Three Dimensional Hydrodynamic Mine Impact Burial Prediction

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Naval Oceanographic Office
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Hydrodynamics of Mine Burial

Bushnell Keg Mine, 1776
http://www.ae.utexas.edu/~industry/mine/bushnell.html
Acknowledgements

• Mr. Steven D. Haeger – NAVO
• Mr. Mark Null - NAVO
• Dr. Philip Valent – NRL-SSC
• Dr. Linwood Vincent - ONR

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Work Overview

• Participated in two critical path experiments within the ONR sponsored Mine Burial Prediction Program
  ➢ Carderock Mine Drop Experiment, 10-14 Sept 2001
    NSWC-CCD, Carderock, MD, 1/3 scale mine shapes, 5 meters depth.
  ➢ Corpus Christi Mine Drop Experiment, 2 –17 May 2002
    Corpus Christi Mine Warfare Operating Areas, full scale mine drops, 16-18 meters depth.
• Full data analysis of 1/15 scale mine drop (Gilless 2001) and 1/3 scale mine drop data sets. Performed preliminary analysis of full scale mine drop data set for NRL-SSC.
• 3-D hydrodynamic model development and validation.
Brief Overview

- Mine Warfare Overview
- Mine Impact Burial Doctrine
- Impact Burial Prediction Model Development
- Hydrodynamic Theory
- 3-D Model Development
- NPS Mine Drop Experiment
- Carderock Mine Drop Experiment
- Corpus Christi Mine Drop Experiment
- Data Analysis
- Results
- Discussion
- Conclusions
Mine Warfare History Lesson
Wonson Harbor, Korea, 1950

"We have lost control of the seas to a nation without a Navy, using pre-World War I weapons, laid by vessels that were utilized at the birth of Christ"
Rear Admiral Allan "Hoke" Smith
Commander, Amphibious Task Force, Wonson, Korea, 1950

Republic of Korea minesweeper YMS-516 is blown up by a magnetic mine, during sweeping operations west of Kalma Pando, Wonsan harbor, on 18 October 1950. From http://www.history.navy.mil
Naval Warfare Operational Focus Shift

- Breakdown of Soviet Union Forced Change in U.S. Navy Mission Requirements.
- Primary Guiding Documents: *Joint Vision 2010, … From the Sea, Forward … From the Sea, Operational Maneuver from the Sea, and Sea Strike, Sea Shield, Sea Basing 2002.*

- Shift in Mission Focus from open Ocean to the Littoral.
- Greatest Threat to U.S. Forces operating in the Littoral: the Naval Mine.
Naval Mine Threat

Inexpensive Force Multiplier
- 3rd world countries
- Non-government factions
- Terrorists

Widely Available
- Over 50 Countries
  (40% Increase in 10 Yrs)
- Over 300 Types
  (75% Increase in 10 Yrs)
- 32 Countries Produce
  (60% Increase in 10 Yrs)
- 24 Countries Export
  (60% Increase in 10 Yrs)

Gulf War Casualties
Roberts (FFG-58)
Tripoli (LPH-10)
Princeton (CG-59)
Damage: $125 Million
Mines Cost: $15K

Numerous Types
WWI Vintage to Advanced Technologies
(Multiple Sensors, Ship Count Routines,
Anechoic Coatings and Non-Ferrous Materials)
Naval Mine Characteristics

Characterized by:

- **Method of Delivery**: Air, Surface or Subsurface.
- **Position in Water Column**: Bottom, Moored or Floating.
- **Method of Actuation**: Magnetic and/or Acoustic Influence, Pressure, Controlled or Contact.

- Composed of metal or reinforced fiberglass.

- Shapes are Typically Cylindrical but Truncated Cone (Manta) and Wedge (Rockan) shaped mines exist.

WWII Vintage; 300,000 mines in stockpile
Naval Mine Characteristics
by littoral battle space region

Mines can also be characterized by the regions they occupy in the littoral battle space

From the U.S. Naval Mine Warfare Plan
Important Environmental Parameters for MCM Operations

• Water Properties
• Weather
• Beach Characteristics
• Tides and Currents
• Biologics
• Magnetic Conditions

❖ Bathymetry (Bottom Type)

From NRL-SSC: Dr Philip Valent
Mine Countermeasure Doctrine

- Mine Impacting Bottom will Experience a Certain Degree of “Impact Burial (IB)”.
  - Highest Degree of IB in Marine Clay and Mud.
  - IB Depends on Sediment Properties, Impact Orientation, Shape and Velocity.
- MCM Doctrine Provides only a Rough “anecdotal” Estimate of IB.

<table>
<thead>
<tr>
<th>Bottom Composition</th>
<th>Predicted Mine Case Burial %</th>
<th>Bottom Roughness</th>
<th>Bottom Category</th>
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<tr>
<td>Rock</td>
<td>0</td>
<td>Smooth Moderate Rough</td>
<td>B C C</td>
</tr>
<tr>
<td>MUD OR SAND</td>
<td>0 TO 10</td>
<td>Smooth Moderate Rough</td>
<td>A B C</td>
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<tr>
<td></td>
<td>10 TO 20</td>
<td>Smooth Moderate Rough</td>
<td>A B C</td>
</tr>
<tr>
<td></td>
<td>25 TO 75</td>
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<td>A B C</td>
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<tr>
<td></td>
<td>75 TO 100</td>
<td>All</td>
<td>C</td>
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Mine Warfare Bottom Category

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<tr>
<th>NOMBOS KM²</th>
<th>Clutter Category</th>
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<tr>
<td>&lt; 4</td>
<td>1</td>
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<tr>
<td>&gt;4 and &lt;12</td>
<td>2</td>
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<td>&gt;12</td>
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Development of Navy’s Impact Burial Prediction Model (IBPM)

- IBPM was designed to calculate mine trajectories for air, water and sediment phases.
- Improved IBPM (Satkowiak, 1987-88)
- Improvements made by Hurst (1992)
  - Included torque calculation and rotation
  - More Accurately Calculates Fluid Drag and Air-Sea and Sea-Sediment Interface Forces.
  - Improved Treatment Layered Sediments.
- Improvements made by Mulhearn (1993)
  - Allowed for offset between COM and COV
Simple Hydrodynamic Theory and Motion

Arnone-Bowen IBPM Without Moment Equation

Improved IBPM with rotation but without Moment Equation
Mine Burial Prediction Model
IMPACT 28

- Main Limitations of Hydrodynamic portion:

1. Model numerically integrates x-z momentum balance equations only. Does not consider moment balance equations.

2. Introduces an artificial rotation around the pitch axis to calculate dampening torque.

3. Limited empirical drag and lift coefficient data.

- If a mine’s water phase trajectory is not accurately modeled, then IB predictions will be wrong.


Hydrodynamic Theory

• A solid body falling through a fluid medium should obey two Newtonian principles:

1. Momentum Balance

\[ \int (\frac{dV^*}{dt^*})\,dm^* = W^* + F_b^* + F_d^* \]

2. Moment of Momentum Balance

\[ \int [r^* \times (\frac{dV^*}{dt^*})]\,dm^* = M^* \]

• Denotes dimensional variables

V* → Velocity
W* → gravity
F_b* → buoyancy force
F_d* → drag force
M* → resultant moment
Hydrodynamic Theory

- By considering all degrees of freedom, mine will exhibit a complex fall pattern.
Hydrodynamic Theory

- Considering both momentum and moment of momentum balance yields 9 governing component equations that describe the mine’s water phase trajectory and orientation.

\[
\begin{align*}
\frac{du}{dt} &= \frac{F_{sx}}{\bar{\rho} \cdot \Pi} \\
\frac{dv}{dt} &= \frac{F_{sy}}{\bar{\rho} \cdot \Pi} \\
\frac{dw}{dt} &= -\left(1 - \frac{\rho_w}{\bar{\rho}}\right) g + \frac{F_{sz}}{\bar{\rho} \cdot \Pi}
\end{align*}
\]

\[
\begin{align*}
\frac{d\Omega}{dt} &= \frac{M_{s1}}{J_1} \\
\frac{d\omega_2}{dt} &= \frac{\Pi \chi_g \rho_w \cdot \cos\psi_2 + M_{s2}}{J_2} \\
\frac{d\omega_3}{dt} &= \frac{M_{s3}}{J_3}
\end{align*}
\]

\[
\begin{align*}
\frac{d}{dt}\cos\psi_1 &= \omega_3 \cos\psi_2 - \omega_2 \cos\psi_3 \\
\frac{d}{dt}\cos\psi_2 &= \omega_4 \cos\psi_3 - \omega_3 \cos\psi_1 \\
\frac{d}{dt}\cos\psi_3 &= \omega_2 \cos\psi_1 - \omega_4 \cos\psi_2
\end{align*}
\]
Hydrodynamic Model
3 Reference Frames

- Earth Fixed Coordinate Reference Frame
- Mine Body Coordinate Reference Frame
- Drag-Lift Force Coordinate Reference Frame
Hydrodynamic Model
3 Reference Frames - 3 Transformation Matrices

Earth Fixed Coordinate to Mine Body
Coordinate Transformation Matrix

\[ \vec{i}_M = e_{11} \vec{i} + e_{21} \vec{j} + e_{31} \vec{k} \]
\[ \vec{j}_M = e_{12} \vec{i} + e_{22} \vec{j} + e_{32} \vec{k} \]
\[ \vec{k}_M = e_{13} \vec{i} + e_{23} \vec{j} + e_{33} \vec{k} \]

\[ \vec{E}_M^E R = \begin{bmatrix} \cos \psi_3 & -\sin \psi_3 & 0 \\ \sin \psi_3 & \cos \psi_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \psi_2 & 0 & \sin \psi_2 \\ 0 & 1 & 0 \\ -\sin \psi_2 & 0 & \cos \psi_2 \end{bmatrix} = \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix} \]

Earth Fixed Coordinate to Drag-Lift
Force Coordinate Transformation Matrix

\[ \vec{i}_f = e_{11} \vec{i} + e_{21} \vec{j} + e_{31} \vec{k} \]
\[ \vec{j}_f = e_{12} \vec{i} + e'_{22} \vec{j} + e'_{32} \vec{k} \]
\[ \vec{k}_f = e_{13} \vec{i} + e_{23} \vec{j} + e'_{33} \vec{k} \]

\[ \vec{E}_D^E R = \begin{bmatrix} e_{11} & \vec{e}_{12} & \vec{e}_{13} \\ e_{21} & \vec{e}_{22} & \vec{e}_{23} \\ e_{31} & \vec{e}_{32} & \vec{e}_{33} \end{bmatrix} \]

Mine Body Coordinate to Drag-Lift Force
Coordinate Transformation Matrices

\[ \vec{M}_D^M R = \vec{M}_E^E R \cdot \vec{E}_D^E R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & d_{22} & d_{23} \\ 0 & d_{32} & d_{33} \end{bmatrix} \]

\[ \vec{D}_D^M R = \vec{D}_E^E R \cdot \vec{E}_D^E R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & d_{22} & d_{32} \\ 0 & d_{32} & d_{33} \end{bmatrix} \]
Hydrodynamic Model
Momentum and Drag/Lift Forces

\[ \bar{F} - m \frac{d\bar{V}}{dt} = 0, \quad \bar{F} = \bar{F}_b + \bar{F}_s \]

\[
\begin{align*}
\frac{du}{dt} &= \frac{F_{uw}}{\rho \cdot \Pi} \\
\frac{dv}{dt} &= \frac{F_{uv}}{\rho \cdot \Pi} \\
\frac{dw}{dt} &= -\left(1 - \frac{\rho_w}{\rho}\right) g + \frac{F_{sw}}{\rho \cdot \Pi} \\
\bar{F}_b &= -\Pi (\bar{\rho} - \rho_w) g \bar{k} \\
\bar{F}_s &= \bar{F}_{d1} + \bar{F}_{d2} + \bar{F}_{d3} + \bar{F}_l \\
\bar{F}_l &= \frac{1}{2} \frac{C_l \cdot d \cdot L \cdot \rho_w}{f_{k2}} \bar{V}_2 \cdot \bar{V}_2 \\
\bar{F}_{d1} &= \frac{\left(\frac{1}{2} C_{d1} \cdot \pi d^2 \cdot \rho_w \right) \bar{V}_1 \cdot \bar{V}_1}{f_{k1}} \\
\bar{F}_{d2} &= \frac{\left(\frac{1}{2} C_{d2} \cdot d \cdot L \cdot \rho_w \right) \bar{V}_2 \cdot \bar{V}_2}{f_{k2}} \\
\bar{F}_{d3} &= \frac{1}{2} \frac{C_{d3} \cdot d \cdot \rho_w \cdot \omega_2 \cdot |\omega_2|}{f_{k2}} \left(\int_0^{b-z} y^2 dy - \int_0^{b-z} y^2 dy \right) \bar{k}_f \\
&= \frac{1}{12} \frac{C_{d3} \cdot d \cdot \rho_w \cdot \chi (3L^2 + 4 \chi^2) \cdot |\omega_2| \cdot |\omega_2|}{f_{k2}} \bar{k}_f \\
&= C_{f3} \cdot (e_{13} \bar{i} + e_{23} \bar{j} + e_{33} \bar{k}) \\
\end{align*}
\]

\[ \bar{V}_r = \bar{V}_w - \bar{V}_o = \bar{V}_1 + \bar{V}_2 = V_1 \cdot \bar{i}_f + V_2 \cdot \bar{j}_f \]

\[ \bar{k}_f (\bar{F}_{d2}) \]

\[ \bar{k}_f (\bar{F}_{d1}, \bar{F}_{d3}) \]

\[ \bar{j}_f (\bar{F}_{d2}) \]

\[ \bar{V}_7 \]
Hydrodynamic Model
Moment of Momentum and Torques

\[ J \cdot \frac{d\vec{\omega}_m}{dt} = \vec{M} - J \cdot \frac{d\vec{\omega}_f}{dt} \]
\[ J \cdot \frac{d\vec{\omega}}{dt} = \vec{M}_b + \vec{M}_s \]
\[ \vec{\omega} = \Omega \vec{\omega}_m + \omega_2 \vec{j}_m + \omega_3 \vec{k}_m \]

\[ \vec{M} = \vec{M}_b + \vec{M}_s \]

\[ J = \begin{bmatrix} J_1 & J_{12} & J_{13} \\ J_{21} & J_2 & J_{23} \\ J_{31} & J_{32} & J_3 \end{bmatrix} \]

\[ J_1 = \int (r_2^2 + r_3^2) \, dm \]
\[ J_1 = \frac{1}{8} m \cdot d^2 \]

\[ J_2 = \int (r_3^2 + r_4^2) \, dm \]
\[ J_3 = \int (r_1^2 + r_4^2) \, dm \]

\[ J_2 = J_3 = \frac{m}{4} \left( \frac{d}{2} \right)^2 + \frac{m}{12} \cdot L^2 + (\chi^2 + \xi^2) \cdot m \cdot L^2 \]

\[ J_{31} = \int r_1 r_3 \, dm \]

\[ J_{12} = J_{21} = J_{13} = J_{31} = J_{23} = J_{32} = 0 \]

\[ \vec{M}_b = \Pi \chi \rho \cdot g \cdot \cos \psi_2 \cdot \vec{j}_m \]
Hydrodynamic Model
Moment of Momentum and Torques

\[ M_{sd3} = \frac{\int_{\frac{L-x}{2}}^{\frac{L-x}{2}} \frac{1}{2} C_{d2} \cdot d \cdot \rho \cdot (V_2 - \omega_3 y)^2 \cdot y \cdot dy}{\int_{\frac{L-x}{2}}^{\frac{L-x}{2}} f_{kr}} = C_{m3} \cdot \omega_3 + m_{cm3} \]

\[ -\omega_3 |\omega_3| \int_{\frac{L-x}{2}}^{\frac{L-x}{2}} \frac{1}{2} C_{d2} \cdot d \cdot \rho \cdot y^2 \cdot |y| \cdot dy = M_{sd2} \frac{L-x}{2} f_{kr} \]

\[ M_{sd} = \frac{\int_{\frac{L-x}{2}}^{\frac{L-x}{2}} \frac{1}{2} C_1 \cdot d \cdot \rho \cdot (V_2 - \omega_3 y) \cdot y \cdot dy}{\int_{\frac{L-x}{2}}^{\frac{L-x}{2}} f_{kr}} = \frac{- \int_{\frac{L-x}{2}}^{\frac{L-x}{2}} \frac{1}{2} \Omega \cdot d^2 \cdot \rho \cdot \int_{\frac{L-x}{2}}^{\frac{L-x}{2}} (V_2 - \omega_3 y) \cdot y \cdot dy}{\int_{\frac{L-x}{2}}^{\frac{L-x}{2}} f_{kr}} \]

\[ \frac{1}{2} \Omega \cdot d^2 \cdot \rho \cdot L \cdot \left( V_2 x + \frac{1}{12} L^2 \omega_3 + x^2 \omega_3 \right) = C_{ml} \cdot \omega_3 + m_{cm1} \]
Model Numerical Basics

The external torques and linear forcing terms are converted to
The appropriate reference frame and \( \frac{d\hat{V}}{dt} \) and \( \frac{d\hat{\omega}}{dt} \) are computed
For each time step

\[
\begin{align*}
    x^{n+1} &= x^n + \int_0^{dt} u dt \\
    y^{n+1} &= y^n + \int_0^{dt} v dt \\
    z^{n+1} &= z^n + \int_0^{dt} w dt
\end{align*}
\]

\[
\begin{align*}
    d\psi_2 &= \int_0^{dt} \psi_2 dt \\
    d\psi_3 &= \int_0^{dt} \psi_3 dt
\end{align*}
\]

\[
\begin{align*}
    E M R^{n+1} &= \begin{bmatrix}
        \cos \psi_3 & -\sin \psi_3 & 0 \\
        \sin \psi_3 & \cos \psi_3 & 0 \\
        0 & 0 & 1
    \end{bmatrix} \cdot \begin{bmatrix}
        \cos \psi_2 & 0 & \sin \psi_2 \\
        0 & 1 & 0 \\
        -\sin \psi_2 & 0 & \cos \psi_2
    \end{bmatrix} \\
    &= \begin{bmatrix}
        \cos \psi_3 \cdot \cos \psi_2 & -\sin \psi_3 & \cos \psi_3 \cdot \sin \psi_2 \\
        \sin \psi_3 \cdot \cos \psi_2 & \cos \psi_3 & \sin \psi_3 \cdot \sin \psi_2 \\
        -\sin \psi_2 & 0 & \cos \psi_2
    \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
    \psi_2^{n+1} &= \arccos(E M R^{n+1}(3,3)) \\
    \psi_3^{n+1} &= \arccos(E M R^{n+1}(2,2))
\end{align*}
\]
Required Modeling Parameters

Mine Parameters:
\[ \chi \] Center of mass offset
\[ \bar{\rho}_m \] mine mean density
\[ l \] mine length
\[ d \] mine diameter
\[ m \] mine mass
\[ [J] \] moment of inertia tensor

Initial Conditions
\[ x_0, y_0, z_0 \] initial position vector
\[ u_0, v_0, w_0 \] initial linear velocity vector
\[ \Omega_{l0}, \omega_{z0}, \omega_{z0} \] initial angular velocity vector
\[ \psi_{20}, \psi_{30} \] initial angle vector
\[ \Delta t \] time step

Hydrodynamic Parameters:
\[ \overline{V}_r = \overline{V}_1 + \overline{V}_2 \] relative water velocity vector
\[ R_e \] reynolds number
\[ C_{da} \] axial drag coefficient
\[ C_{df} \] cross flow drag coefficient
\[ C_l \] lift axis coefficient
\[ T \] water temperature
\[ \rho_w \] water density
\[ \nu \] water kinematic viscosity
MIDEX
(July 2001)

1/15 scale Mine Shapes:
Length: 15, 12, 9 cm
Diameter: 4 cm
MIDEX Mine Shape

Defined COM position as:
2 or -2: Farthest from volumetric center
1 or -1
0: Coincides with volumetric center

MODEL # 1
L=15.1359 cm D=4 cm m=2.7 cm
Weight=322.5 g Volume=190.2028 cm³ Density=1.6956 g/cm³
H:  10.360  8.052  5.725 cm
h:  -1.462  0.866  3.193 cm
M:  0.000  18.468  36.935 mm

MODEL # 2
L=12.0726 cm D=4 cm m=1.7 cm
Weight=254.2 g Volume=151.709 cm³ Density=1.6756 g/cm³
H:  8.450  6.609  4.768 cm
h:  -1.564  0.277  2.119 cm
M:  0.000  12.145  24.290 mm

MODEL # 3
L=9.1199 cm D=4 cm m=1.47 cm
Weight=215.3 g Volume=114.6037 cm³ Density=1.8786 g/cm³
H:  6.662  5.592  4.521 cm
h:  -1.368  -0.297  0.774 cm
M:  0.000  6.847  13.694 mm
Carderock Experiment Participants
NSWC-CCD Explosive Test Pond

ONR
Dr. Linwood Vincent, Dr. Roy Wilkens

NRL-SSC
Dr. Philip Valent, Dr. Mike Richardson
Mr. Conrad Kennedy, CDR Chuck King
Mr. Todd Holland, Mr. Grant Bower

NSWC-CCD
Mr. Bill Lewis, Mr. Peter Congedo,
Mr. Jim Craig

NPS
Dr. Peter Chu, LCDR A Evans

JHU
Ms. Sarah Rennie

MIT
Dr. Dick Yue, Dr. Yuming Liu
Dr. Yonghwan Kim,

TAMU
Dr. Wayne Dunlap, Mr. Charles Aubeny

OMNITECH
Dr. Albert Green

Naval Reserve
LCDR R. McDowell, LCDR Pat Hudson
HM2 William McKinney
# Carderock Mine Drop Experiment

## CHARACTERISTICS OF MINE MODELS USED IN TEST POND, NSWC CARDEROCK, MD, 10-14 Sept 2001 (Revised 28 Feb 2002)

<table>
<thead>
<tr>
<th>Model number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blunt Mine Parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter, m (in.)</td>
<td>0.168 (6.63)</td>
<td>0.168 (6.63)</td>
<td>0.168 (6.63)</td>
<td>0.168 (6.63)</td>
<td>0.168 (6.63)</td>
<td>0.168 (6.63)</td>
</tr>
<tr>
<td>Length, blunt, m (in.)</td>
<td>0.477 (18.78)</td>
<td>0.477 (18.78)</td>
<td>0.982 (38.65)</td>
<td>0.982 (38.65)</td>
<td>0.982 (38.65)</td>
<td>0.982 (38.65)</td>
</tr>
<tr>
<td>L/D for blunt nose</td>
<td>2.8</td>
<td>2.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Volume, cu m (cu ft) (blunt)</td>
<td>0.0106 (0.374)</td>
<td>0.0106 (0.374)</td>
<td>0.0218 (0.771)</td>
<td>0.0218 (0.771)</td>
<td>0.0218 (0.771)</td>
<td>0.0218 (0.771)</td>
</tr>
<tr>
<td>Weight (lbs)</td>
<td>38</td>
<td>49</td>
<td>76</td>
<td>102</td>
<td>100</td>
<td>98.5</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>17.2</td>
<td>22.2</td>
<td>34.5</td>
<td>46.3</td>
<td>45.4</td>
<td>44.7</td>
</tr>
<tr>
<td>Mass Wet kg (4) (blunt)</td>
<td>6.33</td>
<td>11.33</td>
<td>12.13</td>
<td>23.93</td>
<td>23.04</td>
<td>22.34</td>
</tr>
<tr>
<td>Bulk density, pcf (Mg/cu m)</td>
<td>101.6 (1.63)</td>
<td>131.0 (2.10)</td>
<td>98.6 (1.58)</td>
<td>132.3 (2.12)</td>
<td>129.7 (2.08)</td>
<td>127.8 (2.05)</td>
</tr>
<tr>
<td>( \chi )</td>
<td>-0.0002385</td>
<td>-0.001908</td>
<td>-0.001964</td>
<td>-0.008838</td>
<td>0.045172</td>
<td>0.076596</td>
</tr>
<tr>
<td>( \chi ) / (mine length)</td>
<td>-0.0005</td>
<td>-0.004</td>
<td>-0.003</td>
<td>-0.009</td>
<td>0.046</td>
<td>0.079</td>
</tr>
</tbody>
</table>

## Moment of Inertia about CM

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{xx} ), kg·m² (lb·in²)</td>
<td>0.0647 (221)</td>
<td>0.0806 (275)</td>
<td>0.1362 (465)</td>
<td>0.1696 (579)</td>
<td>0.1693 (578)</td>
<td>0.1692 (578)</td>
</tr>
<tr>
<td>( I_{yy} ), kg·m² (lb·in²)</td>
<td>0.356 (1216)</td>
<td>0.477 (1627)</td>
<td>2.90 (9910)</td>
<td>3.82 (13,050)</td>
<td>3.94 (13,440)</td>
<td>4.57 (15,600)</td>
</tr>
<tr>
<td>( I_{zz} ), kg·m² (lb·in²)</td>
<td>0.356 (1214)</td>
<td>0.476 (1625)</td>
<td>2.90 (9910)</td>
<td>3.82 (13,050)</td>
<td>3.94 (13,430)</td>
<td>4.57 (15,600)</td>
</tr>
</tbody>
</table>

**Note:**

1. \( I_{xx} \) about long axis (Roll)
2. \( I_{yy} \) about transverse vertical axis (Yaw)
3. \( I_{zz} \) about transverse horizontal axis (Pitch)
4. Wet mass calculations required for IMPACT28

Wet mass calculation based on water density 1025.8 kg/m³
Carderock Data Acquisition
Digital Collection 125 fps
Carderock Data Acquisition
3 Camera Tracking Data Analysis and Archive
Full Scale Mine Drop Experiment Results

- Blunt, Chamfered and Hemispherical noses on 1200 lb mine shape

Telemetry Package
- 3 FOGs
- 6 accelerometers
- 3 magnetometers
- On board data recorder

Corpus Christi Mine Drop Experiment
Data 2-17 May 2002

12 drops into 80ft of water
Corpus Christi Experiment Participants
Corpus Christi Mine Warfare Operating Areas A-E

NRL-SSC        Dr. Philip Valent, Dr. Mike Richardson
               Mr. Conrad Kennedy, CDR Chuck King
               Mr. Grant Bower, Mr. Dale Bibee

NAVOCEANO     Mr. J. Burrell
University of Hawaii   Dr. Roy Wilkens
Columbia University  Dr. Ives Bitte, Dr. Yue-Feng Sun
NPS             LCDR A Evans
TAMU           Dr. Wayne Dunlap, Mr. C Brookshire
OMNITECH       Mr. Dan Lott, Mr. J. Bradley
Naval Reserve   HM2 William McKinney
USM            Mr. Andrei Abelev
RV Gyre        Captain Desmond Rolf
1. Each Video converted to digital format
2. Analyzed 2-D data to obtain mine’s x, y and z center positions; $\psi_2$ and $\psi_3$ angle; u, v, and w components of velocity; and $\Omega_1$, $\omega_2$, and $\omega_3$ angular velocities
3. The data transformed to the reference framework of the model
4. Initial model conditions mine parameters and hydrodynamic parameters fed to the model
5. Results prepared for presentation graphics and database archive
Sources of Error

1. Grid plane behind mine trajectory plane. Results in mine appearing larger than normal, MIDEX.
2. Camera reference to calibration grid error, Carderock.
3. Position data affected by parallax distortion and binocular disparity from camera reference, NRL estimates +/- 5cm.
4. Air cavity affects on mine motion not considered in calculations.
5. Camera plane not parallel to x-y plane due to pool slope.
6. Determination of initial linear and angular velocities from position data can lead to large errors.
Trajectory Patterns
(Chu et al 2001)

1. Straight
Trajectory Patterns
(Chu et al 2001)

1. Straight
2. Slant
Trajectory Patterns
(Chu et al 2001)

1. Straight
2. Slant
3. Spiral
Trajectory Patterns
(Chu et al 2001)

1. Straight
2. Slant
3. Spiral
4. Flip
Trajectory Patterns
(Chu et al 2001)

1. Straight
2. Slant
3. Spiral
4. Flip
5. Flat
Trajectory Patterns
(Chu et al 2001)

1. Straight
2. Slant
3. Spiral
4. Flip
5. Flat
6. See Saw
Trajectory Patterns
(Chu et al 2001)

1. Straight
2. Slant
3. Spiral
4. Flip
5. Flat
6. See Saw
7. Combination
Carderock Data Trajectory Analysis

<table>
<thead>
<tr>
<th>Mine Drop Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blunt Nosed Mine Shapes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal Drops</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1w-series</td>
<td>Flat-Spiral</td>
<td>Flat-Spiral</td>
<td>Flat</td>
<td>Flat-Spiral</td>
<td>Slant</td>
<td>Slant-Spiral</td>
</tr>
<tr>
<td>10w-series</td>
<td>Flat</td>
<td>Flat</td>
<td>Flat</td>
<td>Flat</td>
<td>Slant</td>
<td>Slant-Spiral</td>
</tr>
<tr>
<td>11w-series</td>
<td>Flat-Spiral</td>
<td>Flat</td>
<td>Flat</td>
<td>Flat</td>
<td>Slant-Flat</td>
<td>Slant-Spiral</td>
</tr>
<tr>
<td>Vertical Drops</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2w-series</td>
<td>Straight-Flat</td>
<td>Straight-Flat</td>
<td>Straight</td>
<td>Straight</td>
<td>Straight</td>
<td>Straight-Slant</td>
</tr>
<tr>
<td>12w-series</td>
<td>Straight-Flat-Seesaw</td>
<td>Straight-Flat-Spiral</td>
<td>Straight-Spiral</td>
<td>(flooded mine)</td>
<td>Straight</td>
<td>Straight</td>
</tr>
<tr>
<td>13w-series</td>
<td>Straight-Flat</td>
<td>Straight-Flat</td>
<td>Straight</td>
<td>(flooded mine)</td>
<td>Straight</td>
<td>Straight</td>
</tr>
<tr>
<td>45 degree down</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17w-series</td>
<td>Flat-Seesaw-Spiral</td>
<td>Flat-Seesaw</td>
<td>Flat-Seesaw</td>
<td>Slant-Flat</td>
<td>Straight-Slant</td>
<td>Slant-Spiral</td>
</tr>
<tr>
<td>20w-series</td>
<td>Flat-Seesaw</td>
<td>Flat-Seesaw</td>
<td>Slant-Flat-Seesaw</td>
<td>(flooded mine)</td>
<td>Slant-Spiral</td>
<td>Slant-Spiral</td>
</tr>
<tr>
<td>21w-series</td>
<td>Seesaw-Spiral</td>
<td>Flat-Seesaw</td>
<td>Flat-Seesaw</td>
<td>(flooded mine)</td>
<td>Slant-Spiral</td>
<td>Slant</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mine Trajectory Pattern</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>Mine exhibited little angular change about z-axis. $\delta \psi &lt; 10^\circ$.</td>
</tr>
<tr>
<td>Spiral</td>
<td>Mine experienced rotation about z-axis. $\delta \psi &gt; 10^\circ$.</td>
</tr>
<tr>
<td>Flip</td>
<td>Initial water entry point rotated at least $180^\circ$ during mine motion.</td>
</tr>
<tr>
<td>Flat</td>
<td>Mine's angle with vertical near $90^\circ$ for most of the trajectory.</td>
</tr>
<tr>
<td>See-Saw</td>
<td>Similar to the flat pattern except that mine's angle with vertical would oscillate between greater (less) than $90^\circ$ and less (greater) than $90^\circ$ - like a see-saw.</td>
</tr>
<tr>
<td>Combination</td>
<td>Complex trajectory where mine exhibited several of the above patterns.</td>
</tr>
</tbody>
</table>
Simple Motion Model Mechanics
Straight Motion

Carderock Experiment Run: 2w-4
3-D Model Solution: 2w-4

Model Initial Parameters

- $\theta_{20} = 89.4^\circ$
- $\omega_{20} = 0.018 \, (\text{radians/s})$
- $V_{10} = 0 \, (\text{m/s})$
- $V_{y0} = 0.0129 \, (\text{m/s})$
- $V_{z0} = -0.015 \, (\text{m/s})$
- $\Delta t = 1/15 \, (\text{s})$

Depth (m)
Path Distance (m)

Mass center trail
Yaw Velocity
Depth (m)
Path Distance (m)

Depth (m)
Path Distance (m)
Simple Motion Model Mechanics

Flat Motion

Carderock Experiment Run: 11w-4
3-D Model Solution: 11w-4

Model Initial Parameters
\( \Psi_{20} = -1.29^\circ \)
\( \dot{\Psi}_{20} = 0.076 \, (r/s) \)
\( V_{x_0} = -0.0383 \, (m/s) \)
\( V_{y_0} = -0.0358 \, (m/s) \)
\( V_{z_0} = -0.0617 \, (m/s) \)
\( d_l = 1/15 \, (s) \)
Simple Motion Model Mechanics

Slant Motion

Carderock Experiment Run: 10w-6

3-D Model Solution: 10w-6

Model Initial Parameters:

- $\Psi_0 = 6.98^0$
- $\Omega_{20} = 0.24 \text{ (rad/s)}$
- $V_{z0} = -0.0304 \text{ (m/s)}$
- $V_{z1} = -0.0633 \text{ (m/s)}$
- $V_{z2} = 0.00375 \text{ (m/s)}$
- $\Delta t = 1/15 \text{ (s)}$

- Depth (m)
- Path Distance (m)
- Yaw Velocity
- Mass center trail

UNCLASSIFIED
Simple Motion Model Mechanics

Complex Motion

Model Initial Parameters

\[ \begin{align*}
\Psi_{20} & = 60^\circ \\
\dot{\phi}_{20} & = -0.7 \text{ (r/s)} \\
V_{x_{20}} & = 0 \text{ (m/s)} \\
V_{y_{20}} & = -0.858 \text{ (m/s)} \\
V_{z_{20}} & = -1.5 \text{ (m/s)} \\
dt & = 1/30 \text{ (s)}
\end{align*} \]
Impact Velocity Correlation

3-D Model Impact Fall Velocity Versus Composite Experimental Data Impact Fall Velocity

Regression Equation
\[ y = 0.84x + 0.5621 \]
\[ R^2 = 0.6363 \]
Impact Angle Correlation

3-D Model Impact Angle Versus Composite Experiment Data Impact Angle

Regression Equation
\[ y = 0.7899x + 16.765 \]
\[ R^2 = 0.2099 \]
Probability Distribution Function Characterization of Mining Factors in an Operating Area

Sarah Rennie and Alan Brandt
Johns Hopkins University
Applied Physics Laboratory, 2002
An Expert Systems Approach for Predicting Mine Burial

Sarah Rennie and Alan Brandt
Johns Hopkins University
Applied Physics Laboratory,
2002
Conclusions

- Simple two dimension hydrodynamic model extended to three dimensions encompassing all 6 degrees of freedom using modern modeling application.
- Carderock data displayed the same six types of trajectories discussed in Gilless (2001).
- Model Mechanics correctly model vertical and horizontal hydrodynamics of mine shapes.
- Model does handle complex trajectories such as spiral slants and flip rotations, but the outcome is highly sensitive to initial parameters.
- Model provides a good statistical measure of impact fall velocity.
- Model is inadequate at producing a statistical measure of impact angle. Performs worse than IMPACT28. Future work in this area includes stability analysis for neutrally stable mine shapes.
- Database now exists of ~ 300 mine drops including initial conditions and complete position data.
- 120 hemispheric nose 1/3 scale model drops to model and incorporate into the database. Full scale mine drop series from Corpus Christi Experiment will be available in January for analysis, as well as data from full scale drops in Mississippi in 2001.
- Investigation required into modeled mine stability for a neutrally stable mine shape to improve impact angle output results.