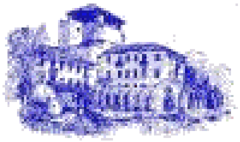

Three Dimensional Hydrodynamic Mine Impact Burial Prediction

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Naval Oceanographic Office

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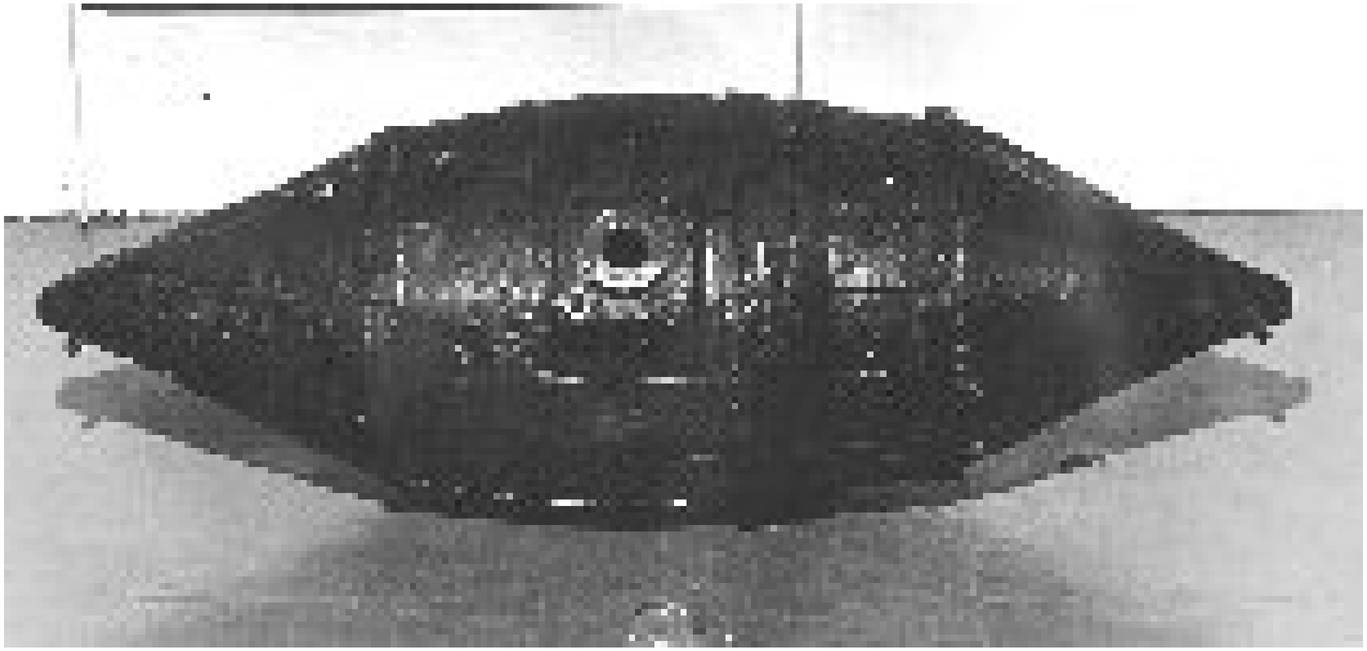
Hydrodynamics of Mine Burial



Bushnell Keg Mine, 1776

http://www.ae.utexas.edu/~industry/mine/bushnell.html

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

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ONR contract N0001202WR20174.

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

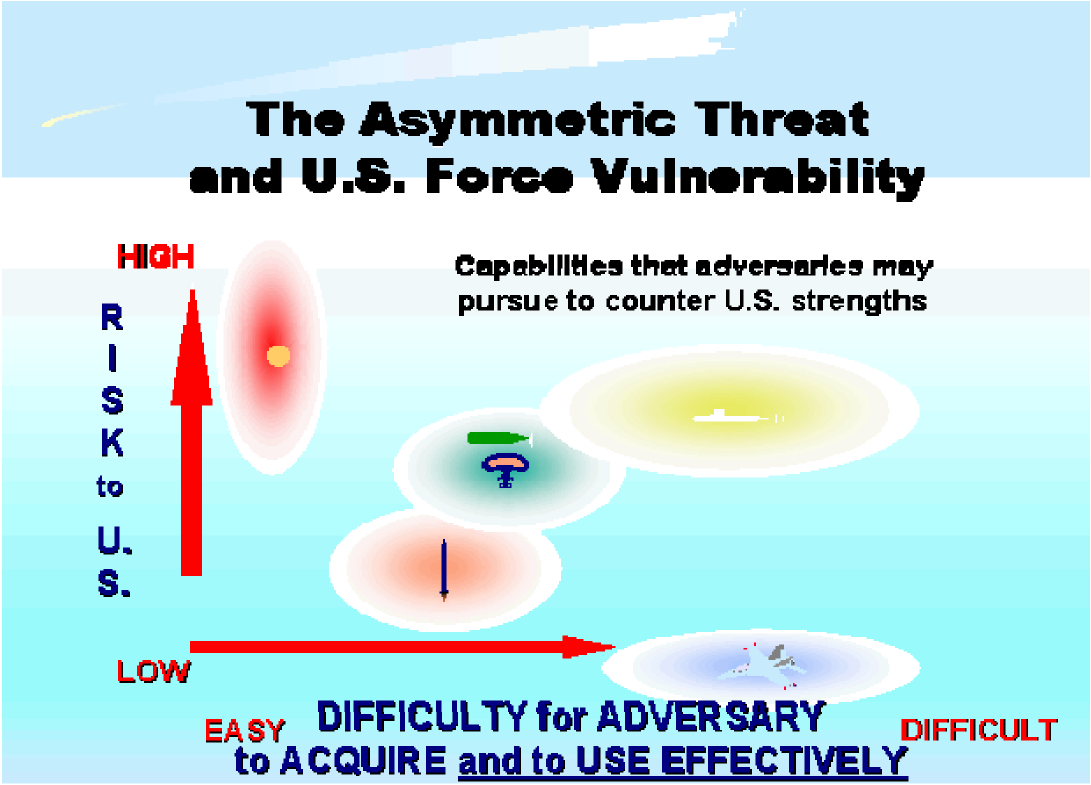
Wonson Harbor, Korea, 1950

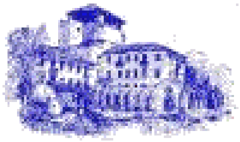
> **"We have lost control of the seas to a nation without a Navy, using pre-World War I weapons, laid by vessels that were utilized at the birth of Christ"**
>
> **Rear Admiral Allan "Hoke" Smith**
> **Commander, Amphibious Task Force, Wonson, Korea, 1950**

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

Gulf War Casualties

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

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)

Numerous Types

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

Naval Mine Characteristics

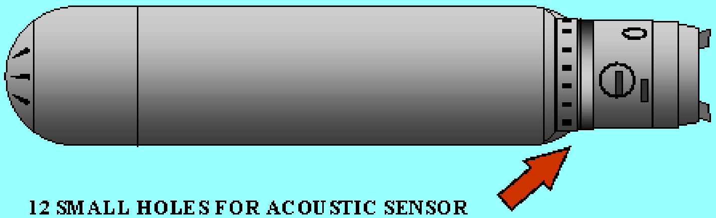
Characterized by:

- *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.

RUSSIAN AMD/KMD - II - 1000
BOTTOM CYLINDRICAL



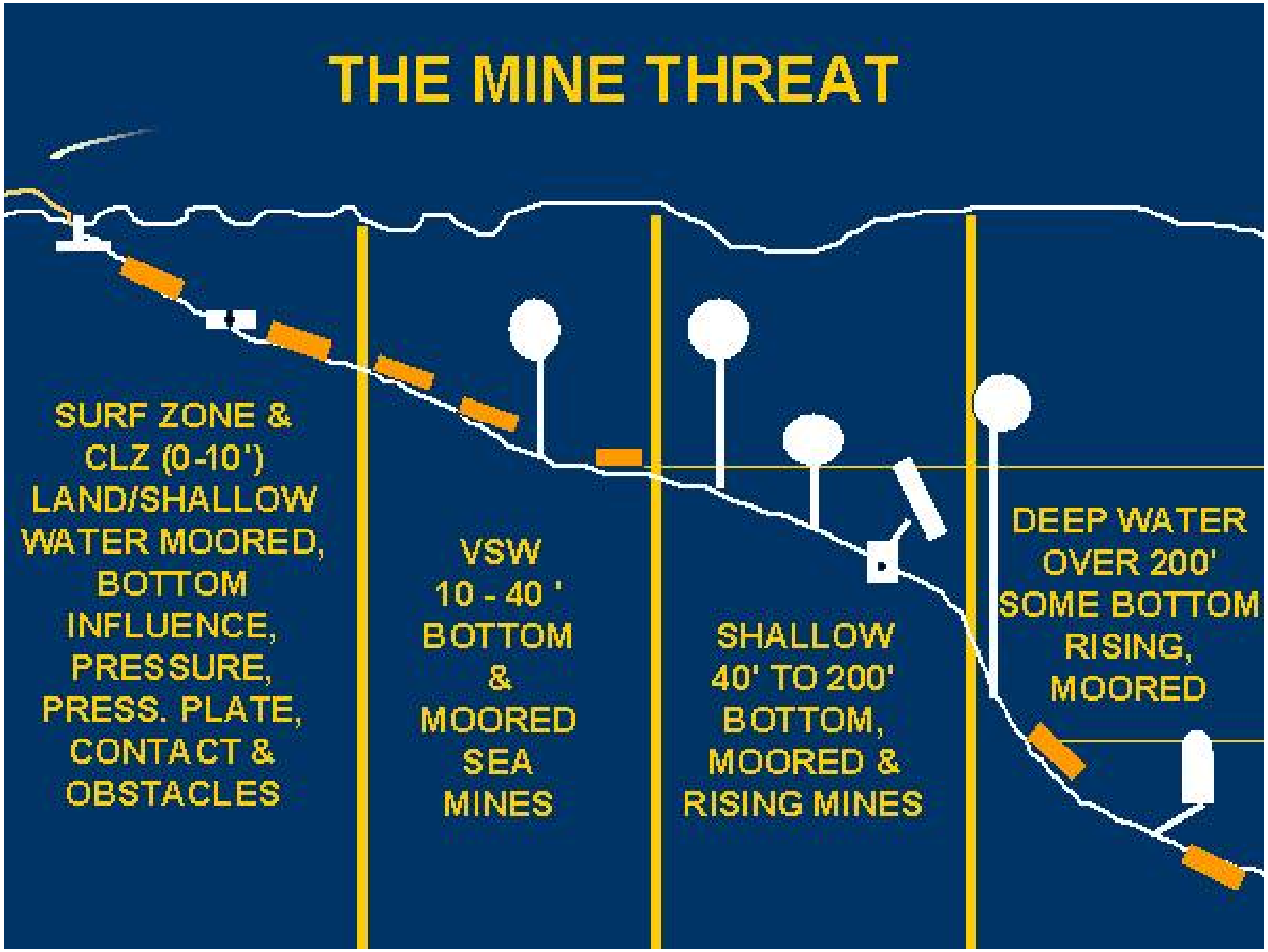
12 SMALL HOLES FOR ACOUSTIC SENSOR

285 CM LENGTH/53 CM DIAMETER
1000 KG WT/700 KG WARHEAD
6 - 50 M DEPTH
MAGNETIC, ACOUSTIC

WWII Vintage; 300,000 mines in stockpile

Naval Mine Characteristics

by littoral battle space region



From the U.S. Naval Mine Warfare Plan

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

Important Environmental Parameters for MCM Operations

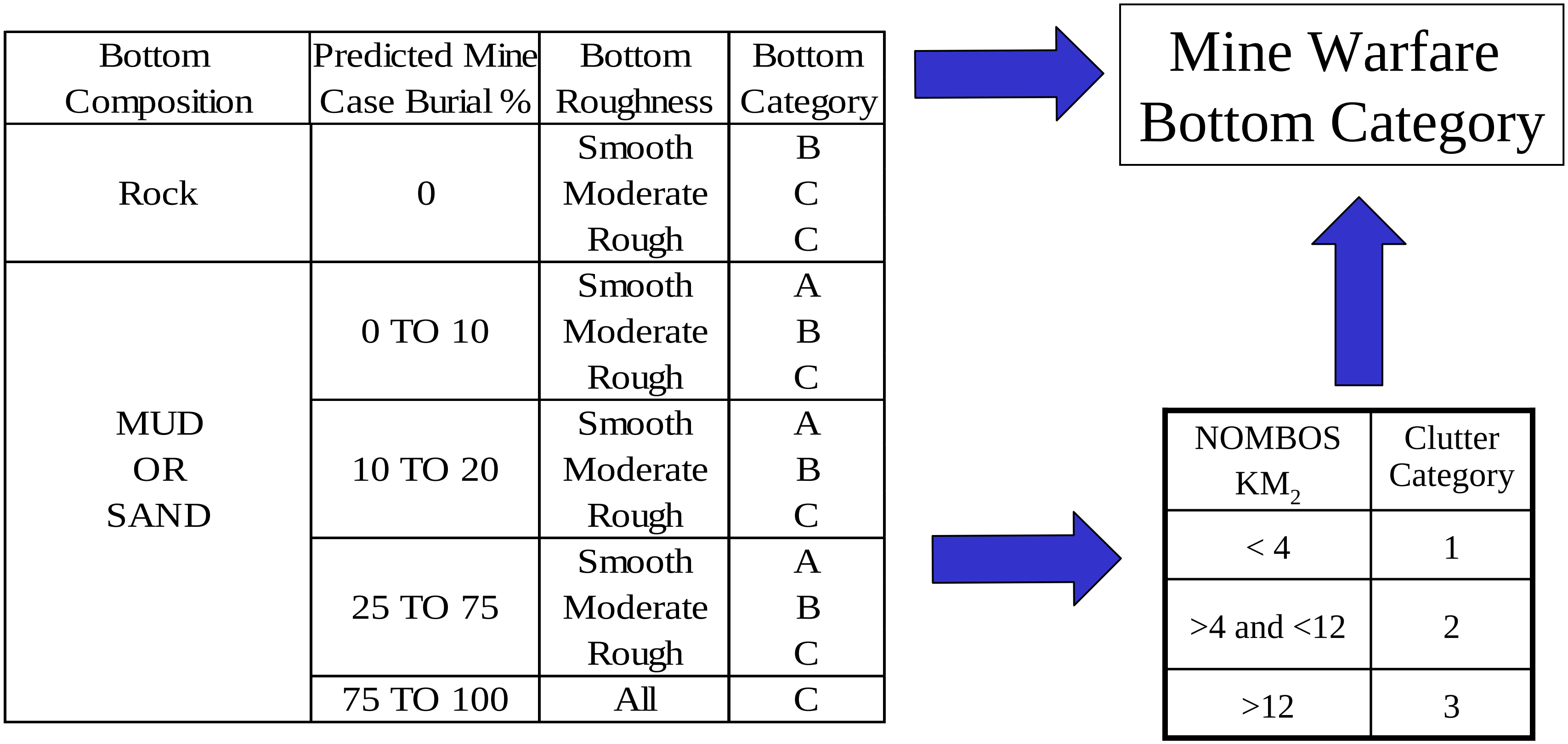
- Water Properties
- Weather
- Beach Characteristics
- Tides and Currents
- Biologics
- Magnetic Conditions

❖ 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.



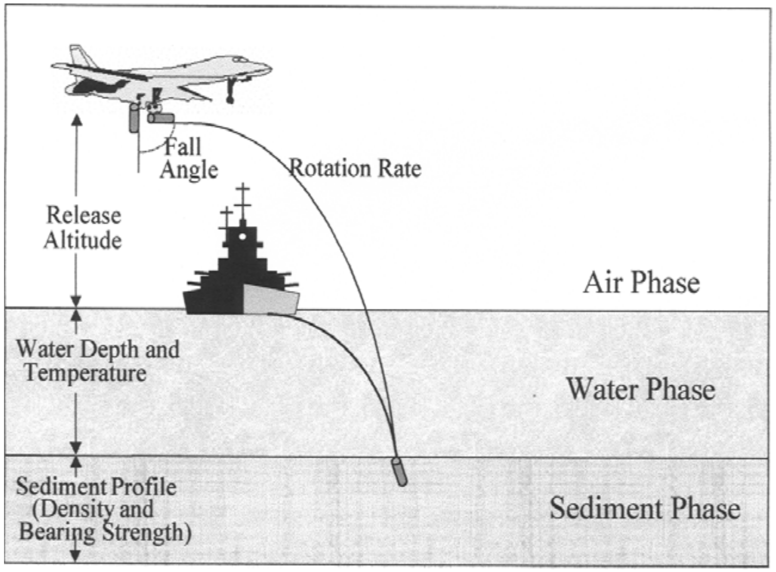
Bottom Composition	Predicted Mine Case Burial %	Bottom Roughness	Bottom Category
Rock	0	Smooth	B
		Moderate	C
		Rough	C
MUD OR SAND	0 TO 10	Smooth	A
		Moderate	B
		Rough	C
	10 TO 20	Smooth	A
		Moderate	B
		Rough	C
	25 TO 75	Smooth	A
		Moderate	B
		Rough	C
	75 TO 100	All	C

Mine Warfare Bottom Category

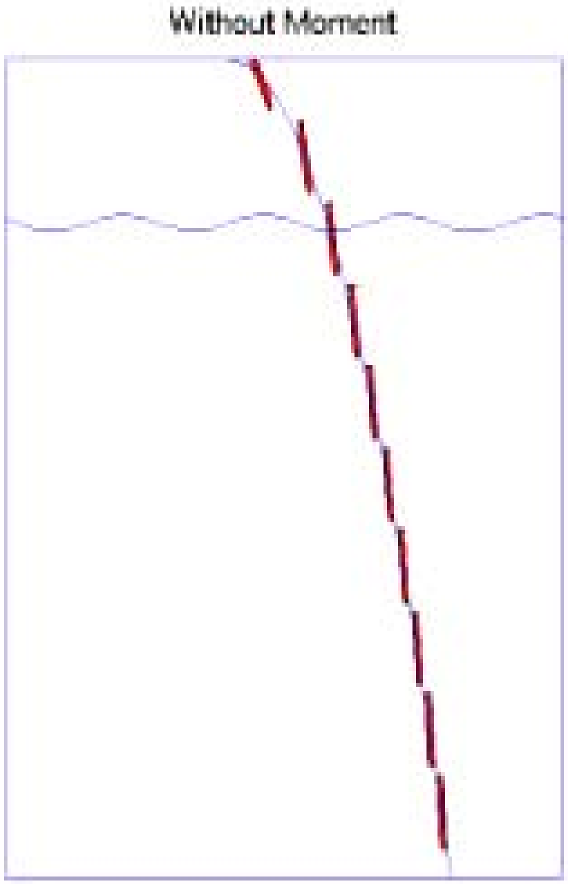
NOMBOS KM$_2$	Clutter Category
< 4	1
>4 and <12	2
>12	3

Development of Navy's Impact Burial Prediction Model (IBPM)

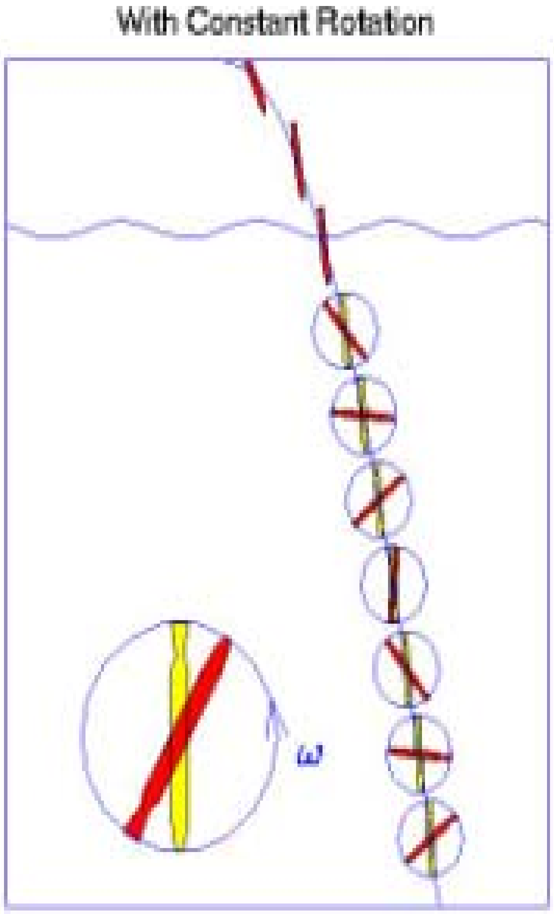
- IBPM was designed to calculate mine trajectories for air, water and sediment phases.
- Arnone & Bowen Model (1980) – No Rotation.
- Improved IBPM (Satkowiak, 1987-88)
- Improvements made by Hurst (1992)
    - Included torque calculation and rotation
    - More Accurately Calculates Fluid Drag and Air-Sea 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.

- Recent sensitivity studies by (Mulhearn 1993, Chu et al. 1999, 2000, Taber 1999, Smith 2000) focused on sediment phase calculations.

- Gilless (2001) pursued and demonstrated sensitivities in the hydrodynamic portion of IMPACT28.

Hydrodynamic Theory

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

1. Momentum Balance

$$\int (dV^* / dt^*) dm^* = W^* + F_b^{\ *} + F_d^{\ *}$$

2. Moment of Momentum Balance

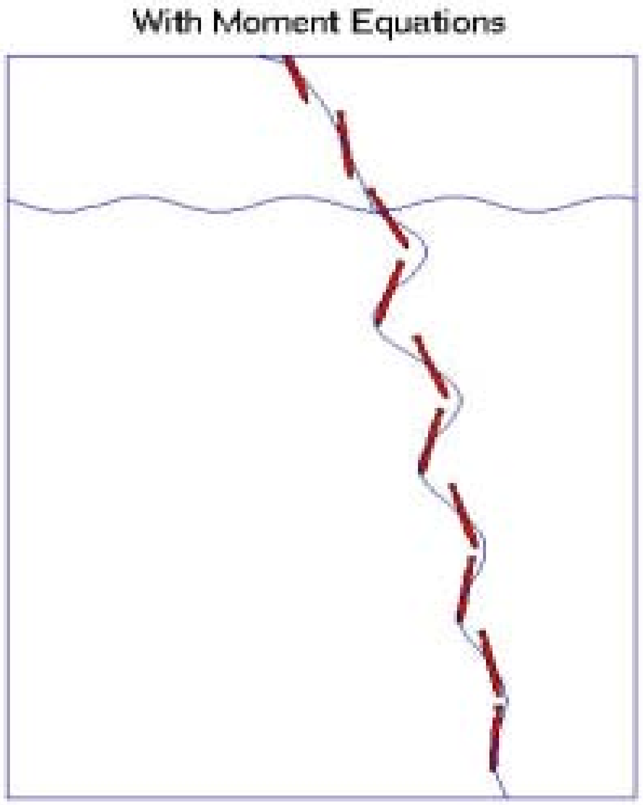
$$\int [r^* \times (dV^* / dt^*)] dm^* = M^*$$

- **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.

$$\frac{du}{dt} = \frac{F_{sx}}{\bar{\rho} \cdot \Pi}$$

$$\frac{dv}{dt} = \frac{F_{sy}}{\bar{\rho} \cdot \Pi}$$

$$\frac{dw}{dt} = -\left(1 - \frac{\rho_w}{\bar{\rho}}\right) g + \frac{F_{sz}}{\bar{\rho} \cdot \Pi}$$

$$\frac{d\Omega}{dt} = \frac{M_{s1}}{J_1}$$

$$\frac{d\omega_2}{dt} = \frac{\Pi \chi g \rho_w}{J_2} \cdot \cos \psi_2 + \frac{M_{s2}}{J_2}$$

$$\frac{d\omega_3}{dt} = \frac{M_{s3}}{J_3}$$

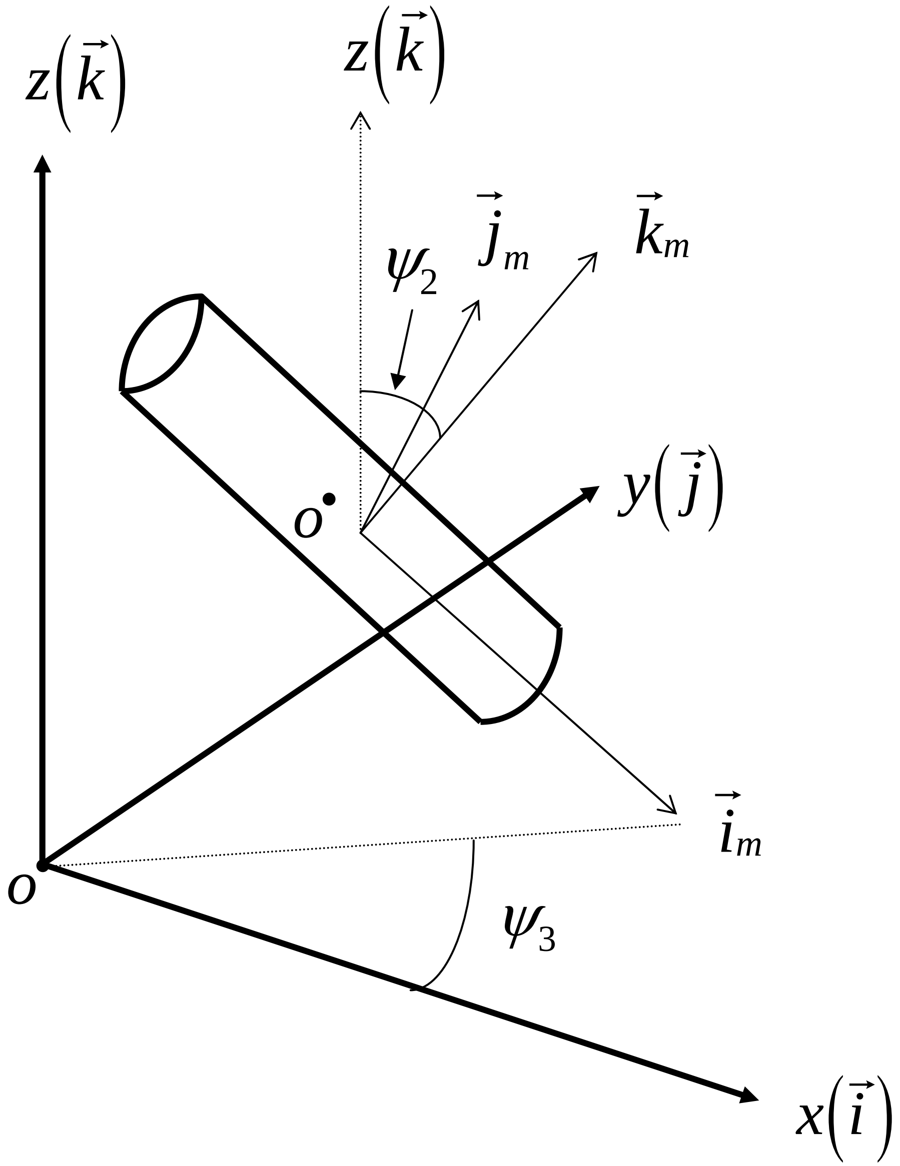
$$\frac{d}{dt} \cos \psi_1 = \omega_3 \cos \psi_2 - \omega_2 \cos \psi_3$$

$$\frac{d}{dt} \cos \psi_2 = \omega_1 \cos \psi_3 - \omega_3 \cos \psi_1$$

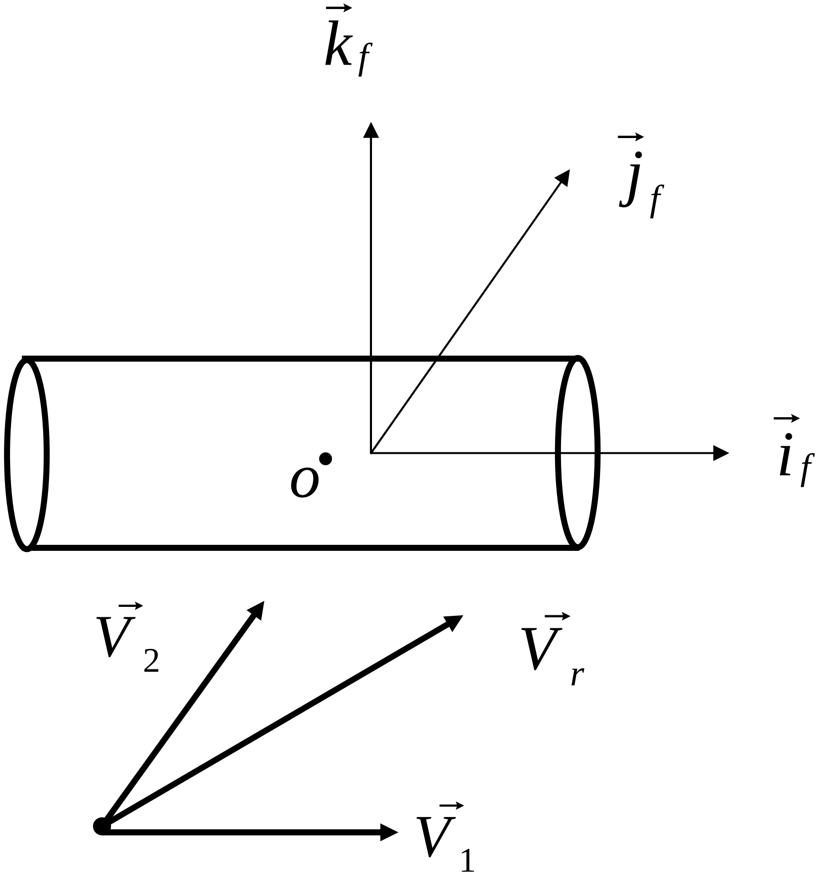
$$\frac{d}{dt} \cos \psi_3 = \omega_2 \cos \psi_1 - \omega_1 \cos \psi_2$$

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

$$
\begin{aligned}
\vec{i}_M &= e_{11}\vec{i} + e_{21}\vec{j} + e_{31}\vec{k}\\
\vec{j}_M &= e_{12}\vec{i} + e_{22}\vec{j} + e_{32}\vec{k}\\
\vec{k}_M &= e_{13}\vec{i} + e_{23}\vec{j} + e_{33}\vec{k}
\end{aligned}
$$

$$
{}^{E}_{M}R = \begin{bmatrix} \cos\psi_3 & -\sin\psi_3 & 0 \\ \sin\psi_3 & \cos\psi_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\psi_2 & 0 & \sin\psi_2 \\ 0 & 1 & 0 \\ -\sin\psi_2 & 0 & \cos\psi_2 \end{bmatrix} = \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix}
$$

Earth Fixed Coordinate to Drag-Lift Force Coordinate Transformation Matrix

$$
\begin{aligned}
\vec{i}_f &= e_{11}\vec{i} + e_{21}\vec{j} + e_{31}\vec{k}\\
\vec{j}_f &= e'_{12}\vec{i} + e'_{22}\vec{j} + e'_{32}\vec{k}\\
\vec{k}_f &= e'_{13}\vec{i} + e'_{23}\vec{j} + e'_{33}\vec{k}
\end{aligned}
$$

$$
{}^{E}_{D}R = \begin{bmatrix} e_{11} & e'_{12} & e'_{13} \\ e_{21} & e'_{22} & e'_{23} \\ e_{31} & e'_{32} & e'_{33} \end{bmatrix}
$$

Mine Body Coordinate to Drag-Lift Force Coordinate Transformation Matrices

$$
{}^{M}_{D}R = {}^{M}_{E}R \cdot {}^{E}_{D}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & d_{22} & d_{23} \\ 0 & d_{32} & d_{33} \end{bmatrix}
$$

$$
{}^{D}_{M}R = {}^{D}_{E}R \cdot {}^{E}_{M}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & d_{22} & d_{32} \\ 0 & d_{23} & d_{33} \end{bmatrix}
$$

Hydrodynamic Model

Momentum and Drag/Lift Forces

$$\vec{F} - m\frac{d\vec{V}}{dt} = 0, \qquad \vec{F} = \vec{F}_b + \vec{F}_s$$

$$\frac{du}{dt} = \frac{F_{sx}}{\bar{\rho}\cdot\Pi}$$

$$\frac{dv}{dt} = \frac{F_{sy}}{\bar{\rho}\cdot\Pi}$$

$$\frac{dw}{dt} = -\left(1 - \frac{\rho_w}{\bar{\rho}}\right)g + \frac{F_{sz}}{\bar{\rho}\cdot\Pi}$$

$$\vec{F}_b = -\Pi\left(\bar{\rho} - \rho_w\right)g\vec{k}$$

$$\vec{F}_s = \vec{F}_{d1} + \vec{F}_{d2} + \vec{F}_{d3} + \vec{F}_l$$

$$\vec{F}_l = \frac{\frac{1}{2}C_l \cdot d \cdot L \cdot \rho_w \cdot \left|V_2\right| \cdot \vec{V}_2}{f_{k2}} = C_{fl} \cdot V_2 \cdot \left(e'_{13}\vec{i} + e'_{23}\vec{j} + e'_{33}\vec{k}\right)$$

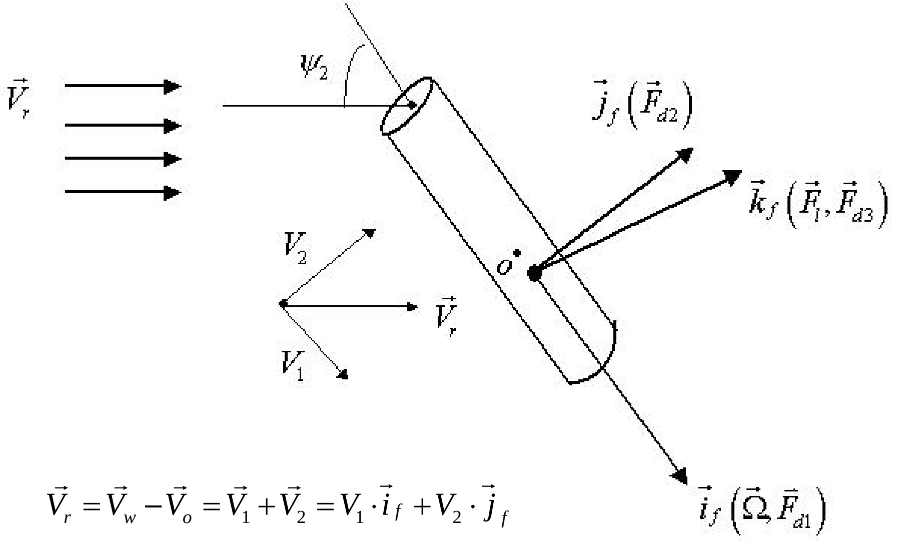
$$\vec{F}_{d1} = \frac{\left(\frac{1}{2}C_{d1} \cdot \frac{\pi d^2}{4} \cdot \rho_w \cdot \left|\vec{V}_1\right| \cdot \vec{V}_1\right)}{f_{k1}} = C_{f1} \cdot \left|V_1\right| \cdot \left(e_{11}\vec{i} + e_{21}\vec{j} + e_{31}\vec{k}\right)$$

$$\vec{F}_{d2} = \frac{\frac{1}{2}C_{d2} \cdot d \cdot L \cdot \rho_w \cdot \left|V_2\right| \cdot \vec{V}_2}{f_{k2}} = C_{f2} \cdot V_2 \cdot \left(e'_{12}\vec{i} + e'_{22}\vec{j} + e'_{32}\vec{k}\right)$$

$$\vec{F}_{d3} = \frac{\frac{1}{2}C_{d3} \cdot d \cdot \rho_w \cdot \omega'_2 \cdot \left|\omega'_2\right|}{f_{k2}}\left(\int_0^{\frac{L}{2}-\chi} y^2 dy - \int_{-\frac{L}{2}-\chi}^{0} y^2 dy\right) \cdot \vec{k}_f$$

$$= -\frac{\frac{1}{12}C_{d3} \cdot d \cdot \rho_w \cdot \chi\left(3L^2 + 4\chi^2\right) \cdot \left|\omega'_2\right| \cdot \omega'_2}{f_{k2}} \cdot \vec{k}_f = C_{f3} \cdot \vec{k}_f$$

$$= C_{f3} \cdot \left(e'_{13}\vec{i} + e'_{23}\vec{j} + e'_{33}\vec{k}\right)$$



$$\vec{V}_r = \vec{V}_w - \vec{V}_o = \vec{V}_1 + \vec{V}_2 = V_1 \cdot \vec{i}_f + V_2 \cdot \vec{j}_f$$

Hydrodynamic Model

Moment of Momentum and Torques

$$J \cdot \frac{d\vec{\omega}_m}{dt} = \vec{M} - J \cdot \frac{d\vec{\omega}_f}{dt}$$

$$J \cdot \frac{d\vec{\omega}}{dt} = \vec{M}_b + \vec{M}_s$$

$$\vec{\omega} = \Omega \vec{i}_m + \omega_2 \vec{j}_m + \omega_3 \vec{k}_m \qquad \overrightarrow{M} = \vec{M}_b + \vec{M}_s$$

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

$$J_1 = \int (r_2^2 + r_3^2) dm$$

$$J_1 = \frac{1}{8} m \cdot d^2$$

$$J_2 = \int (r_3^2 + r_1^2) dm \qquad J_3 = \int (r_1^2 + r_2^2) dm$$

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

$$J_{31} = \int r_3 r_1 dm$$

$$J_{12} = J_{21} = J_{13} = J_{31} = J_{23} = J_{32} = 0$$

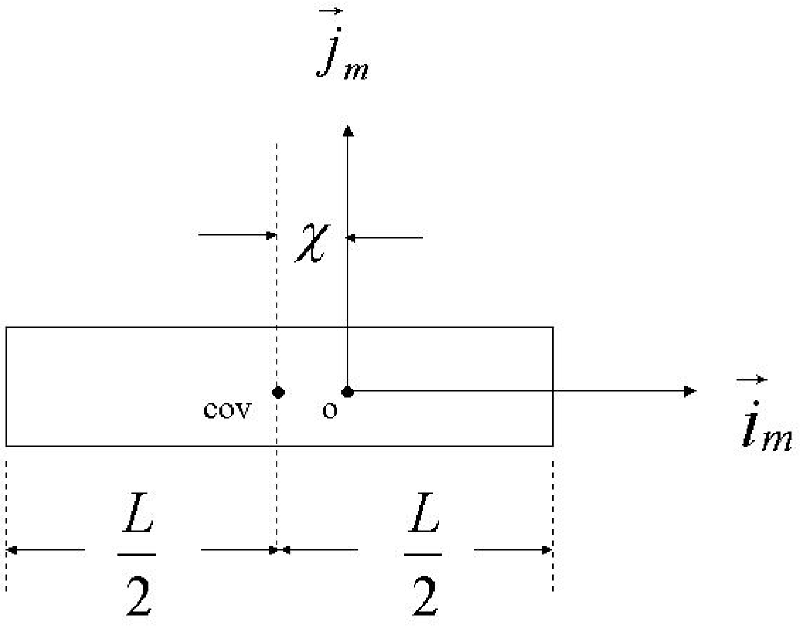
$$\vec{M}_b = \Pi \chi \rho_w g \cdot \cos\psi_2 \cdot \vec{j}_m$$

$$\frac{d\Omega}{dt} = \frac{M_{s1}}{J_1}$$

$$\frac{d\omega_2}{dt} = \frac{\Pi \chi g \rho_w}{J_2} \cdot \cos\psi_2 + \frac{M_{s2}}{J_2}$$

$$\frac{d\omega_3}{dt} = \frac{M_{s3}}{J_3}$$

$$\chi = \frac{\int_{-\frac{L}{2}}^{\frac{L}{2}} \rho \cdot x \cdot dx}{\int_{-\frac{L}{2}}^{\frac{L}{2}} \rho \cdot dx} = \int_{-\frac{L}{2}}^{\frac{L}{2}} \frac{\rho}{\bar{\rho}} \cdot \frac{x}{L} \cdot dx$$



Hydrodynamic Model

Moment of Momentum and Torques

$$M_{sd3}=\frac{\int_{-\frac{L}{2}-\chi}^{\frac{L}{2}-\chi}\frac{1}{2}C_{d2}\cdot d\cdot\rho_{w}\left(V_2-\omega_3' y\right)^2 y}{f_{kr}}\cdot dy=C_{m3}\cdot\omega'_3+m_{cm3}$$

$$M_{sd2}=\frac{-\omega_2'\left|\omega_2'\right|\int_{-\frac{L}{2}-\chi}^{\frac{L}{2}-\chi}\frac{1}{2}C_{d2}\cdot d\cdot\rho_{w}y^2\left|y\right|}{f_{kr}}\cdot dy$$

$$M_{sl}=\frac{\int_{-\frac{L}{2}-\chi}^{\frac{L}{2}-\chi}\frac{1}{2}C_{l}\cdot d\cdot\rho_{w}\left(V_2-\omega_3' y\right)y}{f_{kr}}-dy=\frac{-\frac{1}{2}\Omega\cdot d^2\cdot\rho_w}{f_{kr}}\int_{-\frac{L}{2}-\chi}^{\frac{L}{2}-\chi}\left(V_2-\omega_3' y\right)ydy$$

$$=\frac{\frac{1}{2}\Omega\cdot d^2\cdot\rho_w\cdot L}{f_{kr}}\cdot\left(V_2\chi+\frac{1}{12}L^2\omega_3'+\chi^2\omega_3'\right)=C_{ml}\cdot\omega_3'+m_{cml}$$

Model Numerical Basics

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

$$x^{n+1} = x^{n} + \int_0^{dt} u\,dt$$
$$y^{n+1} = y^{n} + \int_0^{dt} v\,dt$$
$$z^{n+1} = z^{n} + \int_0^{dt} w\,dt$$

$$d\psi_2 = \int_0^{dt} \psi_2\,dt$$
$$d\psi_3 = \int_0^{dt} \psi_3\,dt$$

$$\begin{aligned} {}_{M}^{E}R^{n+1} &= \begin{bmatrix} \cos\psi_3 & -\sin\psi_3 & 0 \\ \sin\psi_3 & \cos\psi_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\psi_2 & 0 & \sin\psi_2 \\ 0 & 1 & 0 \\ -\sin\psi_2 & 0 & \cos\psi_2 \end{bmatrix} \\ &= \begin{bmatrix} \cos\psi_3\cdot\cos\psi_2 & -\sin\psi_3 & \cos\psi_3\cdot\sin\psi_2 \\ \sin\psi_3\cdot\cos\psi_2 & \cos\psi_3 & \sin\psi_3\cdot\sin\psi_2 \\ -\sin\psi_2 & 0 & \cos\psi_2 \end{bmatrix} \end{aligned}$$

$$\psi_2^{n+1} = arc\cos\left({}_{M}^{E}R^{n+1}(3,3)\right)$$
$$\psi_3^{n+1} = arc\cos\left({}_{M}^{E}R^{n+1}(2,2)\right)$$

Required Modeling Parameters

Mine Parameters:

χ	Center of mass offset
$\overline{\rho}_m$	mine mean density
l	mine length
d	mine diameter
m	mine mass
$[J]$	moment of inertia tensor

Initial Conditions

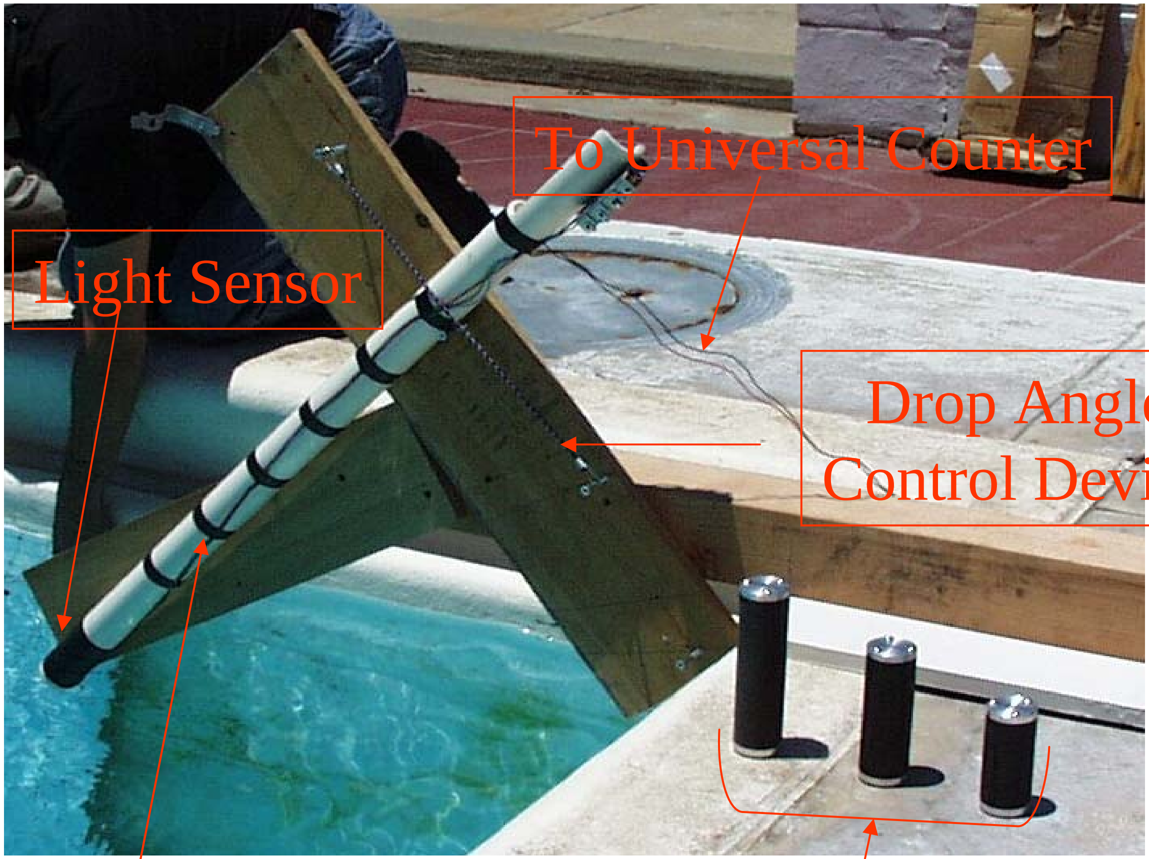
x_0, y_0, z_0	initial position vector
u_0, v_0, w_0	initial linear velocity vector
$\Omega_{1_0}, \omega_{2_0}, \omega_{2_0}$	initial angular velocity vector
ψ_{2_0}, ψ_{3_0}	initial angle vector
Δt	time step

Hydrodynamic Parameters:

$\vec{V}_r = \vec{V}_1 + \vec{V}_2$	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
ρ_w	water density
ν	water kinematic viscosity

MIDEX

(July 2001)



To Universal Counter

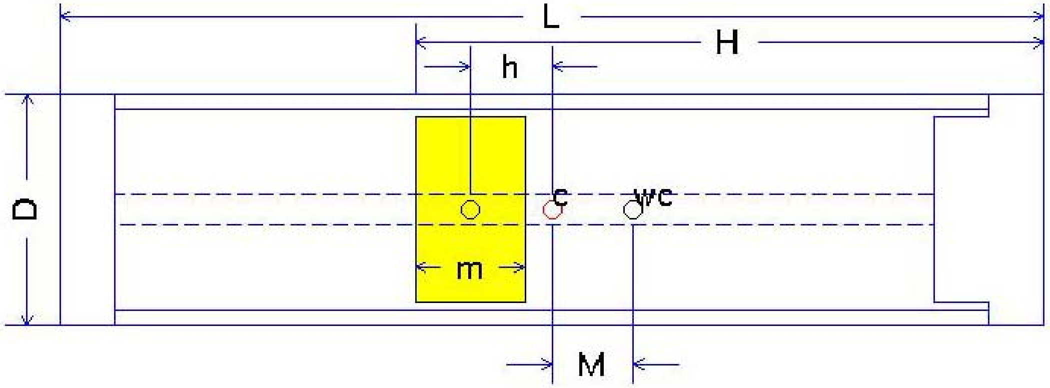
Light Sensor

Drop Angle Control Device

Mine Injector

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

MIDEX Mine Shape



MODEL # 1

L=15.1359cm D=4cm m=2.7cm

Weight=322.5 g Volume=190.2028 cm^3 Density=1.6956 g/cm^3

H:	10.380	8.052	5.725	cm
h:	-1.462	0.866	3.193	cm
M:	0.000	18.468	36.935	mm

MODEL # 2

L=12.0726cm D=4cm m=1.7cm

Weight=254.2 g Volume=151.709 cm^3 Density=1.6756 g/cm^3

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=9.1199cm D=4cm m=1.47cm

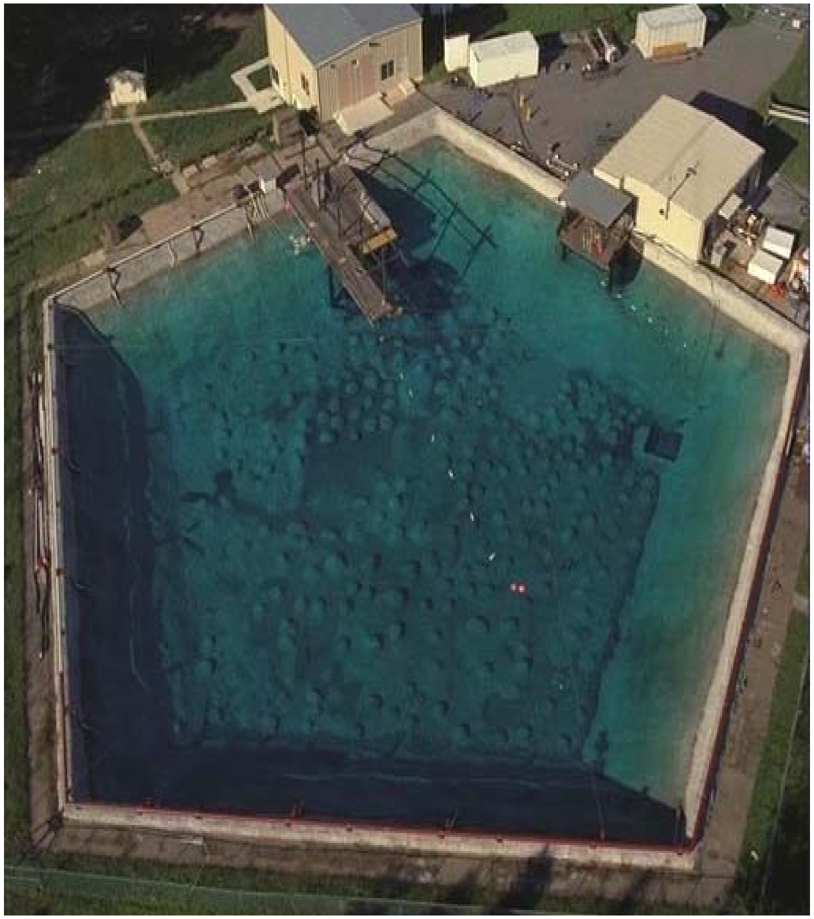
Weight=215.3 g Volume=114.6037 cm^3 Density=1.8786 g/cm^3

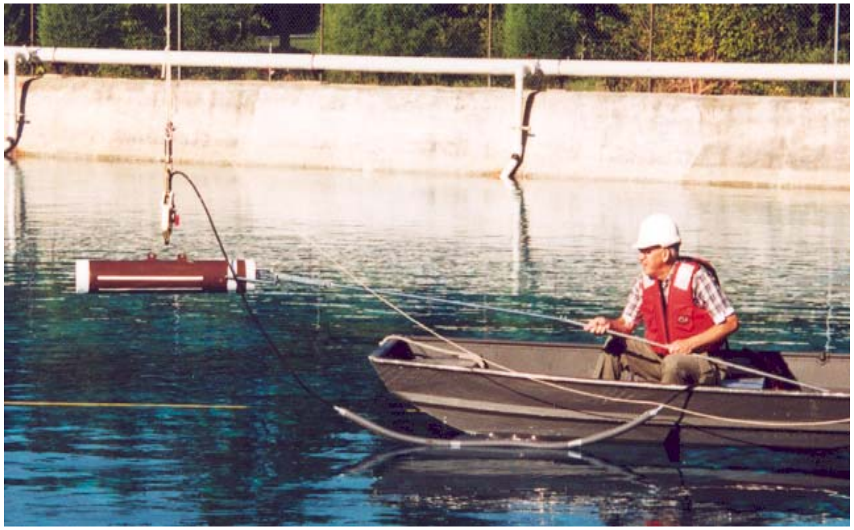
H:	6.662	5.592	4.521	cm
h:	-1.368	-0.297	0.774	cm
M:	0.000	6.847	13.694	mm

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

Carderock Mine Drop Experiment

September 2001



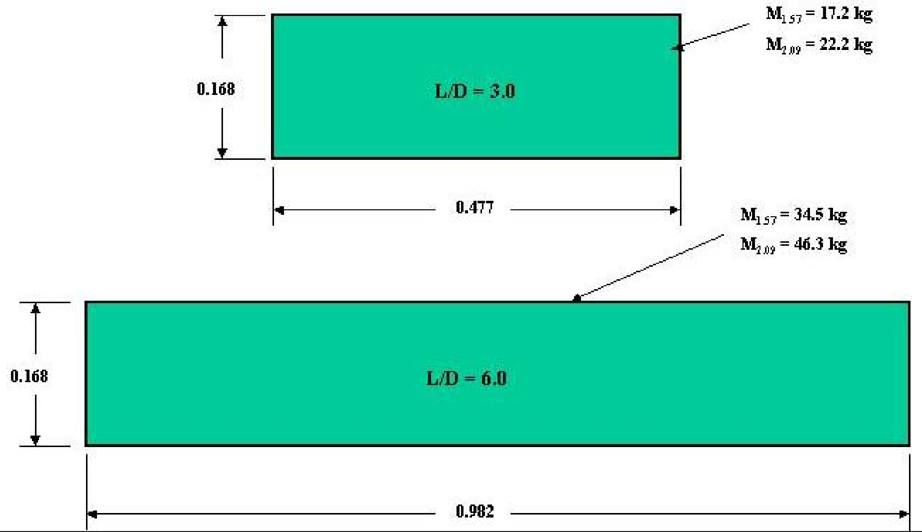


Carderock Experiment Participants

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

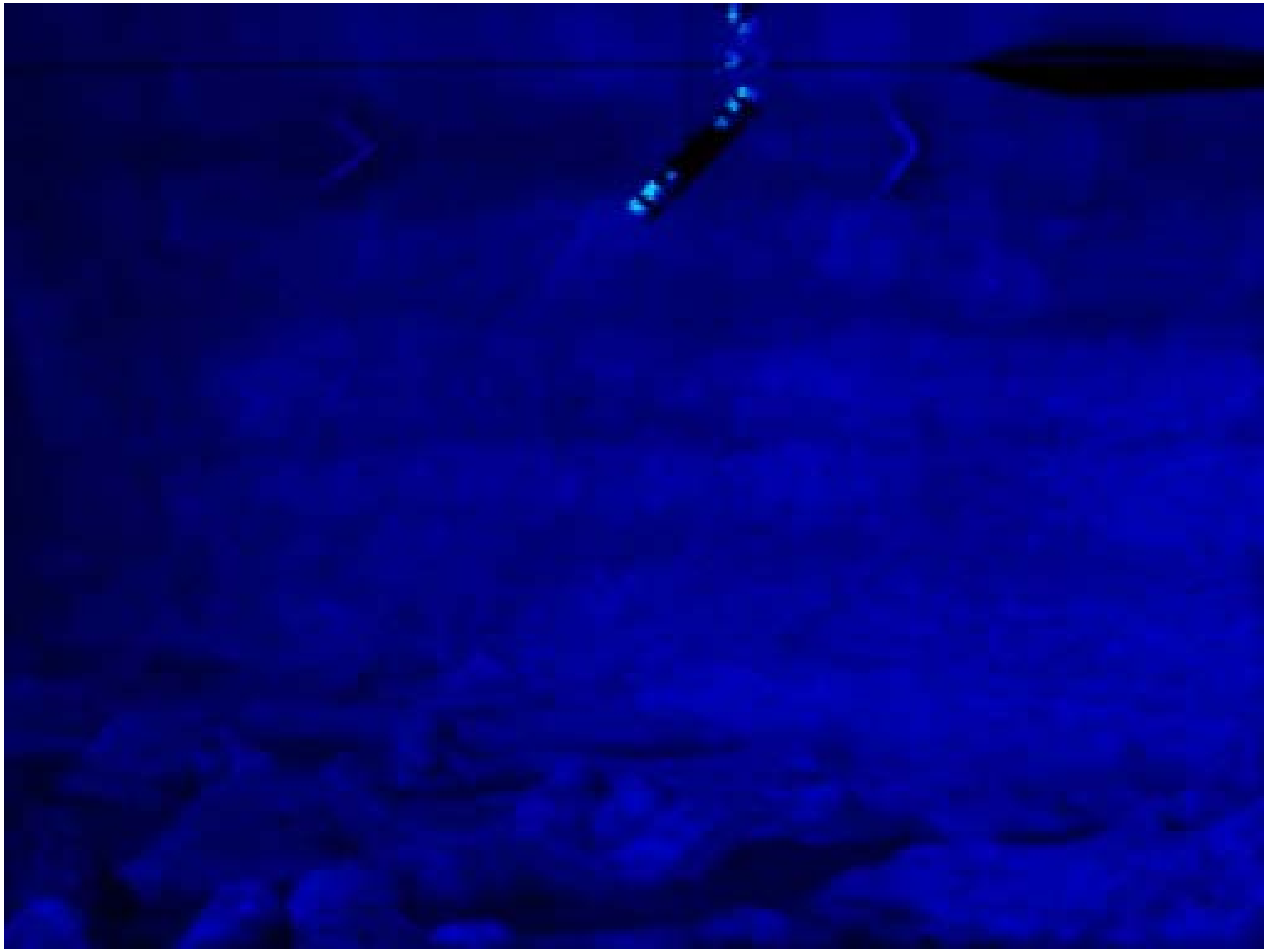
Carderock Mine Drop Experiment



CHARACTERISTICS OF MINE MODELS USED IN TEST POND, NSWC CARDEROCK, MD, 10-14 Sept 2001 (Revised 28 Feb 2002)						
Model number	**1**	**2**	**3**	**4**	**5**	**6**
Blunt Mine Parameters						
Diameter, m (in.)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)	0.168 (6.63)
Length, blunt, m (in.)	0.477 (18.78)	0.477 (18.78)	0.982 (38.65)	0.982 (38.65)	0.982 (38.65)	0.982 (38.65)
L/D for blunt nose	2.8	2.8	5.8	5.8	5.8	5.8
Volume, cu m (cu ft) (blunt)	0.0106 (0.374)	0.0106 (0.374)	0.0218 (0.771)	0.0218 (0.771)	0.0218 (0.771)	0.0218 (0.771)
Weight (lbs)	38	49	76	102	100	98.5
Mass, kg	17.2	22.2	34.5	46.3	45.4	44.7
Mass Wet kg (4) (blunt)	6.33	11.33	12.13	23.93	23.04	22.34
Bulk density, pcf (Mg/cu m)	101.6 (1.63)	131.0 (2.10)	98.6 (1.58)	132.3 (2.12)	129.7 (2.08)	127.8 (2.05)
χ = **(CM - CV) (m)**	-0.0002385	-0.001908	-0.001964	-0.008838	0.045172	0.076596
(CM - CV) / (mine length)	-0.0005	-0.004	-0.002	-0.009	0.046	0.078
Moment of Inertia about CM						
I_{xx}^1, kg–m^2 (lb–in^2)	0.0647 (221)	0.0806 (275)	0.1362 (465)	0.1696 (579)	0.1693 (578)	0.1692 (578)
I_{yy}^2, kg–m^2 (lb–in^2)	0.356 (1216)	0.477 (1627)	2.90 (9910)	3.82 (13,050)	3.94 (13,440)	4.57 (15,600)
I_{zz}^3, kg–m^2 (lb–in^2)	0.356 (1214)	0.476 (1625)	2.90 (9910)	3.82 (13,050)	3.94 (13,430)	4.57 (15,600)
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/m^3						

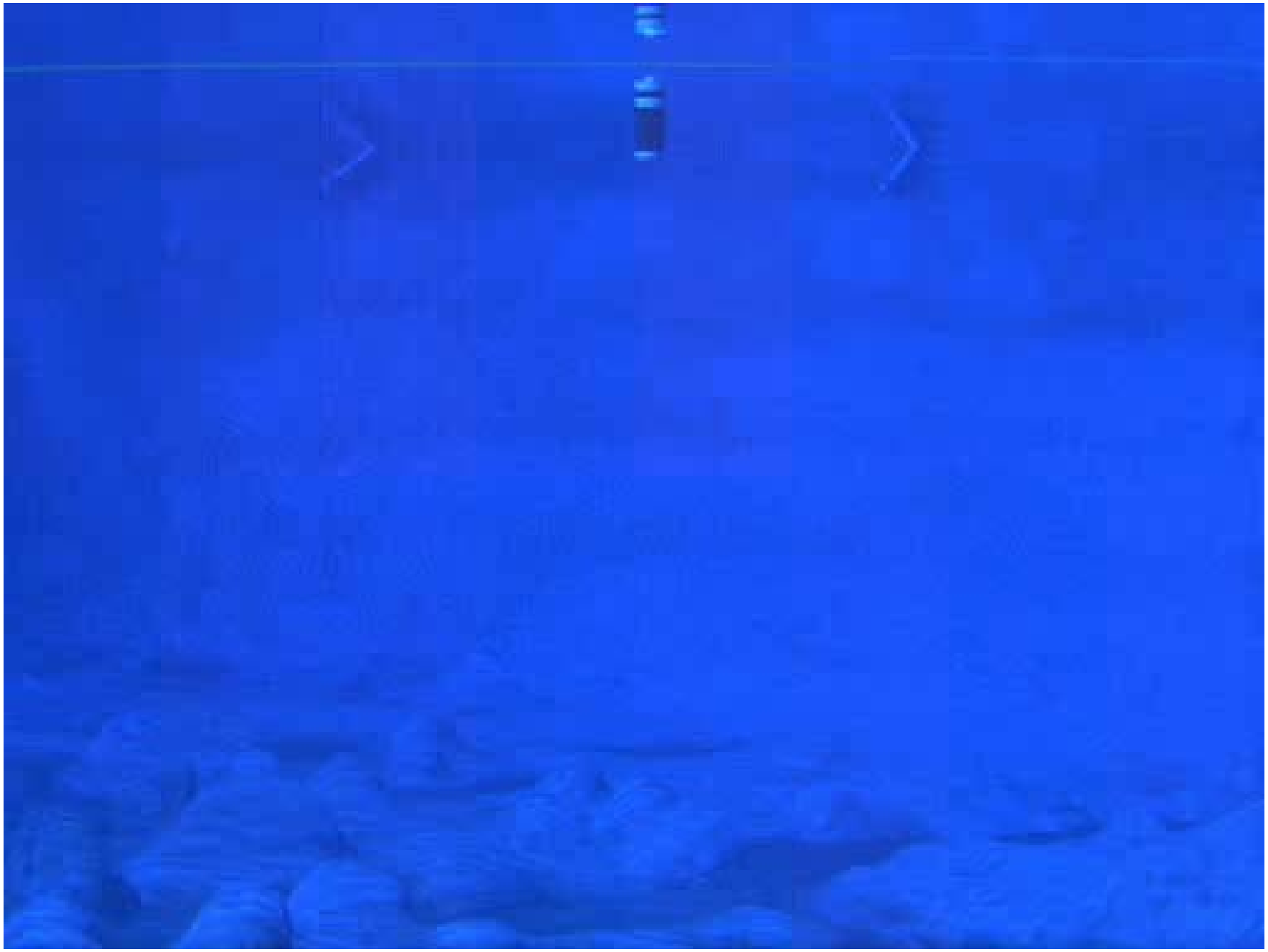
Carderock Data Acquisition

Digital Collection 125 fps



Carderock Data Acquisition

3 Camera Tracking Data Analysis and Archive



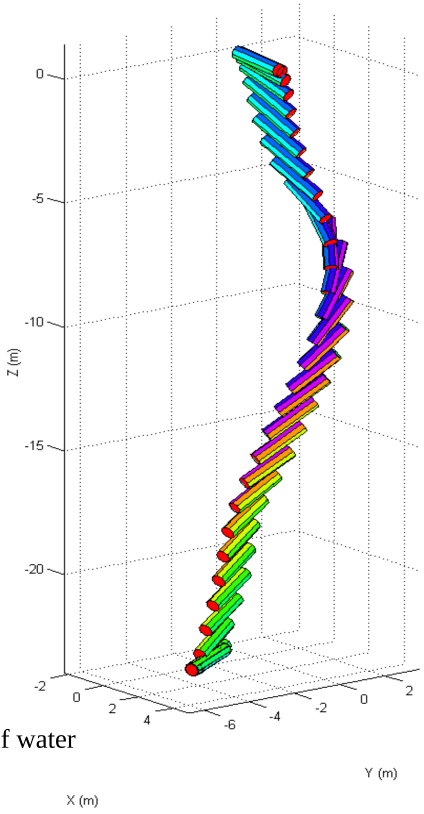
Full Scale Mine Drop Experiment Results

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

Image courtesy of Mr. Grant Bower, NRL-SSC

Corpus Christi Mine Drop Experiment
Data 2-17 May 2002

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



12 drops into 80ft of water

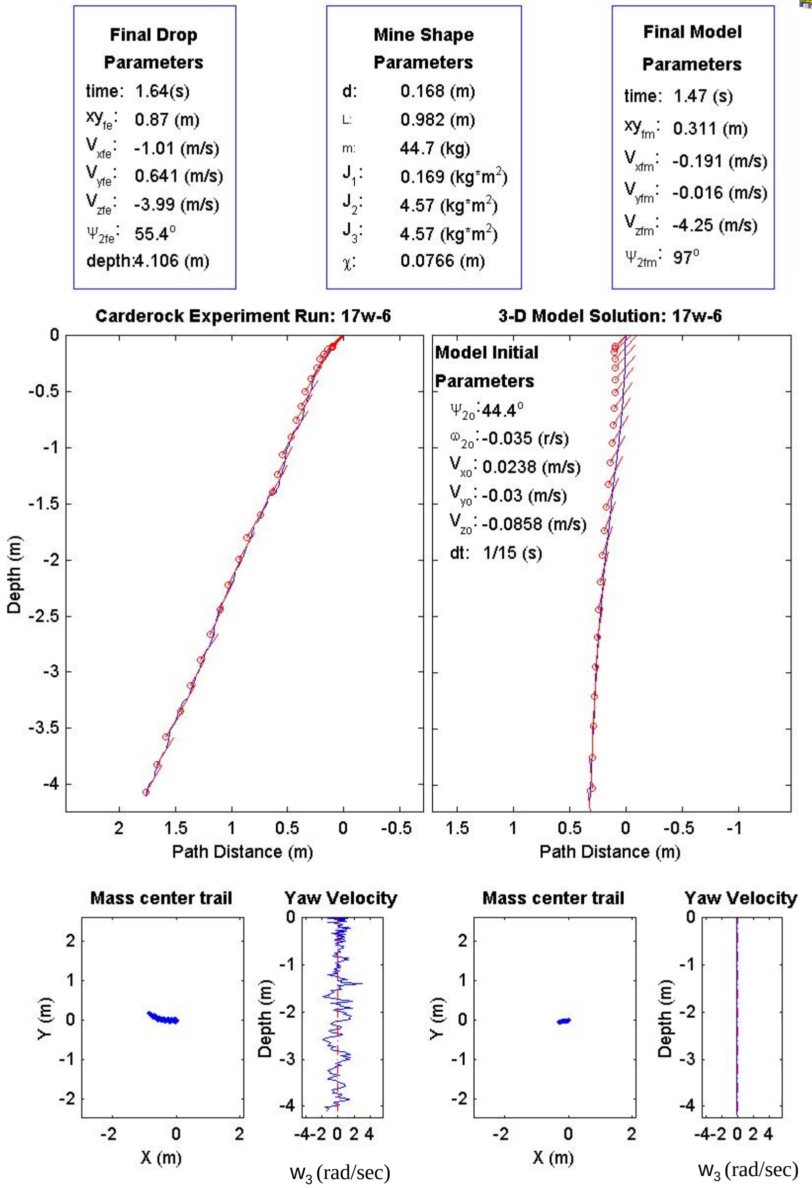
Corpus Christi Experiment Participants

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

Data Analysis

1. Each Video converted to digital format
2. Analyzed 2-D data to obtain mine’s x,y and z center positions; ψ_2 and ψ_3 angle; u, v, and w components of velocity; and Ω_1, ω_2, and ω_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



Final Drop Parameters

time: 1.64(s)
xy_{fe}: 0.87 (m)
V_{xfe}: -1.01 (m/s)
V_{yfe}: 0.641 (m/s)
V_{zfe}: -3.99 (m/s)
ψ_{2fe}: 55.4°
depth:4.106 (m)

Mine Shape Parameters

d: 0.168 (m)
L: 0.982 (m)
m: 44.7 (kg)
J_1: 0.169 (kg*m^2)
J_2: 4.57 (kg*m^2)
J_3: 4.57 (kg*m^2)
χ: 0.0766 (m)

Final Model Parameters

time: 1.47 (s)
xy_{fm}: 0.311 (m)
V_{xfm}: -0.191 (m/s)
V_{yfm}: -0.016 (m/s)
V_{zfm}: -4.25 (m/s)
ψ_{2fm}: 97°

Model Initial Parameters

ψ_{2o}:44.4°
ω_{2o}:-0.035 (r/s)
V_{xo}: 0.0238 (m/s)
V_{yo}: -0.03 (m/s)
V_{zo}: -0.0858 (m/s)
dt: 1/15 (s)

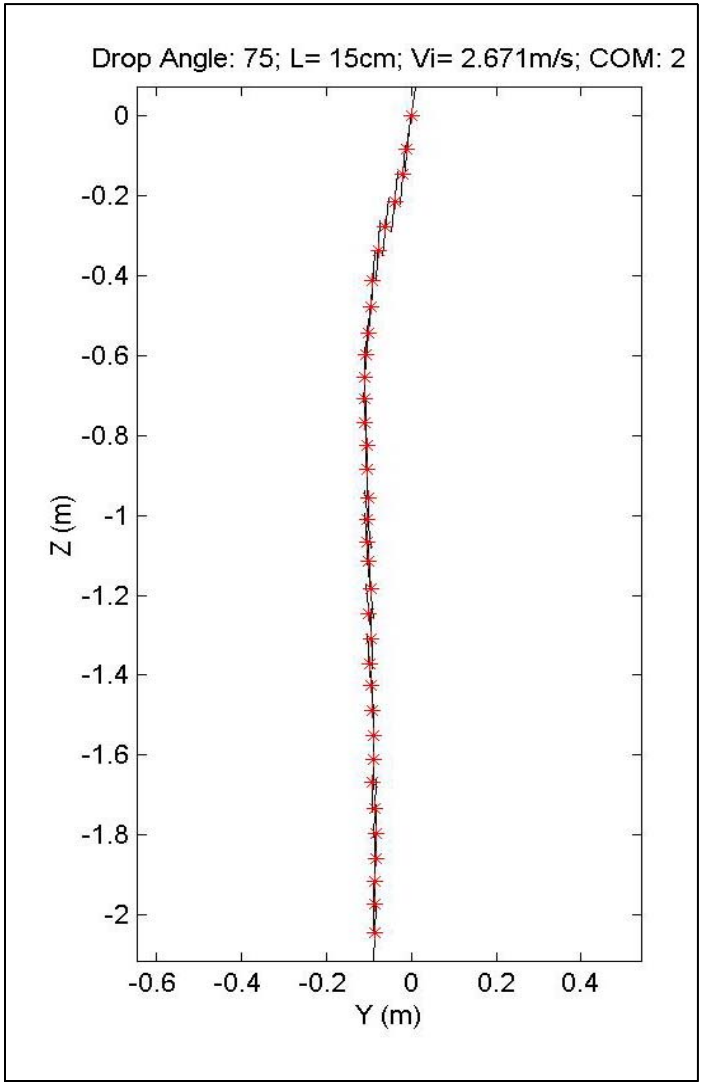
Sources of Error

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)

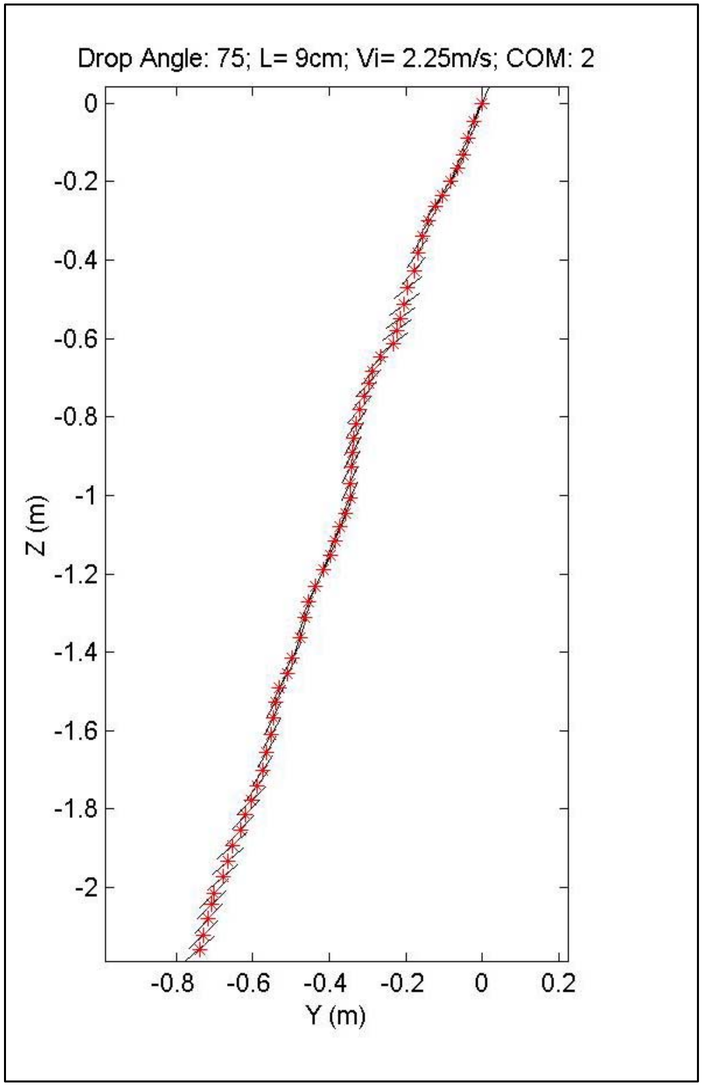
1. Straight



Trajectory Patterns

(Chu et al 2001)

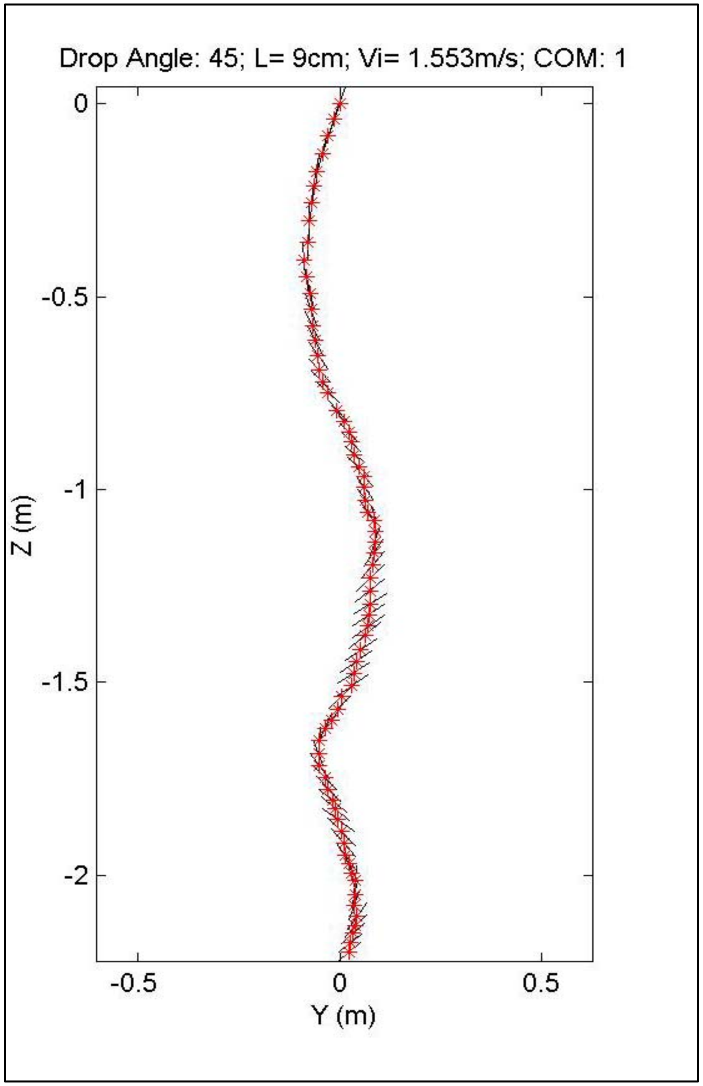
1. Straight
2. Slant



Trajectory Patterns

(Chu et al 2001)

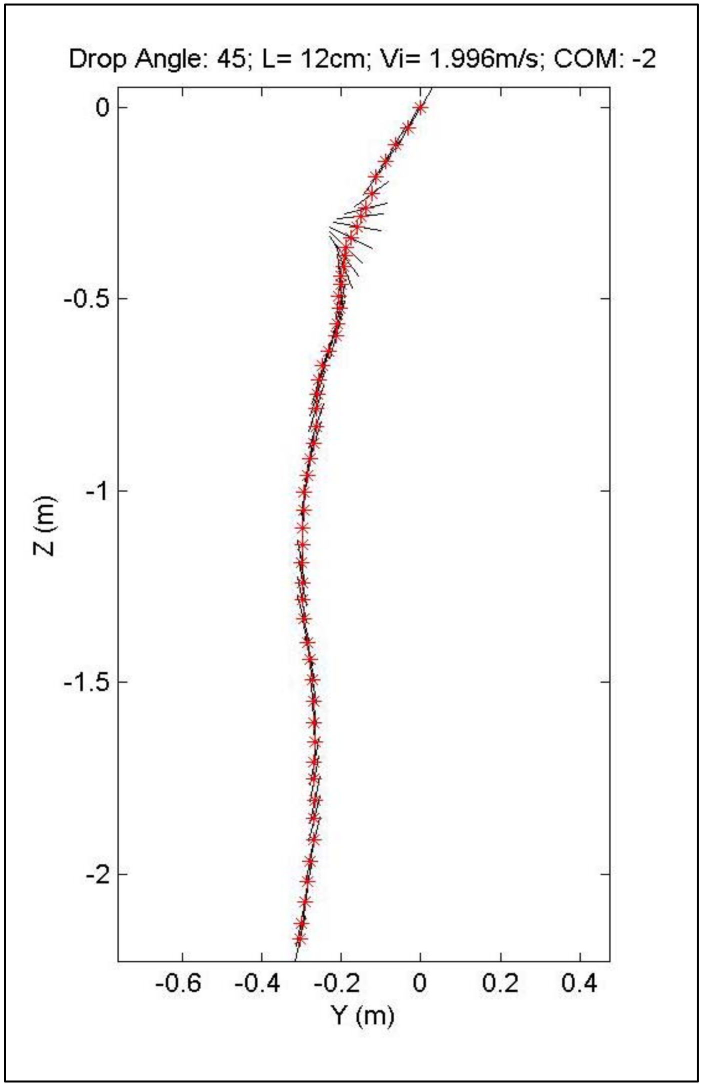
1. Straight
2. Slant
3. Spiral



Trajectory Patterns

(Chu et al 2001)

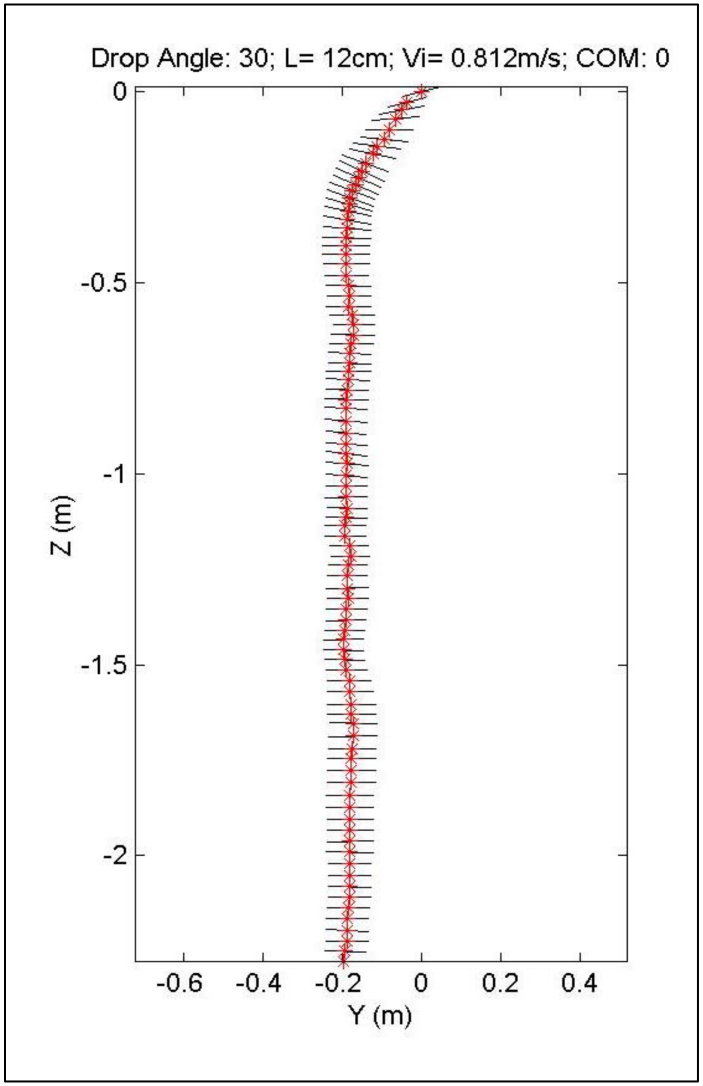
1. Straight
2. Slant
3. Spiral
4. Flip



Trajectory Patterns

(Chu et al 2001)

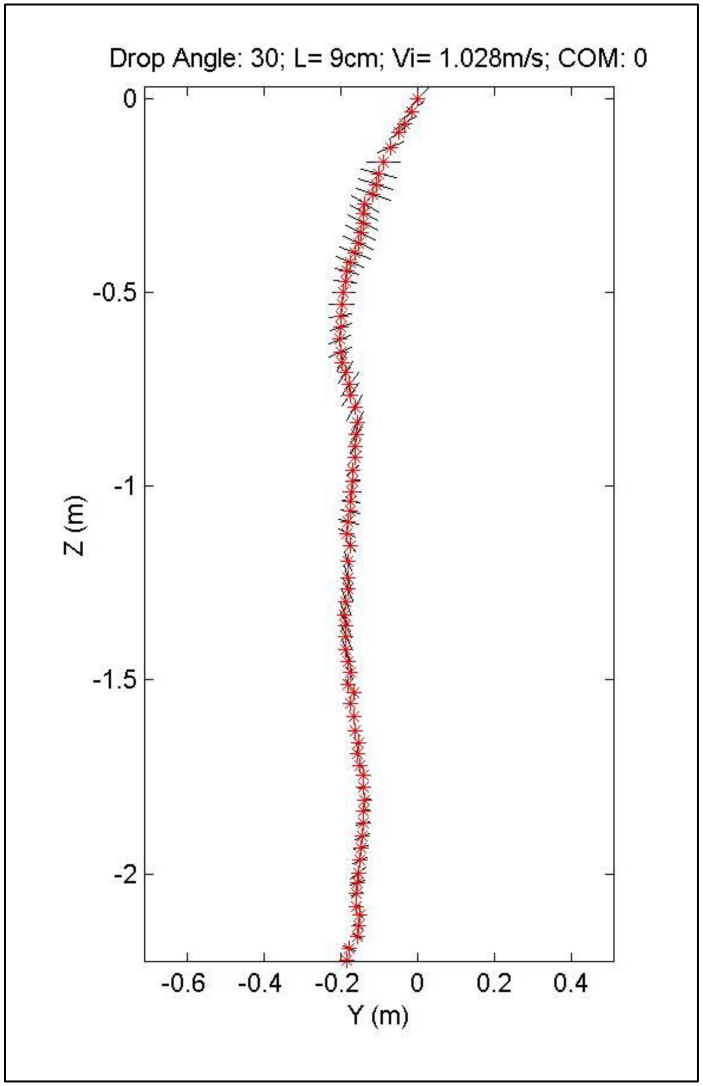
1. Straight
2. Slant
3. Spiral
4. Flip
5. Flat



Trajectory Patterns

(Chu et al 2001)

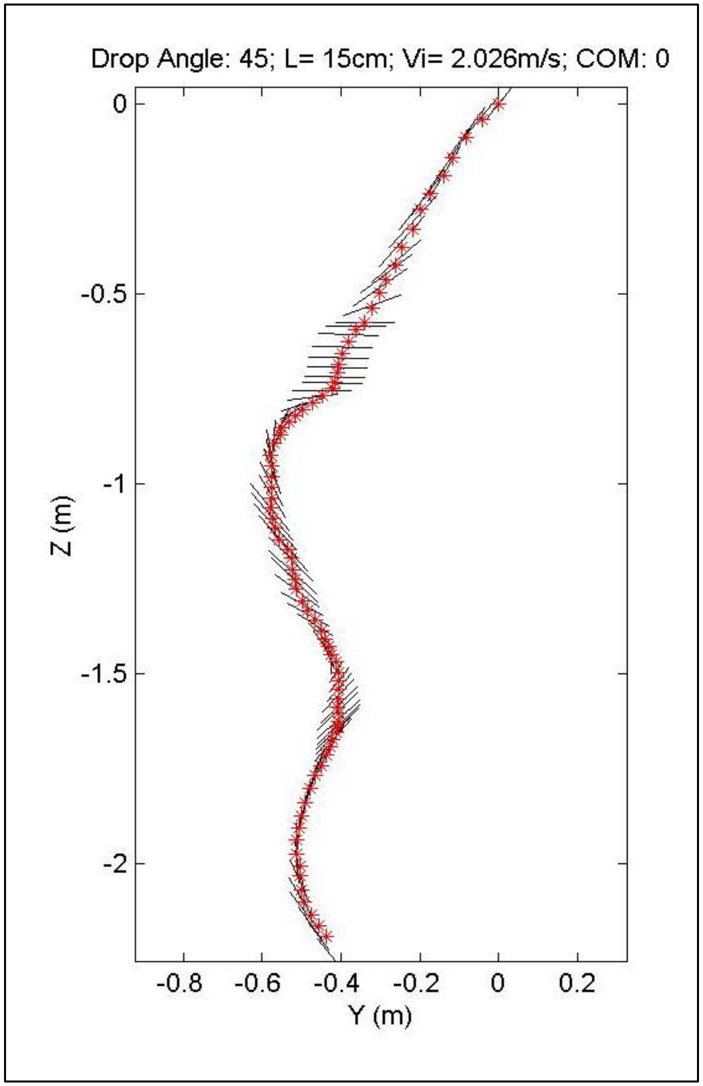
1. Straight
2. Slant
3. Spiral
4. Flip
5. Flat
6. See Saw



Trajectory Patterns

(Chu et al 2001)

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



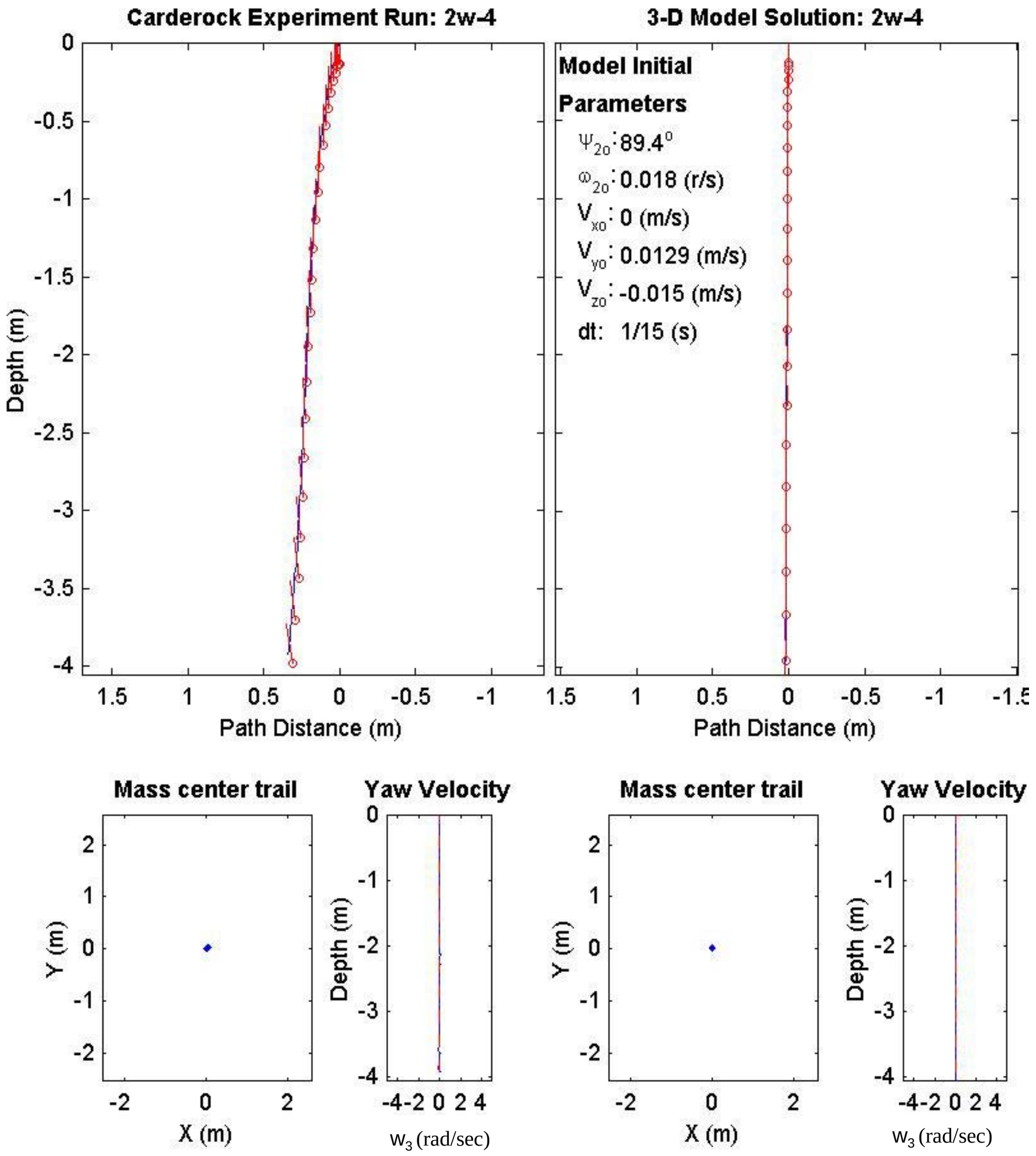
Carderock Data Trajectory Analysis

Mine Drop Number:	1	2	3	4	5	6
Blunt Nosed Mine Shapes						
Horizontial Drops						
1w-series	Flat-Spiral	Flat-Spiral	Flat	Flat-Spiral	Slant	Slant-Spiral
10w-series	Flat	Flat	Flat	Flat	Slant	Slant-Spiral
11w-series	Flat-Spiral	Flat	Flat	Flat	Slant-Flat	Slant-Spiral
Vertical Drops						
2w-series	Straight-Flat	Straight-Flat	Straight	Straight	Straight	Straight-Slant
12w-series	Straight-Flat-Seesaw	Straight-Flat-Spiral	Straight-Spiral	(flooded mine)	Straight	Straight
13w-series	Straight-Flat	Straight-Flat	Straight	(flooded mine)	Straight	Straight
45 degree down						
17w-series	Flat-Seesaw-Spiral	Flat-Seesaw	Flat-Seesaw	Slant-Flat	Straight-Slant	Slant-Spiral
20w-series	Flat-Seesaw	Flat-Seesaw	Slant-Flat-Seesaw	(flooded mine)	Slant-Spiral	Slant-Spiral
21w-series	Seesaw-Spiral	Flat-Seesaw	Flat-Seesaw	(flooded mine)	Slant-Spiral	Slant

Mine Trajectory Pattern	Description
Vertical	Mine exhibited little angular change about z-axis. $d_{\psi}<10°$.
Spiral	Mine experienced rotation about z-axis. $d_{\psi}>10°$.
Flip	Initial water entry point rotated at least 180° during mine motion.
Flat	Mine's angle with vertical near 90° for most of the trajectory.
See-Saw	Similar to the flat pattern except that mine's angle with vertical would oscillate between greater (less) than 90° and less (greater) than 90° - like a see-saw.
Combination	Complex trajectory where mine exhibited several of the above patterns.

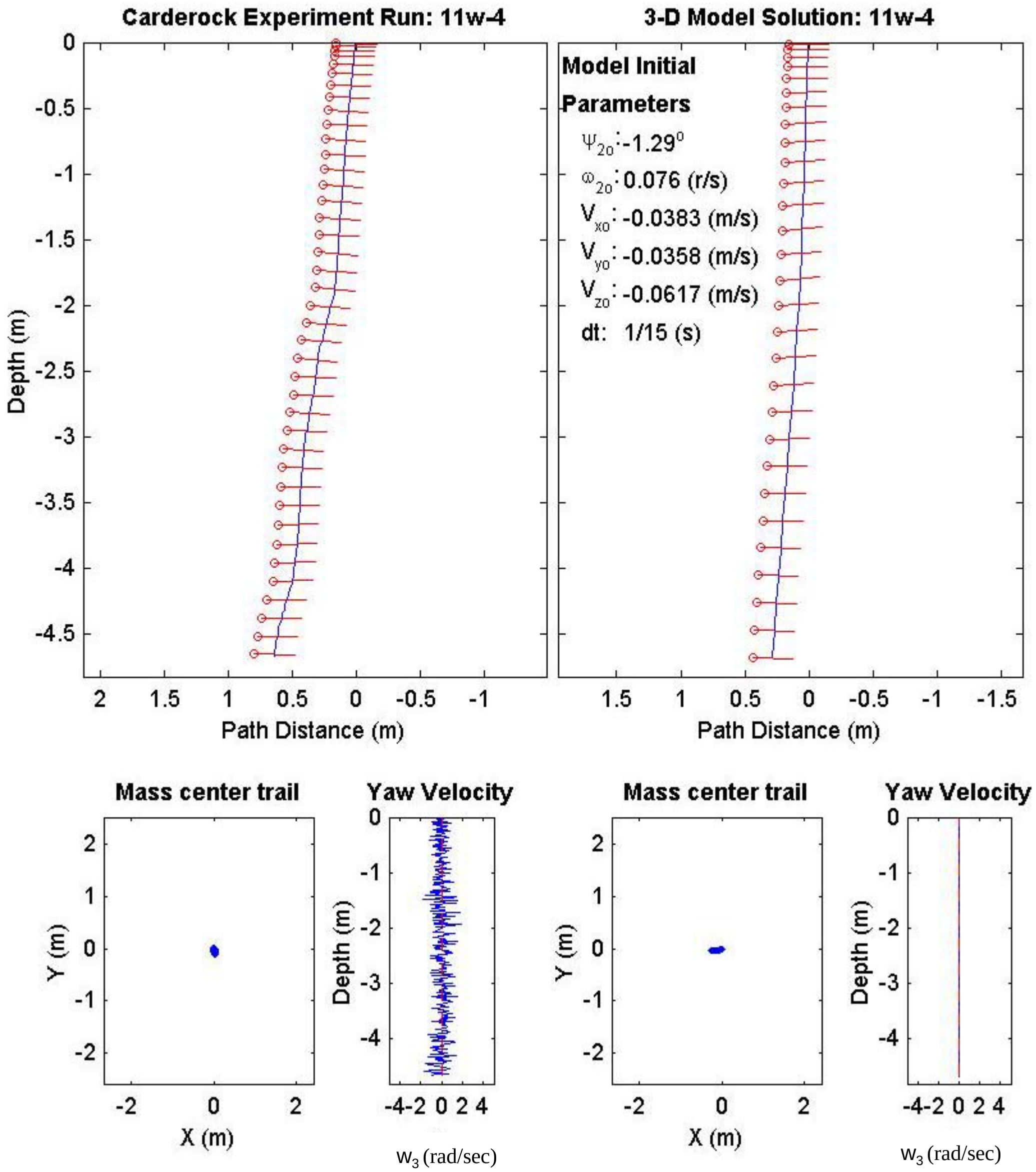
Simple Motion Model Mechanics

Straight Motion



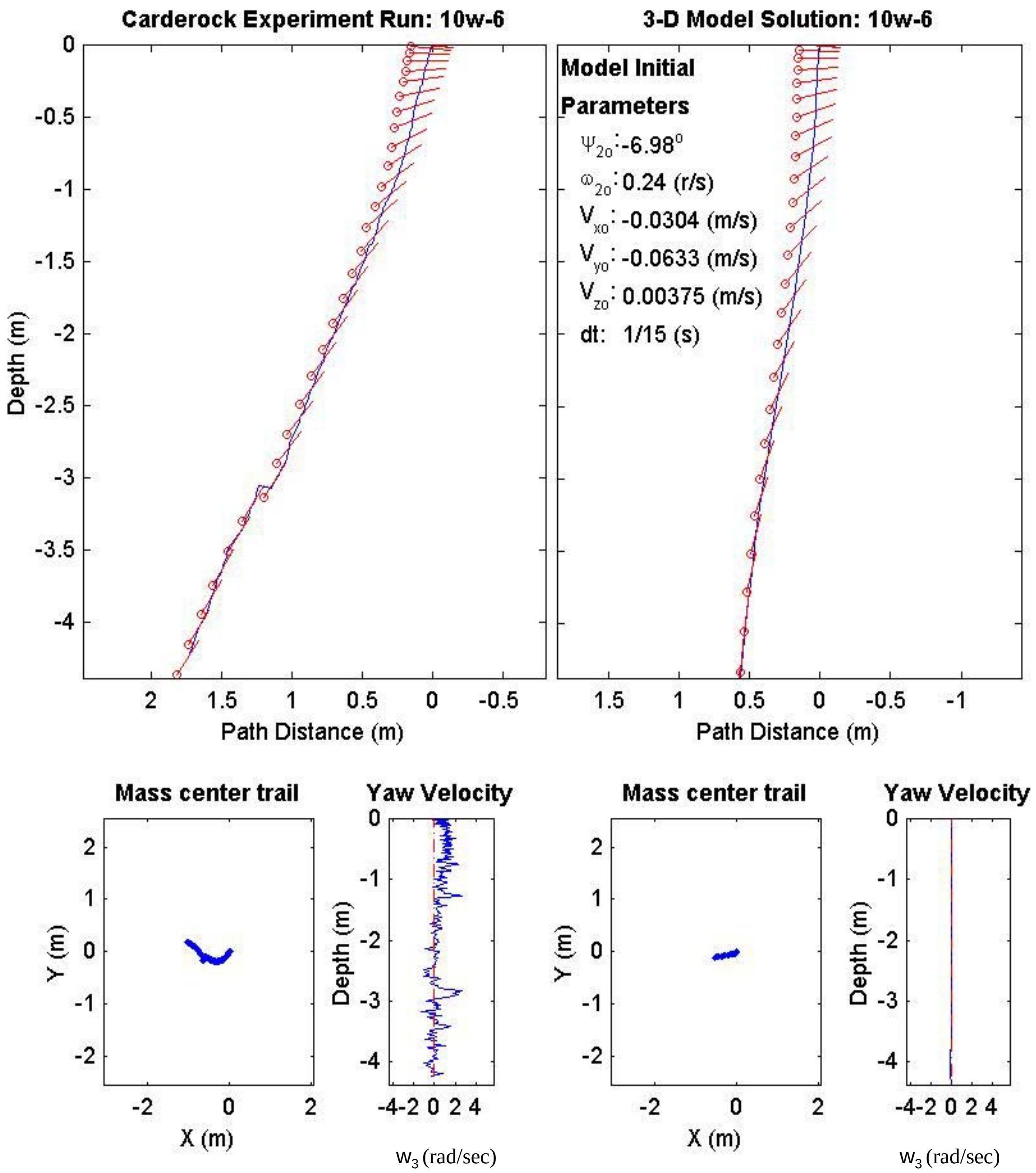
Simple Motion Model Mechanics

Flat Motion



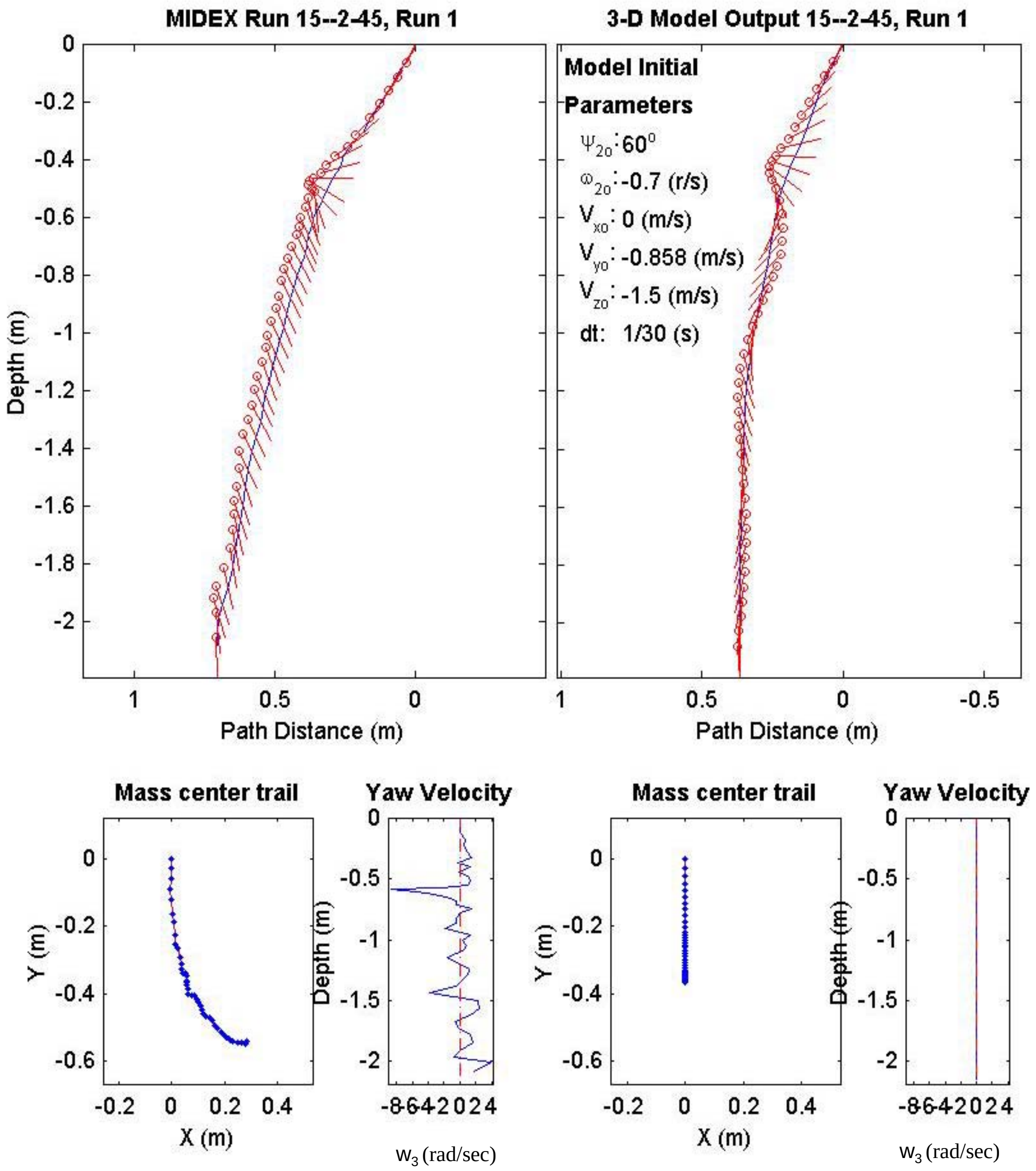
Simple Motion Model Mechanics

Slant Motion



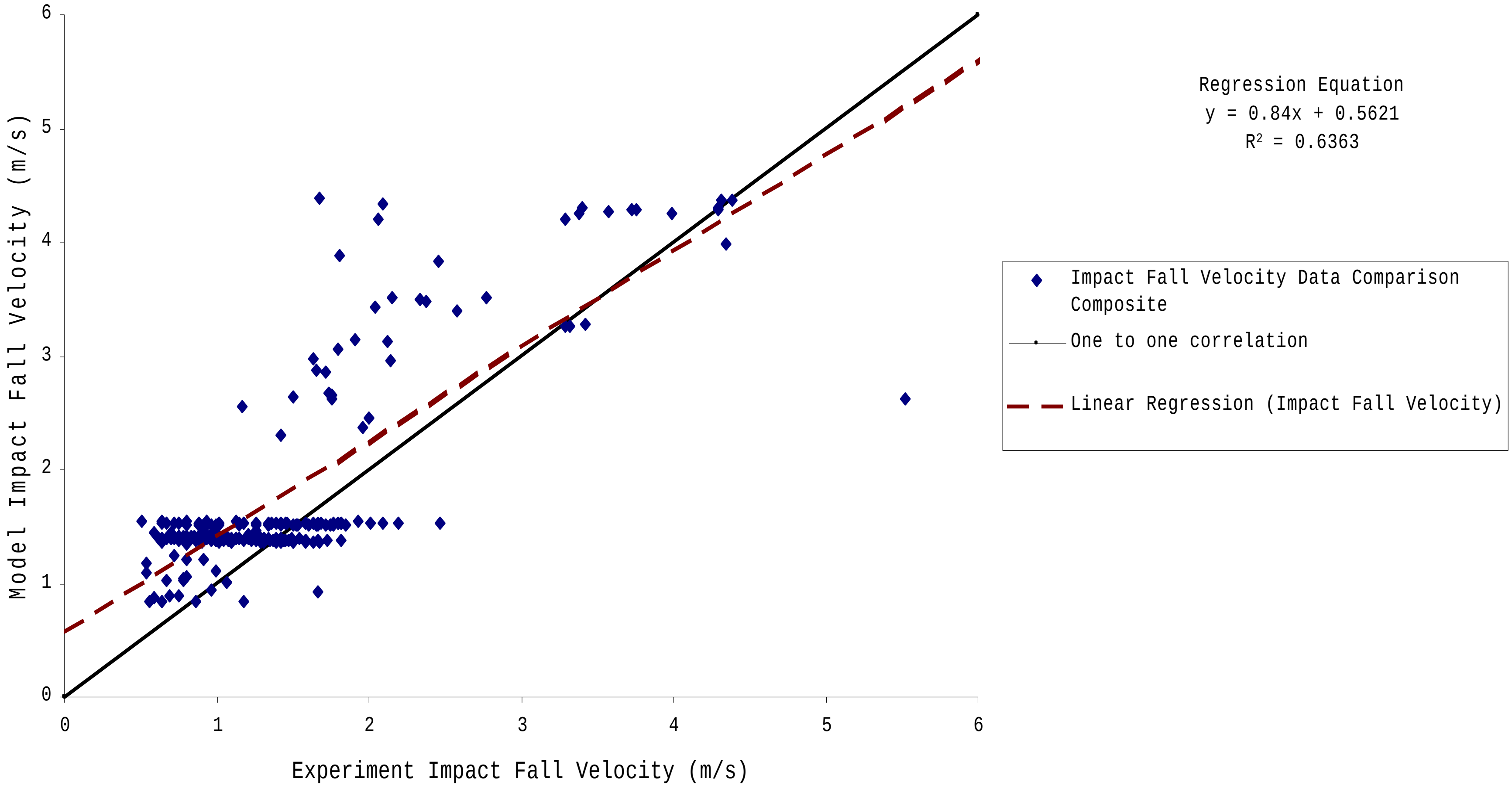
Simple Motion Model Mechanics

Complex Motion

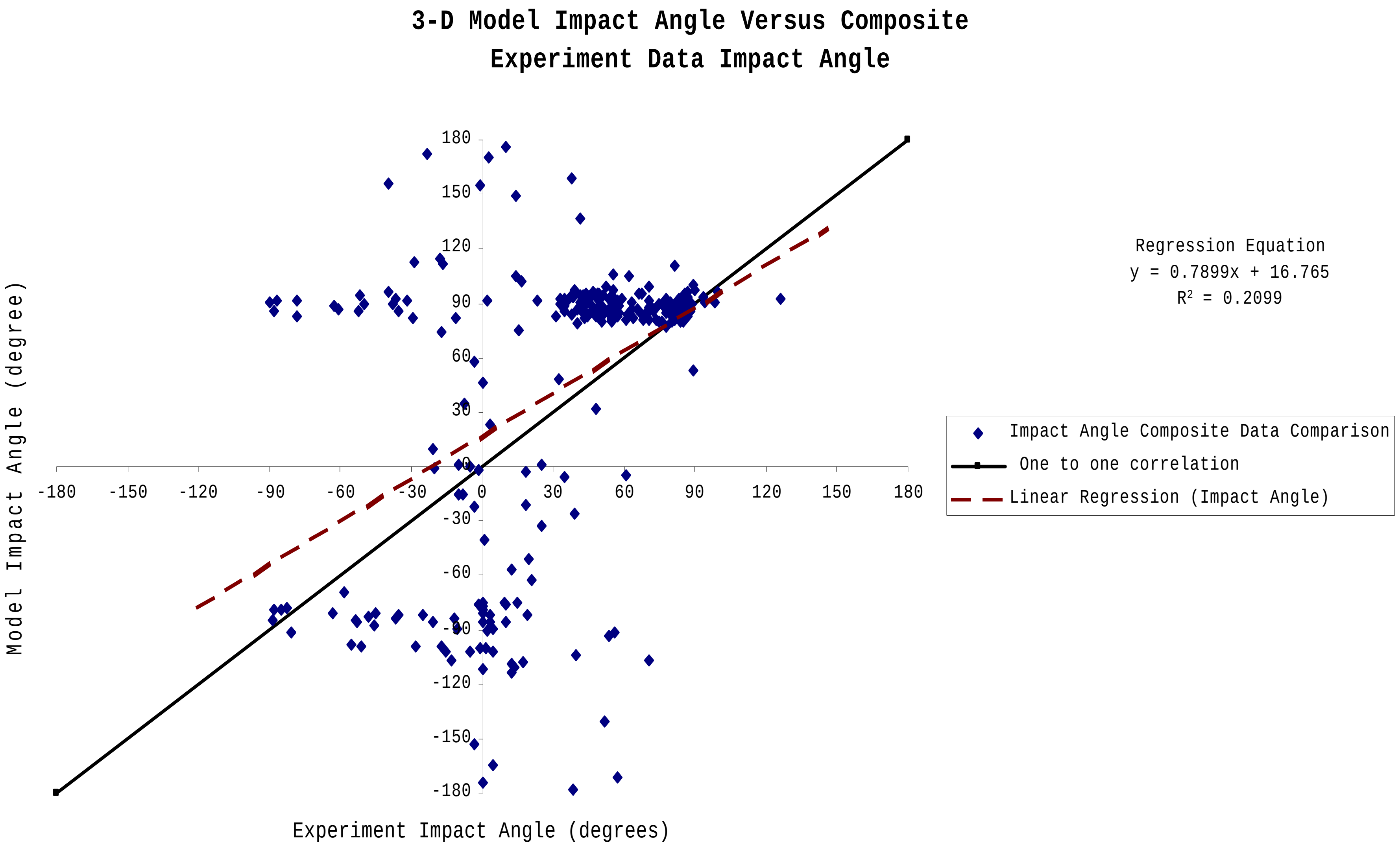


Impact Velocity Correlation

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

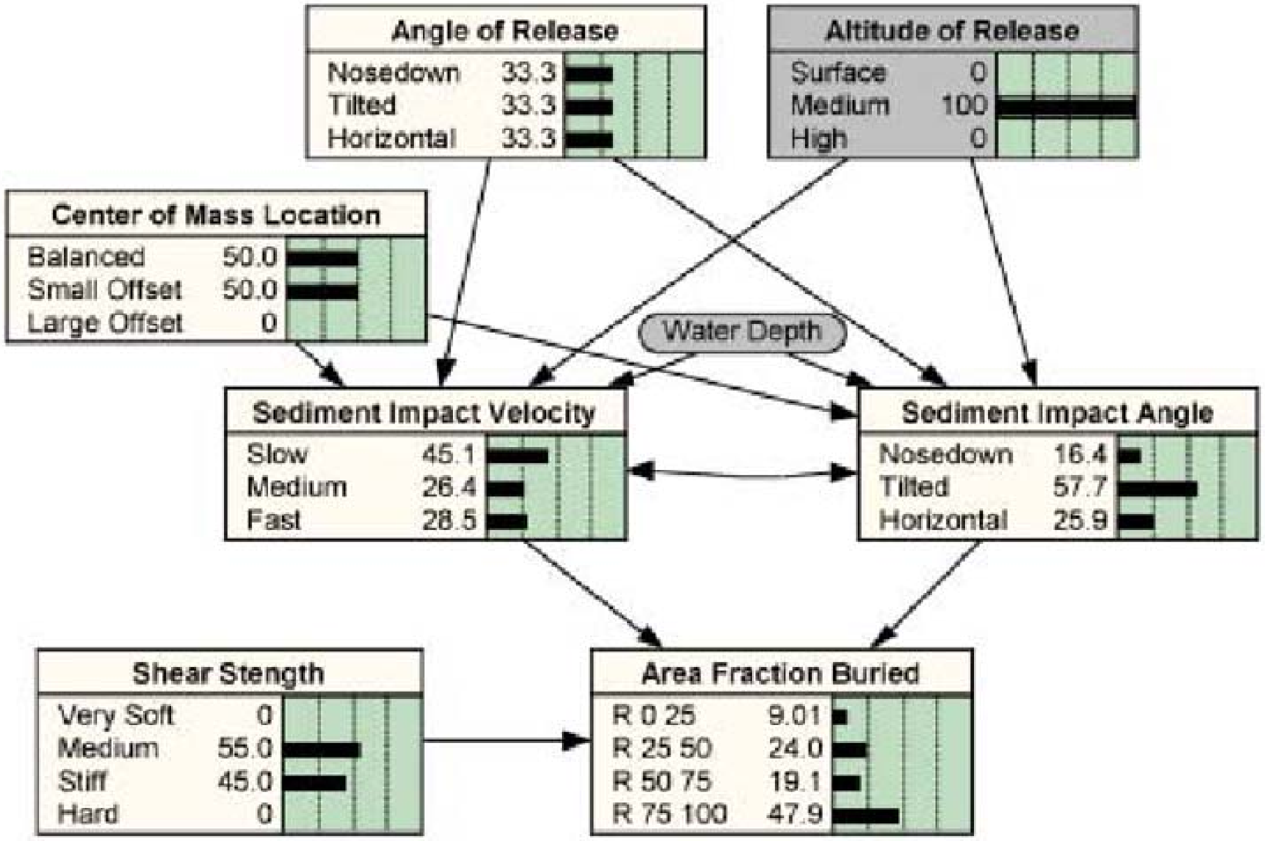


Impact Angle Correlation



Mine Burial Prediction Future

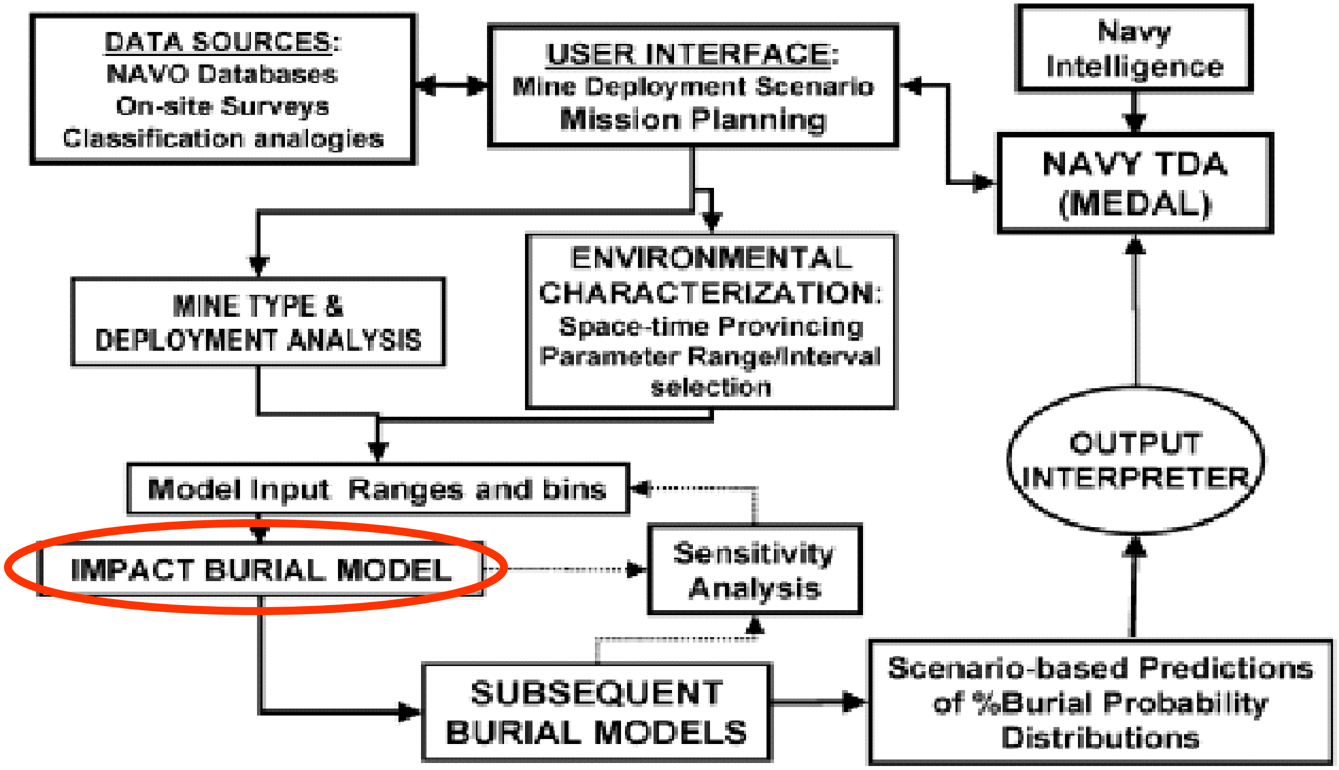
Probabilistic Prediction



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.