FINAL REPORT

Modeling of Sediment Mechanics for Mine Burial Prediction

Prepared for:

Office of Naval Research
Mine Burial Prediction Program
Code 321
Award No. N00014001-1-0513

Horst G. Brandes
H. Ronald Riggs

UNIVERSITY OF HAWAII
COLLEGE OF ENGINEERING
Department of Civil and Environmental Engineering

December 2004

AWARD/ MODIFICATION

3a. ISSUED BY:
OFFICE OF NAVAL RESEARCH
BALLSTON CENTRE TOWER ONE
800 NORTH QUINCY STREET
ARLINGTON VA 22217-5660

1. INSTRUMENT TYPE: Grant
3b. CFDA: 12.300
2. AUTHORITY: 10 USC 2358, 31 USC 6304
3c. DUNS NUMBER:

4. AWARD NO.:	5. MODIFICATION NO.:	6. MODIFICATION TYPE:	7. PR NO.:	PAGE
N00014-01-1-0513	P00002	Increment	02PR03389-00	1 of 5

8. ACTIVITY/AGENCY PROPOSAL NO.:	9. RECIPIENT PROPOSAL NO.:	10. PROPOSAL DATE:	11. ACTIVITY TYPE:	12. PROGRAM TYPE:
N/A	N/A	Undated	Research	N/A

13. ISSUED TO
13a. ADDRESS:
UNIVERSITY OF HAWAII
2530 DOLE STREET SAKAMAKI HALL D 200
HONOLULU, HI 96822

13b. CAGE: 0W411
13c. EDI/EFT NUMBER: 1152AB
13d. BUSINESS OFFICE CONTACT:
13e. TELEPHONE NUMBER:
13f. EMAIL ADDRESS:

14. REMITTANCE ADDRESS (IF DIFFERENT FROM BLOCK 13):
Same as block #13

15. RESEARCH TITLE AND/OR DESCRIPTION OF PROJECT AND/OR PROPOSAL TITLE:
Modeling of Sediment Mechanics for Mine Burial Prediction

16. FUNDING	ACTIVITY/AGENCY SHARE	RECIPIENT SHARE	TOTAL
PREVIOUSLY OBLIGATED:	$91,656.00	$.00	$91,656.00
OBLIGATED BY THIS ACTION:	$92,511.00	$.00	$92,511.00
TOTAL OBLIGATED ON AWARD:	$184,167.00	$.00	$184,167.00
FUTURE FUNDING:	$.00	$.00	$.00
GRANT TOTAL:	$184,167.00	$.00	$184,167.00

17. CURRENT FUNDING PERIOD
N/A
THROUGH
N/A

18. PERIOD OF PERFORMANCE
01-FEB-2001
THROUGH
31-JAN-2003

19. ACCOUNTING AND APPROPRIATION DATA:
See attached Financial Accounting Data Sheet(s)

20a. PRINCIPAL INVESTIGATOR/RECIPIENT TECHNICAL REPRESENTATIVE:
(PI) Horst G. Brandes
20b. TELEPHONE NUMBER: (808) 9568689
20c. EMAIL ADDRESS:

21. TECHNICAL REPRESENTATIVE
21a. NAME: Dawn Lavoie
21b. CODE: ONR 322GG
21c. ADDRESS:
OFFICE OF NAVAL RESEARCH
BALLSTON CENTRE TOWER ONE
800 NORTH QUINCY STREET
ARLINGTON VA 22217-5660
21d. TELEPHONE NUMBER: (703) 6964070
21e. EMAIL ADDRESS: lavoied@onr.navy.mil

22. AWARDING OFFICE CONTACT
22a. NAME: Diane Gales
22b. CODE: ONR 252
22c. ADDRESS:
OFFICE OF NAVAL RESEARCH
BALLSTON CENTRE TOWER ONE
800 NORTH QUINCY STREET
ARLINGTON VA 22217-5660
22d. TELEPHONE NUMBER: (703) 6962595
22e. EMAIL ADDRESS: galesd@onr.navy.mil

23a. ADMINISTRATIVE OFFICE:
OFFICE OF NAVAL RESEARCH REGIONAL OFFICE SEATTLE
1107 NE 45TH STREET SUITE 350
SEATTLE WA 98105-4631
Fax: (206) 5263210
23b. CODE: N63374

24. SUBMIT PAYMENT REQUEST TO:
Same as block #23a

25a. PAYING OFFICE:
DFAS CHARLESTON, SC
25b. CODE: N68892

26a. PATENT OFFICE:
OFFICE OF NAVAL RESEARCH
ATTN: ONR 00CC
BALLSTON CENTRE TOWER ONE
800 NORTH QUINCY STREET
ARLINGTON VA 22217-5660
26b. CODE: N00014

AWARD NO.	AWARD/MODIFICATION	MODIFICATION NO.	PAGE
N00014-01-1-0513		P00002	2 of 5

27. SPECIAL INSTRUCTIONS:

28. DELEGATIONS: The administration duties listed below have been delegated to the administrative office (block 23a). Upon request the awarding office contact (block 22) will make their full text available. Please direct questions to the contacts @: http://www.onr.navy.mil/02/024/offices.htm

Full Delegation

29. TERMS AND CONDITIONS: The following terms and conditions are incorporated herein by reference with the same force and effect as if they were given in full text. Upon request the awarding office contact named in block 22 will make their full text available, or they can be found at the specified URL.

DOCUMENT	URL	CLAUSES

30. OPTIONS OPTION NO. AMOUNT PERIOD

(1)
(2)
(3)
(4)

31. REPORTS: The following reports must be submitted to the indicated addressees, in the indicated quantities, within 90 days following the expiration or termination of the project, Final Technical Reports must have a SF298, Report Documentation Page, accompanying them. Unless otherwise stated in the award/modification, complete Block 12a of the SF298 as follows: "Approved for Public Release; distribution is Unlimited".

ADDRESSEE	REPORT TYPE	COPIES
See block #21 (Frequency)	Performance/Technical Report (As Required) w/ SF298	1
See block #23a	Report of Inventions and Subcontracts - DD 882 Performance/Technical Report (As Required) Final Financial Status Report - SF269A - If advances used	1 1 1
See block #26a	Report of Inventions and Subcontracts - DD 882	1
DEFENSE TECHNICAL INFORMATION CENTER 8725 JOHN J KINGMAN ROAD STE 0944 FORT BELVOIR VA 22060-6218	Performance/Technical Report (As Required) w/ SF298	1
NAVAL RESEARCH LABORATORY ATTN: CODE 5227 4555 OVERLOOK AVENUE SW WASHINGTON DC 20375-5320	Performance/Technical Report (As Required) w/ SF298	1

32. FOR THE RECIPIENT		33. FOR THE UNITED STATES OF AMERICA	
32a. SIGNATURE OF PERSON AUTHORIZED TO SIGN N/A - SIGNATURE NOT REQUIRED ON THIS AWARD		33a. SIGNATURE OF AWARDING OFFICER Diane Gales	
32b. NAME AND TITLE OF SIGNER	32c. DATE SIGNED	33b. NAME AND TITLE OF AWARD OFFICER Diane Gales	33c. DATE SIGNED 04-JAN-2002

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
6/12/2004	Final research report	2/1/2001 - 7/31/2004

4. TITLE AND SUBTITLE
Modeling of sediment mechanics for mine burial prediction

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-01-1-0513

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Brandes, Horst G.
Riggs, H. Ronald

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Hawaii
2530 Dole St.
Sakamaki Hall, D-200
Honolulu, HI 96822

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Ballstone Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Numerical model development and testing were carried out for the purpose of assessing the influence of seafloor liquefaction on the burial of mines in shallow water due to cyclic loading by surface water waves. This project was conducted as part of the Office of Naval Research Mine Burial Prediction program (Code 321).

15. SUBJECT TERMS
Seabed liquefaction, mine burial, sediment constitutive modeling, numerical analysis, cyclic soil testing

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU		Brandes, Horst G.
					19b. TELEPHONE NUMBER *(Include area code)* 808-956-8969

OBJECTIVES

This study was part of the first phase of ONR's Mine Burial Prediction program (Coastal Geosciences, Code 321). The original objectives of this study were to:

- Develop a numerical procedure for modeling mine burial as a time-dependent process with a focus on sub-seabed liquefaction and sediment mechanics.
- Collect necessary material parameters, including pore pressure generation characteristics under cyclic loading conditions, from planned field and laboratory tests.
- Integrate findings from this study with parallel modeling efforts underway as part of ONR's Mine Burial Program (MBP), which is investigating burial processes due to bedform migration and local scour.

Funding for the project was terminated after the first two years of an anticipated 5-year program due to a drastic reduction in funds for the overall Mine Burial Prediction program, requiring that some projects be dropped. Therefore, substantial progress was only achieved on the first objective and the laboratory component of the second one. No major field experiments had been completed by the time funding for this project was ended.

OUTCOMES

1. ***Research.***
   A methodology and an associate numerical code (MINE-B) were developed for the analysis of liquefaction in shallow sediments due to cyclic loading by surface water waves. In addition, a laboratory testing program was conducted on specimens collected from the Tampa Bay experiment site to develop a more accurate non-linear cyclic stress-strain model for use in MINE-B or other similar numerical codes. Scientific achievements are described in the publications listed below and more recent findings are highlighted in this report.

2. ***Publications & Conference Presentations.***
   Brandes, H.G. and Riggs, H.R. (2002a). Modeling of seabed liquefaction and other processes responsible for mine burial. *Proceedings of OMAE'02, 21st International Conference on Offshore Mechanics and Arctic Engineering*, OMAE2002-28242, pp. 1-8.

   Brandes, H.G. and Riggs, H.R. (2002b). Numerical modeling of seabed liquefaction due to surface water waves. *Proceedings of the 12th International Offshore and Polar Engineering Conference*, 2:558-562.

   Brandes, H.G., Seidman, J. & Wang, S. (2005). Cyclic simple shear testing and modeling of two calcareous sediments. *15th International Offshore and Polar Engineering Conference, Seoul, Korea, June 19-24.*

3. ***Students.***
   Shentang Wang – Ph.D. Programming and constitutive modeling. Mr. Wang is expected to complete his dissertation work in 2005. Title: *OpenSees model development for static and cyclic soil-structure interaction modeling.*

Jason Seidman – B.S. Assisted with equipment development and laboratory testing of field specimens. Mr. Seidman is expected to continue with graduate studies upon graduation in 2005.

4. ***Equipment.***
A direct simple shear system was acquired with funds from this project and a matching contribution from the University of Hawaii. This major piece of instrumentation enabled us to carry out cyclic laboratory tests to simulate loading from surface water waves. Results from these tests are presented by Brandes et al. (2005) and are briefly discussed in this report. The equipment adds a unique state-of-the-art laboratory testing capability to the geotechnical laboratory at the University of Hawaii. It continues to be used extensively.

5. **Research Meetings & Presentations.**
ONR Mine Burial Meeting, March 5, 2002 – Phoenix.

2nd Annual ONR Mine Burial Prediction Workshop, January 15-17, 2002 – San Diego.

Coastal Processes Driving Mine Burial Workshop, January 30-February 1, 2001 – St. Petersburg.

NUMERICAL AND CONSTITUTIVE MODELING

A finite element code based on Biot's physically consistent theory of consolidation for poro-elastic media was developed in an effort to predict time-dependent mine burial due to the effects of surface water wave propagation. Initially, a linear elastic constitutive sediment model was implemented for comparison of 2D stress and strain predictions with closed form solutions (Yamamoto et al., 1978; Madsen, 1978). A simple case study was selected for this purpose. It consisted of a uniform seabed of linearly elastic sand with a single sinusoidal surface water wave propagating along the sea surface. Linear wave theory was assumed. Predictions obtained with MINE-B for a level seabed agree quite well with theory (Figures 1-2; Brandes & Riggs, 2002).

Although this problem is overly simplistic, it does allow for model verification and can be used for preparing preliminary liquefaction charts for estimating the extent of momentary liquefaction as a function of water depth and wave characteristics. The depth to which liquefaction is predicted may correlate with mine burial, since by definition a liquefied seabed cannot support any object whose weight is larger than that of the sediment. An example of such a chart is shown in Figure 3, which can be used to predict the depth of momentary liquefaction below the seabed that occurs under the crest of single linear waves. The conventional criteria for the onset of liquefaction proposed by Seed and Lee (1966) is used here:

$$\frac{p}{\gamma' z} \geq 1.0 \qquad (1)$$

In other words, this criteria assumes that liquefaction will occur when the ratio of excess pore pressure p exceeds the effective overburden stress $\gamma' z$. Here we have assumed that γ'=10 kN/m^3 and z is the distance below seabed.

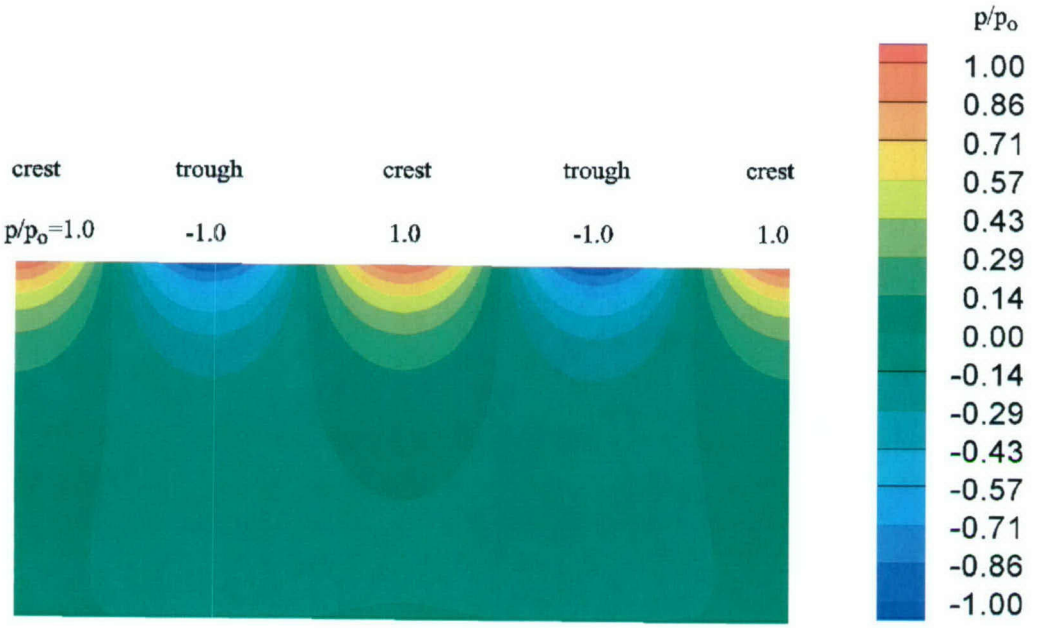

Figure 1. Excess pore pressure in 2-D seabed deposit after 150 wave cycles (wave length=48 m, period=6 seconds, wave amplitude=2.4 m)

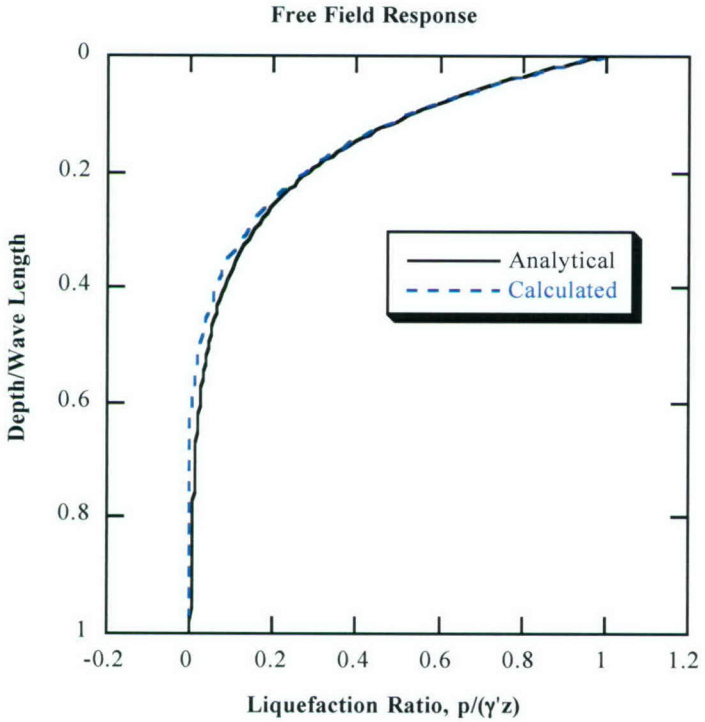

Figure 2. Calculated versus predicted pore pressure ratio below crest of wave.

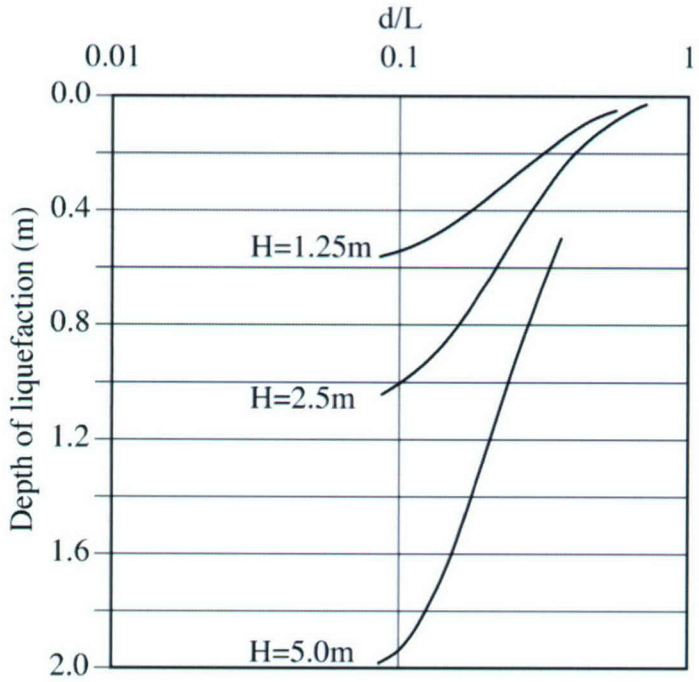

Figure 3. Predicted depth of liquefaction below seabed for single, linear surface wave (d=water depth, L=wave length, H=wave height. Period T is given by linear wave theory).

A linear elastic constitutive model is not adequate when strains and stresses induced in the seabed exceed a certain level and the material begins behaving in a non-linear and irreversible, i.e plastic, fashion. In order to account for such effects, work was begun on implementing a more robust non-linear cyclic constitutive model (Brandes and Wang, 2004). This model takes into account gradual stiffness and strength degradation with repetitive cycles of loading and allows for pore pressure dissipation due to pore fluid diffusion. An example of cyclic shear stress and pore pressure predictions using this model is shown in Figure 4. It is clearly seen that liquefaction develops near the end of the test, resulting in very large strains and hence failure. The computations used a set of reasonable but assumed material parameters. In order to adapt the model for use with sediments from the field, a laboratory testing program was conducted on specimens from the Tampa Bay field experiment site. This is discussed in the next section.

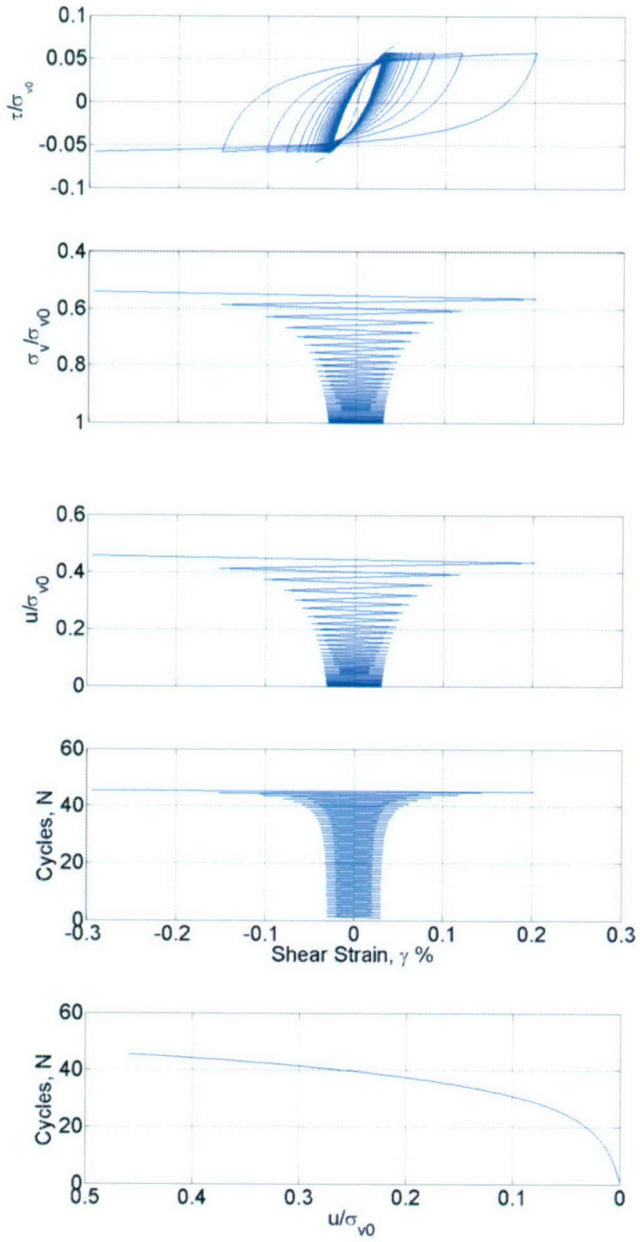

Figure 4. Model predictions of cyclic shear behavior.

LABORATORY TESTING

The laboratory testing program was designed to provide material parameters for the constitutive model. It was conducted on fine carbonate sand collected during the Mine Burial program's Tampa Bay field experiment. A summary of tests conducted to date is shown Table 1 and further details on results and analysis are given in Brandes et al. (2005). An example of the shear stress-strain response is illustrated in Figure 5. Note the stiffness degradation that occurs as the test progresses, much as the model predicts (Figure 4, top graph). One important difference between model and test results is that permanent shear strains accumulate toward the end of the test as the material approaches liquefaction.

It is therefore evident that the constitutive model needs to be modified to allow for irreversible deformations. On the other hand, the model predictions in Figure 4 do account for the dual stiffening and softening behavior within a single cycle that are apparent toward the end of the test.

Bender elements were used during testing to determine stiffness at very low strains, which complement the stiffness data at larger strains from the cyclic testing. An example of the results is shown in Figure 6 and more details are presented in Brandes et al. (2005).

Table 1. Cyclic simple shear test program

Test designation	Normal stress (kPa)	Density (gm/cm^3)	Cyclic stress amplitude (kPa)
SS-TB-LD-1	86	1.47	11.4
SS-TB-LD-2	143	1.46	11.4
SS-TB-LD-3	200	1.39	11.4
SS-TB-LD-4	257	1.40	11.4
SS-TB-HD-1	86	1.76	11.4
SS-TB-HD-2	143	1.79	11.4
SS-TB-HD-3	200	1.73	11.4
SS-TB-HD-4	257	1.66	11.4

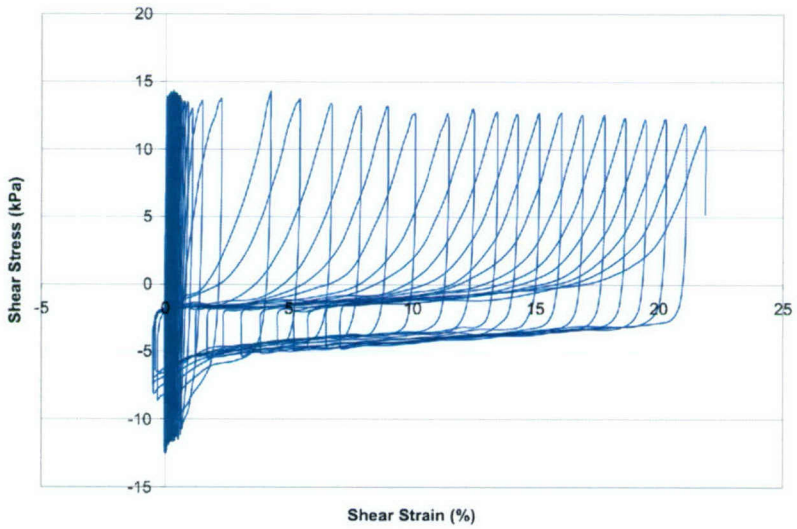

Figure 5. Cyclic stress-strain behavior for test SS-TB-HD-4.

SUMMARY

Significant progress has been made in understanding the cyclic stress-strain behavior of granular calcareous sediments through laboratory testing to guide the development of an appropriate constitutive model. A specific model has been developed to the point where it is now ready for implementation in a numerical code. Once this is achieved, burial of objects into the seafloor can be computed in the conventional way by creating 2D or 3D mine-seabed finite element geometries and conducting a time-dependent analysis.

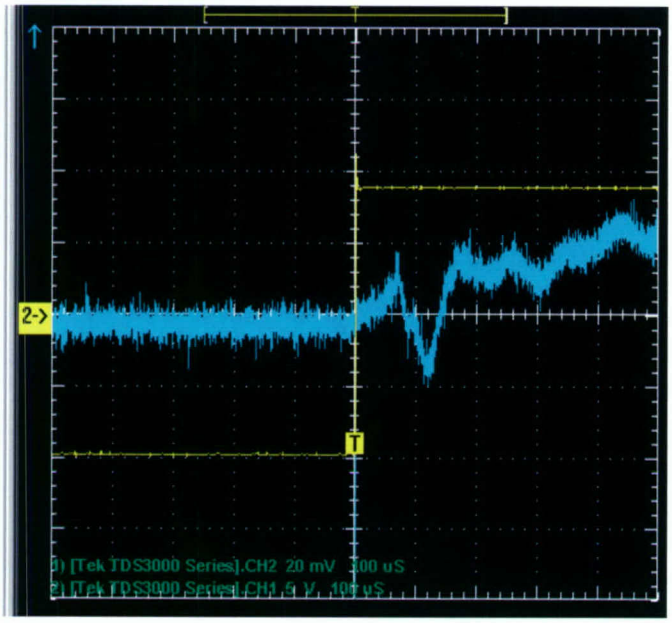

Figure 6. Shear wave measurement using bender elements. Test SS-TB-HD-4.

REFERENCES

Brandes, H.G., Seidman, J. & Wang, S. (2005). Cyclic simple shear testing and modeling of two calcareous sediments. *15th International Offshore and Polar Engineering Conference, Seoul, Korea, June 19-24.*

Brandes, H.G. and Wang, S. (2004). Failure and post-failure mechanics of submarine landslides. *Proceedings, 23rd International Conference on Offshore Mechanics and Arctic Engineering*, OMAE 2004-51141, pp. 1-8.

Brandes, H. G. and Riggs, H.R. (2002). Modeling of seabed liquefaction and other processes responsible for mine burial. *Proceedings of OMAE'02, 21st International Conference on Offshore Mechanics and Arctic Engineering*, OMAE2002-28242, pp. 1-8.

Madsen, O. S. (1978). Wave-induced pore pressures and effective stresses in a porous bed. *Geotechnique*, 28(4):377-393.

Seed, H. B. and Lee, K. L. (1966). Liquefaction of saturated sands during cyclic loading. *Journal of the Soil Mechanics and Foundations Division, ASCE*, 92(SM6):105-134.

Yamamoto, T., Koning, H. L. and Hijum, E. V. (1978). On the response of a poro-elastic bed to water waves. *Journal of Fluid Mechanics*, 87(1):193-206.