USER GUIDE

Underwater Munitions Expert System for Remediation Guidance

Prototype Underwater Munitions Expert System:
Demonstration and User Guide

SERDP Project MR-2645

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A probabilistic expert system has been developed to predict underwater migration and burial into the seabed of munitions. The Underwater Munitions Expert System (UnMES) is a computer-based tool to help guide remediation management of underwater sites contaminated with abandoned munitions. This report documents the progress made in the development of UnMES during the Project MR-2645 contract period (2017-2019), and includes a guide for installation and usage of UnMES. A number of examples demonstrating use of the expert system are shown. The computer code will be delivered as supplementary material to the report.

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Prototype Underwater Munitions Expert System: Demonstration and User's Guide

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Acronyms

API	–	Application Programmer Interface
APL	–	Applied Physics Laboratory
BN	–	Bayesian Network
CERCLA	–	Comprehensive Environmental Response, Compensation, and Liability Act
CFD	–	Computational Fluid Dynamics
CPT	–	Conditional Probability Table(s)
DEM	–	digital elevation model
d_{sed}	–	Sediment grain size
ESTCP	–	Environmental Security Technology Certification Program
FRF	–	Field Research Facility, USACE, Duck, North Carolina
GIS	–	Graphical Information System
GoM	–	Gulf of Mexico
H_{sig}	–	Significant wave height
JHU	–	The Johns Hopkins University
MEC	–	Munitions and Explosives of Concern
MC	–	Monte Carlo
MR	–	Munitions Response
NBDC	–	National Buoy Data Center
NOAA	–	National Oceanic and Atmospheric Administration
PDT	–	Probability Distribution Table
SERDP	–	Strategic Environmental Research and Development Program
S_g	–	Specific gravity
UnMES	–	Underwater Munitions Expert System
USACE	–	United States Army Corps of Engineers
UXO	–	Unexploded Ordnance
WIMMX	–	Wallops Island Munitions Mobility EXperiment

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Prototype Underwater Munitions Expert System: Demonstration and User's Guide

Abstract

A probabilistic expert system has been developed to predict underwater migration and burial into the seabed of munitions. The Underwater Munitions Expert System (UnMES) is a computer-based tool to help guide remediation management of underwater sites contaminated with abandoned munitions. This report documents the progress made in the development of UnMES during the Project MR-2645 contract period (2017-2019), and includes a guide for installation and usage of UnMES. A number of examples demonstrating use of the expert system are shown. The computer code will be delivered as supplementary material to the report.

Objectives: A comprehensive model for predicting the possible movement, burial and re-exposure of underwater munitions would be a significant benefit for advising site managers as they plan monitoring or clean-up activities. In real-world management scenarios, the initial locations of the munitions or their exact types are often not well known. In addition, the environmental conditions that could move or bury the munitions vary strongly with time and space, and will not be measured precisely. Therefore, a useful approach for predicting munitions' locations and burial extent will of necessity be probabilistic in nature. The objective of this project is to build a prototype computer tool implementing an expert system that can make probabilistic predictions of migration and burial patterns for underwater munitions at specific sites of interest.

Technical Approach: The framework of UnMES is based on a Bayesian Network construct that relates the extant hydrodynamic and geological site characteristics to the processes governing the interaction of munitions with the underlying sediments and forcing by the environment. Simple models connecting causal forces acting on the underwater munitions and the associated sediment responses have been developed to predict scour, motion initiation, and the potential for burial or re-exposure due to bedform migration. These physics-based deterministic models are used in training the probabilistic Bayesian network forming the core of UnMES.

Results: Guided by concurrent SERDP field projects, the focus of the Prototype UnMES is on sandy, wave-dominated coastal environments. The Demonstration version of UnMES, completed during MR-2227 [Rennie and Brandt, 2017a] incorporated causal models for the

effects of oscillatory flow; the effects of the angle of bottom flow; acceleration effects on initiation of motion by the incorporation of an inertial factor for mobility threshold; as well as the role of munitions density on burial and migration and preliminary modeling of migration distance. Additional processes now included are: impact and liquefaction burial, as well as the implementation of spatial variability. The estimation of UXO re-exposure and burial due to longer time scale bathymetric variation, both seasonal and annual, that can be predicted with parameterized models driven by wave observations, has been considered for inclusion through the addition of erosion/accretion input. The potential for far-field seabed variation to expose and bury munitions has been augmented with bedform migration modeling as a new mechanism in UnMES. The previous ad-hoc models for liquefaction burial and estimation of migration distance have been replaced by formulations that reflect the relevant physics. Initial validation of UnMES has utilized the data, albeit limited, available from the SERDP field studies at Martha's Vineyard, MA, and Duck, NC. Reasonable agreement has been demonstrated for most processes, with the exception of the modeling of migration distance.

Benefits: This Prototype Version of UnMES brings together in a coherent and organized manner recent research on the manner in which munitions on the seabed can migrate, bury, or become exposed. The probabilistic predictions feed naturally into risk-assessment tools used by site administrators for remedial management decisions. With expert system guidance regarding the timing, location, and operational choices for assessment surveys and subsequent clean up, these efforts can be more efficiently planned and executed. Prediction of burial, which affects detection and classification performance by magnetic, acoustic, and optical sensors, will guide optimal selection of sensor technologies. Knowledge of migration thresholds at remediation sites will allow evaluation of potential munitions relocation by extreme storms. An additional benefit provided by the expert system is that it functions as a repository to organize the collection of records of laboratory and field research as well as databases of environmental conditions, providing a documented archive. The environmental inputs required to inform UnMES of the relevant hydrodynamic and geologic parameters at the site are listed in Appendix A.

1. Introduction

Development of the Underwater Munitions Expert System was supported by the United States Department of Defense Strategic Environmental Research and Development Program (SERDP), Project MR-2645 (2017-2019). The initial research focused on accumulating domain knowledge of the phenomena and understanding important physical processes relevant to UXO burial and mobility onset, enhanced by focused laboratory experiments. A preliminary model framework was proposed [Rennie and Brandt, 2015] and shared with the munitions response research community to stimulate collaboration, essential for development of a practical expert system. Feedback from the research community identified a number of additional burial and mobility mechanisms that were examined during SERDP project MR-2227 in 2013-2016 [Rennie and Brandt, 2017a]. Further enhancements to UnMES capabilities, supported by the most recent SERDP field experiments, are documented here. A follow-on project, SERDP MR19-1126, scheduled for 2019 through 2022, will focus on increasing UnMES accessibility for the end-user, developing efficient visualization products, along with enhanced validation studies.

1.1 Objective

The Munitions Response (MR) program of SERDP is focused on developing innovative methods to characterize, remediate and sustainably administer sites containing discarded military munitions. The objective of this effort is the construction of an Underwater Munitions Expert System (UnMES) aimed towards providing a computer-based decision support tool for management of aquatic sites. The expert system is a probabilistic modelling approach built on a Bayesian Network that encodes databases of environmental conditions and recent research into physics-based process modeling of munitions' behavior in response to environmental forcing, with the goal of predicting the location of munitions and their degree of burial at underwater locations. The purpose of UnMES is to provide improved guidance for underwater munitions site assessment and remediation efforts.

1.2 Background

As a legacy of years of US military activities, including training and testing, there are many current and former Department of Defense (DoD) underwater sites contaminated with military munitions. The munitions can range in size from bombs and mines down to small arms ammunition. These may be classified as unexploded ordnance (UXO), when they had been primed for action, but remained unexploded due to malfunction, design or some other cause. Other munitions and explosives of concern (MEC) may have been abandoned without proper disposal (Discarded Military Munitions or DMM), and continue to pose a safety hazard. In this report, the term UXO is used to denote MEC of all types and sources. At many of these inland water and coastal areas, the risk of human interaction with UXO is the main concern. The possibility of munitions migrating into a region of the underwater site previously certified as clear is a primary problem for safe management.

Compared to terrestrial sites, underwater environments are subject to more dynamic conditions. Burial or exposure of the UXO by bottom currents is driven by waves and tides. Strong storm waves can also cause mobility for some UXO. The geographic extent of the search area covered for a region containing underwater UXO is constrained due to the limitations of present platform and sensor technology and search rates. Therefore, it is important to predict the fate of munitions, including areas of concentration and probability of exposure, in order to maximize the search, monitoring, and removal of underwater UXO.

1.3 Methods

The core of the underwater munitions expert system is based upon a Bayesian Network (BN) construct, a useful method of modeling systems with complex relationships in a probabilistic manner. The UnMES BN is implemented within the software product Netica™ [Norsys, 2019]. Instructions for the installation of Netica software are given in Appendix B. The variables in a BN are represented by nodes, connected by arrows that symbolize dependent relationships. Variable ranges are discretized into a set of states or bins, and each relationship is characterized by a conditional probability table (CPT) associated with the dependent, or child, node. A BN has a causal graphical structure that allows non-technical users to easily interpret the important factors and how they are interrelated. A schematic for the Prototype Version of the core UnMES BN is shown in Figure 1.1. The input, or parent, nodes describe an environmental scenario or characterize the munitions' types and initial deposition. Input node settings are specified as a Probability Distribution Table (PDT) where both the width of the bins and the spread of the distribution reflect the inherent input uncertainty.

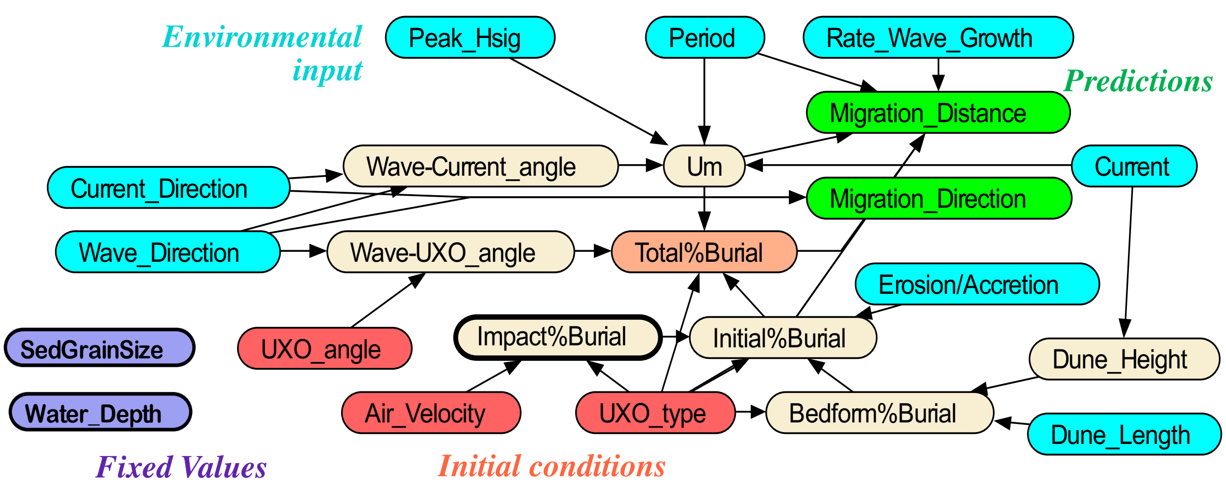

Figure 1.1 Diagram of nodes in Prototype Version core BN of UnMES

In Figure 1.1 the blue nodes indicate the environmental knowledge that describes the geologic setting and quantifies the hydrodynamic forcings. An overview of the environmental inputs required by UnMES is provided in Appendix A. Variables colored red denote site-specific information regarding the munitions of concern: caliber, density, mode of deposition, etc. The conditional probability nodes include tan-colored intermediate variables, and predictive nodes in green. For the core BN, which represents UXO behavior at a single location, the water depth and sediment grain size states are fixed (purple nodes indicate constant values). This core BN structure will be replicated to cover the full area of interest, each replicate serving a province with a different depth, and possibly with varying sediment characteristics. A discussion of the spatially varying approach is found in Section 5, along with a guide to interaction with UnMES using the Netica graphical user interface. A detailed listing of Prototype UnMES nodes with their ranges and bin assignments is found in Appendix C.

A common approach to building a BN network is to train the CPT using a dataset of example cases. However, there is a limited amount of field and laboratory data applicable to UXO burial and mobility. Therefore, our approach has been to develop simple deterministic models that capture the first-order physics of the processes of interest. Extensive Monte Carlo simulations of these models are run over the relevant combinations of input variable ranges in order to populate the CPTs in UnMES. For some variables in UnMES, where a physics-based model is not yet available; the node can be supplied with an interim CPT formed in an ad hoc or statistical manner estimated from the relevant data.

1.4 Utilization

An expert system provides a documented manner of synthesizing previous and present research on the topic of interest. The Underwater section of SERDP's Munitions Response program area has been the most important source of knowledge incorporated into UnMES, as illustrated in Figure 1.2. The preliminary design of UnMES was reported in Rennie and Brandt [2015] where a more complete introduction to Bayesian Networks is provided. As continuing research reveals new knowledge, the expert system is designed to be adaptable: it is straightforward to update a CPT, or add additional nodes to the network. Consonant with the settings of SERDP sponsored field experiments used for development and performance evaluation, the Prototype version of UnMES presented in this report, is focused on predicting conditions at sandy, coastal sites, where surface waves are the primary forcing.

UXO at sites of concern have generally been deposited over an extended time period and over an area that encompasses different bathymetric and hydrodynamic regimes. The spatial application of UnMES partitions the site into provinces that have similar input sediment and water depth characteristics, which allows for efficient computation within the BN as well as for graphical representation of variability in the number and burial extent of UXO within the site. UnMES as implemented focuses on the time scale of a single storm event, as storms are the primary drivers of burial and migration events. The incorporation of statistical information representing the frequency and magnitude of storm events over annual cycles will allow extension to longer time scales.

Further work is continuing under SERDP MR19-1126 to improve the science supporting UnMES along with methods of visualizing and understanding its guidance. Collaboration is on-going with SERDP MR projects to acquire validation statistics and to couple UnMES with CFD modeling efforts. Above all, efforts are being directed at engaging with the remediation community to understand how UnMES can best function as a component in a comprehensive decision support tool that is used as part of structured decision-making for site remediation, as represented conceptually in Figure 1.2

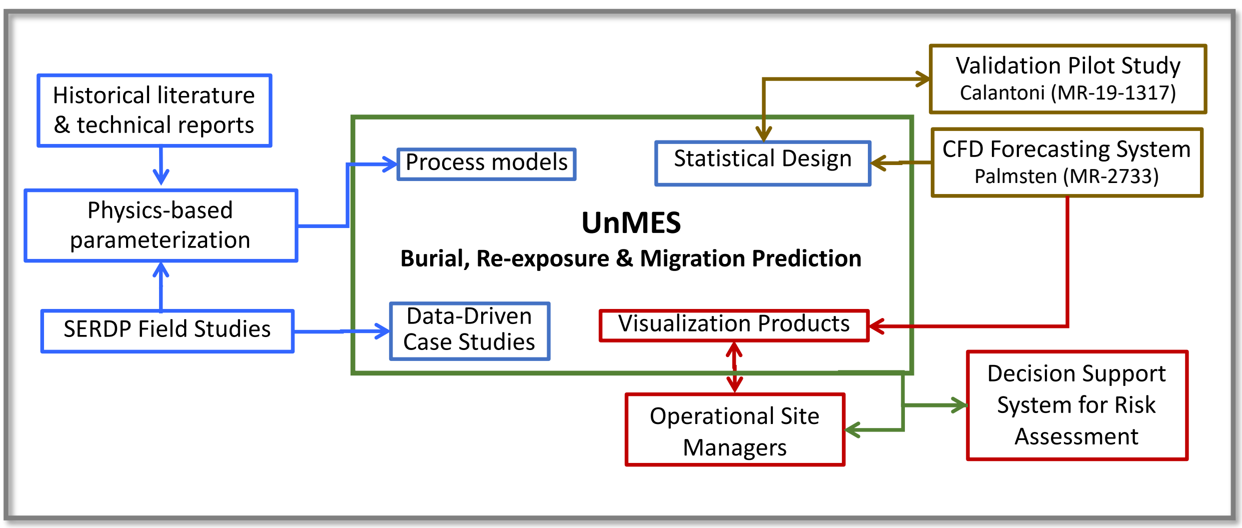

Figure 1.2 Conceptual framework of UnMES development, future extension, and inclusion in decision tool for support of operational site management.

This report documents progress made under SERDP project MR-2645 through 2019. Methods by which process models are integrated into the Bayesian Networks are explained in Section 2. Comparison of UnMES results with the available field observations is presented in Section 3. Examples of how UnMES can be queried for management guidance are demonstrated in Section 4 along with pertinent sensitivity studies. Section 5 constitutes a User's Guide to UnMES, including versions for spatial and CFD applications.

2. Model Integration

The core UnMES BN models UXO response to a storm event at a single location. For this implementation, designated as the Core versio, the water depth (h) and sediment grain size (d_{sed}) remain fixed in the BN. Information on different UnMES modes of operation is given in Section 5.

Equations for most of the process models which capture our present-day understanding of first-order physics controlling underwater UXO burial and movement were published in the Interim and Final Reports from SERDP project MR-2227 [Rennie and Brandt, 2015, Rennie and Brandt, 2017a]. In addition, the Interim Reports from this current project, MR-2645 [Rennie and Brandt, 2017b, 2019a] discuss additional processes, such as impact burial and the effects of bedform interaction, that have been implemented and integrated into the Prototype version defined herein. Table 2.1 lists the important variables used in or computed by the equations, denoted as in the previous reports. In this section, the integration of these models into the UnMES BN is described, with an emphasis on processes which are new or have been modified since the completion of MR-2227.

Table 2.1 Variables in UnMES process model equations

Name	Symbol	Units	Comments
Percentage Burial	%B	%	> 100 means overburden beyond full burial
Significant Wave Height	H_{sig}	m	effective wave height at the location of interest
Wave Period	T	s	dominant period of peak waves
Current Speed	U_c	m/s	depth-averagd current
Nearbed Flow Velocity	U_m	m/s	combined orbital and current flow
Rate of Wave Growth	dH_{sig}/dt	m/hr	most rapid period during storm arrival
UXO Specific gravity	Sg	non-dim	(density of munitions)/(density of sea water)
UXO Diameter	D	m	caliber of munitions
Wave-Current Angle	β	deg	is generally perpendicular very nearshore
Wave-UXO Angle	α	deg	usually angled or perpendicular
Water Depth	h	m	referenced to mean sea level
Sediment Grain Size	d_{sed}	mm	use median of size distribution
Dune Height	η	m	trough to crest (vertical) of bedforms
Dune Length	λ	m	trough to trough (horizontal) of bedforms

Equations governing the deterministic models have been implemented as functions in MATLAB. Source code for important functions is presented in Appendix D, and executable code is part of the supplementary material included with this report. The conditional probability table (CPT) for each dependent (child) variable, or node, in the BN (Figure 1.1) is populated by calculating histograms from numerous example cases. A Monte Carlo (MC) procedure generates these cases by repeatedly executing the process functions with input arguments sampled from the PDTs of the parent nodes.

Each continuous variable in the BN is discretized into a number of states or bins, as Netica manipulates probability tables rather than probability functions. Rationale for the choice of width for each bin, chosen to reflect both the available resolution of the input knowledge, as well as the function's sensitivity, is discussed in Rennie and Brandt, [2015], and documented in Appendix C. Some nodes are naturally discrete, e.g. UXO type.

For practical application, custom versions of the UnMES BN can be easily generated. The range covered by the node's probability distribution, in conjunction with the bin widths can be made specific to the geographic region being modeled. For example, a shallow sheltered site will experience a much smaller range in Peak_Hsig than a coastal site open to the ocean. If there is detailed knowledge about the characteristics of munitions of concern to be found in the area, specifications for UXO types can be refined. For this version of UnMES, a set of munitions with a wide range of density (represented by specific gravity S_g) are included. The majority of munitions are quite dense, with $S_g > 3$ [Calantoni, 2017]; in fact, small UXO such as bullets have densities close to steel ($S_g > 7$). A notable exception is pyrotechnic ordnance such as flares, which can have significantly lower densities ($S_g < 2$). While many real world sites are contaminated by a mixture of munitions, often the UnMES demonstration examples presented in the following sections will designate a UXO_type PDT consisting of a single ordnance in order to clarify the response behavior.

2.1 Lagged Burial, Liquefaction, and Onset of Motion

In general, on mobile sandy seabeds, UXO are commonly found to bury rather than migrate [Wilson *et al.*, 2008a]. However, there exist field observations where UXO motion exhibit large, intermittent variability and occasional substantial migration. In trying to understand the balance between burial and migration, Traykovski (2017) makes note that, while scour burial proceeds over some finite time, the onset of motion occurs instantaneously. The code implementing the deterministic models for scour burial have been re-written to account for the lagged nature of burial, so that burial increases exponentially towards equilibrium burial over some modeled time scale. Computation of lagged scour is integrated with liquefaction burial code prior to determining the onset of UXO motion in order to model the interrelationship between increasing burial and its effect on motion threshold (Appendix D).

Consideration of the importance of effective time scales for each process resulted in the introduction of a new variable for Prototype UnMES, representing the growth rate of waves for a storm event. This variable approximates the speed of a storm's movement into the area of interest as well as the width of the initial storm front. The new node Rate_Wave_Growth is discretized into bins representing "slow," "moderate," and "fast" storm arrivals, corresponding to wave growth ranges of less than 0.3 m/hr, between 0.3 to 0.6 m/hr, and greater than 0.6 m/hr, based on observations from Traykovski (2017). While Traykovski used a measure of change in bottom flow speed with time (dU_m/dt), the UnMES implementation uses change in wave height with time (dH_{sig}/dt), as it is more easily estimated from standard environmental measurements.

The Monte Carlo exercise models storm events with varying peak dH_{sig}/dt drawn from a uniform distribution between 0.2 to 1.0 m/hr. Training data generated by the MC exercise is used to form UnMES conditional probability tables. Figure 2.1a shows a time series of wave heights for simplified storm arrivals with Rate_Wave_Growth in the "moderate" and "fast" ranges (blue and red, respectively). Figure 2.1b compares times series of lagged scour %burial for the two wave growth rates, with the equilibrium scour shown as dashed lines. In the bottom panels, the migration response of two munitions is plotted. The fast storm, with rate of wave growth $dH_{sig}/dt \sim 1$ m/hr is just able to mobilize the heavier howitzer shell, but causes noticeable migration (> 10 m) for the less dense flare. Scour burial during the slower storm (blue) has increased to be too deep before the orbital velocity due to the higher waves can move the howitzer shell at all.

The storm with moderate Rate_Wave_Growth still causes the flare to move, but now the distance migrated is < 2 m. Neither storm could cause the even heavier mortar to migrate (not shown), because only a small amount of burial precludes movement. A review of long-term wave records from both the East and West Coast of the US shows that the most rapid dH_{sig}/dt bin, "fast" storm arrival, is quite unusual, occurring for less than 1 percent of events. This statistic is in accordance with the observation that migration occurs much less frequently than burial.

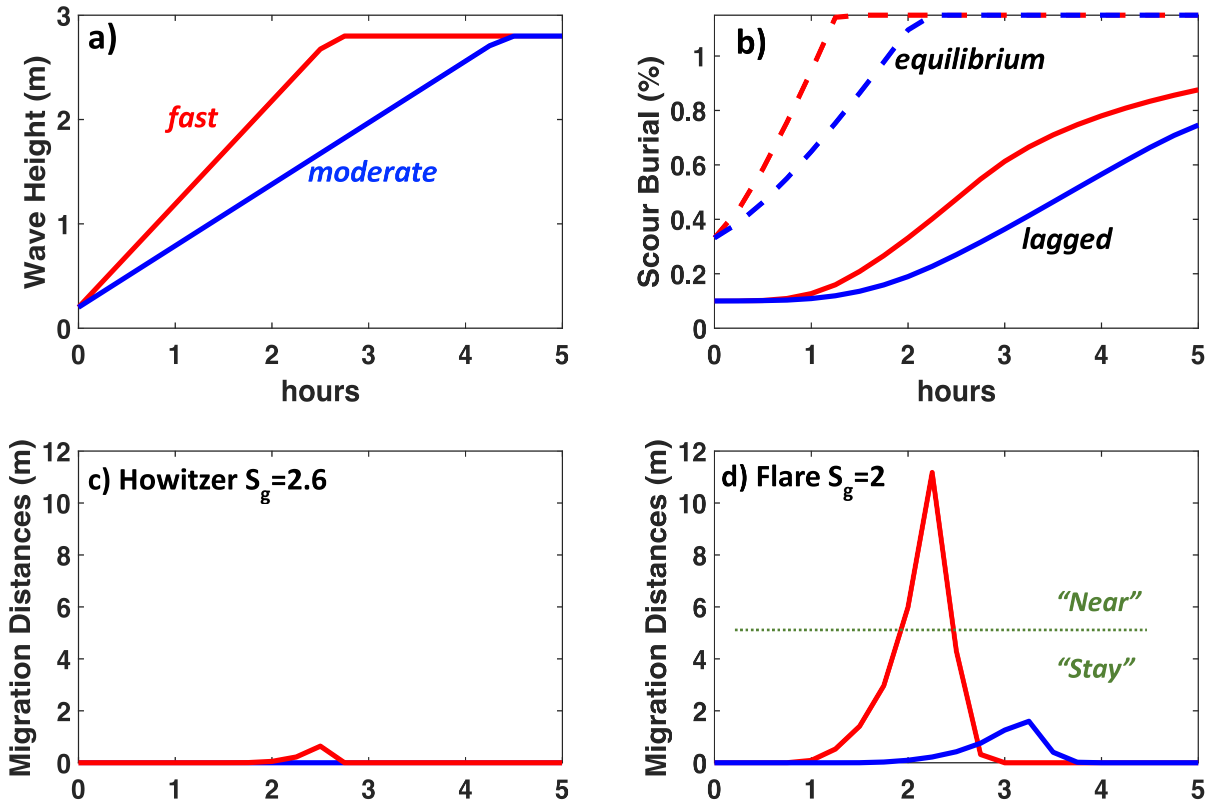

Figure 2.1 a) wave height for Rate_Wave_Growth moderate (blue) and fast (red). b) scour burial (%): equilibrium (dashed) and lagged (solid) for moderate and fast storms. c) Migration distance plotted *vs* time for UXO type howitzer shell with S_g = 2.6. d) Migration distance for flare with S_g = 2.0.

As wave height begins to increase during the storm arrival, scour burial usually dominates. Both scour and liquefaction can contribute to burial after the wave strength is larger than a given threshold (Rennie and Brandt, 2019a). For this reason, the improved liquefaction model is integrated into the scour-migration code, taking over after the threshold is exceeded (see Section 3.1). Because the duration of the storm event is a strong contributor to the total effect of the liquefaction process, further understanding of temporal storm patterns is being pursued.

2.2 Impact Burial

For ordnance originating from firing ranges and proving grounds, a possible factor in burial may be penetration depth into the sediment at initial impact. This will be a dominant process for shallow water firing ranges with soft cohesive sediment. At high speeds, there appears to be potential for heavier projectiles to penetrate into sand. In Rennie and Brandt [2017b] two existing geotechnical engineering models, previously used in mine burial studies, were examined for insight into seabed penetration behavior. Both models were extrapolated beyond their established domains to simulate underwater UXO scenarios, so that their results are considered only to bound the problem, and substantially more research is required for a penetration model to be truly applicable. However, several experts have pointed out that uncertainty in the model's physics is overwhelmed by uncertainty in the geotechnical characteristics of the location's sediment. The SERDP project MR18-1233 (Stark, 2018) is being undertaken to address this lack of geotechnical knowledge.

For the moment, while acknowledging the lack of validation in underwater settings, an implementation of the Sandia ballistic model [Young, 1997] is integrated into the Prototype UnMES, essentially as a placeholder to represent impact burial. For this model the resistance of the sediment to penetration is characterized with a qualitative "S-number," which for sand is set to a value ranging from 6 (dense sand) to 7 (medium compaction). Further details and examples of application of this model are given in Rennie and Brandt [2017b].

The second unknown variable when modeling initial penetration is the speed at which the UXO impacts the seabed. Terminal velocity in air for fired artillery can be determined from ordnance records and is known to be as fast as several hundred meters per second. A range of speeds up to 200 m/s is included in the Air_Velocity node introduced here. The speed through the water is computed using a simple 1D model, which assumes terminal velocity in water, is reached at a balance between vertical velocity and hydrodynamic drag, with the terminal water velocity approached exponentially from the Air Velocity value given at the water surface. The drag is determined by the angle at which the UXO travels through the water; however, this angle is not well known.

The physics controlling munitions trajectory through the water column are extremely complex due to dynamic processes associated with unsteady flow separation and vortex shedding, complicated by air entrainment when passing through the water surface [Mann *et al*., 2007]. Fin-stabilized munitions will generally have a nose-down trajectory, unless some of the fins break off upon impact with the water surface [Chu *et al*., 2010]. Multiple trajectory patterns were observed in these two studies, ranging from see-saw, tumbling, and even reversal of direction. Therefore, the angle of attack of the UXO during its water trajectory is treated as a probability distribution whose shape is guided by the UXO geometry. Tapered projectiles with fins are expected to travel largely nose-down, an attitude that is assigned a low drag coefficient. Some small percentage of the fins are assumed to break off, so that the tumbling munitions can turn broadside, where a high drag is used. A tapered shell with no fins is presumed to be more nose-down than broadside, but a cylinder is presumed to fall with no preferred angle. These probability distributions are illustrated in Figure 2.2a for three of the example UXO: a finned mortar, tapered howitzer shell, and cylindrical flare. These angle distributions can be refined given additional site-specific information about the ordnance and testing procedures. The drag coefficient used to compute the hydrodynamic balance is determined by a draw from the angle of attack PDF relevant to the UXO of interest.

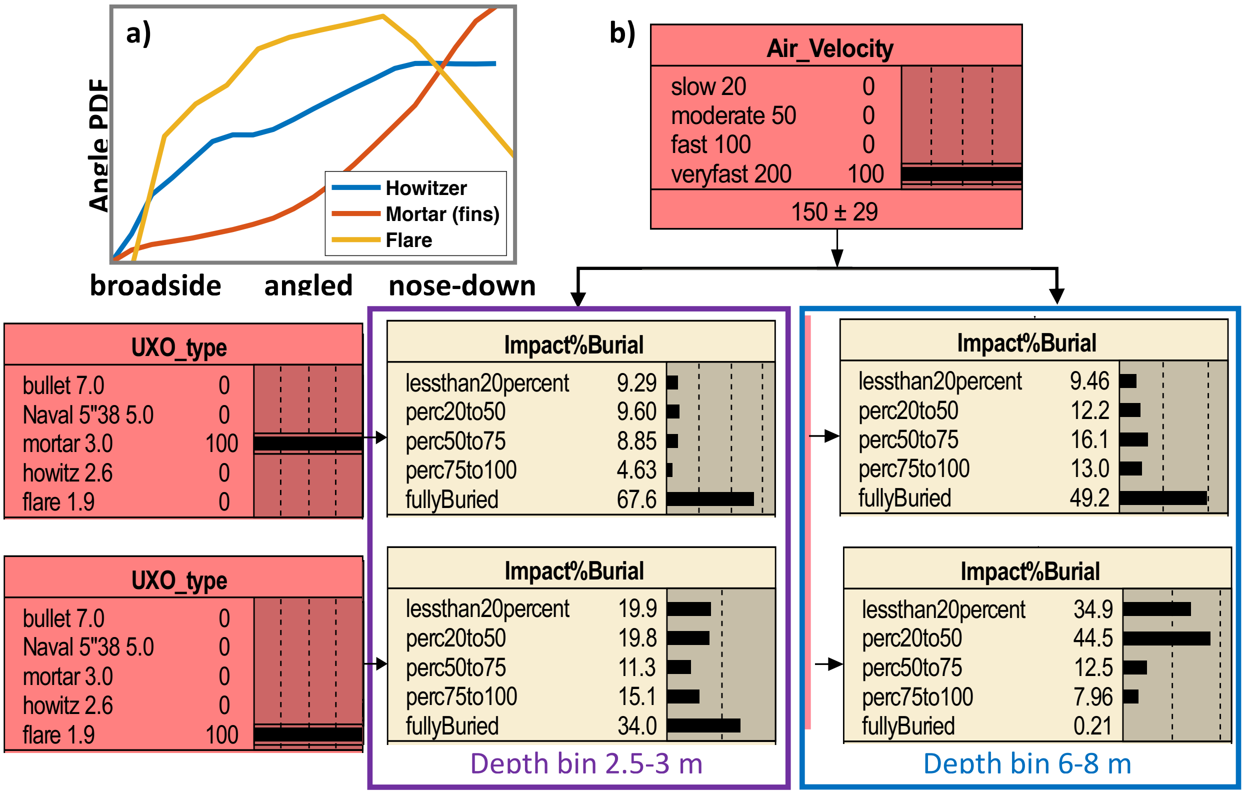

Figure 2.2. a) Probability distribution of water trajectory angle of attack for 3 UXO Types, based on their shape and presence of fins. b) Example percentage burial for the mortar and flare when Air_Velocity set very fast. The leftmost Impact% Burial PDTs correspond to a Water Depth bin of 2.5 to 3 m and the right-hand PDTs are at depths between 6 to 8 m.

The hydrodynamic balance dictates the change in velocity through the water until the defined depth or terminal velocity is reached. Terminal velocities in water are usually less than O(10) m/s; at these low impact speeds, less than 2 cm penetration is predicted. For slow Air_Velocity (< 20 m/s), terminal velocity is generally reached prior to impact at the seabed; little penetration occurs, and the CPT for the Impact%Burial node is set to 100 percent in the lessthan20percent burial bin (not shown). A slow Air_Velocity setting is appropriate for many deployment scenarios where munitions were jettisoned or otherwise discarded. However, for artillery firing, Air_Velocity at the ocean surface may in the fastest bin as shown in Figure 2.2b. In this case, in very shallow water (e.g. $h < 3$ m) the velocity at impact with the seabed can exceed 100 m/s. At these speeds, the Sandia model predicts penetration into sand of over

0.5 m [Rennie and Brandt, 2017b]. The penetration depth is mapped to a percentage burial using the dimensions of defined by the UXO Type.

The bottom panels of Figure 2.2b compares PDTs of the predicted impact burial for two example UXO, where the Air_Velocity is in the very fastest bin (100 - 200 m/s), with results shown for water depth bins at 3 m and 8 m. The low-density flare is included to illustrate the comparison, although in reality, of course, artillery speeds are not applicable to pyrotechnic munitions. At these extremely high speeds, most of the finned mortars are predicted to be fully buried in very shallow depths. Even at 8 m depth, almost half the mortars are fully buried. The flares, being blunt and less dense, experience less burial, and slow during the trajectory through the water so that, at 8 m depth, none are fully buried. The model predictions for the howitzer shell lie in between these 2 results. The bullet UXO type has a mass too small to model with the Sandia equations, and its Impact%Burial is always completely in the bin for least burial. Again, the Sandia model is not validated per se for UXO penetration into underwater sand, and the present results are only illustrative of how impact burial can be integrated into UnMES. Further research is needed to provide a more applicable model for use in UnMES.

2.3 Bedform Migration

A probabilistic model for the potential of burial or exposure due to bedform migration was presented by Rennie and Brandt [2019a] based on dunes moving over a UXO field. The height (η) and wavelength (λ) of the dunes are estimated from empirical formulae depending on water depth, current speed, and sand grain size [van Rijn, 1984]. This scenario is likely to be important in areas where strong tidal currents dominate over wave forcing. Guided by observations from Traykovski [2017], the UXO are estimated to fall to the level of the dunes' troughs, and become buried when the crests pass over. The burial probabilities are assigned based on a geometric argument assuming saw tooth-shaped dunes, as frequently observed. The relevant time scale for this implementation essentially represents an interstorm duration must be much longer than the λ/(migration speed).

A Bedform%Burial node is introduced with parent nodes being UXO Type, which (determines the diameter D), Dune_Height and observed Dune_Length. If the observed λ is longer than the estimated λ, which is modeled solely as a function of water depth, then a gap is assumed to exist between dunes (a commonly-observed geometry). Otherwise, the gap length is assumed to be zero. The Current input node is parent to Dune_Height, along with the fixed values h and d_{sed} for this Core BN. For Current speeds less than 0.2 m/s, no dunes are predicted to occur. If observations of η are available from the location of interest, the values can be entered directly into the Dune_Height node, bypassing the prediction uncertainty.

PDT values of Bedform%Burial are functions of the ratio between D and η, and the length of the gap between dunes. The PDT in each percentage burial bin is computed as shown in Table 2.2 where the parameter noBurial is computed as the ratio between the gap length and λ.

Table 2.2 PDT for Percentage Burial under Saw tooth Bedforms

Bedform %Burial	PDT formula
lessthan20percent	noBurial + 0.20*(1-fullyBuried-noBurial)
perc20to50	0.30*(1-fullyBuried-noBurial)
perc50to75	0.25*(1-fullyBuried-noBurial)
perc75to100	0.25*(1-fullyBuried-noBurial)
fullyBuried	max(0, (1-**D/η**)*(1-minBurial) _
where	noBurial = gap length/observed dune length

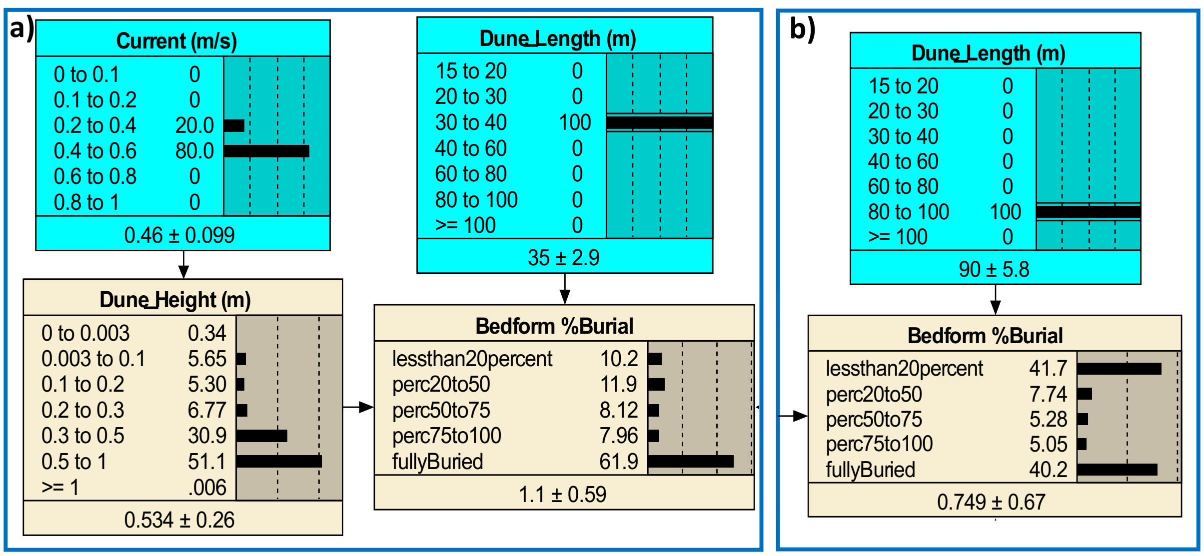

Figure 2.3 Example UnMES prediction of burial or exposure probability by migrating bedforms. The right-hand panel b) is for the same Dune_Height distribution as in a), but with a longer observed Dune_Length.

Example results are shown in Figure 2.3 for UXO type howitzer shell (D = 155mm), in water depth h = 8 m. For shorter λ (implying no gaps), and larger η, these formulae produce PDT dominated by full burial, as expected. For long λ with gaps, the Bedform%Burial PDT becomes bi-modal, with the UXO tending towards either a state of full burial or an exposed state (exposure represented by the lessthan20percent state). The probability of an exposed state is of particular concern, because exposed UXO are more likely to be mobilized.

2.4 Erosion/Accretion

Over long time scales, multiple processes can cause changes in nearshore coastal profiles, which can bury (accretion) or expose (erosion) UXO. A potential model to capture cyclical seasonal shoreface adjustment patterns was discussed in Rennie and Brandt [2019a]. This model showed reasonable skill applied to several US West Coast sites, but produced poor results at an East Coast site, the Field Research Facility (FRF) at Duck, NC. Further investigation of coastal profile modeling is warranted. In the meantime, the Erosion/Accretion variable in UnMES is treated as an input node whose settings are combined with the Impact and Bedform%Burial PDTs to inform an Initial%Burial distribution.

A previous UnMES implementation formed the Erosion/Accretion PDT from a Gaussian distribution with mean and sigma defined at each depth bin from bathymetry data. This is a good option for locations where long-term bathymetric data sets are available. It is the best method for the many coastal sites where non-cyclic erosion with net shoreline retreat is occurring. The SERDP project MR-2733 [Palmsten and Penko, 2018] is pursuing the implementation of the computational fluid dynamics (CFD) model DELFT3D at several representative sites of interest. Results from the MORPH module of DELFT3D can be used to set the Erosion/Accretion values as they vary across the site. Examples of this approach are shown in Section 4.2.

2.5 General Recommendations for Unknown Variables

As shown in Section 4.1, one of the most important inputs is the event maximum wave height (Peak_Hsig). Often waves are available only from offshore wave measurements. Wave heights and directions transform as waves shoal in towards the shore, with the changing wave characteristics a strong function of the local bathymetry. Therefore, surveys to obtain high-resolution bathymetry should be a priority investment at munitions response sites where wave forcing is dominant. The bathymetry variation will determine the number of replicates of the core UnMES BNs required to sufficiently model UXO behavior across the full remediation site (see Section 5.2). An initial assessment of the coastal depth profile at a site of interest may be obtained using data available from previous benchmark regional surveys, or a coarse estimate can be obtained from an equilibrium profile model as discussed in Rennie and Brandt [2019a]. Given offshore wave measurements and knowledge of the shoreface bathymetry, several models of varying complexity are available to model the transformed wave height and directions into the surf zone. Input nodes for each replicate in the spatial implementation of UnMES will be set to the distribution of wave characteristics as determined by the cross-shore transformation.

The standard parameterized 2-D shoaling wave model TG83 [Thornton and Guza, R.T. 1983] is easily implemented, and has been used for several UnMES applications; example results from this simple model are compared against waves modeled by a higher-investment 3-D CFD implementation of DELFT3D in Section 4.2. Traykovski [2017] used a more complex phase-resolving model, SWASH [Zijlema *et al.,* 2011], which is the preferred choice given sufficient resources. Alternately, an investment in direct data gathering can be made, measuring wave characteristics over some representative time period at a few cross-shore positions of interest, and computing empirical transfer functions to relate conditions in shallow locations to the offshore waves.

The choice of some of the environmental input variables originally included in the Demonstration UnMES were guided by specific research concerns. An example is the UXO_angle node, specifying the angle between the long axis of the munitions and the approximate angle of the shoreline, introduced to incorporate results from SERDP studies into the effect of the flow angle of attack, e.g. Garcia and Landry [2018]. During directed field experiments, the surrogate UXO could be deployed in a manner that recorded their orientation, which allowed unambiguous knowledge of the input PDT. However, in practice the angle of a UXO discarded on the seabed will rarely be known; it must be estimated from some probability distribution.

In the face of complete uncertainty, where that is no justification for designating any particular value as more or less likely, it is reasonable to input a uniform distribution of probabilities. See Section 5 for instructions on how to manipulate node tables in the Netica application. However, in many scenarios, there is general guidance that can provide a more informative input distribution. For remediation sites that were former firing ranges, a reasonable initial distribution of UXO angle might be peaked in the direction of firing, which was probably close to shore normal. For the general case of discarded munitions where no impact burial is anticipated, it has been frequently observed that cylinders on the seabed re-orient themselves fairly quickly to lie perpendicular to the dominant flow [Garcia and Landry, 2018], while tapered cylinders take up an angled position. Therefore, if survey observations of UXO orientation are lacking, it is recommended that the UXO_Angle node be bypassed, and the intermediate Wave-UXO_angle node be set directly, as illustrated in Figure 2.4. The setting "perpendicular" for many munitions, or "angled" for strongly tapered shapes such as mortars, is appropriate. Note that scour burial has a noticeable dependence on this angle, and in the face of no knowledge, it is recommended that the Wave-UXO_angle PDT be set to "perpendicular".

The presence or absence of fins on the munitions strongly modifies the ability of UXO to re-orient with the flow. Depending on the age and history of the munitions, an estimate of the probability distribution of intact fins may be able to inform the Wave-UXO_angle setting. Information into fin breakage percentages and other fragmentation situations is being sought from remediation sites where accurate surveys have been completed.

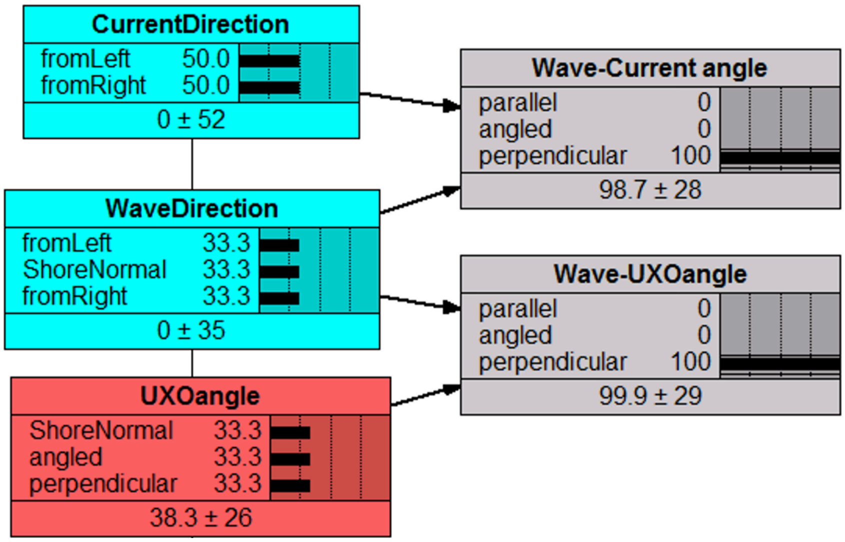

Figure 2.4 Recommended settings for Current, Wave and UXO angles when local conditions are unknown.

In the shallow near-shore region, from the outer surf zone in towards the beach, it highly probable that waves crests are aligned with the shore, due to bathymetric refraction, while currents must travel alongshore. Therefore, when no local knowledge is available, setting the intermediate node Wave-Current_Angle PDT to perpendicular is reasonable (Figure 2.4). Note that the Current_Direction and Wave_Direction input variables also inform the Migration_Direction estimation, so particular effort should be invested into obtaining these directional measurements if migration appears likely.

Further information of recommended bin assignments to use when no input information is available can be found in Appendix C for other UnMES nodes.

3. Comparison to Field Data

Detailed comparisons of time series of predicted scour burial and motion onset were presented in Rennie and Brandt [2017a], focusing on measurements from the TREX13 field test in the Gulf of Mexico [Calantoni, 2017]. Using the Long Point, Martha's Vineyard (MV) data [Traykovski, 2017], agreement between measured and predicted probability distributions of migration distances was obtained, which provided a verification that the

UnMES implementation was correct. This is not a validation of the migration models, since that data set was itself used to adjust the model coefficients.

The field data currently available for burial, and especially for migration, is not sufficiently numerous to determine statistical confidence in probabilistic predictions. In order to accomplish a true validation of UnMES, a significantly larger population of observations is needed. A discussion of the minimum sample numbers required is presented in Section 3.4.

3.1 Verification of Liquefaction Model

An improved process model for burial by liquefaction has been included in Prototype UnMES. The physical basis is described in Rennie and Brandt [2019a] and model integration discussed in Section 2.1. A set of observations from a field experiment where liquefaction burial appeared to dominant occurred during the DUCK15 test [Calantoni, 2017] at FRF. Very deep burial depths were recorded (more than 6 times the UXO diameter) at a location in h = 8 m depth. During this storm, records from the large quadpod system at h = 8 m indicted the far-field bathymetry had not accreted; therefore the observed deep burial must be due to local processes. The seven %Burial observations, plotted in Figure 3.1a, increased with UXO density, as expected from characteristics of the liquefaction process. The PDT of the observations is shown in green, discretized into the % Burial bins commonly used in the expert system.

The largest H_{sig} observed during the two-day storm were largely between 3 to 4 m, with long wave periods (> 12 s). The Prototype Core UnMES is queried for the predicted response to the storm, using these wave input PDTs. The surrogate UXO deployed during DUCK15 organized into 3 density groups, categorized as "bullet" for the most dense (S_g > 7), and "mortar" for the moderate densities. The single data point where S_g < 3 is categorized as "howitzer" (plotted in magenta in Figure 3.1a), and exhibited the least degree of burial. The percentage burial predicted by UnMES (Figure 3.1b) matches the observed PDT quite well.

Note, however, that because the DUCK15 observations were included in the data set used to determine the friction time scale for the current liquefaction model [Friedrichs, 2018], this comparison does not constitute a validation of the liquefaction contribution to Total%Burial, but merely a verification that the liquefaction process model has been correctly implemented, and integrated into UnMES. However, as a prediction that almost all (~95 percent) of the UXO in this location would experience burial during this storm (Total%Burial > 75%), this is a validation point for UnMES, clearly reproducing what was observed.

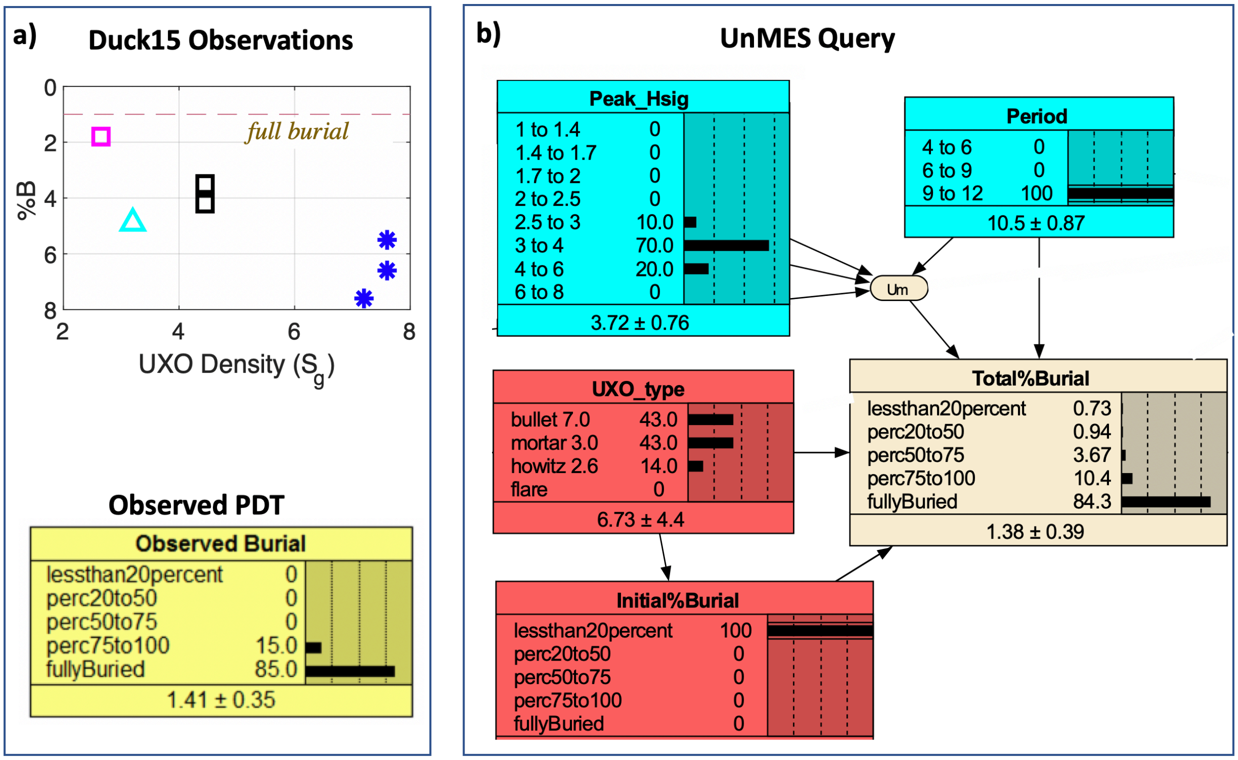

Figure 3.1 Comparison of a) field data and b) UnMES predictions for high-energy storm involving liquefaction burial. Observations from DUCK15 [Calantoni, 2017] experiment.

3.2 Comparison of Migration Predictions

The conditional probability table for the Migration_Distance variable in Prototype UnMES is populated using formulae (see Appendix D) based on the assumption that UXO speed after onset of motion varies as $(U - U_{crit})^3$, where the onset threshold for motion, U_{crit}, was determined from the relationship between the object mobility number and a ratio of the object diameter to a bottom roughness scale as defined in Rennie, Brandt and Friedrichs [2017]. The duration over which movement continues is not well established; the present formula incorporates an estimate based on mobility number exceedance.

The development of a satisfactory model for UXO migration has been hampered by a lack of field observations of migration coincident with measurements of hydrodynamic forcing. In the large majority of coastal field tests, UXO with realistic densities have been observed to bury. For most observations where migration occurred, the precise timing of movement was poorly known. More recent experiments with "smart" surrogate munitions, which internally record IMU data, have helped pinpoint exactly when motion commences. The most extensive field set of migration observations were obtained at Long Point, MV during 2014

(Traykovski, 2017), however no clear correlation between the timing revealed by IMU data and the measured wave and current time series could be discerned. Coefficients in the present mobility number estimation integrated in UnMES have been tuned to match the distances recorded in the Long Point data set.

In late winter 2017, six surrogate UXO (listed in Table 3.1) were deployed on the shoreface off Wallops Island, VA [Calantoni, 2018a] for a late winter field test designated WIMMX. Three surrogates were placed near each of two Quadpods which measured in-situ waves and currents sited in water depths of 9 and 11 m. During a storm event on 14-March-2017, the 81 mm mortar from the 9 m location was observed to migrate a substantial distance (> 60 m, marked yellow in Table 3.1), while the other five surrogates all buried in place.

Table 3.1 Characteristics and Locations of WIMXX UXO Surrogates

Surrogate for UXO Type	Density (kg/m^3)	# @ 9m Quadpod	# @ 11m Quadpod
155 M791	4404	1	1
81 mm Mortar	2745	1	1
4.2" projectile	3712	1	1

The peak H_{sig} recorded at the 9 m Quadpod during 14-March-2017 was about 3 m, with a maximum current speed between 0.3 to 0.4 m/s. The, dH_{sig}/dt for this storm was unusually rapid, with two intervals exceeding 1.3 m/hr. In spite of this large wave growth rate, the Prototype UnMES shows minimal probability (< 4%) that migration will occur for this event scenario, (Figure 3.2), even for the low density UXO_type 81 mm. Instead, UnMES predicts scour burial will lock almost all munitions in place on the seabed.

It has been suggested that the unexpected large migration behavior observed could be due to the presence of patches of muddy sediment at the WIMMX site, where scour burial would be suppressed and the bottom roughness scale reduced, encouraging mobility. The detailed IMU data from the 81 mm mortar revealed that it rolled back and forth in an erratic, oscillatory path, trending onshore [Calantoni, 2018a]. Movement continued for almost 10 hours, until the UXO came to rest in a sandy patch. This duration of migration is longer than that computed in the existing Migration Distance equations. Clearly, the present migration model in UnMES is inadequate: both inherent physics improvement, as well as a more comprehensive manner of characterizing the sediment characteristics are needed.

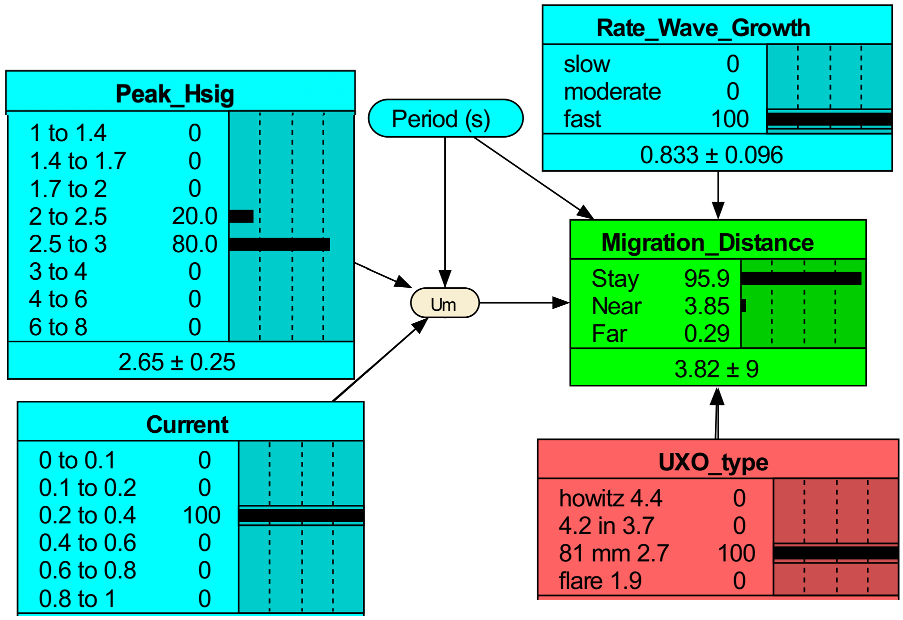

Figure 3.2 UnMES modeling of WIMMX scenario.

3.3 Comparison of Burial and Migration

Another comparison for both burial and migration results can be made using data collected in an early SERDP-ESTCP field test in 2005-2006 conducted by Jenkins [Wilson *et al.*,2008], where a dozen identical surrogates (mimicking rounds for a 5"/38 Caliber naval gun with $S_g \cong 5$) were deployed repeatedly at a two locations at FRF, NC in water depths $h \cong 2.5$ and $h \cong 6.5$ m. The results there showed minimal migration and almost complete burial. Four rounds of deployment were conducted between June 2005 and February 2006, with the burial depths estimated by divers upon recovery, and the surrogates repositioned on the surface at the start of each round. UXO burial was observed in all but one instance, although frequently the surrogates had moved several meters before burying.

Compiled burial and migration statistics of the observations were reported with both locations combined; the resulting data distributions (Figure 3.3a), adapted from Wilson *et al*. [2008], are apportioned in the same bins as used for UnMES nodes (see Appendix C). In the Migration_Distance node, the state "Stay" represents movement less than 5 m. About 70 percent of the measured displacements fell in this category, with the remaining distances ranging between 5 to 13 m, and assigned to the "Near" state. The mean recorded migration distance was 4.6 m.

At the deeper location, the observed wave heights peaked between 2 to 3 m while in shallower depths they had moderated to be between 1.4 to 2.0 m. An UnMES version was made adding a bin in the UXO_type node for the deployed surrogates, with D = 127 mm and S_g = 5. UnMES results for burial and migration distance were modeled at the two depth locations separately, applying the Peak_Hsig ranges given above (Figure 3.3b and c). The currents nearer shore were estimated to be slightly larger than those at h =6.5 m, and all UXO were assumed to have aligned perpendicular to the wave direction. The UnMES PDTs for migration are almost identical at the two locations, with the response largely dominated by the heavy density of the surrogate UXO. There is only a slight difference between the two depths in the predicted burial PDTs. While there is a 10 percent probability of the UXO at h = 6.5 m being less than 3/4 buried, only a minimal probability of increased burial is found at the shallower depth where wave action upon the seabed is generally more pronounced. UnMES PDTs agree with the observed distributions in that both predict a dominant mode at full burial and minimal migration.

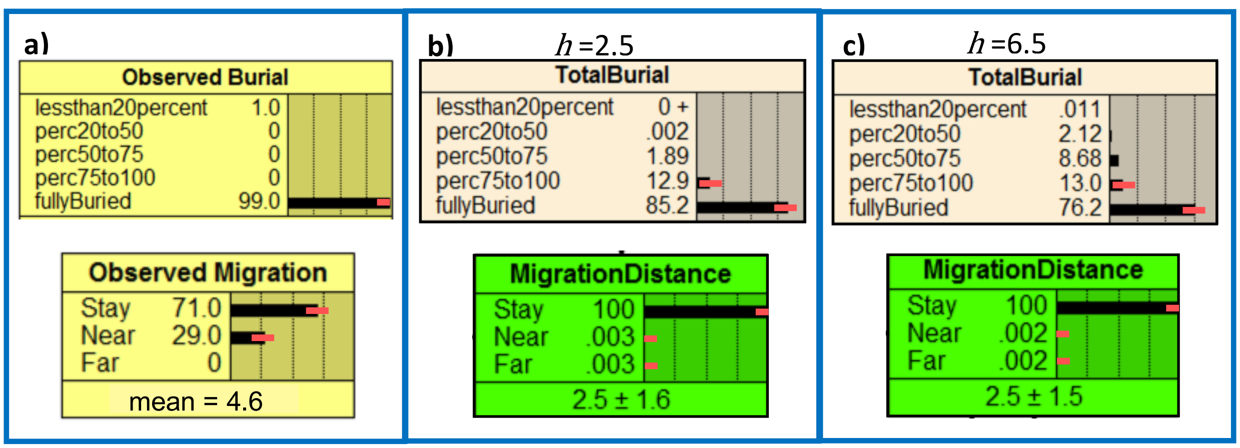

Figure 3.3. Comparison of observed and UnMES probability distributions of burial and migration distance for SERDP-ESTCP field test at FRF, 2005-2006: a) observations [Wilson et al. 2008], b) UnMES PDTs at water depth *h* bin 2-3m, c) UnMES at *h* bin 6-7 m.

In UnMES no migration distance is predicted to exceed 5 m (100 percent in "Stay"). The process model used in the expert system for onset of motion has a strong dependence on UXO density, and significant migration is generally not computed for $S_g > 3$, so the observed movement is not recreated by UnMES. In addition, some probability for partial burial is predicted. Many of the FRF 2005-2006 observations all showed full burial, some very deep, with about a third of the recoveries from 1 m depth or even further beneath the level of the seabed, indicating that other burial processes in addition to scour or liquefaction were active. Accretion of the seabed was occasionally noted, especially at the shallow location. Accretion was not included in the UnMES prediction shown here, which accounts for the reduced burial.

The FRF 2005-2006 field test, using only one surrogate type and repeated deployments at the same location, provided an unusually large number of comparable data points, with about four dozen at each depth location. Overlaid on the results are red bars marking the width of a 90% confidence interval (C.I) about the estimated probabilities. As explained in Section 3.4 below, given a sample size $\boldsymbol{N}$ = 48, a tolerance of ± 10 percentage points is achieved at that 90% C.I. To illustrate, the mode for migration in Figure 3.3a with an estimated probability of 0.71 would really be understood as lying somewhere between 0.61 and 0.81.

Full burial and no migration, as observed and approximately predicted for the FRF 2005-2006 experiment, are the more common UnMES results for dense munitions in shallow coastal sandy locations under even moderate storm conditions. While constituting a point of validation, it is not particularly insightful for remediation management. Of particular concern, due to the potential for human interaction, are situations when UXO are found on beaches or in very shallow water. If the beaches had been previously cleared of munitions, site managers usually infer that newly sighted UXO migrated onto the beach from offshore. However, based on recent research, many SERDP MR experts, e.g. Wilson et al., [2008b] and Traykovski [2019], have concluded that unearthing of buried UXO is the more likely explanation. Nevertheless, this continues to be a point of contention.

3.4 Sampling Requirement for Probabilistic Validation

Due to the limitations and diversity of the field studies of UXO burial and migration , previous comparisons to field data to assess UnMES performance were performed using small numbers of data samples, resulting in a limited degree of confidence in the probability estimates. The key challenge is collecting sufficiently many field observations of comparable UXO in comparable environmental conditions to form reliable probability distributions. There is an inescapable tradeoff between sample size versus the confidence in the validation conclusions that can be drawn.

In order to obtain independent and identically distributed observations, the UXO must reasonably be from the same background distribution, i.e., same munitions type. However, the scientific goals of previous field tests required the use of a range of UXO characteristics in order to improve understanding of the effect of munitions size, density, and disposition on burial and mobility processes. In designing a validation test, the focus should be on deploying many UXO of just a few representative types, in order to make statistically sound comparisons. Based on the statistical analysis below, estimates show that sample numbers of several dozen, at least, are required to achieve reasonable confidence levels at tolerances that yield useful insights.

A standard statistical method to quantify the quality and uncertainty is to compute confidence intervals (C.I.) of the observations. A discretized probability distribution forms a vector $\vec{\boldsymbol{p}}$ whose entries sum to 1. In UnMES, probability distributions are discretized into bins whose widths are determined by the observable level of information, as well as utility for remediation application. An UnMES PDT is an estimate $\hat{\boldsymbol{p}}$ of the true $\vec{\boldsymbol{p}}$. A confidence interval, or confidence level $100(1-\boldsymbol{\alpha})\%$, for $\hat{\boldsymbol{p}}$ based on $\boldsymbol{N}$ observations is the set of values of $\hat{\boldsymbol{p}}$ that satisfy the following: if $\boldsymbol{N}$ samples are repeatedly collected and form confidence intervals from the observations, at least $1-\boldsymbol{\alpha}$ fraction of the intervals computed from each data collection will contain the true $\boldsymbol{p}$.

Typical values used for $\boldsymbol{\alpha}$ are 0.05, or 0.10 (corresponding to the 95th or 90th percent C.I.), however, useful guidance can be found with smaller confidence intervals. Assume the C.I. are of the form $\hat{\boldsymbol{p}} \pm \vec{\boldsymbol{d}}$ for a tolerance vector $\vec{\boldsymbol{d}}$ of some estimate $\hat{\boldsymbol{p}}$**.** With a chosen confidence level $\boldsymbol{\alpha}$, the tolerance achievable is then proportional to $\frac{\mathbf{1}}{\sqrt{\boldsymbol{N}}}$, so quadrupling the sample size halves the tolerance. Each component of the tolerance vector also scales directly with $\sqrt{\boldsymbol{p}(\mathbf{1}-\boldsymbol{p})}$. The algorithm to estimate required sample sizes [Thompson, 1987] was applied as a function of tolerance and confidence level, with examples plotted in Figure 3.4.

Complicating the analysis, the confidence level achieved for fixed $\vec{\boldsymbol{d}}$ and $\boldsymbol{N}$ depends on the shape of the PDT: confidence in a strongly peaked distribution with a dominant mode is more easily obtained than for a distribution close to uniform. The grey bars overlaid on the inset plot illustrate a tolerance of $\vec{\boldsymbol{d}}$=[0.1 0.1 0.1] applied to a 3-bin PDT that has a dominant modal distribution. The same tolerance about small probabilities clearly cautions against interpreting these predictive values as exact, as even a slight change would modify the bin assignments. In Figure 3.4, at a 90% C.I., the same sample size applied to a uniform PDT (plotted in red) yields tolerances about 50% wider than for a modal distribution (solid blue).

Results in Figure 3.4 show that a modal PDT from UnMES could be validated at 80% C.I. with a tolerance of $\boldsymbol{d}$ = 0.1 using a sample size of 33, while to achieve 95% C.I. would require about $\boldsymbol{N}$ = 60 for a modal distribution at $\boldsymbol{d}$ = 0.1. However, for more uniform probability distributions, validation at higher confidence would only be achieved for sample sizes over a hundred, without unacceptably large tolerances. The SERDP field tests conducted so far have reported results for groups of distinct UXO types within a comparable environment numbering less than a half dozen (except for the 2005-2006 data analyzed in the previous section). A validation test for UnMES, will require a more data-intensive approach, such as the field experiment being designed by Calantoni [2018b], as well as a careful choice of just a few UXO types whose characteristics span the domain of interest in a revealing manner. Improvements in "smart" surrogate technology and underwater tracking accomplished in recent SERDP MR projects will help to make such a field experiment more economical. Validation with statistically adequate sampling of a few selected representative UXO types and environmental conditions would lend sufficient confidence in the core processes models and the overall UnMES BN approach.

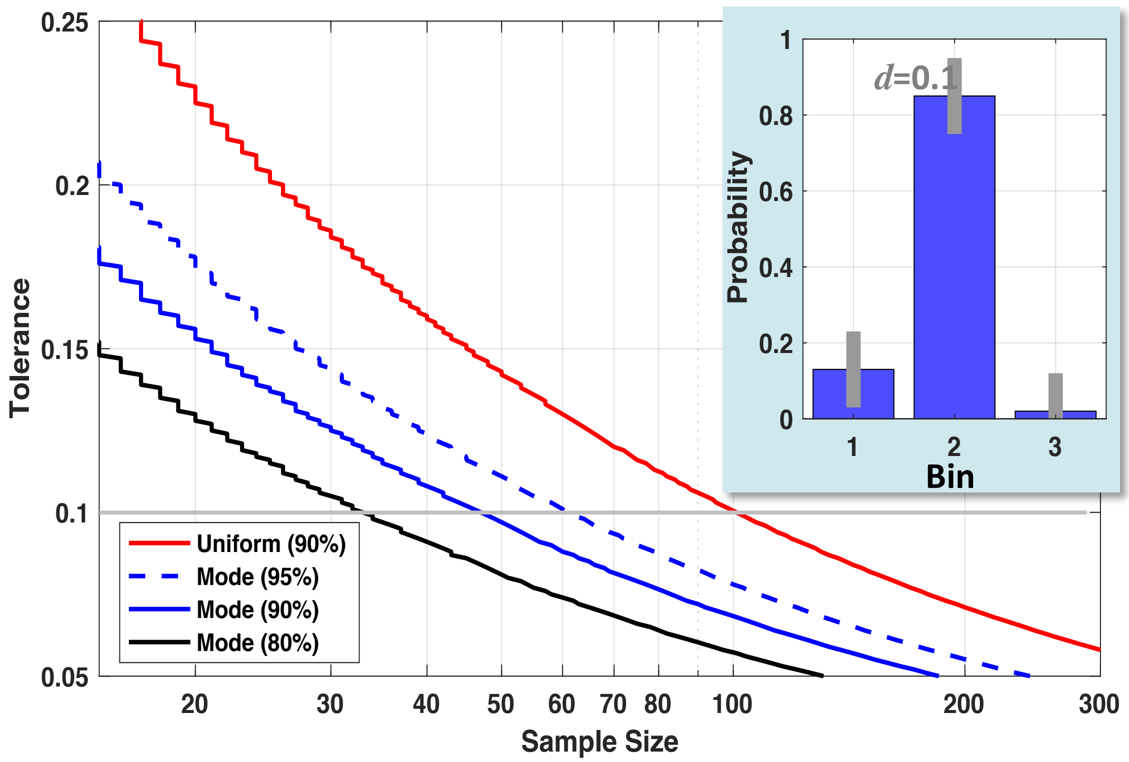

Figure 3.4 Tolerance widths for fixed confidence internals versus sample size.

4. Application of UnMES

Several methods of applying the capabilities of UnMES to explore site management concerns are described in the following sections.

4.1 Sensitivity Assessment

The Netica software provides the capability to perform sensitivity analysis on the Bayesian Network, identifying which nodes provide the most information about a target variable; i.e.

how input at one node will likely change the probabilities at another. In Table 4.1, the input nodes are ranked in a semi-quantitative manner according to the size of their contribution to the response of target (query) nodes Total%Burial and Migration_Distance. The analysis quantifies how much the query node would be influenced by a single finding at each of the other nodes, using variance reduction as the ranking metric. Both the bin ranges chosen for the variables and any node settings can affect the sensitivity values significantly. Here the relative ranking is illustrated for the case where Initial%Burial has been set to lessthan20percent.

Table 4.1 Sensitivity Analysis for UnMES BN Inputs

Shallow *h* = 3 m		Deep *h* = 8 m	
Total%Burial	Migration_Distance	Total%Burial	Migration_Distance
UXO_type	UXO_type	Peak_Hsig	UXO_type
Peak_Hsig	Peak_Hsig	UXO_type	Peak_Hsig
Wave_UXO_angle	Total%Burial	Wave_UXO_angle	Total%Burial
Current	Rate_Wave_Growth	Current	

The sensitivity analysis is presented for both shallow (*h* = 3m) and deeper (*h* = 8m) locations with entries for nodes with the highest contributions. Nodes marked in orange account for variance reduction larger than 10 percent; those in yellow make smaller contributions and the blue entries only about 1 percent. The variance reduction from the unlisted variables is minimal. The dominant contributor in most cases for both query nodes was the intermediate variable U_m, which represents a combination of hydrodynamic inputs, most significantly Peak_Hsig. For the CFD application with UnMES (Section 5.3), U_m is directly input, and would replace both the Peak_Hsig and Current nodes in Table 4.1. It is clear that accurate knowledge of the wave heights and UXO characteristics at a site are crucial to constructive UnMES application, and should be prioritized when planning an environmental assessment budget.

4.2 Comparison of Low versus High Investment in Environmental Characterization

In this section UnMES predictions are used both to examine cross-site variation in burial response, as well as to compare results when different fidelities of environmental input data sets are available for representing site conditions. A minimal, low-budget data-gathering effort is illustrated by the case where only a wave time series is observed at an offshore buoy, and generalized static bathymetry is known from either charts or a baseline survey. A large investment in data gathering and regional characterization is represented by the implementation of a comprehensive CFD model like DELFT3D, for which grid development and tuning requires significant resources. For this example, the Duck FRF modelling results from DELFT3D [Palmsten and Penko, 2018] for a storm event in October 2015 are considered. The FRF maintains a Waverider wave buoy offshore of Duck in 17 m water depth. The initial bathymetry for the DELFT3D grid is used for the static bathymetry, shown in Figure 4.2a. A cross-shore section is selected from about 300 m north of the FRF pier.

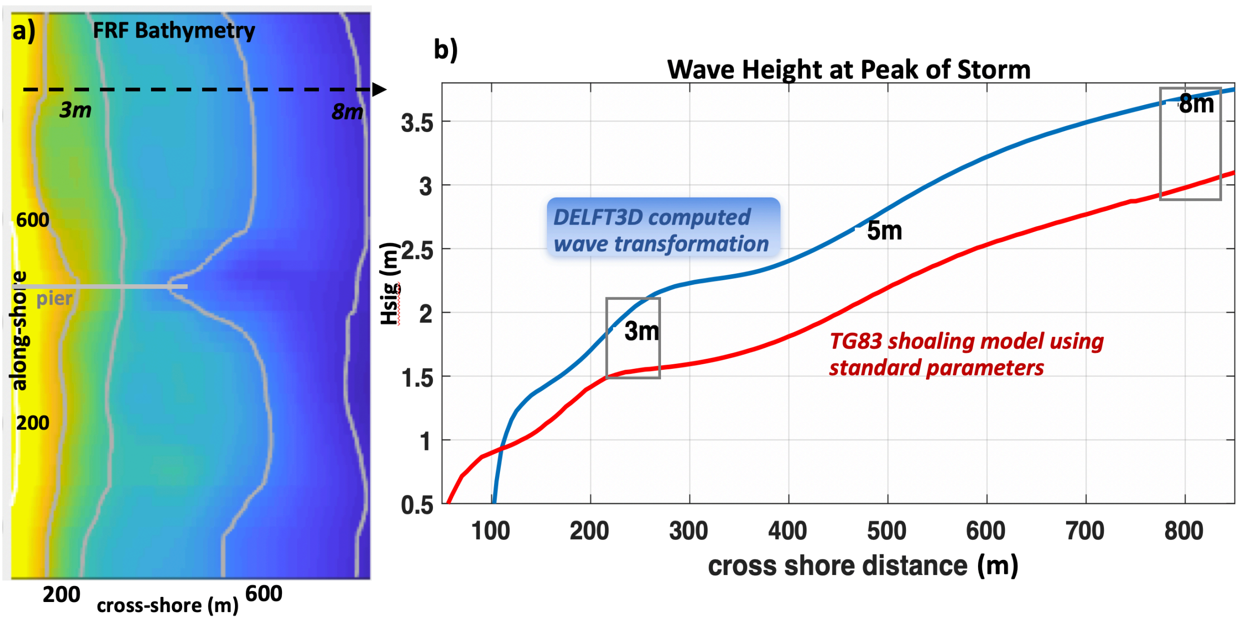

Figure 4.1. a) Bathymetry at Duck FRF. Cross-shore section of interest marked by black dashed line. b) Wave height measured at *h* = 17 m shoaled used two models (red: TG83 and blue: Delft3D). Location in 3m depth is ~ 250 m offshore; 8 m depth is 800 m offshore.

Burial and migration behavior are explored using Spatial Mode UnMES for two provinces (see Section 5.2), with depths *h* = 8 and *h* = 3 m, in this case with the same d_{sed}. As discussed in Section 2.5, the shoaling wave transformation produces significant variation in cross-shore response. Given Waverider measurements at 4 km offshore, two approaches to estimating peak H_{sig} at these locations are applied. The simple TG83 model is applied for the low-investment example, plotted in red in Figure 4.1b, while the more sophisticated wave height model by DELFT3D is shown in blue. The tuned implementation of DELFT3D also provides a detailed time series of currents at all locations in the grid, while a low investment approach might rely on empirically determined relationships between onshore wave conditions and the corresponding nearshore currents.

Burial results for a UXO population consisting of heavy mortars are shown in Figure 4.2. Predictions based on the low fidelity data input are at the top and show similar PDTs, although the potential for partial burial is higher at the shallow location than at *h* = 8 m. Applying the waves and currents provided by DELFT3D, substantially more full burial is predicted (Figure 4.2b) with very little difference between the shallow and deep locations. There are no UXO field data from this storm to verify these predictions, however, the

DUCK15 field test at FRF (h = 8 m) earlier in the year observed full burial for all surrogates. In this case, the high investment environmental input to UnMES produces a better match to the data.

Also available from the high-resolution CFD effort are estimates of erosion and accretion at each grid cell computed by the morphological module of DELFT3D. At the shallow location, a sizable accretion of close to 20 cm is modeled (Figure 4.2c). When the effect of changes in the far-field seabed is included, predictions from high investment data are quite different, with complete certainty reported for full burial at the 3 m water depth.

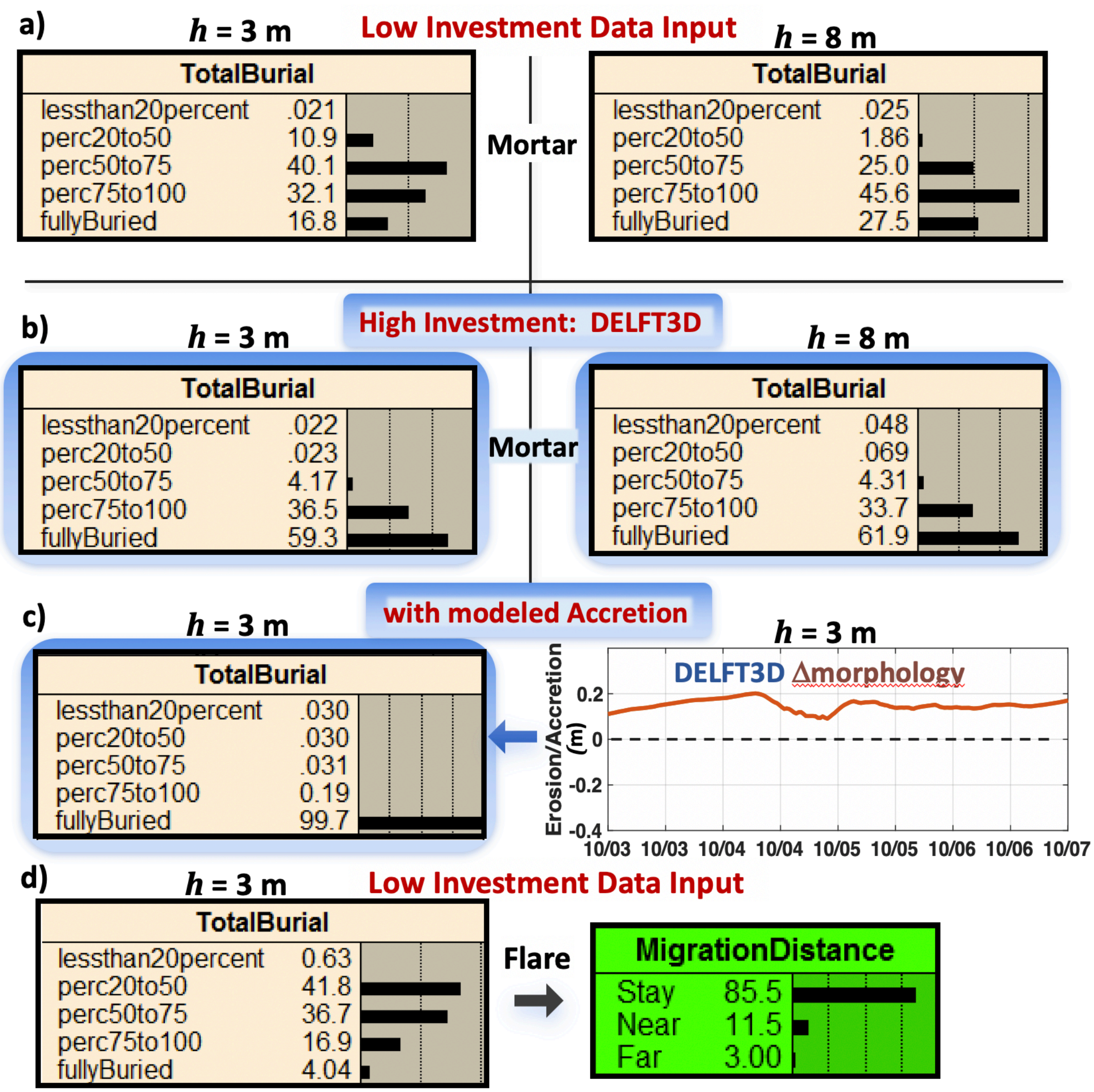

Figure 4.2. a) Burial (%) PDT for UXO mortar from UnMES based on waves and currents derived from TG83 shoaling model and empirical relation. b) UnMES PDT using DELFT3D wave and current input, c) as in b) with the addition of DELFT3D accretion input, d) as in a) but for low density UXO (flare).

No migration is predicted for the heavy mortar at either location based on both input data sets. An alternate case was explored for the low-density pyrotechnic munitions. In this scenario, the TG83 estimated waves at the shallow location would cause noticeably less burial for the flare (Figure 4.2d), largely due to the liquefaction effect. The migration prediction for this lower predicted burial shows over 10 percent chance of "Near" migration distance, along with a small chance of moving "Far," meaning more than 50 m. Burial of flares using DELFT3D input is substantially deeper, especially when the accretion information is included, so that the migration distance PDT remains 100 percent in the state "Stay."

4.3 Diagnostic Query to Characterize Storms of Concern

An alternative use of UnMES for management guidance is to query the Bayesian Network by conditioning on outcomes of concern in order to back-calculate probabilities associated with necessary environmental conditions. In other words, ask the question, what storm forcing would cause a defined disruptive condition at the site. For example, assume that recent surveys have located UXO proud on the seabed and that recovery operations are being planned. Of concern for the site manager is the possibility that the munitions could become buried during in the intervening period, making location reacquisition more difficult. The environmental conditions required for this to occur depend on the type of munitions, the environmental setting, along with the hydrodynamic forcing.

The example diagnostic query is illustrated in Figure 4.3a for a situation where the UXO to be recovered are 155 mm howitzer shells (S_g = 2.6) in spatial province h = 8 m, d_{sed} = 0.26 mm. The distribution of the Total%Burial node is set to the condition of concern (full burial), and results for Peak_Hsig show the wave conditions likely to cause that burial state are concentrated in the highest bins for H_{sig} larger than 4 m, with expected value of 5.3 ±1.6 m shown at bottom of the Peak_Hsig PDT. In order to connect the UnMES model predictions with an analysis that is useful for risk assessment, the probability of very high waves at the location needs to be quantified.

By definition, extreme values are unusual, lying out on the tail of an observed climatological distribution. Statistical characterization of extreme events requires special techniques to model these upper tail distributions using measured long-term time series. There are several statistical approaches for the formulation of extreme value distributions, including Generalized Extreme Value (GEV) fitting to local maxima, or the Generalized Pareto Distribution (GPD) fit to values over a specified threshold [Coles, 2001]. Often a management question requires examining the probability of an extreme event larger than ever observed; these distributions provide the statistical structure to justify that extrapolation in an asymptotic manner. Analysis of maxima (or threshold exceedance) is often organized as return levels associated with return periods (e.g. the "100 year storm" familiar from meteorological forecasting). Because extreme events are rare, the sampling size is fundamentally constrained; therefore, recording the inherent uncertainty is a crucial part of extreme value modeling.

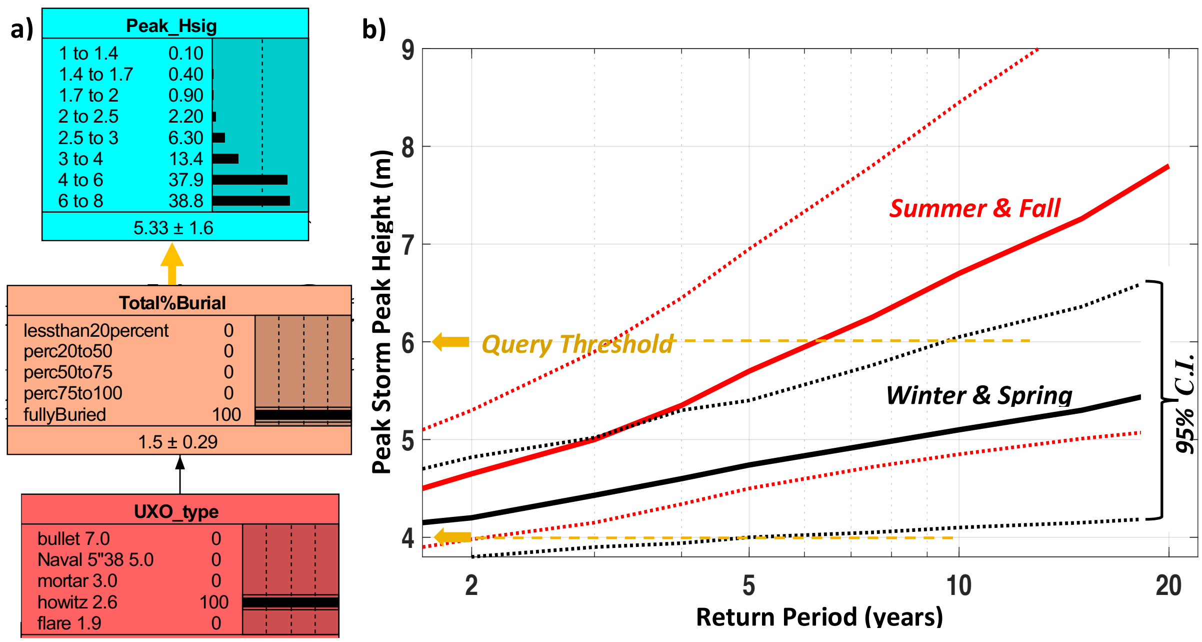

Figure 4.3 a) Example diagnostic query with Total%Burial for howitzer shells set to "fullyBuried" state. b) Extreme value GPD return level for seasonal waves at FRF, Duck, NC. Dashed lines indicate 95% confidence interval.

In temperate latitudes storm statistics commonly vary with season. Therefore for an example analysis of wave records from FRF, wave heights are treated for the winter and spring months separately from summer plus fall. At this location summer and fall experience more extreme waves due to hurricanes and autumn nor'easters. Seasons were omitted for years with excessive (>10%) missing data. The time series were interpolated to a 1 hour time base for sections where gaps between observations were not long, and the data declustered using the peak over threshold method [Coles, 2001], prior to fitting the extreme wave height distribution with a GPD [Ligo *et al.*, 2018]. Figure 4.3b shows the upper tail probability of wave height versus the corresponding return period covering the waves of concern.

Using thresholds based on the UnMES bins identified in the diagnostic query, the likelihood of disruptive conditions can be assessed. During the summer and fall season (plotted in red), the higher threshold, H_{sig} >6 m, for which there is over an 80 percent probability of causing full burial, is likely to be exceeded approximately every 6 years. In contrast, the smaller waves of winter and spring (black) very rarely surpass this threshold. However, the extensive confidence intervals (dashed lines) should be noted. A summary of the query thresholds and seasonal results is given in Table 4.2

Table 4.2 Return period of extreme waves at FRF

Wave Height above threshold	cumulative probability of full burial	Return Period	
		Winter & Spring	Summer & Fall
4 m	58%	likely every year	definately every year
6 m	83%	longer than 20 years	~every 6 years

5. UnMES User's Guide

The Prototype version of UnMES is implemented in the software Netica, provided by the company Norsys [2019]. This section gives a hands-on introduction of how a new user can explore UnMES. Instructions on how to obtain and install Netica are found in Appendix B.

Netica is a relatively accessible program for non-experts working with Bayesian Networks (BN) with an intuitive graphical user interface (GUI). For the prototype UnMES, interaction with the BN can be directly through the Netica GUI, which, for site managers without a background in this type of software, can demand a significant investment in learning. In addition, the prototype spatial implementation relies on wrapper code which is currently written in MATLAB, and therefore requires a MATLAB license. Based on feedback received from preliminary surveys from active USACE and NAVFAC remediation sites (Rennie and Brandt, 2019b), a more manager-friendly interaction, geared precisely to MR site remediation concerns, will be needed. Development of this custom interface is part of our on-going SERDP project, MR19-1126.

Netica can perform various types of inference with a given BN. For example, given a new scenario from which there is limited environmental input, Netica will find the appropriate values or probabilities for all the unknown (output) variables. The relationships between variables in the UnMES network have been learned from training files resulting from Monte Carlo explorations of the deterministic process models whose code is documented in Appendix D.

Several versions of the prototype UnMES have been produced. The edition for general usage models UXO behavior at a single location within a site, meaning that the water depth, h, and sediment grain size, d_{sed}, remain fixed (denoted as the Core UnMES, see Section 5.1). The concept of spatially classifying areas of remediation concern into provinces with unique combinations of h and d_{sed} was introduced in Rennie and Brandt (2015) and is illustrated in Figure 5.1. By holding depth and sediment fixed, this approach reduces the number of nodes required, and makes the Monte Carlo domain simulation much more tractable.

The single site, or Core edition is the most simple, straightforward approach and receives environmental input in the form of standard measured (or estimated) environmental quantities, such as significant wave height and depth-average current. The direct method of interacting with the Core UnMES is by clicking on bins or typing values into the node tables using the GUI, and is best for initial investigation in order to gain an intuitive sense of UnMES management.

A more advanced method, referred to as the Spatial Mode, enables examination of UXO behavior patterns across a spatially varying site. The wrapper code, at present written in MATLAB, allows rapid manipulation of multiple instances of Core editions (each with different h, d_{sed} pairs) that describe the changing bathymetry, sediments and forcing as the region of interest is traversed. When combined as a spatially-provinced framework of UnMES predictions, a map view of UXO burial or migration across site can be presented. The wrapper code facilitates repeated input and output operations that would be tedious to perform using the GUI directly.

The third approach, the CFD version , has been developed specifically to make use of results from a full-physics regional CFD model such as the DELFT3D realization being developed by Palmsten and Penko [2018] for several regions. In this case, DELFT3D directly provides non-observable variables such as effective bottom velocity. By including nodes that represent these computed forcing values, a number of environmental input nodes can be eliminated, making room for water depth and sediment size nodes. This makes implementation of multi-cell grids easier to execute. Figure 5.3 schematically diagrams the relevant difference between the Core UnMES and the CFD version.

5.1 Core UnMES: Single Site Exploration

The best way to get a feel for the insight to be gained from UnMES is to manipulate a single site Core version and observe the responses. To interact with UnMES, it is necessary to master some introductory aspects of the Netica GUI. The Netica user interface for graphically interacting with the Bayesian networks is intuitive and has proven easy to learn and use.

Values in the UnMES nodes can be displayed in several formats, chosen under the Style menu. The most useful style is "Belief Bars" which displays the node's probabilities as percentage bars. The input or parent nodes, which are colored blue or red, represent their probabilities discretized into probability distribution tables (PDT). The child nodes, both intermediate (beige) and predictive (green), display the results of their conditional probability tables (CPT) after updating in response to the input node settings. The displayed CPT results are usually also referred to as PDT.

When launched, Netica will open a small window in the upper left-hand corner of the screen that asks for an optional password; but to run Netica with a small size BN no password is required. Any input parameter, e.g. UXO_type, Peak_Hsig, etc., can be modified by clicking within its node. The most direct and simple PDT can be specified by clicking once on a given input node bin, which forces the PDT to be 100% in that state and zeros in all other bins. Clicking again on a 100% bin (on the name) restores the default PDT for that parameter. Often a uniform distribution is used for the default, indicating that no information is available other than some knowledge of the general range of values that the parameter can take on.

A more detailed input PDT can be specified by double-clicking on the title line of the input parameter node and going to the Table option. This action opens another window where a table of probabilities can be typed into the labeled bins. Netica checks that the entered probabilities add up to 100%. Click "OK" in the Table window and "OK" again in the node pop-up to return to the network. One can observe that the output predicted distributions, e.g. Total%Burial or Migration_Distance, are automatically updated to reflect each new input PDT specification.

5.2 Spatial Mode Implementation

Note that use of the wrapper code that efficiently replicates UnMES inquiries across the spatial variations within the study region currently requires a MATLAB license, as well as additional installation to set up the Java-based Netica application programming interface. This initial installation procedure is outlined in Appendix B. Future development plans include migration to wrapper code written in the open-source Python language, eliminating the MATLAB license requirement. A nominal licensing fee will remain for the use of the Netica API after this transition.

The spatial implementation employs multiple instances of Core BNs, each with different h, d_{sed} pairs, that describe the varying environmental conditions (bathymetry, sediments, forcing) across the area. By holding the water depth and sediment type values fixed within each instance, the BN complexity is substantially reduced, as well as encouraging a useful conceptualization of the different functional provinces that comprise the site. The concept of partitioning the remediation site into provinces is presented in Figure 5.1, illustrated with an initial custom interface for UnMES being prototyped for demonstration to site managers to invoke feedback for further improvement.

The leftmost panel in Figure 5.1 shows the bathymetry at an example sandy site, discretized into seven depth bins at the same levels chosen for the *h* node. In the middle panel is plotted the sediment grain size, which is frequently observed to be larger near the shoreline, and finer offshore, in equilibrium with wave energetics. The five d_{sed} bins are chosen to be fairly wide, as the sensitivity of the results to d_{sed} is small (Section 4.1). The combination yields a set of 16 unique provinces, shown in the right hand panel, less than half of the multiplicative pairing of all *h* and d_{sed} bins, because of the geographic correlation between *h* and d_{sed}, a correlation that is frequently observed. In this example, a set of 16 custom BN (version of the Core UnMES) would need to be generated for a spatial mode implementation.

In the current spatial implementation, the various *h*- and d_{sed},-specific variables are queried independently along a set of provinces. The spatial wrapper code does not add additional functionally, merely facilitating the repetitive input of varying environmental findings, and querying of predicted beliefs at multiple locations. The exception is bookkeeping of possible changes in munitions' abundance and UXO_Type probabilities when Migration_Distance larger than the province size is computed. The overall province dimensions are initially determined by the gradations in depth and sediment, however for ease of implementation, the provinces could be sub-divided into grid cells, similar to the CFD approach as illustrated in Figure 5.2.

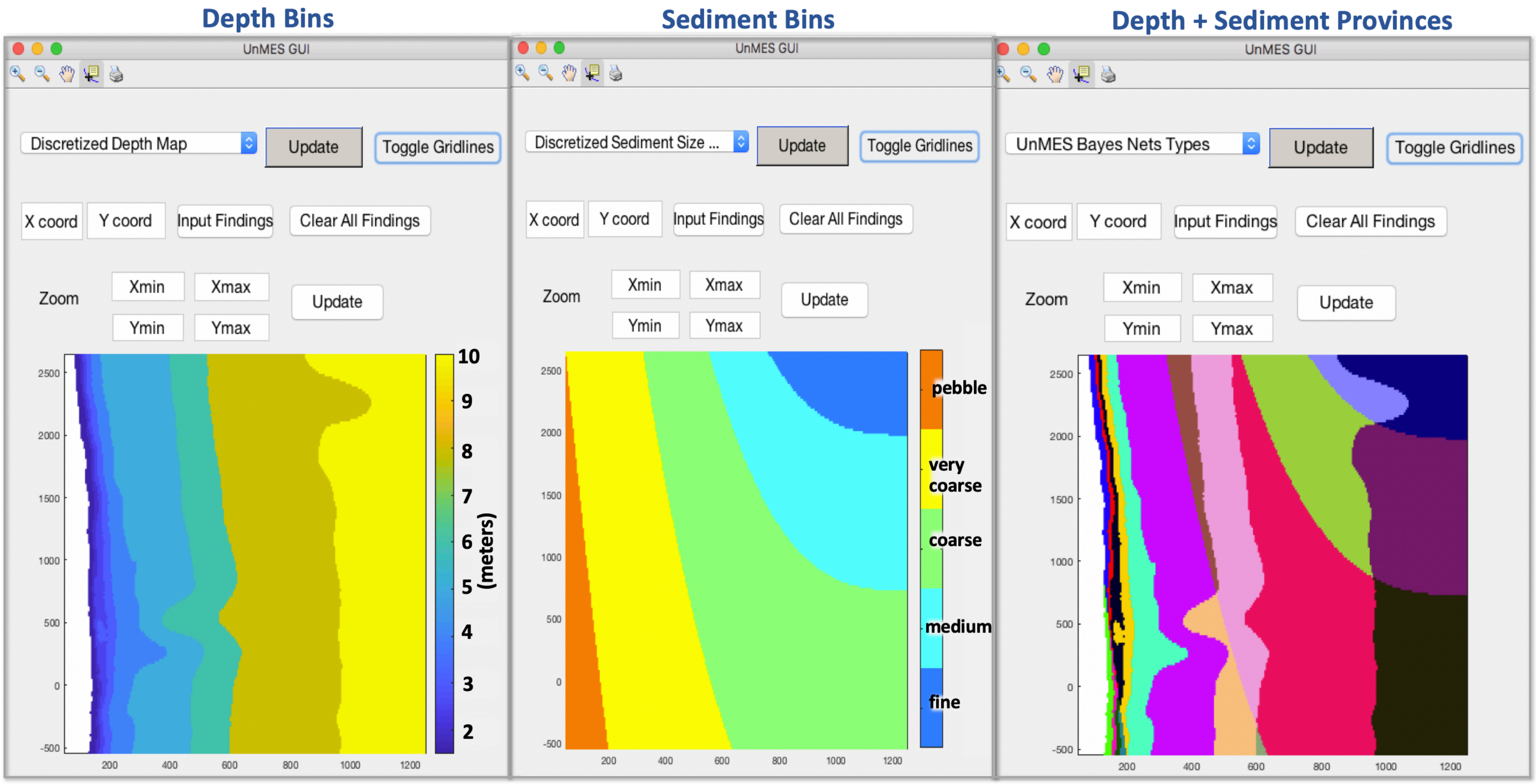

Figure 5.1. Three views using notional UnMES GUI customized to display spatial province maps: a) map of water depth, *h*, discretization, b) map of sediment grain size, d_{sed}, apportioned into standard sand classes, c) all unique combinations of *h* and d_{sed}, totaling 16 provinces.

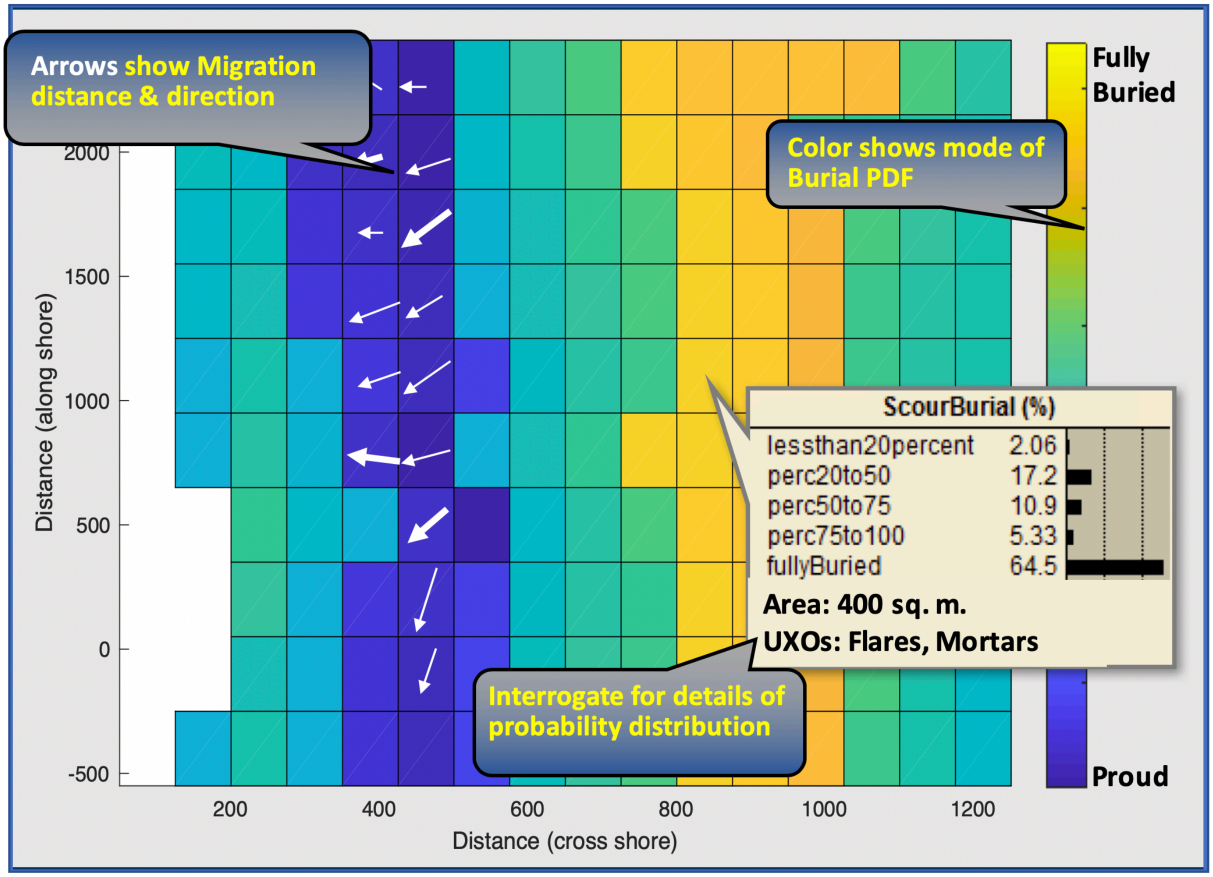

Figure 5.2 Notional output product visualizing spatially varying UnMES output.

The important functionality provided by the spatial wrapper is encompassed in the visualization products presenting map-view summaries of the expert system calculations. Figure 5.2 shows a prototype display developed as a notional product to solicit feedback from end-users. Improved methods to output probabilistic information in a manner readily understood by site managers are under investigation. Map presentations best display scalar values only, e.g. the mode of a PDT as shown by the color assignments in Figure 5.2. To convey complex multi-dimensional information, various methods inviting user interaction and interrogation (indicated by figure pop-ups) appear promising. It is important to translate probabilistic results into simple risk metrics that are relevant to their specific concerns. Spatial visualization, as well as other aspects of spatial implementation, are still being actively researched.

5.3 Version for CFD Model Usage

The combination of the expert system with the DELFT3D gridded CFD model being realized by Palmsten and Penko [2018] prompted creation of an UnMES version where the detailed computed hydrodynamic and morphological variables could be input directly in the BN.

Successful tuning of DELFT3D requires use of successively finer resolution spatial grids on which application of the provincing construct discussed in the previous section would require an inconsistent loss of information. Precise physically relevant quantities such as the orbital velocity and current at the seabed are available from the CFD model, and do not need to be estimated from measurements of wave height or depth-averaged current. In this case, the water depth input is no longer required, and the sediment grain size can be incorporated as a standard input variable, obviating the need to customize versions of UnMES for each spatial province. Spatial implementation and visualization are still under active research Figure 5.3 compare diagrams of UnMES for the Core and CFD versions focusing on the hydrodynamic portion of the BN.

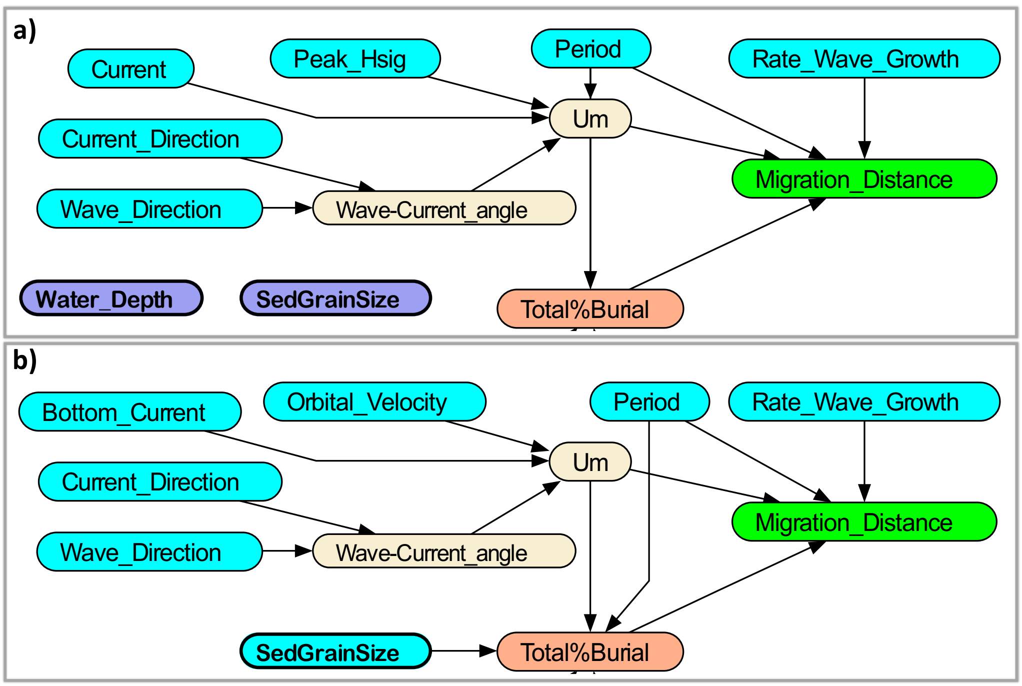

Figure 5.3 Bayesian network diagram for a) Core and b) CFD mode UnMES.

Note that although the Wave_Current_angle is available directly from DELFT3D, the current and wave directions are still included in the network for their use in determine the direction of migration. Although no longer needed as a parent to the U_m node, wave period is nonetheless required as a parameter in estimation of burial and migration distance. Coupling of this streamlined UnMES mode with DELFT3D will be explored in both SERDP projects MR-2733 and MR19-1126.

6. Conclusions and Implications for Future Research

A number of examples applying UnMES to various UXO burial and migration scenarios demonstrate usage, both predictive and diagnostic, of the expert system for remediation guidance. Many cases evidence reasonable agreement between UnMES predictions and field observations. However, a sufficient number of experimental field results under similar conditions are lacking to provide satisfactory statistical validation at this time. Additional examples demonstrate further functionality of UnMES including sensitivity analysis useful for guiding investment decisions in environmental data gathering.

It is recommended that future research to improve UnMES predictive capabilities focus on the following areas:

1. Understanding of temporal storm patterns and occurrence frequencies as the magnitude, duration, and inter-event interval of storms, because storm waves are the strongest driver of scour and liquefaction burial as well as UXO migration.

2. More accurate modeling of burial due to impact penetration for high-velocity munitions.

3. Further investigation of coastal bathymetric modeling to encompass sites with differing profile characteristics, e.g. short and steep (East Coast) versus broad and gradual (West Coast).

4. Improved migration model capturing the inherent physics, particularly addressing the duration of UXO migration events.

5. Obtaining a database of adequate sample size to provide a basis for UnMES validation with statistically sufficient data on several representative UXO types and environmental conditions in order to develop acceptable confidence in the core processes models and the overall UnMES Bayesian Network implementation.

Further development of the expert system will also focus on improving visualization output that graphically conveys the probabilistic information and risk assessment products to site managers for their better understanding. In addition, an enhanced user interface to increase ease of use will be designed in consultation with managers of selected remediation sites of interest.

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Appendix A

Appendix A: Required Environmental Inputs to UnMES

In order to populate the input nodes of UnMES fully defining a predictive scenario, a significant amount of site-specific hydrodynamic and geologic data is required. This Appendix discusses the information that users of the expert system would need to obtain so that effective, actionable predictions can be made.

To apply UnMES at a specific remediation site of interest, it is necessary to have estimates of recent and historic local environmental conditions that provide the forcing for UXO burial and mobility. The mandatory environmental inputs are diagramed as connected nodes in Figure 1.1. Information about the variable ranges and resolution, as applied in the Prototype version focused on wave-dominated coastal locations, can be found in Appendix C. Note that for sites with different conditions, expanded ranges or increased resolution can easily be implemented in a custom version.

In view of the probabilistic approach of UnMES, site assessment can be undertaken with uncertain or even unknown conditions; however, more precise and accurate environmental specifications result in better, more useful UXO burial and mobility estimates. The environmental input information needed to exercise UnMES fall into two categories: hydrodynamic and geologic. Also crucial is information about the munitions of concern present at the site of interest: UXO types, firing or emplacement patterns, time and manner of deposition. For a spatial application of UnMES, required at most management sites where conditions vary across the area, some data will necessarily be two-dimensional, either on a gridded or provinced coordinate system. The CFD approach, discussed in Section 5, where a comprehensive gridded numerical model like DELFT3D is used to simulate the hydrodynamic and morphological responses across a site [Palmsten and Penko, 2018], is the optimal means of obtaining and organizing accurate, detailed multi-dimensional input to UnMES, albeit involving considerable resource investment to implement.

Geologic Input: Site Bathymetry & Composition

Knowledge of the distribution of water depth and sediment composition throughout the site of interest is critical for determination of the burial and mobility of the UXO as each of the constituent physical processes depend on these parameters, e.g. scour, liquefaction, bedform erosion, etc. Based on patterns of bathymetry and sediment characteristics, UnMES will province the site into categories or provinces with similar properties (within the bounds of the discrete values in the node states) in order to facilitate efficient analysis of the BN (Section 5.2). This allows for the development of site maps of burial and mobility potential and analysis of the spatial variation of associated risk.

Specific inputs required include:

- Bathymetry
- Seabed sediment composition
- Characteristics of dunes
- Bathymetric variation (erosion and accretion)

The bathymetry should be referenced to mean-sea-level. Optimal input are precise water depths across the site obtained from repeated site surveys that capture bathymetric changes due to event-driven and seasonal variations. However, estimates can be derived from theoretical equilibrium water depth profiles [Rennie and Brandt, 2019a] or historical measurements at the site, or extant databases, i.e. data available from previous benchmark regional surveys and general bathymetric databases such as the Navy standard Digital Bathymetric Data Base (DBDB-V) produced by the U.S. Naval Oceanographic Office (NAVOCEANO, 2017). Higher resolution coastal digital elevation models (DEMs) are also available for some locations from National Oceanic and Atmospheric Administration (NOAA), many with 1/3 arc sec (~10m) resolution.

In sandy coastal regions, the composition of the non-cohesive sediment is characterized largely by the median of the sand grain size distribution. Geotechnical information such as shear strength, which quantifies resistance to penetration, is assumed to have a fixed representation (Section 2.2). For extension of UnMES capabilities to embody munitions behavior in cohesive estuarine locations, additional sediment input will be needed.

Temporal variation in bathymetry is represented both by information about possible dune formations present in the area (Sections 2.3 and C.2). Dune Height can be modelled as a function of tidal current, or observed height may be entered directly. The wave length of dunes is estimated as a function of local water depth, but can be overridden by entering a PDT of observations into the Dune_Length node. Knowledge of both long-term shoreline retreat and seasonal variability is input through the general purpose Erosion/Accretion node. Lacking specific site knowledge, a gaussian distribution of Erosion/Accretion with standard deviation decreasing to zero at the closure depth is a reasonable assumption. It is also important to consider how the presence of coastal structures at the site, e.g. berms, sea walls, jetties, affect aspects of the geologic setting, although there is at present no specific input mechanism into UnMES.

Hydrodynamic: Waves & Currents

Waves and currents are the driving forces for UXO burial and mobility. Especially critical are larger storm events that generally occur on several occasions during the course of a year, perhaps with seasonal variation in statistics. UXO buried for multiple years are likely to have experienced repeated high forcing events. Waves and current directly affect burial through local processes (scour, liquefaction) and mobility but also indirectly through their effects on far-field seabed processes such as dune formation and migration causing UXO exposure (erosion) and burial (accretion).

Specific inputs required include:

- Wave height, period, and direction
- Tidal currents magnitude and direction
- Along-coast nearshore currents and direction

Astronomical tidal currents are generally very well documented at most locations. Wave statistics can be obtained from historic meteorological records including from buoys maintained by the National Buoy Data Center (NDBC) and others located in the vicinity of the site of interest. Most available wave measurements are from offshore buoys which will be moderated significantly in the shallow depths nearshore; models to compute this transformation are discussed in Sections 2.5 and 4.2. Additional inputs that record storm frequency, durations and inter-storm intervals will be considered for inclusion in future versions that capture long time-scale behavior.

Alongshore currents driven by wave set-up can be significant in the nearshore region, however their magnitude can vary strongly with the local depth profile and incoming wave characteristics. In locations where few in-situ current measurement had been made, approximate patterns can be estimated by comparison to analogous sites. The input to UnMES should represent mean over depth, residual current averaged over a time scale on the order of an hour.

Munitions Characteristics:

Knowledge about the population composition of munitions of concern at a site is usually initially based on historical military records. This knowledge is then updated by findings from surveys conducted during the Site Inspection or Feasibility Study phases. Of particular importance to physical processes modeled by UnMES is the density of the munitions. For locations where penetration upon initial impact is of concern, the presence of fins, and some estimation of their breakage, are influential factors in burial behavior. It was noted in Section 4.1 that burial and migration predictions in the Prototype UnMES show significant sensitivity to the munitions specification. That is largely because of the wide range of densities covered by the available states in the UXO Type node as implemented, ranging from $S_g = 1.9$ for the Flare, to $S_g = 7$ for the Bullet type.

Appendix B: Installation of Netica by Norsys

The Bayesian Network software Netica is available from Norsys Software at https://www.norsys.com/netica.html

By installing and using Netica, you are agreeing to the terms of use, set forth in the license agreement, which is provided during the software download from Norsys in a separate document. Note that an initial exploration of the Mode 1 (single site) UnMES Bayes Net (BN) may be performed without purchasing the Netica license in "limited mode", however network size is restricted. The license is relatively inexpensive.

Requirements: Netica Application requires a PC running any version of Microsoft Windows from XP to Windows10. The 64 bit version of Netica requires Windows 7 or higher. Installation requires less than 10 MB of hard disk space.

Netica will run well even on a very slow PC , using very little RAM (about 30 MB), but working with larger, complex Bayes Nets may require much more speed and large amounts of RAM. The prototype version of UnMES is small enough to not exceed this limit.

To run Netica from a Mac computer, you must install a compatibility layer for running Windows programs. We generally use a Windows virtual machine accessed through Microsoft Remote Desktop.

Windows Installation:

1. First obtain the Netica package file. Download it from the Norsys website. The name of the file will beNetica_Win.exe.
2. Choose “Run” from the download dialog box, or save the file to disk and then double-click its icon.
3. When a dialog box appears, enter where on your hard disk you want the Netica folder placed. You can put it anywhere you wish; popular choices areC:\Netica orC:\Program Files\Netica. Make sure there is a drive letter (e.g. “C:\ ”) , or at least a slash ("\") at the front of the location. You don’t have to include version information in the name, because a folder called Netica ### will be created within it, where ### is the version number.
4. Click the UnZip button and then close the dialog box.

Running:

The UnMES software files have the file extension `.neta` or `.dne`, and are linked to the Netica executable Netica.exe (64-bit version) which resides in the Netica ### *home folder* which is saved by the installation procedure, and has the icon. Within the home folder will be all the files required for Netica, including the 32-bit version,Netica32.exe, The first time you run an executable, you should right-click on it, and choose "Run as administrator". If you want you can run it by double-clicking it, but at some time in the future you should run it as administrator to fully register it with the system (for proper icons, opening document by clicking it, COM interface, etc.). On some systems it may take a long time to start the first time; the next time it will start quickly.

If you wish Netica to be on your Start menu, you can use the normal Windows method of dragging the Netica.exe icon from the Netica ### folder (as mentioned above) and dropping it on the Start button. Or drag it to the desktop if you want to make a shortcut there. During your exploration of UnMES, you may generate multiple versions of the `.neta` files. It is best to keep these files in a separate working folder, rather than the home folder. Note that the `.neta` and `.dne` files have the Windows icon .

Password:

The enter-password dialog box will appear, so when you obtain a license *password* from Norsys by e-mail or on your invoice, you may type it in, or better yet copy and paste it in. If you later wish to remove or change the password, choose **File → Netica Password** from Netica's menu.

Tutorial:

With Netica installed and running, you can get an introduction to how it works by doing the operations described in the Quick Tour, or check out the New Features.

JAVA Links for Spatial Mode:

In order to implement the version of UnMES that allows examination of UXO behavior across a remediation site with varying environmental conditions, there has been written Matlab wrapper code that manipulates the multiple instances of UnMES BN (each custom trained for a given h and d_{sed} pair, examples in Section 4.2). The wrapper code interacts with Netica using NeticaJ, the Java version of the Netica application programming interface (NeticaJ API) programmer's library. An API is a software intermediary that allows two applications to talk to each other. Future plans development plans include migration to wrapper code written in the open-source Python language, eliminating the Matlab license requirement.

Information on connecting correctly with the NeticaJ API, and further details of UnMES intatllation and usage are included with the supplementary materials.

Appendix C: Description of UnMES Input Nodes

The variables and BN organization used in the Prototype Version of UnMES (2019) are described below. The present choices for discretization into states or bins are shown, however, these state level can be readily changed when building a custom Bayes Net (BN) for application at a specific site, to provide increased resolution of the probability distribution tables (PDT).

Environmental Characterization:

The nodes that inform UnMES about the hydrodynamic forcing are displayed in Figure C.1a. The PDT for each node shows the state that is recommended as a "best guess", for the situation where no specific environmental data is available yet. The Mode 1 core BN is generated for a given pair of water depth (h) and sediment size (d_{sed}) bins (Section 5.1), Consequently, h and d_{sed} variables do not explicitly appear, but are implicit in the process model results used to train the BN and are represented by fixed value nodes (purple in Figure 1.1). The width of the depth bins chosen reflect the sensitivity of bottom orbital velocity to h for a given H_{sig}, being generally narrow (0.5 m) for shallow depths (less than 3 m), wider (1 m) for moderate depths (3 to 6 m), and 2 m wide for h deeper than 6 m. The present depth states implemented are listed in Table C.1, along with sediment bins generally used for coastal sandy locations.

Table C1. Water Depth and Sand Grain Size Discretization

Bin Label	2to2.5m	2.5to3m	3to4m	4to5m	5to6m	6to8m
h (m)	2.0 - 2.5	2.5 - 3	3 - 4	4 - 5	5 - 6	6 - 8
Bin Label	fine	medium	coarse	verycoarse	pebbles	*states for nearshore*
d_{sed} (mm)	< 0.26	0.26 - 0.5	0.5 - 1.0	1.0 - 2.0	2.0 - 5.0	

C.1 Hydrodynamic Input

Peak_Hsig:

The Prototype UnMES has been developed with comparison to SERDP field work performed in coastal wave-dominated settings, where the most important variable driving the hydrodynamic forcing is the near bed orbital velocities from incoming waves. A common metric of wave size is the Significant Wave Height, H_{sig}, originally defined as the mean of the largest one third of the observed wave heights. A modern definition of H_{sig} is computed as $4\sqrt{variance}$ of the measured elevation spectrum in meters. Another widely used metric, the RMS wave height, H_{rms}, can be converted as $H_{sig} = 1.4H_{rms}$.

Appendix C

The core BN is envisioned as modeling the UXO behavior for one storm event. Often storm duration is defined as when H_{sig} is greater than some threshold, usually set between 1 to 2m, so that the lowest Peak_Hsig bin starts at 1 m. The PDT for this node should represent the distribution of the largest H_{sig} during the peak of the storm, not the overall distribution of wave heights that occurred before and after the peak. There is no recommended setting for Peak_Hsig; some knowledge of this input is required. Note that the direction of wave orbital velocity is assumed to be oriented approximately shore normal.

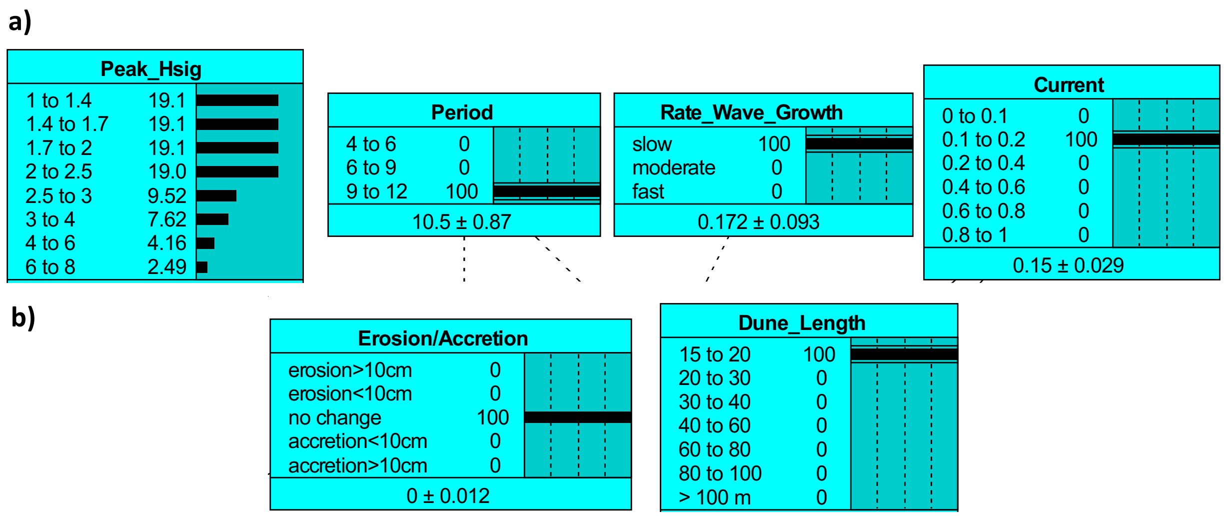

Figure C.1 States for input nodes in UnMES describing hydrodynamic setting.

Period:

This PDT should represent the period of the peak H_{sig} in seconds. Generally, larger waves have longer periods, so this node is nearly always set with the mode probability in the highest bin.

Rate_Wave_Growth:

A variable representing the rapidity with which the waves increase when a storm system impacts the location of interest was added in an effort to capture our understanding of the balance between burial by scour and motion onset caused by larger orbital velocities (Section 2.1). States for dH_{sig}/dt are "slow" for less than 0.3 m/hr, "moderate" for between 0.3 to 0.6 m/hr, and "fast" for wave growth greater than 0.6 m/hr. The large majority of storm events produce wave patterns that fall in the "slow" bin, so that is the preferred setting in the case where the wave growth rate is unknown.

Current:

The Current node represents the contribution to bottom water velocity from longer time scale flows like tidal currents and longshore currents caused by setup. The PDT should be set to express the maximum currents that occurred during the peak storm period. The units are in meters/second. There is no general guidance for current magnitude, except that larger longshore currents will be expected closer to shore. In the case where DELFT3D results provide high resolution information about longshore current patterns, the addition of additional states to further resolve or expand the range of the Current node may be needed.

The direction of the currents and waves are coarsely designated, as shown in Figure 2.4.

Current_Direction:
The current direction bins are limited to either "fromLeft" or "fromRight", denoting the direction (towards)of current flow. The angles assigned to these bins are between -60° to 0° and 0° to +60° from shore normal, respectively. "Left" and "Right" are defined when facing the ocean from the beach. The Current_Direction node PDT setting influences both the Wave-Current_angle and the Migration_Direction nodes. For the CFD spatial application (see Section 5.3), where the nearshore area can be resolved into different sections, there is the potential for offshore-directed flow (e.g. rip currents). Therefore the Current_Direction node in the CFD version should have any addition onshore- and offshore states.

Wave_Direction:
Wave direction is discretized into the bins "fromLeft" (-60° to -20°), "ShoreNormal" (±20°), and "fromRight" (+20° to +60°). Again, "Left" and "Right" are defined when facing the ocean from the beach. The Wave_Direction node PDT setting influences both the Wave-Current_angle and the Migration_Direction nodes. In cases where wave direction is not known, it can be simpler to directly set the PDT of the intermediate Wave-Current_angle node (Section 2.5), overriding the conditional probability settings.

C.2 Geologic Input

Information about the geological setting of the site is given by nodes representing far-field variations in seabed (Figure C.1b).

Erosion/Accretion
Erosional behavior can vary strongly in different coastal regions, depending on geologic history, local sediment supply, and regional sea level rise [Hapke *et al.,* 2010]. Because burial ad exposure behavior is strongly influenced by any seabed variation, the choice of bin numbers, ranges and widths for the Erosion/Accretion node may need to be customized for the site to provide sufficient resolution. Example states shown in Figure C.1b designate "no change" as seabed variation of less than ±2 cm. "No change" should be the default setting for this input node unless there is local evidence of bathymetric change.

Bedform%Burial

The node Dune_Length provides input relevant to estimating local potential for burial or exposure due to bedform migration. The other important factor, Dune_Height, can be estimated from the specified current magnitude (Figure 2.3) or, as mentioned in Section 2.3, a Dune_Height PDT can be designated directly.

C.3 UXO Information

Three input variables are used to designate the characteristics, disposition or initial emplacement of the munitions on the seabed prior to the modeled scenario (Figure C.2).

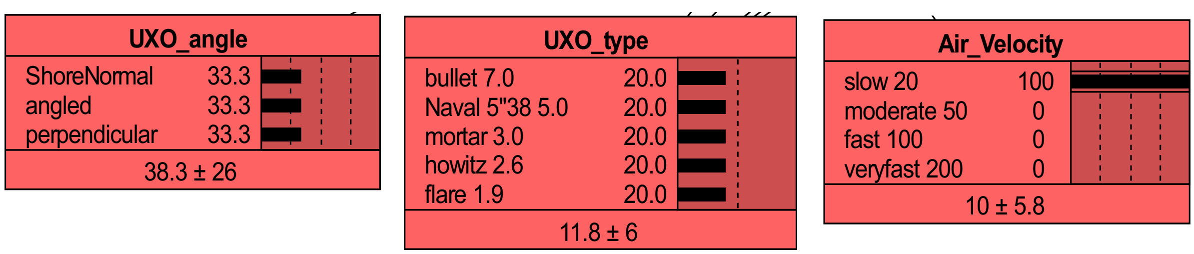

Figure C.2 UnMES nodes defining UXO characteristics and initial disposition

UXO_type:

At many contaminated sites the exact types of munitions of concern are not well known. Even if historical records indicate the general class of ordnance, there are significant variations within some categories [Calantoni, 2017]. Approximations for this input may be derived from wide-area surveys of the remediation site, or estimated from military archives. However, accurate predictions of burial and mobility are strongly dependent on knowing important munitions characteristics such as the UXO size and density (Section 4.1), therefore an effective data-gathering effort is imperative in order to provide adequate definition. The UXO_type input defines multiple characteristics of the UXO including the density and diameter of the UXO, as well as geometry important to impact burial prediction such as tapering and the presence of fins (Section 2.2). The taper of a cylinder is expressed as fraction of the length over which the full diameter is retained, so a completely cylindrical UXO has taper = 1.0, while a strongly tapered shape might have taper = 0.5. The munitions' nose shape, a parameter in the impact penetration model, is estimated from the value, with taper = 1.0 indicating a blunt nose. Future improvements will add additional UXO type information, including the probability of fragmentation, to allow for better discrimination of UXO behavior.

UXO_angle:

The angle of the UXO is defined as the angle its long axis makes from a perpendicular to shore (or shore normal). The bins available in the Prototype version for UXO angle are "ShoreNormal" (0° to 20°), "angled" (20° to 50°), and "perpendicular" (50° to 90°). It does not matter if the angles are to the left or right. In practice, the angle of a UXO discarded on the seabed will rarely be known. Depending on the available surveys or military archives, an informed guess as to a representative PDT may be determined. When lacking knowledge about the UXO angle, there is not recommended input for that node; however, setting the intermediate node Wave-UXO_angle to "perpendicular" is a sensible choice (Section 2.5).

Air_Velocity

The bins for the Air_Velocity node are defined as "< 20 m/s", "20 to 50 m/s", "50 to 100 m/s" and "100 to 200 m/s".This input is of concern only for remediation sites such as artillery proving ground and firing ranges where high-speed impact is a potential cause on initial burial. For other applications, a setting in the lowest velocity bin is appropriate.

Output Variables from Predictive Application

UnMES nodes that are generally examined for insight to burial and migration behavior are shown in Figure C.3. The resolution reflected in the choice of bin widths reflects an assessment of the achievable predictive accuracy.

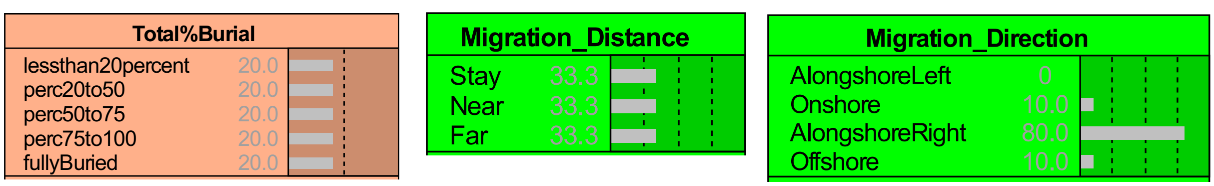

Figure C.3 UnMES nodes indicating burial and migration behavior.

Total%Burial

Total%Burial can be considered as in intermediate node, as it is an important input to predicting onset of mobility, and viewed as a predictive output. In the diagnostic example shown in Section 4.1, it is treated as an input. Although in multiple sections of the UnMES code burial depth is needed in dimensional (length) units, degree of burial is usually reported as a percentage of the UXO diameter, as the relevant information for predicting sensor detection response.

Migration_Distance

Due to the inexact nature of the present state of modeling, this variable is only coarsely partitioned into three states. On the assumption that a shift in position smaller than several meters would not significantly impact ability to reacquire a previously located UXO, the state "Stay" represents movement of less than 5 m. "Near" shows migration between 5 to 5 m.

Migration_Direction

Presently, the assignment to migration direction states is based on rule of thumb, with the assumption that it is dominated by onshore wave forcing. "Onshore" is quantified as between ±30 degrees shore normal. Although the state "Offshore" is designated, it is assigned only a small probability in the Prototype version, which is based on a rule-of-thumb assessment of multiple field observations rather than any physical understanding.

Appendix D: Matlab Code Listing for Deterministic Models

1) **lag_scour_liquify_migrate_ProtoVersion.m**

2) **ZLiquifaction_Proto2019.m**

3) **migrate_estimate_Proto.m**

lag_scour_migrate_ProtoVersion function

- Organize wave-current forcing time series and compute Shields Parameter
- Compute equilibrium scour burial as in Friedrichs et al. [2016] Self-Burial paper
- Estimate lagged burial using increased time scale
- Modify Burial values if high-energy Liquefaction conditions occurred
- Check for possible onset of motion anywhere during time series

```
function [ ScourBeq, Beq, Blag, Bpred, Mdist, Um ] = lag_scour_liquify_migrate_ProtoVersion(Waves, ...
                                                        UXO,  Waterdepth,dsed,  Currents )
```

```
%  1) Compute time-varying (lagged) scour using of longer time scale
%     Implement Friedrichs et al [2016]  Self-Burial paper [2016] ICSE, CRC Press
%     to vompute equilibrium scour burial under combined waves and currents
%  2) Compute lagged cumulative burial under a waves + current time series
%     including Fluidization (Liquefaction) process estimate if high Shields # breaking waves
%
% Input
%    Waves            structure describes wave forcing. Each is scalar (steady) or vector (time series)
%      Waves.deltmin  delta-time (minutes) between each Wave observation in evenly-spaced time series
%                     If deltmin undefined or =0, all  fields should be scalar (steady = fixed in time)
%      Waves.Hsig =   Significant wave height(m). Time series of event or scalar for equilbrium scour
% or   Waves.Uorb =     near bed orbital wave velocity  <-- may be reported instead of Hsig.
%      Waves.T    =     Tperiod  (seconds)
%      Waves.dir  =     wave direction angle(deg) of dominant wave  from perpendicular to shore:
%                                negative = from Left, positive  from  Right, = 0 = shore Normal
%                               "Left" and "Right" are defined when facing the ocean from the beach
%
%    Waterdepth  depth at this location (m)  scalar (assume fixed depth during event)
%    dsed        median sediment grain size (m) scalar or vector  *** Note: in METERS ****
%    UXO         structure describing munition
%     UXO.type         string with name of munitions type (e.g. "mortar")
%     UXO.Sg           specific gravity   (not used in this subroutine)
%     UXO.Diam         diameter (m)
%     UXO.Length       length of long axis (m)
%     UXO.InitBurial   initial burial prior to start of event time sequence
%                               Fractional burial (e.g. 0.2 = 20% of diameter buried)
%     UXO.alpha        angle of attack(deg) between UXO long axis & dominant flow dir (0 = parallel)
%     UXO.mdeploy      index of Waves timeseries to start accumulating burial (default = 1)
%     UXO.mstop        index of Waves timeseries to stop accumulating burial  (default = end)
%
%     Currents.U      Uobs observed current (m/s) (must be same length as Waves.Hsig if time series)
%     Currents.Zobs   Zobs depth of current observation
%     Currents.dir    current direction  angle from perpendicular to shore (deg) of current
%                                     from Left (negative) Along Shore,  to Right (positive)
%                                    "Left" & "Right"  defined when facing the ocean from the beach
%     Currents.beta   alternately, specify angle between orbital wave velocity & current (0=parallel)
%
% Output structure: Each field will be same length as Waves.Hsig input
%   ScourBeq  fractional equilibrium scour burial (= BurialDepth/Diam)  -- accounts for
%             SCOUR Burial only, does not include initial burial
%   Beq   fractional burial assumes equilibrium reached at each time step - Includes Initial burial
%   Blag  cumulative fractional burial applying estimated time scale      - Includes Initial burial
%   Bpred combination of lagged scour plus liquefaction
%   Um    combined wave and currents ( intermediate node in UnMES Bayes  Network)
%
%   S. E. Rennie  November 2019
```

```
%  oceanographic constants
    Ssed = 2.65 ; % Spec grav of sand grain
    g = 9.81;
    kappa = 0.41;
    TE = 15;
    nu = 1.79e-6./(1 + 0.03368*TE + 0.00021*TE.^2);  % viscosity of water
```

Organize wave-current forcing time series and compute Shields Parameter

```
    if ~isfield(Waves,'Hsig')
        UwHsig = Waves.Uorb ;  % If Hsig field not provided,  Bottom velocity MUST be in structure
        flagBreak = 0*UwHsig;  % set all breaking wave flags to zero
    elseif numel(Waves.Hsig) == 0
        UwHsig = Waves.Uorb ;
        flagBreak = 0*UwHsig;
    else
      % Note: flag=1 using Hsig for burial calculation, not Hrms  ( Hrms = Hsig/sqrt(2) )
      [UwHsig, waveLength, flagBreak, waveslope] = bottom_orbital_vel(Waves.Hsig, Waves.T, Waterdepth,1);
    end
    UwHsig(flagBreak==1) = 1.7+0.17*(Waterdepth-2); % Limit bot.Orb.Vel just at breaking in shallow
                             %  (value mostly between 1.7 to 2.7 m/s in surf zone)
    UwHsig(flagBreak==2) = max(UwHsig(flagBreak ~= 2)); % Limit bot.Orb.Vel due to steepness
    % ^^ only makes sense if increasing sequence which has values that are not breaking

    if ~isfield(Waves,'deltmin')
       if  numel(UwHsig) > 1   % a time series must have deltmin defined
          error('Lag Scour routine requires field deltmin in Waves structure')
       end
    end
    delts = Waves.deltmin(1) * 60;  % time step in seconds.   Must be regular time interval

    if ~isfield(UXO,'mstop')      % Apply burial sequence over entire time series input.
       UXO.mdeploy = 1;           % Or "mstop" allows one to compute burial within a subsection
       UXO.mstop = numel(UwHsig); % of the time series (was used for validation testing)
    end
    if ~isfield(UXO,'InitBurial')  % specification of Inital Burial (burial prior to storm event)
       UXO.InitBurial = 0;         % as fractional burial e.g. 0.1 means 10% buried
    end
    Diam = UXO.Diam * (1- UXO.InitBurial); % accout for previous burial, adjust Effective Diameter

   %  u_star for currents from Garcia (2008) presentation of Yalin (1992)
    if ~isfield(Currents,'Zobs')
        Currents.Zobs = Waterdepth/2;  % if unspecified, assume Uc is representative of mid-depth
    end
    if isnan(Currents.Zobs) ||  Currents.Zobs == 0
        Currents.Zobs = Waterdepth/2;  % if unspecified, assume Uc is representative of mid-depth
    end
    CurrentU = Currents.U;
    CurrentU = CurrentU(:);  % force vector form
    kb = 2.5*dsed;
    u_starc=0.01 ;  % initial guess
    for jj=1:10
        Res=u_starc.*kb/nu;  % roughness Reynolds #
        Bs=8.5 + ((1/kappa)*log(Res)-3) .* (exp(-0.121 * (log(Res)).^2.42)) ; % Eq.29-b Garcia 2008
        u_starc = CurrentU./((1/kappa)*log( Currents.Zobs./kb)+Bs);           % in meters/sec
    end
    Uc=real(u_starc .* ((1/kappa).*log(max(0.01,Diam)./kb)+Bs) )';  % Uc at top of object
    %  C. Friedrichs code specified height = UXODiam;  limit to at least 1 cm above bed
    Uc(isnan(Uc)) = 0.0; %  no current, set to 0

%      Shieldc=(u_starc.^2)./(g*1.65*dsed);    % current-based Sheilds not used
%      fwC=2*(u_starc./UcD).^2;    %  may switch to using fc if Uc >> Uw.
```

```
%      At the moment the fUcpar factor adjusts for fc < fw

    if ~isfield(Currents,'beta'), Currents.beta = NaN; end  %  beta = angle between waves & current
                                                            %  beta supplied directly, or direction
    if ~isfield(Currents,'dir'),  Currents.dir = NaN; end   %  of currents and waves are supplied &
    if ~isfield(Waves,'dir'), Waves.dir = NaN; end          %  beta needs to be computed
    if sum(isnan(Currents.beta)) >=1   % this code is not used during UnMES training because
                                       % Currents.beta was supplied by Monte Carlo case generation
                                       % But was % Used during validation testing
        Currents.beta = abs(Currents.dir - Waves.dir);  % does not account for magnitude of velocities
        Currents.beta(Currents.beta>90) = 180-Currents.beta(Currents.beta>90);
    end    % beta is constrained to lie between -90 and 90
    beta = Currents.beta;
    beta(isnan(beta)) = 90; % when either Wave or current direction is unknown, assume perpendicular

    Um = sqrt( UwHsig.^2 + Uc.^2 + 2.*UwHsig.*Uc.*abs(cosd(beta))); % Eq 7 Friedrichs et al [2016]
    Uw10 = 1.27.*UwHsig; % highest 10% of waves can drive mobility (occurs at very short time scales)
                         % as proposed by C. Friedrichs.    H10 = 2.Hsig./sqrt(2) but
                         % more modest 1.27X  suggested by Dean & Dalrymple (1991, p.193)
    Um10 = sqrt( Uw10.^2 + Uc.^2 + 2.*Uw10.*Uc.*abs(cosd(beta))); % Uw10 used for mobility onset

    % compute wave friction factor fw interatively using formulation of Myrhaug (1989)
    % as presentd by Demir & Garcia (2007)
    A = Um.*Waves.T/(2*pi);  % amplitude of wave orbital excursion
    Rew=Um.*A/nu;     % wave Reynolds #  Rw
    sqf=.05;          % initial guess for sqrt(fw)
    Rakf=Rew.*sqf./(A./kb);
    for jj=1:10
        RHS=log(6.36*(A./kb).*sqf)-log(1-exp(-0.0262*Rakf)+4.71./Rakf);
        RHS=RHS.^2+1.64;
        fw=(0.32)./RHS;    % see Eq 6 in Friedrichs, Rennie, Brandt [2016] also Demir&Garcia Eq.(13)
        sqf=sqrt(fw);
        Rakf=Rew.*sqf./(A./kb);
    end
    fw(fw > 0.0414) = 0.0414 ; % following bound applied in Swart 1974
    % Need to revisit this to handle cases where current dominates ?
    % Using wave friction factor formulation but combined UwHsig & Uc
    Shieldw=0.5*fw.*(Um.^2)./(g*(Ssed-1)*dsed);  % Shields using rho_sediment = 2.65 & rho_water=1.0
    Shieldwave=0.5*fw.*(UwHsig.^2)./(g*(Ssed-1)*dsed);  %  Shields parameter using wave orbital only
```

Compute equilibrium scour burial as in Friedrichs et al. [2016] Self-Burial paper

"Self-Burial of Objects on Sandy Beds by Scour", Scour & Erosion, CRC Press

```
if Diam > 0  % Not totally Buried
```

```
% compute SedShields & KC
% Strictly, this should be for when Uw >> Uc however note that
% friction factor for current would be much smaller  fwC < fw
   KC = Um.*Waves.T./Diam;   % modified to use EFFECTIVE Diameter (takes InitBurial into account)

%  adjust for ratio of Current to total Fig. 8(a) in Friedrichs et al. [2016]
%  Cataño-Lopera [2011] B/D  found to decrease as Uc||/Um increased
%  i.e less burial observed if currents are a larger contribution to combined Um
```

```
    UcUm = Uc.*abs(cosd(beta))./Um ; % only count component of current that is parallel to waves
    fUCpar = exp(-1.1*UcUm);         % for combined currents and waves
    %(see Fig 8 in Friedrichs [2016]) adjusts for overestimation due using Uc with fw
    fUCpar(fUCpar<0.6) = 0.6;    % bound correction for currents to approx ~ Uc >= Uw

%  adjust for angle alpha of UXO long axis to wave orbital vel as proposed Friedrichs et al. [2016]
%  See Fig 8(b) f(alpha) = exp(-3.4*(cos(alpha)-0.6)*UcUm)
%  Only for alpha such that cos(alpha) = 0.6 --> alpha = 53 deg
    if ~isfield(UXO,'alpha'), UXO.alpha = NaN; end
    alpha = UXO.alpha;
    if ~isfield(UXO,'dir'), UXO.dir = NaN; end
    if sum(isnan(UXO.alpha)) >=1
        alpha =  abs(UXO.dir - Waves.dir);
        alpha(alpha>180) =  360-alpha(alpha>180);  % alpha angle is defined between 0 and 90
        alpha(alpha>90) =  180-alpha(alpha>90);
    end
    alpha(isnan(alpha)) = 90;                   % if  direction unknown, assume  perpendicular
    falpha = exp(-2.5*(cosd(alpha)-0.6)) ;     % note parameter value -2.5 based on Rennie fit Fall'16
    mperp = find(cosd(alpha) <= 0.6) ;          % find the times when current is mostly perpedicular
    falpha(mperp) = 1.0 ;                       % Note: factor strongly affects UXO parallel to vel

% Summary burial equations for cylinders under waves+current
% see Figures Fig.7 & Fig. 9 in Friedrichs et al. [2016]
% Correcting for alpha, beta and KC
    fKC = 0.103.*KC.^0.5136;
    fKC(fKC > 1.0) = 1.0;     % bound for very large KC (--> steady flow)

% determine dependence on Shields param and then adjust for other factors
  fS =   1.85* Shieldw.^0.34;

% Q = fS .* fKC;
  Beq = fS .*falpha .* fUCpar .* fKC ;
  Beq( Beq > 1.15) = 1.15;      % cap at maximum scour fractional depth

 ScourBeq = Beq;                  % Scour burial fraction of (1-InitBurial) Diam
 Beq   = ScourBeq*(1-UXO.InitBurial) + UXO.InitBurial;    % Beq(t) NOW epresents
 % predicted fractional burial in equilibrium with velocity at time t added to Initial Burial
```

Estimate lagged burial using increased time scale

```
     Awh = 0.095;    % Whitehouse empirical coeffs estimate Burial Time Scale from flume experiments
     Bwh = -2.02;    % negative means time scale goes DOWN as Shields param(shear stress) increases
    %  parameters Awh & Bwh reflect given mine geometry -- see p.111 in R. Whitehouse [1998]
    %  Scour at Marine Structures [SMS1998], for "short cylinder"

    SScw1 = 0.036;   % "clear" water regime
    SScw2 = 0.041;   % behavior regimes defined by Shields number
    % Note that  Demir & Garcia [2007] got all  data for fit
    % from experiments using uniform grain size dsed=0.25mm.
    [ Tdemir, delT] = scour_demirgarcia_timescale_2018(ScourBeq, Shieldw, 0.25/1000, 2.65, Diam, ...
                                                                      1.02, SScw1, UXO.Length);
    tscale = Tdemir;
        mclear = find(Shieldw < SScw1);
        TscaleWH = Awh.*Shieldw.^Bwh*(Diam.^2)./sqrt(g*(Ssed-1)*dsed.^3);
        tscale(mclear) =  TscaleWH(mclear);
        delT(mclear) = 10*60;  % max delay is 10 min
        mtr = find( SScw1 < Shieldw & Shieldw < SScw2);  % ad-hoc transition region
        tscale(mtr) = (TscaleWH(mtr) + Tdemir(mtr))/2.;
        delT(mtr) = 10*60;  % max delay is 10 min. Check that this is smaller than  time step delts
        delT(delT>10*60) = 10*60;  % max delay is 10 min
        if delts < 10*60  % code cannot handle input time step shorter than max allowable scour delay
             disp(' Time Step too short')
```

```
        end
    %   adjustment to burial time scale in the field  (Needs to be confirmed by future tests)
    tscale = 45*tscale; % P. Traykovski evidence for longer (45X) burial time scale in the field

    S = zeros(1,UXO.mstop-UXO.mdeploy+1) + UXO.InitBurial;  % set up segment to accumulate burial
    Blag  = S;   % S(1) is initial burial                      Remember Blag is Fractional Burial

    j0 = 1;                             % first index to start burial accumulation
    for j= UXO.mdeploy:UXO.mstop-1      % integrate burial starting at time=mdeploy
        dt = delts - delT(j);           % inclusion of delT
        if S(j0) < Beq(j)               % Note that Beq can include Initial Burial
                t = tscale(j)*(-log(1-S(j0)/Beq(j)))^(1/.6);
                % see [SMS1998] p19 == where the last Scour depth is along  time axis
                % pcoef = 0.6 for short horiz cylinder from [SMS1998]
                S(j0+1)=Beq(j).*(1-exp(-((t+dt)/tscale(j)).^0.6));  % move along another timestep

                if S(j0+1) > max(Blag)   %  scour up to this point
                    Blag(j0+1)=S(j0+1);  %  combo of integrated previous scour & additional scour
                else
                    Blag(j0+1)=max(Blag);
                end
        else  % for S(j0) > Beq(j)
                S(j0+1)=S(j0); Blag(j0+1)=max(Blag); %  no sediment backfills pit
               %S(j+1)=Beq(j); Bt(j+1)=max(Bt);     % alternate approach: fine sediment backfills
        end
        j0=j0+1;
    end  % end loop to calculate time-varying lagged cumulative scour burial
```

```
  else  %  if totally buried
    ScourBeq = zeros(1,UXO.mstop-UXO.mdeploy+1) ;
    Blag  = ScourBeq  +  UXO.InitBurial;
    Beq   = ScourBeq  +  UXO.InitBurial;
end
```

Modify Burial values if high-energy Liquefaction conditions occurred

Using C. Friedrich preliminary time-dependent zLiquefaction model
presented SERDP MR Spring IPR 2018

```
    % limit "sheet flow" conditions to wave forcing only
    msheet = find(Shieldwave > 1.0);  % note: use Shields due to WAVES only, do not include currents
    % Breaking condition overwhelms Sheetflow condition
    mBreak = find( flagBreak > 0 ); % breaking due to shallow depth or steepness

    [ Bpred, zLmax] = ZLiquifaction_Proto2019( Waves, UXO, Waterdepth, dsed, Blag, msheet, mBreak);
    % note: Bpred is in FRACTIONAL burial units
```

Check for possible onset of motion anywhere during time series

```
    kbed = Bpred.*0.0 + 2.5*dsed ;    % nominal bed roughness if no burial
    BurialDepth = Bpred .* UXO.Diam;  % Make fractional burial into dimensional (meters)

    EffectiveDiam = (1-Bpred) .* UXO.Diam; EffectiveDiam(EffectiveDiam<0) = 0;
    mburied = BurialDepth > kbed;    % these will likely be almost ALL the indices
    kbed(mburied) = BurialDepth(mburied);  % dimensional
    DratioK = UXO.Diam ./ kbed;
    DratioK(DratioK > 300) = 300;  % limit Diameter to bottom roughness effect
                                   % (Relationship set flat for very large D/kbed)
```

```
    %  Impose additional mobility threshold if D/kbed < 1  i.e. fully buried
    %  simulating "lockdown" effect near at 50%  burial, or DratioK <= 2
      factor = (DratioK./(max([DratioK'  2.5+zeros(size(DratioK'))]'))).^3; % force low DratioK to
      DratioK = DratioK.*factor;                                            % be extremely low

    %  Empirical Fit for Motion Onset parameters as published in Rennie, Brandt & Friedrich [2017]
    %  Initiation of motion and scour burial of objects underwater Ocean Eng. 131, 282-294
    acrit_fit = 1.64;  bcrit_fit = -0.71;         % Best fit to Critical Mobility # as function of
    Qobj_crit = acrit_fit*(DratioK).^bcrit_fit ;  % D/k threshold

     denom = g.*( UXO.Sg - 1).*UXO.Diam ;  % denominator of Mobility number
     %U_crit0 = sqrt(Qobj_crit .* denom);  % fixed  for given Sg & Diam
     % likely need to apply an alpha correction on  U values in this section  for small alpha
     Mobnum = Um10.^2./denom;              % Mobility # Qobj not yet corrected for inertial effects

    % Keulegan-Carpenter number becomes small for short-period waves or or large diam UXO
    % KC --> large is steady flow
    % since fI is unbounded as KC--> 0; impose reasonable limit to this factor so  Ucrit does not ->0
     KC = Um.*Waves.T./EffectiveDiam;   % modified to use EFFECTIVE Diameter
                                        % (takes InitBurial + Liquefaction into account)
        KC(KC < 5) = 5;      % this bounds fI to 5.1X which is still a substantial correction
        KC(KC > 999) = 999;  % bounds very large KC (occurs as Blag -> 1,EffectiveDiam -> 0;fI->1.0
    fI = sqrt(1+16*pi^2*4*KC.^(-2)); % Inertial correction for oscillatory flow [Eq10, OceanEng 2017]
    % fI is a significant correction (>2X)for KC < 15.  fI -> 1 for Large KC (steady flow)

    Mobnum_fI = Mobnum.*fI;      %  effective Mobility # including inertial contribution from Waves
    U_crit = sqrt(Qobj_crit./fI .* denom);  % adjusted for inertial factor
    Mdist =  migrate_estimate_Proto(Mobnum_fI, Qobj_crit, U_crit, Um10, Waves.T);
```

```
end
```

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ZLiquifaction_Proto2019 function

Estimate burial due to liquefaction over time

Depth of liquifaction burial based on C. Friedrich's analysis of work by Qi & Gao [2015, 2018] and Chowdhury et al. [2006] .Code adapted from Carl Friedrich preliminary model, SERPD MR Spring IPR 2018

```
function [BDpred, zLmax] = ZLiquifaction_Proto2019(Waves, UXO, Waterdepth,dsed, ...
                                                     BDscour, msheet, mBreak)
% Input
%    Waves             describes wave forcing Scalar (steady) or vector (timeseries)
%    Waves.deltmin     delta-time *in minutes* between each Wave observation
%                      deltmin undefined or =0;  all fields  scalar (steady)
%    Waves.Hsig =      Significant wave height (m)
%    Waves.T    =      Tperiod  (seconds)
%
%    Waterdepth  depth at this location (m) assume fixed depth thru event
%    dsed        median sediment grain size (m) scalar or vector ** meters **
%    UXO         structure describing munition
%        UXO.type       string with name of munitions type (e.g. "mortar")
%        UXO.Sg         specific gravity   not used in this subroutine
%        UXO.Diam       diameter (m)
%        UXO.Length     length of long axis (m)
%        UXO.InitBurial initial FRACTIONAL burial prior to start of time sequence
%
%     BDscour : predicted lagged scour FRACTIONAL burial for this time sequence
debug = 0;

Hs = Waves.Hsig(UXO.mdeploy:UXO.mstop); %subsection index set in calling function
Hs = Hs(:);
if numel(Waves.T) >= numel(Hs)
   T  = Waves.T(UXO.mdeploy:UXO.mstop);
else
    T = Waves.T ; % can be a scalar (fixed Period) even when Hsig is timeseries
end
T = T(:);
T(T<7)=7;  % applicable only to long period waves

Bscour = BDscour*UXO.Diam ; % make Scour burial dimensional  (meters)
                            %  LAGGED scour when called from lag_scour_liquify

%%%%%%%% Fixed or Nearly Fixed Parameters %%%%%%%
g=9.81;        % acceleration of gravity [m/s^2]
Kw=1.95e9;    % true bulk modulus of elasticity of water [Pa = N/m^2]
              % Note: Klammler, Sheremet and Calantoni uses Kw = 2e9
rho=1025;     % density of water (ignore salinity) [kg/m^3]
gam_w=rho*g; % unit weight of water [kg/m^2/s^2 = N/m^3 = Pa/m]
Gs=2.65;      % specific gravity of sand particle [unitless]

%%%%%%%% Calculated Wave Parameters %%%%%%%
```

```
w=2*pi./T;      % wave radian frequency [1/s]
for j=1:length(Waves.T)
    k1=1;
    for jj=1:10
        k2=w(j)^2/(g*tanh(k1*Waterdepth));
        k1=(k1+k2)/2;
    end  % dispersion relation
    k(j,1)=k1; % wave number [2pi/m]
end
po = gam_w*Hs./(2*cosh(k*Waterdepth)); % amplitude wave pressure at seabed [Pa]
Pwo = gam_w*Waterdepth;                % absolute water pressure [Pa]

%%%%%%%% Prescribed Bed Parameters (c.f. Qi 2015 Fig.2) %%%%%%%%%%%%%%%%%

Sr=0.98; % fraction of sand bed saturation [unitless]  C.Friedrichs used Sr=0.993
    % Klammler et al used 0.98 as base condition, with range from 0.96 to 1.0
    % decreasing from Sr=0.993 to Sr=0.98 makes burial about 2X deeper
    % Burial results are very sensitive to Sr and we have little information
    % about what value to use
Kz=1e-4;  % sand bed permeability [m/s]
np = (26.92 + 5.92 * -1*log(dsed*1000))/100 ;  % phi is -1*log2(dsed in mm)
%np=0.4;  % sand bed porosity [unitless]  Carl Friedrichs used np=0.45
     % Klammler et al use base case = 0.30 with range from 0.25 to 0.35
     % Richardson & Briggs formula: Por = 26.92 + 5.92 * phi
     % If  d50=0.2mm, phi = 2.3 and Por ~ 40%  <-- used these values for
     % Tuning FrictCoeff to ~ 17 or 18 reproduces burial observations from DUCK15
mu=0.3;   % Poisson's ratio [unitless]
E=30e6;   % Young's modulus [Pa = N/m^2]

%%%%%%%% Calculated Bed Parameters (Chowdhury 2003, Qi 2015) %%%%%%%%%%%%%%%%%

beta = 1/Kw + (1-Sr)/Pwo;   % compressibility of pore water [m^2/N]
gam_pr=(Gs-1)*(1-np)*gam_w; % submerged unit weight of soil [kg/m^2/s^2=N/m^3=Pa/m]
%Sg_ws=Gs*(1-np)+np;        % specific gravity saturated sand (Freidrichs 1.9075)
 e = np/(1-np);             % void ratio
 Sg_ws = ((Gs + e)*rho/1000)/(1 + e); % DAS formula specific gravity saturated sand
mv=1/E*(1-2*mu^2/(1-mu));     % volumetric compressibility of soil [1/Pa]
B = 1/(1+np*beta/mv);         % compressibility coefficient [unitless]
Cv=Kz*B/(mv*gam_w);           % coefficient of consolidation of soil [m^2/s]
a=sqrt(w/(2*Cv))*(1+1i);      % complex vertical wave number within bed [1/m]
zL = po/gam_pr-1./(real(a)*(1-B)); % liquefaction depth [m]
                                   % Qi & Gao 2015 Wave-Induced moment liquef sand
                            % zL = equilibrium liquifaction NO TIME DEPENDENCE
zLmax = max(zL) ;           % equilibrium burial depth for liquefaction at peak

Sg_obj= UXO.Sg ;             % object specific gravity [unitless]
D  =    UXO.Diam;            % object diameter [m]
dt = Waves.deltmin*60;       % wave observations time step [sec]
FrictCoeff0 = 17*3600;       % friction coefficient [sec]  Held fixed thruout
% Originally FrictCoeff was estimated in hours;  convert to seconds
% Note: order of magnitude for FrictCoeff was estimated using results from
% DUCK15 observations in waterdepth h=8m which is not extreme breaking conditions
% Argue that burial by liquifaction occurs slowly little by little,
```

```
% not all of a sudden
% Note: C. Friedrichs fit to Duck15 used FrictCoeff0 = 11*3600
% with Sr = 0.993 and np = 0.45
% Here apply Sr=0.98 and np = .3xxx;  FrictCoeff0 ~ 17 hours
% This may not be true in the surf zone.
% Proposed: decrease FrictCoeff if VERY high energy (under breaking waves)
  FrictCoeff = ones(size(zL))*FrictCoeff0 ;  %time series of varying FrictCoeff
  FrictCoeff(mBreak) = FrictCoeff(mBreak)/2; %breaking waves: cut timescale 1/2
  dBL=(D./FrictCoeff).*(Sg_obj./Sg_ws-1)*dt; %incremental liquef burial @ time step
%
Bpred = Bscour ;                    % vector will hold combined predicted burial [m]
dBS = diff([ Bscour(1) Bscour]);  % incremental scour at each timestep
dBS(msheet) = 0.0;                 % hi energy: Sheet flow,ignore scour contribution
% ^^^ this is where burial can suddenly decrease
BL = zeros(size(zL));              % liquifaction burial only,ignor scour (debug)

% Combine scour and liquifaction for moderate energy,
% Let liquefaction dominant at higher energy
 for j=2:numel(zL)    % loop thru time series
       if Bpred(j-1) > zL(j)                 % note zL is negative for small waves
          Bpred(j) = Bpred(j-1)  + dBS(j);  % if Liquef not dominant, only scour
       else                                  % zL deeper than previous scour
                                             %    or scour+liquef burial
          Bpred(j) = Bpred(j-1) + dBS(j) + dBL(j); % combine scour and liquef
          % note: if sheet flow or Breaking, only use dBL;
          % if breaking waves, dBL is larger
       end
       if BL(j-1) > zL(j)      % note zL is negative for small waves
          BL(j)=BL(j-1);       % cannot go deeper than liquefied layer thickness zL
       else
          BL(j)=BL(j-1)+dBL(j);
       end
 end
BDpred = Bpred/D;
end
```

migrate_estimate_Proto function

Estimate migration distance traveled during mobility event

```
function Mdist = migrate_estimate_Proto(Sobj, Sthreshold, Ucrit, Ubot, Twave)

%  Prototype version of migration distance estimate based on
%  exceedance of Mobility # over threshold
%  Approach: Migration Velocity is alpha * (U - Ucrit)^3  ( P.Traykovski)
%  ALSO impose some additional ad hoc assumption of the duration of motion

%  This version  adjusted to match the distance ranges
%  observed in 2014 Long Point field data ( P.Traykovski).
%  (assumes those distance occurred in one mobilization occurance )
   alpha1 = 5;
Uobj = min(Ubot, alpha1 .* (Ubot - Ucrit).^3); %cannot be larger than Ubot


   beta2 = 1.5;
Sratio = Sobj./Sthreshold;
numwaves = max( 3.0, beta2 .* (Sratio).^1.1); % #wave periods spent mobile

   Mdist = numwaves.*0.5.*Twave.*Uobj;  % ad hoc scaling

   mm = find(Sobj < Sthreshold);
 Mdist(mm) = 0.0; %  below threshold, no movement

   Mdist(Mdist>999) = 999; %impose maximum limit matching UnMES "Far" state

end
```

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