Experimental and Analytical Investigation of Mine Burial Penetration

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Grant Number N00014-01-1-0367, P00001

LONG TERM GOALS

A comprehensive treatment of the geotechnical aspects of mine burial in cohesive sediments includes characterizing the sediment strength properties, developing and validating an impact burial model, and predicting post-impact settlement. The research in the past two years focused on the second item, developing and validating an impact burial model.

OBJECTIVES

This research was undertaken to develop a practical model for predicting mine impact burial in cohesive sediments and to calibrate the model with laboratory experiments. Inputs to the model include the velocity of the mine at impact, the weight and dimensions of the mine, and the sediment strength properties.

APPROACH

The subject study involves parallel analytical and experimental studies of mine penetration in cohesive seafloor sediments as follows:

- Model tests in a laboratory test basin of mines penetrating in actual (Gulf of Mexico) seafloor sediments.
- Numerical modeling of the mine penetration process.
- After calibration of the numerical model to the test measurements, a simplified model will be proposed for use in practice.

In addition, two research cruises were conducted, one to evaluate sediment properties in a potential mine drop area and a later cruise to conduct mine drop experiments.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Experimental and Analytical Investigation of Mine Burial Penetration**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Civil Engineering Department,,Texas A&M University,,College Station,,TX,77843**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

The analytical studies during the past year were directed toward two areas: developing a function of soil resistance to mine penetration as a function of penetration depth, and developing a simplified model for mine penetration as a function of soil resistance, impact velocity, and the mine weight and dimensions. The major focus of these studies was for cases with the long axis of the mine oriented horizontally. Consideration of mines impacting the seafloor at inclined angles is the subject of a proposed extension to this research.

Experiments have been conducted in a sediment-filled test tank to determine mine penetration characteristics into sediment obtained from the mine drop site off Corpus Christi TX. Sediment was obtained from the site in May 2001, processed to remove foreign matter and to obtain the desired shear strength and placed in a 6-ft diameter by 4-ft deep test tank. A roughly1/3 scale mine was mounted in a support mechanism which was placed on top of the test tank. A cylindrical rod attached to the model mine passes through nearly frictionless ball bushings to guide the mine during penetration. The weight of the mine can be controlled by placing weights on a platform at the top of the rod. To ensure uniformity of the sediment, it is mixed after each test, the surface is leveled then covered and allowed to rest for 24 hours to obtain any thixotropic strength regain before a new test is performed. Immediately after each test, shear strength measurements are made with a hand held vane shear device, and several moisture content samples are taken for a later comparison of shear strength versus moisture content for this sediment.

Two research cruises were conducted, the first in October 2001 to evaluate sediments in a potential mine drop area (Echo 2) off the coast of Corpus Christi, TX, and the second in May 2002 to conduct mine drops in the same area. The platform for both cruises was the R/V Gyre. Although bad weather hampered both cruises, most of the objectives were completed.

Mine drop experiments using NRL's instrumented mine were conducted during the May 2002 cruise. In addition to the instrumented mine tests, some inert mines were dropped and recovered several days later to evaluate the effect of creep on long term mine burial. NRL supplied several participants including divers to recover the mines and others to deploy STING penetrometers; Lamont-Doherty sent personnel to conduct shear strength measurements using the Stat-Pen, PROBOS and XBP, Texas A&M personnel recovered cores which were divided equally with NRL for subsequent testing. Dr. Roy Wilkens, University of Hawaii/ONR also participated. Measurements to date on the TAMU cores have been disseminated to the participants. All measurements by TAMU will be completed by the end of September.

RESULTS

Sediment Resistance Function

A fundamental input into the mine impact penetration model is the bearing factor relating the sediment shear strength to the bearing pressure resisting mine penetration. The bearing factor N_p can be expressed in a number of ways; in this study the following definition is used:

$$N_p = F / S_u L d \qquad \text{Eq. 1}$$

where F is the total soil resistance acting on the mine, S_u is the sediment undrained shear strength, d is the mine diameter, and L is the length of the mine. In general, the bearing resistance factor will be a function of the mine shape, mine inclination, and the degree of penetration of the mine into the sediment.

Since the field and experimental portions of this project mainly consider long, circular cylinders, the analytical studies focused on this mine shape. Analytically this shape can be approximated using two-dimensional plane strain analyses that model the mine as a circular cylinder that extends indefinitely into the third dimension. This approach of course neglects end effects and will accordingly tend to underestimate the resistance of the sediment to mine penetration. To establish an upper bound for the magnitude of the end effects, a series of analyses were also performed for a 'short' mine; i.e., a spherical mine. For this extreme case, neglecting end effects results in an underestimate of sediment resistance of about 20 percent for the range of penetrations h/d most relevant to this study. However, for the relatively long mines under consideration the end effects are likely to be much smaller. When considering the uncertainties of the chief input parameters to the mine penetration model, namely the sediment shear strength and the mine impact velocity, extensive numerical studies to further evaluate the end effects does not appear justified at this time.

Mine inclination, or the angle of the cylindrical axis of the mine from horizontal when it impacts the seafloor, is likely to be a significant factor affecting the resistance of the sediment to mine penetration. However, investigating this affect was not part of the original scope of the project. A proposal for extending this research to evaluate this effect has been submitted to ONR by the authors of this report.

The degree of penetration of the mine will have a very significant influence on the sediment resistance and therefore the ultimate total amount of mine burial penetration. The degree of penetration can be conveniently expressed as a dimensionless ratio, h/d, where h is the penetration distance and d is the mine diameter. In principle, the bearing factor N_p will be influenced by the strain history of the soil as the mine penetrates the sediment. Again, in the interest of developing a simplified model, this effect was neglected in the analytical studies and the instantaneous sediment resistance at a given degree of penetration h/d was taken as the collapse load for a pre-embedded mine.

Two analytical tools were utilized for computing collapse load: plastic limit solutions and finite element analyses. The plastic limit solutions have the advantage that sediment resistance can be estimated from either closed form equations or relatively straightforward numerical schemes; hence, they can be used as reference solutions to validate the accuracy of finite element analyses. The finite element analyses of course have the advantage that they can model a higher level of complexity than the plastic limit solutions. Example finite element solutions are shown in Figure 1, showing the predicted bearing factor N_p as a function of penetration h/d for cylindrical and spherical mines. Comparisons to the plastic limit solutions indicated that the finite element solutions tended to over-predict the reference values by about 7 percent, so the curves shown in Figure 1a should be adjusted downward by about this amount.

The finite element results shown in Figure 1a were based on the assumption that sediment falls in around the back of the mine during deeper penetration; i.e., h/d greater than one-half. However, the experiments tended to show that an open trench forms behind the penetrating mine. In view of this experimental observation, new series of finite element analyses are being performed assuming that an open trench forms behind the mine.

Impact Penetration Model

With the sediment resistance fully defined as a function of penetration depth h/d, mine penetration for a given impact velocity can be predicted using simple equations of dynamic equilibrium and kinematics for a single particle; i.e., W – F = ma, where W is the mine weight, F is the sediment resistance from Figure 1 and Eq. 1, m is the mine mass, and a is the instantaneous acceleration. The acceleration term from this dynamic equilibrium equation can be numerically integrated to obtain the velocity v and penetration h. An example of the outcome of this procedure is shown in Figure 1b. To apply to as wide a range of conditions as possible, the graph in Figure 1b is presented in terms of the following dimensionless parameters:

Soil strength ratio: $S_u L d / W$

Normalized penetration: h/d

Impact velocity ratio: $v_0 / (gd)^{1/2}$

The parameters comprising the impact velocity ratio are the impact velocity v_0, gravitational acceleration g, and mine diameter d.

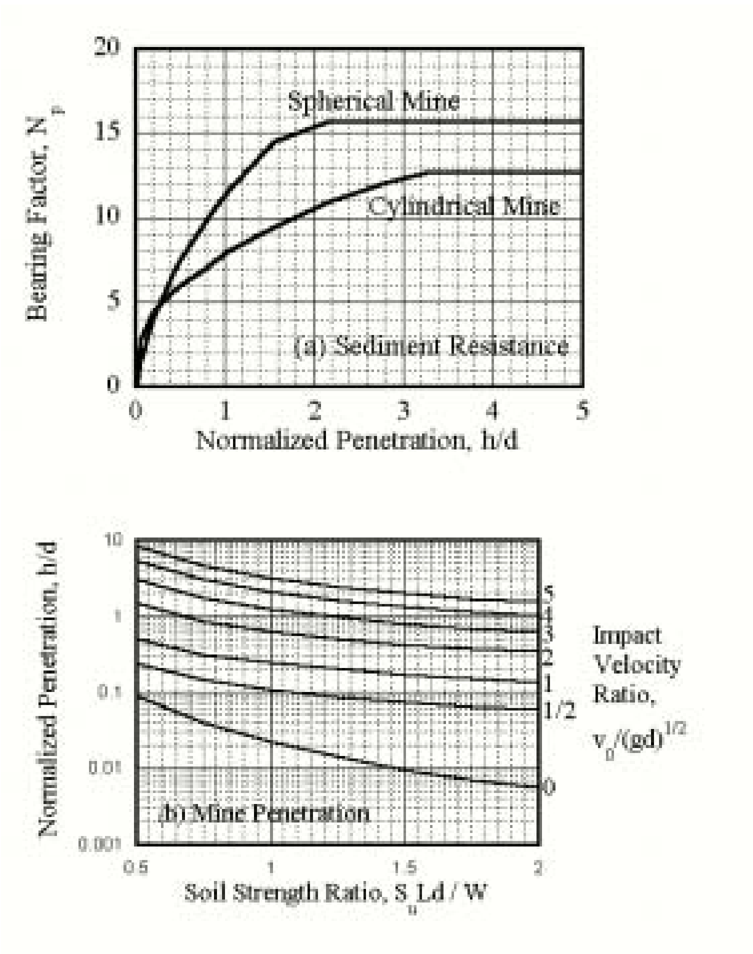

Figure 1. Summary of Analytical Studies

Experimental Results

Two sets of tests have been completed. The first consisted of a series of static tests in which the mine penetrated the sediment after initial placement at the mudline. Three different mine weights were used to encompass a range of actual mine specific gravities. Three different angles of inclination were used: parallel to the sediment surface and at angles of 10 and 20 degrees to the surface. The primary purpose of these tests was to calibrate the ongoing theoretical developments. Initially, penetration data were taken for about one hour after release of the mine. Plots of penetration versus time showed that mine penetration could be significant even after one hour. Subsequent tests were continued for 24 hours at which time penetration had either ceased or slowed significantly. For lack of a better term, these movements have been called creep, although it is realized that they may be at least partially due to consolidation of the sediment under the weight of the mine. Anecdotal evidence of creep in the field has been obtained from personnel involved in mine drop exercises, thus validating the measurements in the test tank.

The static tests were followed by a series of dynamic tests in which the mine was allowed to free fall into the sediment, although the mine was still guided by the attached rod. This approach allowed the mine orientation to be controlled as it was in the static tests. Mine penetration was measured with a displacement transducer and recorded by a National Instruments A-D converter which could record up to 1000 data points per second. With the present arrangement, impact velocities of approximately 2 m/s can be obtained. Although this is slower than has been obtained in the field experiments conducted by NRL, the difference is not considered important since the main purpose of the experiments again is to calibrate the theoretical developments. Example penetration results are summarized in Table 1.

Table 1. Experimental Mine Penetration Measurements

Mine Weight (lbs)	Impact Velocity (inch/sec)	Orientation from Horizontal (degrees)	Penetration (inches)
63.03	59.14	0	2.447
102.63	70.081	0	7.14
168.63	70.459	0	9.286
63.03	66.41	10	4.575
102.63	68.7	10	8.23
168.63	67.69	10	9.282
63.03	55.644	20	7.374
102.63	68.15	20	8.629
168.63	62.21	20	13.72

IMPACT/APPLICATIONS

When the numerical and experimental results are completed and compared, the results will be suitable for a wide range of applications involving the penetration of many types and shapes of objects into soft sediments. It is likely that the method of using these results will be fairly complicated for Fleet use, however. Consequently, the final results will be simplified within reason and placed either in a series of graphs or else a computer program such as a simple spread sheet which will be suitable for calculating impact burial of mine shapes. More complicated shapes will require a more detailed analysis but should fall within the framework of the present study.

TRANSITIONS

It is still too early in the program for the numerical and experimental results to be utilized by others in the impact burial research group. The results of tests on cores taken during the May 2002 cruise have been and will continue to be used by others involved in analyzing the results of mine drops during this cruise.

RELATED PROJECTS

The instrumented mine drop experiments conducted by NRL and their studies on the validity of the IMPACT28 program are closely related to the research reported herein.