2000-03

Environmental Sensitivity Study on Mine Impact Burial Prediction Model

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Dr. Peter C. Chu, LT Victoria Taber, and Prof. Steven Haeger

Institute of Joint Warfare Analysis, Naval Postgraduate School, Monterey, CA

Abstract

The Navy's Impact Burial Prediction Model creates a two-dimensional time history of a bottom mine as it falls through air, water, and sediment. The output of the model is the predicted burial depth of the mine in the sediment in meters, as well as height, area and volume protruding. Model input consists of environmental parameters and mine characteristics, as well as parameters describing the mine's release. In order to determine which parameters had the greatest effect on the model and which could be simplified or eliminated, a series of sensitivity tests were performed. It was found that the model data ingest could be greatly simplified without sacrificing accuracy too much. However, several parameters including sediment shear strength were found to have a large effect on the model.

1. Introduction

Ocean deployed mines currently used by the U.S. and other nations fall into three general categories: bottom mines, moored mines and drifting mines. Bottom mines rest on the ocean floor and are generally deployed in littoral regions. Common placements for bottom mines include shipping channels, harbors, anchorages, rivers and estuaries. Bottom mines are deployed in one of three ways: aircraft, surface ship or submarine. Although mines are designed to be deployed by a specific platform, most mines can be deployed by surface ship with little modification (NMWEA, 1991).

Several numerical models have been developed to simulate the mine burial process, and constitute the only viable means for determining a predicted burial depth, which is critical information when clearing an area of mines. The Impact Burial (IB) model was developed to determine the depth at which the mine comes to rest in the sediment upon impact (Arnone and Bowen, 1980). The IB model was designed to create a two-dimensional time history of a cylindrical mine as it falls through air, water, and sediment phases (Figure 1). The burial depth of the mine in the marine sediment is then calculated from the mine's velocity on contact with the sediment and the sediment characteristics. Several revisions have been made to the model to refine the physics and allow for more realistic geometry and more extensive input from the user. Most notable are the changes made by Satkowiak (1987) and Hurst (1991). Other revisions involved translating to newer computer language. Currently, the model allows the user to input nearly any value for each environmental parameter. Many of these parameters are rarely if ever known by the technician, and their inclusion makes it very difficult for the field user to get an accurate solution. With this in mind, a sensitivity test was designed and executed with the objective of simplifying the input parameters without compromising the accuracy of the model's output.

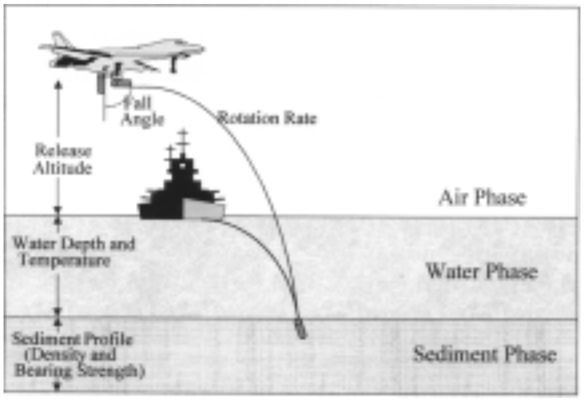

Figure 1. The trajectory of a cylindrical mine as it falls through three phases: air, water, and sediment. Labels are parameters used by the model to calculate the velocity, attitude, and burial depth of the mine.

2. Environmental Parameters in the IB Model

The altitude from which the mine is released determines the velocity and attitude of the mine as it reaches the air-water interface. If a mine does not fall straight down but rather "tumbles" with a constant rate of rotation, simulated in the model by providing a rotation rate θ, the attitude of the mine upon reaching the water is impacted greatly by the release altitude. Although not accounted for in the model, this rotation rate may be caused or affected by wind.

In the water phase, this rotation rate is damped significantly. However, it still has a great effect on the angle the mine makes with the sediment upon impact. Currents may affect the rotation rate in the model, but again are not accounted for in the model. The water depth only has an effect on impact velocity if it is less than that required for the mine to reach terminal velocity, the velocity at which the deceleration due to frictional drag is equal to the acceleration from gravity. The velocity at which this equilibrium is reached is a function of the weight of the mine. Since mines are laid in shipping channels almost exclusively, one may assume that water depths in excess of that required for a mine to reach terminal velocity are the norm. Water temperature has an effect on the viscosity of seawater, and hence increases the drag of the seawater on the mine.

Properties of the sediment are represented by density and shear strength profiles. Density of marine sediment tends to have a s-shaped profile with sharper gradients as density increases. Shear strength, the ability of the sediment to withstand pressure without deforming, also typically has a s-shaped profile and increases with distance from the water interface. The shear strength is related to the level of cohesion between the sediment particles. The density range of concern to the mine impact burial problem is 1375 to 1600 kg/m^3. Factors contributing to shear strength are the type of material, water content, history of stress or disturbance and time since deposition (Noorany, 1985). Although both increase with distance from the interface, there is no clear correlation between shear strength and density. Figure 5 is a scatter plot of density and shear strength values for 62 sediment samples, all taken at the water-sediment interface. For this particular data set, the correlation is extremely weak. Shear strength at the water-sediment interface can be measured in situ with a vane penetrometer or other instrument.

A profile of shear strength such as is called for in the model must be measured from a core sample in the laboratory. This process is time consuming and expensive, and no database of shear strength values currently exists. The term bearing strength, as used in the IB model data ingest, refers to the undrained shear strength times 10. This value, however, is converted back to shear strength and used in the Mulhearn bearing strength equation.

3. Environmental Sensitivity Study

The purpose of this study is to ascertain which variables the model is most sensitive to and which can be simplified or eliminated in order to simplify its use. Since some variables are typically unknown by the user, it is important to determine which of these have the most impact on the model and which can be reduced to toggled values or default values without greatly impacting the accuracy of the model. The model was altered to allow most parameters to be set and a loop run of one variable at a time. The range of each variable was set to represent all possible conditions the model would be used under. It should be noted that wind and currents are not accounted for in this model. However, the only impact they would have would be on the attitude of the mine as it enters each phase. All runs were made with preset mine profile "Korean Mine", which has a dry weight of 538 kg, a wet weight of 251 kg, and a uniform diameter of 0.475 m.

Since the model calculates burial depth and then geometrically calculates the height, volume and area protruding, these values are proportional. To confirm this, we created derivative plots of these values for one case and found the shapes of the curves to be very similar. Burial depth is used to explain most of the sensitivity test, except where height protruding is more descriptive.

3.1. Sensitivity to Release Medium Parameters

Figure 2 demonstrates the variation of the release medium parameters of altitude, water depth and water temperature. Altitude, when varied from 0 to 1000 meters, has a small impact on burial depth (relative difference of 18%). When a more realistic upper limit of 300 meters for a mine laying aircraft is applied, the relative difference drops to just 9%. Water depth has an effect on the burial depth only if less than the depth needed for a mine to reach terminal velocity, in this case 20 meters. At depths greater than this value, the mine reaches terminal velocity in the seawater and excess water depth has no effect on burial depth. At depths from 0 to 20 meters, the variance in burial depth depends on both altitude and water depth since the vertical velocity of the mine as it enters the water becomes pertinent (Figure 3).

Water temperature was found to have no effect on the model's outcome. Although temperature variance does alter the density of water up to 3% and also affects the viscosity (Stanley, 1969), this effect is not significant enough to alter the burial depth value calculated by the model.

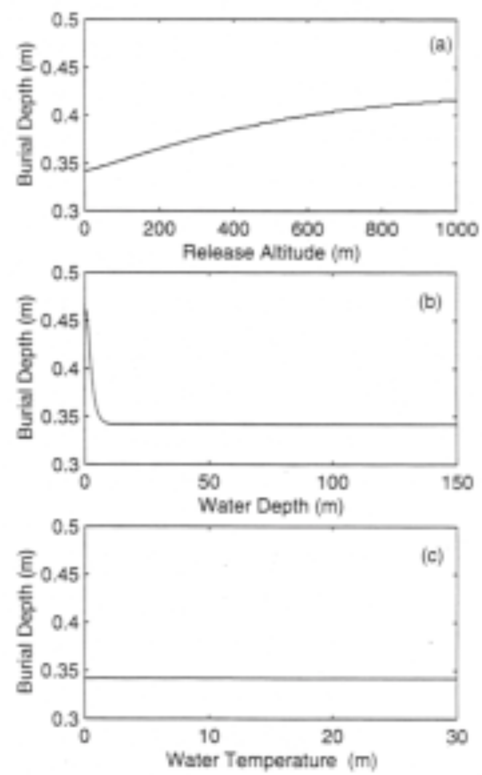

Figure 2. Effect of varying (a) release attitude, (b) water depth, and (c) water temperature on burial depth. Values were preliminarily chosen to represent all conditions under which the IB model may be used.

All cases discussed thus far assumed an initial angle of 90° with respect to the horizontal and with a rotation rate of zero. This produces a situation where the mine is heading directly downward throughout the entire simulation, resulting in the maximum burial depth. When this initial attitude is varied, the burial depth is affected greatly as outlined in Table 1.

3.2. Sensitivity to Sediment Characteristics

As expected, sediment parameters are the most critical element in determining how deep the mine was buried when it came to rest. Sensitivity to the alteration of sediment density and shear strength was tested two ways. First, six sediment profiles were entered into the model and the resulting burial depth was examined (Figure 4). These included three profiles from Sydney Harbor (Mulhearn, 1993) and three profiles available for selection in the IB model. The profiles included in the model are called simply "softsed", "medsed", and "hardsed" and do not clearly correspond to specific sediment types. Second, simplified cases of a single layer of sediment were used with constant density, varying shear strength and constant shear strength with varying density.

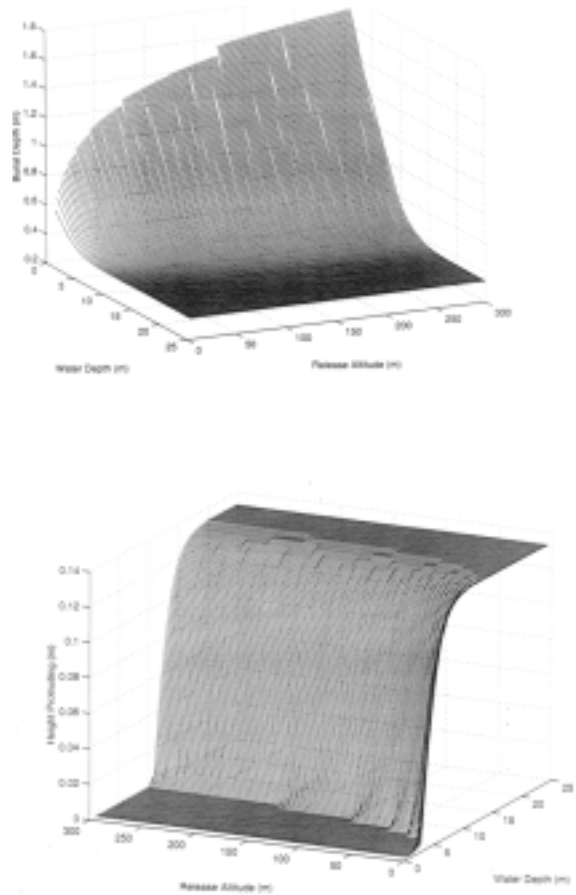

Figure 3. Three-dimensional plot of burial depth (m) and height protruding (m) as both release altitude (m) and water depth (m) are varied. Height protruded is illustrated here to clarify the levels at which these parameters become less influential in the IB prediction.

	Altitude = 1.5 meters	Altitude = 150 meters
Fall Angle = 0°	0.977 m	2.405 m
Fall Angle = 90°	0.342 m	0.359 m

Table 1. Maximum and minimum burial values for a mine released from 1.5 or 150 meters. An initial fall angle and subsequent sediment impact angle of 0° indicates a perpendicular orientation and maximum burial depth. Fall angle of 90° indicates the mine is parallel to the sediment and yields a minimum burial depth.

3.2.1. Sensitivity to Shear Strength and Density

Figure 5 illustrates the sensitivity of burial depth on density and shear strength. Here, a simple profile of just one layer was used and density and shear strength were varied separately. All other parameters were kept unchanged as default values. Plot (a) is the burial depth with shear strength held constant and varying density from 1000 to 2000 kg/m^3. Shear strength of 1 kPa indicates extremely soft sediment, and density has a noticeable effect on burial depth of 37%.

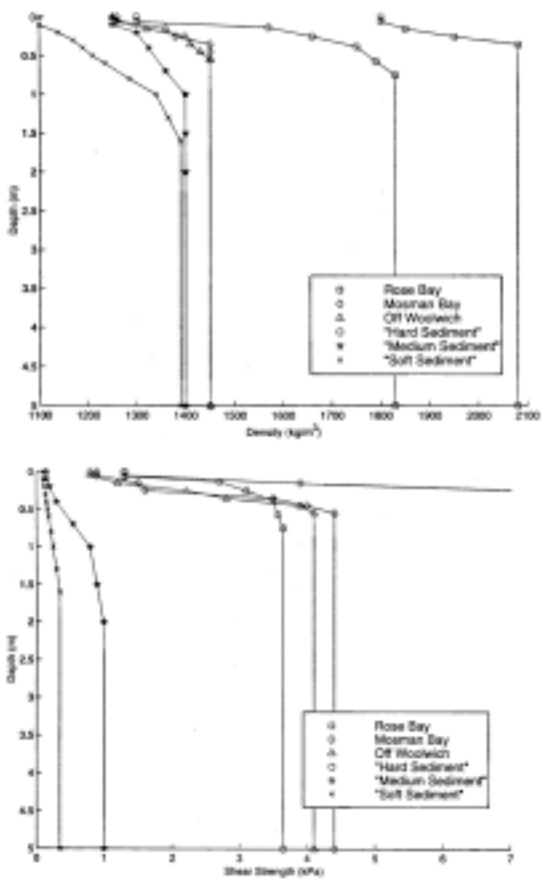

Figure 4. Sediment profiles of (a) density (kg/m^3) and (b) shear strength (kPa) used in the sensitivity study. Data obtained from Mulhearn (1993).

At the more common shear strength values of 5 to 15 kPa density has little effect, just 3.7%. Plot (b) illustrates the effect of varying shear strength while keeping density constant. Again, we see the greatest impact of density value on the model output at low shear strength values. As shear strength increases, so does the influence of varying density.

Several methods for simplifying the sediment profile requirements were investigated, using the full profile case as a control. First, the density and shear strength were held constant to 5 meters. The relative difference is under 26% for all profiles using this simplification. Next, a process of manufacturing sediment profiles using the density values measured at the water-sediment interface was derived and applied to the model. The profiles were assumed to consist of a constant value layer at the surface to a depth h_1, a sharp gradient to h_2, and then constant to a depth of 5 meters.

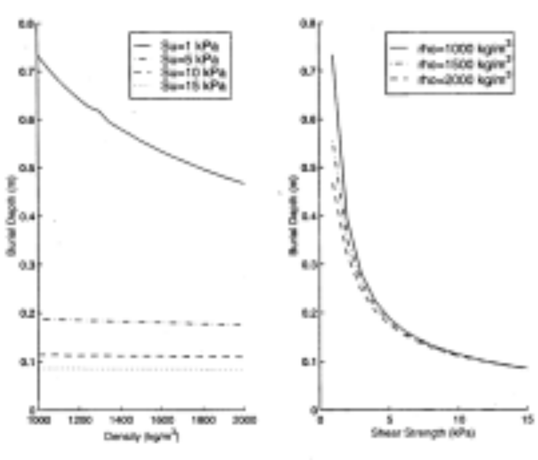

Figure 5. Effect of (a) density and (b) shear strength on burial depth. Density change only impacts the predicted burial depth in very soft sediments. As expected, shear strength has a dramatic impact on predicted burial depth.

The profiles were first applied to density only, holding shear strength constant, and then to both density and shear strength. Values for h_1, h_2, $\rho(h_2)$, and $\tau(h_2)$ were calculated by applying ρ_o and τ_o to polynomials derived from the data. The softsed and medsed profiles create the greatest differences from the control in all cases.

Interestingly, creating a simulated density profile and keeping the shear strength value constant had no effect on the burial depth result when compared to keeping both values constant for five meters. This serves to underscore the fact that it is the shear strength parameter that has the primary influence on burial depth, not the more easily measured density parameter.

3.2.2. Simulated Sediment Profiles

Several attempts were made to manufacture shear strength profiles from density and shear strength values measured at the interface. This was explored in order to determine if a viable method of simplifying the data entry for the sediment phase could be devised. One attempt consisted of applying a fitted polynomial to measured density and shear strength values to create a synthetic profile from only interface values. Values for the sediment profiles used in the study, calculated with the following equations, are listed in table 2.

Based on the density profiles in Figure 4, we empirically derived curve-fitting equations to represent the density profile,

$$h1=-0.000061833*\rho_o + 0.01609$$

$$h2=-0.0015*\rho_o + 3.10$$

$$S_u(h2)=[(2.2048*10^{-5})\rho_o^4]-(0.109\rho^3)+ 201.1381\rho^2[(1.6432*10^5)\rho] + (5.0136*10^7)$$

$$\rho(h2)=\rho_o + 250$$

The prediction of this simplified method of depicting a sediment profile is demonstrated in table 3.

Hayter (1986) discussed an equation originally derived by Krone (1963) for deriving shear strength, S_u, from density using empirically derived coefficients α and β:

$$S_u=\alpha\rho^\beta$$

Values for α and β must be calculated for each separate sediment type, after which the shear strength can simply be calculated using the coefficients. Figure 6 illustrates the impact of varying α and β on the model output, given a constant density. The profile was assumed to consist of one layer of homogenous material. As expected, as α and β increase, shear strength also increases and burial depth decreases. Figure 7 is a series of contour plots with varied values as the axes. The contours represent predicted burial depth values. Known shear strength values are marked on the corresponding density plot. For all cases, there is a unique value of the coefficients that will produce a shear strength value given a specific density. Please note that, while they are plotted here as one density value and one shear strength value per sediment type, a change in density would produce a corresponding change in shear strength that could be determined by use of the same two unique values of the α and β coefficients.

4. Recommendations

As expected, there are several parameters that are both rarely known by the operator and of little import to the outcome of the model. In order to make the model easier to use with out sacrificing accuracy, these parameters should be simplified as much as possible.

Water temperature was found to have no effect on burial depth, and should be eliminated from the list of variables. Altitude values should be simplified to represent a mine laying platform and the most likely height for release from that platform. For instance, it is more likely that an operator would know if the mines were laid by a ship or by a certain type of aircraft that the enemy has than at which altitude that aircraft was flying.

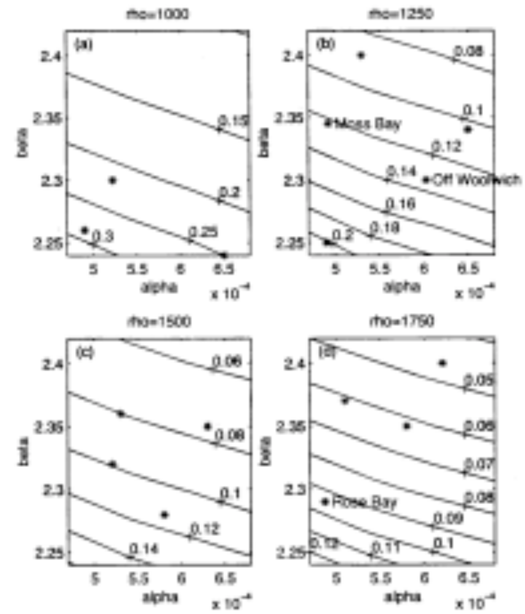

Figure 7. Contour plots of predicted burial depth (m) with respect to α and β coefficients. Asterisks mark the values of α and β that correspond to the interface values of the three sediment profiles from Mulhearn (1993) used in this study and to a subset of the Voelkner (1973) data set.

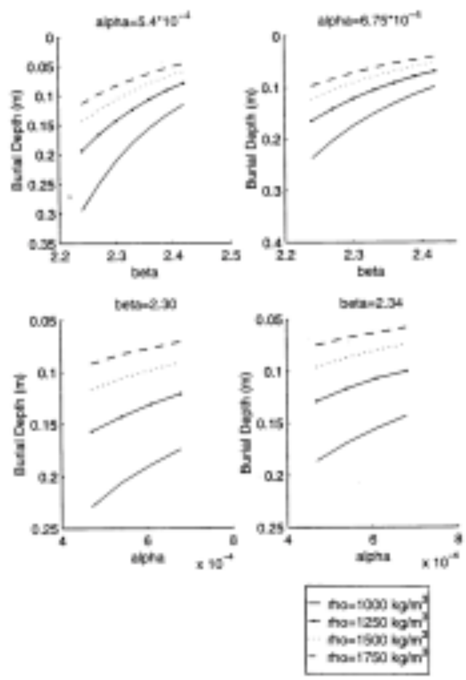

Figure 6. Effect of α and β coefficients on predicted burial depth (m).

	Mossman Bay	Rose Bay	Off Woolwich
h_1 (m)	0.083	0.05	0.084
h_2 (m)	1.21	0.40	1.23
ρ_o (kg/m^3)	1260	1800	1250
$\rho(h_2)$	1510	2050	1500
τ_o(kPa)	9	13	8
$\tau(h_2)$	44	20.9	41

	softsed.sed	medsed.sed	hardsed.sed
h_1 (m)	0.093	0.084	0.081
h_2 (m)	1.45	1.23	1.15
ρ_o (kg/m^3)	1100	1250	1300
$\rho(h_2)$	1350	1500	1550
τ_o(kPa)	1	1.5	13
$\tau(h_2)$	3.5	10	20.9

Table 2. Values calculated using equations derived by fitting a polynomial to known density and shear strength profiles.

Using intelligence and experience, one could form a rough database or platforms that could be chosen from. The difference between an altitude of 1 meter and 300 meters is significant, but the difference between 1 meter and 5 meters is not.

An equation for terminal velocity could be built into the data entry program that takes the weight of the chosen mine into account and asks the user if the water depth is less than that which would produce terminal velocity in the water phase. Assuming no rotation rate was chosen, if the depth was known to be greater than required for terminal velocity, a depth need not be entered. This simplification would also allow the user to have some confidence in the result as he moves about he area, regardless of water depth changes.

The model could be revised to provide a range of values for burial depth, based on a initial attitude of 90° and 0°. In this way, the uncertainty of initial attitude and rotation rate would be eliminated and a more realistic range of values would be produced. This may seem like a reverse in sophistication of numerical modeling, but the reality is that the exact burial depth will never be known due to the unpredictability of the attitude of the mine as it encounters the sediment interface. This would also eliminate any effects due to currents or winds, since the primary effect of these influences would be on the attitude of the mine.

Further investigation is warranted on a method of simplifying the sediment profile data entry. Assuming the values for density and shear strength are either known or can be measured at the interface, a set of equations should be derived and refined to create the remainder of the profile. If this were an option in the model, while still allowing the user to enter the entire profile if known, it would substantially increase the usefulness and precision of the model. The few cases discussed here and the equations derived from that limited data set are encouraging, and may indicate that such equations are possible and beneficial.

5. Acknowledgements

The authors wish to thank Mr. Rob Bourke, Mr. Ed Nath, and the staff of the Naval Postgraduate School Secure Computing and Simulation Laboratory for their expertise and patient assistance.

This study was sponsored by the Naval Oceanographic Office (Code N532) under the contract N6230698OB80001.

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	Mossman Bay	Rose Bay	Off Woolwich
Full Profile	0.103 m	0.074 m	0.115 m
Measured ρ_o, S_u held constant to 5 meters	0.121 m	0.093 m	0.132 m
Relative Difference	15%	20%	13%
Density and Shear strength profiles created using measured ρ_o and S_{uo}	0.101 m	0.059 m	0.105 m
Relative Difference	2%	20%	1%

	softsed.sed	medsed.sed	hardsed.sed
Full Profile	0.523 m	0.342 m	0.084 m
Measured ρ_o, S_U held constant to 5 meters	0.683 m	0.463 m	0.094 m
Relative Difference	23%	26%	11%
Density and Shear strength profiles created using measured ρ_o and S_{uo}	0.300 m	0.179 m	0.085 m
Relative Difference	43%	48%	1%

Table 3. Predicted burial depths using manufactured profiles based on measured values at the interface.