

An Expert Systems Approach for Predicting Mine Burial

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Abstract

An important factor in Naval MCM mission planning is knowledge of whether bottom mines are fully or partially buried beneath the marine sediment. Accurate burial predictions are difficult to make due to uncertainties in deployment conditions as well as in environmental parameters such as sediment composition. An investigation into the application of Expert Systems concepts to the prediction of mine burial is presented. The core of the selected approach is a Bayesian probabilistic network, which can deal with uncertainty in a quantitative manner. The conditional probability distributions that describe the causal relationships within the model will largely be formulated using the physics-based models of burial processes developed by the expert R&D community, including those for impact burial, scour, bedform migration, and sediment transport/deposition. Additional information will come from the collation of reported field and laboratory data as well as assessments from expert interviews. Examples are given of the application of a prototype Expert System to the Norfolk entrance channel.

Introduction

The shifting of the focus of Naval operations from the open ocean into regional littoral areas increases the importance of sea mine warfare. The proliferation of inexpensive, yet sophisticated, moored and bottom-mounted mines make shallow water MCM a critical challenge. An important factor in minehunting is the amount of burial beneath marine sediments, because buried mines are substantially more difficult to detect and classify. As an example, the SACLANTECEN MCM sonar performance model predicts that the SNR of a buried mine will be about 20dB lower for most grazing angles than the SNR of a mine resting on top of the sediment (NATO SG31, 1999).

Accurate burial predictions are difficult to achieve because there will be uncertainties in the mine deployment conditions as well as in crucial environmental parameters. There are multiple factors in the environment that can strongly affect the burial behavior, including bottom sediment composition, tidal and wind-driven currents, wave conditions, and suspended sediment flux.

Available information about the local sediment is usually limited to estimates of the median grain size, whereas the relevant physical factors are difficult-to-measure parameters, e.g. shear strength and porosity. Tidal currents at a given site may be well known, but wind and wave conditions must be forecast or based on climatology.

Improved understanding of the physical processes responsible for mine burial is the focus of the Office of Naval Research Marine Geoscience's Mine Burial Prediction Program. Our current effort at the Johns Hopkins University Applied Physics Laboratory involves the application of Expert Systems concepts to the prediction of mine burial. This project is funded by ONR to explore the optimal method of bringing together the most recent knowledge derived from these deterministic physics-based studies and synthesizing that knowledge in a manner that can explicitly address the uncertainty inherent in the problem.

Concept

The Mine Burial Expert System Model (MBESM) is ultimately envisioned as a part of an operational Tactical Decision Aid such as COMINELWARCOM's Mine Warfare Environmental Decision Aids Library (MEDAL) as shown in Figure 1. As part of a TDA, the MBESM will require an interface with the mission planner to receive intelligence regarding the mine type and deployment, and interfaces with Navy environmental databases to receive the best characterizations of the hydrographic and sediment parameters available. The mismatch between data availability and model input requirements is part of the sensitivity analysis provided by the Expert System, pinpointing the most valuable input that possible on-site surveys might provide. The resultant probability distribution of burial estimates will need to be interpreted in a manner that will best aid the minehunter's decision process.

The concept development phase of this project has been completed and the feasibility of this modeling approach is being explored by building a demonstration expert system that will focus on selected locations of particular interest to the Navy, such as navigation channels into strategic harbours and selected shallow water coastal sites.

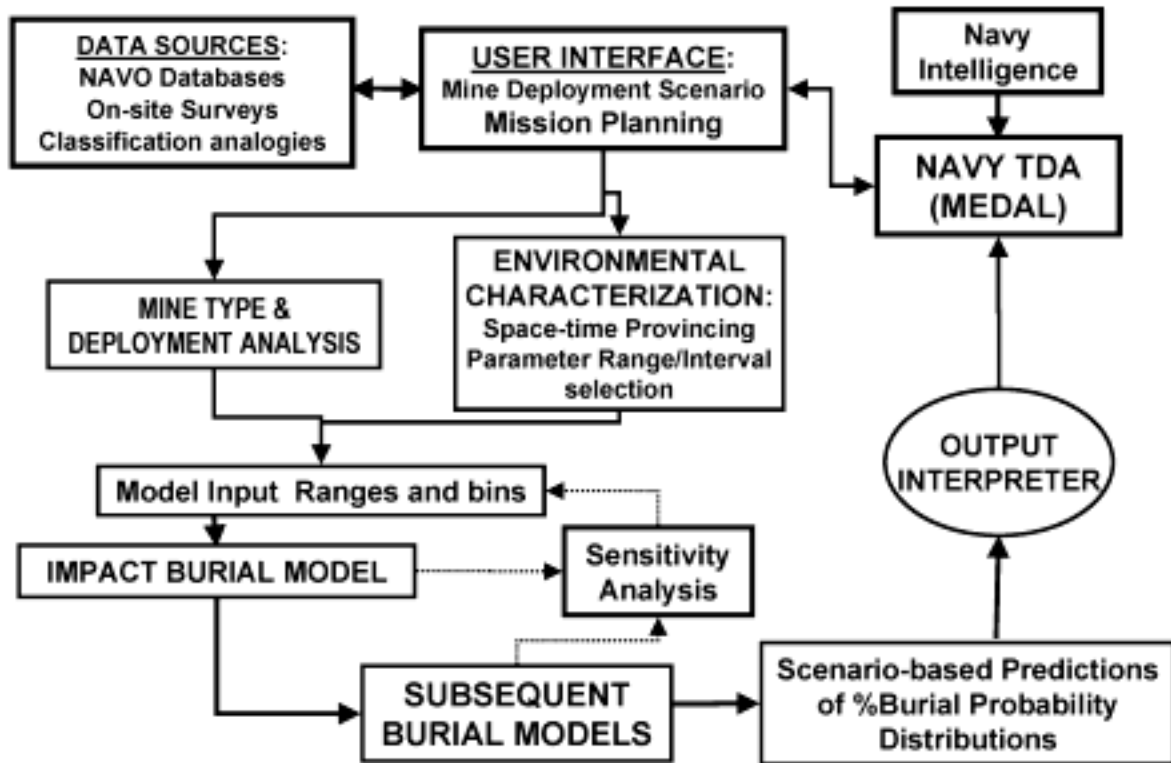


Figure 1. Mine Burial Expert System Model Concept Overview

Approach

Our first task was to identify the experts doing research in mine burial processes. We have established contact with experts in the academic research community, at the coastal research laboratories (in the US and abroad), and in the US Navy laboratories, who have the necessary research background, data, and models.

The second step was to develop the technical approach to formulating the expert system. Bayesian probabilistic networks were chosen as the primary means to implement our prototype MBESM. A Bayesian network represents causal relationships among key variables as connections between “nodes” representing those variables. Connectivity between nodes represents knowledge about the extent to which one variable has a direct causal influence on any other. Causal influences are quantified by a conditional probability distribution (CPD) associated with the

affected variable's node. These CPDs can be developed from field or laboratory data, output from deterministic physics-based models, expert's assessments, or any combination thereof.

The advantage of Bayesian networks lies in their ability to model and reason about uncertainty, within the well-founded mathematical formalisms of probability theory and statistics. This supports decision making through the generation of quantitative, probabilistic measures of uncertainty and error, which can be directly used in cost/benefit decision analysis. The challenge in developing the Bayesian approach is the requirement to specify every direct causal interaction between the variables. This can require the evaluation of a very large number of conditional probabilities. However, expert systems researchers have long recognized this challenge, and tools and techniques are available to address it. For the first prototype MBESM, implementation of the Bayesian network has been made within the software Netica (NorSys, 2002), which allows an easy graphical exploration of the relationships.

The core of the information incorporated into the Mine Burial Expert System are Conditional Probability Tables (CPTs) based on histograms developed through a Monte Carlo exercising of the physics-based models developed by the mine burial R&D community. There is on-going research into modeling the behavior of mines with different shapes and densities during the initial deployment (fall through the water and impact with the sediment) as well as the subsequent burial processes including scour, bedform migration, sedimentation, and liquefaction. Additional information will come from the collation of reported field and laboratory data and the assessment of the applicability of these models based on expert interviews. Estimates of the necessary geomorphic and oceanographic input parameters will be incorporated by developing fuzzy sets to make best use of often-limited databases.

Implementation

A prototype MBESM has been developed that predicts the probability of impact and scour burial for a cylindrical mine. First, a hypothetical deployment scenario is related to an initial impact burial estimate (Figure 2). The causal relationships (quantified as CPTs) were initially derived from Monte Carlo runs of the impact model IMPACT28, which was first developed at CSS-Panama City (Arnone and Bowen, 1980); was improved upon by researchers in Australia (Mulhearn, P.J., 1993); and has been further analyzed and documented by Chu et al (2000).

For the impact case in Figure 2, the initial orientation of the mine at deployment is assumed to be unknown; hence the Angle of Release input distribution is uniform. This scenario illustrates a deployment of cylindrical mines being dropped from a small vessel, so that Altitude of Release is set to “Medium”, a fuzzy category that covers altitudes from approximately 1 to 3 meters above the surface. Intelligence information about these mines could indicate that they should be reasonably well balanced (Center of Mass only slightly offset). These settings result in distributions of predicted impact velocities that are weighted towards slow speeds and impact angles that are mostly tilted. Sediment data was obtained from the Army Corps of Engineers for one demonstration site, the inner entrance channel to Norfolk Naval base (Swean, 1986). The sediment shear strength there largely ranged from 3 to 15 kPa, which was categorized as “Medium” and “Stiff”. The resultant burial distribution, as shown in Figure 2, predicts that close to half of the mines will be over three-quarters buried.

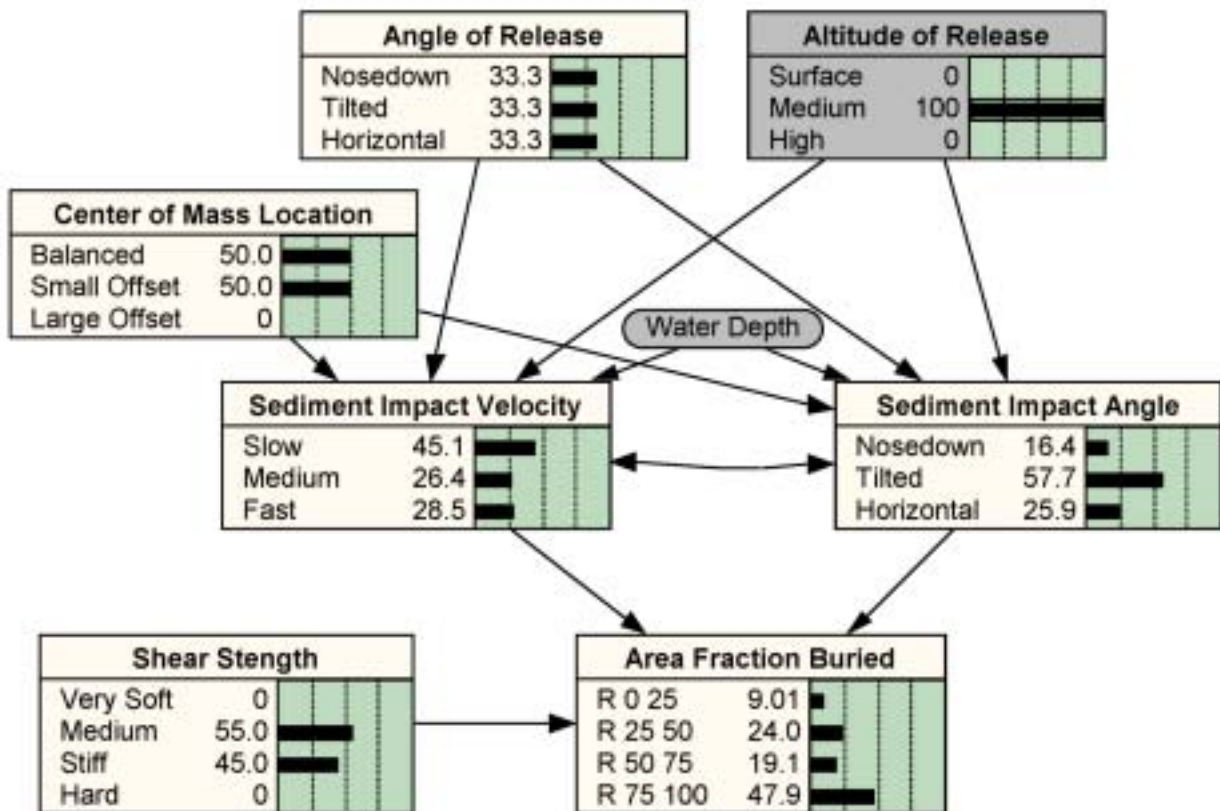


Figure 2. Bayesian Impact Model Example, Data from Inner Thimble Shoals Channel

After the impact burial probability distribution has been determined, estimates of scour can be determined. At present, the MBESM incorporates a simple scour model based on the equations published by HR Wallingford (Soulsby, 1997 and Whitehouse, 1998). Figure 3 illustrates a scenario based on environmental data from the outer Norfolk channel, where the sediments are dominated by coarse sands and initial impact burial will be minimal. The node for Elapsed Time is a “decision variable” within the Bayes network that is set to the time horizon of the proposed minehunting mission. In this example, the prediction shows that after one month of mean tides and climatological waves (Boon et al, 1996), most of the mines will be less than one-quarter buried.

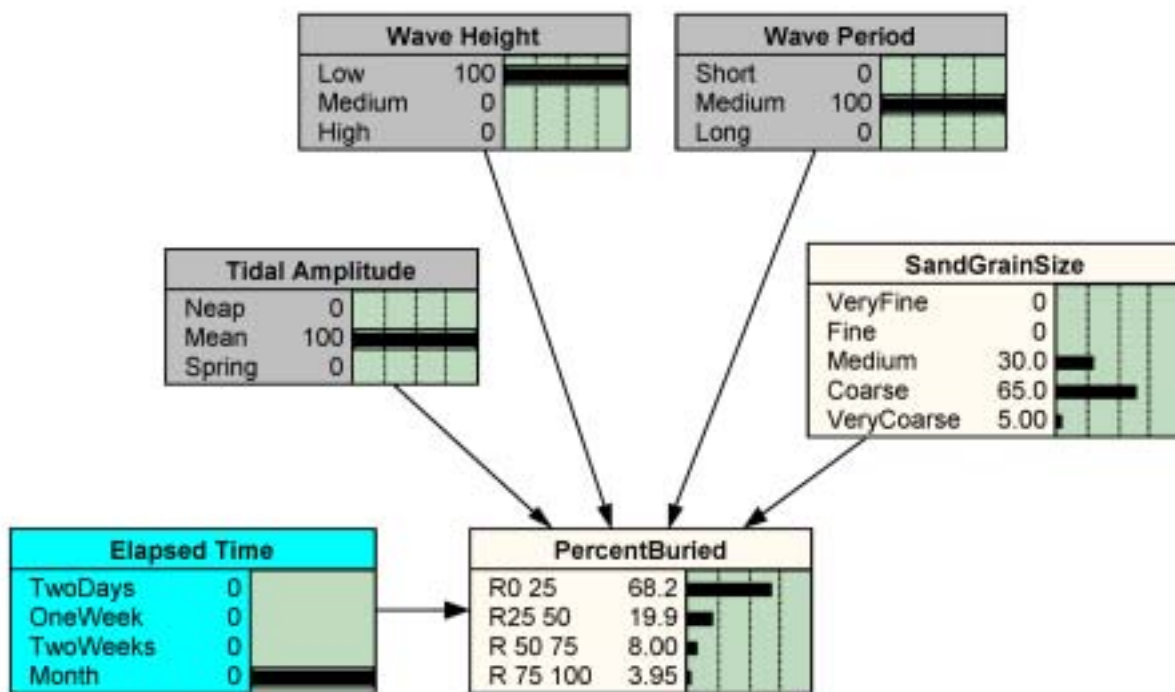


Figure 3. Bayesian Scour Model Example, Data from Outer Thimble Shoals Channel

Issues & Challenges

The resolution and fidelity of a Bayesian network probability distributions is based on the choice of ranges for each bin or category in the CPT. Sensitivity analysis is necessary to make intelligent bin choices that maximize the discrimination. In a Monte Carlo simulation, the number of runs, N , required will be $N = b^P * R$, where b is the number of bins, P is the number of input parameters and R , the number of realizations. For the sample histogram to approach the

underlying probability, the number of realizations should be $O(100)$. For an example with 5 input variables, categorized into 4 bins each, the required number of runs approaches 100,000. This limits the Monte Carlo approach to fairly simple deterministic models.

The Bayesian networks will be limited by the physical understanding that went into the underlying deterministic models, and by the accuracy of the data used to augment the probability distributions. The models currently available are acknowledged to have deficiencies and are often validated only for very limited domains. There is clearly the potential for several of the subsequent burial processes to interact; yet this coupling has not been fully addressed yet. However, the Expert System provides a structure into which new information can easily be integrated by updating the CPTs without having to rebuild the entire framework.

Summary

The goal of this effort is to bridge the gap between the science level models where all basic parameters must be known and the operational level model where a much-reduced parameter set can be used, and estimates and approximations are provided to fill in that input set. The Expert Systems approach will provide a systematic organization of the current knowledge base, combining physics-based models and the expertise of contemporary research scientists into a state-of-the-art prediction of mine burial probability that accurately reflects the uncertainty found in any realistic, operational minehunting scenario.

Acknowledgements

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