INTERIM REPORT

Underwater Munitions Expert System for Remediation Guidance

Improved Models for Burial, Exposure, and Migration of Underwater Munitions

SERDP Project MR-2645

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The Underwater Munitions Expert System (UnMES) is a computer-based probabilistic expert system that synthesizes recent and new research to understand how underwater unexploded ordinance (UXO) bury and/or migrate in a range of underwater environments. UnMES will be a tool to assist in management and remediation of contaminated sites. Advances have been made in efforts to improve the fidelity and scope of physics-based process models used in UnMES. UXO re-exposure and burial can be caused by height variation in the seabed occurring over long time scales, which can be estimated with parameterized models driven by wave observations. The addition of bedform migration modeling is a new mechanism for burial and exposure in UnMES. The previously ad-hoc models for liquefaction burial and estimation of migration distance have been replaced by formulations that reflect the relevant physics. UnMES development is supported by the Strategic Environmental Research and Development Program (SERDP) project MR-2645.

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Improved Models for Burial, Exposure, and Migration of Underwater Munitions

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Johns Hopkins Applied Physics Laboratory

August 2019

Summary

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1. Introduction

The Underwater Munitions Expert System (UnMES) is a computer-based probabilistic expert system that synthesizes recent and new research to understand how underwater unexploded ordnance (UXO) bury and/or migrate in a range of underwater environments. UnMES will be a tool to assist in management and remediation of contaminated sites. Incorporated in UnMES is knowledge of the processes and time scales for burial, re-exposure, migration, and subsequent reburial of UXO. For a detailed description of UnMES see Rennie and Brandt (2015, 2017b). Burial of munitions into the seafloor sediments can proceed by several mechanisms, including scour, liquefaction, or bedform movement. Re-exposure can occur if the level of the seabed drops, caused by large spatial-scale processes such as erosion and seasonal shoreface adjustment, or by smaller scale bedform propagation. Conversely, burial will increase if accretionary processes are dominant. Mobility occurs when the bottom currents exceed the threshold of motion for a UXO, which depends on its density and degree of burial.

Detailed information about the history of munitions deposition at a given site of concern is generally not available. In addition, data on environmental variation, geomorphology and, sediment properties are usually incomplete. In building the expert system, it is appropriate to apply simple physics-based models of wide applicability that relate beach property characteristics to morphological processes. This engineering-style approach was previously used to develop the preliminary version of UnMES which relied on a state-of-the-art summary for predicting burial by scour is described in Friedrichs et al., 2016. Another possible mechanism by which UXO can be buried is penetration into the seafloor upon initial impact (Rennie and Brandt, 2017b). Detailed examination of the scour process in non-cohesive sediments is further found in Rennie et al. (2017), which also investigated the requirements for the initiation of motion of UXO, both on a rigid bottom and on a mobile sand seafloor where scour burial can preclude mobility. A probabilistic model for the potential of burial or exposure due to bedform migration is presented in this report.

A further outstanding issue for the improvement of UnMES is the need for a method to estimate the probability of UXO re-exposure. Scour burial and impact penetration can only increase the depth of the UXO buried in the seafloor. Buried UXO could be only exhumed if the overall level of the seabed were lowered. An exception to this is the special case where the density of the munitions is lighter than the surrounding sediments, so that high-energy processes like liquefaction or fluidization could cause the buried UXO to become less buried. The large majority of munitions are quite dense, > 3000 kg/m³ (specific gravity, $S_g > 3$) while the bulk density of sand is ~2000 kg/m³ ($S_g ~2$) (Calantoni, 2017). A notable exception is pyrotechnic ordnance such as flares, which can have $S_b < 2$. A method to estimate burial by liquefaction is also presented in this report.

The previous demonstration implementation of UnMES (Rennie and Brandt, 2017a) used a location-specific procedure for estimating the total distance that UXO can travel across the seabed once the bottom currents exceed the initiation of motion threshold. In this report, the migration distance sub-model is re-visited and improved.

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1 The term UXO is used here to refer to all forms of discarded munitions of concern
There are multiple, complex factors that govern UXO re-exposure and migration including sediment characteristics, seabed bathymetry, details of the hydrodynamic forcing, as well as munitions density and geometry. Therefore, for practical use in UnMES, general rules governing these processes based on the extant literature are sought. However, published research specifically addressing buried object re-exposure and the extent of object mobility and migration is sparse. This report is intended to provide a basis and general guidance for implementing submerged UXO re-exposure and migration components in UnMES, based on available literature, experience-based conjectures and general rule based patterns. There are currently ongoing several relevant research projects within the SERDP Munition Response Program which should provide additional insights of value in the near future. The Bayesian Network approach used for UnMES provides a modular framework whereby component models are easily upgraded when additional information becomes available.

2. Dynamic Geomorphology: Burial and Re-exposure of Submerged Marine Munitions

The current implementation of UnMES focuses on UXO burial and migration in the nearshore coastal region in depths between 2 and 20 m. Burial models included in UnMES focused on nearfield processes where the presence of the UXO affects the local environment. A primary example of this is scour burial, where the near-bottom currents are accelerated around the UXO, causing enhanced sediment dispersal resulting in the UXO falling into the scour pit. These nearfield burial processes, as well as the onset of UXO motion occur on short time scales, often related to high energy events (storms). However, most munitions of concern have been in place for a long time, and there are often substantial time periods that elapse between initial site surveys and remediation decisions, so that numerous high energy events are likely to have occurred. Therefore far-field changes in nearshore coastal profiles that occur over annual and seasonal timescales must also be considered. Figure 2.1 (adapted from Elko et al., 2014) illustrates the interplay of temporal and spatial scales important in the coastal environment which contribute to the complexity of dynamic nearshore response modeling requirement for predicting munitions behavior.

The re-exposure and migration behaviors of submerged marine munitions are dependent on farfield bedforms that can affect local hydrodynamic forcing. Over a monthly timeframe, the nearshore bathymetry of many sandy beaches changes seasonally. Over longer time scales, many sites of concern experience net shoreline erosion or, less frequently, accretion. Often, upstream shoreline engineering projects such as seawalls, jetties or beach replenishment can cause shoreline modification along extensive distances down the coast. The longer time scales shaded in red in Figure 2.1, indicate where anthropogenic influences can be important in the coastal environment. On the shorter end of those timescales, movement of subaqueous bedforms modify the local bathymetry, driven by tidal and residual currents. Bedforms can be classified within a range from ripples to dunes as will be discussed in §2.2.

The Preliminary version of UnMES (Rennie and Brandt, 2015) proposed inclusion of an input node representing Erosion/Accretion probabilities which were based on Gaussian statistics of annual bathymetric variation. This approach is only reasonable at the very few sites where detailed long term bathymetric data timeseries are available. In this report we will consider the potential of parameterized cyclical models to capture the seasonal shoreface adjustment. Approximate independence between nearfield and far-field processes is assumed by the separation of time scales: UnMES predicts modification of UXO disposition during a storm event, while bathymetric changes are envisioned as developing over the longer time period between storms.
The terminology used to describe typical coastal wave regimes and shore profiles is illustrated in Figure 2.2. UnMES addresses UXO burial, re-exposure and migration in the sandy nearshore coastal environment offshore of the swash zone in the 2 to 15 m depth regime, which generally encompasses the shoaling and surf zones. Because re-exposure of buried munitions can result from temporal changes in the beach profiles, these geomorphological cycles are examined in the following sections.

2.1. Nearshore bathymetry

The amount of energy from incoming waves available to affect UXO burial and/or migration on the seabed is sensitive to the local water depth, \( h \). Wave conditions are generally monitored at locations offshore of the shoaling zone. These waves are modified by changes in \( h \) as they traverse the shoreface. Accurate knowledge of the shoaling bathymetry is the most important factor in the determination of the variation of wave energy across the site. Sandy coastal regions are dynamic, with geomorphic changes responding to hydrodynamic conditions and sediment supply, so that understanding the variation of bathymetry about a mean profile is important. In particular, knowledge of changes in the shoreline, the range of sandbar locations, and the closure depth are important inputs to UnMES modeling. Of exceptional concern are circumstances where UXO, known previously to be buried, could become exhumed and exposed to hydrodynamic forcing causing mobility. Other than a special situation within the process of liquefaction (see §3), no local processes are present that can unbury UXO, whereas it is known that large-scale, farfield variation in bathymetry has potential to cause re-exposure. There is little extant literature (measurements or models) directly related to the mechanisms and frequency of re-exposure of previously buried UXO.
2.1.1 Coastal profile measurements

Ideally, environmental studies to obtain high-resolution bathymetry should be undertaken at munitions response sites prior to applying any remediation decision tools like UnMES, as recommended in Rennie and Brandt (2015). However, complete bathymetry surveys, especially those encompassing time variations, are expensive. An initial assessment of the coastal depth profile at a site of interest may be obtained using data available from previous benchmark regional surveys. The Navy standard Digital Bathymetric Data Base (DBDB-V), produced by the U.S. Naval Oceanographic Office (NAVOCEANO, 2017), is available with worldwide coverage, and can provide an estimate for water depth, \( h \), across a site. While the standard offshore resolution of DBDB-V is 2 arc-minutes, Version 7.3 has coverage at most coastal regions of the US at 0.05 arc min, or approximately 92 m horizontal resolution. Higher resolution coastal digital elevation models (DEMs) are available from National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI), many with 1/3 arc sec (~10m) resolution. At any single location water depth changes over time due to tides, storm surge, or wind and wave induced setup. The discretization interval of UnMES depth bins is chosen as a compromise between resolving first-order information and avoiding over-specification of detail occurring at small or uncertain timescales.

![Terminology describing regions of the nearshore (adapted from Komar, 1998).](image)

At some sites there are archived data sets where repeated studies were performed to measure local beach profile changes over time. A premier example data set, representing US East Coast barrier island conditions, is maintained by the US Army Corps of Engineers (USACE) Field Research facility (FRF) at Duck,
NC, where beach and nearshore bathymetry data out to a depth of 8 m have been measured bi-weekly since 1981 (Birkemeier, 1985). A high-quality data set for beach conditions available on the US West Coast, the Southern California Beach Processes Study (SCBPS), is compiled by Scripps Institution of Oceanography from surveys dating to 2004. The Southern California data set represent both high-energy and more sheltered beaches, and has been used in multiple shoreline response studies (e.g. Yates et al, 2009, Ludka et al., 2015).

If bathymetric profiles for the remediation site are not available, extant literature indicates that simple bulk response models provide a reasonable mean state estimate for many natural beach profiles in equilibrium with the regional wave climate (Bruun, 1954):

\[ h = Ay^m, \tag{2.1} \]

where \( h \) is the depth below mean water level (MWL), and \( y \) is the cross shore distance from the shoreline. The parameters, \( m \) and \( A \), are (likely site dependent) constants: the exponent \( m \), and scale factor \( A \), are found by comparison to measured profiles (Komar, 1998). It has been found that a reasonable value is \( m = 2/3 \) at many east coast sandy beaches (Dean and Dalrymple, 2002). These studies considered the littoral zone as a whole (schematic in Fig. 2.2a) while a study of west coast beaches (Inman et al., 1993) fit Eq. 2.1 to the profile segmented at the breakpoint bar (Figure 2.2b) and determined \( m = 2/5 \). The values for the coefficient \( A \) range from 0.07 to 0.13 (where \( A \) has units of \( \sqrt{\text{meter}} \)). The profiles have been observed to scale with sediment grain size, \( d_{sed} \), exhibiting larger values of \( A \) with coarser sand grain sizes. More complex models incorporating additional parameters have been used to fit specific data sets. These more sophisticated models could make use of detailed local data if it is available at the site of interest.

Two example US East Coast sites where profile data have been measured are shown in Figure 2.3, overlaid with the computed profile from Eq. 2.1, using a mid-range value of \( A = 0.1 \). In Figure 2.3a are plotted repeated bathymetric transects measured at FRF, Duck, NC. Overlaid in red is Eq 2.1, which shows reasonable agreement with the mean of the measurements. In Figure 2.3b, a comparison is shown of average measured beach profiles for multiple locations along the east coast of Florida including predictions that were computed using a detailed, piecewise solution based on the exponential equilibrium profile model, but accounting for the measured grain size distribution to give varying values of \( A \) (Dean and Dalrymple, 2002). Again, the overlaid red curve of Eq. 2.1 with \( m = 2/3 \) and \( A = 0.1 \), yields an agreement comparable to the more complex predictive approach. Multiple comparisons show that Eq. 2.1 is not only reasonable but even provides an arguably better fit than the more sophisticated models, and provides an acceptable static coastal profile estimation procedure for use in UnMES when site measurements are not available. Based on Eq. 2.1, the beach slope, or bed gradient, \( \beta \), would be

\[ \beta = \frac{dh}{dy} = mAy^{m-1}; \quad (\beta = \frac{dh}{dy} = 0.067 \ y^{-1/3}, \ \text{for the values for} \ m \ \text{and} \ A \ \text{cited above}) \tag{2.2} \]

The effect of the slope of seabed will be considered when estimating UXO mobility potential.

As is clear from Figure 2.3a, over time the bathymetry varies considerably from the mean profile. For extended time scales, beaches maintain an equilibrium with the incident wave field and breaker-related currents. The bathymetry in the littoral zone changes seasonally when summer and winter wave climates are different, as is common along US coasts. At FRF, the water depth at a given shoreface location can vary seasonally by up to 0.5 m, larger than the diameter of nearly all munitions of concern. Profiles at Southern California beaches show even larger changes from summer to winter (Ludka et al., 2015), with
increased potential to expose previously buried UXO. Illustrated in the expanded inset in Figure 2.3a is an example UXO (shown in red) with diameter $D = 15$ cm near the 3m isobath which would be completely buried in winter yet exposed under summer conditions. The development of a model of this seasonal bathymetric variation will be discussed in §2.1.3.

![Graph](image)

**Figure 2.3.** a) coastal profiles from FRF Duck (grey); black profile is winter average, green is average of summer. b) averaged measurements and predictions for east coast of Florida from Dean and Dalrymple (2002). Both plots overlaid with equilibrium profile results from Eq 2.1 (red dashed line).

### 2.1.2 Closure depth

Closure depth, $h_c$, is the depth separating the offshore area from the shoal zone region (Fig 2.2b). Seaward of $h_c$, bathymetry maintains a profile without response to changes in wave forcing due to the large depth to wave height ratio (Nicholls et al., 1998). In Figure 2.3a, which shows a compilation of hundreds of bathymetric profiles measured over 16 years at FRF, it can be seen that the profiles begin to converge offshore of $h \approx -4$ m. Shoreward of $h_c$, the bathymetry profile changes at a wide range of time scales. The seasonal variability in the inner beach region is schematically illustrated in Fig. 2.2b. For a spatial
implementation of UnMES, as discussed in Rennie and Brandt (2017a), depth cells shoreward of $h_c$ would have varying (non-zero) probabilities set in the Erosion/Accretion node, while offshore depth cells would have the probability for re-exposure by far-field variation set to the smallest (absolute) value resolved by the input node discretization.

The shape and composition of a beach is determined by its geology and by the wave climate. As described in Wright et al., (1985) the first step to understanding the dynamics of a coastal region will be collecting wave statistics for the area. Incident wave energy is quantified by several metrics including significant or rms wave height, $H_{\text{sig}}$ or $H_{\text{rms}}$, or breaking wave height, $H_b$, which can be interrelated based on known wave physics. Following Komar (1988, p. 276), a simple model for closure depth $h_c$ was developed by Hallermeier (1981)

$$h_c = 2.28 H_e - 68.5 \left( \frac{H_b^2}{g T_e^2} \right),$$

(2.3)

where $H_e$ is the nearshore storm-wave height that is exceeded only 12 hours per year and $T_e$ is the associated wave period. Birkemeier (1985) found that different coefficients provided a better fit to the FRF data, indicating that site dependent tuning of coefficients is probably necessary. Birkemeier however also found that a comparable reasonable fit could also be obtained using the considerably more simplified form

$$h_c = 1.57 H_e.$$  

(2.4)

The average of the values for $H_e$ for the profiles at FRF examined is 3 m giving $h_c \sim 5$ m from Eq. 2.4. This would be a reasonable value for the FRF data shown in Figure 2.3a, where the offshore location for this depth, $y \approx 450$ m, marked with cyan, shows where the profiles have converged. At this cross shore distance, the beach slope from Eq. 2.2 would be $\beta = 0.009$. In the absence of site specific information on the nearshore beach profile at a given remediation site, Eq. 2.4 would be an appropriate general rule for use in UnMES to estimate $h_c$ in data-starved situations to give a rough estimate of the closure depth beyond which minimal re-exposure probability would be predicted. When additional bathymetric and environmental data has been gathered, a version of Eq. 2.3 specifically tuned for the site of interest could be applied to refine the estimate.

2.1.3 Seasonal shoreface adjustment

Examples of buried munitions that were re-exposed by far-field bathymetric variation have been documented at several sites. In studies of sea mines placed off the Scripps beach in La Jolla, CA, a mine located about halfway between the shoreline and $h_c$ was repeatedly observed over several years to become fully buried during the winter and exposed during the summer (Inman and Jenkins, 2002). Another munitions exposure event was reported at FRF in July and August 2016 when old bombs became visible on the foreshore during multi-year low in the summertime profiles (Palmsten and Penko, 2017). Evidence of unburial episodes was also inferred from UXO behavior during the ESTCP field experiment at FRF (Wilson et al., 2008a) where test munitions were surveyed by divers seven times over a two-year period. Although all the surrogate UXO were observed to be completely buried during every survey, they clearly had been unburied at some time between surveys, both because they exhibited small movement (horizontal locations changed by 3 to 10 m) and they also exhibited significant biofouling, which would occur only during periods of exposure.
At the most detailed level, prediction of seabed erosion and accretion patterns can be computed by a 3-D gridded numerical model such as Delft3D with its morphological module (Lesser et al., 2004). This full-physics approach requires implementing nesting grids with specifications of the time-varying hydrodynamic boundary conditions and, once correctly calibrated for the site, can determine seabed variation on a storm-event time scale of a few days. This computationally-intensive method is being tested by SERDP project MR-2733 (Palmsten and Penko, 2018) at representative locations, and the trial results will be made available for incorporation into UnMES. Initial trials show that, after spin-up, waves and currents can be modeled skillfully, but morphological changes will require further tuning. In order to apply UnMES at remediation sites with limited resources for model setup and execution, a simple equilibrium bulk response concept may provide a more efficient and achievable result.

There have been several practical shoreline evolution models proposed to quantify the temporal shoreline profile adjustment that could be adapted for use in UnMES to predict burial or unburial due to far-field changes in seabed level. Jenkins and Inman (2006) adopted an equilibrium concept using the analogy of thermodynamics and found solutions in the form of elliptic cycloid with empirically validated parameters, separately for the regions shoreward and offshore of the bar. A different model approach, applied by a number of researchers including Wright et al. (1985), extends the Bruun equilibrium concept based on conservation of volume to a time-varying form assuming that equilibrium conditions are approached at an exponential rate (Miller and Dean, 2004). This shoreline response model then predicts the position of the shoreline (mean sea level, or msl) over time, \( S(t) \), given the wave energy \( E \) (the wave height variance). Yates et al. (2009) formulate the response as

\[
S(t) = (S_0 - S_{Eq}) e^{-ac \sqrt{Et}} + S_{Eq} \tag{2.5a}
\]

where \( S_0 \) is the initial shoreline position and the equilibrium msl, \( S_{Eq} \), is

\[
S_{Eq} = \left( \frac{E-b}{a} \right) \tag{2.5b}
\]

In Equation 2.5a, \( C \) represents rate of change and in Equation 2.5b, \( a \) and \( b \) are site dependent coefficients which describe the equilibrium energy. The change rate coefficients can be different for accretion (\( C^+ \) for energy disequilibrium \( \Delta E < 0 \)) and for erosion (\( C^- \) for \( \Delta E > 0 \)). Implementation of this model for a given site requires the calibration of four parameters: the coefficients \( a \) and \( b \) and the two rate coefficients, \( C^+ \) and \( C^- \), where erosion is often observed to be faster than accretion (\( C^+ < C^- \)). The e-folding time scale is formulated here as proportional to \( E^{b/2} \), but similar model results can be obtained using a rate parameterization based on \( E \), or using Dean’s parameter \( \Omega \) (Miller and Dean, 2004), which encompasses sediment grain size and wave period information. Several applications, using the SCBPS data which have sufficient topographic surveys and wave observations to accurately determine these four parameters, have successfully reproduced the observed seasonal shoreline movement at several Southern California sandy coastal locations, including Camp Pendleton\(^2\), where the msl position was displaced horizontally over a 30 to 40 m range.

\(^2\) Camp Pendleton is proposed as the site of the SERDP demonstration field experiment (Calantoni, 2018), and an updated validation version of UnMES is being developed for testing there.
For use in UnMES, which is designed to predict changes in UXO burial depth, B, the shoreline behavior needs to be related to changes in shallow bathymetry contours across the shoreface where underwater UXO may be buried. Yates et al. (2009) found a high correlation between shoreline displacement and other depth contours. Ludka et al. (2015) extended this work at Southern California beaches where a strong seasonal cross shore “rocking” pattern is observed (i.e. water depth change at the bar location on the shoreface is out of phase with the shoreline bathymetry), which was modeled using an Empirical Orthogonal Function (EOF) reconstruction which is used to decompose the beach-shoreface profiles into the basic functions. The Mode 1 EOF, found to explain the most variance, has a simple shape corresponding to a seasonal oscillation between the height of the shoreface bar and that of the beach berm. A global set of parameter values performed nearly as well as individually fits at each site, which augurs well for future application at similar beach sites with minimal custom tuning. The Mode 1 EOF cross shore reconstruction performed particularly well at Camp Pendleton, explaining over 65% of the total variance (Ludka et al., 2015). An example implementation of this profile equilibrium model into UnMES will be presented in detail in Rennie et al., 2019.

Note that, unfortunately, the Ludka-Yates annual model fails at FRF, where cross shore fluctuations did not prove to be spatially coherent and are not well described by the Mode 1 EOF. For beaches without a sufficient seasonal equilibrium model, the previous statistical approach can still be applied in UnMES. At a minimum, the cross shore location where sand bars tend to form should be identified, as this is the region of highest bathymetric variability. Remote passive optical imaging, either from drones or a fixed tower, can be a low-cost method of inferring coastal bathymetry (Palmsten and Penko, 2017) to identify the sand bar positioning. Not only is there greater burial and re-exposure probability in the bar-trough region, but the sand bar present steep bottom gradients, which complicates UXO mobility, discussed in §4.

2.2 Bedform Formation and Migration

Seabed variations also occur over a range of time and space scales shorter than the equilibrium adjustment to annual or seasonal changes of wave forcing. Wave orbital velocities rapidly form ripples on the seabed with height $\eta$ on the order of 0.05 to 0.15 m and length $\lambda$ less than 1 m. Longer timescale flows, e.g. tidal currents, with higher velocities, produce larger bedforms such as mega-ripples or sand waves with $\eta$ from 0.1 to 10 m high and $\lambda$ from 1 m to over 100m. These large bedforms are collectively called dunes$^3$.

When considering the potential of bedforms to affect UXO exposure or mobility, we will generally ignore the smaller ripples and focus on dune formation and migration, because motion of most munitions will not be affected by the presence of ripples due to the small size (Voropayev, et al., 1998). Also, in the high-energy conditions during storm events when significant UXO mobility is possible, sediment sheet flow conditions produce a plane bed with all ripples washed out (van Rijn 1984). However, the presence of dunes, which persist through higher flow velocities, will inhibit the motion of larger munitions (Fahnestock

$^3$ A variety of nomenclature have been used including sand waves, mega-ripples, etc. A 1988 symposium on bedforms concluded that the word “dunes” should be used for all subaqueous bedforms in this size range (Ashley, 1990).
& Haushild, 1962). The successive transition from ripples to dunes to plane bed conditions occurs at different flow speeds, depending on sediment characteristics, as shown schematically in Figure 2.4 (adapted from Ashley, 1990). For all sand grain sizes, dunes will form under steady flow for nearbed velocities greater than about 0.75 m/s. The transition to a high-energy regime where ripples, and even dunes, are washed flat has been observed to be quite abrupt. For wave-dominated conditions, this transition (marked in Figure 2.4 by cyan line) defines where the potential for burial by liquefaction becomes significant (discussed in §3.2). Bedforms in UnMES will be modeled assuming that, over the long term, dunes will be present intermittently at high flow velocities, and at extreme coastal velocities, sufficient to remove the dunes, a plane bed will always exist.

Figure 2.4 Schematic showing areas of bedform formation and wash-out dependence on sediment grain size and flow velocity (adapted from Ashley, 1990).

2.2.1 Dune Characteristics

Empirical formulae for dune height, wavelength and slope are presented by van Rijn (1984), based on alluvial laboratory and field data. While these methods are for steady flow they can be used as an approximation for oscillatory tidal forcing. As presented by Soulsby (1977), the dune properties are parameterized in terms of the median sand grain diameter, $d_{50}$, and a transport stage parameter, $T_s$, which represents the excess bed shear-stress ($\tau_s$) above the threshold for sediment motion ($\tau_{cr}$):

$$T_s = \frac{\tau_s - \tau_{cr}}{\tau_{cr}}$$

(2.6)
where $\tau_c$ and $\tau_{cr}$ are implemented in UnMES as previously for the prediction of scour burial under currents (Rennie and Brandt, 2017a). For $1 < \tau_c < 25$, estimates of the dune height $\eta$, and dune length $\lambda$, are estimated as

$$
\eta = 0.11h \left( \frac{d_{50}}{h} \right)^{0.3} (1 - e^{-0.5T})(25 - T_s),
$$

(2.7)

$$
\lambda = 7.3 h,
$$

(2.8)

indicating that the dune length is only a function of the mean water depth, a relationship documented by other studies (Yalin, 1962). Using these formulae, typical dune properties present at a site can be estimated. If the dune has a sinusoidal shape, maximum local slope of the bed ($\beta$ that influences UXO mobility) would be $\beta_{max} = 4\eta/\lambda$. Noting that sand waves are usually not sinusoidal, but asymmetric, with a steep lee (downflow) side, trailing a more gently sloping stoss (upflow) side, a representative geometry is a sawtooth shape, or a triangular cross section (Mulhearn, 1996). For sawtooth dunes with a 3:1 asymmetry, then $\beta_{max}$ could again be as large as $4\eta/\lambda$. The computed dune height and maximum slope over a range of flow velocities in two water depths ($h = 5$ and $10$ m) are plotted in Figure 2.5 for both fine (0.25 mm, cyan) and coarse (0.75 mm, purple) sediment. In this depth range, dependence on sand grain size is as strong as the dependence on water depth. While bathymetric data is often available or readily obtainable by remote methods, an accurate value for the median grain size would require in-situ sampling at the site of interest.

![Figure 2.5. Underwater dune properties from Eq. 2.7-2.8. Solid lines: water depth $h = 10$ m; dashed lines: $h = 4$ m. Purple: coarse sand grains ($d_{50} = 0.75$ mm); cyan: fine sand ($d_{50} = 0.25$ mm). Shaded area indicates range of results in water depth $h = 10$ m for equation coefficients ±50%.](image)

Soulsby (1997) reports that available data sets support a wide range of estimates for the coefficients in Eq 2.7 and 2.8 spreading ±50% about the values used above (van Rijn (1984) cites a 2X range). This substantial uncertainty is illustrated for dune height by the shaded areas in Figure 2.5a for $h = 10$ m. SERDP field work on Wasque Shoals (Traykovski, 2017), a tidal channel off Martha’s Vineyard (MV), observed the behavior of surrogate UXO affected by a migrating dune taller than the maximum $\eta$ computed by the equations in Figure 2.5 ($\eta \approx 3$ m in $h \approx 8$ m). Also, the observed Wasque Shoals dune lengths were much longer than the predicted $\lambda$, indicating there are important factors unaccounted for by this straightforward
approach, such as channel geometries, tidal current asymmetry, etc. This present uncertainty will be included in the UnMES implementation by increased spread in the computed probabilities, while dune models with higher fidelity are being developed.

In shallow water (dashed lines), dune heights are lower but the estimated maximum local slope is greater, which can act either to increase the potential for migration, or to constrain the distance traveled. Traykovski (2017) reported enhanced mobility for surrogate UXO observed on the steep lee slope of the dunes traversing in Wasque Shoals study area. In a location where a bathymetric survey measured $\beta_{\text{max}} > 0.1$, two relatively light UXO ($S_b < 2.2$) migrated a distance of about 13 m under storm wave action (note that more dense UXO buried without moving). The UXO stopped in the trough of the sand wave, implying that bathymetric slope was the controlling factor for total distance migrated. The previous model of onset of UXO mobility implemented in UnMES (Rennie and Brandt, 2017a) ignored the contribution of bed slope. However, for sites with steep bedforms, a modification to the force balance for UXO mobility is proposed.

### 2.2.2 UXO Burial and Exposure under Dune Migration

Dune migration in tidal conditions is driven by flow asymmetry, with movement in the direction of the residual current. Dunes at the Wasque Shoals site were observed to be migrating towards the northeast in the direction of the flood-dominant tidal currents (Traykovski, 2017). Over the course of several months after deployment, the bottom half of the installed quadpod and the heavier surrogate UXO were deeply buried ($B > 2$ m). After another 9 months, the dune migrated further and the instrumentation was unburied enough to be recovered. The inferred dune migration speed ($C$) was approximately $C \approx 0.5$ m/day or around 180 m/year. Results from Morellsen et al. (2003) found slower speeds ($C \sim 10$ to 20 m/year) for an amplitude and migration model tuned for large offshore dunes, but noted that smaller dunes travel faster. Besio et al. (2004) reviewed models of large ($h > 1$ m) sand waves in tide-dominated areas and also observed slower migration rates ($C$ between 4 to 9 m/year), but with substantial variability even at the same location. In general, an inverse relationship between dune height and migration speed is observed, and laboratory studies of bedform migration under combined current and waves (Catano-Lopera & Garcia, 2006) measured faster rates (up to 0.9 m/day, or over 300 m/yr) for small dune heights ($h < 0.15$ m). These measurements were made in very shallow water with large amplitude waves and represent very strong flow conditions such as might occur in certain river deltas. Migration speeds ranging between 0.2 to 1.0 m/day are computed by the model by Mulhern (1996) for mobile sand dunes based on observations in Australian coastal waters. Wever (2004) shows a similar range in a review of bedform data largely from Northern Europe, but concludes that $C > 0.5$ m/day are very unusual for small to moderate dune sizes ($h < 0.5$ m).

Most munitions of concern, i.e those included in UnMES have diameters less than 20 cm, and so would become buried as the dunes pass over them. Both Besio et al. (2004) and Mulhern (1996) make clear that the important controlling factor for computing $C$ is the magnitude of the residual current, a value that is difficult to measure accurately, being usually an order of magnitude smaller than the maximum currents. The residual current generally varies both spatially and over longer time scales. Given the large variability of migration speeds, the long-term potential for burial and unburial in a migrating dune field will be treated statistically in UnMES.

Without specific knowledge of the horizontally spatial UXO distribution at a site, it would a reasonable assumption that the distribution was initially uniform. However, it is also reasonable to assume that UXO
proud on the seabed would descend to the level of a dune trough, either by migrating down the steep lee slope, or by settling after passage of previous dunes, so that the vertical position of the UXO is set at the trough level. The shape of the burial depth probability distribution, held in UnMES as a table (CPT), then becomes a geometric argument, i.e. dependent on the shape, and particularly the height of the dune relative to UXO diameter (the ratio $\eta / D$). The ratio of time scales under consideration and the migration speed also affects the probabilities.

Very long time scales are defined as those greater than $10^*\lambda/C$, where $\lambda/C$ is the period of the migrating dune. When considering long time scales, the phase does not matter, and the probability of burial depth under all sawtooth-shaped dunes is uniform if the trough is not wider than the crest. However, most dunes are observed to have extended troughs (Besio et al. 2004, Traykovski, 2017), which essentially forms a gap between sawtooth waves. Extended time in the trough increases the probability of exposure.

Figure 2.6a illustrates a series of two half-meter high dunes with and without a gap. Example UXO with D = 15 cm are shown as red circles resting at the level of the dune trough. Here the ratio $\eta / D$ is greater than 3 and the UXO clearly spends much of the time buried under the dune. After a long time period, the burial depth probability for any UXO is uniform for the no gap case (CPT in blue, Figure 2.6b). With a modest extension of the trough (specified as 10% of $\lambda$), consonant with the observations in Besio et. al. (2004), the probability of minimal burial ($B < 5$ cm), while still only a small percentage of the time, almost doubles (in brown, Figure 2.6c).

![Diagram showing dune profiles with and without gap, and the effects on burial probability.](image-url)
An example of bedform burial was observed during field experiments studying the sea mines [Richardson and Briggs, 2000]. A dune field in a tidal pass off Destin Florida was measured with approximate height \( h = 0.7 \) m and \( \lambda \sim 30 \) m with no gaps. A surrogate sea mine with \( D = 0.47 \) cm placed in the field was partially covered after 5 days and fully buried after 11 days. For these larger munitions in smaller dune heights (\( \eta / D = 1.5 \)), the simple approach described above estimates that, in the long term, mines would be fully buried about a third of the time, have a little over a 10% chance of being exposed, and spend the rest of the time partially buried.

For some mobility model calculations, the parameter of interest is fractional, or percentage burial (%B, equivalent to B/D), which depends on the diameter of the UXO. The CPT of %B for \( D = 15 \) cm is overlaid in yellow in Figure 2.6, using 20%-wide CPT bins, similar to those previously adopted in UnMES; and all values of %B > 100% assigned to the "fully buried" bin. Accordant with most field observations in sandy environments, the large majority of the time UXO will be fully buried. The probability assigned to the lowest %B bin is of particular interest to site managers, because that helps quantify the potential for UXO mobility and migration. For the dunes with no gaps, the probability of %B < 20% (the smallest %B bin, indicating exposure) is very small, but for the extended-trough dunes, that exposed condition is predicted to occur over 10% of the time, which may be of significance in some management scenarios. No model to estimate trough extension has been included yet in UnMES, but must be determined from the bathymetric surveys available at the site of interest.

For slow-moving dunes, or when only seasonal time scales are under consideration, the UXO location in relationship to the dune phase can be important. The Mulhearn (1996) dune model, originally developed for predicting burial of sea mines after deployment in tidal environments, has been adapted to create conditional probability tables (CPT) for UnMES for short to moderate time scales. In these cases, custom CPTs for the UnMES application at that site must be computed based on recent survey information about the dune and UXO positions.

Some general observations based on knowledge of UXO properties and sediment properties can however be made. Re-exposure of buried UXO can result from temporal changes in far-field sediment morphology, e.g. or local sand dune migration (Mulhearn, 1996). As these processes occur on seasonal and annual timescales (see §2.13) it is reasonable to assume that re-exposure will occur seasonally.

Once exposed the UXO can move (see §4, below) and/or reburry. The interplay between tidally-driven dune migration and concurrent scour due to tidal currents is not modeled in this version. However, it is generally established that extremely small (bullet size) and dense (specific gravity, \( S_g \geq 5 \)) UXO bury very quickly (Rennie & Brandt, 2015; Rennie et al., 2017). Therefore, for UnMES implementation, these small, heavy munitions should be considered to not experience re-exposure (i.e., probability of %B < 0.2 set equal to zero).

### 3.0 Burial by Liquefaction

The frequently-observed scour process causes UXO to bury down to, or just past, the diameter of the munitions. There have been multiple observations of UXO burial to deeper depths within short time scales when accretion processes can be ruled out, indicating that an additional burial mechanism is extant. Under certain circumstances, deeper burial can be caused by the process of liquefaction, where the periodic shear deformation due to waves acting on the saturated seabed causes a progressive build-up of
pore pressure, resulting in a large decrease of soil strength (Sumer, 2014), or fluidization. In this situation, munitions denser than the liquefied sand will sink, while very light UXO could actually float up. These high-energy conditions, usually driven by strong storm waves, often also result in the high shear stress, with mobilization of the top layer of the seabed (sheet flow conditions that would wash away bedforms, discussed in the previous section), so that these two burial mechanisms are often observed in combination. Sheet flow conditions are usually identified by a large value of the Shields parameter value (θ). In the Rennie and Brandt (2017a) implementation of UnMES, the threshold of θ ≥ 1 was used.

UXO burial due to sand fluidization was observed on the high-energy shallow foreshore at Ocean Shores, WA during an early SERPD field experiment (Wilson et al, 2008b). On the shoreface, surrogate UXO were deployed during the SERDP DUCK15 field test at Duck, NC (Calantoni, 2017) in 8 m water depth. These UXO had varying densities, ρ_{UXO}, and diameters, D. A storm with large significant wave height (H_s > 4m), and long period (T > 13 s) that resulted in near-bed flows of near 1.5 m/s, created fluidization conditions. Large observed burial depths (B > 0.6 m), were much deeper than the thickness of any sheet flow layer, indicating that burial due to liquefaction also occurred.

Under liquefaction, when soil has lost its shear strength, the resulting burial depth will be largely controlled by a buoyancy balance where B/D will be proportional to the ratio of the UXO density to the sediment density, ρ_{UXO}/ρ_{SED}. The previous implementation of UnMES (Rennie and Brandt, 2017a) used an empirical statistical relationship proportional to relative density to estimate instantaneous burial during high-energy seabed agitation. An improved method has been provided by Friedrichs (2018), who, based on a review of recent studies of wave-induced liquefaction (Qi and Gao, 2015), and sinking observed during earthquakes (Clement et al., 2018), proposed the inclusion of a drag balance, where the estimated friction coefficient controls the rate at which the UXO sinks or rises to its equilibrium buoyancy.

One estimate for ρ_{SED} is the bulk density of wet sand, which is on the order of ρ_{SED} = 2.0 g/cm³; (specific gravity S_g = 2.0). Alternatively, analysis by Cataño-Lopera et al. [2007], Fahnstock and Haushild [1962], and Calantoni et al.[2017] point to the effective ρ_{SED} equal to the sediment grain density (S_g = 2.65), which indicates that aspects of granular sorting physics are dominant. At present there is no reasonably simple model for granular sorting phenomena suitable for inclusion in UnMES, and this area continues to be researched.

During bed fluidization, Cataño-Lopera et al. [2007] observed very different behaviors based on ρ_{UXO}: the extremely dense (ρ_{UXO} = 7.9 g/cm³) steel object sank rapidly into the bed and was buried within seconds, while lighter cylinders (ρ_{UXO} = 2.7 g/cm³) did not bury, but moved horizontally with the flow. There is extensive literature on granular sorting during soil agitation, particularly from geological mining, which often focuses on particle diameter as much as on ρ_{SED}. Patterns of granular sorting behavior can be very complex, even paradoxical, as in the ubiquitous “brazili-nut effect” where a large particle rises to the top, even when the larger particle is more dense than the smaller ones (Clement et al., 2018).

The revised version of UnMES implements the physics-based formulation of liquefaction from Friedrichs (2018) where the liquefied depth into the seabed is computed as in Qi and Gao (2015):

\[ z_L = \frac{p_0}{g\gamma} \left(\frac{1}{A_L(1-B_L)}\right) \]  \hspace{1cm} (3.1)
where \( p_0 \) is the amplitude of wave-induced pressure at the seabed, and \( \gamma = \rho_{\text{UXO}} - \rho_{\text{sed}} \), the submerged wet weight of the sand bed. The coefficient \( A_t \) is a function of the wave period \( T \), and provides an estimate of the bed consolidation, while \( B_t \) represents the coefficient of bed compressibility. Both \( A_t \) and \( B_t \) are dependent on the value of sand bed porosity, \( n \), which can vary between 0.25 < \( n \) < 0.45, while \( B_t \) also depends on bed saturation fraction.

The sinking velocity determines the time required for the UXO to sink or rise, and is estimated as

\[
V_{\text{UXO}} = \frac{D}{f_L} \left( \frac{\rho_{\text{UXO}}}{\rho_{\text{SED}}} - 1 \right)
\]

where \( D \) is the UXO diameter and the friction time scale \( f_L \) has been determined empirically based on observations from DUCK15 (Calantoni, 2017). Under high waves, \( z_L \) can be more than 1 m, while \( V_{\text{UXO}} \) is typically in the range between 0.01 to 0.06 m/hr. Therefore, storm conditions lasting a day or more are required to reach the full liquefied depth. Results are shown for an example storm in Figure 3.1 comparing dense and light munitions. For this case, a porosity value \( n = 0.32 \) and saturation fraction of 0.98 are modeled. At the peak wave height \( H_{\text{sig}} = 4 \) m the full liquefied depth \( z_L = 1.5 \) m. In Figure 3.1b the total burial for a dense 81 mm mortar with \( S_g = 4.5 \) (plotted in black) is comprised of a combination of scour burial (magenta) and burial due to liquefaction (red). Contrasting results for a very light 120 mm flare \( (S_g = 1.9) \) are shown in green. For the first three hours, a scour regime prevails with both munitions burying the same amount. At about \( H_{\text{sig}} = 2 \) m it transitions to a sheet flow so that scour is no longer occurring. The dashed magenta line shows how scour would have proceeded if the energy had not increased into the sheet flow regime where liquefaction begins. While the mortar burial increases during this liquefaction regime, the flare burial actually decreases slightly. Under the highest \( H_{\text{sig}}, \) the waves are breaking, and a smaller \( f_L \) is applied. The fractional burial is shown in Figure 3.1c. Note that after 13 hours, the mortar is buried to a depth more than twice its diameter, while the flare is less than half buried. This is a mechanism that could conceivably exhume pyrotechnic munitions with very low densities.

Unfortunately, results from this model are highly sensitive to environmental parameters describing the seabed, such as the porosity, and the fraction of sand saturation, that will be poorly known. Therefore, the probabilities for burial/re-exposure by liquefaction in UnMES must be encompass some spread of uncertainty. Future improvements to clarify this process are expected from SERDP project results of Foster (MR-2731) field work and insights gained from Liu (MR-2732) modeling efforts.
Figure 3.1 a) significant wave height (Hsig) and equilibrium liquefaction depth (zL) during an example storm event. b) for dense mortar: total burial (black), scour burial (magenta), time-varying liquefaction depth (red). for light flare: total burial (solid green), time-varying liquefaction depth (dashed green). c) fractional burial %B.

4. Migration Distance

The probability of migration of submerged marine munitions is largely driven by hydrodynamic forcing, but dependent on both the potential for re-exposure by seabed elevation changes as well as the local bathymetric slope. Results from observations of the onset of UXO motion is presented in Rennie et al. (2017) where the critical hydrodynamic force ($U_{crit}$) to initiate mobility is determined to have a power law dependence on the ratio of the UXO diameter, $D$, to the roughness scale of the seabed $k$. In sandy sediments, most UXO will experience at least partial burial much of the time, i.e. $B > 0$. Partial burial is implemented in UnMES (Rennie and Brandt, 2017a) as a linear increase in $k$ up to 50% burial ($B/D < 0.5$), after which a "lockdown" condition is rapidly imposed, as suggested by previous SERDP field data (Wilson et al., 2008a). Clearly, an accurate assessment for the potential of migration distance is highly dependent on a correct forecast of the degree of total burial compounded from consideration of scour, liquefaction and erosive mechanisms, so that uncertainty in burial predictions is passed to the migration node.
One improvement in the mobility model in UnMES will be to include the effect of bathymetric slope $\beta$, previously ignored as too small to make a significant contribution. With the addition of models for bedforms, an estimate of the probability of larger $\beta$ is available, and the factor $\mu \cos \beta - \sin \beta$, where $\mu$ represents a friction coefficient, can be included in the force balance for onset of motion as discussed in Rennie et al. (2017).

While UnMES includes a physics based model for the initiation of mobility, the prediction of the total distance travelled after being set in motion had been based on an ad-hoc approach (Rennie and Brandt, 2017a). Information on UXO migration speeds and distances is extremely limited. Studies of object migration in many cases contained data that were too limited to supply parameterizations of the extent of migration as a function of the relevant parameters (e.g. magnitude and duration of wave forcing, bottom composition and slope, object density). Summarized below is the relevant information contained in the extant studies.

Information contained in relevant earlier scientific studies encompasses studies of cobbles and cylindrical objects. Butler (1977) observed that cobbles in a gravel-bed stream moved substantial distances (200-400 m) during flood events but that motion strongly depended on where in the river the cobbles were located. Prior limited laboratory studies of cobbles motion were performed by Fahnestock & Haushild (1962). It was found that under relatively mild forcing cobbles motion was inhibited by the presence of dunes and ripples and that when motion was present the rocks moved at $\sim \frac{1}{2}$ the average water velocity (0.5 $U$). Laboratory studies were reported by Davis et al. (1999, 2007), Williams et al. (2003), Voropayev et al. (1998, 2001) who found the speed of rolling cylinder velocities on flat surfaces to be $0.6 U$ to $0.8 U$. Similar to UXO observations, the cobbles generally moved small distances and then buried under oscillatory wave forcing.

Table 4.1 list the field studies, mostly sponsored by SERDP, at various locations where multiple UXO surrogates were tracked concurrent with hydrodynamics forcing measurements. Field studies with about two dozen UXO surrogates were conducted by Scott Jenkins from Scripps Institution of Oceanography, with assistance from NAVFAC (Wilson et al. 2005, 2008a, b, c). Williams et al. (2003) tracked two cylinders released on the shoreface at Duck. All these field studies were generally of short duration and occurred under relatively mild forcing conditions (no storm events of significance). In all cases only minimal migration occurred, typically less than 10 m. Direction of motion was not uniform and the observations were too limited to obtain correlations with forcings. Further evidence from recent SERDP-funded experiments conducted by Calantoni (2017) and Traykovski (2017) to date has provided results on object migration for a limited number of UXO surrogates under high energy field conditions. In general migration distance in the field is observed at a few widely spaced points in time, when conditions allow surveying. The most recent data are from "smart" surrogates equipped with internal IMUs that can record the exact timing of movement to match up with time-varying hydrodynamic forcing. A few attempts at deriving total distance traveled by integration of the IMU record are been attempted, but often the accumulating errors preclude obtaining useful results.
Table 4.1

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Environment Classification</th>
<th>Munition Diameter</th>
<th>Specific Gravity</th>
<th>Total # UXO</th>
<th>Organization / P.I.</th>
<th>Max Migration observed (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRF Duck, NC</td>
<td>Summer 1998</td>
<td>wave-driven non-cohesive</td>
<td>98 mm</td>
<td>2.7 to 3.1</td>
<td>2</td>
<td>USACE / Williams</td>
<td>29</td>
</tr>
<tr>
<td>Point Mugu, CA</td>
<td>Fall 2003</td>
<td>wave-driven non-cohesive</td>
<td>20 mm</td>
<td>3.3</td>
<td>100</td>
<td>Scripps-NAVFAC/ Jenkins</td>
<td>none</td>
</tr>
<tr>
<td>Ocean Shores, WA</td>
<td>Fall 2004 &amp; Spring 2005</td>
<td>wave-driven non-cohesive</td>
<td>5&quot; &amp; 20mm</td>
<td>&gt; 4</td>
<td>24*2 + 19</td>
<td>Scripps-NAVFAC/ Jenkins</td>
<td>4</td>
</tr>
<tr>
<td>FRF Duck, NC</td>
<td>Winter 2005</td>
<td>wave-driven non-cohesive</td>
<td>5&quot;</td>
<td>&gt; 4</td>
<td>2*24</td>
<td>Scripps-NAVFAC/ Jenkins</td>
<td>13</td>
</tr>
<tr>
<td>PRMF, HI</td>
<td>Winter-Spring 2007</td>
<td>wave-driven coral reef</td>
<td>5&quot;</td>
<td>&gt; 4</td>
<td>24</td>
<td>Scripps-NAVFAC/ Jenkins</td>
<td>3</td>
</tr>
<tr>
<td>Gulf of Mexico / Panama City</td>
<td>Spring 2013</td>
<td>wave-driven non-cohesive</td>
<td>25, 81 &amp; 155 mm</td>
<td>1.2 to 7.8</td>
<td>13</td>
<td>NRL Stennis / Calantoni</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Wasque Shoals, MV, MA</td>
<td>Fall 2014</td>
<td>tidal-driven non-cohesive</td>
<td>74 &amp; 141 mm</td>
<td>2.1 to 3.2</td>
<td>?</td>
<td>WHOI / Traykovski</td>
<td>15</td>
</tr>
<tr>
<td>Long Point, MV, MA</td>
<td>Fall 2014</td>
<td>wave-driven non-cohesive</td>
<td>74 &amp; 141 mm</td>
<td>1.6 to 3.88</td>
<td>21</td>
<td>WHOI / Traykovski</td>
<td>116</td>
</tr>
<tr>
<td>FRF Duck, NC</td>
<td>Winter 2015</td>
<td>wave-driven non-cohesive</td>
<td>25, 81 &amp; 155 mm</td>
<td>2.7 to 7.6</td>
<td>7</td>
<td>NRL Stennis / Calantoni</td>
<td>none</td>
</tr>
<tr>
<td>Wallops Island, VA</td>
<td>Winter - Spring 2017</td>
<td>mixed sand and mud</td>
<td>81, 107, 155 mm</td>
<td>2.7, 3.7, 4.4</td>
<td>6</td>
<td>NRL &amp; UDel / Caiantoni &amp; Puleo</td>
<td>1 moved 62 m 5 stayed in place</td>
</tr>
<tr>
<td>Delaware Bay</td>
<td>Spring 2018</td>
<td>estuarine</td>
<td>60 - 155 mm</td>
<td>?</td>
<td>10</td>
<td>UDel/ Trembanis, Duval</td>
<td>none</td>
</tr>
<tr>
<td>Long Point, Martha's</td>
<td>Fall 2018</td>
<td>wave-driven non-cohesive</td>
<td>74 &amp; 141 mm</td>
<td>2.2 to 3.1</td>
<td>16</td>
<td>WHOI / Traykovski</td>
<td>25 (most &lt; 5)</td>
</tr>
<tr>
<td>Small Fiume, Univ. Delaware</td>
<td>2019</td>
<td>sloping sand</td>
<td>100 mm (BLU61)</td>
<td>1.8 to 7.7</td>
<td>165</td>
<td>UDel/ Puleo</td>
<td>2 m (single wave)</td>
</tr>
</tbody>
</table>

The last row of Table 4.1 lists a dam-break laboratory experiment performed at University of Delaware (Puleo, 2019). Motivated by observed munitions movement in the swash zone under breaking waves, a large number of runs were repeated with the same surge forcing and β while exploring a wide range of UXO densities and initial burial depth. While swash zone processes are not yet included in UnMES, insights from these experiments are included because they constitutes an end-member quantifying migration distance under extreme high forcing conditions. The detailed measurements of changing positions have been examined to determine the distance traveled versus a mobility number Ψ formed as

$$\Psi = \frac{U^2}{(D-B)} \frac{h}{gD} \left( \frac{\rho_{UXO}}{\rho_{water}} - 1 \right)$$

(4.1)

In these controlled laboratory conditions over smooth sand, the migration distance shows a strong linear relationship with Ψ, with $r^2 > 0.8$. In contrast, analysis of the recorded motions of surrogate UXO in the field did not conform to a clear pattern, nor did they correlate well with appropriate scaling parameters. An obvious complicating factor in the field are bedforms that can arrest the object’s movement.

The current migration distance model used in UnMES incorporates several physics-based assumptions. The UXO velocity after onset of motion is assumed to vary as $(U - U_{crit})^3$, a scaling derived from sediment
transport studies while the time period for migrating incorporates a form of the mobility number. The coefficients are tuned to match the distances recorded at Long Point, MV during 2014 (Traykovski, 2017) where the most extensive migration was observed.

Systematic understanding how changing topography of the seabed contributes to the large variability in field migration data will take additional research. Traykovski (2017) observed that UXO among the large dunes appeared to roll and remain in the trough. It was also noted that migration of the surrogates in the surf zone at Long Point, MV tended to stop in about water depth of $h = 1.5m$, where the incoming wave energy had decreased through breaking. None of the surrogates traveled up onto the beach in either the 2014 or 2018 field experiments there. Another effect of the seabed can be varying sediment composition. The single instance of extensive migration recorded at the Wallops Island 2017 field site continued moving over a mixed packed mud and sand area, but came to a halt in a softer sandy region. The best method for inclusion of sediment variation into the prediction of migration distance in UnMES is under consideration.

Of interest for site managers is the migration of UXO that were initially deposited on the seabed years if not decades ago. As a result, the migration observed at the time of remediation will be the sum of incremental movements that result from sufficiently large forcing events (e.g. storms) that occur when the munitions are unburied. Thus, the total migration distribution needs to be formed from a combination of re-exposure probability (see previous sections) with the expectation that strong forcing events will occur where the onset of motion criteria is exceeded.

5. Summary

Advances have been made in efforts to improve the fidelity and scope of physics-based models used in UnMES. The conclusions based on a review of the extant literature relevant to UXO re-exposure and migration processes are discussed.

Estimation of long time scale bathymetric variation, which previously were dependent on local bathymetric data archives, can now be predicted with parameterized models driven by wave observations (§2.1). The addition of bedform migration modeling is a new mechanism for burial and exposure to be included in the expert system(§2.2). The previously ad-hoc models for liquefaction burial and estimation of migration distance have been replaced by formulations that reflect the relevant physics (§3 and 4), although these still require further validation and tuning with future data sets.

The expert system approach puts the emphasis on practical models that are simple and efficient. Some environmental data is required for input, although UnMES can run with only broad, general guidance while more extensive environmental input will result in narrower uncertainty. The goal is to provide site guidance that will be reasonably accurate at lower cost than the significant investment required to calibrate and tune a full-physics numerical gridded model such as DELFT3D. In order to populate conditional probability tables for the nodes of the Bayesian Network which comprises the core of UnMES, these simple models are exercised in a Monte Carlo procedure to explore the relevant domain. Details of how these processes are implemented for use in UnMES will be discussed in Rennie et al., 2019. (in preparation). With these improvements, the Underwater Munitions Expert System is closer to becoming a useful tool that can make credible engineering assessment of risks associated with munitions management at underwater remediation sites.

i. Nomenclature and Acronyms:

B – burial depth
β – bed slope
C – dune migration speed
CPT – Conditional Probability Table(s)
D – Diameter
DBDB-V – Digital Bathymetric Data Base, Variable resolution (DBDBV)
d$_{sed}$ – Sediment grain size; also d$_{50}$ for median grain size
EOF – Empirical Orthogonal Function
ESTCP – Environmental Security Technology Certification Program
$f_s$ – friction coefficient (liquefaction)
FRF – Field Research Facility, USACE, Duck, North Carolina
h – water depth
h$_c$ – closure depth
H$_{sig}$ – significant wave height. H$_{rms} = H_{sig}*(2^{-1/2})$
λ – wavelength
MWL – Mean water level, also mean sea level
MV – Martha’s Vineyard
η – dune height
NAVOCEANO – Naval Oceanographic Office
NCEI – National Centers for Environmental Information
NOAA – National Oceanic and Atmospheric Administration
NRL – Naval Research Laboratory
r$^2$ – regression coefficient of determination
Ω – Dean’s parameter
ρ – Density
SERDP – Strategic Environmental Research and Development Program
SCBPS – Southern California Beach Processes Study
S$_g$ – Specific gravity
T – period of wave
T$_s$ – transport stage
U – Velocity of fluid flow
UnMES – Underwater Munitions Expert System
USACE – United States Army Corps of Engineers
UXO – Unexploded Ordnance
WHOI – Woods Hole Oceanographic Institute
Ψ – Mobility #
ii. References: Improved Models for Re-Exposure and Migration of Underwater Munitions


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Wilson, J.V., DeVisser, A., Sugiyama. B. 2008b Predicting the Mobility and Burial of Underwater Predicting the Mobility and Burial of Underwater Unexploded Ordnance (UXO) using the UXO Mobility Model: Application Guidance Document, ESTCP Project MM-200417.


