burial, and Re-exposure of Underwater Munitions in Energetic Near-Shore Environments. Dr. Peter Traykoviski (Woods Hole Oceanographic Institute)

Field measurements of mobility, burial, and re-exposure of munitions in both a tidal ebb shoals and surf-zone environments with high potential for mobility have been conducted. The surrogate munitions type, size, and density were varied to enhance potential for migration processes. The researchers developed an autonomous four-transducer ultra-short baseline (USBL) transceiver system to continuously track objects during energetic conditions. The system acoustically measured range and bearing to surrogate munitions equipped with acoustic transponders. Hydrodynamic forcing parameters were measured using a combination of conventional acoustic Doppler velocimeters and more advanced pulse coherent profilers. In year 1, the measurements were located on Wasque Shoals, adjacent to the Muskaget Channel between Martha's Vineyard and Nantucket, MA. This location has strong tidal flows (1.5 m/s) and wave (1 to 3 m height) forcing. Bedforms consist of large scale sandwaves with wavelengths of approximately 100 m and heights of 3 m in 6 m water depth. Smaller scale tidally reversing mega-ripples (1 to 5 m wavelength, 0.1 to 0.5 m height) were superimposed on the large scale sandwaves. The large scale sandwaves migrate at rates of one wavelength per 4 months, and a crest migrated past the study site during the observational period burying the instrumented frame and the densest (3 g/cm^3) UXO surrogates. The burial process was imaged with a rotary sidescan sonar indicating the UXO transient (hours to days) burial under the migrating megaripples and long-term (months to years) burial under the large sandwave. Less dense (ρ <= 2500 kg/m^3) UXO surrogates migrated distances up to 20 m in front of the advancing sandwave and came to rest in the trough of the large scale sandwaves (Figure D-1).

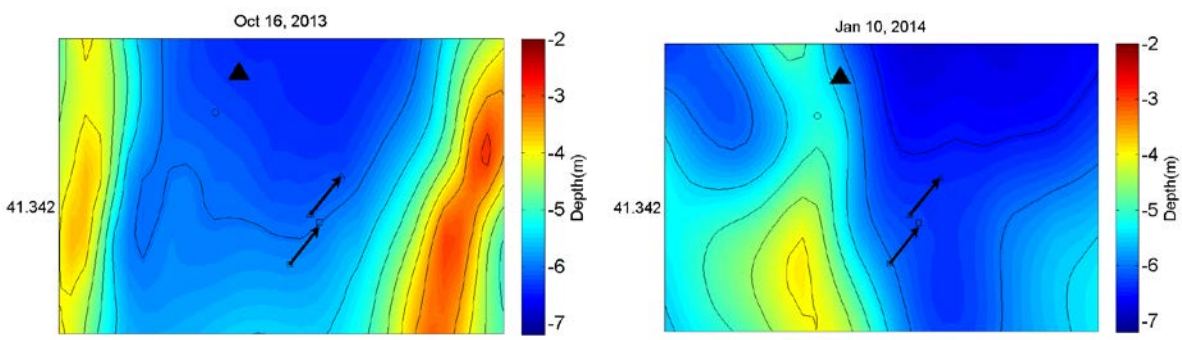


Figure D-1. Migration of surrogate UXO in front of a migrating large scale sandwave.

On Oct. 16, 2013 (left panel) the UXO were deployed in the trough of 100 m wavelength, 3 m height sandwaves. By Jan. 10, 2014 (right panel) the sandwave had migrated over the instrument frame (black triangle), burying the frame and a nearby high density UXO. Lower density UXO migrated downslope into the trough of the advancing sandwave.

The year 2 (fall of 2014) measurements were performed at a surf-zone location on the south shore of Martha's Vineyard with 1 to 4 m waves and weak tidal currents. Bedforms at this site are typically wave orbital scale ripples with wavelengths of up to 1.5 m and heights up to 0.2 m. The bedforms migrate onshore in response to waves with high velocity skewness. The UXO are tracked by the acoustic USBL system and very small surface floats. GPS Surveys of the surface float locations and USBL tracking indicate larger migration rates at the surf-zone site relative to the tidally forced site (Figure D-2).

Lower density UXO (ρ <= 2000 kg/m^3) deployed at the offshore locations migrated 170 m onshore and came to rest 40 to 60 m from the shore in depths of 1 to 1.5 m (Figure D-3a&b). Our current hypothesis for the final resting location of the objects is the wave energy has dissipated sufficiently in shallow water to become lower than the threshold for motion of the UXO. This will be tested using wave transformation models, as measurements of the wave velocities in these shallow locations were not conducted. UXO with densities greater than 3.0 g/cm^3 did not migrate, and were buried to depths of approximately 0.5 m. While, the primary factor controlling mobility appears to be object density, the role of other parameters such as wave forcing as described by the object Shield's parameter are under investigation. The relative timing of burial vs mobilization is also under investigation as the conditions that are above the threshold for migration are also sufficient to cause scour burial.

In summary the two data sets from the tidal shoals environment and the surf zone with objects spanning a wide parameters space to ensure that some object migrate will provide a useful data set to test models for UXO mobility and burial. Data from these deployments is available by contacting P. Traykosvki at (ptraykovski@whoi.edu).

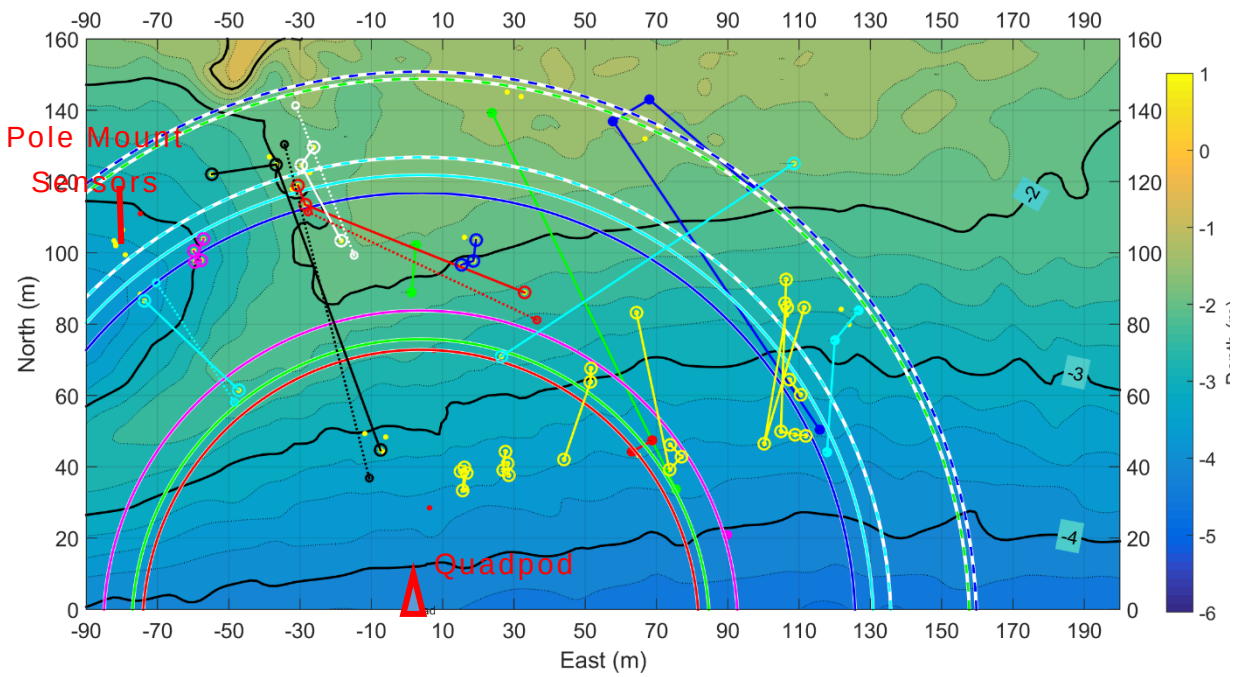
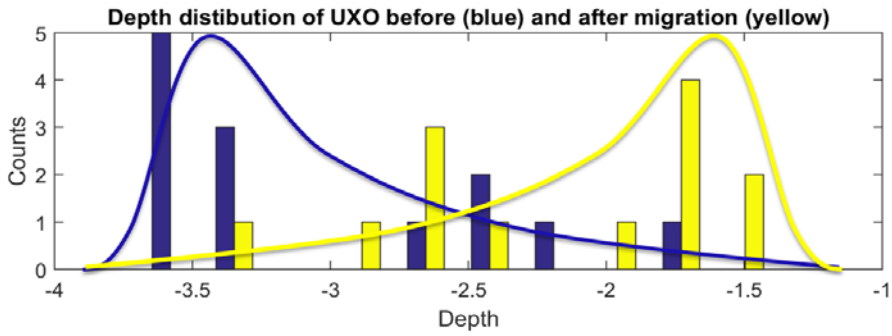
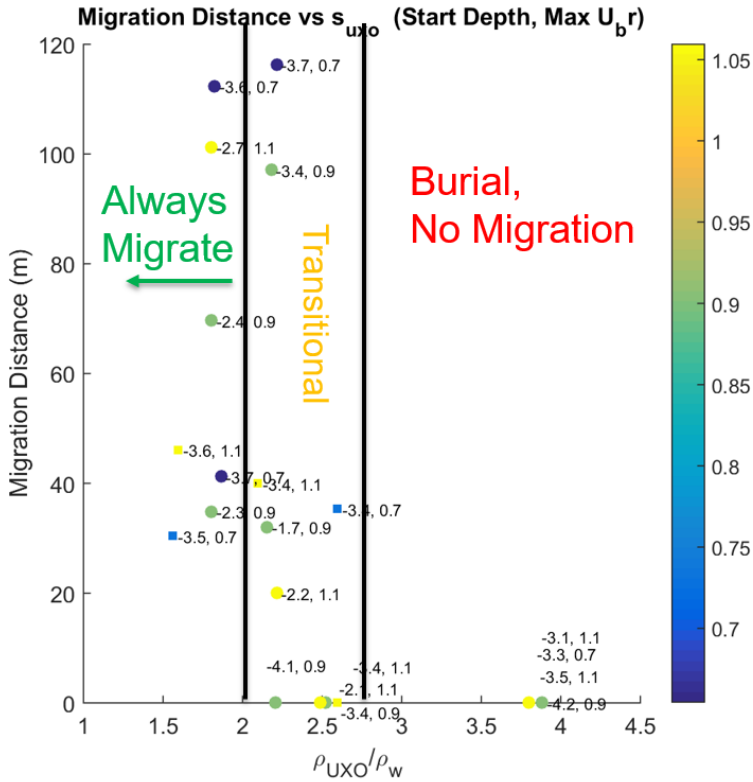


Figure D-2. Migration of surrogate UXO in the surf-zone off of Long Point, Martha's Vineyard. Lines are migrations trajectories both GPS Buoy (solid) fixes and USBL tracking (dashed).

Range Rings are from a USBL array with a broken directional sensor. Yellow trajectories are from smaller diameter objects with only buoy tracking



a)



b)

Figure D-3. Depth Dependence of UXO migration in the surf-zone.

No objects migrated onshore of the 1.5 m contour. b) Object relative density vs. Migration distance indicates relative density appears to be the predominant controlling factor of mobility or burial.

Appendix E. MR-2320: Long Time Series Measurements of Munitions Mobility in the Wave-Current Boundary Layer – PI: Dr. Joseph Calantoni, Naval Research Laboratory

The project objective is to provide detailed time series measurements of the in situ boundary layer processes responsible for munitions mobility including transport, burial, and re-exposure. A pair of field experiments have been performed to characterize the environment in which munitions are found while simultaneously recording the location of munitions relative to the seafloor at high spatial and temporal frequency. The relevant boundary layer processes were observed including wave height and direction, current profiles, and sediment erosion and deposition while simultaneously monitoring the mobility and burial of surrogate munitions (ranging from 20 mm to 155 mm in diameter). During the first field experiment at Panama City Beach, FL, munitions mobility and burial for the largest munitions deployed were observed in 7.5 m water depth during the passage of an atmospheric front from 5 – 6 May 2013. During the same storm event, similar munitions mobility and sediment transport were not observed in 20 m water depth. The more surprising observation was the subsequent and rapid burial of all munitions during a 24-hour period following the observed mobility in 7.5 m water depth. During the second field experiment at the U.S. Army Corp of Engineers, Field Research Facility, Duck, NC, extreme munitions burial for all munitions deployed was observed in 6 m and 8 m water depth during a series of intense winter storms from 26 January – 10 March 2015. Munitions with four different sizes and four different densities were observed to bury themselves from 15 cm to 60 cm deep while the seafloor bathymetry remained nominally unchanged as measured before and after the experiment. Preliminary data analysis suggested a strong relationship between the non-dimensional bulk density of munitions, ρ_m/ρ_s (where ρ_m is the bulk density of the munitions and ρ_s is the density of the sediment bed), and the non-dimensional burial depth (by munitions diameter), $\delta s/Lm$ (here Lm represents a munitions length scale commonly chosen as the diameter, D), consistent with granular sorting physics.

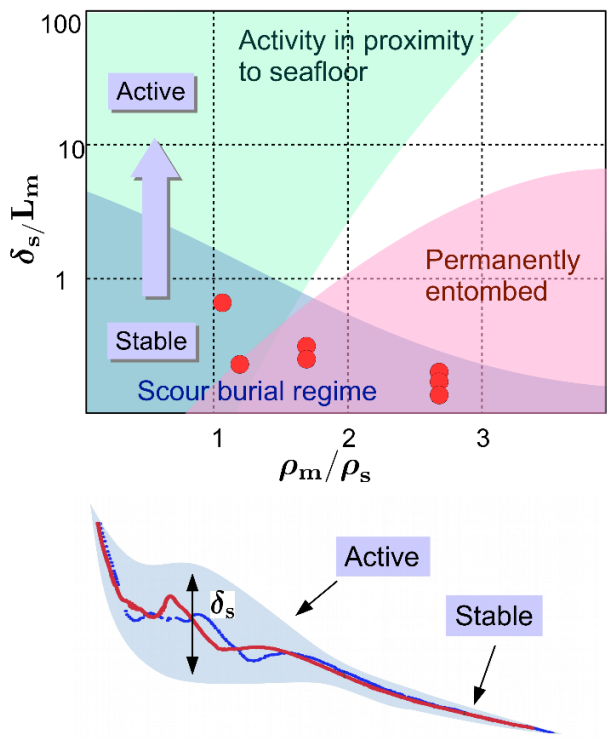


Figure E-1. How the relationship between munition bulk density and burial depth affects mobility.

Appendix F. MR 2410: Large-Scale Laboratory Experiments of Munitions Incipient Motion, Transport, and Fate of Underwater Munitions under Waves, Currents, and Combined-Flows, Marcelo H. Garcia (PI) and Blake J. Landry (co-PI).

To date (12/15) we have conducted upwards of 200 laboratory experiments to better understand the initiation of motion and transport in unidirectional flow of various surrogate munitions over two hard substrates having different roughness (smooth PVC and pitted steel). Particle image velocimetry measurements were conducted in both unidirectional and oscillatory flows. These measurements were performed with flow velocities near the threshold velocities determined from the initiation of motion experiments. The goal of these measurements was to resolve the flow structure and estimate drag forces on the munitions and ultimately help develop relationships to predict initiation and transport of munitions. To better track the munitions after initiation and resolve the six-degrees of freedom, optical tracking techniques were developed, deployed, and honed for use in tracking munitions.

Under unidirectional flows over a hard substrate, the mean flow velocities required to initiate motion shows a strong dependence on the angle of attack (θ). For most munitions tested at a non-zero attack angle, this relationship is most pronounced between 10° and 40° (see Figure F-1). The type of motion exhibited by cartridges and warheads was distinct. Warheads rolled in a linear path on their long side with constant radius. Cartridges rolled at two points of contact. The radius of the cartridge at the point of contact nearest the munition tip was smaller than the point of contact toward the middle of the cartridge. This caused the munition to rotate its orientation as it rolled. That is, the munition would roll and rotate, eventually coming to a stop at an orientation that was different than its original angle with respect to flow direction. The warhead munitions retained the same, or almost the same, orientation with respect to flow direction. Comparing angle of attack trials on the steel bed for a mild slope (S=0.4°) to a horizontal bed, showed no notable difference (refer to Figure F-2). We expect that the local roughness of the steel bed around the munition is enough that the munitions are held in place by individual bumps and divots in the steel. When comparing horizontal steel bed angle of attack results to those over the horizontal PVC bed, similar trends were exhibited between angle and motion-inducing flow velocity, however due to the increased roughness of the steel, trials on steel required greater flow velocities to initiate motion (Figure F-3). Due to the hydrodynamic shape of the munitions when positioned at a 0° angle of attack, the onset of full motion was unclear, since the munitions frequently vibrated or rocked, inching back slowly with each tiny oscillation. For all of the munitions, the threshold velocities for the 0° angle of attack are roughly double the threshold velocities for the 10° angle of attack case. The current experimental data (previously plotted in Figures F-1, 2, and 3) were plotted to compare against the prior data compiled by Friedrichs (2013), refer to Figure F-4. It can be seen that current data regarding surrogate munitions are within the range of scatter of the prior data for spheres, cylinders, and natural sediment. Also, the current data provide a plausible reason for the spread in the data for each diameter; the initiation of motion velocity threshold is highly dependent on the angle of attack of the munition.

With threshold velocity insights from the initiation of motion experiments, the current set of particle image velocimetry experiments (PIV) explored the flow structure around the munitions for a subset of the threshold conditions (i.e., 20 mm shell at 0° and 90°angles of attack and 81 mm mortar without fin at 90°angle of attack). For the present PIV experiments with the munition, the velocity scales in the free stream and the wake of the munition are one order of magnitude apart (Figure F-5). To resolve the turbulent dynamics in the wake and the rest of the flow, a large effort was put to find the optimum PIV straddling time. Regarding observed flow dynamics in the Small Oscillatory Tunnel during PIV experiments, flow separation (vorticity generation) always originated at the base of the munition, i.e., the plane where the primer is located (Figure F-5). This separation was irrespective of the direction flow with respect to the munition orientation.

In addition, for an oscillatory flow case, phase averaged PIV measurements were conducted with twenty image pairs acquired per piston cycle. In Figure F-6, it can be observed that the free stream flow is a sine wave. The flow velocity field near the munition is well resolved. The region just above the munition has the fastest streamwise velocity that increases and decreases with the speed of the free stream flow. On the downstream side of the munition, the flow is reversed. The region with a reversed velocity grows as the free stream velocity decreases. In the future, we plan to better identify the regions by calculating the vorticity at various phases in the oscillation. In addition to the PIV measurements with the munitions, we conducted further experiments based on our APS presentation (Wu et al., 2015) to examine the pivoting model in sediment transport (e.g., measurements around cylinders and spheres at incipient motion). Current PIV measurements show the presence of noticeable turbulence fluctuations (Figure F-7), at the onset of motion. With additional PIV measurements coupled with inertial measurement unit (IMU) measurements, we will be able to compare with the pivoting model proposed by Komar and Li (1986), especially on how impactful the turbulence parameter (Γ) is on initiation of motion of the munitions.

References:

Friedrichs, C., (2013) "Simple Parameterized Models for Predicting Mobility, Burial and Re-Exposure of Underwater Munitions", MR-2224.

Komar, P. D., and Li, Z. (1986). Pivoting analyses of the selective entrainment of sediments by shape and size with application to gravel threshold. Sedimentology, 33 (3), 425-436.

Wu, H., Zamalloa, C. C. Z., Blanco, J. E. S. J., Landry, B. J., Garcia, M. H. (2015). Two-dimensional PIV measurements for studying the effect of bed permeability on incipient motion of synthetic sediment particles". American Physical Society: 68th Annual Meeting of the APS Division of Fluid Dynamics. November 2015. Boston, MA

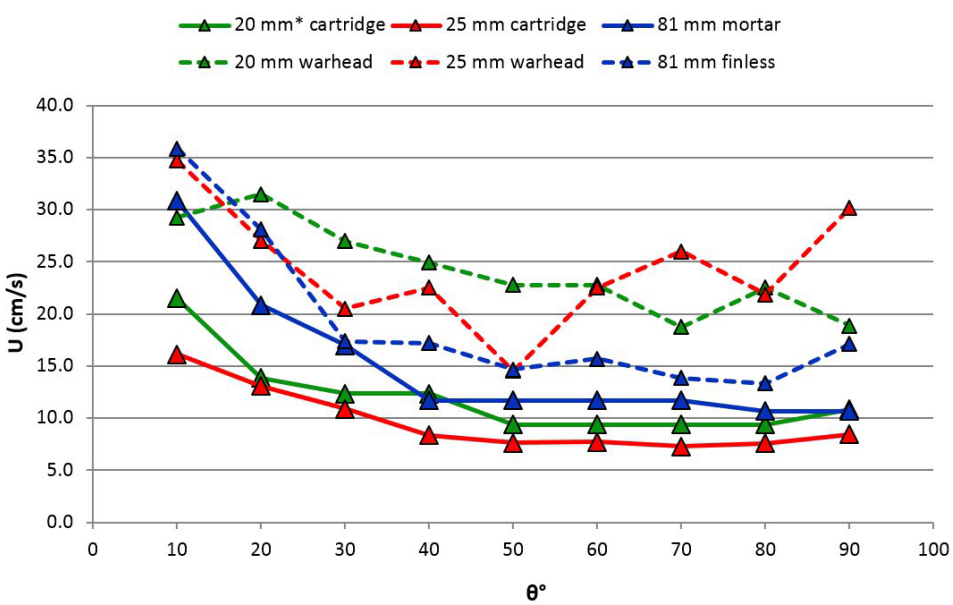


Figure F-1. Initiation of motion for munitions and warheads on <u>a horizontal PVC bottom</u>.

*Note the * denotes that the NRL surrogate used (Figure 13 from MR-2410 interim report on 2015-11-30)*

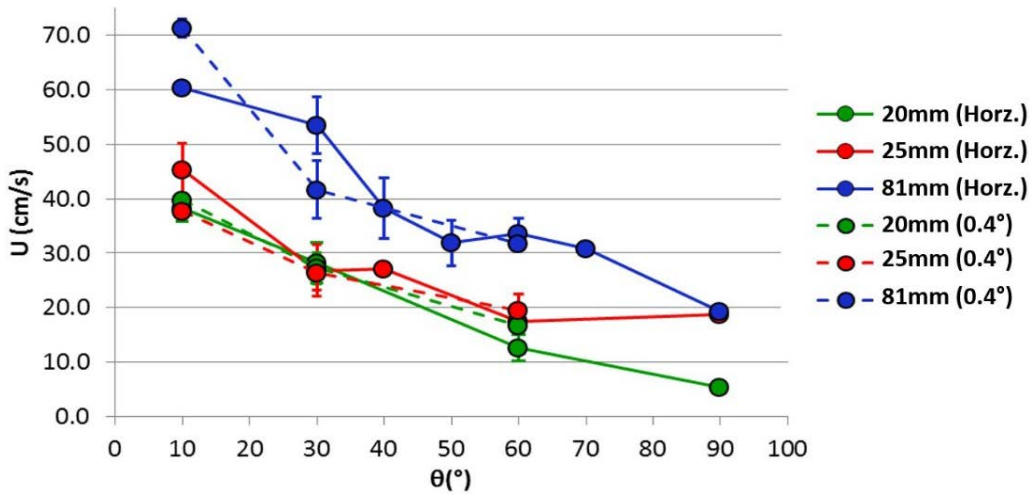


Figure F-2. <u>Effect of steel bed slope</u> on cartridge angle of attack trials.

Two flume slopes are a mild slope of 0.4° and horizontal slope (Horz.) (slope of 0.04°, taken as horizontal). (Figure 15 from MR-2410 interim report on 2015-11-30)

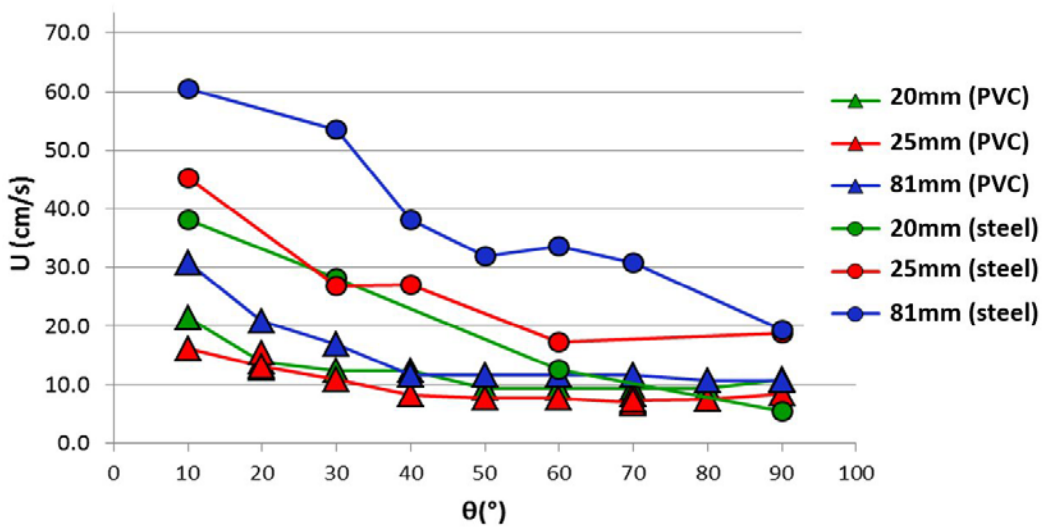


Figure F-3. <u>Effect of horizontal bottom roughness</u> on cartridge initiation of motion.

WHOI flume was used for PVC bottom and STF was used for the steel bed. (Figure 16 from MR-2410 interim report on 2015-11-30)

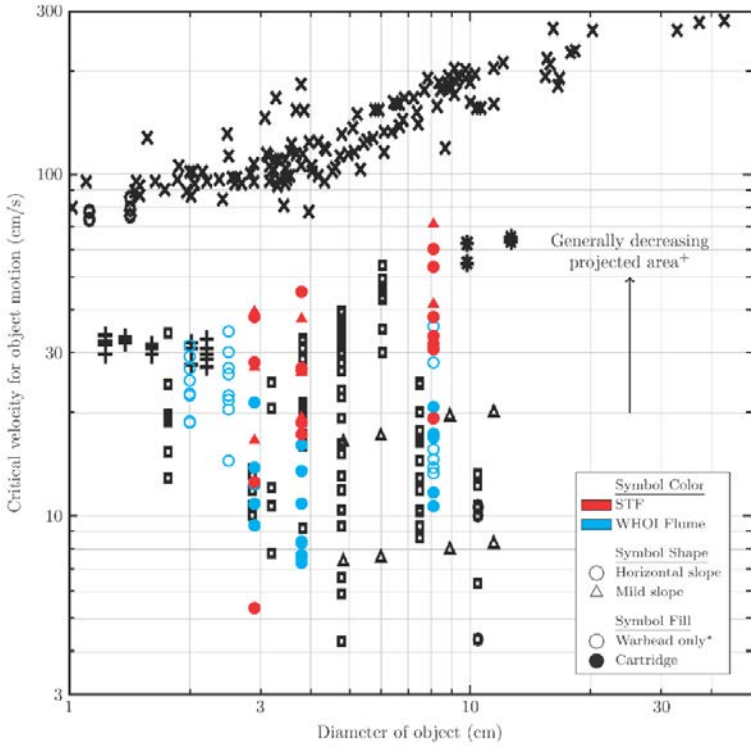


Figure F-4. Comparison of the current IOM experiments (from Figure 1, 2, and 3) to data compiled by Friedrichs (2013).

*Black symbols are prior data from Friedrichs (2013), and red and blue symbols are from current experiments. Symbology can be interpreted as follows: a light blue open circle is a data point collected in the WHOI Flume with a horizontal slope and the warhead only. A filled red triangle is a data point collected in the STF with a mild slope (S = 0.4°) using the whole UXO cartridge. (+ Generally decreasing projected area only applies to data collected by UIUC for the current effort. * The warhead only for the 81 mm UXO is with the fins removed). (Figure 17 from MR-2410 interim report on 2015-11-30)*

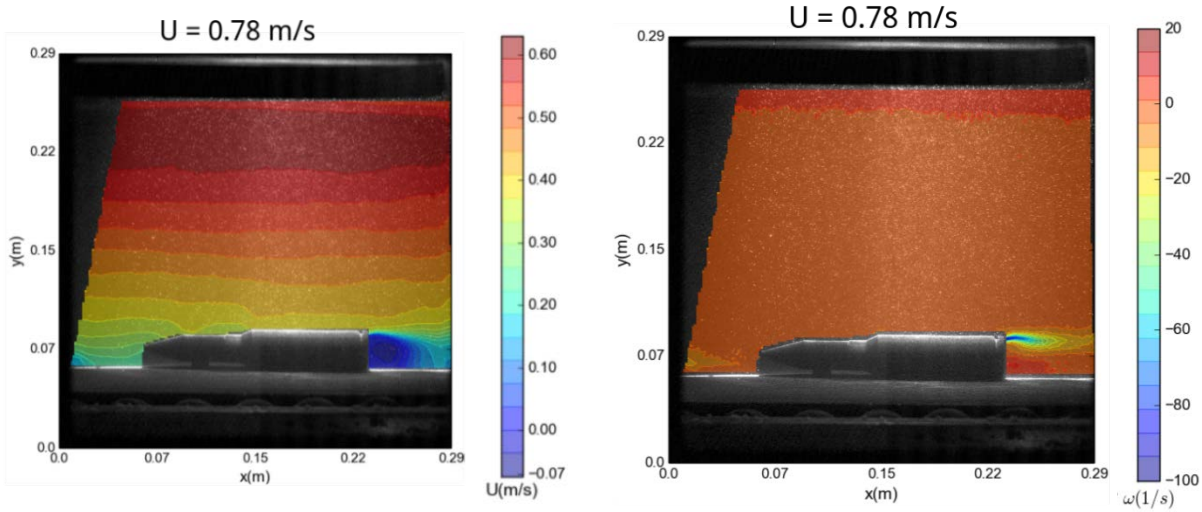


Figure F-5. Unidirectional PIV experiment results for mean flow velocity of 0.78 m/s.

Left subfigure: contours of the mean streamwise velocity field around the munition across the centerline. (The velocity is defined to be positive to the right.) Right subfigure: vorticity around the munition across the centerline. (The positive vortex is counterclockwise.)

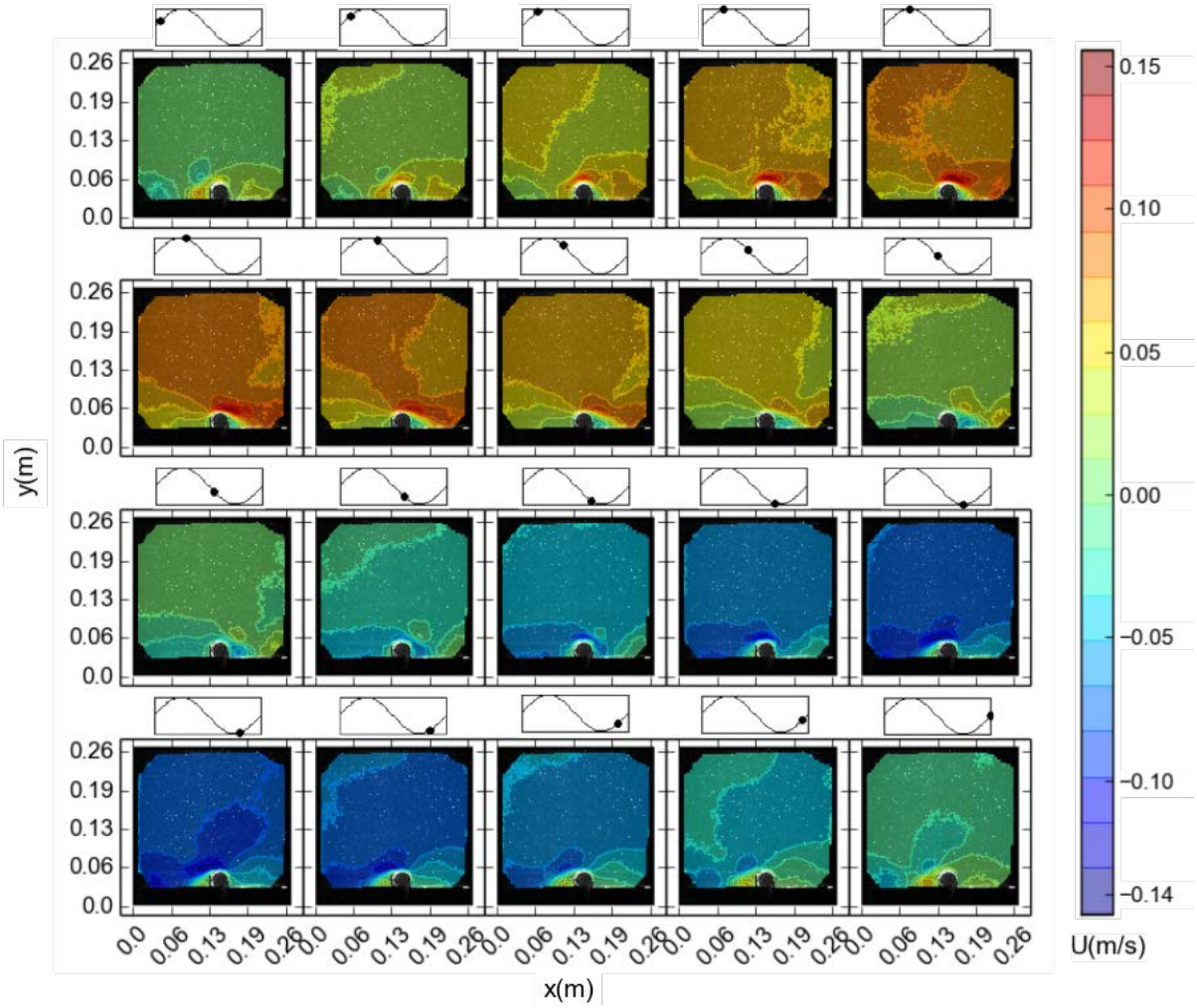


Figure F-6. The contour of the streamwise mean velocity at each phase in a cycle.

In this test, the period of the oscillation is 3 seconds and the amplitude of the stoke is 0.04 m.

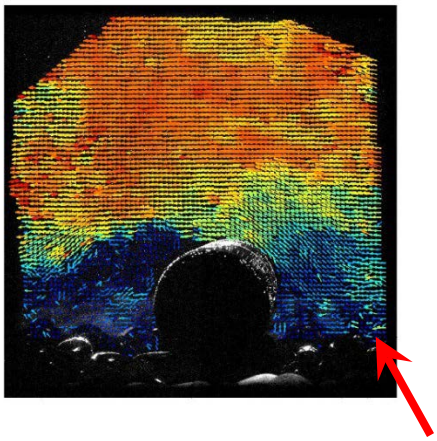


Figure F-7. Noticeable turbulence fluctuation from mean flow observed at the onset of motion.

Velocity field taken at 2.5Hz (i.e., images at 0.4 second intervals).

Appendix G. MR 2647 Simple Parameterized Models for Predicting Mobility, Burial and Re-exposure of Underwater Munitions. Dr. Carl Friedrichs (Virginia Institute of Marine Science)

Carl Friedrichs was PI of SERDP investigation MR-2224 "Simple Parameterized Models for Predicting Mobility, Burial and Re-exposure of Underwater Munitions", and he is now PI of the new SERDP award, MR-2647 "Parameterized Process Models for Underwater Munitions Expert System" (start date early 2016). Both projects focus on compiling available, relevant data on sediment and UXO-like object mobility and deriving/applying relatively simple, parameterized models for UXO fate as a function of UXO, sediment and hydrodynamic properties. (Here UXO is shorthand for underwater munitions.) MR-2224 focused on initiation of object motion and scour-induced burial of UXO-like objects, while MR-2647 will focus on the effects of bedform/beach profile evolution, and bedform washout/bed liquefaction. Both projects involve close collaboration with SERDP investigators Rennie and Brandt (MR-2227, MR-2646) in support of the underwater munitions mobility expert system.

Based on a compilation of >390 individual observations of the initiation of motion of UXO-like objects, the figure below shows theoretically and empirically that the near-bed water velocity at UXO threshold of motion is predicted by the object's critical mobility number (θ_{crit}, proportional to the fluid drag force divided by the object's weight). Furthermore, the critical mobility number (i) decreases as the size of the object, d_{object}, grows relative to scale of the bed's roughness, k_{bed} (ii) increases with the angularity of the object, and (iii) increases if the underlying bed is mobile.

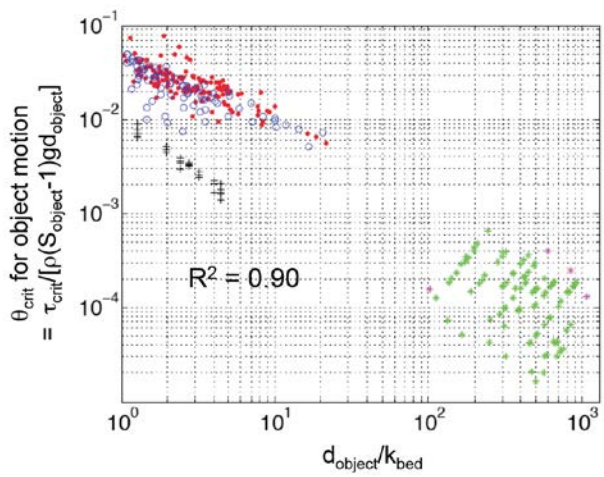


Figure G-1. Near-bed water velocity at UXO threshold of motion is predicted by the object's critical mobility number.

Based on a compilation of >570 individual observations of scour-induced burial of UXO-like cylinders in sand, results of MR-2224 showed that the most important single parameter for predicting increased scour-induced burial is an increase in the sediment mobility number (or, equivalently, the sediment Shields parameter). Inclusion of a wide variety of conditions (cylinder diameters 1 to 50 cm, length-to-diameter ratios of 2 to 30, densities relative to water (S_{object}) of 1 to 10, sand diameters from 0.1 to 0.7 mm, maximum flow velocity from 0.1 to 1.3 m/s, and wave periods from 1 to 12 seconds plus steady currents) limited the overall predictive power of the mobility or Shields parameter. In addition to the mobility or Shields parameter, burial was found to increase significantly with wave period, cylinder density, and cylinder length.

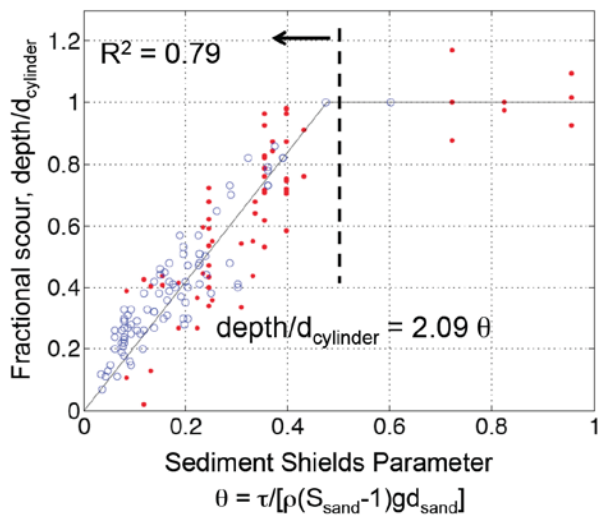


Figure G-2. Increased scour-induced burial is predicted by an increase in the sediment mobility number.

The plans for MR-2646 are motivated by previous results from the coastal engineering and geological literature which have highlighted three distinct regimes of mobile bed morphology as a function of sediment grain size and near-bed flow velocity. At lower energies ("Regime 1"), scour around objects dominates. However, as the "far field" bed becomes more mobile, interaction of objects with bedforms ("Regime 2") will become more important. (If objects are sufficiently large relative to the bedforms, scour-induced burial will still dominate in Regime 2.) At still higher energies, under sheet flow, bedforms will washout in "Regime 3", and the degree of bed fluidization along with object density will determine the object's fate. Recognizing the importance of these distinct regimes, MR-2646 will compile relevant observations of bedform evolution (Regime 2) and bedform washout/fluidization (Regime 3) to further develop parameterizations for the fate of UXO-like objects.

Appendix H. MR 2227 Underwater Munitions Expert System to Predict Mobility and Burial. Dr. Sarah Rennie (Johns Hopkins University Applied Research Laboratory)

There are a large number of inland water and coastal sites contaminated with unexploded ordnance (UXO). To support planning for efficient site remediation, it is important to have a mechanism for identifying the locations and degree of burial of extant UXO. Key to providing such a predictive capability is knowledge of the process and time scales for the scour, burial, re-exposure, migration and subsequent re-burial of UXO at specific sites of interest. We are developing a computer-based, probabilistic expert system to model munitions burial and mobility for a range of underwater environments. The Underwater Munitions Expert System (UnMES) employs a Bayesian network as the decision structure where domain parameters are treated as random variables; incorporating the inherent uncertainty (e.g. unknown initial and environmental conditions, poorly documented munitions disposal events). The development of an expert system is inherently an effort of synthesis, requiring the input and collaboration of other experts in the field. To be a useful risk-assessment tool for site managers, the UnMES could be a module in a larger decision support system that provides access to environmental and historical databases providing estimates of UXO burial and accretion to visualization and risk assessment modules, as illustrated in Figure H-1.

A prototype version of the UnMES Bayesian network has been developed. It provides probabilistic estimates of local burial and mobility in a wave-driven coastal environment. This version of UnMES has been implemented in Netica™ software [Norsys, 2015], illustrated in Figure H-2.

At this stage several key processes are not as yet well understood and will be the focus of model development in the near term (MR-2645). These processes include impact burial, re-exposure by sand-wave migration, as well as migration distance and direction. The conditional distribution tables for these nodes are currently represented by rule of thumb or uniform distributions. At contaminated sites, we also need to know whether certain areas are more susceptible to munitions migration/aggregation or burial than others. In some cases, regions of higher munitions contamination are identified in the initial site conceptual model, while in others there may be sub-regions where the potential for human interaction is particularly great. To represent the spatial variability across a contaminated underwater site, the core network is replicated at cells across a two-dimensional representation of the geographic region of interest, amenable to representation in a GIS framework. Because it appears that important migration events are driven by extreme rare environmental events (e.g. strong storms), a specific methodology for extending the Bayesian construct in the temporal domain is needed. Determination of a viable approach for representing extreme events is currently under investigation. One such approach under consideration is the use of Generalized Extreme Value distributions.

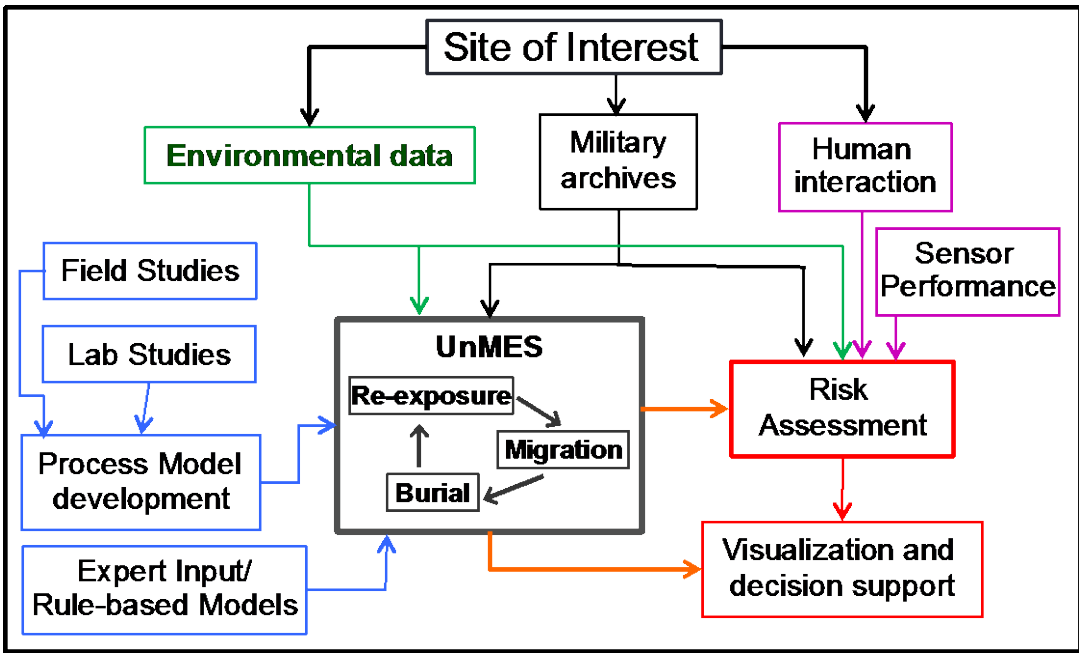


Figure H-1. Conceptual diagram of UnMES module within a decision support system.

Connections with environmental and military databases are needed to populate the input distributions and forcing models. The blue modules present the UnMES development system in collaboration with other MR SERDP projects. The modules on the right-hand side represent modules that use the UnMES predictions to allow site managers to characterize risk and plan for remediation efforts.

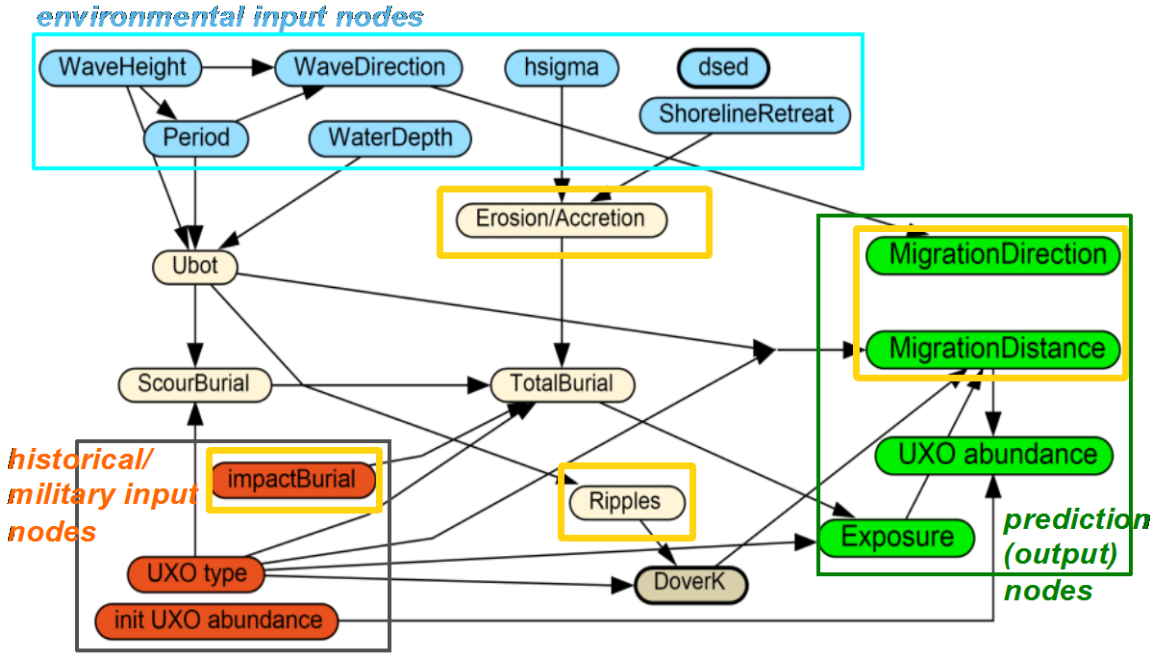


Figure H-2. Diagram of a prototype Bayesian Network (BN) in UnMES modeling the burial and migration response for specified environmental settings (indicated by the blue nodes).

Knowledge of the quantity, type, and initial burial condition of the munitions are specified by the orange nodes. The resulting predictions are found in the output (green) nodes.

Appendix I. Nonlinear Shoaling of Directional Waves: The TRIADS Model. Dr. Alex Sheremet (University of Florida)

I-1. Nonlinear Shoaling.

In general, the statistics of wave evolution can be described in terms of competing dispersion and nonlinearity (Benney and Saffman, 1966; Newell and Aucoin, 1971). Nonlinearity builds phase correlations and skews the statistical distribution of the wave-field; dispersion breaks phase correlations and restores the symmetry of the distribution. The process of wave transformation in the nearshore exhibits the full range of the nonlinearity/dispersion competition: deep water dispersion is strong and nonlinearity is weak; in shallow water, dispersion weakens and nonlinearity dominates. A schematic of nonlinear processes and their distribution zones in the nearshore is shown in Figure I-1. The shoaling zone, where these two processes balance, is interesting and challenging.

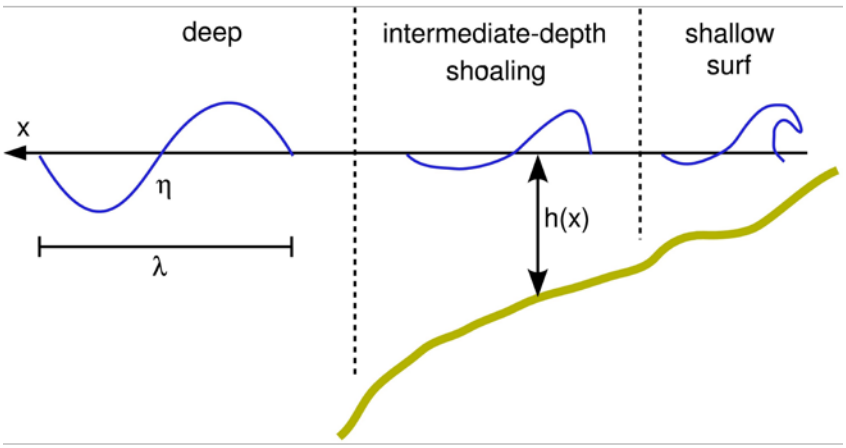


Figure I-1. Schematic of the three general zones of wave transformation in the nearshore.

Deep water: dispersion > nonlinearity; nearly sinusoidal shapes; random-phase (Gaussian) statistics; homogeneous wave fields; nonlinearity is cubic (4-wave interaction, slow), effective over large scales (hundreds of wavelengths).

Intermediate depth (shoaling zone): dispersion ≈ nonlinearity; shapes peak and lean forward (skewed and asymmetric); phase correlations (non-Gaussian); wave fields are non-homogeneous; nonlinearity is quadratic (3-wave interaction, fast), effective over smaller scales (tens of wavelengths); spectrum widens; generation of spectral peak harmonics and low-frequency (infragravity) waves.

Shallow water (surf zone): dispersion < nonlinearity; waves break; flow is strongly turbulent; a fully nonlinear description (e.g., Navier-Stokes) is required.

Deep-water wave propagation is well understood, and has been implemented in models used routinely for operational wave forecasting (so-called WAM-class models, built on the WAM framework; Komen et al., 1994). Examples are WAVEWATCH 3 (Tolman, 1991), and SWAN (Booij et al., 1999). In intermediate depth water, the dominant nonlinear evolution mechanism is 3-wave (triad) interaction. Because this type of interaction is not exactly resonant, its dynamics are complicated and difficult to model. Efforts have been made to extend the WAM-class models into shallow water (SWAN is in fact advertised as a shallow water model); however, due to their lack of, or poorly implemented, triad interaction physics, these are effectively linear models in shallow water. For example, SWAN description of nonlinear shoaling (a parametrization of triad interaction mechanism due to Eldeberky and Battjes, 1995) ignores the non-locality of the process, as well as important effects such as infragravity wave generation, recurrence effects, and spectrum widening.

I-2. NMSE and TRIADS.

A deterministic unidirectional 3-wave interaction formulation was first introduced by Freilich et al. (1984) based on the Boussinesq approximation. The models discussed below are implementations of the general Nonlinear Mild-Slope Equation (NMSE) framework proposed by Agnon et al. (1993) and Agnon and Sheremet (1997).

The NMSE approach generates a family of spectral models that describe the nonlinear shoaling transformation of a directional wave field propagating over a mildly-sloping, cylindrical beach (laterally-uniform beach). The formulation accounts for linear processes such as refraction and shoaling, and nonlinear triad interactions.

Current NMSE implementations include phase-resolving and phase-averaged implementations (e.g., Sheremet et al. 2011a); also, unidirectional and directional versions.

Phase-averaged formulations average the governing equations at the theoretical formulation stage. The resulting numerical implementations are fast but closure assumptions made at the theoretical development stage limit the order of statistics described; most common models only output second order statistics (variance, spectral shape; no skewness and asymmetry). This restriction can be relaxed, but at a high numerical integration cost.

Phase-resolving versions are run as Monte-Carlo simulations, in which the complex spectral amplitudes are specified at the offshore boundary of the model by combining deep-water spectral densities (e.g., generated by a WAM-class model), with sets of initial phases randomly distributed between 0 and 2π. Numerical integration for a single phase set produces a single realization of the shoaling process. Repeated runs with the model generate statistical ensembles, based on which the nonlinear statistics of the wave field are estimated. The advantages of this approach provide

1. a native formulation of the nonlinear shoaling process with minimal a priori assumptions.
2. an explicit characterization of wave dynamics, including full reconstruction of the flow field associated with the waves.
3. easy access to arbitrary order statistics (power spectra and associated parameters, significant height, peak period, direction, spread; skewness and asymmetry; bispectra, etc.). The effects of nonlinear interaction, dissipation, wave current interaction, etc., can also be examined directly and explicitly.
4. fast estimate of the shoaling process, which is another way of saying that they can cover large spatial and temporal domains. The run time of a spectral model run covering an area on the order of 100 km alongshore is on the order of minutes on a desktop machine. This is essential for describing larger-scale infragravity waves (IGW, alongshore wavelength on the order 1 km) generated through nonlinear interaction.

The TRIADS model for directional nonlinear shoaling of arbitrary wave spectra is the most comprehensive implementation of the NMSE framework. TRIADS has been tested in various environments (Agnon and Sheremet, 1997; Sheremet et al. 2011a, Sheremet et al. 2011b; Sheremet et al., in review; Safak et al., in review), incorporating parameterizations for additional physics such as wave breaking, wind input and dissipation due to white-capping and interaction with bed sediment.

I-3. Possible applications within the scope of the "Munition Response" project.

The most efficient deployment of TRIADS is on relatively large-scale alongshore domains (10-100 km), and between 20-1 m water depth. TRIADS provides an essential interface between the WAM-class, deep-water wave models, and very-high resolution, small-scale, fully 3-D, non-hydrostatic, etc. DNS-type formulations for the very-shallow water and swash zone. For this purpose, the phase-resolving implementations are the most adequate.

A possible application of TRIADS is generating a database of nearshore wave climatology. The model could be used to propagate the deep-water wave information derived, for example, from NOAA buoy data, or deep water wave numerical fore-/hindcasts, or measurements from field experiments conducted within the project. The data base could be built based on a discretization of deep-water characteristic parameters (wave height, peak period, peak direction) as well as a discrete set of bathymetric profiles for the site. Such a database would become richer and more useful with every additional run, by providing a quick "look-up table" generation of wave statistics required by the project. In addition, comparison of observations (as they accumulate) with the runs stored in the database provides a valuable tool for the validation and future development of the model.

State of development. A unidirectional version of TRIADS (uTRIADS) exists and has been used routinely in research studies. uTRIADS is numerically light and can be run on existing desktops, thus it can be used for research purposes. A portable Linux/Matlab package will be developed for the project and distributed to the interested researches associated with the project within a couple of months.

The comprehensive TRIADS model is heavier and is particularly suitable for parallel computing. Although the intention is to eventually make this model available to the community as open source, the development of the code is not finished, and the model is not recommended for "unsupervised" use. This version, however, is best suited for the development of a nearshore wave climate database, and should represent the focus of any future development plans.

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