Statistical Database Generation and Geotechnical Mine Burial Prediction Maps for Coastal Shallow-Water Fine-Grained Sediments

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LONG-TERM GOALS

One research goal is the correlation of shallow-water coastal sediment properties and environments of deposition with the engineering/geotechnical properties. Sedimentary coastal environments must be statistically characterized in terms of a suite of "key" sediment properties. Another long-term goal is to develop reliable empirical equations/techniques to predicting mine burial using the sediment properties such as natural water contents and sediment (soil) state defined by the Atterberg limits (Bennett et al., 1999a, 2000a and b, and 2004). In addition, SEAPROBE is providing essential input data required for the Mine Burial Expert System Model (MBESM) presently being developed by the Johns Hopkins University, Applied Physics Laboratory (Brandt et al., 2004). The overall long-term goal is to establish a comprehensive geotechnical and sedimentological data base of coastal muds that will provide statistically significant data for predicting mine burial for a variety of depositional environments and sediment types. The geotechnical, soil physics, and sediment properties statistical approach is essential to quantitatively evaluate and ultimately map mine burial and predicted depths of burial in shallow-water coastal environments. This basic and applied research provides a strong basis for developing statistically significant sedimentary analogues for predicting mine burial in remote areas of the world.

OBJECTIVES

The thrust of this project was to apply marine geotechnical techniques and practices, based on sediment physics and quantitative statistical techniques, to understand the shallow-water sediment properties in selected coastal environments and physiographic provinces. The coastal areas included areas of the Chesapeake Bay, the offshore southern and southeastern coast of Korea, and an offshore site near Corpus Christi, Texas that was required to test the IMPACT28 Model and the MBESM with field data (Brandt et al., 2004). Each province is different in terms of the environmental forcing, sedimentation patterns, sediment types, and sediment properties. A statistical approach was essential to quantitatively evaluate sediment properties and to map predicted depths of mine burial for shallow-

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water coastal deposits in the selected depositional environments. SEAPROBE, Inc. researchers compiled shear strength data and other selected geotechnical properties data for marine sand deposits. A short discussion was provided as a caution regarding various techniques used to determine the shear strength of sand as reported in the literature.

The basic and applied research objectives were 1) to select strategically important shallow-water coastal areas and carry out a comprehensive synthesis of the surficial sediment textural (grain size) and geotechnical properties of the nearshore (≤100 m water depth) environments; 2) to conduct a comparative analysis of the geological environments in terms of the sediment geotechnical properties; 3) to develop and analyze the statistical distribution of the sediment and geotechnical properties in terms of the environment(s) of deposition and geological setting; and 4) to develop predictive empirical equations and relationships of sediment geotechnical properties and mine burial potential as a function of sediment properties variability. An integral part of the effort was to develop statistical relationships of sediment shear strength to selected geotechnical properties and sediment type (grain size) for application to the Mine Burial Expert System Model.

APPROACH

The Master Database developed is a Microsoft Excel-based spreadsheet consisting of key parameters compiled from numerous source materials, such as previously unpublished data (primary data) and published data (secondary data) in professional papers and technical reports. Secondary data were extracted and digitized from reports by optical character recognition (OCR) software and measurements from available figures, graphs, and maps. After OCR, extensive formatting and change of units of measurement and coordinate systems were necessary for some data. Excel macros were used to simplify these tasks. Source data were abstracted for the Chesapeake Bay and selected areas of Korea. In addition, geotechnical data for the mine drop area off Corpus Christi were obtained from Dr. Wayne Dunlap (TAMU) and Dr. Phillip Valent (NRL) for addition to the Master Database. To insure the reliability of the database, all input values were double-checked against the original source and subject to validation testing.

Data were analyzed to determine relationships between parameters. Data was plotted on a graph or histogram to visually inspect the distribution and relationship between parameters. Some quantitative analysis was performed using correlation coefficients to measure correlation between parameters, descriptive one-variable statistics, and linear regression to determine functional relationships between parameters. The analyses and interpretations were performed carefully to avoid errors due to the secondary analysis of the quantitative data, such as artificial truncation and unknown precision of data.

Statistical analysis was used to assess geotechnical properties relationships, variability, with depth below the sea floor. Field data were used for comparing diver measured depths of mine burial with the new method of predicting mine burial based on the Atterberg limits and natural water contents.

WORK COMPLETED

This project was a combined effort for the Office of Naval Research (ONR) and the Naval Oceanographic Office (NAVO). The general tasks completed during this work are as follows.

A comprehensive database was compiled for selected coastal areas. The database was used for completing a statistical analysis of near-shore fine-grained sediment including geotechnical (physical and mechanical properties) data for the two major coastal areas plus a Corpus Christi Site and additional sites were included for the study of sand deposits. The main areas are the mid- and lower estuarine environments of the Chesapeake Bay (relevant to Homeland Defense) and the southern and southeastern coastal areas of Korea. A comparative study was made to quantitatively present sedimentary and geotechnical (engineering) properties in terms of geological environments of deposition and associated sediment types. Geotechnical and sedimentological data were used to classify the surficial sediments from each selected area to water depths of up to 100 meters. Using results and analysis obtained from the Master Database, we constructed mine impact burial prediction tables integrating NAVOCEANO surficial geology maps with the geotechnical properties data and criteria. The technical report describes the methodology used to predict impact burial in fine-grained sediments. Results and geotechnical data are tabulated for the areas of interest. Predicted mine burial for the mid- and lower estuarine environments of the Chesapeake Bay and the southern and southeastern coastal areas of Korea were included in tables keyed to NAVO surficial sediment maps.

In summary, results from applied research and analysis and the development of the Master Database provided a basis for developing a geotechnical mine burial prediction methodology based on sediment geotechnical properties (soil physics/sediment behavior and sediment state/consistency). The applied research included the development of statistical techniques that correlate sediment types and environments of deposition with selected geotechnical properties (e.g., natural water content and Atterberg limits, shear strength, wet bulk density, etc.).

RESULTS

Geotechnical properties largely depend upon the amount of water and organic matter contained in the sediment mass. The sediment mass consists of water, solid, gas, and organic matter of varying proportions (Bennett et al., 1999).

1. Fine-grained sediment shear strength is highly variable for all three sites (Chesapeake Bay, offshore Korea, and Corpus Christi). Shear strength averages, ranges, and standard deviations found for the Shepard classes are depicted in Figure 1. Shear strength largely depends on the water content, clay minerals, and percent organic matter. The average shear strength for the three areas are Chesapeake Bay 3.74 kPa (3.35 stdev), Korea 4.22 kPa (1.64 stdev), and offshore Corpus Christi 4.18 kPa (1.66 stdev). Because of the relatively high variability within even the Shepard Classes, shear strength may be an inappropriate (questionable) mine burial prediction parameter in fluid-like muds.

2. The Atterberg Limits and natural water contents are the mine impact burial prediction criteria. The liquidity index or simply the use of the Atterberg limits and the natural water contents (i.e., w_n/w_l) is an appropriate parameter for predicting mine burial in these water-rich surficial sediments. The Atterberg limits provide a proxy shear strength by placing the sediment in a specific consistency state. Fluid-like consistency is defined by the liquidity index or the ratio w_n/w_l is also useful. A liquidity index of 1.0 defines the boundary between the liquid and plastic states (Lambe, 1951; Lambe and Whitman, 1969). The plasticity index (liquid limit minus the plastic limit) is the range in which the sediment can be deformed plastically. As the natural water content of a marine sediment decreases from a fluid-like consistency below a liquidity index of 1.0, further dewatering places the *in situ* sediment in a dryer, more rigid consistency, usually with higher shear strengths than the fluid-like muds. Chesapeake Bay and Korean sediments have liquidity index values generally higher than 1.0.

3. Based upon data analysis from Chesapeake Bay, Korea, and offshore Corpus Christi, environments of deposition can be differentiated based on the Atterberg limits, water content, and other physical properties (Figs. 2 and 3). Values of liquidity index equal to or greater than one (1) are indicative of muds that are very weak, have high porosities, and usually are highly compressible, especially fine-grained sediment with greater than 2% TOC. Penetration and burial of objects in these soft fluid-like sediments are highly probable based on previous studies (Bennett et al., 1995, 1999b, 1999c). Mine burial depths can be predicted on the basis of the water content and the liquid limit (Fig. 4) and appear to be unique to the depositional environment. Note the significant differences in burial depth for the different depositional environments based on Atterberg limits and natural water contents (Fig. 4). The ratio w_n/w_l is shown to be closely related to the measured mine burial depth and to the apparent interrelationships among the geotechnical properties.

4. Predicted depths of burial (PDB) were made using the techniques described in the study using sediment consistency (soil state) defined by the Atterberg limits and the natural water contents. A mine burial prediction map (Fig. 5) was developed and actual mine drops and diver measured depths of burial were compared. Data were superimposed on the NAVO sediment textural classification from Shepard (1954). The methods used to predict mine burial depths from the data obtained in the study is an example of the application and use of “analoges” (sediment types and environments of deposition) to mine burial prediction. The technique was applied to the lower part of the Chesapeake Bay and also empirical equations for predicting mine depth of burial were developed for areas offshore Korea based on the Atterberg limits and natural water contents.

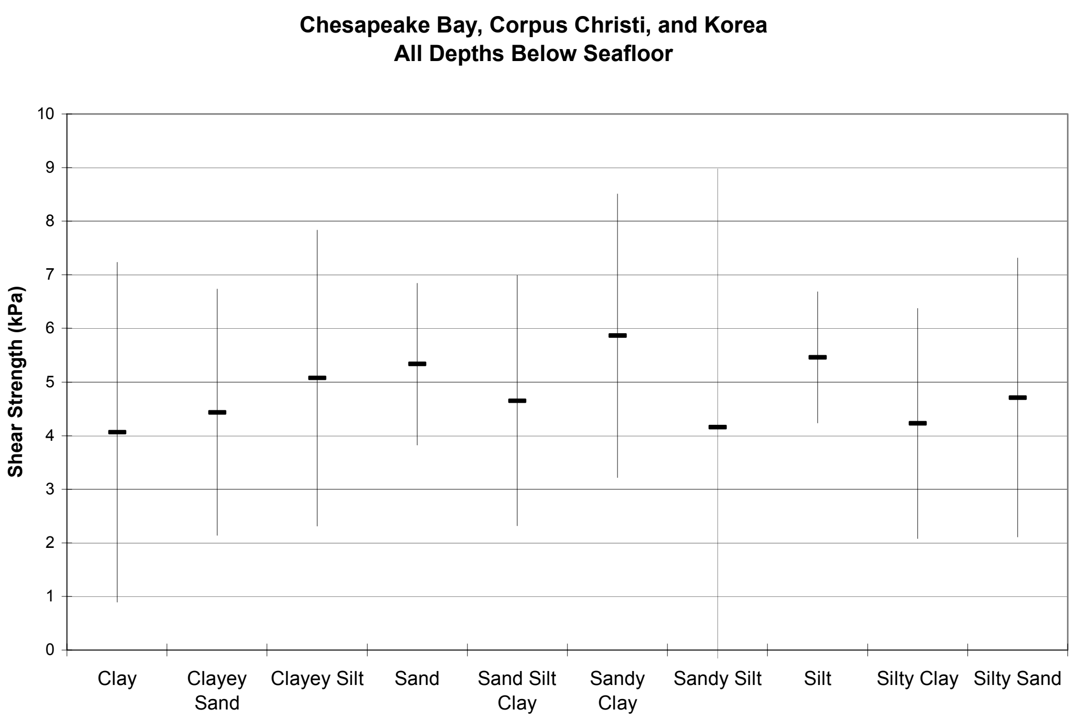

Figure 1. Chesapeake Bay, Corpus, and Korea undrained shear strengths by the Shepard (1954) sediment classes (average values and standard deviations).

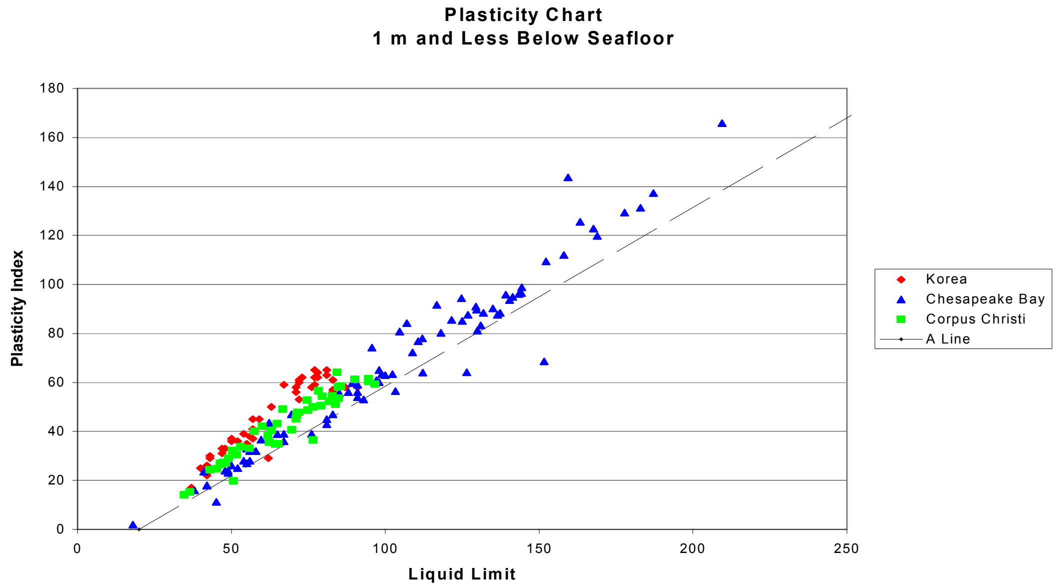

Figure 2. Plasticity Chart for Chesapeake Bay, Corpus Christi, and Korea. Liquid limit versus Plasticity index clearly depicts the differences in the sediments and thus differences in the depositional environments.

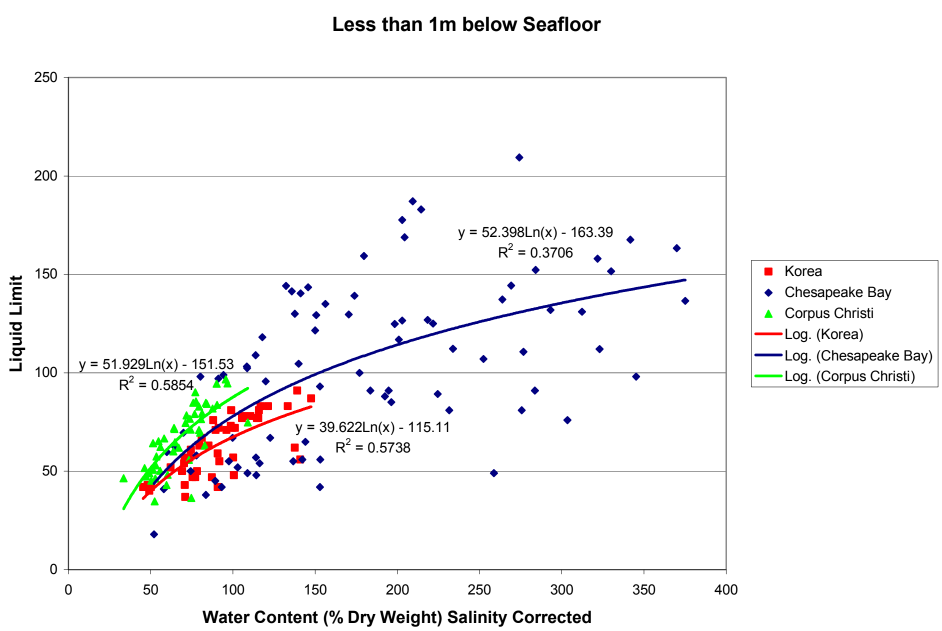

Figure 3. Liquid limit versus water content clearly depicts differences in the sediments and thus differences in the depositional environments.

Data analysis of Chesapeake Bay, Korea, and offshore Corpus Christi, reveal that environments of deposition can be differentiated based on the Atterberg limits, water content, and other physical properties. The study clearly revealed that coastal sediments can be typed using selected geotechnical properties (Bennett et al., 2004). Mine burial depths can be predicted (independent of undrained shear strength measurements) based on the water content and the liquid limit and appear to be unique to the depositional environment. An initial demonstration including a technical background and methodology using geotechnical properties, sediment characteristics, and basic principles of sediment physics to predict minimum depths of mine

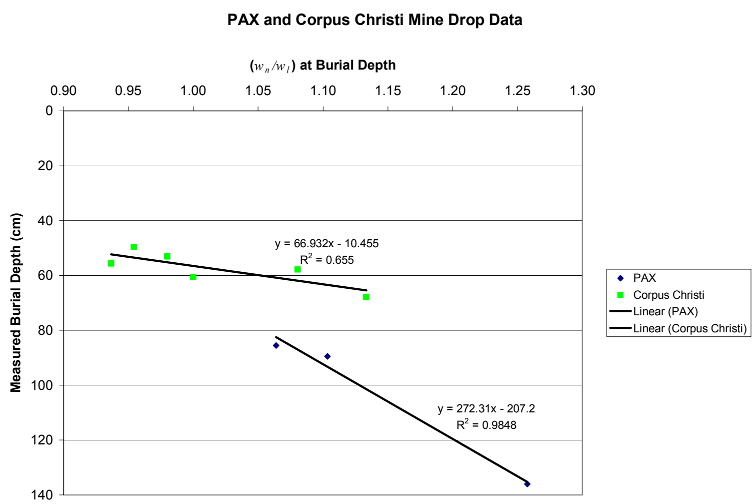

Figure 4. Measured mine burial depths versus the ratio of w_n/w_l for PAX (Chesapeake Bay) and offshore Corpus Christi mine drop sites. Data are taken from water content and liquid limit profiles at the mine drop sites. Note significant difference in burial depths for the different depositional environments.

burial has provided new concepts, techniques, and methods to ONR and NAVO in an initial FY-04 study (Bennett et al., 2004). As demonstrated, mine burial prediction maps and empirical equations can be developed using the geotechnical properties of coastal marine muds independent of sediment undrained shear strength.

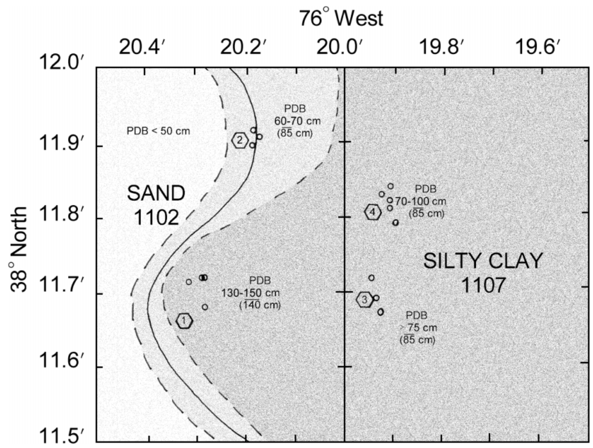

Figure 5. Mine burial test site at Chesapeake Bay near the Patuxent Naval Air Station. Predicted depths of mine burial (PDB) based on water contents and liquid limits compared with actual field tests of buried mines (average depth of burial in parenthesis). Penetration depths measured by divers.

IMPACT/APPLICATIONS

Because sediment shear strength is not readily available in many instances, the MBESM requires technical procedures for incorporating "proxy" shear strengths based upon sediment properties such as grain size, organic matter content, water content, Atterberg limits, etc. from which estimates are made, utilizing the Master Database, to obtain reliable shear strength estimates. Thus, environments of deposition, geography, mineralogy, grain size, and statistical analysis of other geotechnical and sediment parameters can lead to a "robust" generalized shear strength prediction when no real strength data are available. This can only be accomplished, with confidence, through the development of the Master Database for coastal sediments. The Master Database includes, but is not limited to, geotechnical properties such as shear strength, sediment grain size, wet bulk density, and sediment classifications of sediment types including the Atterberg limits. Inasmuch as sediment geotechnical properties data are not available for all coastal areas of the world, it was necessary to develop analoges (type areas) for predicting sediment properties and mine burial in remote areas of the world. Thus, an ongoing thrust of the effort is the correlation/association of sediment properties and environments of deposition with the engineering/geotechnical sediment properties characteristic of the coastal environments.

TRANSITIONS

The Mine Burial Expert System Model (MBESM) will be ultimately transitioned to the Naval Oceanographic Office (NAVO) in support of the Operational Navy. The MBESM runs on IMPACT28 utilizing the critical parameter of shear strength and other sediment properties provided by the SEAPROBE Master Database. Coastal sedimentary environments must be statistically characterized in terms of a suite of "key" sediment properties with appropriate statistics. These properties can then be used for predicting mine burial by the MBESM using the impact burial model IMPACT28 and other developing techniques, such as sediment state as described herein. These databases are essential to developing mine burial prediction maps, which is a longer-term goal in support of the U.S. Navy.

Extending the mine burial predictive capabilities based on sediment geotechnical properties and sediment physics will greatly enhance the cost effectiveness and past investment committed to developing NAVO surficial sediment maps produced for several years.

RELATED PROJECTS

The basic and applied research supports the ONR mine burial prediction science program and the NAVO strategic forward effort in mine burial prediction and mapping for the Operational Navy and the recommended U.S. Navy operational needs identified in earlier studies and ONR workshops (Bennett et al., 1999a, 2000a and b, and 2001). Extending the mine burial predictive capabilities based on sediment geotechnical properties and sediment physics will greatly enhance the cost effectiveness and past investment committed to developing NAVO surficial sediment maps produced for several years. Specifically, the research results can be used for predicting mine burial by the MBESM using the impact burial model IMPACT28 and other developing techniques, such as sediment state as described herein.

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