Seabed-Structure Interaction

Workshop Report and Recommendations for Future Research

Convened in Metairie, LA November 5-6, 1991

February 1992

PR 92:016:360

In Support of the Coastal Benthic Boundary Layer Special Research Project

Workshop Organizers:

Richard H. Bennett
Seafloor Geosciences Division
Ocean Science Directorate

Wayne A. Dunlap
Offshore Technology Research Center
College Station, TX 77845-3400

Homa J. Lee
USGS Branch Pac. Mar. Geol.
Menlo Park, CA 94025

Technical Group Chairmen:

James R. Hooper
Fugro-McClelland Engineers
Houston, TX 77274

Steven A. Hughes
U.S. Army CORPS CERC WES
Vicksburg, MS 39180

Sponsored by:
Naval Oceanographic and Atmospheric Research Laboratory
and
Naval Research Laboratory

Under the general guidance of:
The Office of Naval Research

ACKNOWLEDGMENTS

This workshop was supported by the Naval Research Laboratory, under Program Element 0601153N, Miriam Oliver, Program Manager. The organizers of the workshop express their appreciation to Dr. Michael Richardson, Chief Scientist for the Coastal Benthic Boundary Layer Special Research Project, for his support and encouragement during the development of the workshop and compilation of this report. We appreciate the contributions and efforts of all the workshop attendees. The organizers are grateful for the critical reviews of a draft copy of this report by Dr. Robert Dalrymple, Dr. Donelson Wright, Dr. William R. Dally, and Dr. Keith Bedford. We appreciate the efforts of Lee Nastav for the computer development of the figures used in this report. We also appreciate the initial typing and assistance by Phyllis Cruthird and Mary Simmons, and editorial and graphics assistance provided by Code 125.

SEABED-STRUCTURE INTERACTION

CONTENTS **PAGE**

SUMMARY OF RECOMMENDED RESEARCH THRUSTS

SEABED-STRUCTURE INTERACTION
COASTAL BENTHIC BOUNDARY LAYER SPECIAL RESEARCH PROJECT

Intrinsic to the topic of Seabed-Structure Interaction (S-SI) of objects coupled with the sea floor is the dynamics of the "system." The dynamic process include environmental forcing of the object and the seabed, the fundamental properties of the geological material, the size and shape of the object, and the time-dependent processes associated with the coupling of the water column, seabed, and the object. Thus, the most crucial S-SI research problems to address in the Coastal Benthic Boundary Layer Special Research Project (SRP) should focus on the dynamic and time-dependent processes affecting objects coupled to the sea floor. The research efforts should include a range of scales from micro to macro but largely focused on the dynamic processes in proximity to the object rather than broad scale geological and oceanographic processes. Much is to be gained by interdisciplinary research well focused on specific S-SI phenomena.

The S-SI Workshop addressed two important technical topics: (1) Sediment Transport: Scour and Fill, and (2) Geotechnical: Seabed Mechanics. Numerous research topics were identified in each of the two technical areas and additionally two general subtopics were identified as (A) Object Sensing Methods (Detect/Classification) and (B) Sediment Properties Measurements and Data Analysis. Although important to the understanding of S-SI processes, these two subtopics will be thoroughly developed by other SRP workshops and the details will not be discussed here. The most important topics recommended to be part of the SRP, S-SI basic research program, are outlined below.

The purpose of the R&D in Sediment Transport, Scour and Fill, is to improve existing models and create new reliable models of Wave-Current-Seabed-Structure Interaction (W-C-S-SI). This is to be accomplished through quantitative studies of the combined effects of W-C-S-SI directed at understanding the dynamics of the coastal environments and time-dependent processes. Studies should include all sediment types common to coastal environments; sands, silts, clays and organic rich deposits, and mixtures of each.

<u>Sediment Transport: Scour and Fill</u>

- o Development and testing of physical models incorporating the time-dependent S-SI interactions. Small-scale and full-scale studies are needed.

- Understanding of scaling effects and scaling laws involving S-SI processes; facilitated by laboratory and field studies.
- Understanding of the turbulent hydrodynamic variations (small to large scales) induced by the presence of an object in the flow field.
- Understanding of the nonlinear wave-current interactions with the sea floor and the object coupled with the sea floor.
- Understanding of the time scales and transient phenomena driving and controlling pore water flow in proximity to bottom-sitting objects in dynamic motion.
- Understanding the role of dynamic pore pressure on sediment transport and stability around a solid body coupled with the sea floor (muds and sands) and driven by different (frequency) environmental wave-current forces.

The purpose of the R&D in Geotechnical, Seabed Mechanics, is to create a reliable predictive model of the object-seabed mechanical interaction. The sediment reactions are a combination of:

(a) stresses and deformations caused by direct interactions between seabed and object.

(b) stresses and deformations caused by the regional hydrodynamic field.

The effects of the combined system (a)(b) are exhibited by a range of phenomena

1. static—no deformations—object at rest
2. slow settlement and displacements of supporting sediment
3. rocking, gap development, self-embedment
4. sliding, gouging, etc.

To accomplish development of a reliable model, studies are required in diverse areas of sediment structure interactions.

Geotechnical: Seabed Mechanics

- Understanding of the processes responsible for gap formation in cohesive sediments by object/sediment/fluid interaction.
- Understanding of the role of gas charged sediment in the dynamic behavior of object-sediment coupling.
- Understanding of the wave-induced sediment deformations stresses and pressures (total stress and pore pressures) of objects in dynamic motion on a clayey (mud) sea floor when object is allowed to rock, sway, heave, etc.
- Understanding of the development of excess pore pressure and degradation of sediment strength under dynamic loading conditions with object coupled with the seabed; the importance and influence of permeability, sediment type (grain size and mineralogy), and microfabric on the time-dependent processes.

- Understanding of wave induced pore pressure attenuation with subbottom depth in sands, silt, clays and admixtures and an understanding of the energy transfer in different sediment types under various wave climates in coastal areas.
- Understanding and development of modeling laws for scaling from laboratory tests to field conditions.

The above topics will largely dictate what types of instrumentation are required in developing laboratory and field studies and what specific environmental data and seabed properties measurements are needed.

SEABED-STRUCTURE INTERACTION

INTRODUCTION

Background...The topic of Seabed-Structure Interaction (S-SI) is one of four crucial research elements in the Coastal Benthic Boundary Layer Special Research Program (SRP). The program is designed to address important basic research issues directed toward support of the U.S. Navy's coastal, mine counter measures (MCM), and amphibious mine warfare (AMW) operations. The other three topics of interest to the SRP include (1) Environmental Processes and High Frequency Acoustic Scattering/Propagation Phenomena at the Benthic Boundary Layer, (2) Sediment Classification Methodologies Required for Improved MCM Systems Performance and Performance Prediction, and (3) Processes Responsible for Fine-Scale Electro-Magnetic and Electro-Optical Variability in Near Shore Marine Sediments. These three topics are not directly addressed in this report although the basic research involved in each of the four topics has important synergism that supports the Coastal Benthic Boundary Layer SRP. The research thrust that links the four major research topics is the objective to improve the performance and performance prediction of MCM systems used to detect, classify, and neutralize mines located within or on the sea floor. This is accomplished through basic research directed toward understanding environmental processes that affect MCM and AMW operations in coastal waters.

The technology issues involving S-SI processes include the predictions of mine burial at impact and by scour, sand wave migration, and deposition including well defined but poorly understood S-SI mechanisms. A host of technical problems exist for basically all marine sediment types including sands, silts, clays, and admixtures of each. The environmental processes and the types of data requirements necessary for addressing technical problems in S-SI have been summarized by Valent et al. (1988) (Tables 1 and 2). The complex marine environment combined with the high spacial and temporal variability of sediment properties and processes, at the sediment-water interface and within the seabed, provides a unique challenge for future research on the subject of S-SI.

The coupling of an object with the seabed and their combined dynamic response is described as S-SI. Implicit in the definition of S-SI is the importance of the forcing by and the interaction with hydrodynamical processes in the benthic boundary layer. Because the marine environment is characterized by a variety of geological materials, seabed properties, and hydrodynamic processes, the problems of modeling, analysis, and prediction of S-SI time-dependent processes are complex; and thus present capabilities that are

Table 1.1-1. Potential S-SI problems for consideration.

Environmental Processes (mass processes)

- Bottom failure (without structure on bottom)
  - — Environmental forcing functions, e.g., waves, earthquakes (seismic shock), internal waves
  - — Scour-oversteeping by sedimentation (may be seasonal), bioerosion, iceberg keels
  - — Strength decrease: pore pressure increase due to:
    - waves
    - osmotic pressure changes
    - biogenic methane production
  - — External, man-induced: ships, construction activities, weapons effects (shock waves, etc.)
  - — Tide-induced flow slides (sands / silts)
  - — Collapse of bottom due to environmental conditions (little or no translation)
- Nepheloid layer (high-density bottom water)
- Sand wave migration due to storms
- Changes in water column characteristics due to differences in bottom characteristics (properties), i.e., wave degradation characteristics, water velocity, pressure

Processes Due to Structure on Bottom (localized processes)

[structure configuration (effects of) and changes produced by currents and waves]

- Scour: sand/silt/clay scour resulting in the following:
  - — settling
  - — tilting
  - — movement
  - — burial, differential settling
- Localized strength degradation and pore pressure changes due to repeated loading (cyclic loading of structure on bottom)
  - — thermal gradients (frozen ground/permafrost) freeze-thaw
- Bottom failure/bearing capacity
  - — initial failure and failure due to strength degradation
  - — prediction of penetration depth
  - — breakout forces required
- Settlement - consolidation
- Prediction of skidding and sliding

Table 1.1-2 Data requirements for S-SI analysis.

Soil Properties (required for all stratigraphic units)

- Noncohesive sediment
  - — Grain size (mm)
  - — Specific gravity and water content
  - — Bulk density
  - — Angle of internal friction (on effective stress basis obtained from direct shear or triaxial tests)
  - — Permeability
  - — Relative density
- Cohesive sediments
  - — Grain size (mm)
  - — Specific gravity and water content
  - — Atterberg limits (liquidity index)
  - — Bulk density
  - — Undrained shear strength (by miniature vane or unconfined compression - UU)
  - — Remolded strength/sensitivity
  - — Consolidation and permeability data
  - — Consolidated undrained shear strength (on effective stress basis with pore pressure measurements, CU - test)

Environmental Data (required for all sites)

- — Bottom slope
- — Wave climate and currents
- — Water depth
- — Water density (salinity)
- — Bottom roughness

Structure Data

- — Size, shape, and weight
- — Footprint/configuration/shape
- — Static and dynamic bearing pressure on footings (secondary vibrations)
- — Influence of structure on currents and waves around footings

In Situ Data

- — Cone penetrometer resistance
- — Pore pressures
- — Vane shear strengths
- — Resistivity/conductivity

(from Valent et al., 1988)

unreliable for critical Navy applications. Four fundamental S-SI processes, Shakedown, Skidding and Lateral Motion, Scour and Fill, and Dynamic Penetration, are identified in this report, and the related research issues recommended are directed toward gaining a fuller understanding of the basic mechanisms and environmental processes important in the dynamic coupling of the sea floor and an object (Figures 1 and 2). By definition, **Shakedown:** is a dynamic bearing capacity process due to cyclic loading by waves and currents (objects experiencing penetration under cyclic loading conditions [complex dynamic effects]); **Skidding and Lateral Motion:** is considered here for small normal loads when the object experiences lateral movement or skidding; **Scour and Fill:** removal and/or deposition of sediment around an object (static or in motion) that may experience burial or net transport; **Dynamic Penetration:** the dynamic penetration of an object into the seabed at various entry angles and velocities and the response of the sediment to deformation (stress and strain). Scientific issues and research thrusts are directed toward understanding the physics and modeling of the benthic boundary layer processes (with and without bottom sitting objects), time-dependent changes in the environment and sediment response, and their impact on the sea floor properties as they affect MCM operations.

Purpose...This report is a result of a one and a half day workshop on the subject of S-SI convened in Metairie, LA in November 1991. The meeting was attended by professional engineers and scientists from academia, government, and industry. Technical disciplines represented at the workshop included marine geology and geotechnique, sedimentology, oceanography, fluid dynamics and hydraulic engineering, signal processing, and physics and modeling, which provided a strong interdisciplinary forum. The purpose of the workshop was to identify important research issues that require additional research on the topic of S-SI in support of the Navy's Coastal Benthic Boundary Layer SRP. Names and affiliations of the participants who attended the S-SI workshop are included in Appendix A.

Organization of Workshop and Report...During initial deliberations on the topic of S-SI by the workshop attendees, the decision was made to organize the workshop into two technical groups to address interrelated but discipline oriented subject areas. Group One was identified as the Sediment Transport: Scour and Fill technical group and Group Two was the Geotechnical: Seabed Mechanics technical group. Members of each group are identified in Appendix B. Leaders were Steven Hughes, CERCWES, for the Sediment Transport group and James Hooper, Fugro-McClelland, for the Geotechnical group. The rationale for this division was for the purpose of focusing on specific technical issues by experts most closely associated with the required disciplines. Linkage and synergism between the two groups were maintained by regrouping

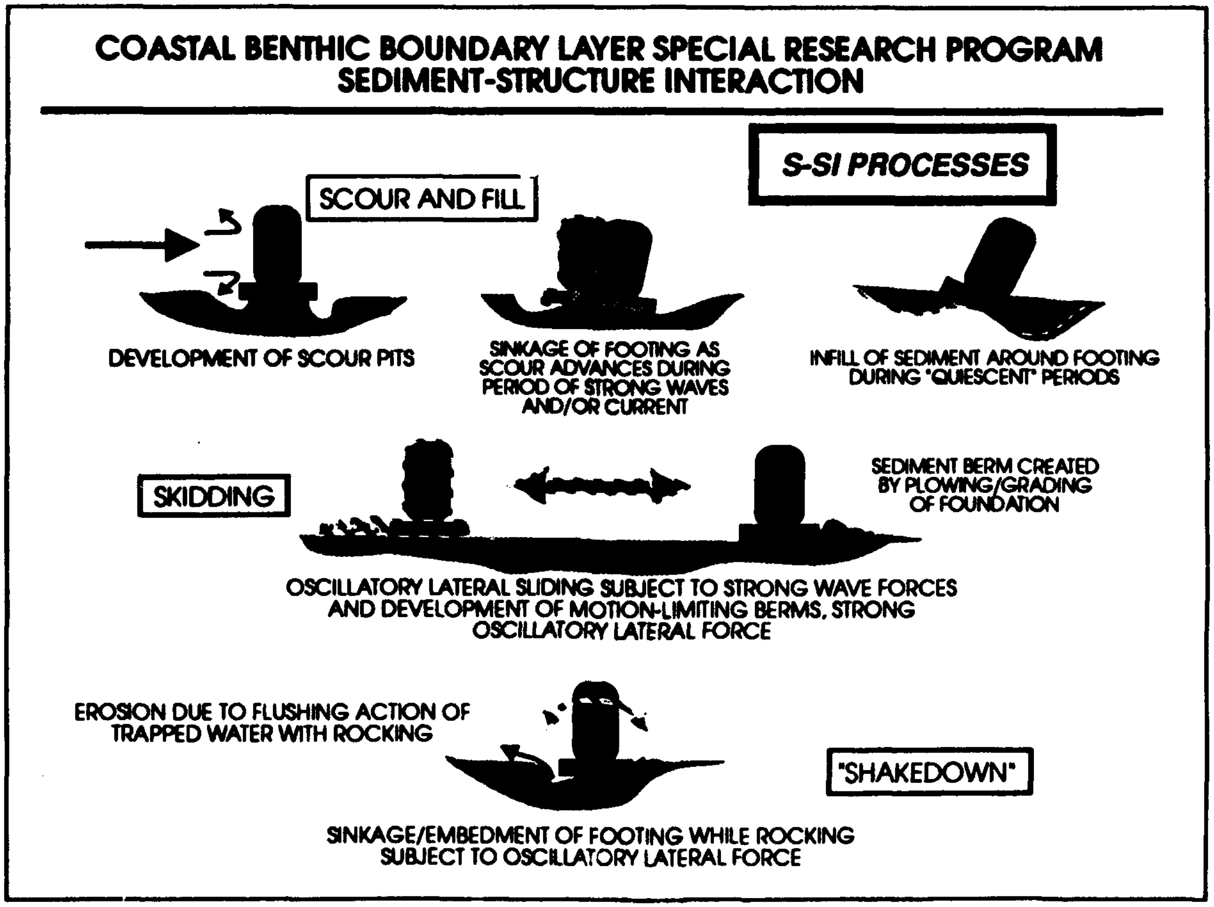
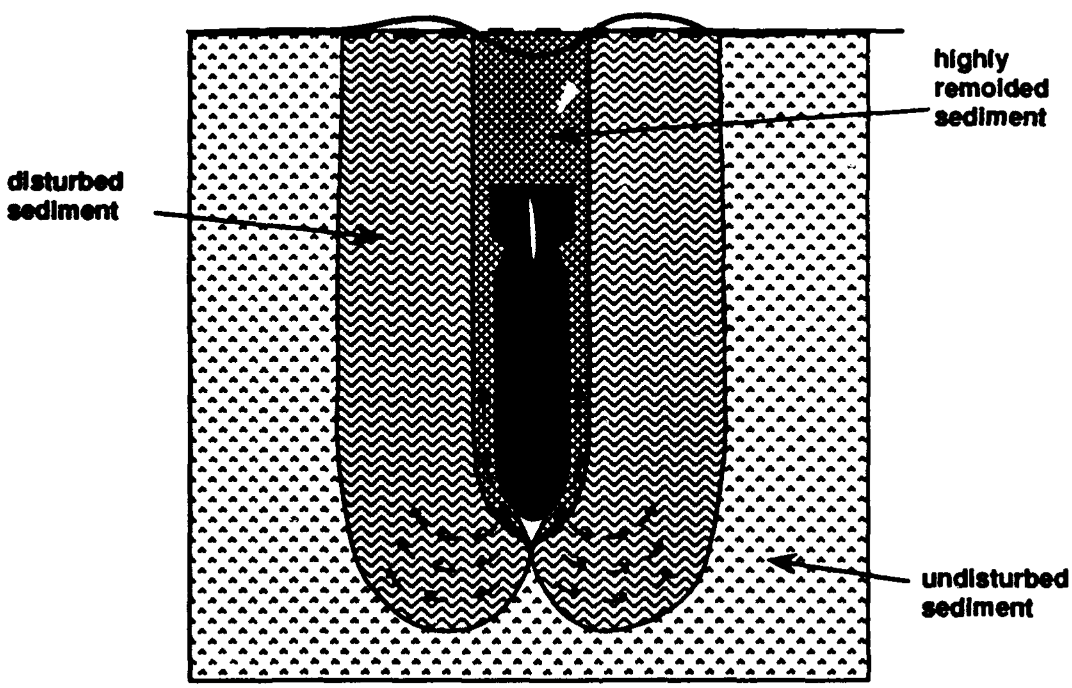


Figure 1. Sediment-structure interaction processes involving the coupling and dynamic interaction of an object and the seabed driven by complex environmental forces that vary with time. (Modified from Valent et al., 1988. Does not represent actual mine configurations; rather depicts particular sediment-structure interaction processes and mechanisms.)

COASTAL BENTHIC BOUNDARY LAYER SPECIAL RESEARCH PROGRAM

SEDIMENT-STRUCTURE INTERACTION



Picture of Penetrator

Figure 2. Sediment-structure interaction of an object penetrating the seabed, involving complex sediment remolding - deformation, pore pressure response and time-dependent changes in sediment properties. (Compliments of Phillip Valent)

all participants during the workshop to discuss technical issues identified by the two separate groups. Thus, this report is organized in two parts; recommendation for research in (1) Sediment Transport; Scour and Fill, and (2) Geotechnical: Seabed Mechanics. The methodology and organization proved successful and resulted in the recommendations identified in this report. It is anticipated that this report will provide a springboard for future research on the coastal marine environment in the important subject area of S-SI processes and mechanisms.

SEDIMENT TRANSPORT: SCOUR AND FILL

BACKGROUND

Seabed-Structure: Scour and Fill

Scour that occurs around a solid body resting on the sea floor, and the partial or complete subsequent burial of the body, is dependent upon the complex interaction of the fluid, sediment, and the solid body itself. These interactions include the turbulent hydrodynamic variation induced by the presence of the solid body in the flow, the transport of sediment by the flow, and the response of the sediment bed to the solid body surcharge (loading). Individually, these separate interactions are poorly understood, at best; taken collectively, the combined interactions of the scour process are virtually unknown. Consequently, reliable prediction of seabed scour around a solid body is beyond the current state-of-knowledge.

Fundamental research into the complex fluid/structure/sediment interaction is needed in order to improve our understanding of the scour problem to at least the same level as our present capability to specify the environmental forcing conditions. A crucial aspect of the problem of reliable S-SI predictive capabilities is a fundamental understanding of the nonlinear wave-current interactions and coupling with an object on the sea floor. Complex time-dependent interactions exist and reliable physical models are urgently needed.

The following list details those aspects of the solid body/scour problem where physical understanding and research are most needed. Several of these research issues are somewhat broad and encompass several separate topics that could be individually investigated. However, it will be important for individual efforts to be well coordinated within each of the research issues.

Research Issues:

1. What are the significant, time-dependent interactions between the small-scale, near-bed, wave boundary layer and the large-scale, benthic boundary layer?

2. How do suspended sediments affect the wave and benthic boundary layer? How does suspended sediment affect turbulence?

3. What is the role of dynamic pore pressures on sediment transport in the vicinity of a solid body resting on the sea floor? What are the time scales and transient phenomena driving and controlling pore water flow in proximity to the bottom sitting object?

4. How does the presence of a solid body impact spacial and temporal 3-D turbulent structure in the water column, and how does it affect the pressure distributions within the bed?

5. How can our understanding of the empirically based coupling between shear stress and sediment transport be improved? Specifically, what is the relationship between the spacial and temporal stress distribution in the wave boundary layer and the suspension and deposition of sediments?

6. How do large- and small-scale bedforms interact with the turbulent flow in the wave and benthic boundary layers?

7. What new methodologies must be developed in order to successfully apply advances in scour mechanics to practical applications?

8. New technology is required for the direct, nonintrusive, measurement of sediment transport in the field. Examples may include infrared optical backscatter sensors and ground penetrating radar.

9. Fluidization of a sandy sea floor: initiation of suspension under nonuniform and oscillatory flows. Effects of local gradients of density, sediment concentration, velocity, pressure and stresses due to waves, turbulence and to the presence of a structure. Possible extension of granular flow mechanics to the dynamics of bedload transport under oscillation and nonuniform flow conditions. Theoretical and experimental advances are needed beyond Meyer-Peter formula for sediment transport rate in steady flows. Collisions among particles are accounted for (S.A. Savage, McGill, and Jim Jenkins, Cornell).

10. Effects of suspended sediments on the structure of the turbulent boundary layer (turbulence intensity variation, vertical structure of Reynolds stresses).

11. The role of large scale (vertical and horizontal) variations on the benthic boundary layer and on the sediment motion within. The large scales may correspond to Ekman boundary layer depth, wavelength of the water wave, or the sandbars. Understanding of the three dimensional structure (velocity and stress) in the wave boundary layer over sandbars or irregular bathymetry is needed and the mechanics of sandbar formation and migration due to large scale variations of boundary layers needs to be more fully understood.

12. Sediment instability, formation and migration of ripples: ripples are due to unstable sand motion under oscillatory flows and are a major source of bottom roughness. Given the amplitude and frequency of an oscillatory flow outside the boundary layer and the grain size, what are the likely sand-ripple wavelengths and ripple heights? How does the role of vortices in the boundary layer affect ripple development? How do the vortices affect scour at the object/sediment-water interface? How is orbital wave particle dynamics in the benthic boundary layer affected by the presence of an object on the sea floor? How do large scale horizontal gradients in the boundary layer, due to a structure of surface waves of the order of 100 m, affect ripple development and migration? How do ripples on large bars develop and affect the formation and movement of the bars?

13. Dynamics of cohesive sediments in and below the wave boundary layer.
   A. Fluidization of cohesive seabed
   B. Bulk motion of fluid mud due to nonuniform gradient and transients.
   C. Instability of a muddy seabed, with or without a structure.
   D. Non-Newtonian rheological behavior of fluid mud.
   E. Time-dependent response of sediment pore water pressure as a function of surface wave activity and the response of pore pressure as a function of the combined effects sediment-structure dynamics and surface wave activity. These processes are poorly understood especially for complex sediment types with admixtures of sand, silt, and clay that are common in the marine coastal environments.

   F. Dynamic behavior and properties of soft mud possessing total organic contents of greater than 2% (>2% TOC). Rheological behavior, cohesion, compressibility, physical properties, erodibility, etc., in relation to depositional environment, sediment type, mineralogy, and microfabric.

GEOTECHNICAL: SEABED MECHANICS

BACKGROUND
Geotechnical: S-SI, Properties, and Sensing Methods

The mechanics of Sediment(seabed)-Structure Interaction phenomena are poorly understood particularly with regard to the coupling processes and mechanisms and time-dependent changes in the seabed as a function of the dynamics of the sediment-structure system and the energy of the environment. The processes and mechanisms are complex and additional research is required to develop reliable predictive capabilities for the response of objects coupled with the sea floor.

Important research areas of investigation that would improve modeling and predictive capabilities include factors such as scaling effects, penetration rate functions, dynamic forces, coupling phenomena, and strength degradation effects and the significance of these factors on the analyses of penetration, sinkage, sediment liquefaction and pumping, and punch-through. Punch-through is a problem in layered sediments where the bearing resistance of a stiff surficial layer is exceeded and the object "punches through" into a soft underlying layer. These geological conditions can occur in coastal environments and are a result of changing environmental conditions and changes in source material. The physics and modeling of dynamic penetration of objects into the seabed is another area where research is required and has particular importance to problems in mine warfare. Reliable models for layered sediments are sorely needed particularly in cases of punch-through and dynamic penetration of objects in seabed sediments.

An important topic of research related to Sediment(seabed)-Structure Interaction is in the area of object sensing methods and detection of structures on and buried within the seabed. New technologies that offer rapid means of detection with high resolution are crucial to Naval applications.

Three broad technical areas were discussed by the Geotechnical Group and research recommendations and issues were identified. The three areas included, (1) Sediment(seabed)-Structure Interaction, (2) Sediment Properties and Processes, and (3) Object Sensing Methods. Object Sensing Methods will be covered in greater detail in another SRP workshop, but the topic is covered briefly here because of its importance to S-SI processes and technical issues.

I. Sediment-Structure Interaction

Research Issues:

1. Prediction of threshold loading for gap formation.
2. Prediction of object/sediment/fluid interaction for cohesive sediments (in particular at gap between sediment and object).

   On a clayey (mud) sea floor:
   a. Burial of a structure into the soft bed by self weight. Large amplitude nonlinear deformation.
   b. Wave-induced sediment deformation stresses and pressure when the structure is allowed to move (sway, heave, rock, etc.). Nonlinear constitutive behavior of clayey sediment should be considered (under undrained condition).
   c. Current-induced stress and pore pressure and sediment deformation in a nonlinear sediment.
3. Prediction of skidding vs. sinking (gouging).
4. Development of excess pore pressure under dynamic loading (local effects).
5. Dynamic sediment–rheology/viscoelastic wave-structure interaction.
6. Evaluation of forcing function and dynamics on seabed objects.
7. Self-weight sinkage-static and dynamic loading.
8. Effect of gassy sediments on sinking.
9. Object implanting by bioturbation.
10. Develop modeling laws for scaling (lab to field).
11. Modeling variations of engineering properties of sea floor sediments; evaluate their effects/influence on S-SI.
12. Prediction of fluid/sediment structure interaction (cohesionless sediment)
13. Refine analytical models for projectile penetration. Dynamics of penetration of mine into a viscoelastic sediment.

II. Sediment Properties and Processes

Research Issues:

1. Bioturbation effects on material types and on micro and macro variability of properties.
2. Diagenesis is a process and important factor in the lateral and vertical variability of sediments and it is important in cement types and effects on sediment properties. Processes are poorly understood in relationship to environments of deposition, various sediment types and oxic and anoxic environments.
3. Gas/Sediment compressibility/strength/moduli; Gas bubble mobility in soft clay/loose sand.
4. Excess pore pressures under dynamic loading (including

gassy sediment); different sediment types, environments, and wave loading. Attenuation of pressure signal with subbottom depth and time-dependent changes in excess pore pressure.

5. Pore pressure in Oxidation/Reduction zones caused by microbiological activity and in gassy sediment.
6. Degradation of vessel signatures by sediment; Change in neutralization explosion pressure in sediments.
7. Thermal signal properties of geological materials.

Measurements of Sediment Properties and Data Analysis:

1. Determination of sediment properties
   a. Using surface shear waves.
   b. Tools and analysis methods for resistivity of fine-layered sediments (probe).
   c. Tools and analysis for thermal pulse method for sediment classification and detection.
2. Classification of sediment properties by side scan sonar; estimation of sediment properties (geotechnical) by other remote detection methods.
3. Perceptual science (i.e., artificial intelligence) to characterize sea floor properties.
4. Tomography for data correlation.

III. Object Sensing Methods (Detect/Classification)

Research Issues:

1. Detection of objects with properties similar to sediment properties.
2. Diffraction pattern recognition of objects.
3. Discrimination of objects on sea floor.
4. Multimode scanning of objects.
5. Rapid rate of areal coverage.
6. Discrimination of manmade vs. natural objects.
7. Exploitable penetrating radiation.
8. Detection of objects by shear wave propagation.
9. Cataloging of object signatures in various sediments.

REFERENCES
(not all cited in report)

Andersen, A., and L. Bjerrum (1967). Slides in subaqueous slopes in loose sand and silt. In the Marine Geotechnique. A. F. Richards, (ed.), University of Illinois Press, Urbana, Illinois, pp. 221-239.

Arnold, Peter (1973). Finite element analysis - A basis for seafloor soil movement design criteria. Proceedings, 5th Offshore Technology Conference, Houston, Texas, pp. 743-752.

Bea, R.G. (1971). How sea-floor slides affect off-shore structures. The Oil and Gas Journal, pp. 88-92.

Bea, R.G., and P. Arnold (1973). Movements and forces developed by wave-induced slides in soft clays. Proceedings, 5th Offshore Technology Conference, Houston, Texas, pp. 731-742.

Bekker, M.G. (1960). Off the Road Locomotion: Research and Development in Terra-Mechanics. The University of Michigan Press, Ann Harbor, Michigan.

Bennett, R.H., H. Li, M.D. Richardson, P. Fleischer, D.N. Lambert, D.J. Walter, K.B. Briggs, C.R. Rein, W.B. Sawyer, R.S. Carnaggio, D.C. Young, and S.G. Tooma (1992). Geoacoustic and Geological Characterization of Surficial Marine Sediments by in situ Probe and Remote Sensing Techniques. In R.A. Geyer, ed., CRC Handbook of Geophysical Exploration at Sea, 2nd Edition Hydrocarbons, CRC Press.

Bishop, A.W.(1955). Use of a slip circle for stability analysis. Geotechnique 5(1):7-17.

Brown, J.D. and G.G. Meyerhof (1969). Experimental study of bearing capacity in layered clays. 7th International Conference on Soil Mechanics and Foundation Engineering 2:45-51.

Coleman, J.M., D.B. Prior, and L.E. Garrison (1978). Submarine landslides in the Mississippi River Delta. Proceedings, 10th Offshore Technology Conference, Houston, Texas, pp. 1067-1074.

Davis, E.H. and J.R. Booker (1973). The effect of increasing strength with depth on the bearing capacity. Geotechnique 23(4):551-563.

Dunlap, W.A., W.R. Bryant, A.F. Richards, and R. Bennett (1978). Pore pressure measurements in underconsolidated sediments. Proceedings, 10th Offshore Technology Conference, Houston, Texas, pp. 1049-1066.

Ehlers, C.J., A.C. Young, and J.A. Focht, Jr. (1980). Advantages of using in situ vane tests for marine soil investigations. Proceedings, International Symposium on Marine Soil Mechanics, Mexico.

Elsbury, B.R. (1971). A Primary Investigation of Submarine Landslides off the Birdfoot Delta. M.E. Report, Civil Engineering Department, Texas A&M University.

Esrig, M.I., R.S. Ladd, and R.G. Bea (1975). Material properties of submarine Mississippi Delta sediments under simulated wave loading. Proceedings, 7th Offshore Technology Conference, Houston, Texas, pp. 399-411.

Gibson, R.E., G.L. England, and M.J.L. Hussey (1967). The theory of one dimensional consolidation saturated clays. I: finite nonlinear consolidation of their homogeneous layers. Geotechnique **17**, 261-273.

Hanna, A.M. and G.G. Meyerhof (1980). Design charts for ultimate bearing capacity of foundations on sand overlying soft clay. Canadian Geotechnical Journal 17(2):300-303.

Helfrich, S.C., A.G. Young, and C.J. Ehlers (1980). Temporary seafloor support of jacket structures. Proceedings, 12th Offshore Technology Conference, Houston, Texas 2:141-150.

Henkel, D J.(1970). The roll of waves in causing submarine landslides. Geotechnique 20(1):75-80.

Hvorslev, M.J.(1970). The basic Sinkage Equations and Bearing Capacity Theories. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, Technical Report M-70-1.

Jacobson, M., K.V. Christensen, and C.S. Sorensen (1977). Gennemlokning of tynde sandlag. Vag-och Vattenbyggaren, Sevenska Vag-och Vattenbyggares Riksforbund, Stockholm, pp. 23-25.

Janbu, N.(1956). Stability Calculations for Fillings, Cuts and Natural Slopes. Norwegian Geotechnical Institute, Oslo, Publication No. 16, Chapter 2.

Kezdi, A. (1975). Pile foundations. In Foundation Engineering Handbook, H. F. Winterkorn and H.-Y. Fang (eds.), Van Nostrand Reinhold, N.Y., Chapter 19, pp. 556-600.

King, J.B. (1976). Characterization of Viscoelastic Properties of Submarine Sediments. M.S. Thesis, Civil Engineering Department, Texas A&M University.

Koppejan, A., B. van Wamelan, and L. Weinberg (1948).

Coastal flow slides in the Dutch Province of Zeeland. Proceedings, 2nd International Conference on Soil Mechanics and Foundation Engineering 5:89-96.

Kraft, L. and D. Watkins (1976). Prediction of wave induced seafloor movements. Proceedings, 15th International Coastal Engineering Conference, American Society of Civil Engineers, New York, New York, pp. 1605-1623.

Langborne, D. (1992). Environmental Modelling for Mine Countermeasures with Particular Reference to Mine Burial Predictions (personal communication).

Lee, Fallou, and Mei (1992). Subsidence due to pumping in a layered soil with a soft aquitard. Phil Trans. Royal. Soc. London (forthcoming).

Lee, H.J. (1972). Unaided Breakout of Partially Embedded Objects from Cohesive Seafloor Soils. Naval Civil Engineering Laboratory, Port Hueneme, California, Technical Report R-755.

Li, H. M.C. Wang, and R.H. Bennett (1992). Significance of Pore Pressure in Marine Sediments: Measurements and Derived Properties. In R.A. Geyer, ed., CRC Handbook of Geophysical Exploration at Sea, 2nd Edition Hard Minerals, CRC Press.

Mei, C.C. and M.A. Foda (1981). Wave induced stress around a pipe laid on poro-elastic sea bed. Geotechnique 31, 509-517.

Meyerhof, G.G. (1953). The bearing capacity of foundations under eccentric and inclined loads. Proceedings, Third International Conference on Soil Mechanics and Foundation Engineering, Zurich, 1:440-445.

Meyerhof, G.G.(1971). Ultimate bearing capacity of footings on sand overlying clay. Canadian Geotechnical Journal 11(2):223-229.

Morgenstern, N.R. (1967). Submarine slumping and the initiation of turbidity currents. In Marine Geotechnique, A.F. Richards (ed.), University of Illinois Press, Urbana, Illinois, pp. 189-220.

Morgenstern, N.R. and V.E. Price (1965). The analysis of the stability of general slip surfaces. Geotechnique 15(1):79-93.

Mynett A.E. and C.C. Mei (1982). Wave induced stresses in a saturated poro-elastic sea bed beneath a rectangular caison. Geotechnique 32, 235-247.

Peck, R.B., W.E. Hanson, and T.H. Thornburn (1953). Foundation Engineering. John Wiley, New York.

Perloff, W.H.(1975). Pressure distribution and settlement.

In Foundation Engineering Handbook, H.F. Winterkorn, H.-Y. Fang (eds.), Van Nostrand Reinhold, N.Y., Chapter 4, pp. 148-196.

Rocker, K.(ed.)(1985). Handbook of Marine Geotechnical Engineering. Naval Civil Engineering Laboratory, Port Hueneme, California, pp. 5-9.

Schapery, R.A. (1968). On a thermodynamic constitutive theory and its application to various nonlinear materials. Proceedings, International Union of Theor. and Applied Mech., East Killbride.

Schapery, R.A. (1974). Wave-Sea Bottom Interaction Study (phase one) Part 1: Theory and Results. Texas A&M University, Report No. MM 3308-74-1.

Schapery, R.A. and W.A. Dunlap (1978). Prediction of storm induced sea bottom movement and platform forces. Proceedings, 10th Offshore Technology Conference, Houston, Texas pp. 1789-1797.

Schapery, R.A. and W.A. Dunlap (1984). Theoretical and Experimental Investigation of Mud Forces on Offshore Pipelines. Performed by Center for Marine Geotechnical Engineering, Texas A&M University, for American Gas Association, Arlington, Virginia, Project Report PR-149-113.

Shepard, F.P. (1955). Delta-front Valleys Bordering on the Mississippi Distributaries. Bulletin of the Geological Society of America 66:1489-1498.

Skempton, A.W. (1951). Bearing Capacity of Clays, Division 1. Building Research Congress, London, pp. 180-189.

Stevenson, H.S. (1973). Vane Shear Determination of the Viscoelastic Shear Modulus of Submarine Sediments. M.S. Thesis, Civil Engineering Department, Texas A&M University.

Sybert, J.H., R.M. Meith, and J.D. Gass (1978). A drilling platform for a soft foundation location. Proceedings, 10th Offshore Technology Conference, Houston, Texas, pp.49-54.

Teramoto, S., K. Tagaya, K. Yatagai, Y. Marase, and K. Nonomiya (1973). Study of scouring on sit-on-bottom type offshore structure. Technical Review (Japan).

Terzaghi, K. (1943). Theoretical Soil Mechanics. Wiley, New York, pp. 119-120.

Terzaghi, K. (1956). Varieties of submarine slope failures. Proceedings, 8th Texas Conference on Soil Mechanics and Foundation Engineering, Austin, Texas.

Terzaghi, K. and R. Peck (1967). Soil Mechanics in Engineering Practice. John Wiley & Sons, New York.

Trabant, P. (1978). Submarine Geomorphology and Geology of the Mississippi River Delta Front. Ph.D. Dissertation, Texas A&M University.

Valent, P.J., R.H. Bennett, and W.A. Dunlap (1988). Dynamic Soil-Structure Interaction Behavior on the Seafloor. Naval Ocean Research and Development Activity, Stennis Space Center, MS NORDA Report 227.

Wright, S.G. (1976). Analyses for wave induced seafloor movements. Proceedings, 8th Offshore Technology Conference, Houston, Texas, pp. 41-52.

Wright, S.G., and R.S. Dunham (1972). Bottom stability under wave induced loading. Proceedings, 4th Offshore Technology Conference, Houston, Texas, pp.853-862.

Yamamoto, T., H.L. Koning, H. Sellmeijer, and E. Van Hijum (1978). On the response of a poro-elastic bed to water waves. J. Fluid Mech., V. 87, Part I, p. 193-206.

Young, A.G., et al. (1981). Foundation performance of mat-supported jack-up rigs in soft clays. Proceedings, 13th Offshore Technology Conference, Houston, Texas, 4:273-284.

Young, A.G., B. Remmes, and B. Meyer (1984). Foundation performance of offshore jack-up drilling rigs. Journal of Geotechnical Engineering, ASCE 110(7):841-859.

Appendix A

SEABED-STRUCTURE INTERACTION WORKSHOP PARTICIPANTS
November 1991-Metairie, LA

Attendees

Dr. Richard Bennett
NRL Code 360
Bldg. 1005
SSC, MS 39529

Dr. Ronald Chaney
Department of Engineering
Humbolt State University
Arcata, CA 95521

Dr. John Cornette
Staff Planner
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

Dr. Richard Crout
Planning Systems Inc
115 Christian Lane
Slidell, LA 70458

Dr. Wayne Dunlap
Offshore Technology Research Center
1200 Mariner Drive
TAMU
College Station, Texas 77845-3400

Dr. Patrick Gallacher
NRL Code 322
SSC, MS 39529

Mr. Douglas Lambert
NRL Code 361
SSC, MS 39529

Dr. Homa Lee
USGS Branch Pac Mar Geol
345 Middelfield RD MS999
Menlo Park, CA 94025

Dr. James R. Hooper
Fugro-McClelland Engineers
P.O. Box 740010
Houston, TX 77274

Dr. Steven Hughes
3909 Halls Ferry Rd
Vicksburg, MS 39180

Dr. Donald Johnson
NRL Code 321
SSC MS 39529

Dr. Lakshmi Kantha
CCAR
Colorado University
Campus Box 431
Boulder, CO 80309

Dr. Joseph Kravitz
Marine Geology & Geophysics
Office of Naval Research
800 North Quincy St.
Arlington, VA 22217

Mr. Gregory Page
NAVSWC Code U-42
White Oak, Silver Spring, Maryland 20910

Dr. Michael Richardson
NRL Code 361
SSC, MS 39529

Dr. Norman Scheffner
US CORPS CERC WES
3909 Halls Ferry Road
Vicksburg, MS 39180

Dr. Charles Libicki
Dept of Civil Engineering
Ohio State University
495 Hitchcock Hall
2070 Neil Avenue
Columbus, OH 43210

Dr. Chiang C. Mei
Parson Laboratory
M.I.T.
Cambridge, MA 02139

Dr. Derek Morris
Dept of Civil Engineering
TAMU
College Station, TX 77843

Dr. Dan True
NCEL
Port Hueneme CA 93043

Mr. Donald Walter
NRL Code 361
SSC, MS 39529

Dr. M.C. Wang
Dept of Civil
Engineering
Penn State University
University Park, PA
16802

Appendix B

TECHNICAL WORKING GROUPS

SEDIMENT TRANSPORT: SCOUR AND FILL

Steven A. Hughes, Chairman
Patrick Gallacher
Richard Crout
Norman Scheffner
Chiang C. Mei
Joseph Kravitz
Charles Libicki
Donald Walter
Michael Richardson
Donald Johnson
Richard H. Bennett

GEOTECHNICAL: SEABED MECHANICS

James R. Hooper, Chairman
Mark C. Wang
Douglas N. Lambert
Wayne A. Dunlap
Dan True
Greg Page
John Cornette
Ronald Chaney
Derek Morris

Distribution List

Naval Oceanographic & Atmospheric Research Laboratory
Stennis Space Center, MS 39529-5004
Attn: Code 300, Dr. Herb Eppert (2)
Code 310, Dr. Phil Valent (2)
Code 321, Dr. D. Johnson & R. Arnone
Code 322, Dr. Patrick Gallacher
Code 352, Dr. Edward Mozley
Code 360, Dr. R. Bennett (50)
Code 360, S. Tooma
Code 361, D. Lambert, D. Walter, M. Richardson (50)
Code 125P, Code 125L (10)
Code 200, Dr. E. Franchi

Department of Engineering
Humbolt State University
Arcata, CA 95521-6199
Attn: Dr. Ronald Chaney

Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217-5000
Attn: Dr. John Cornette (2), Code 10P2
Dr. J. Kravitz (2), Code 1125GG
Dr. Thomas Kinder, Code 1121CS
Dr. Melbourne G. Brisco, Code 124
Dr. Wallace Ching, Code 235
Dr. Marshall Orr, Code 11250A
Dr. J.T. Warfield, Code 234

Planning Systems Inc.
115 Christian Lane
Slidell, LA 70458
Attn: Dr. Richard Crout

Offshore Technology Research Center
1200 Mariner Drive, TAMU
College Station, Texas 77845-3400
Attn: Dr. Wayne Dunlap (10)

USGS Branch Pac Mar Geol
345 Middlefield Rd MS999
Menlo Park, CA 94025
Attn: Dr. Homa Lee (10)

Fugro-McClelland Engineers
P.O. Box 740010
Houston, Texas 77274
Attn: Dr. James R. Hooper (10)

US Army CORPS CERC WES
3909 Halls Ferry Rd
Vicksburg, MS 39180
Attn: Dr. Steven Hughes (10)
Dr. Norman Scheffner

CCAR
Colorado University
Campus Box 431
Boulder, CO 80309
Attn: Dr. Lakshmi Kantha

Dept of Civil Engineering
Ohio State University
495 Hitchcock Hall
2070 Neil Avenue
Columbus, OH 43210
Attn: Dr. Charles Libicki
Dr. Kieth Bedford (2)

Parson Laboratory
M.I.T.
Cambridge, MA 02139
Attn: Dr. Chiang C. Mei (2)

Dept of Civil Engineering
TAMU
College Station, Texas 77843
Attn: Dr. Derek Morris

NCEL
Port Hueneme, CA 93043
Attn: Dr. Dan True

Dept of Civil Engineering
Penn State University
University Park, PA 16802
Attn: Dr. M.C. Wang

Dept of Ocean & Oc. Engineering
Florida State University
150 West U. Boulevard
Melbourne, FL 32901-6988
Attn: Dr. William R. Dally (2)

Marine Sciences Research Center
State University of New York
Stony Brook, N.Y. 11794-5000
Attn: Dr. Charles A. Nittrouer (2)

Department of Civil Engineering
Duport Hall
Newark, DL 19716
Attn: Dr. Robert Dalrymple (2)

Scripps Inst. of Oceanography
Center for Coastal Studies
University of California
San Diego, CA 92093-0209
Attn: Dr. Douglas Inman

Virginia Institute of Marine Sciences
School of Marine Science
Gloucester Pt. VA 23062
Attn: Dr. Donelson Wright

Dept of Geology
Lafayette College
Easton, PA 18042
Attn: Dr. Richard Faas

Dept of Geology & Geophysics
WHOI
Direcotor Coastal Res. Int.
Woods Hole, MA 02543
Attn: Dr. David G. Aubrey

Naval Coastal Systems Center
Panama City, Florida 32407
Attn: D. Todoroff, Code 2120

Defence Research Agency
USM Dept. DRA Maritime Div.
ARE Bincleaves
Weymouth, Dorset DT4 8UR, UK
Attn: Dr. Langhorne

Naval Observatory
34th & Massachusetts Ave., NW
Attn: Code OP-096 (Dr. Bob Winokur)

Applied Physics Laboratory
1013 NE 40th Street
Seattle, WA 98105
Attn: Dr. Darrell R. Jackson

Naval Research Laboratory
Acoustics Division
Washington, DC 20375-5000
Attn: Code 5100, Dr. David L. Bradley
Code 5110, Dr. Peter Vogt,
Dr. Henry S. Fleming
Library

Mine Warfare Command
Charleston, SC 29408
Attn: Mr. George Pollitt, Code 007

Department of Oceanography WB-10
University of Washington
Seattle, WA 98195
Attn: Dr. Peter A. Jumars

Applied Research Laboratory
Penn State University
P.O. Box 39
State College, PA 16804
Attn: Dr. Ralph R. Goodman

Applied Research Laboratory
The University of Texas at Austin
P.O. Box 8029
Austin, Texas 78713-8029
Attn: Dr. Chester McKinney
Dr. Thomas G. Muir

Dr. Clarence S. Clay
5033 St. Cyr Road
Middleton, WI 53562

Office of Naval Sea Systems Command
Mine Warfare Systems Program Office
Washington, DC 20362
Attn: Mr. James D. Grembi

NSWC
Code U-42, White Oak
Silver Spring, Maryland 20910
Attn: Gregory Page

Geoacoustics Laboratory Div of Applied Marine Physics and Ocean Engineering
Rosentiel School of Marine & Atmospheric Science Un. of Miami
4600 Rickenbacker CSWY Virginia Way
Miami, Fl 33149
Attn: Dr. T. Yamamoto (2)

REPORT DOCUMENTATION PAGE

Form Approved
OBM No. 0704-0188

1. Agency Use Only *(Leave blank).*

2. Report Date.
February 1992

3. Report Type and Dates Covered.
Final

4. Title and Subtitle.
Seabed-Structure Interaction

5. Funding Numbers.

Program Element No.	0601153N
Project No.	R3103
Task No.	000
Accession No.	DN252025
Work Unit No.	93612B

6. Author(s).
R.H. Bennett, et al.

7. Performing Organization Name(s) and Address(es).
Naval Oceanographic and Atmospheric Research Laboratory
Ocean Science Directorate
Stennis Space Center, MS 39529-5004

8. Performing Organization Report Number.
PR 92:016:360

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Naval Research Laboratory
Code 333.2
Washington, DC 20375-5000

10. Sponsoring/Monitoring Agency Report Number.
PR 92:016:360

11. Supplementary Notes.

12a. Distribution/Availability Statement.
Approved for public release; distribution is unlimited.

12b. Distribution Code.

13. Abstract *(Maximum 200 words).*

Intrinsic to the topic of Seabed-Structure Interaction (S-SI) of objects coupled with the sea floor is the dynamics of the "system." The dynamics involve environmental forcing of the object and the seabed, the fundamental properties of the geological material, the size an shape of the object, and the time-dependent processes associated with the coupling of the water column, seabed, and the object. Thus, the most crucial S-SI research problems to address in the Coastal Benthic Boundary Layer Special Research Project (SRP) should focus on the dynamics and time-dependent processes affecting objects coupled to the sea floor. The research efforts should include a range of scales from micro to macro but largely focused on the dynamics and processes in proximity to the object rather than broad scale geological oceanographic processes. Much is to be gained by interdisciplinary research well focused on specific S-SI phenomena.

14. Subject Terms.
Acoustics, Sediments, Mines

15. Number of Pages.
23

16. Price Code.

17. Security Classification of Report.
Unclassified

18. Security Classification of This Page.
Unclassified

19. Security Classification of Abstract.
Unclassified

20. Limitation of Abstract.
SAR