Factors Affecting Munitions Mobility Underwater and In Situ Measurements

May 7, 2015
Welcome and Introductions

Rula Deeb, Ph.D.
Webinar Coordinator
Agenda

- **Webinar Logistics**
  Dr. Rula Deeb  
  Geosyntec (5 minutes)

- **Overview of SERDP and ESTCP**
  Dr. Herb Nelson  
  SERDP and ESTCP (5 minutes)

- **Factors Affecting Munitions Mobility Underwater**
  Dr. Carl Friedrichs  
  Virginia Institute of Marine Science (25 minutes + Q&A)

- **In Situ Measurements of Munitions Mobility**
  Dr. Joseph Calantoni  
  Naval Research Laboratory (25 minutes + Q&A)

- **Final Q&A session**
How to Ask Questions

Type and send questions at any time using the Q&A panel.
SERDP and ESTCP Overview

Herb Nelson, Ph.D.
Munitions Response Program Manager
SERDP

- Strategic Environmental Research and Development Program
- Established by Congress in FY 1991
  - DoD, DOE and EPA partnership
- SERDP is a requirements driven program which identifies high-priority environmental science and technology investment opportunities that address DoD requirements
  - Advanced technology development to address near term needs
  - Fundamental research to impact real world environmental management
ESTCP

- Environmental Security Technology Certification Program
- Demonstrate innovative cost-effective environmental and energy technologies
  - Capitalize on past investments
  - Transition technology out of the lab
- Promote implementation
  - Facilitate regulatory acceptance
Program Areas

1. Energy and Water
2. Environmental Restoration
3. Munitions Response
4. Resource Conservation and Climate Change
5. Weapons Systems and Platforms
Munition Response

- Munitions on land
  - Classification

- Munitions underwater
  - Wide area and detailed surveys
  - Cost-effective recovery and disposal
  - Characteristics of munitions underwater, their environment and mobility
ESTCP Funding Opportunities for Innovative Technology Transfer Approaches

- FY15 BAA & DoD Call for Proposals
  Innovative Technology Transfer Approaches
  • Proposals are sought for innovative technology transfer approaches as candidates for funding beginning in FY15.
  • Approaches should be applicable to technologies that have been successfully demonstrated under ESTCP or to mature bodies of knowledge that are appropriate for direct transfer that have been developed under the SERDP.

- Proposals due no later than 2:00 p.m. ET on May 14, 2015.
Technology Transfer Solicitation

https://serdp-estcp.org/Funding-Opportunities/ESTCP-Solicitations/Technology-Transfer-Solicitation
## SERDP and ESTCP Webinar Series

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Factors Affecting Munitions Mobility Underwater

Carl Friedrichs, Ph.D.
Virginia Institute of Marine Science
Problem Statement

- **Problem being addressed**
  - Data on mobility of UXO-like objects had not been compiled and synthesized
  - Lack of robust parameterizations based on a wide range of data limits DoD predictions

- **Limitations of previous approaches**
  - Previous studies focused on limited parameter ranges
  - Previous parameterizations were less physics-based
Technical Objectives

- Compile data on UXO-like object mobility
  - From geology (movement of gravel, cobbles)
  - From coastal engineering (forces on pipelines)
  - From DoD research (cylinders in flumes, mine burial)
- Develop simple, physics-based relationships
  - Balance of forces at initial object movement
  - Scour of sediment by eddies shed by UXO
  - Movement of sediment across UXO (ongoing)
- Provide formulations to DoD Expert System
  - Close collaboration with Rennie and Brandt (MR-2227)
Technical Approach

- Compile existing data on mobility of underwater UXO and UXO-like objects
  - Internet searches, journals, dissertations, interlibrary loan
  - Results from field and lab experiments

Carling (1983)

Catano-Lopera et al. (2007)
Technical Approach

- Compile existing data on mobility of UXO-like objects
  - Initial motion of objects larger than surrounding sediment (if any)

![Graph showing critical velocity vs. diameter of object](image)

- Field measurements of natural sediment
- Lab flume containing natural sediment
- Lab flume with spheres
- Lab flume with cylinders
- Lab flume with cylinders under waves
- Field measurements of cylinders in sand under waves
Technical Approach

- Compile existing data on mobility of UXO-like objects
  - Scour-induced burial in sand of UXO-like cylinders

![Graph showing relationship between wave orbital velocity and object scour depth.](image)

- Field data under waves, cylinder diameter = 50 cm
- Lab data under waves, cylinder diameter = 8 to 25 cm
Technical Approach

- Compile existing data
  - Movement of sediment across UXO (ongoing)

Voropayev al. (1999)
Technical Approach

- Provide formulations to DoD Expert System
  - SERDP MR-2227
  - By Rennie and Brandt

“Underwater Munitions Expert System to Predict Mobility and Burial”

Offshore wave distribution represents 1-week period during SERDP field test, June 2005 at Duck, NC (Wilson et al, 2008)
Results

INITIAL MOVEMENT OF UXO
Balance of Forces at Initial Object Movement

When does an seabed object move?

Answer -- if: \((\sum \text{Forces})_x \geq (\tan \Phi) (\sum \text{Forces})_z\)

So at initial motion: \(F_D + F_I + F_W \sin \beta = (\tan \Phi) (F_W \cos \beta - F_L)\)

Simple to keep \(\beta\), but usually negligible \(\Rightarrow F_D + F_I + (\tan \Phi) F_L = (\tan \Phi) F_W\)

\(\sum\) Mobilizing forces = Resistance

\(F_L = \) lift force
\(F_D = \) drag force
\(F_I = \) inertia force
\(F_W = \) object weight
\(\Phi = \) friction angle
\(\beta = \) bed slope
\(x = \) downslope distance
\(U = \) wave + current near top of object

(Modified from Wiberg and Smith, 1987)
Parameterization of Forces at Time of Initial Motion

Object begins to move when:
\[ F_D + F_I + (\tan \Phi) F_L = (\tan \Phi) F_W \]

Forces parameterized by:
\[ F_D = \rho_w \frac{1}{2} C_D A_D U^2 \]
\[ F_W = (\rho_{\text{obj}} - \rho_w) g V_T \]
\[ F_L = \rho_w \frac{1}{2} C_L A_L U^2 \]
\[ F_I = \rho_w C_I V_I \frac{\partial U_I}{\partial t} \]

Next step: Substitute and solve for \( F_D/F_W \)

Symbols

- \( C_D, C_L, C_I \) = drag, lift and inertia coeffs.
- \( A_D, A_L \) = object area exposed to drag, lift
- \( V_T, V_I \) = object total volume and volume exposed to flow
- \( \rho_{w, \text{obj}} \) = density of water, object
- \( D, e \) = object diameter, exposure
- \( U \) = current + wave orbital velocity
- \( g \) = gravity
- \( \Phi \) = friction angle

(Modified from Kirchner et al., 1990)
Derivation of the Object “Mobility Number”, Θ₀

Algebra then gives the critical mobility condition:

\[
(1+f_ι)(1+f_L) \frac{U^2}{(\rho_{obj}/\rho_w - 1)Dg} = \tan Φ \frac{F_D}{(e/D)(1+f_L)}
\]

= object mobility number, Θ₀

Critical value:

\[
Θ_{₀, cr} \approx \frac{\tan Φ}{(e/D)}
\]

Symbols

- \(\rho_{w, obj}\) = density of water, object
- \(D, e\) = object diameter, exposure
- \(U\) = current + wave orbital velocity
- \(g\) = gravity
- \(Φ\) = friction angle
- \(f_ι\) ≈ \(F_ι/F_D\) (generally < 1)
- \(f_L\) ≈ \(F_L/F_D\) (generally < 1)

(Modified from Kirchner et al., 1990)
Effect of Bed Roughness ($k$) on Initial Movement

Object mobility # $\Theta_o = \frac{U^2}{(\rho_{obj}/\rho_w - 1) D g}$

$\Phi$ and $e$ are, in turn, affected by $k$

Critical value is $\Theta_{o, cr} \approx \frac{\tan \Phi}{(e/D)}$

$D/k > 1$

$D/k < 1$

(Modified from Kirchner et al., 1990)
Relate Critical Mobility # \( (\Theta_{o \text{ cr}}) \) to Bed Roughness (\( k \))

As \( (D/k) \uparrow \) it is easier to move an object

As \( (D/k) \uparrow \) the friction angle \( (\Phi) \downarrow \)

As \( (D/k) \uparrow \) the object exposure \( (e/D) \uparrow \)

So \( \Theta_{o \text{ crit}} \approx \frac{\tan \Phi}{(e/D)} \downarrow \)

\[
\Theta_o = \frac{U^2}{(\rho_{\text{obj}}/\rho_w - 1) D g}
\]

So as \( (D/k) \uparrow \) the \( U \) needed to move object \( \downarrow \) (for a given \( D \))

(Modified from Wiberg and Smith, 1987)
$\Theta_{o\,cr}$ vs. $D/k$ Greatly Reduces Scatter (but with a Gap)

\[ \Theta_{o\,cr} = \frac{(U_{crit})^2}{(\rho_{obj}/\rho_w - 1) D g} \]

- Lab flume with cylinders
- Lab flume containing natural sediment
- Lab flume with spheres
- Lab flume with cylinders under waves
- Field measurements of cylinders in sand under waves
- Field measurements of natural sediment

Field measurements of natural sediment

Lab flume with cylinders under waves

Lab flume with spheres
Iterative Collaboration with other SERDP Investigators

Advances in model parameterizations by Friedrichs MR-2224

Year 1

Year 2

Interaction with Rennie and Brandt MR-2227

New observations by Rennie and Brandt

(Figures from Brandt and Rennie, August 2013 report to SERDP)
**Θ_o cr** vs. *D/k* with Gap in Data Filled in by Rennie and Brandt

\[ \Theta_o = \frac{(U_{\text{crit}})^2}{(\rho_{\text{obj}}/\rho_w - 1) D g} \]

- Field measurements of natural sediment
- Lab flume containing natural sediment
- Lab flume with spheres
- Lab flume with roughened bed and cylinders
- Lab flume containing cylinders
- Lab flume with cylinders under waves
- Field measurements of cylinders in sand under waves

![Graph showing Θ_o cr vs. D/k with marked data points and legend](image-url)

- Θ_o > Θ_o cr: Motion
- Θ_o < Θ_o cr: No Motion
Results

SCOUR-INDUCED BURIAL OF UXO
Bed Under UXO is Often not Fixed in Place

Demir and Garcia (2007)

Scour-induced burial depth, $B$:

\[ D \]
Sediment Mobility Number, $\Theta_{\text{sed}}$, Explains Scour Burial

$$B = \text{Scour burial depth (cm)}$$

$$\Theta_{\text{sed}} = \frac{U^2}{(\rho_{\text{sed}}/\rho_{\text{w}} - 1) \cdot d_{\text{sed}} \cdot g}$$

- $U = \text{Wave orbital velocity (cm/s)}$
- $B = \text{Scour burial depth (cm)}$
- $\Theta_{\text{sed}} = \text{Sediment mobility number}$
- $d_{\text{sed}} = \text{Sand grain size}$

Field data under waves, cylinder $D = 50 \text{ cm}$

Lab data under waves, cylinder $D = 8$ to $25 \text{ cm}$
Rennie and Brandt (2014) Found Similar Results for Currents

Field data under waves, cylinder $D = 50$ cm

Lab data under waves, cylinder $D = 8$ to $25$ cm

Lab data under steady current, $D = 10$ cm

$$B/D = \text{Fractional burial depth}$$

$$\Theta_{sed} = \frac{U^2}{(\rho_{sed}/\rho_w - 1) \, d_{sed} \, g}$$
Scour Seems to Violate Initiation of Motion Condition

\[ \Theta_{o \, cr} = \frac{(U_{\text{crit}})^2}{(\rho_{\text{obj}}/\rho_{\text{w}} - 1) \, D \, g} \]

\[ D > \Theta_{o \, cr} \quad \text{Motion?} \]

\[ D > \Theta_{o \, cr} \quad \text{No Motion} \]

\[ = \text{Cylinders that didn't move after starting to scour, even under accelerating flow as observed by Rennie and Brandt} \]

Rennie and Brandt (2014)
Scour Inhibits Motion by Increasing Effective Roughness, $k$

\[
\Theta_{o \text{ cr}} = \frac{(U_{\text{crit}})^2}{\left(\frac{\rho_{\text{obj}}}{\rho_{w}} - 1\right) D g}
\]

Recall:
\[
\Theta_{o \text{ crit}} \approx \frac{\tan \Phi}{(e/D)}
\]

Partial burial decreases $(e/D)$ and increases $\Phi$.

Scour-induced burial depth, $B$

Define $k = B$

\[\Theta_{o} > \Theta_{o \text{ cr}} \quad \text{Motion (mostly)!}\]

\[\Theta_{o} < \Theta_{o \text{ cr}} \quad \text{No Motion!}\]

\[\downarrow = \text{Cylinders that didn’t move with } D/k \text{ based on } k = d_{\text{sed}}\]

\[\bigcirc = \text{Cylinders that didn’t move with } D/k \text{ based on } k = B_{\text{scour}}\]

Rennie and Brandt (2014)
CONCLUSIONS AND FUTURE WORK
Mobility of UXO is Governed by $\Theta_{\text{sed}}$ and $\Theta_{\text{o cr}}$

$B/D = \text{Fractional burial depth}$

$\Theta_{\text{sed}} = \frac{U^2}{(\rho_{\text{obj}}/\rho_{\text{w}} - 1) d_{\text{sed}} g}$

$\Theta_{\text{o cr}} = \frac{(U_{\text{crit}})^2}{(\rho_{\text{obj}}/\rho_{\text{w}} - 1) D g}$

$\Theta_{\text{o}} > \Theta_{\text{o cr}} \quad \text{Motion}$

$\Theta_{\text{o}} < \Theta_{\text{o cr}} \quad \text{No Motion}$

(But this neglects far field effects!)
Better Understand the Role of Independent Bed Movement

i.e., the “far field”

(Modified from Stow et al., 2009)
Movement of Sediment Across UXO and Bed Wash-out

“Regime 2”: Exposure determined mainly by bedforms, objects don’t move downstream.

“Regime 3”: Bedforms washed out, objects re-exposed by scour & move downstream.

(Modified from Fahnestock, 1962; Voropayev, 1999)
For additional information, please visit https://www.serdp-estcp.org/Program-Areas/Munitions-Response/Underwater-Environments/MR-2224

Speaker Contact Information
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Q&A Session 1
In Situ Measurements of Munitions Mobility

Joseph Calantoni, Ph.D.
Naval Research Laboratory
Project Team and Contributors

- NRL scientists, engineers and students
- Co-PI, Alex Sheremet (Univ. of Florida)
  - Tracy Staples and Uriah Gravios
- Jesse McNinch (USACE)
  - Entire staff at the FRF
- Diane Foster (Univ. of New Hampshire)
  - Meagan Wengrove
- Rob Holman (Oregon St. Univ.)
Agenda

- Problem statement
- Technical approach overview
- Observations of mobility and burial
- Granular sorting physics
- Munitions burial during large storm events
- “Sorting Diagram” for fate of munitions
- Conclusions
Problem Statement

- Needs in the underwater environment include:
  - Assess predict location of munitions relative to the bed
  - Assess environment where munitions are found

- Need to couple munitions mobility with hydrodynamic and sedimentary processes

- Environmental forecasting critical for optimizing sensor performance

23 April 2014

Technical Approach Overview

- Obtain observations of munitions mobility
  - Measure waves, currents, and sediments
- Focus on sandy field sites
  - Panama City Beach, FL (lower wave energy)
  - Duck, NC (higher wave energy)
- Conceptual model for fate of munitions
  - Density and length of munitions
  - Hydrodynamics and sedimentology
TREX13 Field Site

Panama City Beach, FL

- Leverage experiment of integration – collaboration between 12 institutions funded by ONR and SERDP
- Lower wave energy
Deploying Instruments

- Quadpods deployed at 7.5 m and 20 m depth
- 20 April – 23 May 2013
- Instruments per quadpod:
  - 1 Pencil beam sonar (targets)
  - 1 Sector scanning sonar (targets)
  - 2 HR-Aquadopp (currents and pressure)
  - 1 AWAC (waves and currents)
  - 1 PC-ADP (SSC, currents, and pressure)
  - 2 OBS-3 (SSC)
  - 1 OBS-5 (SSC)
  - 1 MicroCat (CT)
  - 2 ADV* (SSC and turbulence)
DIVER POV MOVIE
Surrogate and Replica Munitions

- Combined specs from Army Technical Manuals (e.g., TM43-0001-27 and TM43-0001-28) with low cost replicas (http://www.inertproducts.com)
- Designed/fabricated surrogate munitions with similar overall size, weight, and rolling moment (around symmetry axis)
- Fabricated replica munitions from solid materials with different densities with similar overall dimensions
MOBILITY AND BURIAL MOVIE
Granular Sorting Physics

Cartoon on the role of density in burial of munitions during intense transport events

Non-dimensional parameter: \( s_m = \frac{\rho_m}{\rho_s} \)

- \( s_m < 1 \) \( \quad \text{Always proud after intense transport} \)
- \( s_m \approx 1 \) \( \quad \text{Proud to partial burial after intense transport} \)
- \( s_m > 1 \) \( \quad \text{Always buried after intense transport} \)
Role of Density in Burial – Lab

- Scaled sediment density with nylon beads (0.5 mm)
- Cylindrical munitions of varying density (10 X 2 cm)
- Generated sheet flow conditions for nylon beads
  - 1 – 2 cm thick mobile layer
- Plotted non-dimensional burial depth (by diameter) versus relative density
- Need extreme storm conditions to test in the field with full scale munitions

Sediment Dynamics Laboratory, Naval Research Laboratory, Stennis Space Center, MS
DUCK15 Field Site

- 26 Jan – 10 Mar 2015
- US Army Corps of Engineers Field Research Facility
- Instrument arrays deployed at 8 m and 6 m depths
  - Sonars cabled to pier
- Higher wave energy
Custom 8 m Array (Horseshoe Crab)
Deploying Instruments

- 8 m array (shown left):
  - Cabled to end of pier
  - 2 Sector scanning sonar
  - 1 pumped CTD
  - HD video camera
  - Autonomous
  - 2 HR-Aquadopp (currents)
  - 1 AWAC (waves and currents)
  - 1 ADV (SSC and turbulence)

- 6 m array (not shown):
  - Autonomous
  - 1 Pencil beam sonar (targets)
  - 1 HR-Aquadopp (currents)
  - 1 ADV (SSC and turbulence)
Link to Remote Sensing

During deployment 26 Jan

During largest storm 10 Feb

Wave Height and Frequency

14 s wave period

TREX1
3 wave height
Observed Bathymetry

- 6-m Array
- 8-m Array
Historic Bathymetry 700 m Offshore
Bathymetric Activity

Active

Stable

depth (m, NAVD88)
cross-shore distance (m, FRF)

6-m Array

8-m Array

17 Mar 2015
16 Jan 2015
Munitions at 8 m Array

- Small caliber (20 and 25 mm) with embedded pinger
- Large caliber (81 and 155 mm) with attached pinger and embedded in fishing float
Role of Density in Burial – Field

- Preliminary analysis using diver observations
- 5 large caliber from 8 m array
- 2 small caliber from 6 m array (blue stars)
- Trend is similar to lab data
- Assumed maximum depth of closure obtained during largest storm
Towards a Conceptual Model for Fate of Munitions

- Minimize parameter space
  - Bulk density and single length scale for munitions
  - Sediment density and “activity” parameter
- Partition sites into two regions
  - Stable versus active bathymetry

Hypothesis: “Munitions will be trapped in a state of perpetual burial with very low probability of escape in stable bathymetry regions and a finite probability of escape in active bathymetry regions”
Sorting Diagram

- Non-dimensional phase diagram for fate of munitions
- Density ratio of munitions to sediment
- Ratio of activity parameter, $\delta_s$, to the munitions diameter
- Activity parameter subsumes mobility and burial physics
Conclusions

- Observed mobility and burial of surrogate and replica munitions in the natural environment under extreme storm conditions
- Hypothesize munitions will be trapped in a state of perpetual burial in stable bathymetry regions
- “Sorting Diagram” for fate of munitions may have application to all underwater sites
- Measurements and modeling will support estimation of site contamination as part of risk assessment
SERDP & ESTCP Webinar Series

For additional information, please visit https://www.serdp-estcp.org/Program-Areas/Munitions-Response/Underwater-Environments/MR-2320

Speaker Contact Information
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BACKUP SLIDES
Surf zone vs. tidal shoals: Where will we see the most UXO surrogate mobility?

On the tidal shoals, we used GPS buoys (B):
- Too big for smaller targets, they were swept away and not recovered
- May have biased migration of large objects high

In the surf zone we used, acoustic USBL tracking (C) and tiny marking buoys and manual surveys

Relative Density ($R = \rho_o/\rho_w$) of objects was 3.9, 2.2, and 1.8:
- Heavy (realistic) objects did not move significant distances

All UXO had IMU data loggers to measure rotations and accelerations
Long point MV, surf zone deployment: Large waves, weaker mean currents

This complicated figure shows migration tracks of all objects:

- Similar to Wasque, only less dense UXO moved.
- Here, UXO moved up to 150 m. From outer surf zone to 1 m water depth.
- No objects made it to the beach, except quadpod!
  - Ran out of Wave energy in very shallow water, due to depth limited breaking offshore.
- Bedforms are smaller here, with 0.75 * wave orbital diameter scaling, so motion in a single wave could exceed ripple wavelength.
Q&A Session 2
The next webinar is on May 28, 2015

New Tools for Characterizing and Remediating Munitions and Energetics at Military Ranges
Survey Reminder

Please take a moment to complete the survey that will pop up on your screen when the webinar ends.