MIT Center Proposal, October 1987

Sections 2.1.2, 2.1.3 and 2.1.5 refer to the work of Dr. S. Shyam Sunder

# SUBMITTAL LIST OF OIL COMPANIES

for

Consortium Cooperative Research on Arctic Offshore Engineering and Construction

by

Center for Scientific Excellence in Offshore Engineering
Departments of Civil Engineering and Ocean Engineering

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# Proposal For

# Consortium Cooperative Research

on

# ARCTIC OFFSHORE ENGINEERING AND CONSTRUCTION

by the

CENTER FOR SCIENTIFIC EXCELLENCE IN OFFSHORE ENGINEERING

Departments of Civil Engineering and Ocean Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

November 4, 1987

## SUMMARY

The Center for Scientific Excellence in Offshore Engineering was established at MIT in September, 1983 by a five year grant of $2 million from The Standard Oil Company with three principal objectives: 1) to conduct coordinated interdisciplinary research on Arctic offshore engineering in partnership with industry; 2) to support students engaged in offshore engineering research; and 3) to develop a scientific interchange program. The Center has typically involved about 30 MIT faculty and graduate students from the Departments of Civil Engineering and Ocean Engineering. They have conducted from four to eight individual research projects each year with funds from the Center and other sponsors in collaboration with several Technical Representatives from Standard Oil Production Company (SOPC). An Advisory Committee, with members from MIT and SOPC, annually reviews research results and budgets and recommends changes in program emphasis or direction.

Establishment of the Center has contributed to the following accomplishments during the past four years:

1) Provided an unique opportunity for faculty, students and industry to work together on a large scale cooperative, interdisciplinary effort encompassing ice and structural, geotechnical, risk and reliability and hydrodynamic aspects of offshore engineering in the Arctic.
2) Made significant progress in development of innovative applied and basic technology to specifically address major technical problems posed by the design, construction and operation of offshore hydrocarbon facilities in the Arctic environment. The Center has also provided leadership to the Arctic offshore engineering community via participation in conferences, workshops and technical committees and by its professional publications.
3) Attracted top quality graduate students who have acquired

special expertise in offshore engineering and Arctic technology (12 SM theses and 5 doctoral theses to date, with 7 doctoral theses currently in progress).

4) Generated broad based support, mostly from governmental agencies, for the Center's activities totalling $1.7M in addition to $1.5M from Standard Oil over the past four years.

Last year, Standard Oil reduced the amount of the original grant due to the decline in oil prices. The original contractual Agreement with MIT has also been modified to enable continued support of the Center by the oil industry.

This proposal invites oil companies to become sponsors of the Center starting January 1, 1988 for an annual fee of $30,000 to support interdisciplinary research in the areas of ice mechanics, ice-structure interaction, geotechnical engineering and hydrodynamic modeling. Consortium Members will receive the following benefits.

1) Immediate access to all prior research results developed as part of the Center's activities over the past four years.
2) The right to representation on the Advisory Committee.
3) An invitation to actively engage in cooperative research by a variety of mechanisms, including technical review meetings and exchange of personnel.

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# 1. BACKGROUND

## 1.1 OVERVIEW OF THE CENTER

The Center for Scientific Excellence in Offshore Engineering was established at MIT in September, 1983, by a five year grant of two million dollars awarded by the Standard Oil Company (now BP America, Inc.) on the basis of a national competition. As described in the Center's Administrative Progess Report No. 7 (enclosed), the criteria used to evaluate the nearly preliminary 1,000 proposals and to select five universities from among 35 finalists stressed excellence in the area of study, support and training of students, collaboration with Standard Oil and innovative research on problems of national significance.

The grant to MIT originally provided $400,000 annually over five years to undertake three tasks.

1) Conduct coordinated research with the primary objective of developing the technology necessary for an overall evaluation of alternative design concepts for Arctic offshore exploration and production platforms. This interdisciplinary effort would encompass basic and applied research on ice and structural, geotechnial, risk and reliability, and hydrodynamic aspects of offshore engineering in the Arctic.
2) Provide support to graduate students engaged in Arctic offshore engineering research.
3) Develop a scientific interchange program between MIT and Standard Oil involving: technical collaboration on research projects, personnel exchange and a program of symposia, seminars and short courses.

Establishment of the Center furthered MIT's goal of playing a leadership role in education and research by extending its already substantial offshore program into the newly developing field of Arctic engineering and by expanding its partnership with industry. This opportunity was considered especially important given forecasts of petroleum reserves in the North American Arctic and the unique technological problems posed by resource development in this geographical frontier due to the severe environment, massive ice floes and weak ocean sediments.

The Center has typically involved about 30 MIT faculty and graduate students from the Departments of Civil Engineering and Ocean Engineering and between five and ten engineers from Standard Oil Production Company (SOPC). An Advisory Committee (six from MIT and three from SOPC) meets once or twice yearly to review research results and budget allocations, to recommend changes in program emphasis or direction, and to evaluate the overall effectiveness of the Center. From four to eight groups of MIT faculty and students conduct individual research projects with funds from the Center and from other sources such as U.S. government agencies, private industry and MIT endowed chairs. Section 2.2 and Table 1 of the Administrative Progress Report No. 7 summarize specific research tasks undertaken by the Center since 1983. Appendix C of that Report shows how the Center has allocated its budget among the various research projects, with about 12% being devoted to administration and the Scientific Interchange Program.

Technical Representatives from Standard Oil served as the key technical link with the research groups. They also lent vital assistance by: providing proprietary data and undisturbed soil samples; identifying newly emerging problems with design and construction; coordinating activities among groups having similar research interests; and helping with practical implementation of research results.

Dr. Charles C. Ladd, Professor of Civil Engineering, has overall responsibility for operation of the Center as its Director. He is assisted by Dr. S. Shyam Sunder, Associate Professor of Civil Engineering and Doherty Professor in Ocean Utilization, who acts as the Associate Director. Mr. Richard D.

Goff, SOPC Manager of Facilities Engineering and Construction, serves as Monitor of the Center for Standard Oil.

## 1.2 ACCOMPLISHMENTS OF THE CENTER

As previously noted, three principal objectives of the Center are to: 1) conduct coordinated interdisciplinary research on Arctic offshore engineering in partnership with industry; 2) support students engaged in offshore engineering research; and 3) develop a scientific interchange program. Since Section 2 of this proposal and Section 4 of Administrative Progress Report No. 7 (APR 7) describe research accomplishments, this section will focus on the other features of the Center.

1) Interaction with industry. The original Agreement between MIT and Standard Oil stressed cooperative research in contrast to more traditional arrangements wherein MIT performs research with minimal, if any, sponsor collaboration or interaction. The first year proved difficult for several reasons: inadequate SOPC staff to provide dedicated Technical Representatives for all research areas; initially ill-defined objectives for some of the research tasks; and general confusion regarding access to and use of proprietary data. But during the next two or three years, most of the research tasks involved good to excellent interaction with industry. Examples include the following: SOPC sponsorship of a special $250,000 program of in situ testing and undisturbed sampling; 1985 fall technical review meetings held both at MIT and in Dallas with participation by 11 Standard Oil-BP staff; support of the Arctic silt research by eight engineering-research organizations; successful redirection of hydrodynamic modeling approach at SOPC's suggestion; and direct involvement by Center staff in the foundation design of a drilling platform. Although budget cuts substantially reduced interaction during the past year, we believe that the Center has clearly demonstrated a willingness and ability to work closely with the offshore industry.

2) Student involvement. The Center produced 12 Master of Science and five doctoral theses during its first four years (see listing in Appendix B of APR 7) and seven doctoral theses are currently in progress. Student theses constitute an extremely important aspect of the Center since: the graduate students are of exceptional calibre; SM and doctoral theses represent the equivalent of about six months and two years full-time effort, respectively; and support of full-time graduate Research Assistants costs only about $2,000 per month for salary, benefits and overhead!

3) Scientific interchange. We believe that the Center has established an international reputation through its publications, participation in and hosting of conferences and workshops, and by leadership in professional societies with interest in Arctic offshore engineering. Appendix B of APR 7 lists papers already published, presented and submitted and Table 2 of APR 7 gives a flavor of their distribution. MIT hosted the June, 1986 International Conference on Ice Technology and conducted two highly successful workshops on ice mechanics in November, 1984 and May, 1985. And Center faculty frequently serve on governmental panels and review boards.

4) Outside funding. Although not a specific objective, Standard Oil did expect its funding to attract other sponsors and hoped that the Center could become self-sufficient after the five year period of the grant. Section 3.4 of APR 7 describes the sources and amounts of outside funding obtained by the research groups to support the Center's activities during the past four years. As summarized in Table 3 (p. 18 of APR 7), the Center received $1.5M from Corporate Contributions of Standard Oil and generated the equivalent of another $1.7M in research and equipment grants. Principal sponsors include the Army Research Office, MIT endowed Chairs, MIT Sea Grant Program, Minerals Management Service, National Science Foundation, Office of Naval Research, Standard Oil Production Co. and several engineering-research organizations.

In summary, we believe that establishment of the Center has contributed to the following accomplishments.

1) Provided an unique opportunity for faculty and students representing various disciplines to work together on a large scale research project of mutual interest.
2) Made significant progress in the development of innovative applied and basic technology to specifically address major technical problems posed by the design and construction of hydrocarbon exploration and production facilities in the offshore Arctic environment.
3) Developed formal mechanisms to provide substantive interaction between MIT and industry via cooperative research that is needed to better guide and conduct the research and to facilitate practical implementation of new technology.
4) Attracted top quality students who have developed special expertise in offshore engineering and Arctic technology.
5) Provided leadership to the Arctic offshore engineering community via participation in conferences, workshops and technical committees.
6) Generated broad based support for research activities in Arctic offshore engineering and construction (though thus far mainly from U.S. government agencies due to the nature of the original Agreement between MIT and Standard Oil).

## 1.3 RECENT DEVELOPMENTS

Based on Standard Oil's favorable evaluation of its Centers for Scientific Excellence program, MIT expected funding for years four and five (i.e. September, 1986 through August, 1988) at $400,000 annually in accordance with the original grant. However, the continued decline in oil prices forced Standard Oil to make substantial budget reductions, including those for Corporate Contributions. As a direct consequence, the Center: submitted revised budgets of $299,000 and $168,000 for years four and five, respectively; terminated its research in the area of Risk and Reliability Engineering rather than making uniform reductions in all research areas; and reduced funds for administration and scientific interchange (revised budget allocations given in Appendix C of APR 7). In return, Standard Oil agreed to substantially modify the contractual Agreement and to assist MIT for the purpose of seeking support for the Center from other oil companies.

In particular, MIT and Standard Oil invited 16 oil companies and 12 government agencies to attend a meeting at MIT on April 6, 1987 entitled "A Research Partnership in Arctic Offshore Engineering and Construction: Recent Results and Future Directions" in order to acquaint them with the Center's activities and accomplishments and to solicit their views on the future for Arctic related research. Appendix A of APR 7 describes the meeting and lists the attendees, which included representatives from ten oil companies. In spite of adverse funding for research by the oil industry, the Center's Advisory Committee was encouraged by the favorable views expressed during the meeting regarding the Center's activities and long range objectives. In fact, several participants considered the Center as being rather crucial for sustaining and advancing relevant long-term research during a period when economic conditions require the offshore industry to curtail its own R&D efforts. Hence, the Advisory Comittee decided to invite other companies to participate in the Center with equal rights to those of Standard Oil before expiration of the five year grant period. It also contacted the National Science Foundation for interim support via its ocean systems engineering program and learned that the program will not be funded in the near future.

### 1.4 CONSORTIUM COOPERATIVE SPONSORSHIP

MIT invites oil companies to become sponsors of the Center under a cooperative agreement starting January 1, 1988 for an annual fee of $30,000. The cooperative aspect is stressed because we believe that a highly interactive relationship with industry will benefit the Center by: keeping it informed of industrial needs and interests; providing access to the sponsors' in-house expertise and proprietary data; enabling interpretations of research results from a different perspective; and providing mechanisms for implementation of new technology. On the other hand, consortium members will receive the following benefits.

1) Immediate access to all prior research results developed as part of the Center's activities over the past four years. This includes specific requests for computer software, experimental data, student theses, Research Reports and professional papers (but excludes Draft Progress Reports as these were informal documents and may contain proprietary data) developed by projects supported by the Center.

2) The right to have a representative serve on the Advisory Committee (see page 9 of APR 7 for current membership, which will be expanded for each new sponsor). As previously described, the Advisory Committee reviews research results and budget allocations, recommends changes in research emphasis or direction and evaluates the overall effectiveness of the Center. Thus, sponsors can represent their own specific interests and goals. MIT requires, however, that final responsibility for directing the research resides with the Director of the Center (Professor Ladd) and the Principal Investigators (i.e. the faculty in charge of individual research projects).

3) An invitation to actively engage in the research via one or more of the following mechanisms: attend periodic briefings by MIT; informal visits to meet with the Center's faculty and students; send a representative to work at MIT on one of the projects (e.g. as a Visiting Scientist, Engineer, etc.); and engage MIT personnel in part-time employment on in-house research.

4) Rights regarding patented inventions and copyrighted software and related documentation equal to those of Standard Oil.

## 1.5 PROPOSED OPERATION DURING 1988

The Center currently has funding from Standard Oil and other (mostly governmental) sponsors to sustain significant research efforts until next fall in the three major areas of research described in Part 2 of the Proposal. New funds obtained by the consortium oil companies will be distributed to the existing projects roughly in proportion to the number of faculty and students. The Center plans to invite the Consortium Members to a meeting at MIT for an extensive technical review of prior, current and future research, probably sometime during February, 1988 (the date would first be cleared with all participants). This meeting may result in changes in research emphasis or direction during 1988 depending upon comments and requests by the sponsors vis-a-vis existing commitments to students and faculty interests and abilities.

A second meeting will be held during the fall, probably at MIT, with two main objectives: 1) technical review of research results and future plans after submittal of Draft Technical Progress Reports by each Principal Investigator; and 2) meeting of the Advisory Committee to recommend budget allocations and research projects for the following year, i.e. starting January 1, 1989. Hence, Consortium Members joining the Center in 1988 can influence research directions during that year and will certainly affect Center activities during 1989. However, the exact scope and nature of the research will obviously depend on the number of oil industry sponsors and the level of funding obtained from other sources to support similar research objectives. Based on recent history, the latter should provide \$300,000±100,000 annually.

# 2. RESEARCH OBJECTIVES, ACCOMPLISHMENTS AND IMMEDIATE-FUTURE PLANS

## 2.1 ICE MECHANICS AND ICE-STRUCTURE INTERACTION

### 2.1.1 Introduction

The overall goal of the research on ice mechanics is to develop the technological knowledge base required for safely and economically engineering constructed facilities in cold regions that either resist ice loads or use ice as a material of construction. This will be accomplished through an extended program of research consisting of the following three interrelated tasks:

1) Constitutive Description of Deformation and Failure in Ice
2) Analytical and Numerical Modeling of Ice-Structure Interaction
3) Analysis of Global Failure Mechanisms of Ice Floes and Ridges

The planned research builds on MIT's disciplinary strengths in the mechanics of materials, mechanics of solids and structures, and computational mechanics as well as its ability to undertake cross-disciplinary research focused on Arctic offshore engineering as evidenced by the accomplishments of the Center for Scientific Excellence in Offshore Engineering. The practical significance of the research has drawn heavily from a continuing dialogue with ice laboratories at home (such as USA CRREL) and abroad, and close interaction with the oil industry. This proposal seeks to further strengthen ties with industry.

The Center's ice research has covered a wide spectrum of problems over the past four years. They include the development of simplified damage models of ice deformation and failure criteria; development of 3-D indentation solutions for an elastic and rigid-plastic material; analysis of 2-D flexural cracking and spalling of edge loaded ice sheets; and a study of splitting failure of finite size ice floes. Most of this work has focused on the summer impact problems associated with large drifting floes.

Significant progress has also been made in the description of ice deformation and failure under "breakout" or creep conditions, characteristic of the winter season. In particular, the problem of indentation in the creeping mode for wide structures in the Arctic nearshore zone has been extensively studied with newly developed numerical simulation models. Advanced constitutive descriptions of three-dimensional viscoelastic flow as well as distributed and local cracking have been developed. Current work is attempting to numerically simulate the formation and propagation of cracks in viscoelastically flowing ice.

A new Low Temperature Materials and Structural Models Testing Facility under development at MIT will represent an integral part of the planned research activity. The primary focus of the laboratory will be to understand and quantify the deformation and failure behavior of ice, specifically to verify the constitutive models under development. Most of the funding for this facility has already been obtained from federal sources such as the National Science Foundation and the U.S. Army Research Office through its Center for Advanced Construction Technology at MIT. Additional funds have been obtained through grants from the Atlantic Richfield Foundation (to MIT's interdepartmental REMERGENCE Laboratory) and the Standard Oil Company.

Descriptions of the individual task areas as well as the Ice Testing Facility are provided in what follows.

### 2.1.2 Constitutive Description of Deformation and Failure of Ice

Boundary value problems in applied ice mechanics involving multiaxial states of stress and complex loading histories, such as those encountered during ice-structure interaction, are increasingly being solved using numerical models including the finite element method. Constitutive models are required to characterize the deformation and progressive failure of ice due to flow, distributed cracking, and localized crack propagation in numerical simulations.

A multiaxial differential flow law has been developed to model the elastic, transient, and steady flow in ice. Flow (or creep) is modeled in terms of two nonlinear deformation-rate mechanisms: the first mechanism governs the transient deformation-rate (creep) which decays to zero as an elastic back stress measure increases asymptotically; the second mechanism, which is modeled in terms of the well-known power law, governs the viscous deformation-rate. The transient deformation, an internal state variable, defines the magnitude and direction of prior deformation history in the material. The uniaxial model, which contains a total of five parameters, satisfies the dimensional requirements identified by M.F. Ashby and P. Duval. The multiaxial generalization follows from conventional elasticity theory and from the rate theory of flow for the viscous and transient deformation-rates. An orthotropic model of incompressible flow has been developed to describe texture anisotropy in ice and equations have been derived for estimating the model parameters from uniaxial data. History effects, which give rise to stress induced or evolving anisotropy, are modeled with a kinematically hardening formulation based on the transient strain (or, equivalently, the elastic back stress) vector. The model predictions have been verified against experimental data, particularly on freshwater polycrystalline ice.

Ice displays purely ductile, purely brittle or combined behavior depending upon the temperature and conditions of loading. The phenomenon of distributed cracking associated with the formation and stable growth of cracks governs the ductile-to-brittle transition or purely brittle behavior of ice. The phenomenon, sometimes termed damage, controls the process of failure of quasi-brittle materials such as ice prior to localization of fracture (formation and propagation of a single crack). Distributed cracking weakens the material; under constant strain rate loading this contributes to "strain-softening" and under constant stress loading to "tertiary" creep. Consequently, the ultimate strength and post-peak response of ice is generally governed by damage. Damage processes are particularly significant when the state of stress involves compression.

Research has been initiated to understand and characterize damage processes and the interaction mechanisms between damage and flow in ice. The study is investigating the influence of confining pressure on damage during constant strain rate loading and under conventional triaxial states of stress. The application of a low to moderate level of confining pressure tends to suppress cracking, which in turn allows a higher shear/distortional stress to be sustained. As the confining pressure is further increased the material displays pressure in sensitive ductile flow, and eventually at very high confining pressures ice may undergo a change in phase or morphology. This research involves the following sub-tasks:

(a) To generate a comprehensive set of experimental data under triaxial loading at constant strain rates in the ductile-to-brittle range.

(b) To investigate the formation of "first" cracks during deformation under <u>triaxial</u> loading by monitoring acoustic emissions.

(c) To develop and apply quantitative acoustic emission theory for locating cracks (position, time, direction, and size) under triaxial loading.

(d) To theoretically characterize the rate-sensitive evolution of damage during deformation by viscoelastic flow.

Previous work at MIT has established the link between the first crack formation under tensile and compressive loading under uniaxial conditions based on a rate-sensitive limiting tensile strain criterion. It has been shown that first crack formation governs the tensile strength and yield in compression for ice with moderate to large grain size. Sub-task (b) will allow generalization of the relationship to multiaxial states of stress. This will result in a rate-sensitive failure theory for ice that will limit deformations and define strength when the state of stress involves tension and define yield in pure compression. The material can sustain additional stress after yield in pure compression.

Localized crack propagation under tension can be characterized in terms of a toughness or energy measure. Ice displays both "quasi-brittle" and "creep" behavior depending on the temperature and rate of loading. Objectives of current MIT research are to (i) establish the conditions under which linear elastic fracture mechanics is applicable and that under which a nonlinear characterization of fracture behavior is necessary; and (ii) characterize the fracture toughness when linear elastic fracture mechanics theory is not applicable. This involves a study of the toughening mechanisms particularly at high rates of loading and low temperatures where ice behaves as a "quasi-brittle" material. In such materials, the "process" zone ahead of the crack tip is localized on a plane and does not resemble the kidney shaped plastic zone of metals. The process zone behavior can be characterized in terms of a stress-separation relationship. The following specific sub-tasks are to be undertaken:

(a) To analyze the fracture process zone in ice using optical techniques such as scanning electron microscopy (SEM).

(b) To experimentally determine the stress-separation relationship for ice under Mode I fracture.

(c) To develop theories for predicting the process zone size and critical crack tip opening displacement (CTOD) during ice fracture based on the experimentally determined stress-separation curves.

(d) To develop specifications for fracture testing of ice, particularly the selection of specimen sizes.

The principal investigator for this task is Professor S. Shyam Sunder.

### 2.1.3 Analytical and Numerical Modeling of Ice-Structure Interaction

This task seeks to develop methods for establishing the local and global contact forces which arise during ice-structure interaction. Crucial insight into this complex problem can be achieved by examining various, suitably idealized, analytical and numerical models. These models are to be developed for various indentation scenarios and therfore employ approximations of ice deformation response which range from linearly elastic to mroe general rate-sensitive constitutive descriptions. The proposed research focuses on analytical models and numerical models separately. They are further described below.

Analytical Modeling of Ice-Structure Interaction: In view of the sensitivity of ice strength to confinement conditions, accurate descriptions of the three-dimensional states of stress in the contact zone are of particular importance. Ice sheet indentation models have previously been developed which idealize the ice as a rigid-perfectly plastic material. Upper and lower bounds for indentation pressures can thus be determined using limit analysis. Various yield functions can be used in the three-dimensional models which are capable of analyzing small, intermediate and large aspect ratios. The transition from plain stress to plain strain conditions can therefore now be determined. The planned research seeks to focus on higher velocities of impact which result in brittle deformation of the ice sheet. Three-dimensional elasticity solutions for an edge loaded sheet have recently been developed for which the edge tractions are prescribed. Future work will involve the analysis of anisotropic ice sheets, for which analytical solutions may be obtained for both prescribed edge forces and prescribed displacements. These results can then be used for the prediction of contact pressures which result in identation, spalling and flaking.

The principal investigator for this task is Prfoessor Dale G. Karr.

Numerical Modeling of Ice-Structure Interaction: The objective of this research is to investigate using numerical models the mechanics of deformation and progressive failure in ice for the purpose of predicting global forces and local pressures generated on offshore structures proposed for deployment in the Arctic. This work includes: (1) the development of finite element methods of analysis to account for nonlinearly viscoelastic flow and smeared crack models of ice; and (2) the numerical simulation of ice-structure interaction processes for ice sheets indenting rigid cylindrical structures.

A finite element method of analysis has been developed for the nonlinear viscoelastic and anisotropic behavior of ice based on a weighted equilibrium-rate formulation. The rate formulation allows realistic simulation of the spatial-temporal variability in the strain rate field and no empirical definition of an average strain rate measure is necessary as in ice load models derived from plasticity theory. The kinematically hardening constitutive model of flow consists of stiff differential equations that pose serious stability and efficiency limitations. An efficient explicit-implicit numerical integration algorithm based on a gradient (Newton-Raphson) technique has been developed which enables fast convergence in problems where inelastic deformations dominate. Variable interface conditions between the ice feature and the structure can be simulated to bound the effects of interface bond or friction.

Numerical simulation studies have been performed under plane stress conditions to study the sea ice indentation problem for wide structures under steady flow conditions. Creep is the predominant mode of deformation for artificial islands in the Arctic nearshore region during "breakout" and/or steady indentation conditions occuring during winter. Further, stresses, strains and strain rates resulting from creep are necessary to predict the growth and propagation of localized and distributed cracks when rate effects influence fracture behavior. The numerical simulations quantify the effect of (i) material model, i.e., isotropic versus transversely isotropic; (ii) natural variability in material parameters; (iii) approximate versus "exact" methods of analysis and the ability of each to model interface adfreeze and friction as well as spatial-temporal variability in the strain rate field; and (iv) grounded rubble pile or accreted ice foot. Theoretical predictions of pressure-area curves used in the design of structural components have been developed.

The primary focus of current research is concerned with modeling quasi-static propagation of discrete tensile cracks and the development of distributed cracking or "damage" zones under compressive loading. The numerical model under development is a generalization of the finite element formulation to account for tensile cracks and damage zones. Two of the more common approaches for studying tensile cracking are the discrete crack models which follow individual discrete cracks between elements and the smeared crack models which treat the gross (smeared) effects of cracks in an element. The latter approach is computationally far more efficient and convenient; and eliminates the need for remeshing as the crack advances. An added advantage is that smeared crack models can be extended easily to allow for an objective energy release rate criterion for propagation of discrete tensile cracks. This criterion helps modify a "tensile strength" based crack propagation criterion, which produces results that may be sensitive to the particular choice of a finite element mesh size, to a "toughness" or "energy" based criterion that governs the fracture behavior of materials. The resulting theory is called the blunt crack theory. The smeared crack model and its variation, the blunt crack bank theory, is known to provide accurate estimates of overall material response although details of individual crack growth patterns are known less precisely. But in applications where the primary objective is to predict the total loads transmitted by an ice feature, as is the case for ice, such details are of less importance.

These crack models will be developed and implemented in conjunction with the rate-sensitive multiaxial failure criterion for compressive yield/tensile fracture strength also under development. Generalization of the finite element formulation for modeling the development of damage zones will require the development and implementation of a numerical algorithm for simulating strain-softening as well as the constitutive theory of rate-sensitive damage.

The principal investigator for this task is Professor S. Shyam Sunder.

### 2.1.4 Analysis of Global Failure Mechanisms of Ice Floes and Ridges

The objective of this task is to describe the process of initiation of cracks in ice sheets and the transition from local compressive failure to global cracking and fragmentation of ice plates. From the analyses, reliable estimates of the magnitude of loads exerted by moving ice sheets impinging stationary structures will be obtained. The same results can be used to improve existing models of ice dynamics at the intermediate and large scale.

The cornerstone of the proposed new approach to ice load prediction is the concept of an interactive failure. This concept is based on the observation that local crushing deformation at the ice-structure interface induces global failure of ice in the form of either horizontal spalling or radial and circumferential cracking. The process of global failure of ice serves then as a force limit which prevents the total contact area from developing its full crushing strength. The above effect, in conjunction with the concept of structural imperfections, and non-simultaneous failure will lead to the derivation of design oriented formulas for applications in offshore structural design. There are a number of practical scenarios that will be addressed during the course of the proposed research. They will include:

(a) Analysis of splitting failure of inertia driven circular and rectangular floes hitting stationary structures.

(b) Determination of cushioning effect of smaller floes trapped between the structure and large incoming floes.

(c) Study of floe-to-floe impact.

(d) Investigation of the effect of edge crushing, chipping and spalling of the initiation of rafting and ridge building activity.

(e) Quantitative assessment of the effect of residual stresses, thickness variation, and load eccentricities on the flexural failure of multi-year ice covers.

The theoretical prediction will be validated by laboratory experiments on brittle disks, large scale tests conducted by the industry (e.g., Hans Island), mesoscale measurement of ice cover provided by the MIZEX project and more recent data acquired by the Arctic Acoustics Group at MIT.

The principal investigator for this task is Professor Tomasz Wierzbicki.

### 2.1.5 Temperature Materials and Structural Models Testing Facility

The Low Temperature Materials and Structural Models

Testing Facility, under development at MIT, will allow experimental research at temperatures in the range of -50°C to 0°C. The facility will include the special sample preparation and testing equipment as well as data acquisition system listed below:

(1) Three cold rooms: for (i) growing seed ice crystals and ice specimens; (ii) sample preparation, thin section photography, and post test sample preparation for SEM analysis; and (iii) mechanical testing. The testing room will be capable of temperature control to within 0.2°C or better. Temperature in the growth room may be reduced up to -10°C with the same variation, but this room will also be able to sustain a temperature gradient in the vertical direction. The third room will operate at temperatures between 0° and -2°C with a coarse temperature control.

(2) Loading frame rated at 220 kips and cross-head speed of 1 in/s and able to accommodate varable size specimens up to 30 in: the frame will be a general purpose four-post uniaxial system capable of applying compression, tension and cyclic loading. Independent control of the radial stress for triaxial testing will be accomplished using a servo-controlled valve attached to a transfer barrier. The hydraulic actuator will be rated at 360 kips in order to deliver 220 kips at 1 in/s. The design will minimize mechanical noise for acoustic emission monitoring.

(3) Triaxial cell to accommodate specimen sizes up to 6 inches in diameter and 14 inches in height. The device will include an internal load cell as well as radial and axial deformation transducers. This cell will be capable of delivering a confining pressure of up to 12 ksi.

(4) Acoustic emission monitoring system with host computer, transducers and multi-channel monitoring system. Available software for location analysis will be included, while others will be written.

(5) Data acquisition system composed of a microprocessor/controller and a high speed analog to digital converter. The systems will include (i) multi-channel signal conditioning, (ii) high speed multiplexer and voltmeter, (iii) computer based controller, and (iv) data processing of graphics display.

Funding for the testing facility has been obtained from the National Science Foundation, the Standard Oil Company (now BP America), the Atlantic Richfield Foundation, Army Research Office, and MIT. The cold rooms have been installed and are operational. Specimen preparation equipment have either been purchased or are being designed and fabricated at MIT. After extensive negotiations, quotations have been obtained for the mechanical testing machine, the triaxial cell, and the acoustic emission equipment. These should be installed within a year's time with some additional financial support from the Army Research Office (through its Center for Advanced Construction Technology at MIT). The overall cost for the testing facility is about $500,000. Funds will be required from the Center for operational costs and salry of laboratory staff.

The principal investigator for this facility is Professor S. Shyam Sunder. Dr. John T. Germaine, Director of MIT's REMERGENCE Laboratory (of which facility is an integral part) is co-principal investigator. The facility also supports 25% of a technician's time.

## 2.2 GEOTECHNICAL ENGINEERING

### 2.2.1 Background and Research Objectives

Beaufort Sea gravity structures must withstand large ice loads at sites where the subsea soil profile often consists of weak Arctic silts overlying relic permafrost. These conditions pose two unique foundation design problems compared to structures located in temperate climates: 1) lack of experience with structures where horizontal forces constitute the dominant design load; and 2) the unusual nature of Arctic silts compared to other offshore soil deposits. Although simplified analyses based on empirically derived soil parameters have generally proven satisfactory for gravel islands in shallow water, such procedures are not adequate for the foundation design of the new generation mobile gravity structures. Hence, the geotechnical research effort has two objectives:

1) Develop specific guidelines regarding recommended in situ and laboratory equipment and procedures to reliably measure the stress-strain-strength properties of Arctic silts subjected to complex loading conditions, which started in fall 1983;
2) Develop theoretical procedures for predicting the foundation stability and deformations during initial set-down and subsequent ice loading, which started in fall 1984.

### 2.2.2 Research Approach and Past Accomplishments: Experimental

The Arctic silt research entails three interrelated experimental phases (also see Section 4.4.1 of APR 7):

1) Develop an understanding of the geologic history of the Beaufort Sea silt deposits, their variability in terms of composition and index properties, and reasons for their unusual behavior compared to other offshore sediments;
2) Detailed investigation of basic strength-deformation properties as a function of temperature, geologic and stress histories, and mode of failure (anisotropy) needed to predict foundation performance during and after set-down;
3) Develop a special laboratory shear testing device to simulate stress-strain-strength behavior under the very complex stress conditions imposed during ice loading.

Work under Phases 1 and 2 during the past four years focused mainly on detailed investigations at three Beaufort Sea sites. At the first site adjacent to Mukluk Island in the "soft zone area" of Harrison Bay, SOPC conducted a special program of piezocone testing and continuous fixed piston sampling for the Center. The laboratory program on these samples (plus others from Harrison Bay) included: carbon dating and pollen analysis; compositional analyses; radiography to assess disturbance and macrofabric; an extensive evaluation of stress history and consolidation properties (including effects of temperature); and assessment of undrained stress-strain-strength properties via $K_o$ consolidated-undrained ($CK_oU$) triaxial compression/extension and direct simple shear testing. The latter employed SHANSEP to measure behavior as a function of overconsolidation ratio and for comparison with the Recompression technique. At the other two sites located in Smith Bay, SOPC furnished comprehensive data from programs conducted as part of design studies for an offshore platform, these including results from piezocone and field vane tests and laboratory consolidation and Recompression $CK_oU$ strength testing. The Center conducted an extensive series of SHANSEP direct simple shear tests for comparison. One of the Smith Bay sites had been subjected to severe ice gouging, whereas the other was heavily overconsolidated throughout and both contained CL-CH clays rather than ML-MH silts. Five unpublished SM theses present research results from this four year study that was co-sponsored by MIT Sea Grant and several engineering-research organizations.

Benefits to date from the Phase 1 and 2 experimental research can be summarized as follows. Regarding basic soil behavioral issues, our comprehensive evaluation of the stress history, strength and consolidation properties at three Beaufort Sea sites:

- Demonstrates the extreme importance that geologic history has on the resultant strength-compressibility profiles, meaning Pleistocene versus Holocene and the effects of ice gouging (although the mechanisms causing preconsolidation in Holocene deposits remain unclear);
- Indicates that the basic stress-strain-strength properties

of Arctic silts are not that different from other offshore sediments (although we are still collecting data from other sponsors to cover a broader range of soil types);

- But correct assessment of these properties requires more careful sampling, laboratory testing and interpretation than usually obtained from routine investigations.

Regarding the impact of our research on engineering practice, we have shown that:

- Site investigations should employ fixed piston sampling, as opposed to prior use of push samples;
- Field vane and conventional laboratory undrained strength testing will often yield unreliable data due to excessive scatter and/or extreme bias on the unsafe side (e.g., by 50 to 500% at Smith Bay);
- Cone penetration data can seriously overestimate design strengths due to partial drainage and/or with highly overconsolidated deposits;
- SHANSEP appears to be more reliable than the Recompression technique for estimating in situ stress-strain-strength properties;
- Undrained strengths for initial foundation stability can be estimated for preliminary design via the following relationship

$$c_u/\sigma'_{vo} = (0.26 \pm 0.02)(OCR)^{0.7-0.8}$$

The above experimental work was supervised by Professor Ladd and Dr. Germaine, Head of MIT's Geotechnical Laboratory, and earlier by Professor Einstein (see Part 3 for biographical data on the Principal Investigators). Section 2.2.4 describes research under Phase 3.

### 2.2.3 Research Approach and Past Accomplishments: Theoretical

Gravity Arctic structures can cause severe stressing of the foundation soils due to vertical gravity loading and especially due to horizontal ice loading, and hence to significantly lower factors of safety against foundation failure than typical of conventional offshore structures. Research in the theoretical area first concentrated on undrained stability due to vertical gravity loads since little information existed on the bearing capacity of very wide rigid structures founded on thin soft layers (e.g., 25 ft of Arctic silt over relic permafrost). It then focused on identification of problems associated with predicting foundation performance under horizontal ice loadings, regarding both the ultimate resistance and especially deformations prior to failure. These studies clearly showed the need for a "generalized" soil model in order to predict undrained, partially drained and fully drained behavior under complex states of stress. Hence, this write-up will focus on that aspect of the Center's theoretical research (Section 4.4.2 of APR 7 summarizes the other work and presents further details on MIT's soil modeling efforts).

Cambridge University developed the first generalized stress-strain model in the 1960's to predict the behavior of isotropically consolidated triaxial compression tests during undrained and drained shear. Although still used in offshore practice to predict foundation performance, the Modified Cam-Clay neglects important soil features such as: initial anisotropic stresses, stress-strain-strength anisotropy and strain softening. Subsequent work at MIT removed these limitations (1982 doctoral thesis by Kavvadas) for its research on piezocone penetration and offshore friction piles. But the MIT-E1 model treats stress-strain behavior within the yield surface in a nonlinear, elastic fashion and therefore, like the Modified Cam-Clay, is restricted to lightly overconsolidated soils.

Research partially supported by the Center has developed the MIT-E3 constitutive model to describe the behavior of soils with varying overconsolidation under both monotonic and cyclic loading (1987 doctoral thesis by Whittle). It has three components: 1) a Perfectly Hysteretic model describing behavior at small strain levels; 2) an Elasto-Plastic model for OCR=1 clay describing evolving anisotropy via rotational hardening of the yield surface; and 3) a Bounding Surface model describing plastic strains for overconsolidated soils. Using model input parameters from fairly standard laboratory test data on Boston Blue Clay, MIT-E3 gives excellent predictions of: the effects of OCR; the anisotropic stress-strain response measured in the Directional Shear Cell; and cyclic loading in undrained direct simple shear tests.

The above theoretical research was supervised by Dr. Baligh, Professor of Civil Engineering.

#### 2.2.4 Planned Research for 1988

Experimental research on the Phase 3 objective of measuring stress-strain-strength behavior of Arctic silts during ice loadings started two years ago as part of a doctoral thesis by Mr. DeGroot. The problem is very complex due to the large radial strains that are likely to occur during initial set-down (especially if the silts exhibit the pronounced strain softening measured in direct simple shear tests), followed by stress increments during ice loading that cause substantial changes in the direction of shearing. An unique shear device capable of simulating this complex mode of shearing has been designed and constructed. The equipment, which incorporates extensive automation, applies normal and shear stresses increments due to gravity loading in one direction (with full or partial drainage) and then shears the soil undrained (similar to a conventional direct simple shear) to replicate the ice loading at angles ranging between zero and 180 degrees. Proof testing is nearly completed and the first comprehensive test series will study basic behavioral trends for Boston Blue Clay since it has an unique data base regarding anisotropic stress-strain-strength properties. The MIT-E3 model will also be used to predict behavior and guide the experimental program. Undisturbed samples from Mukluk will then be tested.

Although the above experimental research, combined with evaluation of the MIT-E3 model's ability to adequately describe Arctic silt behavior, will constitute the main effort during 1988, we also plan to prepare draft guidelines for recommended in situ and laboratory equipment and procedures for measuring engineering properties needed for the foundation design of Arctic offshore gravity platforms. The Center originally planned to have significant input from several geotechnical firms with Arctic offshore engineering experience during preparation of this "manual," plus access to in situ and laboratory test data from other Beaufort Sea sites. Unfortunately, the decline in oil prices and Arctic exploration caused these firms to largely withdraw from our cooperative research. Hopefully, one or more of the new Consortium Members will want to participate both regarding their practical expertise and access to experimental data.

Staff for the Geotechnical Engineering research during 1988 include: Professor Ladd as Principal Investigator; Dr. Germaine (Lecturer and Head of the Geotechnical Laboratory with special expertise in experimental soil mechanics); Dr. Whittle (Research Associate with special expertise in constitutive modeling and computer application) and Mr. DeGroot, who should be finishing his doctoral thesis. Professor Baligh, although on sabbatical leave until June, 1988, will be available to help with problems related to theoretical soil mechanics, foundation engineering and in situ testing.

2.2.5 <u>General Plans for Continuation After 1988</u>

Besides completing any unfinished goals described above, continued research in the general area of soil modeling appears warranted and certainly represents a prime interest of the geotechnical group. Implementation of MIT-E3 into practice first requires development of a suitable finite element code, although this might best be done in close cooperation with Consortium Members. More appropriate research by the Center might then focus on making the model more versatile, especially regarding: incorporation of "rate effects" which can become important in problems involving very fast shearing rates; and improved predictions of heavily overconsolidated clays where behavior may be strongly influenced by development of localized deformations (rupture zones) before reaching critical state conditions.

The following summarizes two other topics of interest to the geotechnical group, although not necessarily restricted to Arctic offshore engineering.

1) Deep water structures, especially involving long friction piles in cohesive soils. MIT has conducted extensive research in this area during the past 10 years via a combination of theoretical studies (Baligh's Strain Path Method and MIT's generalized soil models), behavior observed in a model pile (the Piezo Lateral Stress Cell) and evaluation of pile load tests (Empire, NGI, etc.). This work is currently being supported by MIT Sea Grant and several oil companies.

2) Site characterization by in situ testing. MIT developed the first piezocone device and has long studied the fundamentals controlling undrained penetration and subsequent dissipation of excess pore pressure. It also has experience with the self-boring pressuremeter and more recently with Marchetti's flat plate dilatometer. We expect significant new support from government agences of continued research in this area.

## 2.3 HYDRODYNAMIC MODELING

### 2.3.1 Background and Research Objectives

Periods of open or partially ice-covered waters coincide with the occurrence of rather severe storms in the Arctic. An ability to predict the characteristics of storm-generated waves, wind-induced currents and set-up, and the movement of ice floes in partially ice-covered waters is essential to the proper planning and design of offshore structures and operations in the Arctic.

The ultimate objective of this research is to develop a general numerical model for the prediction of wind wave characteristics, wind-induced currents, wind set-up, and ice floe movements in partially ice-covered Arctic waters. This general model should consist of the following components:

i) A finite-depth wind wave model;
ii) A hydrodynamic circulation and set-up model; and
iii) An ice floe movement model.

### 2.3.2 <u>Research Approach and Past Accomplishments</u>

Our initial efforts concentrated on developing a purely hydrodynamic model consisting of components i) and ii) above. To this end we:

- Developed an improved model for wave-current boundary layer flows [1], and incorporated this model as the coupling link between a wind-wave model and a depth-averaged hydrodynamic circulation model [2].

Following the advice of Standard Oil Production Company's technical representative for hydrodynamic modeling our efforts were subsequently directed towards a coupling of modeling components ii) and iii) above. In pursuit of this goal we:

- Derived the depth-averaged coupled equations governing hydrodynamic circulation and ice floe movement for partially ice-covered continental shelf waters, from first principles [2].
- Developed a novel and simple methodology for the determination of drag coefficients of ice floes from field experiments [3,4].
- Developed a numerical finite element model for the solution of the coupled equations governing hydrodynamic

circulation and ice floe movement, and verified this model for idealized applications [2]. Applied the model to real-world conditions, corresponding to those encountered during a field study of ice floe movements on the North Alaskan Shelf, to predict with reasonable agreement the observed movement of two instrumented ice floes [2,5].

- Supplied to SOPC tapes containing the computer code for the finite element model with an accompanying User's Manual.

While the results obtained from the depth-averaged coupled hydrodynamic and ice floe movement model were encouraging, the basic model formulation - the use of depth-averaged water velocity - was recognized to have certain drawbacks: a) the use of the depth-averaged velocity slows the temporal response characteristics of the water column; and b) a water velocity (direction as well as magnitude) representative of the flow at a depth comparable to the depth of submergence of the ice floe is a more realistic reference water velocity than the depth-averaged velocity when formulating the hydrodynamic ice floe drag.

Both of these shortcomings in the existing model formulation are currently being addressed by developing a model in which the water column is considered to consist of two layers: an upper layer in which both ice floes and water affect the dynamics; and a lower layer which contains only water. This two-layer model is described in some detail in the next section.

Dr. Madsen, Professor of Civil Engineering, supervised the above research and Mr. Terry Walden served as Technical Representative for SOPC.

### 2.3.3 Planned Research for 1988

While believing that we have succeeded in developing an operational model for the prediction of ice floe movement in partially ice-covered Arctic waters, the model does, however, represent no more than a "zeroth order" or "first generation" model, in that the present formulation of the coupled equations governing ice and water movement is based on the volume/depth-averaged equations, i.e., the water velocity variable used in the model corresponds to the water velocity averaged over the water volume/depth. This average velocity is also used, in conjunction with a hydrodynamic drag coefficient, to express the hydrodynamic drag experienced by an ice floe. However, if the ice floe thickness is not comparable to the water depth, e.g., first-year ice floes and/or deep water, a water velocity (magnitude and direction) representative of the floe at a depth comparable to the depth of submergence of the ice floe is a more realistic reference velocity for the hydrodynamic drag than the volume/depth-averaged velocity. As a striking example, consider an ice floe of relatively small thickness moving under the influence of wind on water of large depth. For this condition the depth-averaged water velocity is of negligible magnitude and directed perpendicular to the direction of the wind as a result of Coriolis acceleration, while the near-surface water velocity is nearly in the wind direction (off by 10-15°) and of a magnitude of about 3% of the wind speed. For a model based on the depth-averaged velocity the ice floe would be predicted to move at a speed of about 1.6% of the wind speed in a direction slightly to the right of the wind. However, a model accounting for the near-surface velocity as the appropriate reference velocity for the evaluation of the hydrodynamic drag would predict an ice floe velocity of about 4.6% of the wind speed, i.e., a threefold increase in ice floe velocity. To overcome this weakness of the existing model formulation we are presently developing a two-layer coupled ice-water model in which the water column (in the existing model regarded as a single layer) is considered to consist of two layers: a) an upper layer of a thickness of the order twice the depth of submergence of the ice floes, b) a lower layer which contains only water. In addition to providing a more realistic advective velocity for the ice floes -the water velocity in the upper layer - the two-layer model will also make the surface waters and hence the ice floes respond more quickly to rapid changes in wind velocity and direction - a shortcoming of the existing depth-averaged formulation noted in our comparison with observed ice floe movements:

At this point we have:

- Derived the volume/depth-averaged governing equations for each of the two layers, from first principles.

Of crucial importance to this two-layer model is the interfacial shear stress transferring momentum from the upper to the lower layer. To obtain a realistic parameterization of the interfacial shear stress we have adopted the simple turbulent eddy viscosity model for wind-induced flows in finite-depth waters proposed by Madsen (JPO v7 n2, 1977). Solving the governing equations for steady state conditions, including an arbitrary pressure gradient, allows the shear stress to be determined at any depth below the surface. By relating this shear stress (the interfacial shear stress) to the difference between the depth-averaged velocities of the two layers - obtained by integration of the complete analytical solution - a surprisingly simple relationship for the interfacial shear stress has been shown to hold with good accuracy. Thus, we have:

- Established a simple parameterization of the interfacial shear stress in terms of the difference in depth-averaged velocities of the two layers. The relationship is linear in the velocity difference and independent of depth of the top layer so long as this is less than 40% of the total depth!

Presently, the finite element code of the existing model is being modified to accommodate the two-layer formulation and accept boundary conditions corresponding to a non-straight coastline. In addition to establishing the general numerical model the simple, yet realistic, form of the interfacial shear stress makes it feasible to look for analytical solutions for idealized shelf configurations and wind-forcing events. These analytical solutions will be pursued and will serve as test cases for the numerical two-layer model once it is available. Having established confidence in the numerical two-layer model's ability to reproduce idealized analytical results, it will be applied to the real-world test case for (hopefully improved) comparison with ice floe movement observations.

It is anticipated that the research described above can be completed by January, 1989 and will result in a User's Manual and tapes containing the computer code for the general two-layer finite element model, in addition to a general report (Doctoral Thesis) describing theoretical aspects of the model formulation.

### 2.3.4 General Plans for Continuation After 1988

By the end of 1988 we should have:

1) A purely hydrodynamic model for wind-waves and wind-induced circulation and set-up on continental shelves.
2) A hydrodynamic circulation and ice floe movement model for partially ice-covered continental shelf waters.

While the first model does not account for the presence of ice floes on the water surface - particularly important for the prediction of wind-generated wave characteristics - the second model does not account for the presence of waves and the resulting wave-induced motion of the ice floes. To achieve the overall objective of the research as stated in the Introduction, we must account for the presence of ice in the wave model and for the presence of waves in the ice floe movement model. To achieve this goal, i.e., the merging of the two model components 1) and 2), represents the plans for continuation of this research effort beyond 1988.

It would appear beyond the present state of knowledge of and ability to predict wind generated waves in finite-depth waters to attempt to account for the presence of ice floes in a sophisticated wind-wave model. Similarly, the second-order wave-induced drift force on floating ice floes may be approximately evaluated only for idealized floe geometries, which also suggests the adequacy of a simple and approximate wave prediction model. The approach to be followed therefore stresses simplicity.

Briefly, the literature will be searched for simple formulations of scattering of waves by isolated floating bodies of idealized form, e.g., finite length cylinders. This information will be used to estimate the reflection and transmission of waves incident on an ensemble of floating bodies. For the wave generation problem the energy (or momentum) contained in the reflected waves will be considered lost so that the wind will be acting on a wave field characterized by the transmitted wave. For the wave-induced mean motion of the ice floes the mean momentum of the reflected waves suffices to estimate the wave-induced drift force. In this manner simple models accounting for the effect of ice floes on wave generation by wind and for the effect of waves on ice floe movement can be established.

A unique possibility of testing some of the model components mentioned above will exist in the Ralph M. Parsons Laboratory at MIT by 1989. By this time a three-dimensional wave basin (12 m by 18 m) equipped with 47 individually controlled wave paddles (each 0.3 m wide) currently under construction should be completed. In this facility it will be possible to generate a three-dimensional sea state and test, e.g., reflection and transmission characteristics of realistic waves incident on an ensemble of floating bodies as well as the wave-induced mean motion of the floating bodies caused by the incident waves.

### 2.3.5 References

[1] Grant, W.D., and O.S. Madsen (1986). "The Continental Shelf Bottom Boundary Layer." Annual Review of Fluid Mechanics, M. Van Dyke, ed. 18:265-305.

[2] Bruno, M.S. (1986). "A Coupled Hydrodynamic and Ice Floe Movement Model." Sc.D. Thesis, Department of Civil Engineering, MIT.

[3] Madsen, O.S., and M.S. Bruno (1986). "A Methodology for the Determination of Drag Coefficients for Ice Floes." Symposium Proceedings OMAE'86 4:410-417.

[4] Madsen, O.S., and M.S. Bruno (1987). "A Methodology for the Determination of Drag Coefficients for Ice Floes." Transactions ASME, Journal of Offshore Mechanics and Arctic Engineering.

[5] Bruno, M.S., and O.S. Madsen (1987). "Coupled Circulation and Ice Floe Movement Model for Partially Ice-Covered Continental Shelves." Submitted to Journal of Geophysical Research.

## 3. BIOGRAPHICAL DATA FOR PRINCIPAL INVESTIGATORS

Charles C. Ladd, Director

S. Shyam Sunder, Associate Director

Dale G. Karr

Ole S. Madsen

Tomasz Wierzbicki

11/87

# BIOGRAPHICAL DATA

## CHARLES CUSHING LADD III

## PROFESSOR OF CIVIL ENGINEERING

## MASSACHUSETTS INSTITUTE OF TECHNOLOGY

I **PERSONAL DATA**

Born November 23, 1932, Brooklyn, New York
Married 1954 with four children.

II **MAJOR PROFESSIONAL FIELD**

Geotechnical Engineering with specialization in soil behavior, in situ and laboratory testing, softground construction, foundation stabilization and offshore engineering.

III **EDUCATION**

| | | |
|---|---|---|
| 1955 | A.B. | Bowdoin College (cum laude) |
| 1955 | S.B. | Building Engineering and Construction, M.I.T. |
| 1957 | S.M. | Civil Engineering, M.I.T. |
| 1961 | Sc.D. | Soil Engineering, M.I.T. |

IV **EMPLOYMENT AND MAJOR EDUCATIONAL POSITIONS**

| | |
|---|---|
| 1955 - 1957 | Research Assistant, Department of Civil Engineering, M.I.T. |
| 1957 - 1961 | Instructor of Civil Engineering, M.I.T. |
| 1961 - 1964 | Assistant Professor of Civil Engineering, M.I.T. |
| 1964 - 1970 | Associate Professor of Civil Engineering, M.I.T. |
| 1967 - 1968 | Visiting Consultant, Haley and Aldrich, Inc. |
| 1969 - 1970 | Acting Head of Geotechnical Division, M.I.T. |
| 1970 - 1972 | Chairman, Department of Civil Engineering Committee on Graduate Students and member, Graduate School Policy Committee, M.I.T. |
| 1983 (Jan.) | Visiting Senior Scientist, Norwegian Geotechnical Institute |
| 1983 - | Director, Center for Scientific Excellence in Offshore Engineering, M.I.T. |
| 1984 - | Graduate Admissions Officer and Member of Civil Engineering Department Council, M.I.T. |

## V PROFESSIONAL REGISTRATION

Massachusetts (No. 19788)

## VI PROFESSIONAL SOCIETIES AND ACTIVITIES

American Society of Civil Engineers (Fellow)
- Professional Activities Committee (1982-)
- Committee on Curricula and Accreditation (Chairman 1981-82)
- Geotechnical Engineering Division
  - Publications Committee (1969-84)
  - Awards Committee (1975-1982; Chairman, 1984-)
  - Past Chairman of Soil Properties Committee

American Society for Engineering Education

American Society for Testing and Materials
- Member of several subcommittees

Boston Society of Civil Engineers Section of ASCE
- President, Board of Government (1977-1978)
- Past Chairman of Geotechnical Group
- Past Chairman of Structural Group

British Geotechnical Society

Canadian Geotechnical Society

International Society of Soil Mechanics and Foundation Engr.
- Chairman, Review Committee for U.S. papers for 11th ICSMFE

National Society of Professional Engineers

Transportation Research Board
- Committee on Embankments and Slopes

Board of Commissioners, Department of Public Works, Concord, Mass. (1965-1978)

## VII HONORARY SOCIETIES, AWARDS, ETC.

Chi Epsilon, Phi Beta Kappa, Sigma Xi, Tau Beta Pi

Walter L. Huber Civil Engineering Research Prize (1969) of the American Society of Civil Engineers

Croes Medal of the American Society of Civil Engineers (1973) for paper entitled "Initial Settlement of Structures on Clay"

Norman Medal of the American Society of Civil Engineers (1976) for paper entitled "New Design Procedure for Stability of Soft Clays"

General Reporter, Session I, 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo (1977)

Effective Teaching Award, Dept. of Civil Engr., M.I.T. (1980)

National Academy of Engineering (1983)

Co-Reporter, Session II, 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco (1985)

Karl Terzaghi Lecture of American Society of Civil Engineers (1986)

## IX CONSULTING EXPERIENCE (Con't.)

Review Board Member on MBTA Redline Extension for Sverdrup & Parcel and Assoc.

Consultant to Brown & Root, Inc. on foundation stabilization for cement plant in Mobile, Alabama

Consultant to Ardaman Associates on engineering properties of phosphatic waste clays

Consultant to Woodward Clyde Consultants on:
- Foundation stabilization for highway in Omaha
- Feasibility of guyed tower for offshore drilling
- Evaluation of soil properties for N.Y. Westway Project
- Foundation stabilization for chemical waste storage ponds, Beaumont, Texas

Consultant to Engineering-Science, Inc. for foundation design of Bombay Sewerage Project, India

Consultant to Harding-Lawson Associates for foundation stabilization at Bonny LNG Plant, Nigeria

Member of Committee of Specialists on Sensitive Clays for foundation design of dams for SEBJ hydro-electric power NBR project, James Bay, Canada

Consultant to Dames and Moore for foundation design of Hong Kong replacement airport

Consultant to McClelland Engineers, Inc. for preliminary design of rapid transit system for Houston

Consultant to Brian Watt Assoc. to evaluate foundation design for Arctic mobile drilling caisson

Consultant to Sverdrup & Parcel and Assoc. for preliminary design of bridge approach embankments, N.H.

Consultant to Norwegian Geotechnical Institute for foundation design of CONDEEP T300 at Troll site in North Sea

Consultant to Sohio Petroleum Company for preliminary evaluation of alternative foundations for Arctic offshore mobile drilling structures

Consultant to Wehran Engineering for preliminary design of solid waste disposal plan at Staten Island

Consultant to Univ. of Utah for preliminary geotechnical feasibility study, Superconducting Super Collider, Utah

Member of Review Consulting Board for West Desert Pumping Project, State of Utah Division of Water Resources.

Consultant to Daniel Construction Co. International for evaluation of harbor bulkhead failure, Saudi Arabia

Consultant to Dames and Moore for West Desert Pumping Project, Great Salt Lake

Special testing to evaluate hydrodam foundation stability for American Electric Power Service Corp., Ohio

Consultant to Stone & Webster Engineering Corp. for foundation design of hydro project, Oregon

Member of Quality Assurance Committee for feasibility study for the Messina Straits Bridge, Italy

Consultant to Wehran Engineering on investigation of clay liner failure at waste disposal site, Illinois

Consultant to Oosterbaan Assoc. on foundation design of landfill for resource recovery facility, New Jersey

Consultant to Lavalin on foundation design for hydro dam in western Canada

## VIII PUBLICATIONS AND ORAL PRESENTATIONS (see attached lists)

Professional publications on soil behavior, soil stabilization, and foundation engineering
Guest lecturer or panel member at universities, professional societies, and technical conferences

## IX CONSULTING EXPERIENCE

Major projects as a member of T. William Lambe and Associates include:

- Earth oil storage reservoirs in Venezuela, Colombia, Italy, and Aruba
- Highway and airfield projects in Venezuela and Libya
- Foundations for oil tanks in Venezuela and Libya
- Major building foundations in Boston
- Identification of expansive clays for FHA
- Stability of slopes in clay shales
- Subsidence of oil bearing sands

Major projects as a Consultant to Haley and Aldrich, Inc., include:

- Highway embankments utilizing jetted sand drains on sensitive clays in Portsmouth, N.H.
- Highway embankments utilizing sand drains on organic and sensitive clays in Portland, Me.
- Excavations and embankments for sewage and flood control in Bangkok, Thailand
- Highway embankment on peat deposit, N.H. Turnpike
- Foundation design for bridge approach embankments, Vermont
- Great Salt Lake Railroad Crossing, Board of Consultants
- Design Manual for prefabricated vertical drains (FHWA)
- Foundation stabilization for bridge approach fills, Hartford

Other Major Projects:

- Consultant to Louis Berger International Inc. for design of highway embankments on swamp deposits in Nigeria
- Preparation of design manual on tank foundations for Dames and Moore
- Consultant to Dames and Moore on soil properties and static analyses for Atlantic Generating Station
- Consultant to Chas. T. Main on stability of clay shales for pumped storage project, Nebraska
- Preparation of design manual for embankments constructed on varved clays for FHWA
- Expert Witness in PPG vs. Dames and Moore litigation involving foundation design of chemical storage tanks
- Consultant to Ardaman Associates on foundation stabilization for Atchafalaya Basin flood control levees

IX CONSULTING EXPERIENCE (Con't.)

Consultant to Goldberg-Zoino & Assoc. on foundation stabilization for MBTA replacement bridge

Consultant to Foott Assoc. on feasibility study for siting Superconducting Super Collider, Great Salt Lake, Utah

# PRESENTATIONS

Charles C. Ladd

## 1963

Visiting Lecturer, Rensselear Polytechnic Institute
Panel Member, ASTM Symposium on Laboratory Shear Testing of Soils, Ottawa

## 1964

Panel Member, Session on Shear Strength of Soils, ASCE Annual Meeting, New York

## 1965

Lecturer, Seminar on Shear Strength of Cohesive Soils - Determination and Utilization, Metropolitan Section ASCE, New York

## 1966

Guest Lecturer, University of Minnesota
Lecturer, Lecture Series on Soil Mechanics and Foundation Engineering, BSCE, Boston
Lecturer, Lecture Series on Design and Construction of Earth Structures, Illinois Section of ASCE, Chicago

## 1967

Lecturer, Pan-American Soils Course, Universidad Catolica Andres Bello, Caracas
Panel Member, Division I on Soil Properties, Third Pan-American Conf. on Soil Mech. and Fdn. Engr., Caracas
Panel Member, Session 1 on Strength of Soft Clays, Geotechnical Conference on Shear Strength Properties of Natural Soils and Rock, Oslo
Guest Lecturer, SEATO Graduate School of Engineering, Bangkok

## 1968

Guest Speaker, Structural Section, BSCE, Boston
Guest Speaker, Soil Mechanics and Foundations Group, Pittsburgh Section of ASCE, Pittsburgh
Panel Member, Session on Foundation Problems, Construction Engineers Conference, Hartford

1969

Participant, Symposium on the Shear Strength and Consolidation of Normally Consolidated Clays, Norwegian Geotechnical Institute, Oslo

1970

Guest Lecturer, Haley and Aldrich Professional Development Committee
Guest Lecturer, Woodward-Clyde Associates Seminar Program
Guest Lecturer, Montana State University
Gerry Mann Lecturer, Purdue University
Panel Member, Panel Discussion on Vertical Sand Drains, BSCE, Boston
Speaker, Experiences with LEASE, ICES Users Conference, Boston
Lecturer, Seminar on Soft Ground Construction, U.S. Army Engineers Waterways Experiment Station, Vicksburg
Speaker, Role of Computers in Soil Engineering, Geotechnical Section, BSCE, Boston

1971

Guest Lecturer, Haley and Aldrich Professional Development Committee
Guest Lecturer, Dames and Moore, Inc., New York
Lecturer, Seminar on Settlement Analyses, Woodward-Clyde Associates Seminar Program

1972

Lecturer, Lecture Series on Building Foundations on Soft Soil, Washington Section ASCE, Washington, D.C.
Co-Speaker, Soil Mech. and Fdn. Group of New York Metropolitan Section ASCE, New York
Guest Lecturer, University of Alberta
Panel Member, Session I Embankments on Soft Ground, ASCE Specialty Conference on Performance of Earth and Earth-Supported Structures, Purdue University

1973

Speaker, Student Chapter ASCE, Worcester Polytechnic Institute
Lecturer, Seminar on Settlement of Structures, Metropolitan Section ASCE, New York
Discusser, Session IV Problems of Soil Mechanics and Construction on Soft Clay, Eight Inter. Conf. on Soil Mech. and Fdn. Engr., Moscow
Lecturer, Embankment Construction on Soft Ground, Philadelphia Section, ASCE

1974

Lecturer, Embankments on Varved Clays, Geotechnical Section, BSCE, Boston
Co-Presenter, Workshop on Finite-Element Analyses in Soft Soils, ASCE Specialty Conference on Analysis and Design in Geotechnical Engineering, Univ. of Texas, Austin
Principal Instructor, Workshop on Design, Installation and Performance of Vertical Sand Drains, North Carolina State University
Predictor, Foundation Deformation Prediction Symposium, M.I.T.
Guest Lecturer, Vertical Sand Drains, Ecole Polytechnique, Montreal

1975

Panel Member, Session III In Situ Measurement of Shear Strength, ASCE Specialty Conference on In Situ Measurement of Soil Properties, North Carolina State University, Raleigh
Lecturer, One Week Course on Design of Foundations on Compressible Soils, the Iraqi Society of Civil Engineers, Baghdad

1976

Lecturer, Seminar on Field and Laboratory Determination of Soil Parameters for Geotechnical Design, National Capital Section ASCE, Washington, D.C.
Chairman, Symposium on Performance of Embankments on Varved Clays, TRB Annual Meeting, Washington, D.C.
Lecturer, Soil and Site Improvement, Continuing Education in Engineering, University of California, Berkeley

1977

Speaker, In Situ Testing of Cohesive Soils, Urban Mass Transit Tunneling Seminar, DOT-TSC, Cambridge
General Reporter, Session I, Ninth International Conference on Soil Mechanics and Foundation Engineering, Tokyo
Speaker, Site Investigation in Soft Ground, 3d Annual DOT Conference on Tunneling Technology, Atlanta
Speaker, Stress-Deformation and Strength Characteristics of Soil, Geotechnical Group, BSCES
Lecturer, Evaluation of Soil Parameters for Design of Shallow Foundations, Fugro Seminar Program, Long Beach

1978

State-of-the-Art Speaker on In Situ and Laboratory Testing of Cohesive Soils, DOT Symposium on Site Exploration in Soft Ground Using In Situ Techniques, Alexandria
Lecturer, Precompression and Vertical Sand Drains, Soil Improvement Seminar, Metropolitan Section ASCE, New York
Lecturer, Evaluation of in Situ Soil Parameters, Professional Development Seminar, Woodward-Clyde Consultants, Houston

1979

Lecturer, Evaluation of Shear Strength of Soils, 27th Annual Conference on Soil Mechanics and Foundation Engineering, Minnesota Geotechnical Society, St. Paul
Panel Member, Session 3 Embankments on Soft Soils, 32nd Canadian Geotechnical Conference, Quebec
Panel Discussion, Measurement of In Situ Undrained Strength for Stability Analyses, 6th Pan American Conference on Soil Mechanics and Foundation Engineering, Peru

1980

Panel Member, Symposium on Shear Strength of Soils, Amer. Society for Testing and Materials, Chicago

1981

Presentation, Symposium on Past, Present and Future of Geotechnical Engineering, MIT

1982

Lecturer, Hong Kong Institute on Civil Engineers, Hong Kong
Special Lecture, Chinese Institute of Civil Hydraulic Engineering, Taipei, Taiwan
Moderator, Panel Discussion on Tropical and Residual Soil Science, Properties and Problems, ASCE Geotechnical Specialty Conference, Honolulu, Hawaii

1983

Lecture Series, Norwegian Geotechnical Institute, Oslo
Lecture Series, Technical University of Tronheim
Speaker, New Analysis Techniques for Evaluating Stability of Clays, Metropolitan Section ASCE, New York
Lecturer, Italian Geotechnical Society, Milan
Lecturer, University of Rome
Lecture Series, Technical University of Turin
Speaker, ASCE Spec. Conf. on Geotechnical Practice in Offshore Engineering, Austin
Lecture and Seminar, University of Illinois, Urbana
Lecturer, University of Massachusetts, Amherst
Lecturer, Haley and Aldrich, Professional Development Program, Cambridge

1984

Lecturer, Bromwell and Carrier, Inc., Florida
Lecturer, Recent Advances in Applied Geotechnical Engineering, Nebraska Section of ASCE, Omaha
Lecture and Seminar, Purdue University
Chairman, Session on Tailings Dams, Inter. Conf. on Case Histories in Geotechnical Engineering, St. Louis
Speaker, Performance Evaluation and Monitoring of Wick Drains, ASCE Geotech III Spec. Conf., Atlanta
Speaker, Application of SHANSEP to Offshore Clay Deposits, Geotechnical Group, BSCES, Boston

1985

Luncheon Speaker, ASCE National Conference on Civil Engineering in the Arctic Offshore (ARCTIC '85), San Francisco

Panel Member, Discussion Session 2B on Laboratory Testing, Eleventh International Conference on Soil Mechanics and Foundation Engineering, San Francisco

1986

Lecturer, Stability Evaluation of Embankments on Soft Ground, Lecture Series of Illinois Section of ASCE, Chicago

Lecturer, University of Rome

Lecture Series on Stress-Strain-Strength Anisotropy of Soils, Technical University of Turin

Lecturer, Italian Geotechnical Society, Milan

Karl Terzaghi Lecture on Stability Evaluation During Staged Construction, ASCE National Convention, Boston

1987

Session Co-Chair, ASTM Inter. Sym. on Lab and Field Vane Testing, Tampa

Lecturer, ASCE Geotechnical Group, Pittsburgh

Lecturer, Virginia Polytechnic Institute

Lecturer, Univ. of California, Berkeley Geotechnical Society Special Lecture Series

Lecturer, Geotechnical Group, Montreal

Lecturer on Engineering Properties of Varved Clays, Seminar Program on Fdn. Problems in N.Y. Metro. Area, Fdn. and Soil Mech. Group, Metropolitan Section ASCE, New York

Lecturer, 13th Geotechnical Conference, Technical University of Turin, Italy

# LIST OF PUBLICATIONS

Charles C. Ladd

1. Ladd, C.C., "Mechanisms of Swelling by Compacted Clay," Highway Research Board Bull. 245, pp. 10-26 (1959).

2. Ladd, C.C., Z.C. Moh and T.W. Lambe, "Recent Soil-Lime Research at the Massachusetts Institute of Technology," Highway Research Board Bull. 262, pp. 64-85 (1960).

3. Whitman, R.V., C.C. Ladd and P. DaCruz, "Discussion on Shear Strength of Saturated, Remolded Clays," ASCE Research Conference on Shear Strength of Cohesive Soils, pp. 1049-1056 (1960).

4. Whitman, R.V., C.C. Ladd and P. DaCruz, "Discussion on Testing Equipment, Techniques, and Errors," ASCE Research Conference on Shear Strength of Cohesive Soils, pp. 1017-1021 (1960).

5. Ladd, C.C. and T.W. Lambe, "The Identification and Behavior of Compacted Expansive Clays," Proc. Fifth International Conf. on Soil Mechanics and Foundation Engineering, Paris, Vol. 1, pp. 201-205 (1961).

6. Ladd, C.C., Discussion of "Use of Stress Loci for Determination of Effective Stress Parameters," by R. Yong and E. Vey, Highway Research Board Bull. 342, (1962).

7. Ladd, C.C., Discussion of "The Heaving of Buildings and the Associated Economic Consequences, with Particular Reference to the Orange Free State Goldfields," by J.E. Jennings and J.R. Kerrick, a paper presented at the South African Institution of Civil Engineers, November, (1982).

8. Bromwell, L.G. and C.C. Ladd, Discussion of "Direct Shear Test for Effective Parameters," by H.M. O'Neil, J. Soil Mech. and Found. Div., ASCE, Vol. 89, No. SM1, pp. 313-316 (1963).

9. Ladd, C.C. and T.W. Lambe, "The Strength of 'Undisturbed' Clay Determined from Undrained Tests," ASTM-NRC Symposium on Laboratory Shear Testing of Soils, Ottawa, Canada, ASTM Special Technical Publication 361, pp. 342-371 (1963).

10. Ladd, C.C., "Stress-Strain Modulus of Clay in Undrained Shear," J. Soil Mech. and Found. Div., ASCE, Vol. 90, No. SM5, pp. 103-132 (1964).

11. Schiffman, R.L., C.C. Ladd and A.T-F Chen, "The Secondary Consolidation of Clay," Symposium on Rheology and Soil Mechanics, International Union of Theoretical and Applied Mechanics, Grenoble, France, pp. 273-304 (1964).

12. Ladd, C.C., Discussion of "Shearing Resistance of Soils as a Rate Process," by J.K. Mitchell, J. Soil Mech. and Found. Div., ASCE, Vol. 90, No. SM6, pp. 181-185 (1964).

13. Ladd, C.C. and W.A. Bailey, Correspondence on "The Behavior of Saturated Clays during Sampling and Testing," by A.W. Skempton and V.A. Sowa, Geotechnique, Vol. 14, No. 4, pp. 353-358 (1964).

14. Ladd, C.C., "Stress-Strain Behavior of Anisotropically Consolidated Clays During Undrained Shear," Proc. Sixth Intern. Conf. on Soil Mechanics and Foundation Engineering, Montreal, Vol. 1, pp. 282-286 (1965).

15. Wissa, A.E.Z., C.C. Ladd and T.W. Lambe, "Effective Stress Strength Parameters of Stabilized Soils," Proc. Sixth International Conference on Soil Mechanics and Foundation Engineering, Montreal, Vol. 1, pp. 412-416 (1965).

16. Ladd, C.C., "Shear Strength of Cohesive Soils," Proc. of Soil Mechanics Lecture Series on Design and Construction of Earth Structures, Soil Mech. and Found. Div., llinois Section ASCE and Illinois Institute of Technology, Chicago, pp. 33-92 (1966).

17. Ladd, C.C., "Strength and Compressibility of Saturated Clays," Pan American Soils Course, Universidad Catolica Andres Bello, Caracas, 157 p. (1967).

18. Ladd, C.C., "In Situ Undrained Strength of Soft Saturated Clays," Proc. Geotechnical Conference, Vol. II, Session 1, Oslo pp. 112-115 (1967).

19. Ladd, C.C., H.P. Aldrich, Jr. and E.G. Johnson, "Embankment Failure on Organic Clay," Proc. Seventh International Conference on Soil Mechanics and Foundation Engineering, Mexico, Vol. 2, pp. 627-634 (1969).

20. Ladd, C.C., "M.I.T. Plane Strain Device," Specialty Session No. 16, Proc. Seventh International Conference on Soil Mechanics and Foundation Engineering, Mexico, Vol. 4, pp. 527-528 (1969).

21. Ladd, C.C., "The Prediction of In Situ Stress Strain Behavior of Soft Saturated Clays during Undrained Shear," Bolkesjo Sym. on Shear Strength and Consolidation of Normally Consolidated Clays, Norwegian Geotechnical Institute, 23 p. (1969).

22. Ladd, C.C., Z.C. Moh and D.G. Gifford, "Undrained Strength of Soft Bangkok Clay," Proc. 4th Asian Regional Conference on Soil Mechanics and Foundation Engineering, Bangkok, Vol. 2, pp. 135-140 (1971).

23. Ladd, C.C., Z.C. Moh and D.G. Gifford, "Statistical Analyses of Undrained Strength of Soft Bangkok Clay," Conf. on Application of Statistics and Probability to Soil and Structural Engineering, Hong Kong, Sept. (1971).

24. Ladd, C.C. "Settlement Analyses for Cohesive Soils," Special Summer Program on Soft Ground Construction, M.I.T., 107 p. (1971).

25. Ladd, C.C., "Strength Parameters and Stress-Strain Behavior of Saturated Clays," Special Summer Program on Soft Ground Construction, M.I.T., 280 p. (1971).

26. D'Appolonia, D.J., H.G. Poulos and C.C. Ladd, "Initial Settlement of Structures on Clay," J. Soil Mech. and Found. Div., ASCE, Vol. 97, No. SM10, pp. 1359-1377 (1971).

27. Ladd, C.C., "Test Embankment on Sensitive Clay," Proc. ASCE Specialty Conference on Performance of Earth and Earth-Supported Structures, Purdue University, Vol. 1, Part 1, pp. 101-128 (1972).

28. Ladd, C.C., J.J. Rixner and D.G. Gifford, "Performance of Embankments with Sand Drains on Sensitive Clay," Proc. ASCE Specialty Conference on Performance of Earth and Earth Supported Structures, Purdue University, Vol. 1, Part 1, pp. 211-242 (1972).

29. Kinner, E.B. and C.C. Ladd, "Undrained Bearing Capacity of Footing on Clay," Proc. Eighth International Conference on Soil Mechanics and Foundation Engineering, Moscow, Vol. 1.1, pp. 209-215 (1973).

30. Ladd, C.C., "Estimating Settlements of Structures Supported on Cohesive Soils," Seminar on Settlement of Structures, Foundations and Soil Mechanics Group, Metropolitan Section ASCE, New York, Part I, 114 p. (1973).

31. Ladd, C.C., "Discussion on Problems of Soil Mechanics and Construction on Soft Clay," Session IV, Proc. Eighth International Conference on Soil Mechanics and Foundation Engineering, Moscow (1973).

32. Simon, R.M., J.T. Christian and C.C. Ladd, "Analysis of Undrained Behavior of Loads on Clay," Proc. ASCE Specialty Conference on Analysis and Design in Geotechnical Engineering, University of Texas at Austin, Vol. 1, pp. 51-84 (1974).

33. Ladd, C.C. and R. Foott, "New Design Procedure for Stability of Soft Clays," J. Geotechnical Engr. Div., ASCE, Vol. 100, No. GT7, pp. 763-786 (1974).

34. Martin, R.T. and C.C. Ladd, "Fabric of Consolidated Kaolinite," Clays and Clay Minerals, Vol. 23 (1975).

35. Ladd, C.C., "Discussion on Measurement of In Situ Shear Strength," Proc. ASCE Specialty Conference on In Situ Measurement of Soil Properties, North Carolina State University, Vol. II, pp. 153-160 (1975).

36. Ladd, C.C., "Use of Precompression and Vertical Sand Drains for Stabilization of Foundation Soils," Soil and Site Improvement, Cont. Education in Engineering, University of California, Berkeley, 66p. (1976).

37. Lacasse, S.M., C.C. Ladd and A.K. Barsvary, "Undrained Behavior of Embankments on New Liskeard Varved Clay," Canadian Geotechnical Journal, Vol. 14, pp. 367-388 (1977).

38. Foott, R. and C.C. Ladd, "Behavior of Atchafalaya Test Embankments During Construction," Geotechnique, Vol. 27, pp. 137-160 (1977).

39. Keshian, B., Jr., C.C. Ladd and R.E. Olson, "Sedimentation-Consolidation Behavior of Phosphatic Clays," Proc. ASCE Specialty Conference on Geotechnical Practice for Disposal of Solid Waste Materials, University of Michigan, Vol. 1, (1977).

40. Ladd, C.C., R. Foott, K. Ishihara, F. Schlosser and H.G. Poulos, "Stress-Deformation and Strength Characteristics," State of the Art Report, Session 1, Proc. 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo, Vol. 2, pp. 421-494 (1977).

41. Baligh, M.M., A.S. Azzouz and C.C. Ladd, "Line Loads on Cohesive Soils," Proc. 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo, Vol. 2, pp. 13-16 (1977).

42. Leathers, F.D. and C.C. Ladd, "Behavior of an Embankment on New York Varved Clay," Canadian Geotechnical Journal, Vol. 15, No. 2, pp. 250-269 (1978).

43. Saxena, S.K., J Hedberg and C.C. Ladd, "Geotechnical Properties of Hackensack Valley Varved Clays of New Jersey," ASTM Geotechnical Testing Journal, Vol. 1, No. 3, pp. 148-161 (1978).

44. Olson, R.E. and C.C. Ladd, "One-Dimensional Consolidation Problems," J. Geotechnical Engr. Div., ASCE, Vol. 105, GT1, pp. 11-30 (1979).

45. Foott, R., D. Devecseri, C.N. Aneke, J.O. Jackson and C.C. Ladd, "Embankments through Cross River Swamp," J. Geotechnical Engr. Div., ASCE, Vol. 106, GT3, pp. 219-234 (1980).

46. Baligh, M.M., V. Vivatrat and C.C. Ladd, "Cone Penetration in Soil Profiling," J. Geotechnical Engr. Div., ASCE, Vol. 106, GT4, pp. 447-461 (1980).

47. Ladd, C.C. and R. Foott, "The Behaviour of Embankments on Clay Foundations: Discussion," Canadian Geotechnical Journal, Vol. 17, No. 3, pp. 454-460 (1980).

48. Azzouz, A.S., M.M. Baligh and C.C. Ladd, "Three-Dimensional Stability Analyses of Four Embankment Failures," Proc. 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, Vol. 3, pp. 343-346 (1981).

49. Foott, R. and C.C. Ladd, "Undrained Settlement of Plastic and Organic Clays," J. Geotechnical Engr. Div., ASCE, Vol. 107, GT8, pp. 1079-1094 (1981).

50. Ladd, C.C., "Discussion on Laboratory Shear Devices," ASTM Symposium on Laboratory Shear Strength of Soil, Chicago, ASTM STP 740, pp. 643-652 (1981).

51. Arthur, J.R.F., S. Bekenstein, J.T. Germaine and C.C. Ladd, "Stress Path Tests with Controlled Rotation of Principal Stress Directions," ASTM Symposium on Laboratory Shear Strength of Soil, Chicago, STP 740, pp. 516-540 (1981).

52. McKown, A.F. and C.C. Ladd, "Effects of Cementation on the Compressibility of Pierre Shale," Symposium on Geotechnical Properties, Behavior and Performance of Calcareous Soils, ASTM STP 777, pp. 320-339 (1982).

53. Azzouz, A.S., M.M. Baligh and C.C. Ladd, "Cone Penetration and Engineering Properties of the Soft Orinoco Clay," Proc. Conf. on Behavior of Offshore Structures, Cambridge, Vol. 1, pp. 161-180 (1982).

54. Ladd, C.C. and A.S. Azzouz, "Stress History and Strength of Stiff Offshore Clays," Proc. ASCE Spec. Conf. on Geotechnical Practice in Offshore Engineering, Austin, pp. 65-80 (1983).

55. Azzouz, A.S., M.M. Baligh and C.C. Ladd, "Corrected Field Vane Strength for Embankment Design," J. Geotechnical Engineering, ASCE, Vol. 109, No. 5, pp. 730-734 (1983).

56. Ting, J.M., R.T. Martin and C.C. Ladd, "Mechanisms of Strength for Frozen Sand," J. Geotechnical Engr., ASCE, Vol. 109, No. 10, pp. 1286-1302 (1983).

57. Ghionna, V., M. Jamiolkowski, S. Lacasse, C.C. Ladd, R. Lancellotta and T. Lunne, "Evaluation of Self-Boring Pressuremeter," International Symposium on In Situ Testing, Paris, Vol. 1, pp. 293-301 (1983).

58. Ladd, C.C., "Use of Precompression and Vertical Drains for Stabilization of Foundations Soils", Recent Advances in Applied Geotechnical Engineering, Nebraska Section ASCE, (1984).

59. Koutsoftas, D.C. and C.C. Ladd, "Design Strengths for an Offshore Clay," J. Geotechnical Engineering, ASCE, Vol. 111, No. 3, pp. 337-355, (1985).

60. Ladd, C.C., J.S. Weaver, J.T. Germaine and D.P. Sauls, "Strength-Deformation Properties of Arctic Silt," Proc. ASCE Spec. Conf. on Civil Engineering in the Arctic Offshore, San Francisco, pp. 820-829, (1985).

61. Jamiolkowski, M., C.C. Ladd, J.T. Germaine and R. Lancellotta, "New Developments in Field and Laboratory Testing of Soils," Theme Lecture for Session 2, Proc. 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, Vol. 1, pp. 57-153, (1985).

62. Lefebvre, G., C.C. Ladd and J.-J. Pare, "Comparison of Field Vane and Laboratory Undrained Shear Strength in Soft Sensitive Clays," ASTM Symposium on International Laboratory and Field Vane Shear Strength Testing, Tampa (1987).

63. Ladd, C.C., "Characteristics and Engineering Properties of Northeastern Varved Clays," Seminar Program on Foundation Problems in the New York Metropolitan Area, N.Y. Metro. Section ASCE (1987).

October 6, 1986

S. SHYAM SUNDER

CURRICULUM VITAE

## EDUCATION

| | |
|---|---|
| Indian Institute of Technology, Delhi | 1972-1977, B.Tech. |
| Massachusetts Institute of Technology | 1977-1979, S.M. |
| Massachusetts Institute of Technology | 1979-1981, Sc.D. |

## EMPLOYMENT

| | |
|---|---|
| Teaching Assistant, MIT | Feb. 1978 - May 1978 |
| Research Assistant, MIT | June 1978 - Aug. 1980 |
| Instructor, MIT | Sept. 1980 - May 1981 |
| Research Assistant, MIT | June 1981 - Aug. 1981 |
| Assistant Professor of Civil Engineering, MIT | Jul. 1981 - June 1985 |
| Winslow Assoc. Prof. of Civil Engineering, MIT | Jul. 1985 - |

## INDUSTRIAL TRAINING

| | |
|---|---|
| Gammon-India Limited, Bombay | May 1976 - July 1976 |

## CONSULTING

| | |
|---|---|
| Arthur D. Little, Inc. | July 1981 - July 1981 |
| A/S Norske Shell, Norway | July 1982 - July 1983 |
| Tera Corporation, Berkeley | Aug. 1983 - Aug. 1983 |
| Snamprogetti, Italy | Feb. 1984 - Feb. 1984 |
| Stone & Webster Engineering Corporation | Oct. 1984 - Jan. 1984 |
| Norwegian Seismic Array, NORSAR | Dec. 1984 - Jan. 1984 |
| U.S. Geological Survey | Jan. 1985 - Jan. 1985 |

## PROFESSIONAL SOCIETIES AND COMMITTEES

| | |
|---|---|
| American Society of Civil Engineers | Assoc. Member |
| Committee on Special Structures | Member 1983 - 1986 |
| Committee on Reliability of Offshore Structures | Member 1984 - |
| Sub-Committee on Arctic and Frontier Regions | Chairman 1984 - |
| Task Committee on Reliability-Based Techniques for Designing Arctic Offshore Structures | Vice-Chairman 1985 - 1986 |
| Publications Committee, Technical Council on Computer Practices | Member 1986 - |
| Committee on Dynamics | Member 1986 - |
| Boston Society of Civil Engineers | Member |
| American Society of Mechanical Engineers | |
| Ice Mechanics Committee | Member 1985 - |

October 6, 1986

PROFESSIONAL SOCIETIES AND COMMITTEES (Contd.)

| | |
|---|---|
| Earthquake Engineering Research Institute | Member |
| American Association for the Advancement of Science | Member |
| Journal of Applied Ocean Research, Editorial Board | Member 1986 - |
| Journal of Engineering Mechanics, Journal of Structural Engineering, Journal of Energy Resources Technology (ASME), Earthquake Engineering and Structural Dynamics, Structural Safety, Journal of Applied Ocean Research, Journal of Cold Regions Engineering, Rock Mechanics and Rock Engineering | Reviewer |
| National Science Foundation | Proposal Reviewer |
| ASCE Specialty Conference - ARCTIC'85; Ninth International Conference on Port and Ocean Engineering Under Arctic Conditions (POAC'87) | Committee Member |
| Center for Scientific Excellence in Offshore Engineering, MIT | Assoc. Director 1985 - |

HONORS AND AWARDS

| | |
|---|---|
| Gilbert W. Winslow Career Development Chair | 1985 - 1987 |

PRINCIPAL FIELDS OF INTEREST

Structures and Materials, Ice Mechanics, Offshore Engineering

Publications of S. SHYAM SUNDER

1. Books

2. Papers in Refereed Journals

   1. Shyam Sunder, S., and Connor, J.J., "Sensitivity Analyses for Steel Jacket Offshore Platforms," Journal of Applied Ocean Research, 3(1), 13-26, February 1981.

   2. Angelides, D.C., Veneziano, D.V., and Shyam Sunder, S., "Random Sea and Reliability of Offshore Foundations," Journal of the Engineering Mechanics Division, Proceedings of the American Society of Civil Engineers, 107(EM1), 131-148, February 1981.

   3. Kawamoto, J., Shyam Sunder, S., and Connor, J.J., "An Assessment of Uncertainties in Fatigue Analyses of Steel Jacket Offshore Platforms," Journal of Applied Ocean Research, 4(1), 9-16, February 1982.

   4. Shyam Sunder, S., and Connor, J.J., "A New Procedure for Processing Strong-Motion Earthquake Signals," Bulletin of the Seismological Society of America, 72(2), 643-661, April 1982.

   5. Shyam Sunder, S., and Schumacker, B., "Earthquake Motions Using a New Data Processing Scheme," Journal of the Engineering Mechanics Division, Proceedings of the American Society of Civil Engineers, 108(EM6), 1313-1329, December 1982.

   6. Laya, E.J., Connor, J.J., and Shyam Sunder, S., "Hydrodynamic Forces on Flexible Offshore Structures," Journal of Engineering Mechanics, 110(3), 433-448, March 1984.

   *7. Shyam Sunder, S., and Sanni, R.A., "Foundation Stiffness Identification for Offshore Platforms," Journal of Applied Ocean Research, 6(3), 148-156, June 1984.

   *8. Shyam Sunder, S., and Ting, S-K., "Flexibility Monitoring of Offshore Platforms," Journal of Applied Ocean Research, 7(1), 14-23, February 1985.

   *9 Shyam Sunder, S., Grewatz, S.E., and Ting, S-K., "Modal Identification Using Spectral Moments," Structural Safety, 3, 1-11, 1985.

   *10. Chehayeb, F.S., Ting, S-K., Shyam Sunder, S., and Connor, J.J., "Sea-Ice Indentation in Creeping Mode," Journal of Engineering Mechanics, 113(7), 965-983, July 1987.

   *11. Shyam Sunder, S., Ganguly, J., and Ting, S-K., "Anisotropic Sea Ice Indentation in the Creeping Mode," Journal of Offshore Mechanics and Arctic Engineering, 109(2), 211-219, May 1987.

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12. Shyam Sunder, S., and Gudmestad, O.T., "Earthquake Time Histories for the Norwegian Continental Shelf," Journal of Applied Ocean Research, Technnical Note, In Press, February 1987.

13. Shyam Sunder, S., and Wu, M.S. "A Multiaxial Differential Flow Law for Polycrystalline Ice," Cold Regions Science and Technology, Submitted for Publication, August 1986 (Revised October 1987).

14. Shyam Sunder, S., and Nanthikesan, S., "A Tensile Fracture Model for Ice," Journal of Offshore Mechanics and Arctic Enginering, Submitted for Publication, August 1986.

3. Proceedings of Refereed Conferences

1. Shyam Sunder, S., Angelides, D.C., and Connor, J.J., "A Stochastic Model for the Simulation of a Non-Stationary Sea," Proceedings of the 2nd International Conference on the Behaviour of Off-Shore Structures, London, England, 1979, Vol. I, Paper 9, 95-106. Cranfield, Bedford, England: BHRA Fluid Engineering.

2. Shyam Sunder, S., "Relative Velocity Formulation of Morison's Equation," Discussion, Proceedings of the 2nd International Conference on the Behaviour of Off-Shore Structures, London, England, 1979, Vol. III, 859-860. Cranfield, Bedford, England: BHRA Fluid Engineering.

3. Shyam Sunder, S., and Connor, J.J., "Sensitivity Analyses for Steel Jacket Offshore Platforms," Proceedings of the International Symposium on Offshore Structures, COPPE, Federal University of Rio de Janeiro, Brazil, October 1979, 2.3-2.43. Houston, TX: Gulf Publishing Company, 1980 (same paper as 2.1).

4. Shyam Sunder, S., and Connor, J.J., "Long-Term Random Sea-State Modeling," Proceedings of the 3rd International Conference on the Behaviour of Off-Shore Structures, Cambridge, U.S.A., 1982, Vol. II, Paper PS2.6, 817-827. Washington, D.C.: Hemisphere Publishing Corporation.

5. Shyam Sunder, S., "Numerical Time Integration in Dynamics," Proceedings of the Structural Mechanics of Optical Systems Conference, Cambridge, MA, November 1983. Paper 450-18, 154-163, Bellingham, WA: SPIE-The International Society for Optical Engineering, 1984.

6. Shyam Sunder, S., "Knowledge-Based Expert Systems for Offshore Engineering," Proceedings of the 4th International Symposium on Offshore Mechanics and Arctic Engineering, Dallas, TX, February 1985, Vol. II, 593-600. New York, N.Y.: The American Society of Mechanical Engineers.

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Publications of S. SHYAM SUNDER

*7. Ting, S-K., and Shyam Sunder, S., "Sea Ice Indentation Accounting for Strain-Rate Variation," Proceedings of the ASCE Specialty Conference: ARCTIC'85 - Civil Engineering in the Arctic Offshore, San Francisco, CA, March 1985, 931-941. New York, N.Y.: The American Society of Civil Engineers.

*8. Chehayeb, F.S., Ting, S-K., Shyam Sunder, S., and Connor, J.J., "Sea Ice Indentation in the Creeping Mode," Proceedings of the 17th Annual Offshore Technology Conference, Houston, TX, May 6-9, 1985, OTC5056, 329-341. Richardson, TX: Offshore Technology Conference (same paper as 2.10).

*9. Shyam Sunder, S., and Ting, S-K., "Ductile to Brittle Transition in Sea Ice Under Uniaxial Loading," Proceedings of the 8th International Conference on Port and Ocean Engineering Under Arctic Conditions, Narssarssuag, Greenland, September 7-14, 1985, Vol. 2, 656-666.

*10. Slater, J.H., Petrossian, R.B.P., and Shyam Sunder, S., "An Expert Tutor for Rigid Body Mechanics: ATHENA CATS-MACAVITY," Proceedings of the Expert Systems in Government Symposium, McLean, VA, October 23-25, 1985, Paper 6109. Washington, D.C.: IEEE Computer Society.

*11. Shyam Sunder, S., Ganguly, J., and Ting, S-K., "Anisotropic Sea Ice Indentation in the Creeping Mode," Proceedings of the 5th International Symposium on Offshore Mechanics and Arctic Engineering, Tokyo, Japan, April 13-18, 1986, Vol. 4, 486-496. New York, N.Y., The American Society of Mechanical Engineers (same paper as 2.11).

12. Shyam Sunder, S., "Ice Load Prediction During Indentation," Proceedings of the International Conference on Ice Technology (ITC'86), Cambridge, MA, June 10-12, 1986, 297-309. Southampton, U.K.: Computational Mechanics Institute.

13. Shyam Sunder, S., "An Integrated Constitutive Theory for the Mechanical Behavior of Sea Ice: Micromechanical Interpretation," Proceedings of the International Conference on Ice Technology (ITC'86), Cambridge, MA, June 10-12, 1986, 87-102. Southampton, U.K.: Computational Mechanics Institute.

14. Chehayeb, F.S., Connor, J.J., and Shyam Sunder, S., "Numerical Modeling of Ice-Structure Interaction," Proceedings of the International Conference on Ice Technology (ITC'86), Cambridge, MA, June 10-12, 1986, 431-444. Southampton, U.K.: Computational Mechanics Institute.

*outgrowth of supervised thesis.

15. Shyam Sunder, S., "An Integrated Constitutive Theory for the Mechanical Behavior of Sea Ice: Experimental Verification," Proceedings of the Symposium on Ice, International Association of Hydraulic Research, Iowa City, IA, August 1986, Vol. 1, 253-264. Iowa City, IA: Iowa Institute of Hydraulic Research, University of Iowa.

16. Shyam Sunder, S., and Nanthikesan, S., "A Tensile Fracture Model for Ice," Proceedings of the 6th International Symposium on Offshore Mechanics and Arctic Engineering, Houston, TX, March 1-6, 1987, Vol. 2, 225-233. New York, N.Y.: American Society of Mechanical Engineers (same paper as 2.14).

4. Other Major Publications

1. Shyam Sunder, S., and Connor, J.J., "Sensitivity Analyses for Steel Jacket Offshore Platforms," Chapter 2 in Dynamic Analysis of Offshore Structures, Editor: C.L. Kirk, C.M.L. Publications, Southampton, England, 1982 (same as papers 2.1 and 3.3.)

2. Shyam Sunder, S., "Research Topics in Flexibility Monitoring," Proceedings of the ONR/MMS Workshop on Non-Destructive Evaluation Methods for Structures, Washington, D.C., 5.1-5.17, January 1983.

3. Connor, J.J., and Shyam Sunder, S., "Wave Theories, Wave Statistics and Hydrodynamic Loads," Chapter 2 in Offshore Structures, D.V. Reddy and M. Arockiasamy (Eds.), Release Date: October 1987. Melbourne, Florida: Krieger Publishing Company.

5. Internal Memoranda and Progress Reports

1. Shyam Sunder, S., "Stochastic Modeling of Ocean Storms," Research Report R79-7/S.M. Thesis, Department of Civil Engineering, Massachusetts Institute of Technology, February 1979.

2. Shyam Sunder, S., Connor, J.J., and D.C. Angelides, "User Manual for POSEIDON - A Program for Evaluating the Frequency Domain Response of Offshore Steel Jacket Platforms," Research Report R79-15, Department of Civil Engineering, Massachusetts Institute of Technology, March 1979.

3. Kawamoto, J., Shyam Sunder, S., and Laya, E., "User Manual for POSEIDON II - A Program for Evaluating the Short and Long Term Frequency Domain Response of Offshore Steel Jacket Platforms," Research Report R80-36, Department of Civil Engineering, Massachusetts Institute of Technology, June 1980.

4. Shyam Sunder, S., "On the Standard Processing of Strong-Motion Earthquake Signals," Research Report R80-38, Department of Civil Engineering, Massachusetts Institute of Technology, September 1980.

*outgrowth of supervised thesis.

Publications of S. SHYAM SUNDER

5. Connor, J.J., Azzouz, A.S., and Shyam Sunder, S., "Design of Pile-Supported Steel Jacket Platforms," Department of Civil Engineering, Massachusetts Institute of Technology, July 1981.

6. Shyam Sunder, S., "Homomorphic Deconvolution of Strong-Motion Earthquake Signals," Research Report R81-26, Department of Civil Engineering, Massachusetts Institute of Technology, October 1981.

7. Shyam Sunder, S., "Microcomputers in Structural Engineering," Notes for Short Course on Microcomputers in Civil Engineering, Center for Construction Research and Education, Massachusetts Institute of Technology, June 1982.

*8. Luna, R.L., and Shyam Sunder, S., "Cyclic Behavior of Structural Steel with Applications to Offshore Platforms," Research Report R82-38, Department of Civil Engineering, Massachusetts Institute of Technology, June 1982.

*9. Longo, P., and Shyam Sunder, S., "Vibration Monitoring of Offshore Platforms Using the Ibrahim Time Domain Modal Identification Technique," Research Report R82-37, Department of Civil Engineering, Massachusetts Institute of Technology, July 1982.

10. Ting, S-K., and Shyam Sunder, S., "Testing and Monitoring of Offshore Structures: A State-of-the-Art Review," Research Report R82-48, Department of Civil Engineering, Massachusetts Institute of Technology, July 1982.

*11. Grewatz, S.E., and Shyam Sunder, S., "Vibration Monitoring in the Spectral Domain Using the Method of Moments," Research Report R82-47, Department of Civil Engineering, Massachusetts Institute of Technology, August 1982.

*12. Nasir, J., and Shyam Sunder, S., "An Evaluation of the Random Decrement Technique of Vibration Signature Analysis for Monitoring Offshore Platforms," Research Report R82-52, Department of Civil Engineering, Massachusetts Institute of Technology, September 1982.

*13. Sanni, R.A., and Shyam Sunder, S., "Foundation Stiffness Identification for Offshore Platforms," Research Report R83-18, Department of Civil Engineering, Massachusetts Institute of Technology, May 1983.

*14. Ting, S-K., and Shyam Sunder, S., "Damage Detection of Steel Jacket Offshore Platforms Using Flexibility Monitoring," Research Report R83-19, Department of Civil Engineering, Massachusetts Institute of Technology, May 1983.

*outgrowth of supervised thesis.

*15. Bahar, R., and Shyam Sunder, S., "The Mathematics of Generalized Random Decrement Analysis," Research Report R83-20, Department of Civil Engineering, Massachusetts Institute of Technology, September 1983.

16. Ting, S-K., and Shyam Sunder, S., "Comparison of Free, Ambient, and Forced Vibration Measurements of Dynamic Structural Parameters," Technical Note No. 1, MIT/INTEVEP R&D Program: Monitoring of Offshore Structures, October 1983.

17. Gudmestad, O.T., and Shyam Sunder, S., "Design Strong-Motion Earthquake Time-Histories for Intraplate Regions," Research Report R84-05, Department of Civil Engineering, Massachusetts Institute of Technology, March 1984.

18. Shyam Sunder, S., and Connor, J.J., "Numerical Modeling of Ice-Structure Interaction," Technical Progress Report No. 1, Center for Scientific Excellence in Offshore Engineering, Massachusetts Institute of Technology, March 1984.

19. Shyam Sunder, S., and Connor, J.J., "Numerical Modeling of Ice-Structure Interaction," Technical Progress Report No. 2, Center for Scientific Excellence in Offshore Engineering, Massachusetts Institute of Technology, September 1984.

20. Shyam Sunder, S., and Connor, J.J., "Numerical Modeling of Ice Structure Interaction," Technical Progress Report No. 3, Center for Scientific Excellence in Offshore Engineering, Massachusetts Institute of Technology, March 1985.

*21. Ting, S-K., and Shyam Sunder, S., "Constitutive Modeling of Sea Ice with Applications to Indentation Problems," Research Report No. 3, Center for Scientific Excellence in Offshore Engineering, Massachusetts Institute of Technology, October 1985.

6. Invited Lectures

May 1979, "Stochastic Modeling of Ocean Storms," Research in Offshore Engineering Seminars, Massachusetts Institute of Technology, Cambridge, MA.

October 1980, "Standard Processing of Strong-Motion Earthquake Signals," Earthquake Engineering Seminars, Massachusetts Institute of Technology, Cambridge, MA.

October 1980, "Standard Processing of Strong-Motion Earthquake Signals," FUNVISIS, Seismological Investigations Agency, Caracas, Venezuela.

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*outgrowth of supervised thesis.

Publications of S. SHYAM SUNDER

December 1980, "Strong-Motion Data Processing," University of Roorkee, India.

January 1981, Three lectures: (i) "Short and Long Term Frequency Domain Response of Steel Jacket Offshore Platforms," (ii) "A Long-Term Random Sea-State Model," and (iii) "Standard Processing of Strong-Motion Earthquake Signals," Ocean Engineering Center, Indian Institute of Technology, Madras, India.

June 1981, "Effect of Structural Motion on the Hydrodynamic Forcing of Offshore Steel Jacket Platforms," (with Laya, E.J., and Connor, J.J.), First Joint ASME/ASCE Mechanics Conference, University of Colorado, Boulder, CO (also paper 2.6.)

July 1984, "Advanced Structural Analysis for Offshore Structures," Five-Day Short Course for Design Engineers, McDermott Engineering Private Limited, Singapore.

July 1984, "Dynamic and Fatigue Analysis of Framed Offshore Structures," Department of Civil Engineering, National University of Singapore, Singapore.

August 1984, "Computer-Aided Engineering," The Institution of Engineers (India) and Gujarat Institute of Civil Engineers & Architects, Ahmedabad, India.

September 1984, "Strong-Motion Earthquake Signal Processing," NORSAR, Norwegian Seismic Array, Oslo, Norway.

September 1984, "Stong-Motion Earthquake Signal Processing," Norsk Hydro, Oslo, Norway.

September 1984, "Arctic Offshore Engineering," Det norske Veritas (VERITEC) and Norwegian Contractors, Oslo, Norway.

September 1984, "Arctic Offshore Engineering," Statoil, Stavanger, Norway.

January 1985, "Sea Ice and its Mechanical Behavior," Engineering in the Arctic Seminar Series, Massachusetts Institute of Technology, Cambridge, MA.

February 1985, "Knowledge-Based Expert Systems for Offshore Engineering," Shell Development Company and Shell Oil Company, Houston, TX.

October 1985, "Numerical Modeling of Ice-Structure Interaction," Regional Offshore Technology Assessment Committee, Minerals Management Service, U.S. Department of the Interior, Seattle, WA.

January 1986, "Constitutive Modeling of Sea Ice," Seminar Series on Arctic Offshore Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Publications of S. SHYAM SUNDER

January 1986, "Fracture Behavior of Sea Ice," Seminar Series on Fracture in Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.

March 1986, "Advanced Materials and Structures," Meeting of the Corporation Visiting Committee for the Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.

May 1986, "Ice Mechanics Research at MIT," Bi-Annual Joint Meeting of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and the Lease Planning Research Committee (LPRC) of the Alaska Oil and Gas Association (AOGA).

June 1986, "An Integrated Constitutive Theory for the Mechanical Behavior of Sea Ice," Tenth U.S. National Congress of Applied Mechanics, Austin, TX.

September 1986, "Wave-Structure Interaction Models for Fixed Offshore Structures," Structures Congress '86, American Society of Civil Engineers, New Orleans, LA.

April 1987, "Numerical Modeling of Ice-Structure Interaction and Experimental Ice Mechanics," Special Meeting of the MIT Center for Scientific Excellence in Offshore Engineering, April 1987.

# RESUME

## DALE G. KARR

PERSONAL DATA

Date of Birth: April 3, 1953

U.S. Citizen

Registered Professional Engineer

Professional Organization Membership:

National Society of Professional Engineers
American Society of Civil Engineers
American Society of Mechanical Engineers
Society of Naval Architects and Marine Engineers

EDUCATION

1983 Ph.D., Tulane University, New Orleans, Louisiana.

1977 M.S., University of Tennessee, Knoxville, Tennessee.

1974 B.S., Michigan State University, East Lansing, Michigan

PROFESSIONAL EXPERIENCE

Present — Massachusetts Institute of Technology, Department of Ocean Engineering, Associate Professor of Ocean Engineering

1983 — Tulane University, Department of Civil Engineering Adjunct Professor of Civil Engineering. Teaching of Graduate Course: Dynamic Analysis of Structures.

1979 to 1983 — Martin Marietta Aerospace, New Orleans, Louisiana. Senior Engineer - Stress Analyst. Supervisory responsibility for 5 to 7 engineers. Analyzed strength and stability of the barrel panels and domes of the liquid hydrogen tank for the Space Shuttle External Tank (ET). Analyses involved fracture, elastic and elastic-plastic materi l deformation behavior as well as linear and non-linear geometry. Local and general shell stability analyses included linear bifurcation and non-linear plastic collapse studies. Supported the ET structural test program and stress analysis report.

1978 to 1979 — Brown and Root, Inc., Houston, Texas. Engineer - Responsible for structural design and analysis of pier and docking facilities. Analyses involved liveloads, mooring, thermal and seismic loads. Evaluated force-deflection data of site soils for foundation studies for soil-pile interaction.

PROFESSIONAL EXPERIENCE (cont.)

1975 to 1977 — Tennessee Valley Authority Sequoyah Nuclear Plant.
Civil Engineer - Assigned to Office and Civil Engineering Unit at construction site of two reactor unit nuclear power plant. Responsible for design, drafting, and checking of construction plant facilities including shop buildings and additions, sheet piling, equipment foundations, concrete formwork, lifting devices and rigging for installation and erection of plant equipment and facilities.

PUBLICATIONS

"Ice Forces on Offshore Structures," Arctic-Offshore-Deepsea Structures Symposium - First Annual Energy - Sources Technology Conference and Exhibition (ETCE) Sponsored by ASME Petroleum Division, March 1982.

"Stress State Ice Failure Criteria with Applications for Plastic Limit Analysis of Ice Forces on Offshore Structures," Ph.D. Dissertation, April 1983. Thesis Supervisor Dr. Sankar C. Das.

With S.C. Das, "Ice Strength in Brittle and Ductile Failure Modes," Journal of Structural Engineering, ASCE, 109, No. 12, pp. 2802-2811, Dec. 1983.

With S.C. Das, "Limit Analysis of Ice Sheet Indentation", Journal of Energy Resources, ASME 105, pp. 352-355, 1983.

"Analysis of Ice Sheet Breakthrough," David Taylor Naval Ship Research and Development Center, Report SD-9, September, 1984.

"Application of Continuous Damage Models in Ice Mechanics," Proceedings of the 4th International Conference on Applied Numerical Modeling, pp. 73-77 Taiwan, 1984.

With W. Torres, "Stability Analysis - Space Shuttle Liquid Hydrogen Tank," 2nd Annual AIAA Aerospace Technology Symposium, New Orleans, Oct. 1984.

"Constitutive Equations for Ice as a Damaging Material," ARCTIC '85: Civil Engineering in the Arctic Offshore, ASCE Specialty Conference, San Francisco, CA, 1985.

"A Damage Mechanics Model for Uniaxial Deformation of Ice", J. of Energy Resources Technology, Vol. 107, No. 3, pp. 363-368, Sept. 1985.

RESEARCH INTERESTS

Analysis and design of structures including structural dynamics and stability. Research in ice mechanics and nonlinear methods.

COURSES TAUGHT

Structural Mechanics (Fall 1983); Text: Structural Analysis for Engineers, Willems and Lucas, McGraw-Hill Book Company, 1978.

Solid Mechanics (Spring 1984); Text: Mechanics and Materials for Design, N.H. Cook, McGraw-Hill Book Company, 1984.

SUMMER 1984

U.S. Navy-ASEE Summer Faculty Research Appointment at Naval Ships Research and Development Center.

1984/85 Freshman Advisor

1985 Member Institute Humanities Committee

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

School of Engineering Faculty Personnel Record

Date: March 1, 1986

Full Name: Ole Secher Madsen
Department: Civil Engineering

1. Date of Birth: February 24, 1941

2. Citizenship: Danish
   If not a U.S. citizen, immigration status: Permanent Resident

3. Education:

| School | Degree | Date |
|---|---|---|
| Technical University of Denmark | S.M. | January 1964 |
| Massachusetts Institute of Technology | Sc.D. | January 1970 |

4. Title of Thesis for Most Advanced Degree:

   "Long Waves over an Uneven Bottom"

5. Principal Fields of Interest: Coastal and Oceanographic Engineering, Sediment Transport, Coastal Processes, Free Surface Flow

6. Name and Rank of Other Department Faculty in Related Field:

   Chiang C. Mei, Professor

   W. Kendall Melville, Associate Professor

7. Name and Rank of Faculty in Other Departments in Related Field:

   Jerome H. Milgram, Professor (Ocean Engineering)

   John B. Southard, Associate Professor (Earth and Planetary Sciences)

8. Non M.I.T. Experience (including military service):

| Employer | Position | Beginning | Ending |
|---|---|---|---|
| Danish Military Service | Sergeant | Jan. 1964 | Jan. 1966 |
| Tech. Univ. of Denmark | Part-time Teaching Assistant | Sept. 1964 | March 1966 |

Name: Ole Secher Madsen

8. Non M.I.T. Experience (cont.):

| Employer | Position | Beginning | Ending |
|---|---|---|---|
| Bigum and Stenfoss | Consulting Engineer | April 1966 | August 1966 |
| U.S. Army Corps of Engineers, Coastal Engineering Research Center | Oceanographer/ Mathematician | Nov. 1969 | Jan. 1972 |
| Technical University of Denmark, Institute of Hydro-dynamics and Hydraulic Eng. | Visiting Professor | August 1979 | August 1980 |
| University of Buenos Aires | Visiting Professor | 1 week | June 1980 |
| Woods Hole Oceanographic Institution | Guest Investigator | Summers | 1981-1985 |

9. History of M.I.T. Appointments:

| Rank | Beginning | Ending |
|---|---|---|
| Assistant Professor | Jan. 1972 | July 1975 |
| Associate Professor (without tenure) | July 1975 | July 1979 |
| Associate Professor (with tenure) | July 1979 | July 1984 |
| Professor | July 1984 | |

10. Consulting Record:

| Firm | Beginning | Ending |
|---|---|---|
| Whitten Corporation | August 1973 | June 1977 |
| EG & G | Feb. 1974 | April 1974 |
| Dames and Moore | April 1974 | July 1974 |
| Stone and Webster | Dec. 1974 | Nov. 1975 |
| Multisystems, Inc. | Oct. 1975 | June 1976 |
| Coffin and Richardson | 3 days | March 1977 |
| EG & G | May 1977 | August 1979 |
| Bracken, Selig and Baram | June 1977 | Sept. 1977 |
| Hill and Barlow | 3 days | August 1977 |
| T.W. Lambe, Inc. | Nov. 1977 | March 1978 |
| Brian Watt Associates, Inc. | March 1979 | Sept. 1982 |
| Sippican Ocean Systems, Inc. | Feb. 1983 | July 1984 |
| Haley and Aldrich | 4 days | July 1983 |
| Metcalf & Eddy | Jan. 1984 | July 1985 |
| Brown and Root | August 1984 | Oct. 1984 |
| Charles T. Main | 4 days | March 1985 |
| Pio Lombardo | Jan. 1985 | Present |
| Haley and Aldrich | Jan. 1986 | Present |
| Whitten Corporation | Feb. 1986 | Present |

Name: Ole Secher Madsen

11. Department and Institute Committees, Other Assigned Duties:

| Activities | Beginning | Ending |
|---|---|---|
| Advisor to Graduate and Undergraduate Students | Sept. 1972 | Present |
| Advisor to Special Graduate Students, WR & EE Division, Department of Civil Engineering | Sept. 1973 | June 1979 |
| UROP Coordinator, Department of Civil Engineering | June 1974 | Sept. 1976 |
| Member MIT-WHOI Joint Committee on Oceanographic Engineering | Sept. 1974 | Sept. 1983 |
| Member Foreign Scholarship Committee | Sept. 1976 | June 1979 |
| Program Officer, WR&EE Division, Department of Civil Engineering | Sept. 1976 | Feb. 1979 |
| Member Departmental Committee on Graduate Students | Sept. 1976 | Feb. 1979 |
| Program Officer, WR&EE Division, Department of Civil Engineering | Nov. 1980 | Sept. 1984 |
| Member Departmental Committee on Graduate Students | Nov. 1980 | Sept. 1984 |
| Chairman, MIT-WHOI Joint Committee on Oceanographic Engineering | Sept. 1983 | Sept. 1984 |
| Freshman Advisor | Sept. 1985 | Present |
| Department Graduate Student Officer | Jan. 1986 | Present |
| Member Committee on Graduate Student Policies | Jan. 1986 | Present |

12. Government Committees, Service, etc.:

| Committee | Beginning | Ending |
|---|---|---|
| Member Sea Grant Site Visit Team to University of South Carolina | | March 1976 |
| Member Sea Grant Site Visit Team to University of New Hampshire and University of Maine | | Oct. 1976 |
| Member of Steering Committee for Research on Shelf Sedimentation NSF, IDOE | Nov. 1976 | March 1980 |
| Member Sea Grant Site Visit Team to University of Rhode Island | | April 1978 |
| Member Editorial Board, "Applied Ocean Research" | Jan. 1979 | Present |
| Member Editorial Board, "Continental Shelf Research" | March 1981 | Present |
| Member ONR Review Panel on Ocean Sciences | | May 1986 |

Name: Ole Secher Madsen

13. Awards Received

| | Date |
|---|---|
| Effective Teaching Award, Department of Civil Engineering | Sept. 1974 |
| Effective Teaching Award, Department of Civil Engineering | Sept. 1976 |
| Third Henry L. Doherty Professorship in Ocean Utilization | July 1977 |
| Graduate Student Council's Outstanding Teaching Award | Sept. 1978 |
| Effective Teaching Award, Department of Civil Engineering | Sept. 1983 |
| Japan Society for the Promotion of Science Fellowship | Nov. 1984 |

14. Current Organization Membership:

| Organization | Offices Held |
|---|---|
| American Society of Civil Engineers (ASCE) | Member WPCO Publications Committee, Sept. 1981 - July 1983<br>Member Technical Committee on Ocean Engineering, Sept. 1981 - Sept. 1984 |
| International Association for Hydraulic Research (IAHR) | |
| Shelf and Nearshore Dynamics and Sedimentation (SANDS) | Secretary & Treasurer, Nov. 1976 - Nov. 1977<br>Member Executive Committee Nov. 1976 - March 1980 |
| Danish Center for Applied Mathematics and Mechanics | |

15. Patents and Patent Applications Pending: None

16. Professional Registration: None

Publications of OLE SECHER MADSEN

1. Books: None

2. Papers in Refereed Journals:

   1. Madsen, O.S., "A Note on the Equations of Groundwater Flow", Journal of Water Resources Research, V. 5, No. 5, 1157-1158, 1969 (letter).

   2. Madsen, O.S. and C.C. Mei, "The Transformation of a Solitary Wave Over an Uneven Bottom", Journal of Fluid Mechanics, V. 39, Part 4, 781-791, 1969.

   3. Madsen, O.S., C.C. Mei, and R.P. Savage, "The Evolution of Timeperiodic Long Waves of Finite Amplitude", Journal of Fluid Mechanics, V. 44, Part 1, 195-208, 1970.

   4. Madsen, O.S., "On the Generation of Long Waves", Journal of Geophysical Research, V. 76, No. 36, 8672-8683, 1971.

   5. *Madsen, O.S., "Wave Transmission Through Porous Structures", Journal of the Waterways, Harbors and Coastal Engineering, ASCE, V. 100, WW3, 169-188, 1974 (Closure, Vol. 102, No. 1, 94-97, February 1976).

   6. Madsen, O.S., "A Three Dimensional Wave Maker, Its Theory and Application", Journal of Hydraulic Research, V. 12, No. 2, 205-212, 1974.

   7. *Madsen, O.S. and W.D. Grant, "The Threshold of Sediment Movement Under Oscillatory Waves: A Discussion", Journal of Sedimentary Petrology, Vol. 45, No. 1, 360-361, March 1975.

   8. *Madsen, O.S. and S.M. White, "Energy Dissipation on Rough Slopes", ASCE, Journal of the Waterways, Harbors and Coastal Engineering, Vol. 102, WW1, 31-38, February 1976 (Closure, Vol. 103, No. 4, 549-551, November 1977).

   9. Madsen, O.S., "A Realistic Model of the Wind-Induced Ekman Boundary Layer", Journal of Physical Oceanography, Vol. 7, No. 2, 248-255, March 1977.

   10. Madsen, O.S., "A Note on Mass Transport in Deep Water Waves", Journal of Physical Oceanography, Vol. 8, No. 6, 1009-1015, November 1978.

   11. Madsen, O.S., "Wave-Induced Pore Pressures and Effective Stresses in a Porous Bed", Geotechnique, Vol. 28, No. 4, 377-393, December 1978.

   12. *Grant, W.D. and O.S. Madsen, "Combined Wave and Current Interaction with a Rough Bottom", Journal of Geophysical Research, Vol. 84, No. C4, 1797-1808, April 1979.

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* Outgrowth of supervised thesis

2. Papers in Refereed Journals (cont.):

13. *Grant, W.D. and O.S. Madsen, "Moveable Bed Roughness in Oscillatory Flow", Journal of Geophysical Research, Vol. 87, No. C1, 469-481, January 1982.

14. *Trowbridge, J.H. and O.S. Madsen, "Turbulent Wave Boundary Layers; 1: Model Formulation and First-Order Solution", Journal of Geophysical Research, Vol. 89, No. C5, 7989-7997, September 1984.

15. *Trowbridge, J.H. and O.S. Madsen, "Turbulent Wave Boundary Layers; 2: Second-Order Theory and Mass Transport", Journal of Geophysical Research, Vol. 89, No. C5, 7997-8007, September 1984.

16. *Kobayashi, N. and O.S. Madsen, "Turbulent Flow over a Wavy Bed", Journal of Geophysical Research, Vol. 90, No. C4, 7323-7331, July 1985.

17. *Kobayashi, N. and O.S. Madsen, "Formation of Ripples in Erodible Channels", Journal of Geophysical Research, Vol. 90, No. C4, 7332-7340, July 1985.

18. *Madsen, O.S. and M.S. Bruno, "A Methodology for the Determination of Drag Coefficients for Ice Floes", submitted to Transactions, ASME, July 1985

19. Madsen, O.S., "Hydrodynamic Force on Circular Cylinders", accepted for publication, Applied Ocean Research, 1986.

3. Proceedings of Refereed Conferences:

1. Madsen, O.S., "Waves Generated by a Piston-type Wave Maker", Proceedings 12th Conference on Coastal Engineering, ASCE, Vol. 1, 589-607, Washington, D.C., July 1970.

2. Madsen, O.S., "The Stability of a Sand Bed under Breaking Waves", Proceedings 14th Conference on Coastal Engineering, ASCE, Vol. 2, 776-794, Copenhagen, July 1974.

3. *Madsen, O.S. and Y.K. Vyas, "Wave Motions in an Offshore Harbor", Proceedings of Modeling 75, ASCE, Vol. 1, 101-120, San Francisco, September 1975.

4. *Grant, W.D. and O.S. Madsen, "Sediment Transport in the Coastal Zone", Proceedings 3rd Inter-Agency Sedimentation Conference, Denver, Colorado, 6.28-6.38, March 1976.

5. *Madsen, O.S. and S.M. White, "Wave Transmission Through Trapezoidal Breakwaters", Proceedings 15th Conference on Coastal Engineering, ASCE, Vol. 2, 2662-2676, Honolulu, July 1976.

*Outgrowth of supervised thesis

3. Proceedings of Refereed Conferences (cont.):

6. *Madsen, O.S. and W.D. Grant, "Quantitative Description of Sediment Transport by Waves", Proceedings 15th Conference on Coastal Engineering", ASCE, Vol. 2, 1093-1112, Honolulu, July 1976.

7. *Madsen, O.S., D.W. Ostendorf and A.S. Reyman, "A Longshore Current Model", Proceedings Coastal Zone 78, ASCE, Vol. 3, 2332-2341, San Francisco, March 1978.

8. *Madsen, O.S., P. Shusang, and S.A. Hanson, "Wave Transmission Through Trapezoidal Breakwaters", Proceedings 16th Conference on Coastal Engineering, ASCE, Vol. 3, 2140-2152, Hamburg, August 1978.

9. *Greer, M.N. and O.S. Madsen, "Longshore Sediment Transport Data: A Review", Proceedings 16th Conference on Coastal Engineering, ASCE, Vol. 2, 1564-1576, Hamburg, August 1978.

10. Kobayashi, N., V. Vivatrat, O.S. Madsen, and I.B. Boaz, "Erosion Prediction for Exploration and Production Structures in the Arctic", Proceedings Thirteenth Offshore Technology Conference, April 1981.

11. *Madsen, O.S., "A Model of Longshore Sediment Transport Processes in the Surf Zone", Proceedings Conference on Frontiers in Hydraulic Engineering, ASCE, Cambridge, Mass., August 1983.

12. *Graber, H.C., and O.S. Madsen, "A Parametric Wind Wave Model for Arbitrary Water Depths", The Ocean Surface, Y. Toba and H. Mitsuyasu (Eds.), pp. 193-199, D. Reidel Publishing Co., 1985

13. *Madsen, O.S., and M.S. Bruno, "A Methodology for the Determination of Drag Coefficients for Ice Floes", OMAE86 Symposium Proceedings, ASME, Tokyo, April 1986.

14. Madsen, O.S., "Inertia Force for Cylinders in Nonlinear Waves", Ocean Structural Dynamics Symposium '86, Oregon State University, September 1986.

15. *Madsen, O.S., and Y.-K. Poon, "Spectral Model for Wave Attenuation by Bottom Friction", 20th International Coastal Engineering Conference, Taiwan, November 1986.

*Outgrowth of supervised thesis

4. Other Major Publications:

1. Madsen, O.S. and C.C. Mei, "Dispersive Long Waves of Finite Amplitude Over an Uneven Bottom", MIT, Department of Civil Engineering, Technical Report No. 117, November 1969.

2. Madsen, O.S., "On Wind Generated Waves in Deep and Shallow Water", Chapter 6 in Lecture Notes: "Methods of Observation and Analysis of Harbor and Coastal Pollution", MIT, Department of Civil Engineering, 1972.

3. *Briggs, D.A. and O.S. Madsen, "Mathematical Models of the Massachusetts Bay, Part II: Analytical Models for One- and Two- Layer Systems in Rectangular Basins", MIT, Department of Civil Engineering, Technical Report No. 172, October 1973.

4. Madsen, O.S., "The Stability of a Sand Bed Under the Action of Breaking Waves", MIT, Department of Civil Engineering, Technical Report No. 182, March 1974.

5. *Madsen, O.S. and S.M. White, "Reflection and Transmission Characteristics of Porous Rubble-Mound Breakwaters", R.M. Parsons Laboratory, Department of Civil Engineering, MIT, Technical Report No. 207, December 1975.

6. *Madsen, O.S. and W.D. Grant, "Sediment Transport in the Coastal Environment", R.M. Parsons Laboratory, Department of Civil Engineering, MIT, Technical Report No. 209, January 1976.

7. *Madsen, O.S. and S.M. White, "Reflection and Transmission Characteristics of Porous Rubble-Mound Breakwaters", U.S. Army Coastal Engineering Research Center, Misc. Report No. 76-5, 138 pp., March 1976.

8. Madsen, O.S., "Wave Climate of the Continental Margin: Elements of Its Mathematical Description", Chapter 6 in Stanley, D.J. and Swift, D.J.P. (Editors): Marine Sediment Transport and Environmental Management, John Wiley, New York, 65-90, 1976.

9. Madsen, O.S., "Basic Wave Theory", Chapter 1 in Lecture Notes: "Coastal Wave Hydrodynamics", MIT, Department of Civil Engineering, 1.1-1.174, July 1976.

10. *Madsen, O.S., "Quantitative Description of Sediment Transport in the Coastal Environment", Chapter 10 in Lecture Notes: "Coastal Wave Hydrodynamics", MIT, Department of Civil Engineering, 10.1-10.111, July 1976.

* Outgrowth of supervised thesis

4. Other Major Publications (cont.):

11. Stolzenbach, K.D., O.S. Madsen, E.E. Adams, A. Pollack, and C.K. Cooper, "A Review and Evaluation of Basic Techniques for Predicting the Behavior of Surface Oil Slicks", MIT, Department of Civil Engineering, Technical Report No. 222, February 1977.

12. *Madsen, O.S., "Some Aspects of Fluid-Sediment Interaction in the Coastal Environment", Proceedings of the Conference on "Vorticita e Strato Limite in Condizione di Flusso Tridimensionale, University of Padova, Vol. 2, 149-166, June 1978.

13. *Madsen, O.S., "An Analytical Model of Longshore Sediment Transport", Proceedings of a Workshop on Coastal Sediment Transport with Emphasis on the National Sediment Transport Study, University of Delaware, Report DEL-SG-15-78, 95-102, December 1978.

14. *Ostendorf, D.W. and O.S. Madsen, "An Analysis of Longshore Currents and Associated Sediment Transport in the Surf Zone", R.M. Parsons Laboratory, Department of Civil Engineering, MIT, Technical Report No. 241, p. 169, April 1979 (also MIT Sea Grant Report MIT-SG-79-13).

15. *Madsen, O.S. and H.C. Graber, "Finite Depth Wind Wave Model", Proceedings of Workshop on Developments in Coastal Ocean Dynamics, WHOI, Chapter 5, March 1983.

16. Madsen, O.S., "Tracer Theory", Chapter 6A in the Nearshore Sediment Study's Monograph, Seymour, R.J., (Editor), to be published 1985 by Plenum Press.

17. *Madsen, O.S., "Longshore Current Model for Monochromatic Waves", Chapter 16A in the Nearshore Sediment Transport Study's Monograph, Seymour, R.J., (Editor), to be published 1985 by Plenum Press.

18. Earle, M.D. and O.S. Madsen, "Wave Climate", Chapter 3.4 in Georges Bank Book, Backus, R., (Editor), to be published 1985 by MIT Press.

19. *Grant, W.D. and O.S. Madsen, "The Continental Shelf Bottom Boundary Layer", Annual Review of Fluid Mechanics, M. Van Dyke (Ed.), 18, 265-305, 1986.

5. Internal Memoranda and Progress Reports: None

* Outgrowth of supervised thesis

6. Invited Lectures:

June 19-23, 1972, "On Wind Generated Waves in Deep and Shallow Water", MIT Summer Course in Methods of Observation and Analysis of Harbor and Coastal Pollution.

January 28, 1974, "Sediment Transport by Waves", Dames & Moore Coastal Processes Workshop, Jacksonville, Florida.

November 1974, "Wave Climate of the Continental Margin", American Geological Institute, Miami, Florida.

June 8, 1976, "Sediment Transport in the Coastal Environment", Virginia Institute of Marine Sciences.

June 28, 1976, "Quantitative Description of Sediment Transport in the Coastal Environment", NOAA, Marine Geology and Geophysics Laboratory, Miami, Florida.

July 26-30, 1976, "Basic Wave Theory" and "Quantitative Description of Sediment Transport in the Coastal Environment", MIT Summer Course on Coastal Wave Hydrodynamics.

March 31, 1977, "Some Aspects of Sediment Transport in the Coastal Environment", Moore Lecture, University of Virginia, Charlottesville, Virginia.

June 20-24, 1977, "Some Aspects of the Prediction of Winds, Waves and Currents and the Resulting Design Forces", MIT Summer Course on Design and Construction of Offshore Facilities.

June 23-24, 1978, "Some Aspects of Fluid-Sediment Interaction in the Coastal Environment", Conference on Turbulence in Three Dimensional Boundary Layer Flow, University of Padova.

November 27-28, 1978, "Surf Zone Processes - What We Do and Don't Know, With Special Reference to Longshore Sediment Transport", Keynote Speaker, Workshop on Coastal Zone Research in Massachusetts, Woods Hole Oceanographic Institution.

July 17-18, 1979, "Surf Zone Dynamics and Sand Transport", Nearshore Sediment Transport Study Workshop, Scripps Institution of Oceanography.

November 17, 1979, "Wave and Current Interaction With a Rough Bottom", Danish Center of Applied Mathematics and Mechanics.

December 18, 1979, "Wave and Current Interaction with a Rough Bottom", Max-Planck-Institute fur Meteorologie, University of Hamburg.

January 14-18, 1980, "A Theoretical Model of the Boundary Layer for a Combined Oscillatory and Steady Flow", Nordic Symposium on Physical Oceanography, University of Copenhagen.

6. Invited Lectures (cont.):

June 9-14, 1980, "Mechanics of Sediment Transport in Steady and Unsteady Flows", University of Buenos Aires, Argentina.

May 12-20, 1981, "Wave Attenuation by Bottom Friction", Poster Session, IUCRM Symposium on Wave Dynamics, Miami Beach.

April 22, 1982, "Determination of Longshore Sediment Transport Rates by Use of Tracers", University of Florida, Gainesville.

June 9-10, 1982, "Longshore Current Model for Monochromatic Waves", U.S. Corps. of Engineers, CERC, Nearshore Current Model Workshop, University of Delaware.

March 16-17, 1983, "Wind Wave Modeling", Coastal Ocean Dynamics Workshop, Woods Hole Oceanographic Institution.

November 14, 1983, "Mechanics of Shore Processes", 20th Henry M. Shaw Lecture in Civil Engineering, North Carolina State University, Raleigh.

May 22, 1984, "Effects of Finite Water Depths on Wind Waves", Workshop on Modeling of Coastal Processes: Circulation, Dispersion and Waves, MIT Sea Grant.

November 27, 1984, "Wave Boundary Layers and Wave-Current Interaction", University of Tokyo, Tokyo, Japan.

November 28, 1984, "Longshore Sediment Transport and a Model for its Determination by Use of Tracers", University of Tokyo, Tokyo, Japan.

November 30, 1984, "Wave Boundary Layers", Port and Harbour Reserach Institute, Kurihama, Japan.

December 7, 1984, "Wave Boundary Layers", Osaka University, Osaka, Japan.

December 11, 1984, "Wave Boundary Layers", Kyoto University, Kyoto, Japan.

# CURRICULUM VITAE

**Tomasz Wierzbicki**

## PERSONAL DATA

Date of Birth: April 14, 1937
Place of Birth: Warsaw, Poland
Social Security Number: 571-80-2292
Wife: Margaret Vinohradnik
Children: Martin (12), Agnes (9)
Home Address: 12 Wilson Street, Winchester MA 01890
Visa Status: Permanent U.S. Resident

## PRESENT POSITION

M.I.T. Department of Ocean Engineering,
Professor of Applied Mechanics (with tenure)

## EDUCATION

| | |
|---|---|
| M.S. | Warsaw Technical Univerisity |
| Ph.D. | Institute of Fundamental Technological Research, Warsaw, 1965 |
| D.Sc. | Institute of Fundamental Technological Research, Warsaw, 1971 |

## PREVIOUS APPOINTMENTS

Cambridge University, Engineering Department, June 1986, Visiting Professor

M.I.T., Dept. of Ocean Engineering Visiting Professor 1982.

Det Norske VERITAS, Norway, Summer of 1982, Visiting Research Engineer.

Duke University, Civil Engineering Deptartment Visiting Professor 1981.

Volvo, Sweden, Summer of 1977 and 1980, Visiting Research Engineer.

Institute of Fundamental Technological Research, Full Professor 1979.

Brown University, Division of Engineering, Sr. Research Fellow 1973-1974.

M.I.T., September 1974, Visiting Scientist

Stanford University, Fall 1974, Visiting Scientist.

Institute of Fundamental Technological, Research Associate Professor 1972-1978.

Polish Academy of Sciences, Institute of Fundamental Technological Research, Assistant Professor 1967 - 1971.

Stanford University, Deptartment of Applied Mechanics Post-Doctorate 1965-1966.

CONSULTING

1985 Engineering Systems International, Paris, Collision Resistance of Ships

1985 BMW, Munich, Germany, Crashing Strength of Box Columns

1983 Standard Oil Co., California, Prediction of Residual Strength of Dented Offshore Structures.

1981-to date Research Laboratories, Ford Motor Company, Michigan, Contribution to the New Vehicle Concept Design.

1981-to date Product Design and Engineering Department, VOLVO, Sweden, Development of Crash Energy Management Systems.

1981-to date Det Norske Veritas (ship's classification Society), Oslo, Norway, Analysis of the Collision Protection of Offshore Platforms.

1976-1980 FIAT Car Company,Design of an Improved Bumper Protection of Automobiles.

1977 Research Institute of Automotive Industry Budapest, Hungary, Calculation of the Collapse Strength of Frames in the Bus Roll-Over.

TEACHING - COURSES TAUGHT

- Elementary and Advanced Theory of Plasticity (Stanford University 1966).
- Dynamic Plasticity (Institute of Fundamental Technological Research, Warsaw, 1974, 1977).
- Continuum Mechanics (Duke University 1981).
- Advanced Mechanics of Solids (Duke University 1981).
- Plastic Structural Dynamics (Summer Course, International Center for Mechanical Sciences, Udine, Italy 1979).
- Crushing Mechanics of Thin-Walled Structures (Intense Course on "Crashworthiness Engineering" Duke University, November 1981).
- Structural Mechanics (M.I.T., 1982 through 1986)

- Advanced Analysis and Design of Ocean Engineering Structures (M.I.T., 1983).

- "Impact Strength of Marine Structures," (MIT, 1984, 1985)

- "Nonlinear Analysis of Marine Structures," 1985

SPONSORED RESEARCH

- "Structural Aspects of Vehicle Crashworthiness," Jointly sponsored by National Science Foundation USA and Polish Academy of Sciences, special currency program, July 1979 - June 1983, Principal Investigator.

- "Crushing Analysis of Thin-Walled Structures," Office of Naval Research, $31,000, January 1981 - June 1981, Co-Principal Investigator.

- "Local Response of Marine Structures to Hydrodynamic Loads," U.S. Department of Commerce through the Sea Grant Program at M.I.T. July 1983 - June 1986, $150,000 for the period of 3 years, Principal Investigator.

- "Local Collapse of Stiffened Cylindrical Shells Subjected to Impact or Explosive Loading," Office of Naval Research, $100,000 for the period of 2 years, Principal Investigator.

- "Ice Forces on Offshore Structures," Standard Oil of Ohio, $300,000 for the period of 5 years, Principal Investigator.

- "Residual Strength of Dented Tubes," Joint MIT/Industry project, 1985, $100,000, Principal Investigator.

- "Radial Cracking of Multi-year Floes," British Petroleum, Co. $20,000, 1986, Principal Investigator.

- "Vehicle Structural Crashworthiness," Multi-industry project administered through the Center for Transportation Studies at MIT, Funds received to date $90,000, Principal Investigator.

- "Mechanics of Ice Plates Fragmentation," 9/1/86-8/31/88, National Science Foundation, $240,000 (first year), (Pending), Co-Principal Investigator.

- "Intermediate Scale Acoustic and Mechanical Processes of Sea Ice Sheets," National Science Foundation, $165,455 (first year), 7/1/87-6/30/90, (Pending), Co-Principal Investigator.

INVITED LECTURES

Presented papers at ten consecutive Polish Solid Mechanics Conferences over the period 1963 - 1978.

2nd National USSR Congress on "Dynamics of Deformable Bodies," Alma-Ata 1975.

Euromech Colloquium No. 89, "Dynamics of Plastic Continua and Structures," Hungary 1977.

4th National Congress of Applied Mechanics, Bucharest, Romania 1968.

Euromech Colloquium No. 121, "Dynamics and Crushing Analysis of Plastic Structures," Warsaw 1979.

8th Canadian Congress of Applied Mechanics, Moncton, 1981.

IUTAM Symposium on Buckling of Structures in Theory and Practice, University College London, September 1982

1st International Symposium on Structural Crashworthiness, University of Liverpool, England, September 1983.

Seminar on Ice Forces on Structures, Mineral Management Service, Anchorage, Alaska, July 1986.

Winter ASME Annual Meeting, Anaheim, California, 1986.

INVITED SEMINARS

Chalmers University of Technology, Sweden 1976

Tokyo University 1977

Disaster Prevention at Research Institute, Kyoto University, Japan 1977

University of Nagoya, Japan 1977

University of Osaka, Japan 1977

Stanford University 1966 and 1974

University of California, Berkeley 1966, 1974, 1983

University of California, La Jolla 1966 and 1974

University of Washington, Seattle 1974

Northwestern University, Evanston 1977

University of Illinois, Urbana-Champaign 1977

University of Minnesota, Minneapolis 1977

Cornell University 1979

University of Illinois at Chicago Circle 1977

University of Colorado, Boulder 1974

NASA-Langley 1979

Brown University, Providence 1974 and 1981

Massachusetts Institute of Technology 1974 and 1981

Duke University 1981

University of British Columbia at Vancouver 1974

University of Edmonton, Canada 1974

University of Toronto 1979

Naval Postgraduate School, Monterey, California, 1983

Ford Motor Company, Scientific Research Laboratory, 1983, 1985

Dartmouth College, Hanover, New Hampshire, 1986

## AWARDS and RECOGNITIONS

1974 M.T. HUBER Prize for the best work in Mechanics awarded by the Polish Academy of Sciences.

1979 Polish Academy of Sciences Prize for the book, "Design of Structures to Dynamic Loads".

1968 Secretary of the 11th Polish Solid Mechanics Conference.

1977 Chairman of the Symposium, "Dynamic Loading on Structures," Warsaw.

1978 Chairman of the Euromech Colloquium No. 121 on "Dynamics and Crushing of Plastic Structures," Jablonna n/Warsaw.

1977 Session Chairman at the HOPE Int. JSME Symposium, Toyko.

1979 Chairman of the Summer School on "Dynamics of Plastic Structures," International Center for Mechanical Sciences, Udine Italy.

1983 Co-Chairman of the International Symposium "Structural Crashworthiness," held in Liverpool, England.

PUBLICATIONS BY PROFESSOR TOMASZ WIERZBICKI


1. A thick-walled elastic viscoplastic spherical container under stress and displacement boundary conditions, Archives of Mechanics (formerly Archiwum Mechaniki Stosowanej), Vol. 15, No. 2, 1963, pp. 297-308.

2. Impulsive loading of a spherical container with rigid-plastic strain rate sensitive material, Archives of Mechanics, Vol. 15, No. 6, 1963, pp. 775-790.

3. On the impulsive loading of a spherical vessel, Bull. Acad. Pol. Sci., Vol. 12, No. 4, 1964, pp. 217-224.

4. Temperature dependent and strain rate sensitive plastic materials, (jointly with P. Perzyna), Archives of Mechanics, Vol. 16, No. 1, 1964, pp. 135-143.

5. On the temperature dependent and strain rate sensitive plastic material, (jointly with P. Perzyna), Bull. Acad. Ppol. Sci., Vol. 12, No. 4, 1964, pp. 225-232.

6. Bending of rigid, viscoplastic circular plate, Archives of Mechanics, Vol. 16, No. 6, 1964, pp. 1183-1195.

7. Quasi-static flow of rigid, viscoplastic plates, Bull. Acad. Pol. Sci., Vol. 12, 1964, pp. 611-618.

8. Dynamics of rigid, viscoplastic circular plates, (Ph.D. Thesis from the Institute of Fundamental Technological Research), Archives of Mechanics, Vol. 17, No. 6, 1965, pp. 851-869.

9. Dispersion of small amplitude stress waves in pre-stressed elastic viscoplastic cylindrical bars, (jointly with J. Bejda), Quart. Appl. Math., Vol. 23, No. 1, 1966, pp. 63-71.

10. Response of rigid-viscoplastic circular and square plates to dynamic loading, Technical Report No. 162, Stanford University, 1966.

11. A method of approximate solution of boundary value problems for rigid, viscoplastic structures, Acta Mechanica, Vol. 3, No. 1, 1967, pp. 56-66.

12. Impulsive loading of rigid viscoplastic plates, Int. J. Solids Structures, Vol. 3, No. 4, 1967, pp. 635-647.

13. Motion of circular plate subject to projectile impact (jointly with J.M. Kelly), ZAMP, Vol. 18.18, No. 2, 1967, pp. 236-246.

14. Analysis of the propagation of plane-plastic waves at finite strain (jointly with E.H. Lee), J. Appl. Mech., Vol. 34, No. 4, 1967, pp. 931-936.

15. Finite deflection of a circular viscoplastic plate subject to projectile impact, (jointly with Kelly), Int. J. Solids Structures, Vol. 4, No. 11, 1968, pp. 1081-1092.

16. Viscoplastic flow of rotationally symmetric shells with particular application to dynamic loading, Report No. 1, 1968, Institute of Fundamental Technological Research.

17. Large deflections of strain rate sensitive plate loaded impulsively, Archives of Mechanics, Vol. 21, No. 1, 1969, pp. 67-79.

18. On the bending shear interaction in viscoplastic flow of circular plates, Bull. Acad. Pol. Sci., Vol. 17, No. 3, 1969, pp. 153-159.

19. An experimental and theoretical study of impulsively loaded viscoplastic cylindrical shells, Report No. 11, 1969, Institute of Fundamental Technological Research.

20. A theoretical and experimental investigation of impulsively loaded clamped circular viscoplastic plates, (jointly with A.L. Florence), Int. J. Solids Structures, Vol. 6, No. 5, 1970, pp. 553-568.

21. A method of approximation in the large deflection analysis of impulsively loaded rigid-plastic structures, Acta Mechanica, Vol. 68, No. 3-4, 1970, pp. 403-413.

22. Bounds on large dynamic deformations of structures, J. Engl. Mech. Div., Proceedings ASCE, Vol. 96, June 1970, pp. 267-276.

23. Deformation bound theorem for viscoplastic bodies loaded impulsively, Bull. Acad. Pol. Sci., Vol. 18, No. 10, 1970, pp. 427-433.

24. Non-associated constitutive law in viscoplasticity with application to dynamics of plates and shells, Acta Mechanica, Vol. 11, No. 1, 1971, pp. 21-31.

25. On the region of admissible deformation in impulsive loading problems, J. Mech. Phys. Solids, Vol. 19, No. 1, 1971, pp. 1-10.

26. Application of variational methods to the determination of bounds on dynamic deformation of structures, (in Polish), Report No. 4, 1971, Institute of Fundamental Technological Research.

27. Improved lower bound theorem for impulsively loaded continua, Archives of Mechanics, Vol. 23, No. 3, 1971, pp. 423-425.

28. Lower bound on deformation in impulsive loading problems, Bull. Acad. Pol. Sci., Vol. 19, No. 7-8, 1971, pp. 291-298.

29. Dynamics of viscoplastic structures, (in Polish), survey paper in "Theory and Applications of Viscoplasticity," Ossolineum, Warsaw, 1971.

30. Dynamic deformations of cylindrical shells (in Polish), (jointly with H. Andrzejewski), IMP Reports, Vol. 19, No. 1-A, 1971, pp. 32-40.

31. Dynamics of viscoplastic shells (in Polish), Part I Theory, Part II Applications, Rozprawy Inzynierskie, Vol. 19, No. 4, 1971, pp. 667-730.

32. A linear theory of viscoplastic structures, (in Polish), Report. No. 29, 1971, Institute of Fundamental Technological Research (Habilitation Thesis).

33. Comment on "Lower bounds of deformations of dynamically loaded rigid-plastic continua," AIAA Journal, Vol. 10, No. 3, 1972, pp. 363-364.

34. Transient response of viscoplastic rectangular plates (jointly with W. Wojewodzki), Archives of Mechanics, Vol. 24, NO. 4, 1972, pp. 587-604.

35. A new approach to the mode approximation for impulsively loaded rigid-plastic structures, Archives of Mechanics, Vol. 24, No. 4, 1972, pp. 655-658.

36. Lower bounds on deformations for impulsively loaded plastic and viscoplastic structures, Problems in Rheology, Proc. French-Polish Mechanics Conf., Jablonna, Sept. 1971.

37. Impulsive loading of viscoplastic cylindrical shell, (jointly with M. Andrzejewski), in Proc. Symp. Plastic Analysis of Structures, Jassy, Sept. 6-9, 1972.

38. An approximate linear theory of thin viscoplastic shells, Archives of Mechanics, Vol. 24, No. 6, 1972.

39. An analysis of final shapes in free forming problems, Proc. Int. Conf. on the Use of High-Energy Rate Methods for Forming, Welding and Compactions, University of Leeds, 27-29, March 1973.

40. Application of an eigenfunction expansion method in plasticity, J. Appl. Mech., Vol. 41, No. 2, 1974, pp. 448-452.

41. Direct variational approach to dynamic plastic mode solutions, Bull. Acad. Pol. Sci., Ser. Sci. Tech., Vol. 23, No. 6, 1975, pp. 229-641.

42. On an extremum principle for mode form solutions in plastic structural dynamics (jointly with P.S. Symonds), Brown University, Report November 1974, also, J. Appl. Mech., Vol. 42, 1975, pp. 630-641

43. A study of the higher mode dynamic plastic response of beams (jointly with N. Jones), MIT Department of Ocean Engineering, Report No. 76-3, also Int. J. Mech. Sci., Vol. 18, 1976, pp. 533-542.

44. Extremum principles in the dynamics of rigid-plastic bodies - a critcal review of existing applications, Proc. ELCALP Seminar, Berlin, Sept. 1975, also Nuclear Eng. Design, Vo. 37, 1976, pp. 149-160.

45. Large deflection of dynamically loaded structures - critical review of existing methods, IFTR Reports 51/1975, also Eng. Transactions, Vol. 24, No. 2, 1976, pp. 406-432.

46. Survey of solution methods in the dynamics of plastic shells (jointly with G. Bak and D. Niepostyn), (in Polish), Proc. Symp. Shell Structures, Krakow, April 25-27, 1974.

47. Bounds on large inelastic deformations of dynamically loaded structures (jointly with J. Ploch), Proc. 3rd Symp. Dynamics Stability of Structures, Rzeszow, October 1976.

48. Membrane mode solutions for impulsively loaded circular plate (jointly with P.S. Symonds), Division of Engineering, Brown University Technical Report, January 1978, also J. Appl. Mech., Vol. 46, No. 1, 1979.

49. On perturbation solutions for impulsively loaded viscoplastic structures (jointly with W. Wojno), ZAMP, Vol. 30, 1979, pp. 41-55.

50. DESIGN OF STRUCTURES TO DYNAMIC LOADS, (in Polish), (ARKADY), Warsaw, 1980, (in German) Verner-Verlag, Dusseldorf, 1983.

51. Perturbation solution for impulsively loaded viscoplastic plates, (jointly with W. Wojno), Int. J. Non-linear Mechanics, Vol. 15, 1980, pp. 211-223.

52. Bounds for large plastic deformations of dynamically loaded continua and structures (jointly with J. Ploch), Int. J. Solids Structures, Vol. 17, 1981, pp. 183-195.

53. Bounds on deflections of stiff interfaces in vehicles during collision (jointly with E.H. Lee), Stanford University Report SUDAM, May 1975.

54. Calculations of a safe bumper (in Polish), Technika Motoryzacyjna, Vol. 25, No. 5, 1975, pp. 1-7.

55. Dynamic crushing of strain rate sensitive box columns (jointly with T. Akerstrom), Proc. 2nd Int. Conf. on Vehicle Structural Mechanics, April 18-20, 1977, Southfield, Michigan, pp. 19-31.

56. Stabilizing effects in dynamic crushing of sheet metal columns, Proc. HOPE Int. JSME Sympsoium, Tokyo, Oct. 21-Nov. 2, 1977.

57. Experimental-theoretical correlation of dynamically crushed components of bus frame structure (jointly with Cs. Molnar and M. Matolcsy), Proc. Int. FISITA Congress, Budapest, June 8-19, 1978.

58. Kinematic approach to crushing analysis of shell structures (jointly with W. Abramowicz), Proc. 3rd Int. Conf. on Vehicle Structural Mechanics, Oct. 10-12, 1979, Troy, Michigan pp. 211-223.

59. Crushing analysis of strain rate sensitive structures (jointly with W. Abramowicz), Eng. Transactions, Vol. 29, No. 1, 1982, pp. 153-163.

60. Crushing analysis of rotationally symmetric plastic shells, (jointly with J.G. de Oliviera), J. Strain Analysis, Vol. 17, 1982, pp. 229-236.

61. Shape optimization of sheet metal structures against crash (jointly with T. Akerstrom and C. Jernstrom), Proc. 4th Int. Vehicle Structural Mechanics Conference, No. 18-20, Detroit, Michigan, pp. 129-140.

62. On the crushing mechanics of thin-walled structures, (jointly with W. Abramowicz), J. Applied Mech., Vol. 5, No. 4a, pp. 727-734.

63. Extensional collapse mode of structural members in crash loading, (jointly with R. Hayduk), Proc. Symp. Advances and Trends in Structural and Solid Mechanics, Washington, D.C., Oct. 4-7, 1982, Computers and Structures, 1983, Vol. 18, No. 3, 1984, pp. 447-458.

64. On the formation and growth of folding modes, Proc. IUTAM Symp., "The Buckling of Structures in Theory and Practice," ed. J.M.T. Thompson and G.W. Hunt, Cambridge University Press, 1983.

65. Plastic behavior of tubular members under lateral concentrated loading (jointly with J.G. de Oliviera), Det norske Veritas, Technical Report No. 82-0708.

66. Crushing analysis of ship structures with particular reference to bow collisions (jointly with W. Abramowicz and J.G. de Oliviera), Det norske Veritas, Technical Report. No. 82-0709.

67. Crushing behavior or plate intersections, in "STRUCTURAL CRASHWORTHINESS," Edited by Norman Jones and Tomasz Wierzbicki, Butterworth Press, September 1983.

68. Crushing behavior of metal honeycombs, Int. J. Impact Engn., Vol. 1, No. 2, 1983, pp. 157-174.

69. Failure of floating ice plate under impact or impulsive loading, (jointly with P.C. Xirouchakis), Proc. 3rd International Offshore Mechanics and Arctic Engineering Symposium, New Orleans, Louisiana, February 13-15, 1984.

70. STRUCTURAL CRASHWORTHINESS, (editor), Butterworth Press, September 1983.

71. A moving hinge solution for axisymmetric crushing of tubes, (with S. Bhat), Int. J. Mechanical Sciences, vol. 28, No. 3, pp. 135-151, 1986.

72. On the initiation and propagation of buckles in pipelines, (with S. Bhat), Int. J. Solids Structures, Vol. 22, No. 9, pp. 985-1005, 1986.

73. On the transition zone in unconfined buckle propagation, (with S. Bhat), Proc. Symposium on Current Practice and New Technology in Ocean Engineering, Energy-Sources Technology Conference and Exhibition, Feb. 23-28, 1986 New Orleans. J. Offshore Mechanics and Arctic Engineering, Vol. 109, pp. 155-162. 1987

74. Uniaxial constitutive equations of ice from beam tests, (with P.C. Xirouchakis), J. Energy Resources Technology, Vol. 107, No. 4, Dec. 1985, pp. 511-516.

75. Spalling and buckling of ice sheets, Proc. ARCTIC 1985 ASCE/Specialty Conference, March 25-27, San Francisco.

76. Failure of strain softening ice sheets, (with P.C. Xirouchakis and S.K. Choi), Proc. 5th Int. OMAE Symposium, Tokyo, April 1986.

77. A note on shear effect in progressive crushing of prismatic tubes, (with S. Bhat), SEA Paper No.860821, Proc. Sixth Int.l Conference on Vehicle Structural Mechanics, Detroit, April 22-25, 1986.

78. The relationship between retinal vessel tortuosity, diameter, and transmural pressure, (with J.A. Kylstra, M.L. Wolbarsht, B. Landers, and E. Stefansson), A.V. Graefe, Archives for Opthomology.

79. Impact damage of the Challenger crew compartment, (with D. Yue), J. Rocket and Space, Vol. 23, No. 6, pp. 646-654, 1986.

80. Spacecraft crashworthiness - towards reconstruction of the Space Shuttle accident, Proc. ASME Winter Annual Meeting, Anaheim, California, Dec. 1986, pp. 31-46.

81. Dynamic failure of a free-free beam (with N. Jones), Int. Journal of Impact Engineering, in print, 1987.

82. Indentation of tubes under combined loading, (with M.S. Suh), submitted to Int. Journal of Mechanical Sciences.

83. Plastic tripping of flatbar stiffeners, (with S. Bhat), submitted to J. Thin-Walled Structures.

84. Axial crushing of foam-filled columns (with W. Abramowicz), submitted to Int. J. Mech. Sci.

85. Axial crushing of multicorner sheet metal columns, (with W. Abramowicz), submitted to J. Appl. Mech.

86. Mechanics of deep collapse of thin-walled structures, contributing chapter to the book "Structural Failure", ed. T. Wierzbicki and N. Jones, John Wiley Interscience, 1988.