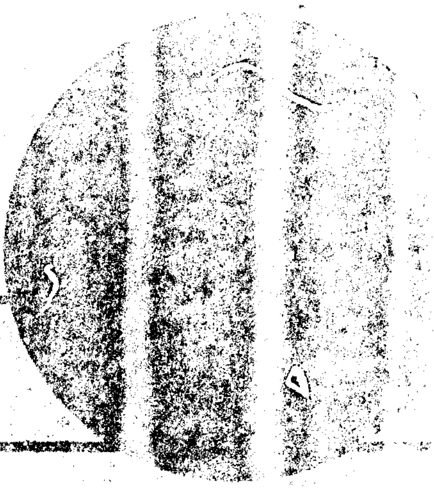
AD/A-094 651

ENVIRONMENTAL EXPOSURE AND DESIGN CRITERIA FOR OFFSHORE OIL AND GAS STRUCTURES

The National Research Council
Washington, D. C.

May 1980

Environmental Exposure and Design Criteria for Offshore Oil and Gas Structures



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ENVIRONMENTAL EXPOSURE AND DESIGN CRITERIA

FOR

OFFSHORE OIL AND GAS STRUCTURES

11 May [illegible]80

A Report Prepared by the
3 Committee on Offshore Energy Technology
~~of the Marine~~ Board
Assembly of Engineering
National Research Council Wash DC

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1980

NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This report represents work supported by Contract Number N00014-76-C-0309 between the Office of Naval Research and the National Academy of Sciences.

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PREFACE

In the quest for new sources of oil and gas to augment dwindling reserves in easily accessible regions on land and at sea, the petroleum industry has reached out to geologic formations in deeper waters and harsher environments.

Prior to 1970, most drilling in U.S. offshore waters was conducted in the relatively shallow areas of the Gulf of Mexico. Now, oil and gas are being produced in deeper waters in the Gulf of Mexico and the Pacific Ocean off Southern California, as well as in the Gulf of Alaska. Elsewhere, drilling and production activities are being carried out in the ice-covered Canadian Arctic and the storm-swept North Sea. In the future, oil and gas will probably flow from the offshore Alaskan Arctic.

Given this trend, engineers face a formidable challenge to design and operate offshore platforms and equipment in a safe, economical, and environmentally acceptable manner. In the hostile frontiers where oil and gas are to be recovered in the future, scientific and technical information is needed on the natural conditions--winds, waves, currents, bottom sediments, weather, and climate. Not only does industry need such data, but the federal government does as well in order to make its policy decisions.

The Department of the Interior sells leases for offshore drilling rights and inspects and verifies offshore drilling and production platforms. To develop offshore petroleum resources in a coherent and timely manner, both industry and the government need to share a better understanding of the offshore environment. Doing so should reduce misunderstandings and uncertainties that could lead to disputes, thus minimizing delays in the exploration and production of oil and gas from offshore waters.

The Marine Board of the National Research Council has had a long-standing concern with such matters and has addressed the issues in a number of its meetings and in several studies by its panels. As a result of this interest, and in response to requests by the U.S. Geological Survey of the Department of the Interior and the Division of Fossil Fuel Extraction of the Department of Energy, the Marine Board organized the Committee on Offshore Energy Technology (COET) in the fall of 1977 to evaluate the technology base to advance:

1) efficient and economic exploration and production of energy resources from beneath the ocean, and

2) standards and procedures the government could exercise to fulfill its statutory responsibilities for conserving vital resources, protecting the environment, and safeguarding human life.

One of the tasks of COET was to review the availability of engineering field data, methods, and procedures for adequately describing and interpreting the environmental conditions that go into criteria for the design, verification, and inspection of offshore oil and gas structures.

Accordingly, the committee examined how industry obtains environmental data, how it uses the data to evaluate environmental exposures, and how it uses environmental exposures to establish criteria to design, build, install, and operate offshore platforms. The committee examined all three phases of developing offshore petroleum reserves: pre-lease, exploration, and production. The purpose was to find where and what types of data were needed by government and industry.

This report represents the work and findings of the committee. Section I presents the committee's recommendations and conclusions and the technical analysis upon which these are based. Section II consists of background papers that lay out in greater detail the concepts and technical analysis developed in this report.

The author(s) of each background paper assumes complete responsibility for its contents. Each author is a member of the committee or a recognized authority on the subject of the paper. While none of the papers has been critically reviewed in accordance with the customary procedures of the National Research Council, each has been found by the committee to be valuable to its study.

Acknowledgements

A number of people in addition to the members of the committee made valuable contributions to the study, especially in the preparation of the background papers that appear in Section II of this report. The committee gratefully acknowledges the assistance of the following:

Paul Aagaard, Chevron Oil Field Research Company

Peter Arnold, Shell Oil Company

J. M. E. Audibert, Woodward-Clyde Consultants

Robert G. Bea, Woodward-Clyde Consultants

Marvin D. Burkhart, Office of the Oceanographer, Department of the Navy (Ret.)

Vincent Cardone, Ocean Weather

E. H. Doyle, Shell Development Company

Robert Kay, National Oceanic and Atmospheric Administration

Neil T. Monney, U.S. Naval Academy

William M. Nicholson, National Oceanic and Atmospheric Administration

Donald T. Resio, U.S. Army Engineers Waterways Experiment Station

J. R. Ruser, Shell Development Company

Paul Teleki, U.S. Geological Survey

E. G. Ward, Shell Development Company

Wilford F. Weeks, U.S. Army Cold Regions Research and Engineering Laboratory

The committee also acknowledges the assistance of G. P. Smedley, Head, Offshore Services Group, Lloyd's Register of Shipping, London, England, and Nils Nordenstrom, Vice President, Det norske Veritas, Oslo, Norway. Mr. Smedley and Dr. Nordenstrom participated in discussions of the committee and provided detailed information on related work in their respective countries.

SUMMARY

To meet the increasing political and economic demands for more self-sufficiency in energy, it is likely that during the next two decades about one-third of the oil and gas produced in the United States will come from wells drilled on the outer continental shelf (OCS). These areas have to be explored and developed in a practical, expedient, and safe manner.

Private industry has developed the technology required to explore and produce oil and gas from reservoirs off the coasts. This technology includes methods to analyze and describe data on natural events like winds, waves, currents, ice, and earthquakes. It also includes methods to compute the loads such forces put on offshore platforms, as well as to evaluate procedures, construction techniques, and equipment. In doing its work, the petroleum industry practices a form of self-regulation for the design and operation of its offshore facilities to increase its effectiveness and decrease its liability.

Meanwhile, the federal government has expanded its role in developing the nation's offshore energy resources. In addition to conducting lease sales along the outer continental shelf, the government now is engaged in developing standards and procedures to fulfill its responsibilities for human safety, resource conservation, and environmental protection. This requires the government to become increasingly knowledgeable about the technology for offshore drilling and production.

To develop offshore petroleum resources in a timely, safe, and economical fashion, government and industry need to come to a mutual understanding of the environmental factors that affect drilling on the outer continental shelf. This is particularly important as drilling activities move from the relatively mild environment of the Gulf of Mexico to deeper waters and Arctic areas. Differences in understanding could lead to delays in development, which are likely to affect resource planning by government and industry and, in turn, substantially increase costs.

Of crucial importance in offshore operations are such environmental, or natural, forces as winds, waves, currents, weather, and earthquakes. Known collectively by the term "environmental exposure," the effects of such forces on offshore platforms, as well as the likelihood of their occurrence, need to be understood and evaluated.

In the process used to design offshore structures to withstand environmental exposure, its functional and operational requirements need to be considered simultaneously.

Equally important are concerns for the safety of operating personnel, the integrity of equipment, and the preservation of the environment within the framework of what the structure is intended to do and at what cost. The process is intended to result in a structure that achieves the desired operational and functional requirements in the particular environment, while maintaining an appropriate balance between safety and economics. Thus, environmental design criteria are the parameters used to design structures to operate in a reliable, safe, and economic manner.

Three methods can be used to select or develop environmental design criteria: (1) experience with prototype structures; (2) projected lifetime maxima; and (3) reliability analysis. Because there are no clear lines of demarcation between them, these methods are often used in varying combinations. Sound judgment and experience are always essential in selecting environmental design criteria.

The hindcast approach is the most appropriate technique for determining environmental exposures. In this approach, environmental models are used with historical data bases to predict the future environmental exposure expected during the structure's lifetime. While environmental data are considered generally insufficient as a sole basis to predict environmental exposure, such data are essential to develop, calibrate, and verify hindcast models. Thus, data are pivotal for developing reliable environmental measurement programs. Even so, large uncertainties exist in such models--in part because data on environmental conditions in new frontiers are sometimes fragmentary or inconclusive.

While the government operates many programs to collect environmental data from the oceans, few are of any substantial help in designing offshore platforms. Indeed, few are designed for that purpose. The Outer Continental Shelf Environmental Assessment Program (OCSEAP) of the Department of the Interior is a case in point. It is the largest non-military data collection effort in the federal government relating to the oceans and their environment. Nearly $200 million has been spent on this program since 1974.

Yet a recent report of the National Research Council* concludes that OCSEAP "...does not now effectively contribute...to the accrual of sound scientific information adequate for OCS management." One reason for such a conclusion is that the environmental data needs of ocean engineers in both industry and government were not adequately considered in the design of the OCSEAP baseline data collection.

Both government and industry need reliable data about the environment in the pre-lease, exploration, and production phases of recovering offshore petroleum resources. In the pre-lease phase, data are needed so that industry and government can agree on what capability is required to minimize the adverse effects of natural events. In the exploration phase, data are required to advance safe exploration and prevent pollution. For the production phase, data are needed to

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*National Research Council. OCS Oil & Gas: An Assessment of the Department of the Interior Environmental Studies Program. Report of the Committee to Evaluate Outer Continental Shelf Environmental Studies, Environmental Studies Board. National Academy of Sciences, Washington, D.C. 1978.

to establish design criteria and exposure parameters for offshore drilling and production platforms, as well as to support the regulations and standards the government will use in its verification and inspection procedures.

The U.S. Geological Survey of the Department of the Interior has proposed environmental design criteria for use in its verification program for structural safety that are based on the expected average period of recurrence for natural catastrophes such as storms and hurricanes (100 year intervals). Experience with offshore platforms and other major civil works has been brought to bear in determining the adequacy of the criteria. In cases where an operator may have reason to deviate from the 100 year criteria, reliability analysis or projected lifetime maxima techniques are substituted to ensure safety. Much of the data for determining environmental exposure has been collected and analyzed by the oil and gas industry or with its support and is sometimes proprietary. It is difficult for the responsible government agency to utilize such data unless it establishes an independent, credible means for assessment and validation. Moreover, since there may be divergences of opinion between government and industry on the degree of severity of design factors, procedures for resolving differences need to be developed.

Sound and timely assessments of environmental exposure risks will require:

1) adequate levels of technical expertise in government agencies and industry;

2) sufficient data to provide a credible basis for environmental models used to estimate environmental exposure; and

3) technical dialogue and rapport between government and industry.

The committee finds that the government now lacks the appropriate technical expertise needed for developing and evaluating environmental exposures. Focal points will be needed in government and in industry so that the technical expertise of each can be brought together and interchanged. A government-industry effort can serve to identify situations where data may be needed for environmental understanding to advance technology. In such cases, government and industry can share costs and avoid duplication.

Although several federal agencies have programs related to OCS development, the safety of oil and gas operations on the OCS is a primary responsibility of the Geological Survey of the U.S. Department of the Interior. Among other things, the Geological Survey is required to establish requirements for safe drilling and production operations on the OCS. Therefore, it assures that environmental hazards and exposure data have been properly identified in selecting OCS acreage for leasing and assessing the design criteria for OCS oil and gas structures. In fulfillment of this responsibility and its other resource management functions, the Geological Survey has established procedures for the acquisition and utilization of industrial proprietary data. Therefore, the committee recommends that the Geological Survey should develop the engineering capability to appraise environmental exposures and to acquire related data. This could be done by creating a new office within the Geological Survey, with the following responsibilities:

1) Perform timely and credible quantitative appraisals, mutually acceptable to both government and industry, of expected environmental exposure risks and their relationship to acceptable design criteria for oil and gas operations on the outer continental shelf.

2) Extend the technology and environmental data bases as may be needed in areas that pose environmental problems not found in the existing body of offshore operating knowledge.

3) Assume the development and maintenance of technical and engineering expertise as may be needed for timely and credible appraisals of environmental exposure risks.

4) Obtain environmental data as may be needed to assure credible bases for estimating environmental exposure risks.

5) Identify situations where expanding the scientific and technical data base for the use of government and industry might result in a cooperative or coordinated program to avoid duplication and reduce costs.

6) Provide a focal point in the government for necessary technical communication and dialogue related to environmental data, exposure, and criteria with industry and other interested parties.

Additionally, after establishing an office to be responsible for obtaining information and data on environmental exposures, the U.S. Geological Survey should invite the oil and gas industry as well as relevant professional and technical groups to identify and name appropriate individuals to further study matters related to environmental exposure. This could be accomplished by creating committees to carry out the studies.

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SECTION I

1. OFFSHORE DEVELOPMENT: THE ENGINEERING CHALLENGE

An important amount of the nation's oil and natural gas is pumped from the outer continental shelves (OCS). Based on statistics prepared by the U.S. Geological Survey (USGS), the American Petroleum Institute (API) states that more than 23,000 wells have been drilled in U.S. coastal waters since 1945.* These wells have produced more than 8.4 billion barrels of oil and 51 trillion cubic feet of natural gas. Estimates of both government and industry experts suggest that as much as 60 percent of the undiscovered oil and natural gas resources of the United States may be located in the OCS.**

Because outer continental shelf production occurs on public lands, it is a major source of revenue for the federal government. Government statistics quoted by API show that from 1953 through 1978, the government received more than $28 billion in bonuses, royalties, and rentals from OCS leasing. The total value of production during this period was more than $40 billion. Thus, the government received about 70 percent of the value of OCS production.

Being able to recover oil and gas from off U.S. shores has been a tremendous technological achievement. Offshore technology has evolved from that sufficient to cope with the moderate conditions present in the Gulf of Mexico to meet challenges presented by deep water, ice, and high latitude storms that are present in newer operating areas around the world. The dimensions of the industry's technological capability can be gleaned from the following information:

- <u>deepest offshore producing well</u>: 6,457 m (21,188 feet) offshore Louisiana

- <u>wells drilled: deepest water</u>: 604 m (1,986 feet) Gulf of Mexico; 1,266 m (4,876 feet) offshore Canada

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*Petroleum Information Package. American Petroleum Institute, Washington, D.C., June 1979.

**Council on Environmental Qualilty. <u>Environmental Quality--1979</u>. U.S. Government Printing Office, Washington, D.C., December 1979.

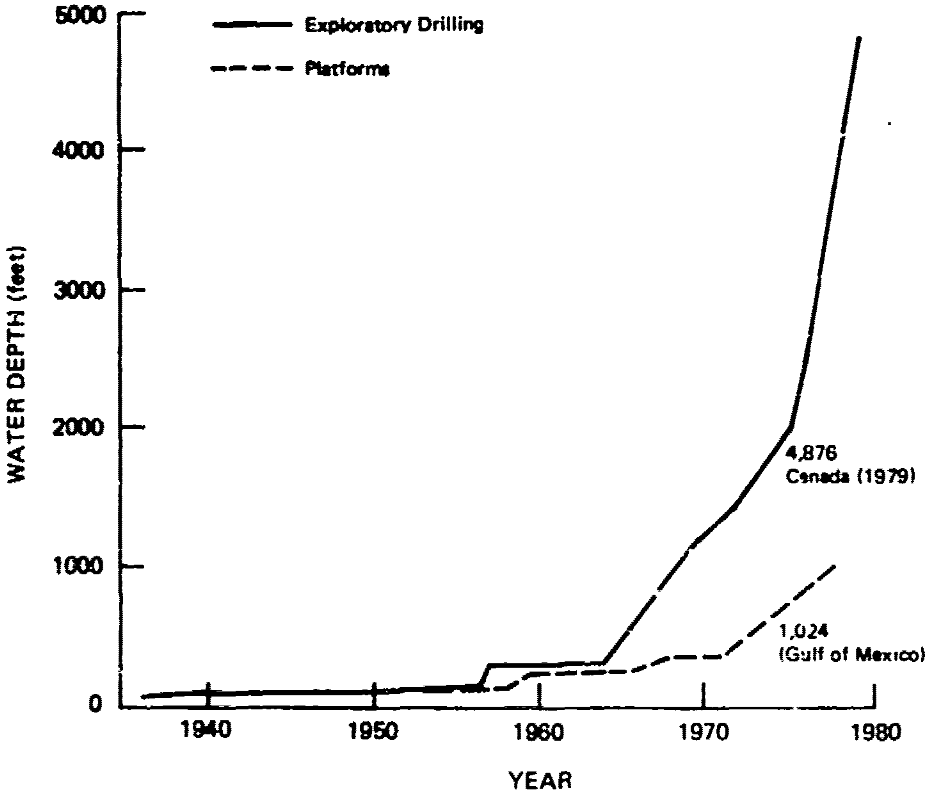
- <u>platforms in deepest water</u>: 311 m (1,024 feet) Gulf of Mexico; 259 m (850 feet) Santa Barbara Channel
- <u>largest platform</u>: 606,000 metric tons, North Sea
- <u>farthest lease from shore</u>: 293 km (158 miles), Gulf of Mexico
- <u>longest offshore pipeline</u>: 515 km (278 miles), Gulf of Mexico

One outstanding trend in the evolution of offshore technology over the past decade has been the ability to explore for and produce oil and gas from even deeper water (see Figure 1).

The major technological challenge of the next decade will be to extend offshore development safely and efficiently to areas that are as yet untapped and largely unexplored. Table I shows that the bulk of future offshore reserves will probably be located in these "frontier" areas. In general, they are characterized by harsher operating environments and deeper water than current offshore producing areas.

The federal government is planning on a more aggressive program to lease, explore, and develop frontier areas. As of June 1979, 31 lease sales were scheduled for the period 1980-1985; 19 of these will be in frontier areas.

Exploring and developing that much frontier acreage in a safe and timely manner will be a major technological achievement. The degree to which government and industry comes to a common understanding on a number of issues will affect how quickly exploration and production can be achieved. One such issue, detailed in this report, is how to design and engineer offshore drilling and production platforms to withstand natural forces, including ice, wind, waves, currents, and weather. To do this requires a thorough knowledge of the environment.



SOURCE: American Petroleum Institute. Washington, D.C.

FIGURE 1 Worldwide Water Depth Records
Exploratory Drilling and Platforms

TABLE I: POTENTIAL FUTURE YIELDS FROM THE OCS

OCS AREA	OIL* (billion bbls.)	GAS* (trillion cu. ft.)
Producing Areas:		
Central Gulf and South Texas	3.8	49
Santa Barbara	1.5	1.7
TOTAL Producing Areas	5.3	50.7
Frontier Areas:		
North Atlantic	0.9	4.4
Mid-Atlantic	1.8	5.3
South Atlantic	0.3	0.7
Eastern Gulf (MAFLA)	1.5	1.3
Southern California	2.3	2.3
Santa Barbara	0.9	1.1
Northern California	0.4	0.4
Washington - Oregon	0.2	0.3
Cook Inlet	1.2	2.4
Gulf of Alaska	1.5	5.8
Aleutian Shelf	0.1	0.1
Bristol Basin	0.7	1.6
Bering Sea	2.2	5.7
Chukchi sea	6.4	19.8
Beaufort Sea	3.3	8.8
TOTAL Frontier Areas	23.7	60.0

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* The numbers entered in this table are the statistical mean (between 95 percent and 5 percent probabilities) of those estimated economic resources not yet discovered that are estimated to exist in favorable geologic environments.

Source: Adapted from Miller, B., et al, Geological Estimates of Undiscovered Recoverable Oil and Gas Resources in the United States. U.S. Geological Survey Circular 725, Washington, D.C., 1975.

2. DEVELOPMENT OF ENVIRONMENTAL DESIGN CRITERIA

Both the U.S. Geological Survey and the oil and gas industry are concerned with making correct estimates of what extreme environmental or natural forces offshore platforms could be buffeted by. Clearly, however, the environment must be considered within the context of the overall design process of an oil and gas platform and not as a separate issue. The determination of the environmental exposure and design criteria is an integral part of the design.

Definitions and Context

Environmental data, mathematical models, design experience, and judgment all play important roles in the development of criteria for the design of offshore structures. It is necessary to clearly identify and define the major terms and elements involved in the context of the design process. For the purpose of this report, the following definitions are used.

Environmental phenomena: Naturally occurring events whose effects can exert significant forces on offshore structures. These include storm-generated winds, waves, currents, ice, and earthquakes. They can be divided into two types: initiating and excited phenomena. An initiating phenomena gives rise to excited phenomena. Examples of initiating phenomena are storm winds and earthquakes. Examples of corresponding excited phenomenon are wind-generated waves and earthquake-induced ground motions. In this report, the terms "environmental phenomenon" and "natural event" are used interchangeably.

Environmental parameters: Dimensional descriptions by which the effects of natural events can be related to the forces imposed on offshore structures. Examples include wave heights and periods, earthquake ground accelerations and velocities, and the ridge size, strength, and velocity of ice.

Environmental data: The quantified values (measured or observed) of natural events and environmental parameters. The data may be for initiating or excited phenomena. Environmental data describing initiating phenomena include severity magnitudes, locations, and frequencies of occurrence. They include earthquake magnitudes and epicenter locations, and storm information such as tracks, atmospheric pressure, and wind intensity. Environmental data describing the effects resulting from the occurrence of an event include the environmental parameters and other measures used to describe the physics of the event and its effects.

Environmental model: The mathematical representation of the key physical processes of environmental phenomenon or natural events to the resulting conditions described by the environmental parameters. Examples include mathematical procedures or empirical relationships to predict wave heights and periods generated by storm winds or the ground motions due to earthquakes.

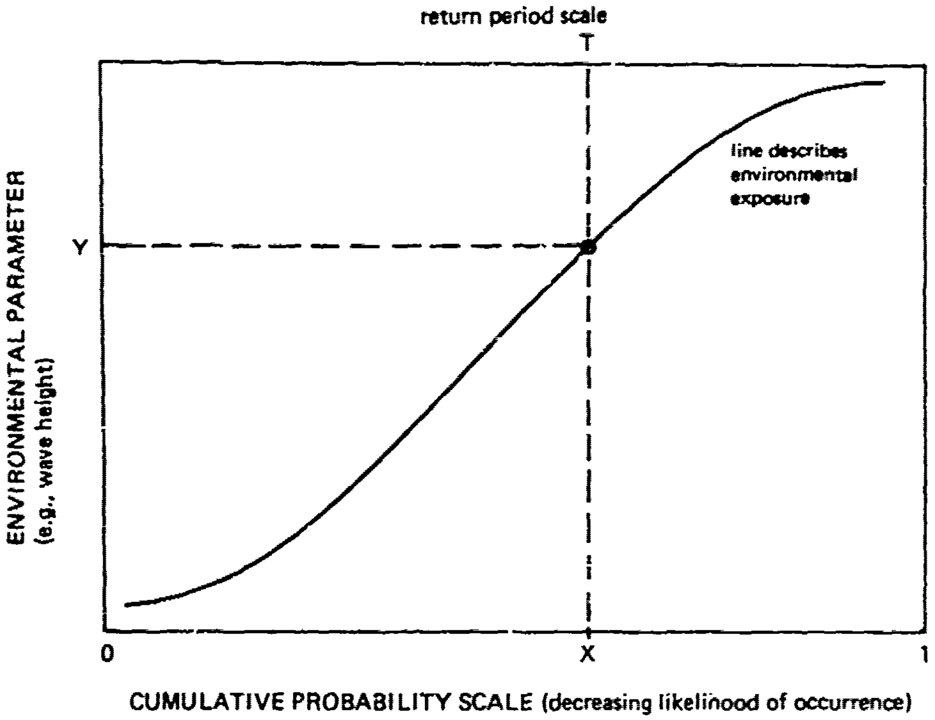
Environmental exposure: A quantitative description of the severity of environmental parameters and their likelihood of occurrence. An example would be the cumulative probability distribution of extreme storm-generated wave heights for a specific location; e.g., a plot of "expected maximum wave height" versus "return period." (See Figure 2 prepared by the committee).

Environmental design criteria: The specific values of environmental parameters that describe the severity of a natural event. The criteria are used to determine the design forces and required support conditions for an offshore structure. For example, if it is determined that an offshore structure is to be designed to withstand wave heights estimated to occur in 100-year intervals, the environmental criteria could consist of the 100-year expected maximum wave height and its associated wave period plus the winds and currents expected to occur with that wave condition.

Force model: The mathematical expressions, empirical coefficients, and analysis methodology required to predict natural forces and support conditions for an offshore structure resulting from the application of environmental parameters. Examples include the mathematical procedures for calculating the wave forces of a specified wave condition on a space frame or template-type structure (one that uses a piece or block under the platform to better distribute its weight) or the resistance of a pile foundation due to the design force on the structure.

Structural criteria: The codes and practices used to configure and size the members of a particular type of offshore structure. An example would be codes for allowable stresses in a space frame-type structure made up of steel tubular elements.

Design criteria: The combination of the environmental design criteria, structural criteria, and force models used to determine the design force, support conditions, and the strength and deformation capacity of an offshore structure.



Note
For point indicated on the line describing the environmental exposure, there is an X percent chance that the environmental parameter will be less than or equal to the value Y, or equivalently there is a 1-X percent chance that the environmental parameter will exceed the value Y, also the environmental parameter of value Y is associated with a return period of T years meaning that, on the average, the environmental parameter will exceed the value Y only once in T years.

FIGURE 2 Environmental Exposure as a Function of Return Period and Cumulative Probability

Figure 3, prepared by the committee, provides a schematic illustration of the relationships between the terms and elements defined above. As indicated, two major areas of analysis are required to develop the environmental design criteria for a structure--analysis of the environment that results in the environmental exposure, and analysis of the structure in that environment.

Design Process

The design of a structure proceeds through two major steps—preliminary design and final design.

Preliminary design: The preliminary design stage seeks to develop a structural concept that fulfills functional and operational requirements within defined environmental constraints and with an acceptable balance between safety and economics. An acceptable design is defined by the design criteria, which are made up of environmental design criteria, structural criteria, and force model. Structural criteria consist of codes and engineering practices used to determine whether a structure will respond to environmental forces in an acceptable manner, and thus be safe for operating personnel. Environmental design criteria consist of environmental parameters that, when used with the appropriate force model, can be used to calculate the maximum environmental load that the structure must withstand to achieve the required level of performance, consistent with safety and economics. Experience plays a major role in preliminary design, especially in determining suitable environmental design criteria.

The environmental exposure and environmental design criteria can also affect the requirements for inspection of offshore platforms. By applying the foregoing process of exposure analysis in the design of the structure, the need for inspection after installation can be minimized and rationally scheduled. Furthermore, environmental design criteria do not depend on environmental exposure alone. The environmental design criteria selected will also depend upon the structural criteria, the projected structural performance, safety, and economics.

Following is a description of the preliminary design process (see Figure 4, prepared by the committee).

1. Determine the functional and operational requirements for the proposed structure, and estimate the economic worth of the oil and gas reserves.

2. Define the design constraints imposed by operational requirements. These include the number of wells to be drilled from the structure, the deck area required for production and drilling equipment, and applicable government regulations.

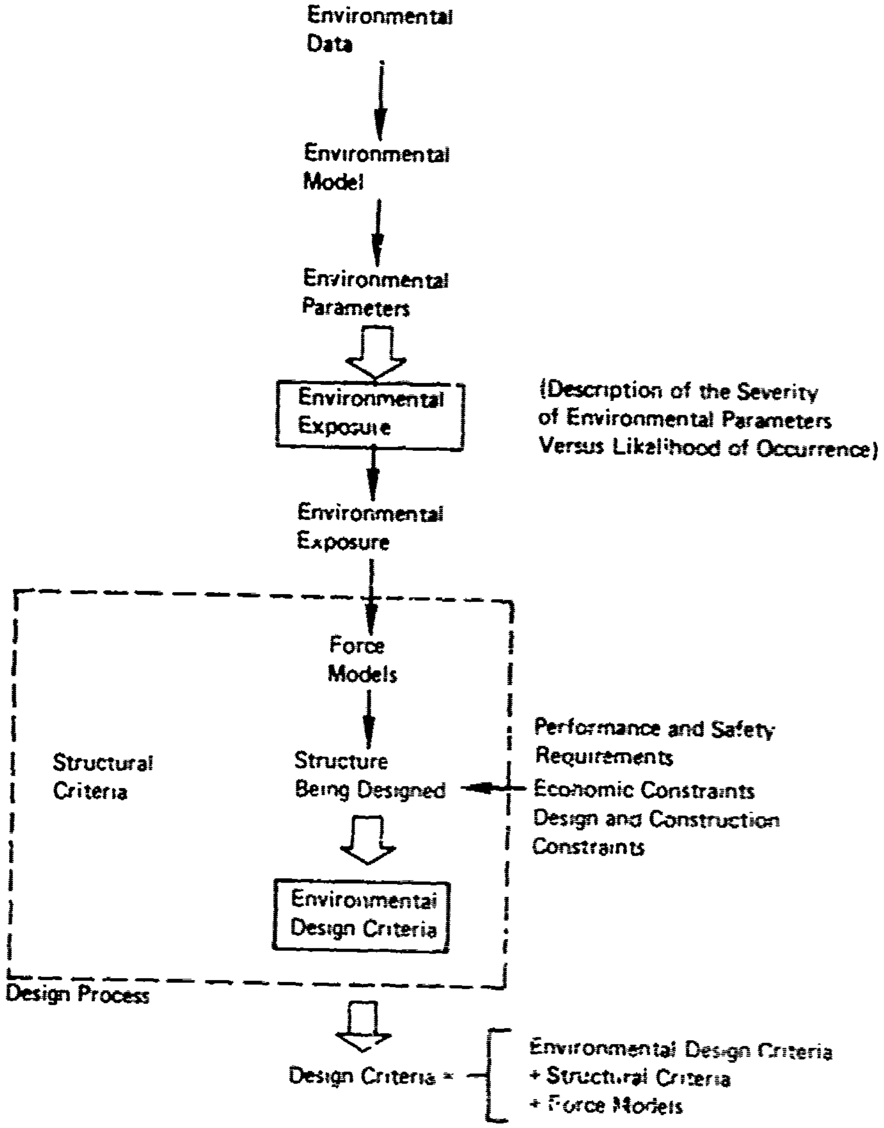


FIGURE 3 Schematic Illustration of Environmental Elements and Processes Used in Developing Design Criteria

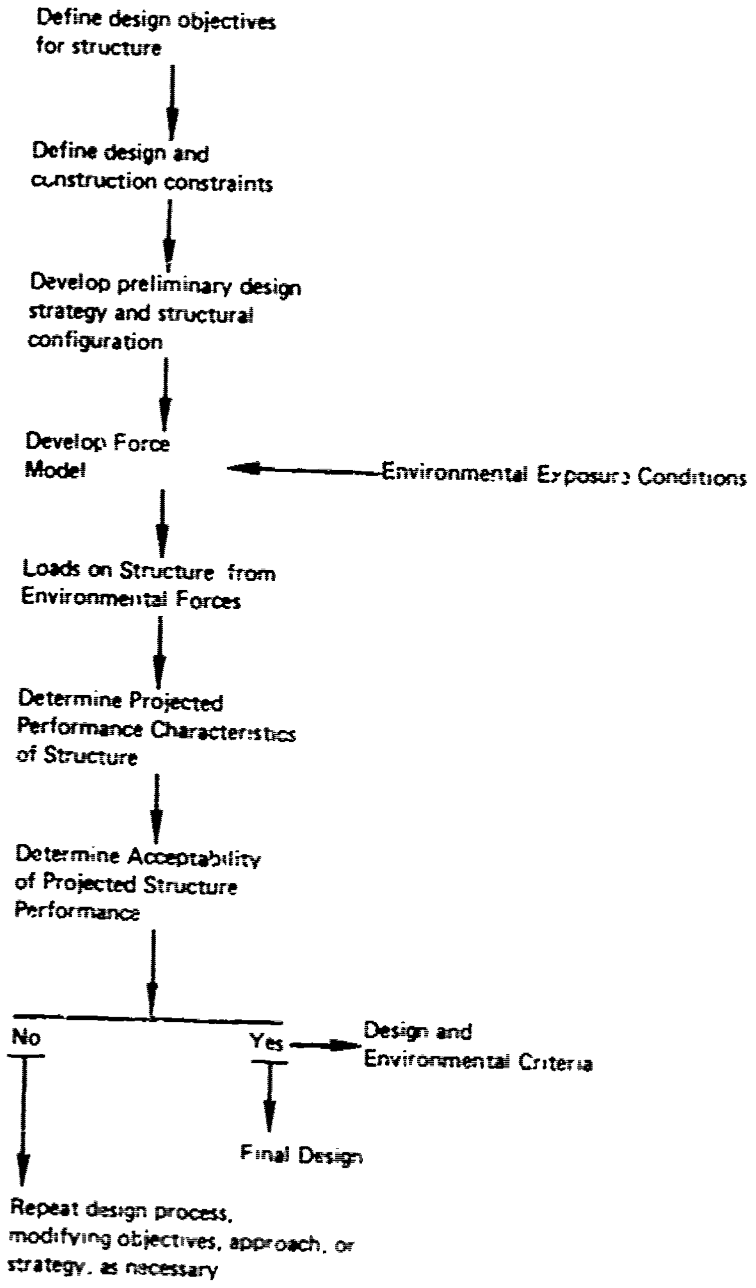


FIGURE 4 Functional Steps
Preliminary Design of Offshore
Platforms

Where the proposed structure is to be located determines the character of the design constraints that the environmental loads and the sea floor place on the structure. These constraints lead to the selection of the type and an initial configuration of the proposed structure. Next, the specific constraints for the initial configuration are defined. These include the appropriate codes and practices to be used in the design, construction, and installation, as well as time and cost limitations. The types and availability of equipment required for construction and installation, and the effect of the natural environment on installation activities, are among the many additional constraints that need to be defined.

3. Evaluate the environmental exposure. A quantitative description is required of the range of severity of natural conditions that impose significant forces on the structure. The likelihood of their occurrence must be measured. This evaluation can be made independent of any consideration of specific structural characteristics, except that the parameters chosen to describe the environment should be those most pertinent to evaluating the forces that will affect the particular type of structure to be designed. Thus, the description of environmental exposure may be developed largely independent of the design process.

4. Develop a preliminary design. Based upon the initial configuration and constraints, an initial design for the proposed structure can be developed and its structural and foundation members sized to meet the design constraints. This will be based on previous experience, engineering principles, and rules of thumb.

5. Determine natural forces and operational loadings. The environmental exposure data, environmental criteria, force models, and the preliminary design configuration are used to compute a set of loadings and forces that would be imposed on the structure and foundation elements. Different force models are required for different natural events as well as for different types of structures subjected to the same environmental phenomenon.

6. Determine the projected performance characteristics. The environmental loadings imposed on the structure, its equipment, and expected auxiliary parts are used to determine what stresses will be placed on different elements of the platform, as well as how they respond and the projected overall platform performance. If the projected performance of

the initial design is unsatisfactory from the standpoint of either economics or safety, the initial configuration is modified until an acceptable projected performance is developed. If substantial changes are made in the design, such as in geometry, stiffness, mass, or projected area, it may be necessary to redetermine the environmental loadings or forces.

The designer can consider many options before arriving at a final design concept consistent with the requirements, constraints, and the environment. Options for the basic structural configuration may include pile-founded template, structures, large gravity structures, or moored structures. Each configuration may respond to the same natural event in significantly different ways. Therefore, each requires different environmental parameters, force models, and structural criteria.

The safety of workers on a platform may be best ensured by planning for their evacuation in the event of a major storm or other severe natural event other than by designing the structure to withstand extreme tempests. Similarly, pollution may be best prevented by using automatic safety valves rather than relying on the structure to survive a storm. Performance requirements related to the survivability of a structure may be met by using highly redundant designs rather than fewer, but stronger, members. Various materials, detailed joint designs, and member sizing can be used to meet stuctural criteria. More stringent structural criteria could be used to increase a structure's capability to meet performance and/or safety requirements. The options selected by the designer to achieve the most favorable overall economics and safety naturally influence the environmental force that the structure will be designed to withstand; i.e., the environmental design criteria.

Final design: Upon acceptance of the preliminary design, a final design can be developed. Following is a description of the final design process.

1. Design the members. After determining the stresses developed in the elements, they must be resized to allowable stress levels.

2. Design the appurtenances or auxiliary parts. These include barge bumpers, boat landings, pull tubes (for pipelines), personnel ladders, and handrails. They must be sized and placed on the structure.

3. Verify the design. In this step, design constraints and solutions are rechecked to ensure that the structure can meet its intended purpose and that analytical and computational errors have been eliminated.

4. Complete and control the fabrication-construction-installation specifications and procedures. Those who build the platform must know what the structure is intended to do. A network of quality control and inspection procedures must be established. This will ensure that the intent of the design is substantially met.

Basic Methods for Selecting Environmental Design Criteria

Environmental design criteria are used to produce a structure that is economic, safe, and reliable. The design criteria, in turn, depend on engineering data on how a specific structure is expected to perform, and/or on related experience with the structure or its basic components. This requires knowing what the environmental conditions are in an area. It also requires the appropriate combination of design values and safety factors, allowable stresses, and redundancy to ensure the structure will perform in an acceptable fashion and to minimize the chances that the platform will collapse if the environmental design criteria are exceeded.

The rationale for selecting the appropriate environmental design values for a specific structure will depend upon a number of factors. These include the interrelationships between design values and structural criteria, acceptable force modeling techniques, inherent redundancy, and reserve strength in the structure. It also depends on a balance between platform costs and losses that may be incurred as a consequence of damage or failure.

Three basic methods are used to develop or specify environmental design criteria--experience, projected lifetime maxima, and reliability analysis. As actually used, clear lines of demarcation do not exist between the methods and many different combinations are used.

Experience

Currently, many industry engineers commonly combine environmental data with their experience in selecting design criteria. This approach relates projected structural performance with the known performance of similar structural types or components. It provides a means for using data and experience from a wide range of sources and field operations to establish criteria for a specific structure.

For example, the oil and gas industry has used stress codes set by the American Institute for Steel Construction (AISC) for steel members developed primarily for buildings, bridges, and for other civil works. These codes are used to set allowable stresses in members of offshore platforms. Accordingly, platform members can be expected to perform at a safety level comparable to those of other major works with which there are many years of operating experience.

Similarly, other elements of the platform can be based in part on experience with comparable parts of other structures. Thus, data and operating experience in one area can be extended to comparable operations in another area. That is, criteria for structures including offshore platforms are clearly set by expected loads. These criteria depend on loading and type of structure and not on the site or geographic location where the loads occur.

Judgment, experience, and sound engineering rationale are the primary factors in this approach to setting design criteria. The approach has been used successfully for dams, levees, buildings, and bridges. These facilities are, in general, designed to perform at safe, allowable stresses in the structural elements under the effects of relatively rare, severe natural events that have a slight chance of occurring over the expected operating lifetime of the facility. Such requirements for structural performance inherently provide a large degree of reserve strength to accommodate the extremely rare event that might possibly occur during the life of the facility.

Offshore platforms in the Gulf of Mexico have been designed largely on the basis of such a procedure. There, experience indicates that environmental exposure levels that recur statistically every 100 years provide adequate performance levels when combined with appropriate construction criteria, allowable working stresses, and force calculation procedures. Conventional engineering analyses and rationale supplemented by specific data where necessary provide a means to extend these criteria to operations in other areas with comparable expected safety levels. As the technology is refined, the specification of criteria will improve further.

Projected Lifetime Maxima

Based on the projected lifetime maxima (PLM) method, estimates can be made of the most severe natural conditions expected to occur during a structure's lifetime in order to predict design loads. In the Gulf of Mexico, for example, the most severe environmental conditions might equal or exceed the maximum winds, waves, and currents caused by the worst hurricane on record for the entire Gulf. Such conditions would have an extremely low likelihood of occuring during the lifetime of an offshore structure. Philosophically, then, the design load is taken as fixed at a "worst case" value.

A significant drawback of this approach is that it fails to consider the possibilities and consequences of a structure experiencing larger or smaller maximum loads than the design value during its lifetime. These possibilities and consequences need to be recognized when designing a structure. They create a degree of uncertainty in the PLM design load due to either natural variability in the environment or professional uncertainties in describing the environment and its forces.

Structures should be designed to resist environmental loads over their projected lifetime maximum without collapsing. That is, reasonable levels of damage during storms are acceptable, but the structures should be designed so that they will not collapse even during "worst case" conditions. Such performance expectations require a different set of structural criteria from those normally used in structural design. These criteria must explicitly account for the true ultimate strength of the structure for proper use in combination with design loads based on PLM conditions.

In general, the structures used on the outer continental shelves lack appropriate structural criteria for ultimate strength. Consequently, it would require additional technical development to use design criteria based on PLM methods for a specific structure. These criteria would also lead to the need to use nonlinear or ultimate strength analysis as a routine part of the design process. Such a requirement would unnecessarily complicate the design process and would exceed the analytical capabilities of many experienced designers.

Philosophically, the PLM method approaches the loading portion of the design problem on a "worst case" basis and offers little or no opportunity to consider economic consequences of trade-offs. In practice, the use of environmental design conditions, in combination with widely accepted structural criteria and design and construction practices less severe than the PLM, will generally lead to a structural design that has a low probability of failure during its lifetime.

Reliability Analysis

Thus, environmental design criteria rely heavily on experience. To make this experience more systematic and quantitative, various procedures have been used to improve and advance the methods used to select environmental design criteria. These are generally referred to as "reliability analysis."

Reliability analysis aims to develop designs that will result in desirable performance and represent an equitable balance of costs and risks. It does this by examining options or strategies for design criteria and their associated risk and cost consequences. This method represents a logical and analytical approach in which the elements of projected natural conditions and forces determine strength and deformation capacity. It also studies costs in a probabilistic framework.

While reliability analysis uses the same information employed in the first two methods, it focuses on the analysis of the statistically anticipated performance characteristics of a structure placed in a given location. It attempts to explicitly consider the engineering and management choices implicated by economic and technological considerations.

The degree to which mathematical formulas and detailed analyses are used varies. The approach used depends on the type of structure, the environment, the experience in the platform area, the accuracy of available data, and the technical judgment of the designer.

Reliability analysis lacks adequate data for an independent quantitative basis unless it includes large amounts of somewhat subjective calibration. The statistical characteristics of both the environment and of the structures would also be needed for completeness, but would be costly to acquire.

Reliability methods can, however, provide a powerful and useful technique to compare the performance of structures in frontier areas with those in other areas. It can also be used to compare the performance of different types of structures.

Present Regulatory Status on Selection of Environmental Design Criteria

The U.S. Geological Survey requires that offshore structures should be designed to withstand a natural event with a return period of 100 years unless the owner can demonstrate, through appropriate analysis, that a less severe design event is appropriate. The 100-year return period fixes the environmental parameter to be used in calculating design forces and support conditions.

The U.S. Geological Survey based its use of the 100-year event principally on the experience with platforms in the Gulf of Mexico. These were designed to and successfully withstood winds, waves, storms, and other environmental forces encountered in the Gulf. For operations elsewhere, particularly in more harsh environments where new concepts are needed for platforms, different design criteria may be required. In such cases, the platform should be analyzed on the basis of the preliminary design process. This may result in design criteria either more or less severe than those used for the 100-year event. (See Figures 3 and 4).

In view of the different approaches to developing environmental design criteria, their applicability in view of the U.S. Geological Survey's requirement should be noted. However, an accurate description of the environmental exposure selected for environmental design criteria is required whether the platform owner adopts the 100-year event or demonstrates that different criteria are more appropriate.

Environmental Exposure and Forces

Environmental design criteria are developed to determine the naturally induced forces. Thus, the designer is concerned with the magnitude of the forces that can reasonably be expected to affect the structure during its lifetime. This involves two separate problems: (1) a quantitative description of the environment, and (2) the relationship between the environment and the forces it imposes on the structural system.

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*U.S. Geological Survey. Requirements for Certifying the Structural Integrity of OCS Platforms. Vol. I. Appendices, Vol. II. Commentary, Vol. III. U.S. Department of Interior. Washington, D.C., October 1979.

Environmental Exposure

Storms, earthquakes, ice pressure ridges, soil movements, and other environmental phenomena or natural events (see Section II) affect structures, although their severity and which specific ones may differ depending on the location. For the design process, each must be described in terms of those parameters that relate directly to the forces imposed on the structures. These include the maximum values for storm-generated waves, earthquake-induced ground motions, and ice thickness and strength. Less severe forces must also be considered as well to evaluate a structure's fatigue life.

Environmental description must also recognize the uncertainty of the future. Uncertainty is created both by the difficulty in predicting natural forces, which may vary over time, and by man's own mistakes in making measurements and in mathematical or empirical modeling. Natural forces cannot be predicted with total certainty. Neither can analytical models predict perfectly the resulting key environmental parameters. To account for these uncertainties, environmental exposures are best described in probabilistic rather than determininstic values.

In describing environmental exposures for a region or site, the fundamental problem is to predict the statistical distribution of future natural events. Environmental extremes cannot be forecast in a deterministic sense; however, it is reasonable to expect that they will be influenced by causative factors that are generally similar to past occurrences. Thus, the future is unlikely to be an exact replica of the past due to the randomness associated with when a natural event occurs. In most instances, future environmental parameters are more readily derived from a statistical model based on what has happened in the past.

To illustrate this, consider a wave height having an average return period of 50 years. This return period corresponds to a 2 percent probability of the wave occurring annually. Thus, there is a 98 percent chance that the most severe occurrence of an environmental parameter during a single year would be less than that of the 50-year event.

Alternately, a more severe occurrence would have only a 2 percent probability of occurring during a single year. Because such severe environmental forces occur rarely, data on environmental exposures should cover a long time. The time span covered should be sufficient to provide a statistically significant sample of occurrences over a representative range of severities.

A sufficient time span cannot be given in terms of a specific number of years. Factors that influence the appropriate length of time include the average number of occurrences of the event per year, the variability in the environmental parameter resulting from occurrences, and evidence of long term cyclic activity in either frequency or severity.

The development of an environmental exposure poses two basic problems: (1) establishing a sufficient data base, and (2) interpreting the historical data base to provide reliable estimates of future rare occurrences.

Historical Data Bases

Neither government agencies nor operators of structures now have data bases that contain environmental parameters of direct significance to the structure's design. Recognition of the need for such data in many geographical locations has arisen only recently. Furthermore, it has only recently become possible to make some of the necessary measurements. Making long term measurements is costly and is likely to become more so. Some variables can be measured at certain locales, but the data generally cover an insufficient time span to establish long term exposures.

Thus, ongoing measurement programs cannot be used to provide information needed now for environmental exposures. On the other hand, satisfactory estimates of exposures can be developed independent of lengthy measurement programs. Indeed, lengthy programs can be prohibitively, costly, and unnecessary. This is not to imply that data are not useful, necessary, or important. Quite the contrary. However, the quantity of measured environmental parameters is now and always will be insufficient to serve as a data base from which environmental exposures could be solely derived.

As an alternative to measuring environmental parameters with costly equipment and lengthy programs, drilling operators and the government could rely on observations made over the years. Man has always been concerned with the ocean environment and has often recorded observations, particularly those pertaining to unusually severe occurrences. In some instances, organized efforts have resulted in extensive archives of observations (e.g., shipboard observations of weather and waves).

Data based on observations are, however, generally inappropriate for developing environmental exposures because they often contain observer biases and errors. Also, observations are data of opportunity and may not be homogeneous in space or time or cover the range of severities adequately. Frequently, the observations are not of the needed environmental parameter, but describe the phenomenon by some other measure of its severity or effect. Although useful in developing environmental exposures, observations alone rarely provide an adequate data base.

Hindcasting Historical Data

Because historical data bases from which measured values of environmental exposure could be extracted are lacking, a technique has been developed to generate the required data. It uses environmental data to determine the likelihood of a natural event's occurrence.

Data are available and represent valuable information on past natural events. As indicated earlier, these data include both measurements and descriptions on the location, severity, and important parameters for various natural events. While such data don't often contain quantitative information on the key environmental parameters for the site of interest, they generally provide the best available description of natural events over time. Examples include storm tracks, atmospheric data (pressure, winds, temperature), earthquake epicenter locations and magnitudes, and ice covers.

Despite deficiencies, such data can be used to develop environmental exposures. The frequency with which natural events like storms or earthquakes of certain magnitudes occur can be calculated based on data describing when and with what force they happened in the past. If the calculations are accurate enough, the environmental parameters can be both quantitatively accurate and cover a long time span.

The calculating of environmental parameters from historical occurrences of environmental phenomenon is termed "hindcasting." Hindcast historical data can often be the most appropriate base for developing environmental exposures. Environmental models are needed to develop historical exposure parameters. The model must be capable of predicting the environmental parameter associated with specific occurrences of a phenomena since it must be applied on an event-by-event basis. Further, the model must be capable of making such predictions from whatever data are available.

Several different environmental models are used to hindcast environmental parameters. Using a mathematical description of historical data on dynamics, windfield models calculate surface wind speed and direction at locations throughout the region affected by the storm. Wave models use a mathematical description of the dynamics and energy transfer between the sea and air to evaluate waves generated by storms. Some models can compute currents and tidal surges generated by storms. Others can calculate ground motions generated by an earthquake from the epicenter location and magnitude by mathematically describing the transmission of seismic energy through geological features.

The same environmental models can be used to hindcast and forecast. Hindcasting and forecasting differs principally in the data used in the environmental model. Hindcasting used data on past natural events while forecasting requires current measured environmental data. Hindcasts of environmental parameters are generally more accurate than forecasts since more detail is known on the life cycle of environmental phenomena.

The development of an environmental model begins with a fundamental understanding of the physics of the phenomenon. Fortunately, recent advances in geophysics have established much of the required understanding. Continuing efforts are seeking further improvements. Developing an environmental model involves translating theoretical understanding into an analytical model. Since man's understanding of the complexities of nature is less than complete, the model must include some empirical understanding to augment the theory. Empirical understanding is derived from measured data. Thus, in this context, measured data play an important role in reducing uncertainty through calibration of environmental models.

Measurements used to calibrate models should include data that describe specific occurrences as well as measure environmental parameters that resulted from the occurrence; that is, the model input and output. The same type of data provide empirical evidence used to develop as well as calibrate models. Such data are termed calibration data. Additional data that describe certain aspects of physical processes involved may also be needed to develop models. Historical data are generally insufficient for independent model development.

Additional data must be obtained through extensive measurements designed specifically to develop a model. As noted earlier, the practical limitations on the time span that can be covered by a measurement program limit the usefulness of a measured data base for independently developing an environmental exposure. Even so, measured data are extremely important in developing and calibrating environmental exposure models in conjunction with hindcast techniques.

After the environmental model has been developed and calibrated, it has to be verified before it can be applied. Calibration data will probably contain more extensive data that describe specific occurrences (i.e., the input to the model) than is available from the historical record. In such cases, the calibration data base should be made to consist only of the data that describe the historical occurrences.

Using the degraded data set as input, the model is exercised to predict the environmental parameters which were measured during the data collection program in which the calibration data were obtained. If the measured data set is sufficiently extensive, additional data not used to develop or calibrate the model should be used to verify it. By comparing the values predicted by the hindcast model with those actually measured, the relative success of the model can be determined. The comparison also establishes the level of technical uncertainty associated with the model. Thus, by predicting environmental parameters from historical data, the model is verified and the level of professional uncertainty assessed in a manner consistent with its intended use.

An advantage of environmental models is their capability to develop data on environmental parameters for numerous sites within the same geographical region. Another advantage is their flexibility. Environmental models are generally developed for a particular area. If based on sound, fundamental physics and well calibrated, the model likely can be successfully applied in other areas subject to the same environmental forces with relatively minor modifications and/or extensions.

The applicability of the model can be assessed with calibration data obtained from the new geographical region. Generally, applying and verifying existing environmental models to new areas is easier than developing new models. Thus, modeling is flexible and saves money.

Predicting Environmental Exposure

Once data have been developed on the historical occurrences of an environmental parameter for a region or a site, the data can be interpreted to develop environmental exposures. It makes little difference whether the historical data were predicted, measured, or observed since they must all be interpreted for a specific site.

For any particular site, natural events occur in a random pattern over time. Such so-called "accidents of nature" include the exact intensity and location of natural events.

Further, the environmental parameters may exhibit short-term random fluctuations so that the maximum value is known only in a probabilistic sense. Such randomness indicates that natural events at a site will not likely recur in an exact replica of the past. Thus, randomness or natural variability must be considered in interpreting historical data to describe the future.

The interpretation can treat the various sources of randomness either implicitly or explicitly. Some may be implicitly included by assuming that the historical data for an environmental parameter are extensive enough to provide a sufficient sample of combinations of various independent sources of randomness. The data can be directly used to estimate the probability distribution function for the magnitude of the environmental parameter that can be expected to occur in a given number of years.

An explicit treatment requires developing a probabilistic description of each independent source of randomness. While the interpretive procedure cannot be completely made general, the data are usually analyzed to describe in probabilistic terms the environmental parameter's magnitude given the single occurrence of an event with random characteristics like intensity or location. A probabilistic description can be calculated by combining the numbers of occurrences expected during a given number of years with the magnitude of a single random event.

Environmental Forces and Force Models

As noted earlier, the force model describes the relationship between an event described by appropriate environmental parameters and the force or load it exerts on the structure. The model is used, first, to transform environmental exposure into environmental exposure force to develop a structure's environmental design criteria. This use of the model is somewhat universal in that the structure's overall behavior under environmental loading is of primary importance in developing criteria.

Second, the force model is used by designers to develop detailed designs of a structure to specific criteria. This use tends to be more detailed in that designers must consider the loads on each structural element in addition to the total structural behavior in developing the design.

It is difficult to offer a general discussion of the force models for all combinations of environmental phenomena and structural systems. The mechanisms and characteristics of environmental loadings are quite different for each phenomenon. Some cause a force to be exerted directly on the structure. Waves and currents distribute structural load as a result of pressure due to water motion. Ice loads a structure as it moves and falls against a structure. Earthquakes, however, cause a structure to move as ground motion is transmitted through the foundation or base. The tendency of a structure to resist applied motion due to its inertia distributes the load throughout the structure.

Whether the response is static or dynamic is determined by the natural response frequency over which the environmental force can impart significant energy. If a structure responds dynamically to the load, its motion and inertia create additional loads.

The forces involved in some combinations of environmental force and structural systems are most appropriately modeled deterministically in time. They describe the force exerted on a structure as a function of time throughout the environmental loading. Other combinations may be more appropriately modeled as random processes and lead to spectral or probabilistic force models.

Thus, force modeling is such a diverse problem that it cannot be easily expressed in general terms. Yet, a model for a combined environmental force/structural system begins with a sound understanding of the physical load put on a structure by natural forces. This can be expressed as an analytical model. Because natural forces and structures interact in a complex manner, the problem's theoretical description needs to be augmented by certain empirical information. Obtaining data from which empirical information must be derived is a formidable task. Ideally, instruments would be placed on a prototype structure to obtain data during a particularly severe storm or earthquake. But it is expensive to equip a structure with the needed instruments to record an event that may not occur for years. In the meantime, the harsh environment could cause the instruments to deteriorate.

Thus, it is easier to obtain data on key natural forces. Both laboratory and <u>in situ</u> experiments can be controlled, although utmost care is required to ensure that the natural event and key parameters are realistically modeled. Even so, modeling at best contains uncertainties.

Finally, whether the environmental force model adequately describes how natural forces and offshore platforms interact can be assessed by measuring certain key structural responses <u>in situ</u>. This requires that measurements taken in conjunction with a major storm be followed by detailed inspection to see how the structure withstood severe environmental loads. It also offers a wealth of information on the adequacy of the modeling process. By determining whether the modeling process was adequate, a measure of the professional uncertainty associated with modeling can be obtained. This measure can then be used to improve the reliability of the predictions made using the model.

Summary

The environmental design criteria selection process depends on the design goals, process, and constraints. It is part of an iterative process used to develop and improve the offshore structures.

The process used to design offshore structures is an integrated and interrelated analysis. It simultaneously considers numerous factors, including: the structure and its functional and operational requirements, safety requirements, natural exposure and loads, structural criteria (i.e., the codes and engineering practices used to assure acceptable structural performance), and economic constraints. The design process results in a structure that operates and functions with an appropriate balance between safety and economics.

The environmental design criteria is that set of environmental parameters used to establish the design loads. It results in a reliable, safe, and economic structure. Environmental design criteria are not solely a function of the environment but also depend on structural criteria, required structural performance, safety, and economics.

Three fundamental methods are used to select or develop environmental design criteria. These use experience with prototype structures, projected lifetime maxima, and/or reliability analysis. As actually practiced, there are no clear demarcation lines between these methods. Sound judgement and experience are essential factors in selecting environmental design criteria.

Finally, hindcasting is the most appropriate technique for developing environmental exposures. It uses environmental models with historical data bases to predict the historical environmental exposure. The historical environmental exposure is then used to predict future environmental exposures expected during a structure's lifetime. While measured environmental data are generally insufficient as a sole basis for developing an environmental exposure, such data are essential in developing, calibrating, and verifying hindcast models. This role ot measured data is the most important justification for and should be the central theme in developing environmental measurement programs that are viable.

3. GOVERNMENT AND INDUSTRY INTERESTS IN ENGINEERING-ORIENTED ENVIRONMENTAL EXPOSURE DATA

The foregoing chapter emphasized the need for environmental data that are adequate for and compatible with engineering purposes. Industry needs the data in order to design safe and economical structures that can withstand the rigors of offshore environments. Government needs the data to regulate offshore oil and gas development.

A data base on environmental exposure conditions could contribute to management of the outer continental shelf in several ways:

- By acquiring adequate and timely understanding of the severe environmental conditions present in the offshore before rather than after leases are granted, the government could streamline its procedures for tract selection.
- An understanding of the severe environmental conditions experienced offshore is needed to verify platforms, as well as to review and approve of exploration and development plans.
- An enhanced ability to make independent and defensible judgments on safety and on economic factors relative to offshore developments.

Industry has traditionally gathered data for its engineering work. The oil and gas companies that sponsor such work tend to regard data banks as proprietary in view of their large monetary and manpower investments.

While the federal government has collected oceanographic and atmospheric data, little of it is relevant to the development of offshore oil and gas resources. The major government effort is supported by the Department of the Interior through its Bureau of Land Management (BLM) and the U.S. Geological Survey. BLM supports an environmental assessment program to determine the effect of oil and gas production on the ecology. That program yields limited exposure data. (See Appendix B)

Table II lists environmental conditions on the outer continental shelf that have been identified by the U.S. Geological Survey as potentially hazardous. More detailed information appears in the background paper "Environmental Exposure Conditions Taken into Account in Lease-Sales Decisions" (see Section II). Many of these factors are considered the by U.S. Geological Survey in its platform verification program, as shown in Appendix C.

TABLE II

Potential Hazards in OCS Areas

Geological

Sediment scour/fill. Thermal erosion. Shallow faulting. Sand waves. Sediment transport (storm-induced). Turbidity currents, submarine canyons.

Geotechnical

Offshore permafrost. Frozen gas hydrates. Slope instability/slumps and slides. Shallow gas/cratering. Dynamic loading/liquefaction. Weak bearing capacity. Carbonates/Karst.

Seismicity

Strong ground motion. Weak ground motion. Vulcanism. Tectonic deformation. Fault rupture.

Ice

Ice forces - pack ice. Ice forces - shear zone ice. Ice gouging/grounding. Melt water flooding. Ice strength/brine content. Ice dynamics/motion.

Oceanographic

Strong currents (including tidal). Storm surges. Storm waves in winter storm. Storm waves in hurricanes. Sea surface water temperature variation. Tsunamis.

Meteorologic

Wind forces (including gusts). Air-water temperature differences (icing).

In the developing environmental exposures, numerous studies may be needed (see Section II). In new and particularly remote areas, where studies may have only begun and where more information on environmental conditions would obviously be of help, oil and gas companies have common interests in gathering information related to offshore development. Thus, they often jointly fund data collection and analysis programs.

For example, working through the Alaskan Oil and Gas Association (AOGA), 29 companies have sponsored more than 99 projects studying Arctic conditions. These include oceanographic, transportation, sea ice-platform interactions, permafrost, and oil spill studies (see Appendix D). As oil and gas efforts continue in offshore Arctic waters, a lot of information will be required to environmental exposures.

Since the government needs the same data as do oil and gas companies, though for different purposes, it would make sense for them to cooperate to acquire such data. Cooperative research would provide a common data base for both.

For example, both government and industry need information on environmental exposures through the use of models to hindcast data. Joint field measurement programs could obtain data to develop, calibrate, and verify environmental models. Both government and industry would also benefit by jointly developing new instrumentation or data analysis procedures for certain environmental parameters and natural events.

Each could be achieved in the context of the three phases of offshore resource development: pre-lease, exploration, and production. The activities and operations undertaken by government and industry in each of these phases vary greatly from phase to phase. Figure 5, prepared by the committee, shows that, while their motivations are different, they have overlapping needs for environmental data.

The interactions depicted in Figure 5 relate primarily to the collection of environmental data and the determination of environmental exposures. Joint efforts can ensure that both government and industry needs are considered in developing environmental exposure and that both will have an equivalent understanding of the environment for the design (by industry) and subsequent approval (by government) of offshore structures. Shared data collection would reduce duplication and regulatory delays because of different interpretations of environmental exposures.

Widely varying levels of sophistication, completeness, and accuracy of the estimates of the environmental exposures are needed with each phase. Yet, the phases are artificially distinct time frames in resource development. In actuality, the phases overlap and interact. In some cases, the time required to collect data necessitates that it be undertaken in one phase so that environmental exposures can be calculated for use in the following phase.

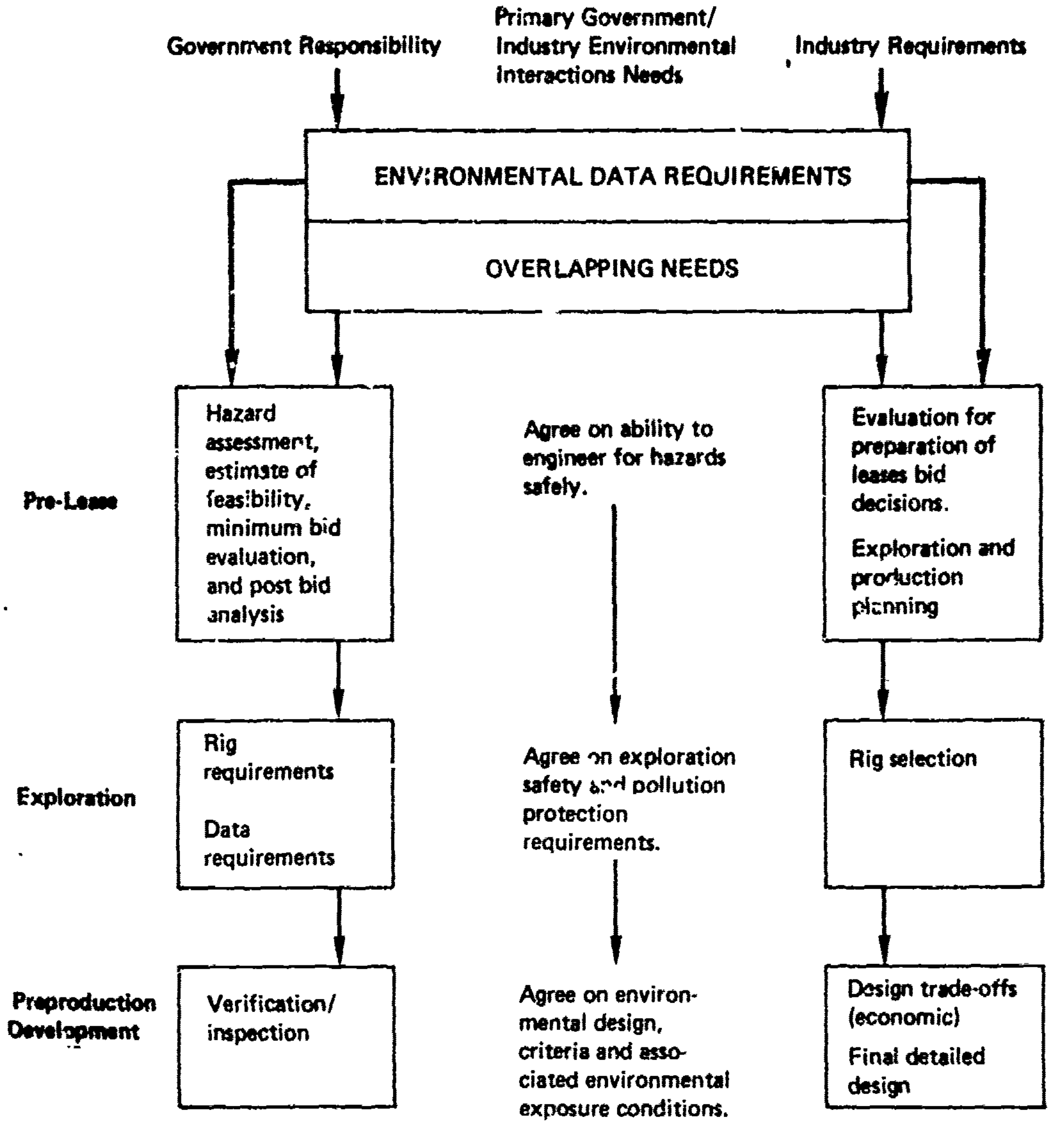

FIGURE 5 Government/Industry Interactions in Use of Environmental Exposure Data

Pre-Lease Phase

In the pre-lease phase, government and industry both must define what measurements and analysis will be required to characterize the environment, as well as how to get them. Specifically, both must determine what data are needed. The government must do so to assess hazards and potential constraints on outer continental shelf development. Industry must ascertain the factors that will influence the strategies and costs of development. Communication between them can be invaluable at this point in defining data needs to each other's satisfaction.

During the pre-lease phase, the government collects, evaluates, stores, and disseminates data, including pertinent measurements of environmental parameters or natural events. Since summaries of historical data could be of vital interest to industry and state governments, the federal government should prepare the summaries and distribute them widely. Indeed, relevant summaries, including estimated environmental exposures, developed by government and industry have been completed for a number of offshore areas and provide appropriate data needed in the pre-lease phase.

The federal government should also evaluate what additional data are needed. At present, government and industry conduct such evaluations independent of one another. Collaboration would improve these evaluations to the benefit of both.

During this phase, the government may initiate programs to obtain basic data. Such programs seek to identify and quantify possible sources of future natural events. Such programs include surveys of features like faults, ice, and areas of soil slumping or liquefaction. Of course, data collection programs initiated at this early stage may continue for years.

Oil and gas companies may work with the federal government on an industry-wide basis during the pre-lease phase. After leasing, interaction tends to be on a single lease, lessee/lessor basis.

Exploration Phase

In the exploration phase, industry and government both need to develop information on specific sites. Both are concerned with ensuring safety, maintaining environmental quality, and conserving resources.

Early in the exploration phase, industry must determine what data may be required for specific sites. This may be accomplished by evaluating regional data in light of conditions at specific sites. Through this process, the need for special studies or measurements may become evident. For example, in some areas water depth may vary widely in a complex fashion. The effect of such variation on waves must be accounted for in developing wave data for specific sites from regional wave data. Such analysis would help industry formulate its exploratory drilling plans, as well as the government's approval of them.

Generally, precise descriptions of extreme environmental conditions are still not needed in this phase. However, industry may initiate measurements that take a long time to complete if it appears that exploration will be successful, and that permanent structures will be required. Of course, each offshore lessee must develop site-specific data for its own purposes, including submittal of development plans to government for approval.

Production Phase

Industry constructs, installs, and operates structures like production platforms and pipelines in the production phase. Accordingly, most calculations of environmental exposures as well as development of design criteria, occur in this phase. While industry needs detailed information to do its work, government needs similar information to evaluate and approve industry's plans.

The three phases all require similar kinds of information, although the level of necessary detail and sophistication increases with each stage of development. The production phase requires the most detailed data for engineering work, and state of the art methods. Decisions made in the exploration and pre-lease phases will logically employ more approximate methods and less detailed data. Nevertheless, the time and resources required to provide the information base for environmentally dependent decisions should be consistent with the types and consequences of the decisions. The state-of-the-art design methods used in the production phase may require a large data base, the assembly of which may have to be initiated in the pre-lease phase.

4. GOVERNMENT AND INDUSTRY LIAISON

Both government and industry have responsibilities and needs that require mutual agreement on the environmental factors that affect offshore development. Accordingly, it is paradoxical that so little interchange between them has taken place in regard to environmental technology. Mutually acceptable measures of environmental exposure and design criteria would aid in the orderly and timely development of outer continental shelf resources needed to maintain and expand the nation's domestic oil and gas supply.

The federal government's failure to recognize engineering as a discrete program area hinders an interchange on the technical aspects of environmental factors and data programs. If a company sought to design a program to collect environmental data for engineering purposes and thought that the program would also produce useful information for the government, it would be hard put to find a federal office that was sufficiently cognizant of the discipline to lend an expert ear. Conversely, if the government were interested in technical interchange regarding environmental factors or data collection, it would have some difficulty at present locating a central organization in industry to work with on short notice. However, various industry committees and associations could form committees to reflect industry technical expertise.

Joint government-industry efforts to acquire environmental data have been difficult to achieve. Although the regulatory agency with the greatest knowledge of the engineering needs for data is the U.S. Geological Survey, it is reluctant to enter into cooperative efforts with the industry it regulates. Other agencies lack either relevant missions, adequate funding, or the knowledge of the needs as applied to the engineering problems.

Before the federal government and industry can work together, they must develop the organizational relationship that can make this possible. Each will have to provide a focal point for internal coordination to strengthen its own programs, and for coordination with the other. This does not preclude establishing joint industry-government committees at a later date to carry out specific and mutually agreed upon studies.

A Government Focal Point

The government could provide a focal point by creating a program office to collect, evaluate, and disseminate data on environmental exposures. The office would work within the government to inject engineering objectives into relevant data collection and research programs. It would also coordinate government needs and programs with those of industry.

The office would need a technical staff capable of planning research and acquiring and managing data on environmental exposure. Specific skills required might include physical oceanography, meteorology, ice mechanics, and seismic, ocean, and geotechnical engineering. Of course, the technical staff would also have to be supported by contracting and administrative personnel.

The office should share its mandate to foster the timely development of energy resources with other relevant government offices. It must also be thoroughly familiar with the needs of the U.S. Geological Survey to effectively represent them in program definition and execution. Additionally, the office would need to interact with industry without concern for possible conflicts of interest that could stem from government's regulatory responsibilities. It should also have the capability to administer and fund its own activities.

The committee considered several possible government agencies for housing such a program office.

The National Oceanographic and Atmospheric Administration (NOAA) in the Department of Commerce (DOC) has statutory authority to maintain an environmental science research capability, including an oceanographic research fleet, a pool of marine scientists, and interdisciplinary environmental science data management programs. However, it has limited background and experience in acquiring the specific kinds of data that are required for offshore oil and gas activities. Where its programs have a relationship to OCS oil and gas development, the information derived is shared with interested units of the Department of Interior, as explained later.

The Department of Energy (DOE) is responsible for encouraging the development of energy resources and advancing the state of energy technology. This could be interpreted to encompass many technical areas, including developing a better understanding of environmental phenomena and their effect on structures used to develop resources.

Several other agencies undertake activities related to environmental data such as the U.S. Coast Guard and the Office of Pipeline Safety within the Department of Transportation. Also, the U.S. Navy has an extensive responsibility for development of an appropriate oceanographic and meteorological data base for their internal use, some of which is shared with industry. However, the Department of the Interior is the lead agency for the development of oil and gas resources in the outer continental shelf. It has the most extensive understanding of the data needs and the use of such data for offshore oil and gas activities. The Outer Continental Shelf Lands Act of 1953 charged the Department of the Interior with the responsibility of administering leases and overseeing the development of tracts once they were leased. These tasks were assigned to the Conservation Division and the Branch of Marine Oil and Gas Operations of the U.S. Geological Survey. The U.S. Geological Survey must assure that environmental hazards and exposure data have been properly identified in selecting OCS acreage for leasing and assessing the design criteria for outer continental shelf oil and gas structures. The U.S. Geological Survey matches funds with the Bureau of Land Management to participate in the OCS environmental assessment programs with respect to marine hazards in lease areas. U.S. Geological Survey ships are used to map surficial sediment distributions, sediment transport, scour, and bedform mechanics, cores geochemical analysis, and fault distribution.

Because of the number of additional federal agencies that are involved in OCS development, Memoranda of Understanding (MOU's) have been drawn up between the various units of the Department of the Interior; for example, the U.S.Geological Survey, the Bureau of Land Management, and the Fish and Wildlife Service, or between units of other agencies of the federal government. Thus, MOU's are in effect between the Department of the Interior and the Department of Transportation covering OCS safety, pollution prevention control activities, and safety of operating personnel. Other coordinating mechanisms include interagency committees for program coordination. For example, NOAA and the U.S. Geological Survey have related responsibilities in a number of programs relating to OCS development, and closely coordinate their activities so that they are mutually supportive.

Industry Focal Points

Industry has long recognized the need for individual oil and gas companies to cooperate in engineering and environmental research and data collection programs. For example, several companies participated in an extensive program in the Gulf of Mexico to obtain data on hurricane-caused wave characteristics. In Alaska, a number of companies are sponsoring an offshore environmental and engineering data collection program.

In the past, these cooperative programs have frequently been operated by individual companies who have elected to take a leadership role. Some national and regional industry groups have conducted cooperative data programs. These include the American Petroleum Institute, the Offshore Operators Committee for the Gulf and Atlantic regions, and the Western Oil and Gas Association (WOGA) for the Pacific and Alaskan regions. In particular, the Alaskan Oil and Gas Association (AOGA) which is a part of WOGA, has an effective research program, some of which is related to Arctic ocean conditions.

While these organizations tend to be complex because they serve a host of functions from developing technical standards to lobbying, they have often focused industry attention effectively on mutual technical problems related to safety and protection of the environment. They have achieved this even in those instances where the resulting cooperative program was operated by an individual company.

These same organizations that have brought an industry focus to technical problems can also serve, when invited, as a focus for technical interchange with the federal government. Many have traditionally maintained committees to comment on government orders and regulations pertaining to offshore operations.

These organizations have the structure to accommodate committees reflecting technical expertise in environmental engineering and data collection even though such committees may not now exist. They can also assist government agencies to identify industry participation in environmental data collection programs. Perhaps technical appraisals of such programs can also be made through the organizations. However, it seems likely that a decision regarding actual financial participation in data gathering would be made on a company-by-company basis, as is the case for all joint industry programs.

If industry were to establish a national focal point for working with the government on engineering programs related to developing environmental exposures, then the government would only have to work with or through one organization. Coordination would be more easily established and simpler to maintain. On the other hand, regional organizations could possibly better serve as foci of coordination because they are more familiar with problems and programs in their specific areas.

An alternative focal point might be a group completely independent of both government and industry. This would not eliminate the need, however, for a strong technical capability within the government, nor extensive technical interchange between government and industry.

Funding Programs for Engineering Oriented Environmental Data

The number, types, and costs of engineering programs related to environmental exposures will vary from year to year depending on the needs from area to area, as determined by lease sale schedules, and available technology and data. This uncertainty in funding requirements will pose budgeting difficulties for government and industry alike. However, maintenance of orderly lease schedules will mitigate these budgeting problems.

At best, it is only possible to speculate on an appropriate funding level for a government program to collect, analyze, and disseminate environmental data in cooperation with industry. Annual spending in the range of $5 million to $10 million would be consistent with the needs as well as with available research and data collection resources. Financial planning will also have to reflect the fact that Arctic programs will cost approximately twice as much as programs in other areas.

5. CONCLUSIONS AND RECOMMENDATIONS

The committee reached the following conclusions as a result of its review:

- For orderly development of oil and gas resources on the outer continental shelf, the federal government and industry must reach timely, mutually acceptable, and credible quantitative appraisals of both the severity of environmental exposure and of the environmental design criteria for operations in OCS areas of interest.

- Offshore platform experience supplemented by experience with other major civil works supports the adequacy of structural safety provided by environmental design criteria using 100-year recurrence intervals when used with appropriate structural criteria. The U.S. Geological Survey has already proposed such criteria for its verification requirements. Techniques such as reliability analysis and design for probable lifetime maximum exposure give alternative approaches for cases where an operator may have reason to deviate from 100-year criteria.

- Hindcasting techniques using verified environmental models coupled with statistical treatment of occurrences of natural events give an appropriate and adequate technical basis for determining environmental exposure. Much of the technology and data for determining environmental exposure has been developed or supported by industry and is, consequently, proprietary. Proprietary and related issues may impede acceptance and use of the best available information on environmental exposure. Genuine differences in professional technical views may also require resolution in reaching concurrence among interested parties on matters of severity of environmental exposure.

- Operations in areas where different types of natural events (like ice in Alaskan waters) may affect design criteria may require the extension of technology for environmental modeling and an extension of environmental data bases. Some of the related data will be needed by both the federal government and industry operators. There likely will arise opportunities to share in programs and avoid duplication.

- Timely development of environmental exposure appraisals mutually acceptable to government and industry operators will require:
    - Adequate levels of technical expertise in government agencies as well as in industry;
    - Sufficient data to provide a credible basis for environmental models used to estimate environmental exposure; and
    - Technical dialogue and rapport between interested parties.

- The body of technical expertise related to environmental exposure to meet government needs does not now exist in the federal government.

- Necessary technical communication and dialogue will require focal points in government and in industry so that the technical expertise of each group can be exchanged. Such focal points can also identify situations where data needs of government and industry might make the sharing of costs attractive to avoid duplication.

Therefore, the committee recommends that the U.S. Geological Survey establish an engineering capability to appraise environmental exposures and to acquire related environmental data. Responsibilities of the office containing this capability would include:

1. Reaching timely and credible quantitative appraisals, mutually acceptable to the government and the industry, of both the severity of environmental exposures and of the environmental design criteria for oil and gas operations on the outer continental shelf.

2. Extending of technology and environmental data bases as may be needed by the government to regulate and administer oil and gas operations on the outer continental shelf. Particular attention should be given to areas whose natural events pose problems not embraced in the existing body of offshore operating technology.

3. Assuming the development and maintenance of technical and engineering expertise as may be needed within the government for timely and credible appraisals of environmental exposure.

4. Obtaining environmental data as may be needed by the government to assure credible bases for estimating environmental exposures.

5. Identifying situations where data needs of the government and industry might coincide to avoid duplication.

6. Providing a focal point in the government to exchange information with industry and other interested parties.

The committee also recommends that the U.S. Geological Survey, after establishing an appropriate office, invite the oil and gas industry and relevant technical groups to identify and name correspondent committees for matters related to environmental exposure.

APPENDIX A

Review of Previous Studies

Many committees and conferences have sought to determine the programs needed to acquire engineering data on environmental exposures to use on the outer continental shelf and off the shores of Alaska. These studies have identified needs and recommended that government and industry share responsibility for acquiring engineering data on the environment. The studies have consistently recommended the need for additional comprehensive long-term data on: (1) ocean wave and current characteristics, and probabilities of occurrence of extreme events; (2) soil characteristics tending to produce potential mud slides or liquefaction; (3) frequency and magnitude of forces produced by moving sea ice; and (4) location and severity of past earthquakes in selected frontier areas.

A listing of the most prominent and pertinent committee reports relevant to this report follows:

1. Commission on Marine Science, Engineering and Resources. Our Nation and the Sea. A Plan for National Action. Report of the Commission. United States Government Printing Office. Washington, D.C. January 1969.

   - Also known as the Stratton Report, this document identifies many of the needs presently recognized as important for the effective, economical development of U.S. offshore resources.

2. National Security Industrial Association. The Adequacy of Forecasting, Hindcasting, and the Use of Ocean Surface Wave Information. A Report of the Ocean Science and Technology Advisory Committee. Interstate Electronics Corporation, Oceanics Division, 707 E. Vermont Avenue, Anaheim, Calif. January 1976.

- Outlines the basic wave forecast techniques used to forecast wind-generated ocean waves, and discusses the use of such information.

- Concludes that wave forecasts now in preparation and wave statistics for engineering use are generally inadequate. Timely and accurate ocean wave and meteorological data are lacking.

3. Marine Board. Outer Continental Shelf Resource Development Safety: A Review of Technology and Regulation for the Systematic Minimization of Environmental Intrusion from Petroleum Products. Panel on Operational Safety in Offshore Resources Development. National Academy of Engineering, Washington, D.C. NTIS No. PB-215629/66. National Technical Information Service. Springfield, VA 22161. 1971.

   - Recognizes the intensity and distribution of winds, wave heights, and storm tides for locations of interest throughout the world. The wide variety of soil materials that may be encountered in deep water, or in the Arctic, needs further study. The frequency and magnitudes of forces produced by ice sheets and icebergs, as well as the location and severity of past earthquakes for selected geographic sites, needs to be investigated further. Several data gathering programs are currently in progress and more will develop as specific needs arise.

4. Geer, Ronald L. "The Scientific and Technological Problems of Major Concern." Presentation at Conference on The Oceans and National Economic Development, sponsored by the National Oceanic and Atmospheric Administration, Seattle, WA, July 17-19, 1973.

   - Identifies the need for oceanographic, meteorological, Arctic, and soil data.

5. Commission on Marine Science, Engineering and Resources. Keys to Oceanic Development. Vol. 2. Industry and Technology. Report of the Panel on Industry and Private Investment. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 1969.

   - Recommends that "...problems involving physical environmental prediction and modification continue to be the prime technology area in which several government efforts could have a major impact."

6. National Security Industrial Association. Relationship Between the Offshore Petroleum Industry and the U.S. Government. Report of the Petroleum Panel of the Ocean

Science and Technology Advisory Committee. National Security Industrial Association, Washington, D.C. Library copy only. 1974.

- Presents industry views on federal marine goals and programs. Written soon after the oil embargo of 1973-1974, the report recommends that government efforts should emphasize those performed for the benefit of multiple users as related to assisting in the exploration and production of domestic petroleum. Specific recommendations address the determination of fate and effects of oil in the marine environment, assistance to coastal states in coastal zone management, improvement in knowledge of weather and marine conditions, improvement in bathymetry and seafloor geologic mapping, offshore navigations, and weather modification. The report also recommends that industry should be encouraged to undertake research and development essential for maintenance of an economically viable and competitive industry. Closer cooperation among those responsible in government, industry and academia will enhance a greater undertaking of the roles of each and reduce costly duplication of efforts.

7. National Research Council. Seafloor Engineering: National Needs and Research Requirements, Committee on Seafloor Engineering of the Marine Board, Assembly of Engineering. National Research Council, Washington, D.C. NTIS No. PB-254171/66. National Technical Information Service, Springfield, VA 22161. 1961.

    - Clearly identifies a national need for additional information on basic environmental conditions and how they are transferred into forces acting upon structures. These physical conditions include surface wave motion (especially during storms), currents, and scour, and sheet and pack ice behavior. Data on environmental extremes, including more accurate statistical description of the loads are needed, particularly for Arctic operations.

    - Recommends initiating a cooperative effort involving the public, federal government, and the oil and gas industry.

8. National Planning Conference on the Commercial Development of the Oceans. Commercial Development of the Oceans. June 9-12, 1976. Sponsored by the U.S. Maritime Administration, National Oceanic and Atmospheric Administration, Department of the Interior, and Energy Research and Development Administration. Vol. 1. Addresses and Summary. Vol. 2. Program Elements. U.S. Government Printing Office, Washington, D.C. 1977.

9. National Research Council. Verification of Fixed Offshore Oil and Gas Platforms: An Analysis of Need, Scope and Alternatives Verification Systems, Panel on Certification of Offshore Structures of the Marine Board, National Research Council, National Academy of Sciences, Washington, D.C. NTIS No. ADA042139. National Technical Information Service, Springfield, VA 22161. 1977.

- Identifies need for establishing an environmental data base, including winds, waves, currents, ice, seismic activity, and geotechnical data, for use in the verification process for offshore oil and gas platforms.

10. University of Delaware. Atlantic Offshore Users Workshop Report. College of Marine Studies, University of Delaware, Newark, DE. February 1978.

- Identifies need for both measured (wave) data and improved capability to predict and describe wave conditions mathematically.

11. National Research Council. Information and Data Exchange for Ocean Engineers: An Approach to Improvement. Panel on Marine Engineering Information and Data Exchange, Marine Board, Assembly of Engineering, National Research Council, Washington, D.C. 1975.

- Recommends action by the federal government, including the establishment of an information and data liaison office by academic institutions and increasing the awareness of students of available information and data sources.

12. National Research Council. Engineering at the Ends of the Earth: Polar Ocean Technology for the 1980's. Panel on Polar Ocean Engineering, Marine Board, Assembly of Engineering. National Academy of Sciences, Washington, D.C., 1979.

- Recognizes that data are needed to develop predictive models and to understand and characterize the relationship between ice and other environmental factors, the seabed, and engineered structures in the polar oceans.

- Recommends the use of remote sensing to determine environmental forces and to maintain surveillance of the interactions of the environment with man-made structures in polar regions.

APPENDIX B

BUREAU OF LAND MANAGEMENT (BLM)
ALASKAN OCS ENVIRONMENTAL ASSESSMENT STUDIES PROGRAM
(PERTAINING TO ENVIRONMENTAL EXPOSURE CONDITIONS)

Through its outer continental shelf program, the Bureau of Land Management (BLM) program addresses the possible environmental, ecological, and societal effects of oil and gas operations off the coasts of the United States. A relatively small portion of this effort (estimated to be slightly greater than $1 million for FY 1979 and FY 1980) seeks to determine the effect of natural forces on drill structures and operations. The purpose is to guide leasing decisions and to set drilling stipulations.

The environmental assessment process is a persistent and cumulative exercise in which new information is continually being added to the body of available data. Resource managers must make their decisions using data that exists at the time a decision is required. The environmental studies program seeks to continually update the quality of available information on a priority basis.

Since new sales are successively being scheduled for each outer continental shelf area, the decision process generally operates at several different stages simultaneously. At the time advanced decisions are being made on one sale, initial decisions are being considered for subsequent or later sales. Thus, the data available when initial tracts are selected increases in complexity and refinement with each new sale scheduled. This information provides the basis of the environmental assessment process for each new sale.

The following chart, excerpted from BLM's study plan for FY 1979, summarizes that portion which might provide limited environmental exposure data for drilling operations off the coasts of Alaska.

TABLE CODE

Alaska OCS Lease Area

GA - Northeast Gulf of Alaska
CI - Cook Inlet
K - Kodiak
AL - Aleutians
BB - Bristol Bay
SG - St. George Basin
BN - Bering-Norton Sound
CS - Chukchi Sea
BS - Beaufort Sea

Decision Points/Steps

LS - Preparation of Lease Schedule
TT - Tentative Tract Selection
  /DES (with stipulations) - Draft Environmental Statement
  /FES (with stipulations) - Final Environmental Statement
  /SID (with stipulations) - Secretarial Issue Document
S - Sale (Notice of Sale with Stipulations)
Exploration Plan Approval
Development Plan Approval

SPATIAL RESOLUTION

0 = Information in hand, literature reviews
1 = Qualitative, area-wide, cursory
2 = Semi-quantitative, hundreds of square miles scale or 25 miles of coastline
3 = Quantitative, 3-10 tract scale or 10 miles of coastline
4 = Quantitative, tract specific (2 to 5 mile resolution)
5 = Quantitative, site specific
6 = No spatial resolution (non-site specific)
7 = Refinement of data, no additional resolution
8 = Local, Regional, State Socioeconomic Data

TEMPORAL RESOLUTION

N = No temporal resolution
A = Annual
S = Seasonal

SUMMARY OF PROPOSED REGIONAL STUDY PROGRAM ACTIVITIES - FY 1979
REGION: ALASKA/PACIFIC

SENSITIVITY ISSUES	STUDIES NEEDED
Effect of seismic and other geological hazards on OCS structures and activities. (Need information on potential geohazards and natural oil seeps to drilling and/or siting of structures for preparation of environmental impact statement.)	a. Seismic Hazards (10) CI:N7; K:N3-N4; AL:NO Description and location of epicenters, focal depths; seismic risk map of magnitudes, frequencies, probabilities. b. Volcanic Hazards (11) CI:N7; K:N4; AL:NO Description and location of active volcanoes; volcanic risk map of eruptions, lava flows, nuees ardentes. c. Surface and Nearsurface Faulting (12) CI:N7; K:N4; AL:NO Description and location of surface and nearsurface faults and their relationship to seismic activity. Also, the magnitude and frequency of strong bottom movements. d. Sea Floor Instability (13) CI:N7; K:N4; AL:NO Description of types and extent of potential slumps and other unstable sediment masses. Risk classification and sediment cross-section analysis. e. Erosion and Deposition (14) GA:N4; CI:N7; K:N4; AL:NO Location, description, and rates of burial and scour.

f. Overpressured Sediments (17)
CI:N7; K:N3; AL:NO
Distribution and depth of sediments with high pore pressures.

g. Subsidence Potentials (18)
GA:N3; CI:N7; K:N4; AL:NO
Location of potential areas of subsidence.

h. Stratigraphic Unconformities (19)
GA:N3; CI:N7; K:N4; AL:NO
Location and distribution of potential reservoir channels through surface fault zones; natural seeps, other stratigraphic unconformities.

The ability of industry technology to operate in severe weather or under extreme oceanic conditions.

a. Extremes of Winds, Waves Currents (22)
CI:S7; K:S3; AL:NO
Distribution and frequency of extreme events of wind, waves, currents.

b. Tsunamis (23)
CI:S7; K:S3; AL:NO
Distribution frequency, and probability of occurrence of tsunamis and shoreline inundation. Historical damage assessment and correlation to seismic events.

c. Storm Surges (24)
CI:S7; K:S3
The distribution, magnitude and frequency of occurrence, extent of shoreline inundation, predictability.

d. Ice Storms and Icing of Structures (25)
CI:S7; K:S3
Distribution, magnitude, and frequency of ice storms.

e. Visibility (26)
CI:S7; K:S3
Frequency of extremes of fog, haze and precipitation.

Assess geotechnical properties of sediments.

REGION: ALASKA/BERING

Effect of geological hazards on OCS structures and activities. Conflict for bottom space vs. seismic hazard.

Information is needed on geohazards for tract selection and environmental impact statement.

a. Seismic Hazards (10)
SG:NO; BB:NO; BN:N4
Description and location of epicenters, focal depths; seismic risk map of magnitudes, frequencies and probabilities.

b. Volcanic Hazards (11)
SG:NO: BB:NO;
Description and location of active volcanoes; volcanic risk map of eruptions, lava flows.

c. Surface and Near Surface Faults (12)
SG:NO; BB:NO; BN:N4
Description and location of surface and near surface faults and their relationship to seismic activity. Also, the magnitude and frequency of strong bottom movements.

d. Seafloor Instability (13)
SG:NO; BB:NO; BN:N4
Description of types and extent of potential slumps and other unstable sediment masses. Risk classification and sediment cross section analysis.

e. Erosion and Deposition (14)
SG:NO; BB:NO; BN:N2
Location, description and rates of burial and scour.

f. Permafrost (15)
BN:N2
Distribution and depth of subsea permafrost; engineering characteristics and indices of strength properties.

g. Ice Gouging (15)
BN:N2
The density, trends, maximum gouge depth, recurrence rates of ice gouging; predictive analysis from ice data.

	h. Overpressured Sediments (17) SG:NO; BB:NO; BN:N2 Distribution and depth of sediments with high pore pressures.
	i. Subsidence Potentials (18) SG:NO; BB:NO; BN:N2 Location of potential areas of subsidence.
	j. Stratigraphic Unconformities (19) SG:NO; BB:NO; BN:N2 Location and distribution of potential reservoir channels through surface fault zones; natural seeps.
Potential hazards to OCS technologies/activities from sea ice.	a. Sea Ice Stress - Strain Relationship (20) BB:NO; BN:S2 Sea ice size - force relationships including: movement forces from ridging and ice shore; fast ice displacement factors; mechanisms of force exertion; and stress - and strain extreme event analysis.
Vessel traffic control. Ability of industry to operate under extreme conditions. Historical information is needed on extreme environmental conditions in potential lease areas for future scheduling and call area determination.	a. Extreme events of wind, waves, (22) SG:NO; BB:NO Historical distribution and frequency of extreme events of wind, waves, currents, storm surges, ice storms, and tsunamis.
	b. Tsunamis (23) SG:NO; BB:NO Distribution, frequency rates, extent of shoreline inundations, risk prediction.
	c. Storm Surges (24) SG:NO; BB:NO Distribution, frequency rates, extent of structural icing.
	d. Ice Storms (25) SG:NO; BB:NO Frequency of occurrence, magnitude, extent of structural icing.

	e. Visibility (26) SG:NO; BB:NO Frequency of extremes of fog, haze, and precipitation.
Impacts resulting from transport and accumulation of contaminants in sea ice. Need information on the types of major ice features, distributions, and movements as well as information on the behavior and transport of spilled oil in ice covered waters for tract selections and eventual preparation of environmental impact statement.	a. Sea Ice Characteristics (36) BB:S2 BN:S2 Characteristics BN:A2 Dynamics Sea Ice characteristics including types, sizes, geometrics; frequency and magnitude of occurrence; distribution of major features (especially hazards); under ice morphology. b. Sea Ice Dynamics (37) Movements, trajectories of sea ice; deformation and ridging dynamics; lead formation dynamics. c. Oil and Ice Interactions (38) BB:NO; BN:A2 Oil and ice interactions including incorporation and release of oil from ice; bulk transport of oil in ice.
	Assess geotechnical properties of sediments.

REGION: ALASKA/ARCTIC

Information is needed for preparation of environmental impact statement. Melting by pipelines in permafrost. Ice gouging on pipelines and wells. Shallow gas pocket hazards.	a. Erosion and Deposition (14) BS:N3; CS:NO Location, description, and rates of burial and scour. b. Permafrost (15) BS:N3; CS:NO Distribution and depth of subsea permafrost; engineering characteristics and indices of strength properties.

	c. Ice Gouging (16) BS:N3; CS:NO The density, trends, maximum gouge depth, recurrence rates of ice gouging; predictive analysis from ice data.
	d. Overpressured Sediments (17) CS:NO Distribution and depth of sediments with high pore pressures.
	e. Subsidence Potential (18) CS:NO Location of potential areas of subsidence.
	f. Stratigraphic Unconformities (19) CS:NO Location and distribution of potential reservoir channels through surface fault zones; natural seeps.
Effects of ice on structures.	a. Sea Ice Stress-Strain Relationships (20) BS:S2; CS:NO Creep and strength properties of sea ice, magnitude and frequency of ice loads and structures.
	b. Sea Ice Size-Force Relationships (21) BS:S2; CS:NO Sea ice size-force relationships, including movement forces ridging and ice shove, fast ice displacement vectors, mechanisms of force exertion, extreme event analysis, stress-strain relationships, and strength properties of sea ice.
Lack of technology to work in arctic environment.	a. Extreme Events of Winds, Waves, Currents (22) CS:NO; BS:S3 Distribution and frequency of extreme events of wind, waves, currents.

	b. Storm Surges (24) BS:S3; CS:NO Distribution, magnitude and frequency of storm surges; extent of shoreline inundation, predictability.
	c. Ice Storms (25) BS:S3; CS:NO Extremes of magnitude, occurrence; icing of structures.
	d. Visibility (26) BS:S3; CS:NO Frequency of extreme fog, haze,and precipitation.
Lack of technology to work in ice environment. Feasibility of ice islands. Dynamics and hazards of ice.	a. Sea Ice Characteristics (26) CS:NO Sea ice characteristics including types, sizes, geometrics; frequency and magnitude of occurrences; distribution of major features (especially hazards); under ice morphology.
	b. Sea Ice Dynamics (37) CS:NO Movements and trajectories of ice flows; dynamics of deformation, ridging, lead formation.
	c. Oil and Ice Interactions (38) BS:S3; CS:NO Oil and ice interactions including incorporation and release of oil from ice; bulk transport of oil in ice.
Effects of chronic discharges. (Information is needed on the fate of spilled oil in the proposed lease area.)	a. Hydrocarbon Degradation Rates (45) BS:S2 Microbial degradation of hydrocarbons including natural populations of hydrocarbon utilizers, and rates of degradation under natural and enhanced environmental conditions.

	b. Effects of Contaminants on Microbial Activity (57) CS:NO Effects of contaminants on normal microbial activity including changes in population and activity rates due to contaminants.
Clean-up and long term effects of spilled oil.	a. Environmental Recovery Rates (55) CS:A2 Environmental recovery rates of ecosystems including persistence of oil on shorelines, in sediments, and the recovery of oil habitats. Assess geotechnical properties of sediments

REGION: NON-SITE SPECIFIC--FOR ALL REGIONS

Transport and fate of oil spills. Information is needed on oil slick dynamics for trajectory analysis.	a. Oil Slick Dynamics (33) S3 Oil slick dynamics including algorithms of plume behavior, wind shear, and oil slick spreading
Technology to operate in severe weather and in seismically active areas. Effects of ice gouging on pipelines and wells.	a. Vulnerability of OCS Structures to Extreme Events (60) Engineering characteristics of structures, technology scenarios, risk analysis of structure failure.

APPENDIX C

ENGINEERING INFORMATION REQUIREMENTS FOR PLATFORM VERIFICATION

The U.S. Geological Survey (USGS) ensures that offshore oil and gas operations conserve natural resources and do not endanger the environment. As a part of its process to grant drill permits, USGS reviews industry's designs and construction plans. Of particular concern are the environmental exposure data. The following list contains most types of information required by the U.S. Geological Survey for its verification process and has been supplied by the USGS. They may vary somewhat from site to site.

A. Wave Data

1. 50-, 100-, and 150-year recurrence heights and corresponding periods, depending on design life of structure.

2. Directional wave spectra

    a. Site measurements
    b. Hindcast data
    c. Mathematical formulation

3. Wave refraction (where applicable)

4. Seiches and corresponding recurrence (where applicable)

5. Tsunamis and corresponding recurrence (where applicable)

B. Wind Data

1. Gusts (less than 1-minute duration)

    a. Extreme values
    b. Corresponding periods
    c. Duration
    d. Direction
    e. Spectra

2. Long-term statistical distributions

C. Current Data

1. Tidal variations
2. Winds (based on statistical data)
3. Recurrence
4. Density current (where applicable)
5. Unusual bottom currents (where applicable)
6. Turbidity current (where applicable)

D. Tide Data

1. Astronomical
2. Wind Tide
3. Pressure-induced storm surge
4. Recurrence

E. Temperature Data

1. Extreme low temperature data and statistical distribution for
    a. Sea
    b. Air

F. Snow and Ice Data

1. Concentration and distribution of snow and recurrence
2. Concentration and distribution of ice
    a. Character of sea ice (floes, ridges, rafted ice, etc.)
    b. Mechanical properties
    c. Drift speed and direction
    d. Ice thickness and keel depth of pressure ridges
    e. Probability of encountering icebergs, ice floes, floe fragments, and hummocks
    f. Average data of ice formation
    g. Earliest and latest recorded dates of seasonal ice appearance
    h. Average data of open water

- i. Seasonal occurrence of pressure ridges and rafted ice
- j. Ice boundary (leads, edges) conditions
- k. Maximum thickness of accumulated ice
- l. Ice growth rate

G. Marine Organism

1. Anticipated maximum thickness of growth at various depths below the water level

2. Anticipated rate of growth

3. Anticipated character

H. Sea Bed Data

1. Contours

2. Location of possible unstable slope areas

3. Presence of boulders, obstructions, and small craters

4. Shallow faults

5. Shallow gas and gas seeps

6. Slump blocks

7. Scour potential

8. Hydraulic instability and occurrence of sand waves

9. Existence and depth of subsea permafrost and ice lenses

10. Mud slide proximity

11. Flow slide probability

12. Presence and depth of unconsolidated sediments

13. Faulting that could contribute to tectonic activity in the area

14. Existence of reefs

15. Soil borings and analysis

I. Earthquake Data

1. Time histories for 100-, 150-, and 200-year recurrence intervals

2. Response spectra for 100-, 150-, and 200-year recurrence intervals

J. Other Data

1. Water depth

2. Anticipated corrosion rates

3. Water salinity

4. Amount of dissolved oxygen

5. Abrasiveness of water flow

6. Storm data and recurrence

APPENDIX D

Alaska Oil and Gas Association OCS Projects

Description of Project	Status	Cost ($M)
Bristol Bay Environmental Study-Detailed historical study with wind wave hindcast	Completed Dec. 1970	144
Sea Ice Investigation - North Slope - Field measurement of fast ice movement and characteristics	Completed Dec. 1970	198
Chukchi Sea - Arctic Coast Environmental and Ecological Data	Completed 1970-1971	115
Chukchi Sea Environmental Study - Review and compilation of historical data	Completed June 1970	3
Beaufort Sea Environmental Study - Review and compilation of historical data and make new bathymetric maps	Completed 1969	113
Beaufort Sea - Reconnaissance studies of soils, sediments, and ice	Completed Aug. 1970	241
Beaufort Sea - Ice Scouring on the Arctic Sea floor (Alaska) - two seasons	Completed Nov. 1972	115
North and South Bering Sea Environmental Study - Review and compilation of historical data	Completed Oct. 1970	6
Western Alaska (Onshore) Environmental Study - Review and compilation of historical data	Completed July 1971	3
Arctic Marine Terminal Facilities, Chukchi Sea - Engineering Study	Completed Nov. 1969	1,272
Offshore Oil Terminal Structure Facilities in the Chukchi Sea - Design Feasibility Study	Completed Dec. 1968	29

Description of Project	Status	Cost ($M)
Sea Ice Activity and Pressure Ridge Growth - Vicinity of the surcharged grounded ice islands Unak 1 and Unak 2, Beaufort Sea	Completed Nov. 1969	330
Beaufort Sea Environmental Study	Completed	49
Study of Behavior of Oil Spills in the Arctic	Completed Feb. 1971	15
Manhattan Voyage Study	Completed Dec. 1970	40,000
Arctic Tanker Design Study	Completed Aug. 1970	1,615
Overflights: Nome to Resolute	Completed 1969	163
Offshore Pipelaying on the Alaskan North Slope - Feasibility Study	Completed June 1973	60
Characteristics and Distribution of Near Shore Permafrost, Beaufort Sea	Completed 1975	30 (1st yr.)
Sea Ice Dynamics Study, Beaufort Sea	Completed 1975	65 (1st yr.)
Arctic Oil Biodegradation	Completed 1975	30 (1st yr.)
Investigation of Ice Forces on Cylindrical and C[illegible]al Offshore Structures	Completed Sept. 1973	10*
Artificial Ice Islands Feasibility Study, Beaufort Sea	Completed Nov. 1975	68
Analysis of Arctic Ocean Under-Ice Profiles Analysis of U.S. Navy Submarine Sonar Data Under Polar Ice Pack	Completed July 1975	48.5
Bering and Chukchi Seas--Feasibility Study of Production Operations and Marine Crude Transportation During Ice-Covered Periods	Completed Nov. 1975	70

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* Cost to next participant

Description of Project	Status	Cost ($M)
Beaufort Sea Ice Statistics from Satellite (ERTS-1 Data) - To Derive Statistics of Sea Ice Distributions in the Beaufort Sea Using Imagery from ERTS-1.	Completed July 1976	77
Ice Movement Study for Winter, 1975-1976, Beaufort Sea - Measure the Rate and Extent of Ice Movement at Select Locations	Completed Sept. 1976	458
Aerial Reconnaissance 1974-1975 - Prudhoe Bay - Harrison, Point Lay and Kotzebue Sound and Ice Movement - Prudhoe Bay - Harrison Bay	Completed Dec. 1975	20*
Bering/Chukchi Sea Ice Statistics from Satellite Data	Completed Mar. 1979	79
Unmanned Subsea Work Vehicle Study - To Evaluate the Application of U.S. Navy Unmanned Subsea Technology to Exploration and Production Tasks	Completed Dec. 1975	54
Crushing Pressure of Ice - To Provide Up-to-date Assessment of What is Known and Unknown about Failure of the Ice Sheets Crushing Against Cylindrical Structures	Completed Dec. 1975	10*
Triaxial Ice Measurements - To Determine the Strength of Fresh-water Ice Under Triaxial Stress States	Completed June 1975	10*
Arctic Ice Islands - To Develop a Model to Estimate the Risk of Collisions Between Ice Islands and Selected Offshore Sites in Coastal Waters of the Beaufort Sea	Completed Dec. 1975	10*
Feasibility Study for Construction of Artificial Gravel Islands, Beaufort Sea	Completed Mar. 1976	77

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*Cost to next participant

Description of Project	Status	Cost ($M)
Summer Sea Ice Conditions, North Alaskan Coast - Cape Halkett to Camden Bay, June through October, 1953 through 1975	Completed Dec. 1976	5*
Artificial Ice Islands, Beaufort Sea - To Build an Ice Island Capable of Being Used as a Drilling Platform for Oil Exploration in Shallow Arctic Offshore Situations	Completred Nov. 1976	20*
St. George Basin Sea Ice Statistics from Satellite	Completed Mar. 1977	41
Saline Ice Triaxial Tests - Determine the Strength of Laboratory Grown Saline Ice Under Triaxial Stress States	Completed Nov. 1977	134
Beaufort Sea Ice Movement Study 1976-1977	Completed June 1978	530
Developing Ridging Statistics in the Bering and Chukchi Sea From Submarine Under-Ice Profile Data	Completed Mar. 1977	32
Oil spill Response in the Nearshore Beaufort Sea	Completed Aug. 1978	40
Beaufort Sea Ice Movement Study 1977-1978	Completed Jan. 1979	510
Aerial mapping of 1978 Sea Ice in Norton Sound and Northern Bering Sea	Completed Dec. 1978	110
Beaufort Sea Meteorological and Oceanograhic Measurement Program (BEAUMOP)	Completed Feb. 1979	286
Arctic Mobile Drilling Structure	Completed June 1978	60*
Study of Methods and Costs of Offshore Pipeline Installation and Trenching in the Beaufort Sea	Completed Jan. 1979	126
Yukon Delta Rubble Pile Investigation 1978	Completed Feb. 1979	25

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*Cost to next participant

Description of Project	Status	Cost ($M)
Beaufort Sea Floor Geophysical Study	Completed Apr. 1979	120
Ice Island Experiment	In Progress	
Offshore Alaska Seismic Study (OASES)	Completed Mar. 1978	380
Aerial Mapping of 1979 Sea Ice in Norton Sound and Northern Bering Sea	In Progress	141
Beaufort Sea Ice Movement Study 1978-1979	In Progress	134
Beaufort Sea Ice Movement Studies (BSIMS) Three Year Summary and Analysis	In Progress	150
Norton Sound and Northern Bering Sea Rubble Pile Investigation 1978-1979	In Progress	166
Beaufort Sea First-Year Ice Survey	In Progress	163
Bering Sea Phase I Oceanographic Study	In Progress	204
Reindeer Island Ice Island and Ice Bridge Studies	In Progress	
Arctic Skimmer Final Design	In Progress	66
Arctic Dispersant Study	Completed June 1979	20
Review Air Cushion Platform Capabilities for Oilspill Cleanup in Beaufort Sea	In Progress	32
Conical Structure Test Program	In Progress	400
Under-Ice Rig Noise Measurement Program	Completed	50
Beaufort Sea Hindcast	Completed	20*
Bering Sea Aerial Photography Data - 1977	Completed Jan. 1978	16*
RIST Mud and Cutting Dispersal Study		

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*Cost to next participant

Description of Project	Status	Cost ($M)
GOAOC PROJECT--Yakutat Wave Data	Completed Oct. 1970	25
GOAOC PROJECT--Group Oceanographic Survey - Gulf of Alaska	Completed Sept. 1970	1,400
GOAOC PROJECT--Weather Forecast Trial	Completed 1972	38
GOAOC PROJECT--1973 Soil Boring Program	Completed 1973	359
GOAOC PROJECT--Dynamic Soil Analysis	Completed Fall, 1974	35
GOAOC PROJECT--ARCO COST Well	Completed Oct. 1975	11,930
GOAOC PROJECT--Lab Dynamic Soil Analysis	Completed Nov. 1975	25
GOAOC PROJECT--Oil Spill Trajectory	Completed 1974	5
GOAOC PROJECT--Socio-Economic Impact of Drilling and Production	Completed May 1975	80
GOAOC PROJECT--Sea and Subsea Floor Properties	Completed 1975	60*
GOAOC PROJECT--Seismic Risk Analysis for the Gulf of Alaska	Completed Sept. 1975	20
GOAOC PROJECT--Superstructure Icing	Completed Sept. 1975	
GOAOC PROJECT--1974 Ocean Current Measurement Program	Completed Sept. 1975	20*
GOAOC PROJECT--Gulf of Alaska Hindcast Evaluation (WHEP)	Completed 1975-1976	69
GOAOC PROJECT--Continued Earthquake Ground Response	Completed 1976	70
GOAOC PROJECT--Gulf of Alaska Meteorological and Oceanographic Forecasting Program (MOFP)	Completed July 1976	416

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*Cost to next participant

Description of Project	Status	Cost ($M)
GOAOC PROJECT--Gulf of Alaska Wave and Wind Measurement Progam (GAWWMP)	Completed July 1976	1,300
GOAOC PROJECT--Platform Seismic Study	Completed Nov. 1976	36
GOAOC PROJECT--Gulf of Alaska Wave Hindcast Pilot Study (GAPS)	Completed Sept. 1978	197
ASOC PROJECT--St. George Basin/ Western Bristol Bay Wave and Wind Measurement Program (BOMP)	Completed Feb. 1978	534
ASOC PROJECT--Bering Sea Oceanographic Measurement Program 1977-1978	Completed Apr. 1979	324
Yakutat Wave Data		
Kodiak COST Well		
Kodiak COST Well Geotechnical Study		
St. George COST Well		
Marathon Satellite Current Study		
Shell Kodiak Geotechnical		
Shell Phase I Soil Response Program		
1979 Break-up	In Progress	
1974-1975 Aerial Reconnaissance Study	In Progress	
Model Tests and Analysis of Multi-year Pressure Ridges Failing Against a 45° Cone	In Progress	30*
Sonar Ice Mapping System (SIMS) - The Development and the 1977-1978 Measurement Program	Completed	30*

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*Cost to next participant

Description of Projects	Status	Cost ($M)
Feasibility Study of an Air Cushion Drilling System for Shallow Water Areas of the North Slope of Alaska	Completed	25
Yukon Delta Tide Gauge Program 1979	In Progress	61

SECTION II

BACKGROUND PAPER I

WINDS, WAVES, CURRENTS, AND TIDES

By Paul Aagaard

INTRODUCTION

Scope of Paper

The focus of this paper is on the development of "extreme" environmental exposure data. It should be noted, however, that data on the full range of conditions are needed for analyzing structural fatigue, selecting appropriate drilling and construction equipment, and scheduling operations. For brevity, details are omitted; a more complete discussion of ocean phenomena and force calculations is presented in Reference 1.

Background

The technology for predicting environmental exposure was meager when offshore operations started in the Gulf of Mexico but in these shallow water operations extreme wave heights were limited by the breaking height of waves, and the cost of conservative design assumptions was not a severe economic penalty. The technology improved as operations moved into deeper water. The oil industry has relied heavily on oceanographic and meteorological specialists for the prediction of the necessary environmental data. In the early 1950s consultants drew heavily on work done by or for the U.S. Navy and the U.S. Army Corps of Engineers.

The oil industry started measurement programs in the early 1950s. Two major wave force projects, along with a listing of several additional projects, are described in Reference 2. A sequence of wave height measurements and the subsequent development of improved hurricane wave height prediction models for the Gulf of Mexico are well documented in Reference 3 through 6. Measurements were made in the Gulf of Alaska in the late 1960s and again in the 1970s. [7] Further work has been done in extending the type of wave height calculation model developed for the Gulf of Mexico into the Gulf of Alaska and other frontier areas.

The amount of detailed information on winds, waves, currents, and tides now available for the proposed OCS lease sale areas varies considerably among areas; for example, projects for determining environmental exposure data for the Bering Sea OCS areas are at a relatively early stage of development compared with the Gulf of Mexico studies noted above. Sufficient information is probably known about wind, wave, current, and tide conditions for all prospective OCS sale areas so that significant environmental hazards can be adequately identified for purposes of pre-lease sale planning.

SUMMARY

In planning any program for developing environmental exposure data, careful attention must be given to identifying the specific environmental parameters used in the various steps of the program. The form of the recorded data and the subsequent data processing steps must be designed to produce the various parameters needed for (1) correlation with existing data, (2) calibration of mathematical models, and (3) use in force calculations. Table I lists environmental parameters typically used.

Development of environmental exposure data requires a long-term data base. Meteorological data files are the key source for developing long-term data. Hindcasting techniques, with meteorological data as input, are used to mathematically model, utilizing historical events to establish the data base for the particular parameters needed. The calculation methods used in hindcasting are in a relatively advanced state of development, but calibration of the methods used is desirable before the results are applied in important studies.

Except for measurement of the directional properties of waves, commercial instrumentation is adequate for measurement programs needed for calibration of wind, wave, current, and tide calculation methods. The critical consideration in measurement programs is the location and mechanical support of the sensors. Special attention must be given to locating sensors free of obstuctions and mounted so as to be free of bothersome motion and vibrations. Calibration of the entire system, including effect of supporting platform, is desirable.

Environmental exposure data are developed from the hindcast sequence of historical events [illegible] representing the magnitude of the events in the form of a probability distribution. The assumption is made that if a distribution function fits the data in the range of the measured data, then extreme values can be estimated from the "tail" of that distribution function.

Not all circumstances justify comprehensive investigations to develop environmental exposure data. Instead of hindcasting many severe storms, a single "design storm" might be chosen to simulate extreme conditions at the site of interest.

Table 1

TYPICAL ENVIRONMENTAL PARAMETERS

WIND*

Sustained Windspeed (Typically 10 minute average)
Gust Speed (Typically 5 second average)
(Or gust factor - ratio of gust speed to sustained speed)
Direction
Elevation (Elevation of sensor or reference datum)

WAVES**

A. Significant Wave Height Description
Significant Wave Height (Average of highest 1/3 of waves in a wave train (or record))
Significant Wave Period (Average period associated with highest 1/3 of the waves)
Direction
NOTE: Wave descriptions may be either as sea (local generation) and swell (distant generation) with significant height, period, and direction given for each, or combinded sea and swell with a single composite significant height and period given.

B. Non Directional Spectra
Wave Energy Spectra (Energy Density vs Frequency with all directions combined as obtained by fourier analysis of time series recorded from a single wave staff or based on a theoretical relationship; e.g., Bretschneider or Pierson Moskowitz.)
Direction (Reported from associated observations, measurements, or hindcast)

C. Directional Spectra
Matrix of energy density as a function of frequency and direction

CURRENT*

Current Speed (Typically 15 minute average)
Direction
Depth
NOTE: Current may be given as total current or as separate values for storm, tidal, and general oceanic circulation, also, current may be given as values at discrete depths or as a current profile.

TIDE

Total Tide (Average water level over duration many wave periods relative to reference datum)
NOTE: Tide may be given as total tide or as separate values for storm and astronomical tides.

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*All factors required for complete description
**A, B, and C are alternative descriptions

The program needed for a specific OCS area will depend on experience in the area, severity of conditions, type and frequency of storms, type of facilities or operations under consideration, and the time available for developing the required information. These considerations apply to data for both design and verification.

Specific recommendations for further work relate to the following activities: (1) archiving and disseminating environmental data, (2) improving instrumentation for directional wave measurements, (3) improving wind, wave, and current models, (4) conducting limited, well planned, special purpose measurement programs, and (5) conducting hindcast studies as appropriate.

DISCUSSION

The development of useful and reliable environmental exposure data for the design and verification of offshore structures requires (1) careful consideration of the physical phenomena involved, (2) characterization of the phenomena in terms of parameters that are readily useable in engineering calculations, (3) a thorough understanding of data already available, and (4) knowledge of methods that can be used to develop the required data.

Description of Wind, Wave, Current, and Tide Phenomena

Typically, at an exposed site waves, winds, currents, and tides are dominated by the effects of a local storm, but these effects may be superimposed on other independent phenomena; e.g., swell propagating from distant storms, the general oceanic circulation currents, or astronomical tides. Figure 1 illustrates the interrelationships of these phenomena.

Wind

Winds are important as a phenomenon loading a structure and as a phenomenon generating ocean waves, currents, and storm tides. The winds of particular significance are the surface winds. Surface winds or boundary layer winds vary with elevation and are influenced by the character of the sea surface. Surface wind data must include sensor elevation for proper interpretation.

Waves

The waves of engineering significance are wind-generated waves and tsunamis; the latter are a hazard only in coastal areas. Wind-generated waves are the principal oceanographic design consideration for OCS areas (except where ice conditions prevail). Wave growth is a function of wind speed, fetch length, and wind duration. Figures 2 and 3 further describe the generation and propagation of wind-generated waves and tsunamis.

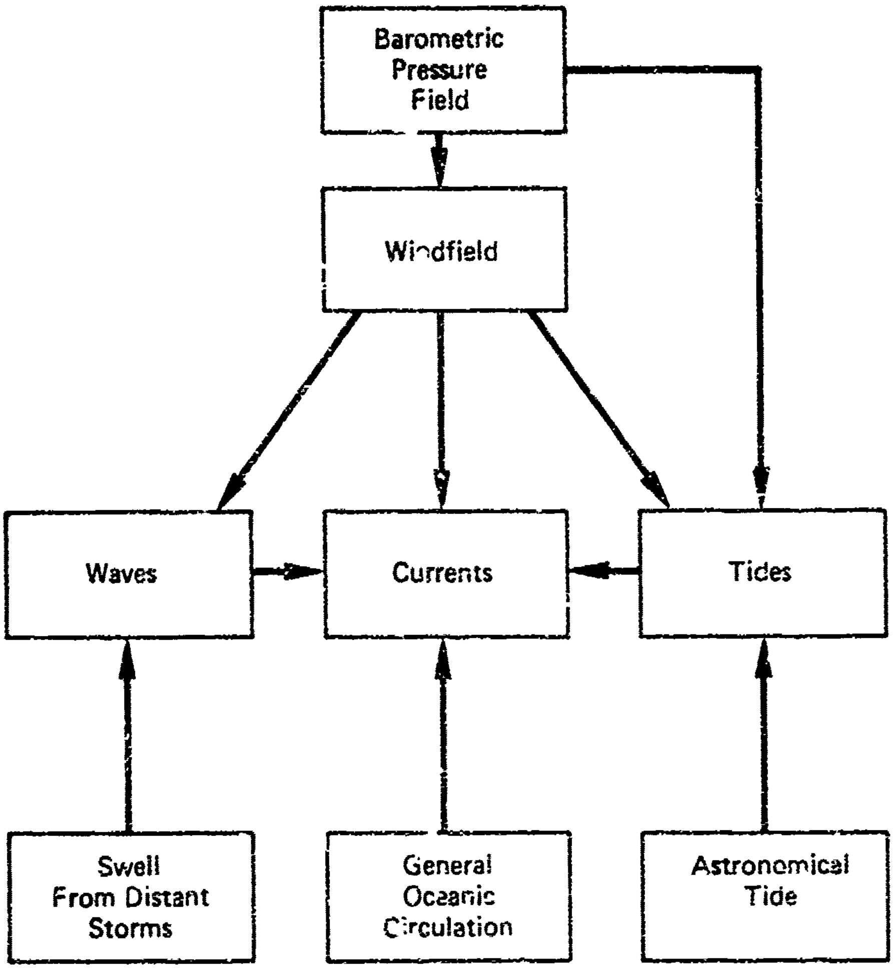

FIGURE 1 Interaction of Ocean Phenomena

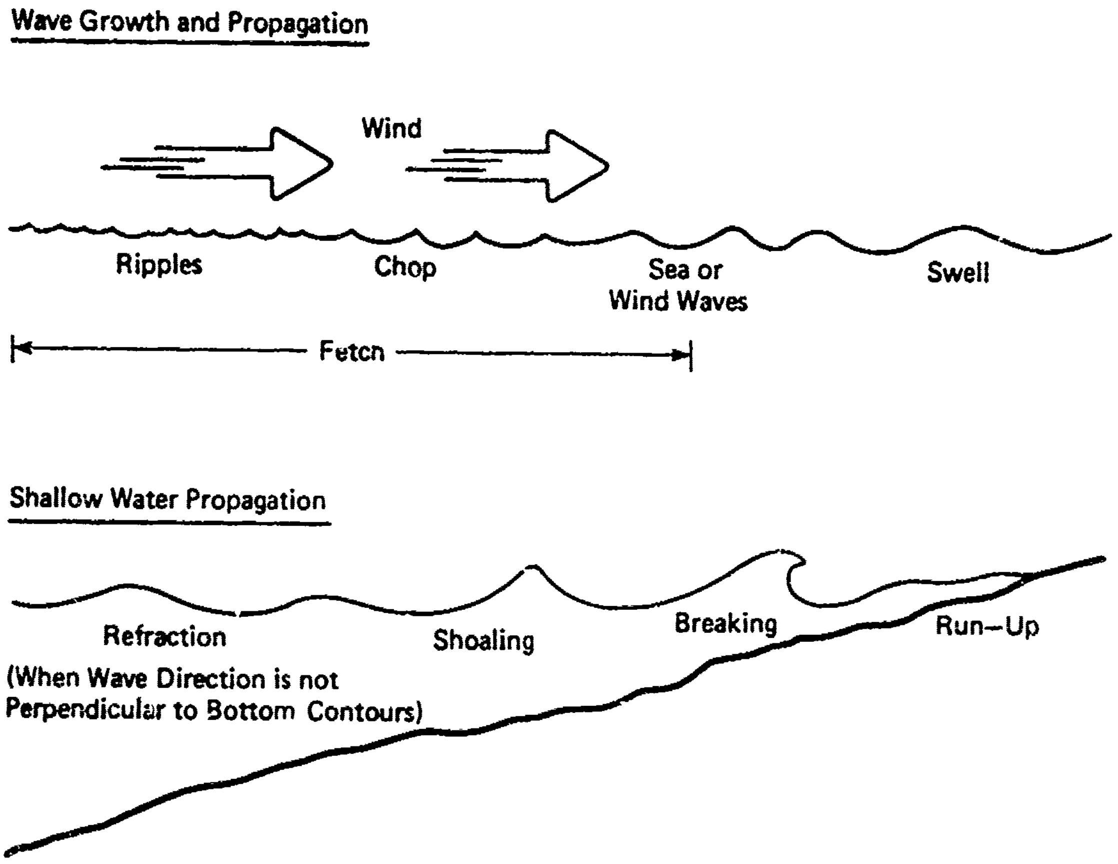

FIGURE 2 Wave Processes

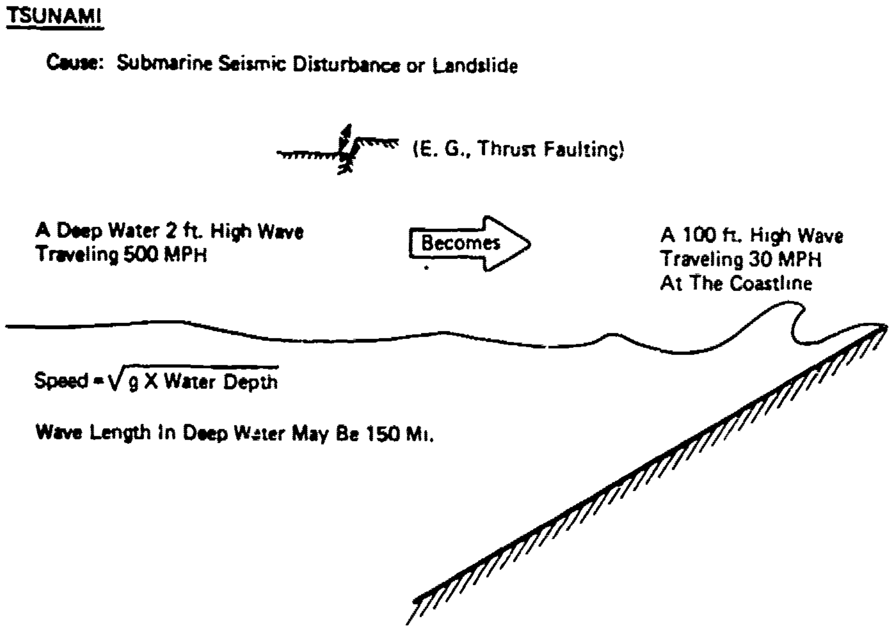

FIGURE 3 Tsunami Propagation

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In intermediate and shallow water the effects of wave refraction, shoaling, breaking, and energy dissipation must be considered. Bathymetry and sea-floor sediment characteristics are important in shallow water studies. (For consideration here, intermediate depth water is less than approximately 300 feet.)

Currents

Factors controlling ocean currents are water level changes (e.g., tide, storm surges, etc.), wind stress, earth rotation, sea water density differences, sea-floor configuration and coastal boundaries, river outflow, and ocean waves (nearshore currents). For purpose of analysis, currents are generally classified into three types: (1) general oceanic circulation, (2) storm (wind drift, storm tide, and wave-related), and (3) tidal (astronomical). Ocean currents at a site vary in speed and direction in both depth and time because of the large number of factors controlling currents.

Tides

Factors affecting tides are typically classified into two categories: astronomical and storm. Astronomical tides include the gravitational attraction of the moon and sun, centrifugal force due to the earth's orbit, and resonnances in the water body. Storm tides are caused by low barometric pressures, coupled long waves, and wind set-up.

Key Environmental Parameters

Various dimensional descriptions of complex oceanographic phenomena are possible. For example, a given sea state can be described by some "average" wave height, associated wave period, and dominant wave direction; or it could be described in great detail by contouring the water surface from a stereo-pair of photographs. The latter, however, would be difficult to use in engineering calculations. Practical constraints limit the dimensional descriptions that can be used. These constraints include: type of data available, type and quantity of measurements that may be practicable, form of statistical analysis and extrapolation to be applied to the data, and finally, need to describe the phenomena in a form compatible with the appropriate force model. Other considerations include developing data for mathematical model calibration; in this case it is desirable for data to contain the same amount of detail as included in the mathematical models. Thus, wave data in the form of directional spectra are desirable for calibrating directional spectra-type wave calculation methods.

From the point of view of design and verification of offshore structures, the parameters needed to calculate forces are most important. Table I lists the typical environmental parameters used, and Table II identifies specific applications of these parameters. As noted earlier, other forms of environmental exposure data are needed for planning operations, etc.; discussion of such data is presented in Reference 8.

Methods for Developing Environmental Exposure Data

As concluded in the body of the report, development of environmental exposure data requires a long-term data base and the interpretation of this data base to provide a reliable estimate of the full range of future occurrences, particularly the rare occurrences. Another conclusion is that hindcasting is the most reliable method of establishing the long-term data base in a timely fashion because very little, if any, relevant long-term measured data in the vicinity of proposed installations are available. This section reviews briefly the type of data generally available, the calculation methods used in hindcasting, instrumentation for calibration progrms, and the interpretation of the data.

Data Sources

Data used to develop wind, wave, current, and tide environmental exposures fall into the following categories: general meteorological data files; short-term, site-specific measurements; ad hoc regional oceanographic studies; routine coastal measurements and observations; statistical summaries; and atlases. Background paper II lists references that are examples of such data sources.

Meteorological data files are the key data source for developing long-term data. Background paper III discusses windfield hindcasting from this data base and the type of data available. The meteorological data files include ship-reported barometric pressure, wind speed and direction, and sea state (in order of decreasing reliability). Several of the statistical summaries described in Background paper II derived from ship-reported data.

Examples of short-term, site-specific measurements include NOAA data buoy programs; the oil industry's cooperative data collection programs in the Gulf of Mexico [3], Gulf of Alaska [7], and Bering Sea [7]; various measurements made during exploratory drilling operations [9-10]; and measurements made in support of planning specific facilities. Measurements of this type can serve in a variety of ways in developing environmental exposure data, the most important of which is calibrating hindcasting models. Other uses include establishing correlations with long-term coastal station data and determining seasonal, monthly, or diurnal variation in oceanic phenomena.

TABLE 2

ENVIRONMENTAL PARAMETER APPLICATIONS

PARAMETERS	STATISTICAL REPRESENTATIONS	TYPICAL APPLICATIONS
WIND		
Storm maximum sustained speed*	Sustained speed vs return period	Design loads on deck installations
Storm maximum gust speed	Sustained speed design criteria multiplied by gust factor	Design loads on single elements
Sustained speed at time of peak wave loads*	Sustained speed vs return period	Total design load
WAVES		
Storm maximum significant peak wave height*	Storm maximum significant wave height vs return period or "expected maximum wave height" vs return period. NOTE: Typically wave height design criteria for static wave load calculation is given as "expected maximum wave height," which is the average maximum wave height for a given number of random waves [47]	Total design load for static wave load analysis
Non Directional	Theoretical spectrum or spectrum derived from measured data. Total energy in spectrum scaled to be equivalent to energy of significant wave height selected as design criteria.	Total design load - dynamic wave load analysis using spectra approach
	Theoretical wave surface time series or measured time series. Total energy scaled to be equivalent to energy of significant wave height selected as design criteria.	Total design load - dynamic wave load analysis using time - series approach
Directional Spectra	Various forms used.	Application is in developmental stage
Significant wave height - climatology data for fatigue analysis	Significant height vs period vs direction frequency of occurrence for exposed life of structure.	Fatigue Analysis
	Cumulative probability distributions for all waves in exposed life of structure.	Fatigue Analysis
CURRENT		
Storm maximum speed*	Speed vs return period.	Pipeline design loads
Speed at time of peak wave loads	Speed vs return period.	Total structure design load
TIDE		
Storm maximum total tide	Elevation vs return period.	Flooding, etc.
Total tide at peak wave loads	Elevation vs return period.	Breaking limit, deck clearance.

*Includes associated direction (and elevation data as appropriate).

Ad hoc measurement programs are often conducted by oceanographic institutions to investigate particular phenomena of scientific interest. Reports on such studies frequently serve to identify significant oceanographic conditions in an area and are valuable in pre-lease sale planning. [11-12] The propensity of oceanographers to seek out unusual conditions has lead to the identification of most of the severe hazards encountered in OCS areas.

A wealth of information exists on coastal conditions, including systematic meteorological observations, wave height data recorded at piers by the U.S. Army Corps of Engineers [13], logs of harbormasters and lifeguards, and local newspapers. These sources frequently cover many decades and are valuable in developing long-term site-specific data in adjacent offshore areas. Such data may help to identify unusually severe storms and thus aid in screening candidate storms for hindcasting.

Statistical summaries and oceanographic atlases are useful in making preliminary appraisals of operating conditions but are of very little value in developing information on extreme conditions.

Background paper II lists several examples of wave hindcast studies conducted at various times for various purposes. Use of these studies for other purposes requires careful evaluation of hindcast model used, calibration, data base, effect of grid size (if applicable), shallow water considerations, etc.

Calculation Methods

For hindcasting to produce satisfactory predictions of environmental exposure, it is imperative that the calculation methods accurately simulate nature's physical processes and the method's input data be readily derived from data covering a long period. In recent years good progress has been made in understanding the various physical processes taking place in the ocean and in developing mathematical formulations that approximate these processes in tractable computation procedures.

Wind

Barometric pressure fields, which are developed from the meteorological data base, are the basic input to windfield calculation methods. Tropical storms and extratropical storms are different in time and space scales and in the type of data available in meteorological files; hence, different calculation schemes have emerged for these two storm types.

Tropical storms have a tight cyclonic pattern that is highly organized. In most cases the density of meteorological observations is completely inadequate to represent the details of a tropical storm.

However, wind models and parametric representations of tropical storm windfields have been developed to the point where they produce adequate descriptions of surface windfields for the purpose of wave calculations. The information on which these models are based evolved from years of investigations using coastal station data, aircraft-based measurements, and oil industry offshore platform data. Reference 5 describes the development of windfields for tropical storms.

Extratropical storms are typically not as organized as tropical storms and have a much larger areal extent; hence, meteorological observations are used directly to develop surface windfields. Reference 14 discusses methods used for developing windfields, the historical data bases used, and error characteristics for extratropical storms.

Typically, the output of the windfield analysis is sustained windspeed at a specified elevation. Gust speeds are usually derived from "gust factors" determined from measured data.

Waves Methods for calculating wave heights have evolved to the point that the physical processes of wave growth, dissipation, and propagation are modeled satisfactorily for engineering calculations. Background paper II discusses the two basic methods used: the significant wave method and the wave spectra method. It also summarizes several of the important wave height calculation models and discusses the methods developed specifically for hurricanes. Additional comments on directional wave spectra are included.

Background paper IV presents an assessment of present methods for wave height calculations. The author of that paper, D. T. Resio, warns that the various wave height calculation methods produce different results given the same input windfield and further recommends that the models must be carefully evaluated and verified with data before the results are used in important studies.

Wave hindcasts for several days before the peak of a storm may be required to include swell and adequately establish the background sea conditions.

The basic output of "significant wave height" models is significant wave height, wave period, and wave direction. The output for the directional spectra-type models is a matrix of wave energy density as a function of both wave direction and wave frequency. Empirical correlations for estimating wave spectra from significant wave height predictions are discussed briefly in Background paper II.

For water depth less than 300 feet, the effect of sea-floor bathymetry and friction must be accounted for in the wave growth, dissipation, and propagation. In most regions of the world where water depth is less than 50 feet, the extreme wave heights are limited by breaking height; this is usually considered to be 75-80 percent of the water depth.

Most wave height calculation models are for "deepwater" and do not include the shallow water effects. When using such models, wave refraction, shoaling, and breaking must be accounted for separately.

Currents The determination of extreme current probabilities is usually difficult because ocean currents vary considerably from location to location and current is the vector sum of a number of independent components; e.g., general circulation, tidal currents, storm wind currents, storm tide currents, river outflows, and local eddies. Each component may have its own independent direction and probability of occurrence.

Methods used for developing extreme current exposure data depend on the overall severity of the current in the area and the significance of the various components contributing to the total current. Another consideration is that in calculating wave forces the current must be added to the wave orbital velocity.

If the ocean current problem requires a very accurate answer, then a combined measurement and calculation program may be required. A lengthy current measurement project may not be as necessary as with waves, and the measurement project can perhaps be performed during exploratory drilling operations. A measurement program should be designed to record the features of the dominant current types for the area. Thus, if the general circulation dominates, data representative of each season may be adequate; if tidal currents dominate, continuous data during one lunar cycle may be adequate; if storm currents dominate, continuous data during one storm season may be adequate; and if currents are highly irregular in a region of interest, an areal array of measurements may be necessary.

The availability of large digital computers has permitted the development of detailed numerical current calculation methods. References 15 and 16 are examples of the application of such methods.

The current parameters needed are the current speeds and directions as a function of depth. In general, there may be significant changes in direction with depth. This is particularly true for wind-driven currents. Current speed is typically reported as an average speed over a 15-minute period.

Tides Storm tides and astronomical tides are calculated independently. The required accuracy depends on the type of structure under consideration, the water depth, and proximity to the coastline. Tides are a factor when selecting the maximum breaking wave heights in shallow water, setting platform deck elevations, and designing coastal facilities. Storm tides are intimately related to storm currents and, in fact, may be calculated in the same computer program.

Astronomical tides are predicted on a yearly basis for representative shore stations along the entire United States coastline. In some cases measurements at offshore locations may be needed to relate the site to nearby tide-table stations.

The important tidal parameter needed is the combined astronomical and storm tide to be used in calculating the breaking wave height or the maximum elevation of a wave crest at the site of interest. Care must be taken in selecting the appropriate tide height at the time of the peak wave because storm and astronomical tides are independent phenomena.

Instrumentation for Calibration of Calculation Methods

The design and execution of successful measurement programs requires careful attention to the following considerations:

1. Nature of phenomena to be measured (threshold, dynamic range, frequency response, other phenomena on which validity of measurement depends, etc.).

2. Characteristics of sensors (threshold, dynamic range, frequency response, drift stability, resistance to fouling, mechanical shock resistance, etc.).

3. Characteristics of data logging system (data logging format, threshold, dynamic range, stability, record length, servicing interval, temperature/humidity/vibration of logging system location, weight/size, power requirements, etc.).

4. Type of sensor platform (anchored floating drilling rig, fixed offshore structure, buoy, ship, aircraft, etc.).

5. Effect of platform on sensor (disturbance of phenomena being measured and motion of platform).

6. Calibration of sensor/data logging system/platform (tests and comparisons with primary or secondary standard, either as single element in system or preferably as a complete system).

7. Processing steps required to obtain parameters of interest (manual vs. computer analysis vs. computer analysis, analog-to-digital conversion, statistical analysis, etc.).

The following sections discuss specific considerations relevant to wind, wave, current, and tide measurements.

Wind Measurement The main difficulty in wind speeds and direction measurement is location and support of the sensors and not the sensors themselves. Sensors, which must be located on a rigid mast free of obstructions in all directions, often fail because of mast vibrations at high windspeeds. Sensors on offshore platforms and drillships are difficult to locate free of obstructions. The top of the derrick is clear, but it is usually difficult to service an instrument located there. Many choice locations are eliminated because the helicopter landing approach must be clear. Wind measurements from buoys should only be considered for buoys that are very stable in pitch and roll and that have a good mast.

Wind measurements should be made at the reference elevation (usually 10 meters), but this is not practicable for most platform and buoy installations. Careful consideration should be given to making the appropriate elevation corrections by accounting for obstructions and sea surface roughness. Documentation of conditions around the installation is valuable to subsequent investigators using data from that installation.

Wave Measurements The highly random nature of the sea surface in both time and space creates a very difficult measurement problem. As noted earlier, it is usually necessary to cast the parametric representation of the sea surface in relatively simple terms.

Most wave surface measurements are nondirectional. The most reliable and accurate measurements are from fixed platforms. Measurements made from semisubmersible drillships require compensation for the heave displacement of the platform. The most popular sensor used for platform measurement is the rugged, inductive-type wave staff, which consists of two parallel steel cables. Electrical resistance-type staffs tend to foul and require frequent cleaning. Wave measurements with radar and laser devices are in the early stages of commercial application. These devices are mounted above the water surface and beamed downward. They measure the two-way travel time between the source/receiver and the water surface.

In water depths less than about 100 ft. wave measurements can be made with bottom-mounted pressure sensors. The water depth limit of such measurements depends upon the frequency content in the wave energy. Pressure sensor data will require compensation for the decay of wave energy, with depth as a function of wave frequency. Nearshore installations are usually connected to shore by power and signal cables. When this is not practical, batteries and data logging must be incorporated with the sensor unit.

Surface-following buoys containing a gimbaled vertical accelerometer are the most popular type of sensor used in open ocean, deep water wave measurements. The buoys are moored on location with highly compliant moorings. Data may be telemetered to a nearby drillship, platform, or shore location and/or recorded internally. Further measurement comparisons between this type of sensor and wave staffs on fixed platforms are desirable for severe sea states.

Shipborne wave height measurements have been attempted using a combination of sensors that measure water pressure on the hull (to sense hull submergence), vertical heave acceleration, pitch, and roll. Most of the experience with such measurements has been in the North Sea and North Atlantic.

Successful directional wave measurements have been made in recent years from fixed offshore platforms using a wave staff and electromagnetic current meters. The electromagnetic current meter is needed for this application because the directional information is obtained from the measurement of the two horizontal components of wave orbit velocity. Directional wave properties may also be measured with an array of wave staffs or pressure sensors.

An essential part of planning directional wave measurements is the selection of a compatible data analysis procedure for calculating the directional sea characteristics from the recorded data. It should be recognized that directional sea characteristics can be represented in a variety of forms. Examples illustrating significantly different forms are (1) wave direction given as a single value representing direction of dominant wave energy, and (2) a matrix presenting wave energy in narrow bands of wave frequency and wave direction. The form of the directional properties needed and the resolution of direction are important considerations in selecting the appropriate arrangement of sensors. Directional properties of waves have been measured with a variety of other schemes such as stereophotography, high resolution laser altimeters mounted in low-flying aircraft, SEASAT 1 synthetic aperature radar, and surface-following buoys containing gimbaled vertical accelerometers and pitch and roll sensors. Several of these schemes appear to be promising but require further evaluation, development, and calibration. (See Figure 4)

Data logging for wave monitoring systems requires the following considerations: (1) expected frequency content of wave energy and the resolution desired in the subsequent analysis, (2) storage capacity consistent with frequency and duration of storms as well as servicing interval, (3) length of individual record as required for FFT spectral analysis or simple statistical averages, and (4) time coherence of data from multiple sensors for use in directional analysis.

Minicomputers and microprocessors provide the capability for real-time data processing. Such processing can substantially improve the time durations monitored without servicing. For example, small surface-following buoys using microprocessors have the capability of logging processed data (maximum and significant wave height and the zero crossing period) at hourly intervals for several months on standard-size magnetic tape cassettes.

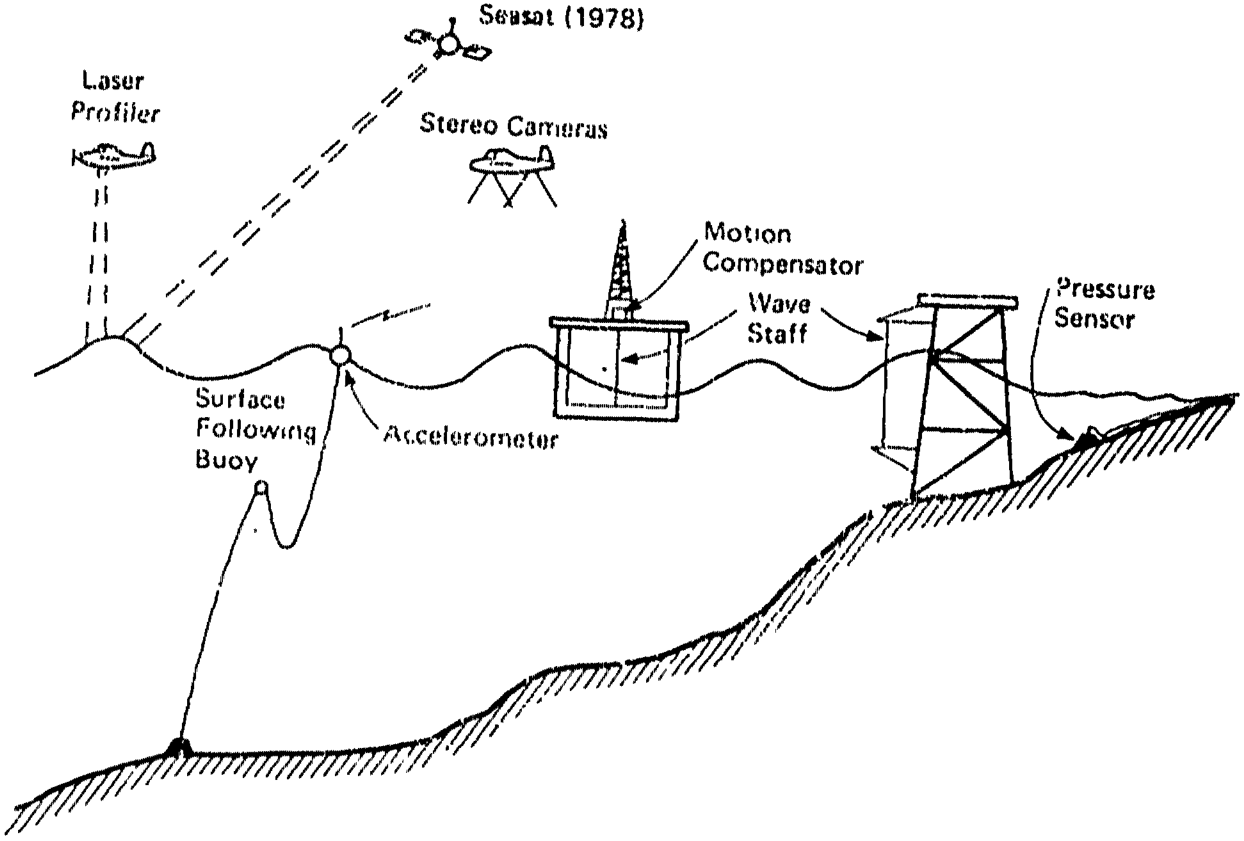

FIGURE 4 Wave Measurements

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Current Measurements Ocean current measurements of engineering interest are made from buoys moored in the open ocean, moored oceanographic ships, anchored drillships, and fixed platforms.

In terms of the accuracy required for engineering data, commercially available sensors appear to give adequate performance; however, reliability of certain commercial units is marginal. Several types of sensors are in use. Current meters, using either ducted rotors or vector averaging, are often used in the near-surface zones because the reversing water particle orbital velocity can be averaged out of the net flow. Savonius rotor current meters should be used below the zone of wave action; flow reversal cannot be detected by the conventional Savonius rotor meters and a false value of net flow may be obtained. Electromagnetic current sensors can detect rapidly changing conditions and are useful when measurements of both wave orbital velocity and net flow are desired. The state of the art in current measurements is described in Reference 17. Figure 5 illustrates several types of current measurement operations.

The moorings for current meters must be carefully designed for good stability, adequate strength, and easy retrieval for servicing. Significant improvements have been made through the years in the durability of mooring systems.

Current sensor calibration, both before and after deployment, is an important consideration in critical studies.

Data logging for systems deployed at unattended, remote locations is usually done with internal recorders. A variety of techniques are used. Typically, short-term average current speed and instantaneous direction values are recorded at relatively frequent intervals. Data from electromagnetic current sensors are logged along with the associated wave profile data in the same format and at the same sampling rate when the data are used in directional wave studies.

Tide Measurements Most tide information is gathered in harbors, using relatively simple mechanical float-type sensors. Measurements at remote locations in deep water have been made with high resolution pressure sensors coupled with internal recorders. In connection with exploratory drilling operations, tide data have been obtained by measuring the vertical position of the vessel relative to some mechanical connection to the sea floor (such as a guideline), and appropriately averaging.

Interpretation of Data on Historical Occurrences

The discussion up to this point has dealt with the procedures for reconstructing the historical occurrences of environmental phenomena at a given site. This section illustrates one of several approaches applicable to developing the probability distributions that describe environmental exposure, given a sequence of historical events. The intent

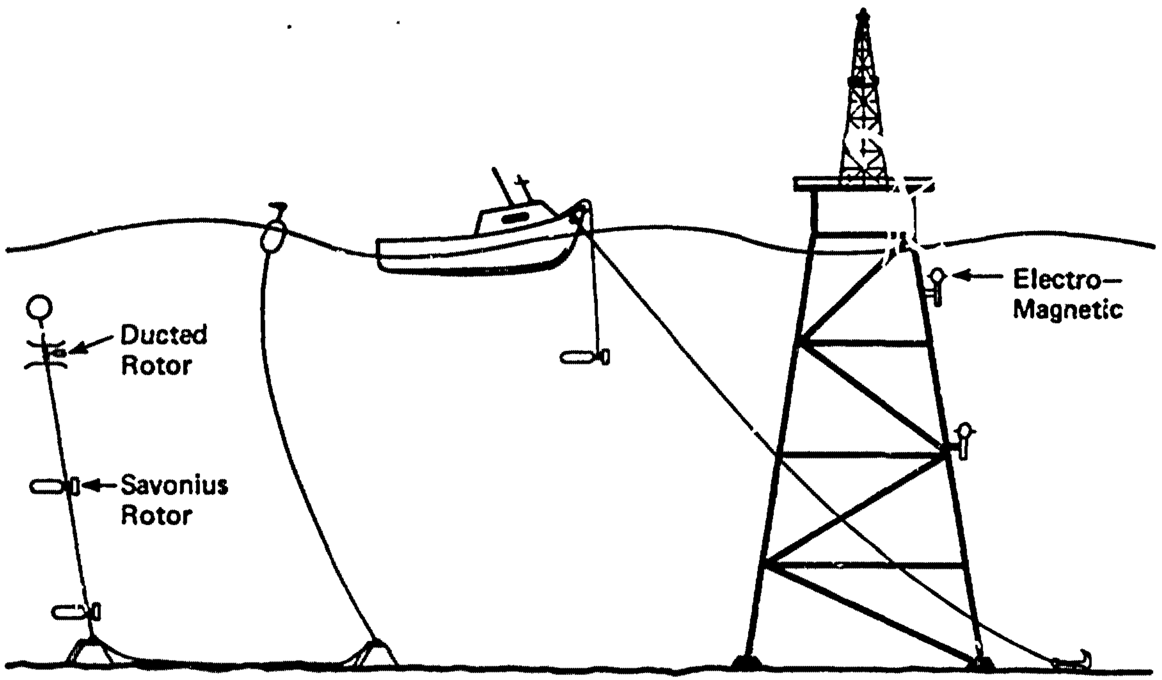

FIGURE 5 Current Measurements

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here is to illustrate important considerations in the interpretation of hindcast results. References 18-20 present fundamental discussions of extrapolation procedures.

The basic steps in the method discussed here are to: (1) develop criteria for selecting the severest events affecting the site, (2) reconstruct the historical occurrences of these events, and (3) use an extrapolation procedure to obtain the extreme values. These steps are illustrated in Figure 6.

The extrapolation methods are based on the assumption that if a probability distribution function fits the data represented by the occurrences of historical storms, then the extreme values of that storm population can be estimated by that distribution function. The basic steps are as follows:

1. Rank the magnitude of the historical events in descending order.

2. Assign probabilities of occurrence to each of them according to a "plotting position" formula.

3. Plot the magnitude of events vs. their exceedance probability on special graph papers on which particular types of distribution functions plot as straight lines.

4. Construct the best-fit straight line through the data (steps 3 and 4 are frequently done using computer techniques), and select the distribution function that best describes the data.

These steps are illustrated in Figure 7. The straight line is in essence the distribution function representing the data, and extreme values beyond the data are extrapolated using the straight line. No *a priori* basis exists for selecting a particular distribution function; Weibull, Extremal (Gumbel), and Log-normal distributions are often used. Reference 21 discusses the selection of the "best" distribution function for a given set of data.

The restrictions on data used in the extrapolation of data characterized by a single parameter such as wave height are rather obvious but bear repeating: (1) the data must have a common definition and be derived by consistent methods; (2) the magnitude of the event used for each storm must be the largest event at the site of interest for that storm; (3) the data set must include all storms occurring in the hindcast period that exceed the magnitude of the lowest ranked storm; (4) all storms must be from the same population but statistically independent; and (5) the results are not applicable where the phenomenon of interest is truncated by physical limitations such as breaking-height limitations of waves in shallow water or wind-fetch limitations.

The probability distribution function represented by the straight line as plotted in step 3 above is used to describe the probability of exceeding the magnitude of an event given the event has taken place.

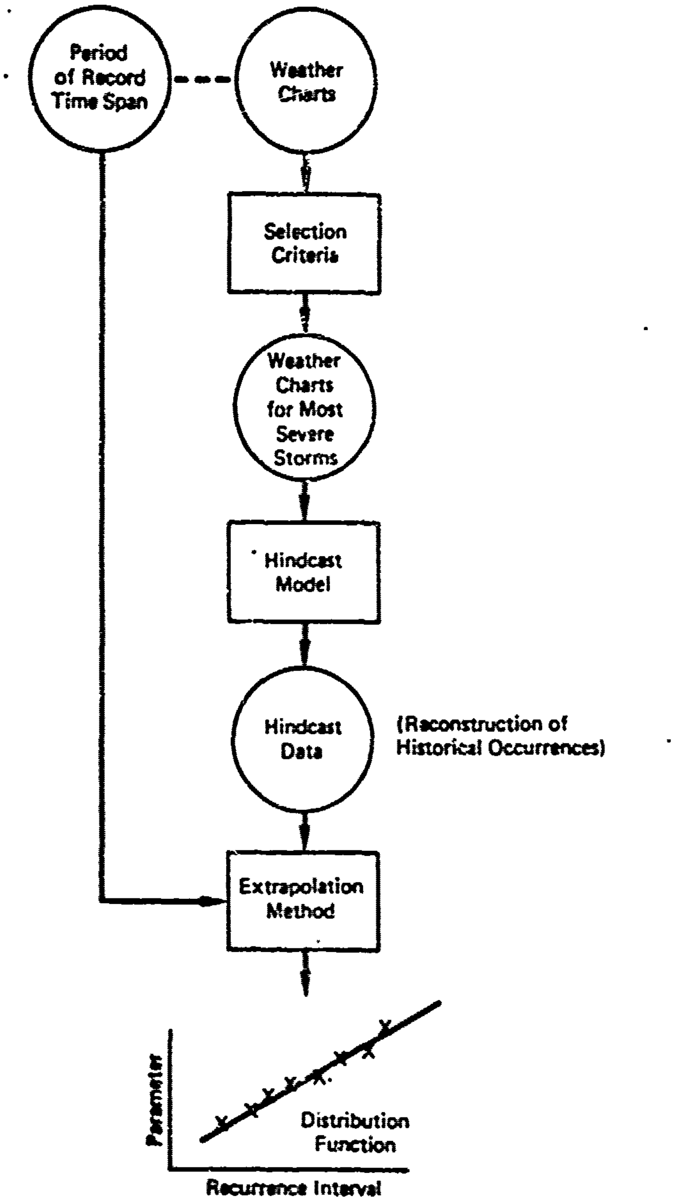

FIGURE 6 Basic Steps in Using Hindcast Method for Developing Environmental Exposure Data

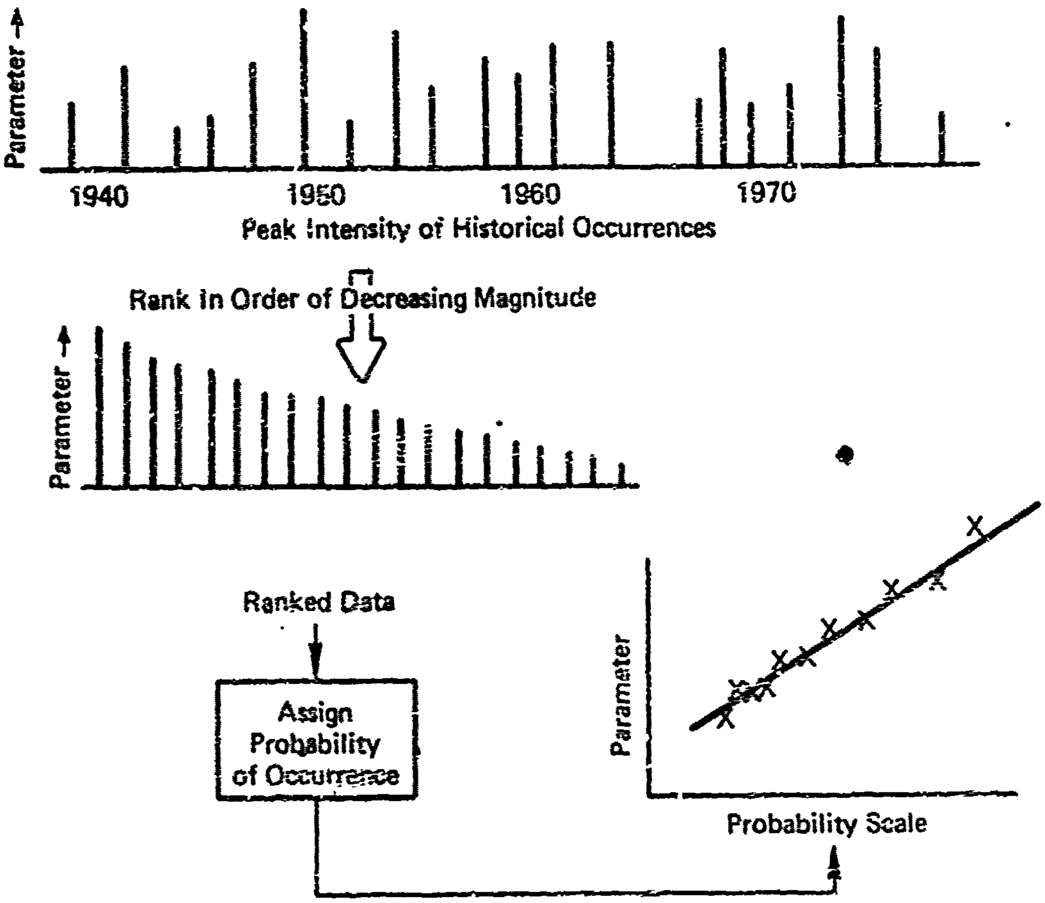

FIGURE 7 Extrapolation Method

The distribution function does not give information about the interval of time between occurrences of the events. The conversion of the exceedance probability scale to return period (average interval in years between events equal to or greater than a prescribed magnitude) is accomplished by multiplying it by the average number of events per year that were included in the ranked data, and then taking the reciprocal of the result.

A meaningful measure of the chance of occurrence of an extreme event is the probability than an event corresponding to a given return period is not exceeded during the exposed life of the structure. This probability of nonoccurrence is called the nonencounter probability (NE); its relationship to return period (R_p) and exposure life (t_d) is given by the following equation. [22] The equation is based on the

$$NE = e^{-t_d/R_p}$$

assumption that the Poisson distribution is a valid representation of the number of occurrences of severe storms during a given time interval and that the storms are statistically independent.

If separate phenomena, each having its own probability of occurrence, combine to produce an event (e.g., storm tide and astronomical tide combining to produce the total tide), then the probability of occurrence of the separate phenomena and their interdependence must be considered appropriately.

Next it should be recognized that circumstances may not justify the lengthy sequence of hindcasting a large number of storms to develop an adequate long-term data base. The "design storm" approach is an alternative that has merit for particular cases.

In the design storm method an extreme hypothetical or real storm is used to calculate extreme conditions at a site. A block diagram of the method is presented in Figure 8.

The use of design storms for developing the data on extreme conditions is a variation of the extrapolation of hindcast data approach discussed above. Instead of hindcasting, for example, the 20 most severe historical storms, a storm of "design intensity" is characterized in the form of an idealized model or scaled historical storm. The storm path is selected so as to produce the most extreme condition at the site of interest. The conditions for the site of interest are calculated using a "hindcast" model of the type discussed in the previous section.

In practice, considerable subjectivity is used in characterizing the design storm. However, in principle, the analysis involves the following: (1) investigation of storms affecting the region surrounding the site of interest (not just storms at the site), (2) verification that storm statistics are uniform for the region selected, (3) characterization of storm by simple parameters (e.g., for tropical cyclones: radius to maximum winds, central pressure depression, and forward velocity), and (4) selection of the combination of parameters that produce the "design" condition.

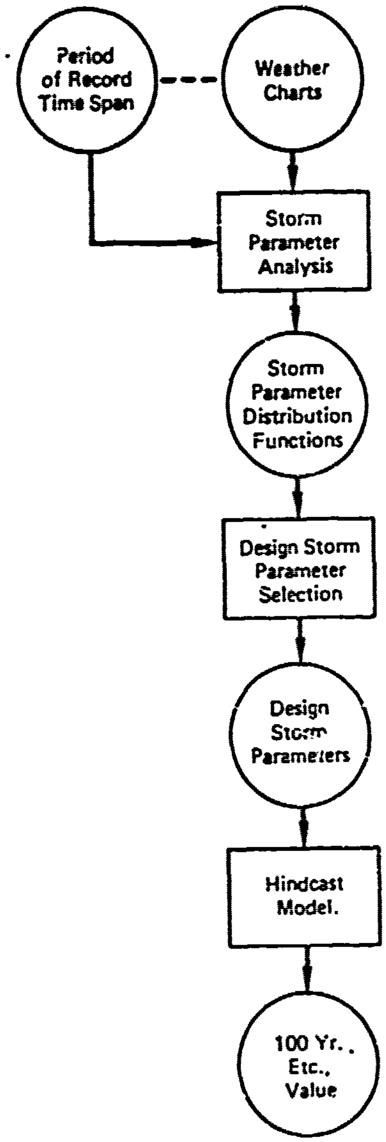

FIGURE 8 Basic Steps in Using Design Storm Method for Developing Approximate Environmental Exposure Data

The disadvantage of the method is that considerable subjectivity may be required in specifying the characteristics of the design storm, particularly assigning the recurrence interval. In nature, a unique storm description will not exist that will produce a 100-year wave height for a site, but rather, several combinations of storm characteristics might create the 100-year condition.

Experience with hindcasting and familiarity with the area of interest are important factors in deriving satisfactory results using the design storm method.

Force Calculations

This section presents a brief review of force calculations from the point of view of what parameters are used in present force calculation methods. A good summary of force considerations is contained in the API recommended practice RP2A. [23]

Wave Forces

Wave forces usually dominate the other environmental forces discussed in this section. Wave forces are also the most complex and have been the subject of a very significant amount of research since the early 1950s. Much of this work has been sponsored by the oil industry.

Two of the early wave force measurement projects are described in Reference 2. The first of these, Wave Project 1, involved the measurement of wave forces on vertical cylinders having diameters of 1, 2, 3, and 4 feet. Forces were measured at 7 levels for each cylinder diameter. The installation was located in the Gulf of Mexico in about 30 feet of water and waves up to 22 feet in height were measured at this installation.

The second of these projects, Wave Project 2, involved the measurement of forces on dynamometers clamped around the legs of a Gulf of Mexico platform. The outside diameter of the sensing unit was 3.7 feet. The water depth at this location was 100 feet; the largest wave measured was about 40 feet. The wave force data provided the basis for several analyses, many of which have been published. [24-26]

A very comprehensive wave force measurement program, the Ocean Test Structure (OTS), was conducted in the Gulf of Mexico for two winter seasons and one hurricane season (1976-1978). Total forces and overturning moment were measured on an approximately one-quarter scale structure, which was located in 65 feet of water. In addition, local wave forces were measured at several locations on vertical, horizontal, and inclined members. References 27-29 describe the project data collected and References 30-36 present some of the results from the analysis of the data.

Wave force prediction problems relevant to offshore structure design can be classified as (1) static wave load predictions for space frame structures, (2) dynamic wave load predictions for space frame structures, and (3) static load predictions for large bodies (e.g., concrete gravity structures). The static wave force prediction procedures can be used when the natural period of the structure is sufficiently short so that dynamic amplification factors can be neglected in calculating structural response. Space frame structures with natural periods greater than three or four seconds usually require a dynamic wave force prediction.[37] Wave force calculations for space frame structures are based on the assumption that the structure is sufficiently transparent to waves that waves are not disturbed by the wave propagating through the structure. Wave force calculation methods that account for wave diffraction around large bodies are required for the large monolithic-type gravity offshore structures.[38-39] Reference 40 is a comprehensive overview of force calculations.

Wave forces for static analysis for a space frame structure are calculated using an empirical force equation consisting of a drag term and an inertia term. The following equation presents the basic functional relationship:[41]

$$F = F_D + F_I = F_D(C_D.\ u^2) + F_I(C_M.\ u)$$

where:

F = wave force
F_D = drag component
F_I = inertia component
C_D = drag coefficient
C_M = inertia coeffiecient
u = wave orbital velocity
u = wave orbital acceleration

The drag and inertia coefficient are empirically derived from experimental data; e.g., Wave Projects 1 and 2 [24-26] and the Ocean Test Structure.[30] Water particle velocity and acceleration values are calculated from wave theory.

Typically the wave theories used for static force predictions represent smooth, symmetrical, unidirection waves specified by wave height, wave period, and water depth. A variety of wave theories are used; each has a discrete range of applicability which depends on wave height, wave period. and water depth. API-RP2A lists several wave theories typically used. Background paper V lists additional wave theory references.

The selection of the drag and inertia coefficients used in design wave force predictions must be made with the recognition that the wave theories used in determining these coefficients must be consistent with the theories used in force predictions. Wave theories are usually used in determining the coefficients because wave orbital velocity and acceleration are needed; [24] until recently, orbital velocity was not readily measured in the ocean.

For cases where currents are superimposed on waves, the total wave-plus-current force is calculated using the current added vectorially to the wave orbital velocity.

Two methods are typically used in dynamic wave force prediction: time history and spectral. These approaches utilize a modified form of the force equation used in static analysis. This modification accounts for the movement of the structure. References 37 and 42 illustrate the time history approach and 43 and 44 the spectral approach.

Wave force predictions for large monolithic gravity structures are typically made using a combination of small scale model tests along with mathematical calculations. Input data in these force calculations are wave height, period, and water depth, as in the case of forces for space frame structures. References 40 and 45 present examples of model studies and force calculation methods for such structures.

Wind Forces

Wind force calculations typically follow procedures prescribed in building codes. Wind force is proportional to wind velocity squared, multiplied by the appropriate shape coefficient. Sustained wind velocities are usually used in the computation of the overall platform wind load, and gusts are used for the design of individual structural elements. The wind velocity used is a function of elevation. Equations for the adjustment of wind for elevation are given in Reference 23; they are also included in building codes.

Current Forces

As noted earlier, when waves and currents act simultaneously, the force calculation for the combined action of waves and currents includes the current velocity added vectorially to the water particle orbit velocity. When the current is acting alone, current drag and lift forces are calculated using empirical drag and lift coefficients and the current velocity at the elevation of the member. The drag forces act in-line with the current direction, and the lift forces act perpendicular to the current direction. Lift forces are typically caused by vortex shedding, which induces transverse forces alternating in direction.

Practical Considerations

The intent of the preceding sections in this paper has been to describe methodology appropriate for developing environmental exposure data for design and verification of offshore structures. It should also be recognized, however, that such a program is not needed in all OCS areas at this time. The specific requirements vary from area to area depending upon the maturity of operations and the type of hazards in the area. Some knowledge already exists on wind, wave, current, and tide conditions in each of the prospective OCS sale areas. Some areas have been the subject of detailed studies for the development of environmental exposure data.

The results of an accurate detailed environmental exposure study are needed at the time of starting the final design of an offshore structure. The timing of this final design may vary substantially from area to area. As a rule, final designs are only initiated after wells have confirmed a commercial discovery and the type and size of production facilities needed are identified. The timing for the final design may thus be on the order of two years after a lease sale; however, in the more difficult operating areas, this period may be much longer. The timing for initiation of a detailed program for developing environmental exposure data will depend on whether adequate calibrated hindcast models and data are available for the area and the length of time needed to develop a model and gather adequate data for hindcast model calibration, if needed.

At earlier stages of OCS lease planning and development, less accurate environmental exposure data are needed. In the pre-lease sale planning phase, only approximate descriptions of environmental hazards are necessary for identification of sensitive areas and critical operating requirements. This is needed by industry for proper preparation of lease bids and by government for preparation of environmental impact statements. More accurate studies may be needed for particularly critical phenomena if the ability to cope with such phenomena is a deciding factor in whether a lease is offered.

In planning exploratory drilling operations, the accuracy of the information needed ranges somewhere between that required for presale planning and final design information. Generally exploratory drilling operations are conducted from world-class drilling rigs designed for conditions more severe than most of the OCS lease areas.

When a detailed and accurate environmental exposure study is needed, a carefully thought out program of modest proportions is probably all that is required to obtain the desired information. This planning requires experienced personnel.

The pressing need within government is to assimilate the experience that now rests with industry and industry consultants. Much information already exists; the need, then, is to first establish the credibility of the available information and judge its adequacy in the context in which this environmental exposure data will be used. New programs should be defined jointly by government and industry to efficiently cover new areas.

RECOMMENDATIONS

Specific recommendations for further work on wind and ocean forces relate to the following activities: (1) Archiving and disseminating environmental data, (2) improving instrumentation for directional wave measurements, (3) improving wind, wave, and current models, (4) conducting limited, well planned, special purpose measurement programs, and (5) conducting hindcast studies, as appropriate.

Data

The principal need in archiving data is the expansion of the meteorological data files to include a longer data base and additional observations. In addition, it would be desirable to encourage investigators to deposit both raw and analyzed data in public archives. The general awareness of available data would be improved by compilation of specialized indexes that identify data sources, analyzed results, and related technical reports.

Instruments

In the technical area of instrument development, measurement of directional wave characteristics at remote, open ocean locations deserves first attention. Several directional wave measurement schemes are in the development stage. These schemes were discussed at the Atlantic Offshore Program Planning Workshop, held at the University of Delaware, September 19-21, 1977.[46] The workshop concluded that additional funds are required to bring some of these systems to the stage where they can be field tested, and proposed the following steps:

1. Continuation of development of promising systems to the point where they can be field tested (1 to 2 years).
2. Development of directional wave analysis techniques.
3. In-ocean comparisons of the promising systems with "rigorous" ground truth.
4. Development of "best" system for operational use.

5. Fundamental research (probably at universities) on new directional wave measurement systems.

Wind Models

Good progress is being made in evolving practical methods for predicting surface windfields over the ocean, but relatively few investigators are active in this technical field. In view of the well-funded government programs on atmospheric research and weather predictions, greater effort should be placed in marine surface windfields. One objective should be to improve understanding of the basic physical process in storms through analysis of data from offshore platforms, satellites, and other sources. This improved understanding should lead to a more accurate assessment of the validity of the different windfield models for various areas, types of storms, and types of input data available. This assessment of models will in turn provide a better basis for reconstructing the historical events needed to develop the long-term data base.

Wave Models

The University of Delaware workshop referred to above also evaluated the status of wave height calculation methods. It recommended further development, calibration, and verification of wave prediction models. In particular, the development work on models should include "modeling wave generation in intermediate and shallow water depths simultaneously with wave refraction, nonlinear wave-wave interactions, bottom friction, and wave-current interaction for irregular bottom contours."

Current Models

Ocean current modeling appears to be receiving considerable attention in connection with ocean dumping studies, oil spill migration, and global climatology studies. The component of ocean current that is most relevant to extreme environmental exposures is the storm current. Further improvement in storm current models is desirable. In order to make progress in storm current modeling, additional storm current measurements are needed, along with related wind, wave, tide, water temperature, and water salinity measurements.

Measurements

Future measurement programs for the overall assessment of wind, wave, current, and tide conditions for an OCS area must be planned in the context of the data need and timing for that area, along with the recognition that the principal use of the data is to calibrate the appropriate models needed for hindcasting the long-term data base.

Hindcasts

The final recommendation is that the hindcasts be undertaken in frontier areas as needed and that the studies be conducted using the most qualified personnel available.

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BACKGROUND PAPER II

WAVE FORECASTING AND HINDCASTING MODELS AND TECHNIQUES

By Charles L. Bretschneider

Introduction

There are a number of wave forecasting models for ocean waves. This paper discusses them and traces their development, including revisions and calibrations that are being made as more and more wind and wave data become available.

There are essentially two methods of wave forecasting: the significant wave method and the wave spectra method. Each has its value, depending upon the preference of the researchers and the type of information required. The two methods are competitive and complement each other, and they also serve as calibration techniques for each other. Each method has about 10 variations. A short discussion on the differences between them follows, with an abstract included on each of the variations.

The paper also includes a brief history on the various methods of wave forecasting used in the U.S. (see the list of references), up to the present state of the art, and sections on hurricane wave forecasting models and wave spectra. It ends with general comments on wave forecasting models and on Ekna wind drift and wave mass velocity. Ice forecasting has not been included.

Comparison of Wave Forecasting Techniques

The significant wave method is based on a very simple concept. It forecasts the principle parameters, that is, the significant wave height (H_s) and either the significant wave period (T_s) or the modal period of the frequency spectrum, f_o^{-1}. The normal unit form of the theoretical spectrum can be used to estimate the wave spectrum. The normal form of the directional spectrum, which is frequency dependent, can be used to estimate the complete directional spectrum.

The wave spectrum method is the reverse of the significant wave method; that is, it predicts the directional spectrum, from which the one-dimensional spectrum and the significant wave are determined. The significant wave period (T_s) is closely related to the modal period (f_o^{-1}) of the frequency spectrum.

In both methods the Rayleigh distribution is used to determine the most probable maximum wave height. Some forecasters prefer to use the Weibull distribution for wave heights and wave periods.

Both methods are based on measured wave data for calibration. If the same or similar wave data are used, then both methods should give essentially the same results in regard to directional spectrum, the one-dimensional spectrum, the significant wave height and period, and the period (f_0^{-1}) of maximum energy density.

The significant wave method is easier to use and certainly less expensive, since the wave spectrum method requires a highly sophisticated computer program. Users should select the method based on the particular purpose for which the data is to be used, and the choice should be cost-effective.

Both methods are needed to complement and serve as calibration techniques for each other.

Both methods include the extreme wave conditions associated with design criteria and day-by-day or operational wind and wave forecasting.

Other reasons for selecting one concept over the other generally have to do with user preference.

Brief Description of Models

SMB Wave Forecasting Model (1947, 1951, 1952, 1970)

The Sverdrup-Munk-Bretschneider, or SMB model, is the model used by the U.S. Army Corps of Engineers Research Center in its Shore Protection Manual (1973). This is a very useful model, which has been calibrated by measured North Atlantic wind-fetch-duration wave data. It is intended primarily for winds of constant speed and direction and is therefore a one-direction significant wave forecasting model. The forecasting charts relate significant wave height and period to wind speed and the equivalent fetch length. However, the forecasting wave charts are presented in such a manner that graphical integrations are possible to take into account both wind speed and wind directional variability. This has led to the two-directional significant wave forecasting model, which has special applications to hurricane-generated waves and is discussed under the section on hurricane wave forecasting models. The three-parameter Bretschneider (1959) wave spectral formulation is also useful.

Wilson Model (1965)

The Basil W. Wilson model for wave forecasting is based essentially on the SMB model, in particular in the data analysis. The hyperbolic tangent equation of Wilson, and later the quadratic equations for wave forecasting, are based on additional wave data used for the SMB model.

This model uses various traverses in which the wind is time dependent. Wave forecasts and hindcasts are then made for significant wave height and period. Satisfactory hindcasts for significant waves have been obtained by use of this model.

PNJ Method (1965)

The Pierson, Neumann, James (PNJ) method of wave forecasting is given in USN H.O. Pub. No 603, "Practical Methods for Observing and Forecasting Ocean Waves by means of wave spectra and statistics." The wave spectrum used is after Neumann (1949, 1952, 1953). This method has been used extensively both to forecast and hindcast waves.

The method was modified later by Baer (1963) and calibrated by use of North Atlantic wind and wave measurements. The original computer program of Baer (1963) was modified and adapted by the U.S. Naval Fleet Numerical Weather Center (FNWC), as discussed below.

L. Baer Model (1962) ("An experiment in numerical forecasting of deep water ocean waves," Ph.D. Dissertation, New York University, Department of Meteorology and Oceanography)

This method is based on the original NYU Atlantic Wave Model, which became known as the Icosahedral-Gnomonic Wave Spectral Model (the I.G. Wave Model) originally designed by Professor Pierson. The 1962 Baer model was modified and later calibrated by use of North Atlantic wind and wave data, as detailed by Lockheed Missile and Space Co. in its 1963 report No. LMSC-801296. (Identical to Baer dissertation.) The Baer forecasting model was the basis for the model used by the U.S. Naval Fleet Numerical Weather Center (FNWC).

The FNWC Singular Advective Wind Wave/Swell Analysis and Forecast Model (Fleet Numerical Weather Center, Technical Note No. 72-3, July 1973, by Schwartz, E. and W. E. Hubert)

A new wind wave/swell analysis and prediction model has been developed for operational use at Fleet Numerical Weather Center, Monterey, California. This model is singular in that it treats only the predominant wind, wave, and swell components, but it maintains wave continuity through advective propagation. Wave dissipation is a function of the angle between the direction of propagation and the new wind direction. Preliminary calculations involving advective propagation and decay are used as the base for scalar analysis of synoptic wave height observations from ships. Although the model is run on a Mercator grid system for a global band extending from 40°S to 60°N, values are extracted for substitution into the standard FNWC polar stereographic grid from the northern hemisphere. Northerly swell trains which originate in the Arctic are inserted into the global band grid at the northern boundary.

The FNWC Hemispherical Operational Wave Spectral Model (Numerical) (Fleet Numerical Weather Center, Technical Note No. 75-3, June 1973, 103 pp.)

The open ocean numerical wind wave spectral model, developed by W. J. Pierson, Jr., of City University of New York, has been in real time operational use at FNWC as Spectral Ocean Wave Model (SOWM) since 1972. It computes semi-daily the spectral analysis and forecasts to 72 hours for the Northern Hemisphere worldwide at points on a "square" grid 5° on a side.

The wave energy growth for a given wind velocity at grid points is predicted by the Miles-Phillips technique, as limited by the Pierson-Moskowitz fully developed spectrum for the given wind speed and energy direction by equation derived by Pierson's Stereo Wave Observation Project (SWOP).

The energy spectrum at each grid point is represented by a 15-frequency by 12-directional matrix.

SOWM has been verified in at least three cases: November-December 1969 against FLIP measurements; October 1973 against weather ship measurements; and December-January 1975 against wave buoy measurements.

JONSWAP Model (Hasselmann, et al., 1973)

Development of this model is based on an extensive wave measurement program. The Joint North Sea Wave Project (JONSWAP) is important for its measurement of fetch limited wave growth. Numerous papers resulted from the project, leading to the JONSWAP spectrum. Other investigators have verified the JONSWAP spectrum for limited fetch length as well as for limited fetch width, such as in the Taiwan Straits (see OU, 1977).

NORSWAM (North Sea Wave Model)

This model was developed at the Max-Planck Institute, Hamburg, and was used to determine long-term wave statistics for the North Sea. The wave statistics were determined from windfields for 42 severe storms during the 10-year period from 1966 to 1976. The selected storms were analyzed from a period 24 hours before the onset of the gale to 24 hours after the abatement. The storms chosen were representative of 113 vigorous gales during the period, preserving their monthly, annual, and class distributions. The spectral shape of the developed wind sea spectrum can be fully described in terms of five parameters - based on the height and width of the peak of the spectrum, the frequency of the peak energy, and the Phillips "Constant."

For 14 of the storms, some wave measurements were available and were used to prove, adjust, and calibrate the wave model for the North Sea environmental conditions.

The statistical data were used to predict the probability of occurrence of extreme significant wave values over a 5-year period.

NORSWAM was jointly funded in the United Kingdom by the Department of Energy and Industry, the United Kingdom Offshore Operators Association, and the Department of the Environment's Hydraulics Research Station, and was carried out in cooperation with the Institute of Oceanographic Sciences.

Two relevant publications are:

1) Ewing, J.A., Weane, T. J. and B. A. Worthington. "A Hindcast Study of Extreme Wave Conditions in the North Sea." Vol. 84, No. C9, pp. 5739-5747. Journal of Geosphysical Research, 1979.

2) Harding, J. and A. A. Binding. "The Specifications of Wind and Pressure Fields Over the North Sea and some Areas of the North Atlantic During 42 Gales from the Period 1966-1976." Institute of Oceanographic Science, IOS Report 55, 1978.

Source of the above information comes from Offshore Research Focus, Department of Energy No. 10, November 1978, ISSN: 0309-4189, published by CIRIA for the Department of Energy, The United Kingdom.

WES Wave Forecasting Model (Donald T. Resio) "An Assessment of Current Methods For Estimating Climatological Sea States"

T. Resio of the U.S. Army Engineer Waterways Experiment Station (WES) has been developing a computer program for forecasting wave spectra on a real time basis. The theory behind this model represents the best components of the various other available models. For example, there are several other models that are supposedly good predictors for fetch but not duration, and several that are good for duration but not fetch. If this is the case, then the WES model should give the overall best prediction in wave growth with respect to both time and distance, that is, to wind duration and fetch distance.

This model seems to hold great promise for future efforts in wave forecasting and hindcasting. By proper calibration of the model and verification of wind and wave data, it should represent an advancement in the state of the art on wave forecasting and hindcasting.

"An Evaluation of Two Great Lakes Wave Models," by Edward F. Thompson (1978)

Two operational numerical Great Lakes wave models are described in detail in this report and evaluated. One is a modern spectral wave model developed at the U.S. Army Engineers Waterways Experiment Station (WES) for hindcasting extreme historic wave conditions in the Great Lakes. The other model is a relatively simple significant wave model developed at the Techniques Development Laboratory (TDL) of the National Weather Service (NWS) for providing predictions to aid local forecasters in the Great Lakes area.

The evaluation of the WES model is based on a comparison of wave hindcasts for nine storms in Lake Erie during fall 1975 with Waverider accelerometer buoy measurements taken near Cleveland, Ohio and Erie, Pennsylvania. Evaluation of the TDL model consists of a comparison of forecasts during fall 1975 and fall 1976 with Waverider buoy measurements at the Lake Erie sites and at three Lake Michigan sites, near Holland and South Haven, Michigan and Michigan City, Indiana.

When all the data in this study are combined, the WES hindcast significant heights for specific times are generally within 0.5 meter (1.6 feet of gage significant heights), but occasional differences of over 1 meter (3.3 feet) are observed. The WES peak spectral periods for high wave conditions have a slight tendency to be shorter than gage peak spectral periods. The hindcasts, especially hindcast spectral shapes, tend to be more accurate for situations where fetches are reasonably well-defined than for situations where fetches are poorly defined and highly variable, with slight changes in wind direction. The difference may be systematic.

TDL-forecast significant heights have a strong tendency to be higher than gage significant heights, although there may be a reverse tendency during very high wave conditions. TDL-forecast significant periods are relatively unbiased but less variable than gage peak spectral periods. (Abstracted directly from the report referenced above.)

HURRICANE WAVE FORECASTING AND HINDCASTING MODELS

Early Work on Hurricane Wave Predictions

The art of wave forecasting as first introduced during World War II, and a report tracing its development was presented by Sverdrup and Munk in 1974. In 1944, Francis, Jr. presented a method for forecasting waves generated by tropical storms. (Report is out of print.) Otherwise, standard wave forecasting techniques based on constant wind speed and direction were adapted to the variable wind speed and direction for hurricanes. The following hurricane wave models have been developed.

The Bretschneider (1959) Model

This was developed as a very simple and useful formula for determining the maximum values of the significant wave height and period, which were related to the hurricane parameters R, or radius of maximum wind; ΔP, or central pressure reduction from normal; and V, the forward speed of the hurricane. The formulae were based on latitude $\phi = 35^{\circ}$, and suggested corrections were given for a latitude of 25°. In 1958 Bretschneider presented a generalized graph which could be used to estimate the hurricane wave field for a slowly moving hurricane, of the type that occurs in the Gulf of Mexico. This was a single direction model that was used quite extensively, but it has now been replaced with a more accurate two-direction variable wind model.

The Two-Direction Significant Wave Forecasting Model (Bretschneider, 1972)

This model represents the vector sum of two one-dimensional (variable wind) significant wave forecasting models. It is not a directional wave spectrum forecasting model. This model has been calibrated by use of North Atlantic wave data, and it was applied to the U.S. Weather Service hurricane wind model to obtain a hurricane wave field model. This was applied to Hurricane Camille (1969), and very good verification was achieved.

There was an error in the scale of the map for Shell Oil Company's Ocean Data Gathering Program (ODGP) location stations. This error was corrected and reported by Bretschneider (1978), and the revision was made for verification of Hurricane Camille, 1969. As a result of this corrected scale, there was found to be a far better correlation between the predicted significant wave heights and the measured significant wave heights. The hurricane wave model had previously been applied to all of the U.S. Weather Service standard project and probable maximum hurricanes for the Gulf of Mexico and the U.S. East Coast, and the corresponding values of the significant wave height and period were given in tables by Bretschneider (1972b). The two-direction significant wave forecasting model can easily be applied to extra-tropical storms; the two-parameter wave spectrum of Bretschneider (1959) can be applied to the significant wave height and period to obtain the corresponding wave spectrum for near or fully developed seas. In case of hurricanes, the three-parameter wave spectrum, which includes the correlation coefficient between wave height and wave length (wave period squared), can be used to estimate the wave spectrum for young steep sea waves, including hurricane generated waves.

The two-direction significant wave forecasting model can be put on a simple computer, and the computer cost is markedly less than the cost of beginning with the wave spectral model approach.

The Cardone, Pierson, and Ward Method (1975)

These researchers developed a method for hindcasting the directional spectra of hurricane generated waves. This method used hurricane wind and wave data, primarily from Hurricane Camille (1959), along with normal wind and wave data. These data were obtained from the Ocean Data Gathering Program (ODGP) for the Gulf of Mexico. A hurricane wind and wave model was developed and calibrated by use of the data. The so-called Pierson-Moskowitz (1964) wave spectrum was used together with the directionality as governed by the $\cos^2\theta$ law. The Pierson-Moskowitz wave spectrum is a special form of the two-parameter Bretschneider (1959) wave spectrum for a fully developed sea. North Atlantic wind and wave spectra data were used to calibrate the fully developed sea parameters, using the measured and/or adjusted wind speed to the 19.5 meter (60 foot) elevation. The $\cos^2\theta$ law of spreading was derived from measured spectra from Project SWOP (Cote, et al. 1960).

Fairly good verification was obtained between the measured significant wave height, H_s and the model wave period f_o^{-1} and that predicted by the model that was calibrated from the same data to be predicted. The wave spectra comparison indicated that the measured wave spectra was narrower and more peaked as compared with the Pierson-Moskowitz wave spectrum (the same is true for the 1959 two-parameter Bretschneider wave spectrum). There is no verification of the directional spectrum because it was not measured and could not be determined from the measured data. It is questionable whether the $\cos^2\theta$ law applies for hurricanes. (See Section 2.1.4 on Directional Wave Spectra.) There is need for directional wave spectra data under strong cyclonic storms such as tropical cyclones.

The Ijima, et al. Model (1968)

Ijima and his colleagues proposed a formula for hurricane wave fields, including the maximum values for significant waves. They used the same model hurricane wave field equation that was used by

Bretschneider (1972). However, to obtain the appropriate 10-meter level wind speed used in the wave forecasting relationships, they used a reduction coefficient of 0.6 instead of 0.865, as recommended by the U.S. Weather Service (0.885 for Zone B Gulf of Mexico). The procedures of the Ijima team for calculating the wave heights and wave periods also differ from that used by Bretschneider; the team first used the wave forecasting relationships given by Wilson (1955), but there is no argument here for the selection of one wave forecasting formula over any other. The real difference in the method is that Ijima and his colleagues made their calculations along a stream line, assuming that the predominant waves change direction as the winds change direction.

The Manabe (1966) and Manabe and Kawakatsu (1968) Model

This represents a very simple method for obtaining hurricane wave fields, based on a model hurricane in the laboratory as well as on field observations. The results relate maximum significant wave height as a function of the square of the maximum sustained wind speed, and the maximum significant wave period as a function of the maximum sustained wind speed. They then give a linear relationship for wave height and wind speed at one part of the storm between wave height and wind speed at some other part of the storm.

Duncan Ross, a simplified model for forecasting hurricane-generated wind waves. (Bulletin American Meteorological Society, January 1976, p. 113.)

Using this simplified model for forecasting hurricane-generated wind waves, observations of surface wind fields and wave spectra in Pacific Hurricane Ava were obtained from an aircraft. Surface winds were determined from 30-second averages of 150 and 3000-meter flight altitude observed winds, computed by an inertial navigation system and reduced to the equivalent 10-meter surface wind, assuming a logarithmic profile held to an altitude of 150 meters near the eye wall and to 500 meters at regions greater than 80 km from the eye. While a peak one-second gust of 68 m/s was observed during penetration of the eye wall at a flight altitude of 3000 meters, the above treatment resulted in a maximum 10 meter equivalent (U_{10}) of 45 m/s.

Observations of wave profiles were obtained by means of a laser altimeter and used for calculation of one-dimensional wave spectra. A remarkable feature of the spectra is the steepness of the forward face, which compared well with spectra obtained from other high wind fetch-limited studies and the JONSWAP spectral form, indicating that the wave field might be determined largely by the local wind and equivalent fetch. Thus encouraged, a data set from Hurricane Camille and the Ava data were combined and the total energy, E, and peak frequency, f_m, were non-dimensionalized in the JONSWAP manner and plotted against the similarly non-dimensionalized radial distance from the eye, R, which is proportional to equivalent fetch. A power law fit to the data yielded $\tilde{E} = 1.0 \times 10^{-4} (\tilde{R})^{0.26}$ and $f_m = 1.6 (\tilde{R})^{-0.25}$: The data scatter about the best-fit line in a manner which indicates quadrant effects were effectively parameterized.

The aircraft experiment is described in the report, and the model is tested against a set of measurements obtained in a subsequent aircraft flight into Atlantic Hurricane Eloise. (Abstracted directly from the Bulletin of the American Meteorological Society, January 1976.)

DIRECTIONAL WAVE SPECTRUM

Experiments and Laws

Project SWOP Directional Spectra (Chase, et al., 1957)

The first great experiment in the ocean on directional wave spectra was the photographic Stereo Wave Observation Project, known as Project SWOP, from which the $\cos^{2s}\theta$ law evolved, limited to the spreading range of $-\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2}$. The exponent, s, is frequency dependent, but it has been common practice to use $s = 1$ when applying this law, in which case 3/4 of the wave energy is resolved in the primary wave direction and 1/4 resolved at right angles, 1/8 to the left and 1/8 to the right. In the case of swell, $s - 4$ has been used, which gives 9/10 of the wave energy resolved in the primary wave direction and 1/20 to the right and 1/20 to the left.

NIO Directional Wave Spectra (Longuet-Higgins, et al., 1963)

The second great experiment in the ocean was made using the buoy-accelerometer technique. This project led to the $\cos^{2s}\frac{1}{2}\theta$ law, limited to the spreading range $-\pi \leq \theta \leq \pi$, where $s = 1$ to 4 and is frequency dependent, not exactly the same s as for the SWOP spectrum. For $s = 1$, for the NIO spectrum, 1/2 the wave energy is resolved in the primary wave direction and and 1/4 to the right and 1/4 to the left. The energy resolved in the primary direction increases with increase of s.

The main difference between the SWOP and NIO calculations has to do with the limits of energy spreading. As pointed out by Longuet-Higgins, et al. (1963), stereo photographic wave observations do not give wave direction but only alignment of the wave crests. For example, there is no way to distinguish direction between waves from the north and the south because the alignment would be east-west in both cases. The buoy-accelerometer experiment does make such a distinction, and thus provides directions which are true. The measurements of Longuet-Higgins show that there were waves traveling opposite to the wind direction. The $\cos^{2s}\frac{1}{2}\theta$ law does not include waves going opposite to wind direction.

Weibull Distribution Directional Wave Spectrum (Ou, et al., 1977)

Based on the data of Longuet-Higgins (1963), an attempt was made by Ou, et al. (1974) and Ou (1977) to improve the directional spreading function. This was done by assuming that the directional distribution of wave energy could be represented by a form of the Weibull distribution function. The data of Longuet-Higgins was reanalyzed to determine the parameter of the Weibull distribution function, relating s to a non-dimensional frequency. This is an improvement in that allowance is made for waves traveling opposite to the wind direction as observed in the NIO wave spectra. However, the method is not as practical as using the analytical expressions of the SWOP $\cos^{2s}\theta$ and NIO - $\cos^{2s}\frac{1}{2}\theta$ laws. It would appear that the NIO - $\cos^{2s}\frac{1}{2}\theta$ law is more accurate than the SOWP $\cos^{2s}\theta$ law, although the $\cos^{2s}\theta$ law is more practical.

It would appear that the NIO - $\cos^{2s}\frac{1}{2}\theta$ law is more accurate than the SOWP $\cos^{2s}\theta$ law, although the $\cos^{2s}\theta$ law is more practical.

COMMENTS ON WAVE FORECASTING MODELS

The various forecasting models have been briefly described, but certain comments are in order. The work of Resio (1979) using the results of Hasselman (1976) has recently advanced the state of the art. Of particular significance is the fact that Resio appears to have established the proper relationship, at least in part, for the generation of waves as a function of time. Whereas the previous significant wave methods of Sverdrup-Munk-Bretschneider, Wilson, and others used the so-called significant wave period time rate of growth as the parameter for wave generation, Resio uses the modal period of the frequency spectrum, that is, the period associated with maximum energy. The non-dimensional modal wave period (f_o^{-1}) determined by Hasselman (1976) has the following form

$$\frac{g f_o^{-1}}{2\pi U} = \frac{1}{7\pi}\left[\frac{gF}{U^2}\right]^{0.33}$$

and is thus related to approximately the 1/3 power of the fetch parameter.

The significant wave period relationship given by Bretschneider (1970) is related to the 1/4 power of the fetch parameter, and that given by Wilson (1965) to the 1/3 power of the fetch parameter.

Thus, there is convincing evidence that the wave period growth as a function of fetch distance is related to the 1/3 power of the fetch parameter, and that its integration with respect to time gives the proper growth rate for wave height, period, and the peak of the spectrum $\max S(f_o) = S_{max}$

However, the formulation of Resio is not yet quite complete, since it does not have an upper transition for large fetch parameters where further increase in fetch length and time will result in no further increase in wave height and period. The original formulation of Sverdrup-Munk-Bretschneider, Wilson, and others have such a transition with an upper limit.

Recent analysis of hurricane wave data for the upper limit shows that the complete formula for the generation of the modal wave period is given by:

$$\frac{g f_{o}^{-1}}{2\pi U} \cong 2.0 \tanh \left\{ \begin{matrix} .0235 \\ (.024) \end{matrix} \left[\frac{g F_e}{U^2} \right]^{1/3} \right\}$$

which reduces almost exactly to the expression used by Resio over the limited range of data given by Hasselman. A formula such as the one above can be used in the Resio model, and we can forget entirely about the significant wave period concept, except for those who still choose to use it. There is not too much difference between the significant wave period and the model period for many practical applications.

The wave height of $\sqrt{E}$ growth parameter of Resio varies as the square root of the fetch parameter, and except for the constant determined by Hasselman, is exactly the same as that given by Bretschneider (1959) for high wind speeds and short fetches used in the first hurricane wave forecasting model. However, for the general relationship, Bretschneider (1970) changed the exponent from 1/2 to 5/12 in order to obtain a better fit over the entire range of data, from the low-to-moderate fetch parameter through the transition zone to large fetch parameters.

The Resio model does not have an upper transition zone, but is limited at a cut-off, with the slope of 1/2 for the wave height - fetch parameter relations. However, the Resio model can be modified for the upper limits in a manner similar to that used by Sverdrup-Munk-Bretschneider, Wilson, and others, wherein Resio's relationship would become:

$$\frac{g\sqrt{E}}{U^2} = A \tanh \left\{ B \left[\frac{gF}{U^2} \right]^{1/2} \right\}$$

and for high wind speeds and short fetches (JONSWAP data of Hasselman expression)

$$\frac{gH_{1/3}}{U^2} = KAB \left[\frac{gF}{U^2} \right]^{1/2}$$

where AB = 1.27×10^{-3}, as given by Hasselman, and only the upper limit coefficient KA needs to be determined and is something like KA = .21, .26, .28, .30, as reported in the literature.

Finally, one of the important parameters which has not yet been given much consideration insofar as wave generation is concerned is the peak energy of the frequency spectrum, S_{max} or E_{max}. It can be shown by use of the Buckingham theory and dimensional analysis that the following functional relationship exists:

$$\frac{g^3 S_{max}}{U^5} = \psi \left[\frac{gF}{U^2}, \frac{gt}{U} \right]$$

Where S_{max} is the maximum and has the dimensions of (L^2T) or H^2sec (ft^2sec). For the two-parameter wave spectrum, the formula is:

$$S(f_o) = \frac{5}{16} e^{-5/4} H_s^2 f_o^{-1}$$

For short fetches and high wind speeds, there is an amplification factor, say G_F, such that the above expression can be written as

$$\frac{g^3 S_{max}}{U^5} = G_F \left[\frac{5}{16} e^{-5/4} H_s^2 f_o^{-1} \right]$$

and in functional form

$$\frac{g^3 S_{max}}{U^5} = K_1 \chi_1 \left[\frac{gF_e}{U^2} \right]^a \cdot \chi_2 \left[\frac{gF_e}{U^2} \right]^{2b} \cdot \chi_3 \left[\frac{gF_e}{U^2} \right]^c$$

where

$$G_F = \psi_1 \left[\frac{gF_e}{U^2} \right]^a$$

$$\frac{gH_s}{U^2} = \psi_2 \left[\frac{gF_e}{U^2} \right]^b$$

$$\frac{g f_o^{-1}}{2\pi U} = \chi_3 \left[\frac{gF_e}{U^2} \right]^c$$

$$K_1 = \frac{5\pi}{8} e^{-5/4}$$

In the above expression F_e is known as the equivalent fetch, or minimum fetch as limited by the wind duration.

Present analysis of a limited amount of data for high wind speeds and short fetches seem to indicate that a+2b+c = 1.0X 1/12, but passes through a transition and reaches an upper limit of $G_F = 1$. The JONSWAP data of Hasselman (1976) high wind speeds and short fetches used G_F X 1.4 to 1.45 and greater. Thus, C_F decreases slowly from low fetch parameters to high fetch parameters, having a slope relationship of about -1/6 to -1/12 with respect to the fetch parameter, depending upon what expressions are used for the wave height and period parameters.

Therefore, it is recommended that in further wave spectra data collection and analysis, determination be made for

$$\frac{g^3 S_{max}}{U^5} = \phi_1 \left[\frac{gF}{U^2} , \frac{gt}{U} \right]$$

as well as

$$\frac{g f_o^{-1}}{2\pi U} = \phi_2 \left[\frac{gF}{U^2} , \frac{gt}{U} \right]$$

$$\frac{g\sqrt{E}}{U^2} = \phi_3 \left[\frac{gF}{U^2} , \frac{gt}{U} \right]$$

$$\frac{gH_{1/3}}{U^2} = K_1 \phi_3 \left[\frac{gF}{U^2} , \frac{gt}{U} \right]$$

The shape factor, G_s, such as in the Hasselman JONSWAP spectrum or the Bretschneider (1959) three-parameter wave spectrum, can be obtained by curve fitting, using the above relationship and the fact that the area under the spectrum is given by

$$E = \int_0^\infty S(f)\, df$$

COMMENTS ON EKMAN WIND DRIFT AND WAVE MASS TRANSPORT VELOCITY

It seems worthwhile to make a few comments on wind drift current and mass transport velocity, since many users in the past have added wind drift current to orbital velocities to obtain the net horizontal particle velocities for calculating wave forces. It is totally wrong to add the wind drift current in this manner, because the mass transport velocity is already included in the wind drift velocity, or vice versa, by the very nature of current measurements and the determination therefrom of the wind stress drag coefficients. Such a procedure would thus be like adding mass transport velocity a second time. This is further complicated by the fact that measured current velocities also include components that are due to tidal and geostrophic flows.

The problem arises from the fact that the drag coefficient of wind on water as reported in the literature has been determined from direct measurements, without taking into account the wave mass transport velocity. Therefore, any theory thus far developed to calculate storm-generated currents that does not take into account wave mass transport velocity should be used with caution. One possible way to get around this is to calculate the mass transport velocity for the wave spectrum and subtract this velocity from that component in the wind direction predicted by use of the available wind current formulas. This net velocity would then be coupled with the wave orbital velocities calculated by higher order wave theory.

An alternative is to start from the beginning with the wave mass transport included in the equations. This was done by Korvin-Kroukovsky (1972), who found that pure wind drift was insignificant, but this was only for deep water conditions.

The problem for shallow water is far more complex, and considerably more theory and measurement will be necessary before a suitable prediction formula can be developed. It seems that Forristal (1974) would have had the right approach if he had included wave mass transport velocity for shallow water, similar to Korvin-Kroukovsky's approach for deep water. The air drag coefficient on the water surface needs a much better definition than is found in the literature. How much of the current is pure drift due to drag, how much due to wave mass transport, how much due to tidal flow and geostrophic flow? If all of the currents coexist in the measurements, then what is the meaning of the drag coefficient in terms of wind speed? The Von Karman wind profile and z_0 measurements would be a better way of determining the drag coefficient instead of using measured currents.

BACKGROUND PAPER III

MOST RECENT DEVELOPMENTS ON WIND AND WAVE FORECASTING

Marine Surface Windfield Analysis in Storms

By Vincent Cardone

Introduction

The need to describe accurately the temporal and spatial distribution of the surface wind over the sea arises both in the calibration of hindcast models designed to simulate environmental factors associated with storm conditions and in the application of the models to long meteorological series to provide a data base of environmental extremes for statistical evaluation. Specification of the most accurate windfield description possible is especially crucial in the calibration studies. There it is important to isolate errors in predictions of environmental factors (waves, currents, surge, etc.) which are model-related (physics, numerics) from those introduced by deficiencies in the input windfields. Of course accurate windfield specification is desired in long-term historical simulations, though the sparsity of historical meteorological data places an upper boundary on attainable accuracy. In lieu of high accuracy, it is important to determine the error structure inherent in historical windfield descriptions and the impact of those errors on the accuracy and reliability of environmental data generated by the hindcast model.

Methods of Windfield Analysis

There are three basic techniques available for specification of marine windfields: (1) use of wind models or parametric representations; (2) objective computer-based analysis of meteorological data; and (3) manual synoptic analysis. The method of choice in a given application depends upon several factors; these include the class of meteorological system under consideration and the type and quantity of basic meteorological data and the time and resources that are available.

Wind Models and Parametric Representations

These methods have been rather successfully applied in the specification of the surface wind in tropical cyclones, which comprise a very special class of storm. In most schemes, the surface windfield is specified from a small number of parameters which describe the storm motion, size, and intensity. Earlier methods were based upon simple empirical models, but recently numerical dynamic models have been shown to provide accurate cyclone windfields when initialized through parametric representations of the storm presure field. A significant new development has been the proliferation of accurate near-surface wind data in severe hurricanes. That data, available as a result of government buoy and aircraft-based programs and industry-sponsored offshore platform-based measurement programs, has allowed precise calibration of hurricane wind models in terms of a meaningful measure of the surface wind, namely, the time-averaged anemometer level wind. Further, recent studies have shown that for the U.S. Gulf coast, the conventional meteorological data available for most hurricanes of this century are sufficient to utilize the wind models for historical hindcast studies.

Parametric representations have not been especially helpful in describing extratropical wind systems. For such systems, the objective or manual methods are required.

Objective Analysis

Objective analysis methods were developed in the 1960s to satisfy the need for fast production, in real time, of fields of meteorological variables on grids for use in numerical weather forecast models. Objective analysis schemes for marine surface wind usually include a procedure for the specification of the sea level pressure field on a regular grid, enabling calculation of a windfield by the use of a transformation relating the surface wind to the local pressure gradient; tests to automatically screen a body of wind reports from ships to eliminate highly discrepant and presumably erroneous wind reports; and a method for blending the pressure-derived winds and the ship wind reports. The accuracy of objective methods depends critically upon the accuracy of underlying pressure fields and the amount of ship data available for use in a given analysis. Systematic errors can be minimized if recent theoretical and experimental results on the wind/pressure transformations are utilized and if ship wind reports are assimilated in a manner which treats accordingly the various types of wind observations made from ships. Objective methods require that marine pressure fields and ship data be in machine-readable form. This limits the ready application of the method to the last decade or so, since gridded sea level pressure fields (6-hourly, Northern Hemisphere) have been archived on magnetic tape since 1966. There is also a considerable amount of ship data which is not in machine-readable form.

Another type of objective analysis method is available for enclosed or semi-enclosed bodies of water surrounded by conventional land-based weather observing stations at which historical wind data series are available. The method involves the transformation of the synoptic wind data from coastal windfield stations to equivalent over-water winds, and the synthesis of an over-water windfield directly from the transformed winds. Recent experimental programs over the Great Lakes have provided reliable transformations, at least for measurement sites situated similarly. Transformed wind data are also useful to validate cyclone windfields produced from parametric models and as an auxilary data source for the manual synoptic analysis methods.

Manual Synoptic Analysis

The third method available for surface wind analysis is the classical subjective synthesis of discrete meteorological observations into a continuous field. Experienced, skilled analysts can produce accurate marine windfields by this technique, though it is more time-consuming than computer-based methods. However, manuscript analysis has certain advantages for historical storm windfield definition over other methods: (1) unrepresentative or erroneous ship reports can be screened more effectively; (2) ship data not at nominal synoptic hours can be incorporated into the analysis; (3) marine and transformed coastal wind data can be utilized whether or not the data are available in machine-readable form; and (4) by imposing continuity considerations, an entire sequence of wind analyses at discrete times in a specific storm can be assembled into a credible three-dimensional series. This capacity for space-time analysis has never been effectively implemented in objective schemes.

Historical Surface Marine Meteorological Data

All of the methods available for marine windfield construction rely directly or indirectly on the historical data base of ship reports.

Despite the efforts of national meteorological and climatic centers in the U.S. and abroad, despite the genuine interest taken by the World Meterological Organization (WMO) in marine weather data, no comprehensive file of historical surface marine observations exists today.

Perhaps the most extensive single archive of ship reports is the Marine Deck, compiled and updated at the National Climatic Center (NCC) of the National Oceanic and Atmospheric Administration (NOAA). This "deck," actually about 500 magnetic tapes, contains about 45 million ship reports from the period 1854 to 1972, sorted by 10° latitude/longitude (Marsden) squares. The Marine Deck results from merging punched decks of ship reports produced in this country and several foreign centers (mainly Germany, Great Britain, Japan, Netherlands, Norway, and USSR). The component decks were produced by manually extracting data from ship's weather logs received at national meteorological centers, usually within a month of their creation. These card decks cover various periods. For example, logs from U.S. merchant ships before 1949 were never punched and so are missing from the Marine Deck; however, an extensive collection of Japanese logs for the period 1933-1961 has been punched and is in the deck. Foreign programs are underway in Germany, Japan, and Holland; the punching program at NCC has recently resumed, and eventually the Marine Deck will include U.S. reports after 1972.

Another important source of marine data consists of ship's weather reports transmitted to shore in real time by radiotelegraph. The density of these transmissions is strongly dependent on local time; a night telegraph operator is a luxury foregone by many ships. No telegraph reports earlier than the mid-1960s exist in machine-readable form. They are to be found either on printouts of weather teletype transmissions or plotted on archived marine surface analyses that were prepared in real time at weather analysis and forecast centers, some civil, some military. From the mid 1960s onward, several centers have recorded on magnetic tape all transmissions of synoptic weather data, including ship reports, through the global weather telecommunications system (GTS); these tapes are archived at FNWC and NCC.

It is not generally realized that the ship reports in archives on non-real time sources (Marine Deck, foreign decks, manuscript logs, etc.) and of real time sources (GTS) are almost non-overlapping sets, so that their union is a much greater set than is available from any one source. Thus standard real time surface analysis charts, such as the 6-hourly "final analysis" series from the U.S. Weather Bureau, have relied on data sets severely limited by the constraints of real time analysis. Historical series such as the 24-hourly Northern Hemisphere surface analysis series also rest on data sets that predate the extensive international exchange of punched decks of marine surface data.

Recommendations

1. A greater effort should be made to synthesize the various international historical ship report data collections into a usable, centrally located machine-readable source. The WMO has established an international framework for exchange of data, but apparently lack of adequate support at the national level, at least within this country, has resulted in a deterioration of the efficiency of the marine data collection archival and distribution system.

2. More studies should be directed toward the derivation of the errors inherent in windfields produced by different methods

and for different historical periods in a given area. Those studies should seek to identify the most accurate analysis method for a given region and class of weather system and to quantify the impact of windfield analysis errors on hindcasts of environmental factors produced by hydrodynamic models.

3. Greater emphasis should be given to the acquisition of accurate and representative wind data as a part of all offshore measurement programs.

4. Studies should be directed toward the development of techniques to assimilate newer sources of marine data from buoys (NDBO) and satellites (e.g., Seasat) into surface windfield analysis schemes.

BACKGROUND PAPER IV

AN ASSESSMENT OF PRESENT METHODS FOR ESTIMATING CLIMATOLOGICAL SEA STATES

By Donald Resio

Introduction

Understanding of the physics of wave generation has increased markedly in recent years. Previous concepts of direct atmospheric input to all frequencies in the wave spectrum have been challenged by theories with indirect mechanisms involving conservative wave-wave interactions. Although many of the details of the physics are not understood at present, there is growing empirical support for these newer theories of wave generation. This might not seem to affect the prediction of wave parameters in actual practice, since such predictions are primarily based on observational, rather than theoretical, evidence. However, it can be demonstrated analytically that the energy transfer in a direct atmospheric input model cannot equal that in a model where the energy gain on the forward face of the spectrum is due primarily to wave-wave interactions. Hence, it is not reasonable to assume that all wave prediction models will produce similar results given the same wind conditions. This would seem to refute arguments that almost any wave prediction technique, properly applied, can supply a good climatological estimate of sea states. It is necessary to examine the interplay among various meteorological, oceanographic, and numerical factors in order to determine the effects of various combinations of data and wave models relative to errors in wave climate estimates. This is particularly true in the range of extreme wave conditions, since these are important relative to structure design.

Quality of Available Meteorological Input Data and Choice of Wave Model

Since all wave hindcasts begin with reconstruction of past windfields from historical records, a baseline error that is present in all final wave estimates is due to inaccuracies in available meteorological data. An implication of this might seem to be that where available meteorological data is of high quality, a wave model of high quality should be used, and that where available meteorological data is of low quality (or sparse in time and space), a simple wave model will suffice. This logic assumes that any errors introduced by the wave model should be of comparable magnitude to those implicit in the meteorological input. It is not at all clear, however, that this is a reasonable argument with respect to errors, since they tend to be additive. Thus, the rms error will be increased by $\sqrt{2}$ when a wave model with independent error characteristics of equal magnitude to the meteorological data is applied. If the error is already large, the additional 40 percent could be quite detrimental to the final results. Likewise, if a wave model is biased toward high or low results, the final results will contain this bias even if the original input windfields are unbiased; if both the input data and the wave model are biased, it is highly unlikely that their biases will exactly cancel.

Rather than pursue this line of argument, let it suffice to say that it is optimal in most cases, especially those involving large economic or environmental consequences, to minimize independently both the errors in the input meteorology and the wave model. Any statement to the effect that errors in results are dominated by errors in input windfields should be viewed skeptically unless fully substantiated by extensive testing and comparisons.

The Selection and Evaluation of Wave Models for Climatological Studies

Given that one is trying to select a wave model with minimal error characteristics, it is important to distinguish between those aspects of wave models which are well established by observational evidence and those which are based on theoretical extensions of basic concepts or perhaps less convincing observational data. The recent multinational experiment off the island of Sylt (the Joint North Sea Wave Project: JONSWAP), appears to have produced at least one result which can now be considered as being well-established: the growth of waves along a fetch under a uniform wind. This result can be summarized in nondimensional form as

$$(1)\quad \overline{H} = K_1 \sqrt{\overline{X}}$$

where K_1 is a constant, $\overline{H}$ is the nondimensional wave height, and $\overline{X}$ is the nondimensional distance along the fetch. These are defined as

$$\overline{H} = \frac{g\sqrt{E_0}}{U_*^2} \quad \text{and} \quad \overline{X} = \frac{g\,X}{U_*^2}.$$

where E_0 is the total variance of the surface elevation through time (multiplied by the specific weight of water, this would be the total energy of the waves), X is the distance along the fetch, g is gravity, and U_* is the friction velocity of the wind. Since this is a stationary process, it is not surprising that a self-similar growth regime appears to be established in this case, not only for wave height, but also for the wave spectrum.

The growth of waves through time under a uniform wind is a nonstationary process and it is not clear at present whether the pattern of growth follows a similarity law such as

$$(2) \quad \bar{H} = K_2 \bar{t}^{n}$$

where K_2 is some constant, $\bar{t}$ is nondimensional time ($=gt/U_*$), and n is another constant. Most so-called significant wave models are based on some form of (2) for duration-limited growth, usually with some additional function added to constrain the wave height within some limit. Spectral models are based on theoretical rates of transfer of energy from the wind to the water and typically do not follow a similarity growth law through time. Consequently, growth rates from different wave models differ markedly in their early stages. Only the widespread acceptance of a fully-developed spectrum forces the duration-growth relationships toward similar results at long durations. In terms of design parameters for offshore, the question becomes whether the design events are associated with very high winds and low duration or somewhat lower winds of longer duration. In any case, since differences by a factor of 2 in wave height are not uncommon for durations of the order of 10 hours, there can be little doubt that the careful application of dissimilar wave models does not always produce similar results. Since it is presumed that there is in fact only one right result for each duration-windspeed combination, the use of other relationships could introduce a significant bias into the climatological estimates, at least in the range of extreme values.

Review of Recent Developments in Wave Forecasting and Hindcasting

In the last few years, there has been a concerted effort in several countries to improve capabilities in modeling wave generation. As a result, there has been both an expansion of the understanding of the physics of wave generation and an improvement in modeling techniques. Earlier methods of wave modeling, such as SMB (after Sverdrup, Munk, and Bretschneider) and PNJ (after Pierson, Neumann, and James), essentially depended on relationships among nondimensional wave characteristics and nondimensional duration and fetch. Following initial efforts by Baer (1963), Pierson, Tick, and Baer (1966), and Barnett (1968), there have been progressive developments of spectral models which do not rely on specific nondimensional relationships. These models attempt to simulate the energy transfer from atmosphere to water, along with dissipative processes, by parametric representations of various source terms. Energy is gained or lost in each separate frequency-direction wave component according to the solution of the source term equation over each time step. For example, if the spectrum is discretized into 20 frequencies and 16 directions, each grid point in this type of a spectral wave model will contain 320 pieces of information that describe the distribution of wave energy in frequency and propagation direction. This is termed the two-dimensional or directional spectrum. If the directional spectrum is integrated over direction, the one-dimensional or frequency spectrum is obtained. Along with the source term integration, each component of the two-dimensional wave spectrum is propagated at each time step. The combination of good parameterizations of the source terms with efficient, accurate modeling techniques for integration and propagation are the major factors which can produce a reliable tool for wave prediction.

In light of the earlier discussion on wave forecasting techniques, it is apparent that the proliferation of wave models has still not answered some of the basic concepts such as time rates of growth under a uniform wind. Instead, most of these models are relatively unverified, and some can be shown to have serious theoretical or numerical flaws. As pointed out previously, it is imperative that, if a model is to be used for design considerations with important economic and environmental consequences, it should be thoroughly evaluated to determine the types and magnitudes of error that its application in a climatological study might produce.

The application of any recent wave forecasting models might produce adequate results for some purposes; however, all of them contain tacit assumptions about things such as spectral adjustments to non-uniform wind speeds and directions, the scaling of wave energy in the equilibrium range, and the directional distribution of energy in specific frequency bands. Since many design parameters are beginning to take account of the entire directional spectrum, these assumptions must be verified through comparisons to actual data. It should also be noted that for wave generation under non-uniform windfields, particularly regarding the adjustment of central wave angles and rates of growth, spectral models do not require the degree of subjectivity in application that the significant wave models do.

Conclusions and Research Priorities

1. There is a wide range of wave models available for application to hindcasting waves for design sea states. It is uncertain, however, whether any of these models has been shown to be accurate over the diverse set of generation conditions which might contribute to design considerations. It is not simple pessimism which leads to this conclusion. The lack of agreement

among various wave models even under simple windfields, and the lack of verification of these models under more complex windfields, make it virtually impossible to determine the expected wave model errors in a climatological simulation. Hence, a primary research objective should be the careful, objective testing of a number of wave models. This testing should be structured in such a manner that discrepencies between wave gauge measurements and model predictions can be stratified into different categories of generation conditions.

In spite of the negative tone of this discussion, it is highly likely that a very accurate wave model can be selected from available sources. The wealth of empirical data and the years of study of wave generation provide an excellent concept of what a reasonable wave height is for most generation conditions.

2. A second high priority research need concerns the effects of limitation of fetch width. At present, wave generation in narrow bodies of water (or along a coastline) is often treated as though it were equivalent to wave generation with unlimited fetch width, but with a scaled-down fetch. Given that direct wind-to-water energy transfer dominates wave growth, this seems a logical assumption. However, if wave-wave interactins play a dominant role in wave generation, it is no longer clear that the fetch should be scaled down at all. The consequences of the application of "equivalent-fetch" methods can be extremely significant for structure design near coasts or in regions such as the Beaufort Sea.

3. A third area that should be given a high research priority concerns the transformation of wave spectra and wave generation processes as one moves into shallower water. There is a great deal of research recently initiated to examine these effects, and many of the preliminary results do not substantiate previous techniques for estimating wave decay across shallow coastal areas. Since many structures along the Atlantic coast are presently planned in relatively shallow water, the proper understanding of shallow water effects is essential to analyses of the economic and environmental risk of different engineering designs.

BACKGROUND PAPER V

ABSTRACTS AND SELECTED LIST OF TECHNICAL REFERENCES OF DATA ON AVAILABLE WIND, WAVE, AND CURRENTS

By C. Bretschneider and H. Burkhart

There are two primary sources of wind and wave data: (1) wind and wave hindcast data; and (2) shipboard wind and wave observations. There are also wave records of short duration, but we have included only the references pertaining to the Gulf of Mexico Ocean Data Gathering Program (ODGP).

Data on currents is generally limited to U.S. Department of Commerce and Department of the Navy atlases on surface currents. Currents at various depths are generally limited to geostrophic and/or tidal computations.

Included are 33 references and corresponding short abstracts. This list is not necessarily complete.

REFERENCES ON SOURCE, TYPE, AND AVAILABILITY OF WIND, WAVE, CURRENT, AND ICE DATA

ABSTRACTS

1. Arthur, R. S. (1947), "A Statistical Study of Wave Conditions at Five Open Localities along the California Coast," Scripps Institute of Oceanography, Wave Report No. 68.

The study presented in this report of the characteristics of ocean waves off the California coast was initiated because (1) information as to prevailing wave action on the coast is needed in connection with engineering problems; (2) direct observations of waves at coastal stations are lacking; and (3) conclusions about wave action on the coast can be drawn if the offshore waves are known. The wave data have been derived by an examination of the wind systems of the North Pacific as they appear on daily weather maps from the 3-year period 1936-1938, inclusive. The results can be expected to give a fairly good repesentation of the average wave conditions, but do not include the most extreme conditions which may occur.

Only in one instance was it possible to undertake a comparison between the wave characteristics as derived from weather maps and the observed wave characteristics at a coastal station. In this instance the results were satisfactory.

2. Bretschneider, C. L., J. M. Cherry, T. K. Pyles, B. B. Scott, and E. E. Tamaye (1977), "OPSES-DEWAC Operational Sea State and Design Wave Criteria for Ocean Thermal Energy Conversion Projects; Offshore U.S.A. and along Equator from N20° S20° latitude," Vol. I. Literature available.

Project OPSES-DEWAC stands for Operational Sea State and Design Wave Criteria. This study includes the state of the art of available information on winds, waves, and surface currents for deep water conditions. The area of the study is limited to the coasts of the U.S.A., including Hawaii but not Alaska, and all ocean areas of the world from the equator to 20°S and 20°N latitude. Shallow regions over the continental shelf are excluded in the scope of this project. Thus, such effects as refraction, reflection, bottom friction, breaking wave criteria, etc., are not included in this study. Also, storm surge and tsunami effects are not included. These are conditions that must be evaluated in detail after OTEC site(s) is (are) selected, in particular, for design criteria for continental shelf and coastal structures as may be required.

Of the many references, 152 were selected as pertinent to the OPSES-DEWAC project. Many other references, either of local interest or papers and reports using the pertinent references, were generally not included, except for a few cases. Once the pertinent references were selected, the abstracts were prepared.

These abstracts were then used: (1) to prepare a code to distinguish between Primary (P), Secondary (S), OPSES (O), DEWAC (D), and Zones 1 thru 32 and (2) to prepare 32 circular sheets, one each for the 32 zones. The circular sheets also include a code for a rating of the references, as follows: two or more primary sources of data, complete (AA); two primary sources of data, almost complete (A); one primary source of data, partially completed (B); inadequate, no primary source of date (I); exceptions (E); strength (+) or weakness (-); and numbers that designate the reference as cited (1,2,3, etc.). At the bottom of each circular sheet evaluations are given for OPSES and DEWAC, together with recommendations.

After the circular sheets were prepared for each of the 32 zones, it appeared they were too subjective for the user. Thus, one step further led to the classification of OPSES-DEWAC data. The classification is less subjective and represents an opinionated classification, which should be of more value to the user. However, it is emphasized that the user can still have his own opinion.

3. Bretschneider, Charles L. and Roy Gaul (1955), "Wave Statistics for the Gulf of Mexico," U.S. Army Corps of Engineers, Beach Erosion Board, Technical Memos No. 85, 86, 87, 88, and 89.

Statistical summaries of hindcast wave data are given for a 3-year period for locations in the Gulf of Mexico of Brownsville, TX; Caplen, TX; Burrwood, LA; Apalachicola, FL; and Tampa Bay, FL, respectively. With the very shallow, gently sloping continental shelf of the Gulf of Mexico, waves occurring off any particular shore station will depend quite critically on the depth of water at the point of interest. Consequently, hindcast data are presented for five depths in addition to deep water (12, 24, 36, 48, and 96 ft. depths).

4. Bretschneider, Charles L. and W. C. Thompson (1956), "Dissipation of Wave Energy on Continental Shelf, Gulf of Mexico," Tech. Report No. 55-9T, Texas A&M Research Foundation, College Station, Texas.

Duration of winds for differing directions and cumulative duration of wind are given for 5 mph ranges of wind speed for Tampa, FL; Burrwood, LA; Galveston TX; Brownsville, TX; and Vera Cruz, Mexico. Additionally, individual duration of wind is given in percentage of a year by direction, and the cumulative durations are graphed. Wave statistics were determined from wind statistics.

5. Habel, John S. (1977), "Deep-water Wave Statistics for the California Coast," prepared by Meteorology International Incorporated of Monterey, CA, February 1977.

The program from which this compilation results was described in the paper "Ocean Wave Statistics for the California Coast" by John S. Habel, which appeared in the July 1977 issue of Shore & Beach. Statistics are presented for six stations in six volumes.

The ocean wave statistics that hitherto have been in general use by coastal engineers for the California coast were derived in 1960 and 1961 from 3 years (1956-1958) of synoptic weather maps. This work was carried out by National Marine Consultants (NMC) and Marine Advisers (MA) on behalf of the Department of the Army, U.S. Army Corps of Engineer Districts.

In order to extend the data base and provide a wider range of useful statistical formats, the Department of Navigation and Ocean Development (DNOD) of the State of California began work in 1975 with the U.S. Navy Fleet Numerical Weather Central (FNWC) and the Naval Postgraduate School (NPGS), both located in Monterey, California. In March 1976, Dr. Warren c. Thompson of NPGS prepared a document entitled, "Specifications for the Production of Ocean Wave Statistics for the California Coast from FNWC Singular Wave Analyses." These specifications formed part of a contract placed in June 1976 with Meteorology International Incorporated (MII), which was selected by DNOD to produce the required ocean wave statistics. The specifications called for ocean wave climatologies, specifically designed for coastal engineering applications and based on FNWC wave analyses, for six representative deep water stations off the coast of California, extending from the Oregon border to the Mexican Border. The results were to be presented in a series of six volumes, one for each station, with a common introductory text. This volume is for one such station. Price: $50.00 plus tax. Available from the California State Department of Navigation and Ocean Development, 1416 Ninth Street, Sacramento, CA 95814. Telephone: (916) 445-2615.

6. Hogben, N. and F. E. Lumb (1967), Ocean Wave Statistics, Ministry of Technology, National Physical Laboratory, England.

Ocean Wave Statistics is a book containing more than 3,000 tables of statistics based on over a million sets of visual observations of the heights, periods, and directions of waves reported, under a scheme organized by the World Meteorological Organization (WMO), from ships in service on the major shipping routes of the world over the 8-year period from 1953-1961. The wave statistics are listed according to a grouping of Marsden-Squares, arranged according to fairly homogeneous conditions within each area. The data are given in number of observations of given wave height and period, both in code. Correlation relations are given to convert this data to significant wave height and average zero crossing wave period. The correlation relations are based on a statistical least squares linear regression analysis between shipborne wave recorder data and weather ship visual observations, and also a correlation between weather ship visual observations and volunteer ship visual observations. The ship observations are along all major shipping routes except the North Pacific. The data is given for all seasons, all directions, all seasons with directional breakdown, and seasonal with directional breakdown. The data includes waves generated by offshore winds. Statistical methods may be employed to extrapolate the data in order to obtain design criteria. It is found that the reliability of the data is quite good. Comparison between observations and measurements show that agreement is quite close with wave heights, though somewhat less so with wave periods.

The book also points out that WMO, in its publication No. 100 TP 44, "Guide to Climatological Practices," divides the world's oceans into nine areas; for each of these, a particular member country is assigned responsibility for collection and dissemination of data. Engineers with particular requirements for data not available in published form can seek help from the appropriate meteorological agency in the relevant member country where access to the most up-to-date data can be provided and, if necessary, statistics for individually specified areas can be extracted.

6a. Hogben, N. (1974), "Five Minutes Slow After Six Years," in Ocean Wave Statistics, Ministry of Technology, National Physical Laboratory, England.

During the processing of the data for Ocean Wave Statistics, the twelve 30° direction classes were assigned code numbers 1 to 12 to be arranged like the numbers on a clock face, with 12 corresponding to North. Unfortunately, these numbers were decoded with 1 corresponding to North. Expressed more precisely, this means that throughout the entire book, 30° should be added to all the directions in the headings to every directional table. For example the heading "350° - 000° - 010°" should read "020° - 030° - 040°."

7. Marine Advisors (1961) "A Statistical Survey of Ocean Wave Characteristics in Southern California Waters." Prepared for U.S. Army Corps of Engineers.

The purpose of this investigation was to develop statistics which would present a detailed analysis by direction, height, and period of the frequency of occurrence of various types of ocean waves characteristic of Southern California waters. The method of investigation involved obtaining historical weather maps and/or weather records and information covering all significant wave-generating areas for the specified years, and then forecasting the waves which would have resulted according to Bretschneider's modification of the Sverdrup-Munk theory.

Forecasts were made for three definite locations, one of them exposure to open-ocean influences representative of conditions outside of the coastal islands and the other two representative of conditions in the protected waters near the mainland shore. The three categories of Northern Hemisphere swell, Southern Hemisphere swell, and Sea were investigated and discussed separately, with the data kept separate in the tables. The results presented include a series of tables which indicate the percentage frequency of occurrence of various types of ocean waves at the three selected locations off the coast of Southern California, classified by location, origin, direction, height, and period. The data are presented for each month, and an annual average is also included. Wave roses for each station indicated the annual average Sea, Northern Hemisphere swell, and Southern Hemisphere swell.

8. National Marine Consultants, Inc. (1961), "Wave Statistics for Seven Deep Water Stations along the California Coast." Prepared for the Department of the Army, U.S. Army Corps of Engineers District, Los Angeles. Santa Barbara, CA.

The work tasks covered in this report included a compilation of deep water wave statistics based upon meteorological records and charts for the years 1956, 1957, and 1958. The statistics compiled are wave height, wave direction, and wave period, and these are presented as monthly and annual averages.

The general area of study covers the entire coast of California and is represented by seven carefully selected deep water stations, including the area from the California-Oregon border to San Nicolas Island. Statistics on an eighth station are presented in a separate report.

The results presented in this report include average annual swell and sea roses for each station, as well as average monthly and annual sea and swell statistics.

9. Neumann, G. and R. W. James (1955), "North Atlantic Coast Wave Statistics Hindcasts by the Wave Spectrum Method," U.S. Army Corps of Engineers, Beach Erosion Board, BEB TM No. 57.

Detailed statistical wave data for deep water off the North Atlantic Coast, based on hindcasts from synoptic weather charts for the 3-year period 1947-1949, are derived by the wave spectrum method as developed by Neumann, Pierson, and James, for the same offshore stations for which data was developed in Technical Memo. No. 55. (See Abstract 4 above. The wave statistics are presented in parameters comparable to those previously derived by the Sverdrup-Munk method and given in Technical Memo. No. 55. Statistical methods can be used to extrapolate the data for design criteria.

10. Putz, R. R. (1952), "Statistical Distribution for Ocean Waves," Trans A.G.U. 33(5), pp. 685-692.

Statistical distributions of wave height and period are given based on analysis of 25 ocean wave records obtained along the California Coasts. Gamma-type distributions are given, which deviate somewhat from the theoretical Rayleigh distribution.

11. Reynolds, F. M. (1976), "Climatic Wave Statistics derived from FNWC," Synoptic Spectral Wave Analysis, Naval Post-Graduate School, Monterey, CA, M.S. thesis, 141 pp.

The U.S. Naval Fleet Numerical Weather Central (FNWC), Monterey, CA in 1974 put into routine operation a spectral ocean wave computer model that produces "real time" computations, termed analysis, of the deep water wave field in spectral form, 12-hourly, for a grid-point field covering the major oceans of the Northern Hemisphere. The wave field is computed in 3-hour time steps from the surface wind field, which in turn is derived from the observed sea level pressure field. The grid point spacing is approximately 150 nautical miles. Details concerning the FNWC Spectral Ocean Wave Model are given by Lazanoff and Stevenson (1975). (See ref. 15 and corresponding abstract.)

12. Saville, Thorndike Jr. (1954), "North Atlantic Coast Wave Statistics Hindcast by C. L. Bretschneider - Revised Sverdrup-Munk Method," U.S. Army Corps of Engineers, Beach Erosion Board, BEB TM No. 55.

Detailed statistical wave data for deep water, based on hindcasts from synoptic weather charts for the 3-year period 1948-1950, are presented for four stations in the North Atlantic off Penobscot Bay, Maine; Nauset Beach, Cape Cod, MA; New York Harbor entrance; and Chesapeake Bay entrance. An example of the method for obtaining shallow water wave data at a point between stations by interpolation and refraction analysis is worked out for Long Branch, NJ. The data are presented in tabular form, with significant wave heights and corresponding significant wave periods, number of hours occurring for each month of the year, and all onshore and parallel-to-the-shore wind speeds. Data is not given for offshore winds. The data are also presented in cumulative frequency graphs. The data are suitable for operational criteria and can be used for statistical evaluation for design criteria.

13. U.S. Naval Weather Service, Summary of Synoptic Meteorological Observations (SSMO) (1973), Vols. as listed below, U.S. Gov't. Printing Office.

Various tables of data are presented for each specific geographical area covered by the report. The tables appear for each month in the annual summary. Of interest to this project are the following:

> Table 3: Percentage frequency of wind direction (8 pts.) by speed and by hour (GMT). This table includes mean wind speed (knots) by direction (8 pts.).
>
> Table 4: Percentage frequency of wind speed by the hour (GMT). This table includes mean speed by hour.

Table 18: Percentage frequency of surface wind speed (knots) and direction (8 pts) versus sea height (ft). Source deck 128, for which data are available from mid-1963, was used for these tables. This deck represents the latest and most complete homogeneous source of wave data available. Here only sea waves generated by local winds in the vicinity of the observer are summarized.

Table 19: Percentage frequency of wave height (ft) versus wave period (sec). In this table, when both sea and swell waves are present in an observation, the higher of the two is used. If both are the same height, the longer period is chosen. When only one of the wave groups is observed, either sea or well, it is used in the summary. Swell waves are those generated by wind distant from the local areas where the observation is taken.

14. U.S. Navy; U.S. Government Printing Office, Marine Climatic Atlas of the World, (1955-74):

Vol. I, N. Atlantic Ocean (1955) (revised 1974)
Vol. II, N. Pacific Ocean (1958) (revised 1977)
Vol. III, Indian Ocean (1957) (revised 1976)
Vol. IV, S. Atlantic Ocean (1958)
Vol V, S. Pacific Ocean (1959)

Climatic data are presented by graphs, tables, and isopleths. Compilations of surface and upper-air weather observations are presented in separate sections. Individual surface charts for surface winds, gales, visibility, low visibility, precipitation, cloudiness, wind-visibility-cloudiness, ceiling and visibility, temperature, wet-bulb temperature, low temperature, sea level pressure, air-sea temperature difference, and low-pressure centers are given for each month. The wind distributions are presented by means of a combination of wind roses and a circular contingency table. The roses give the direction frequency and speed frequency. The circular contingency table serves to facilitate immediate reading of wind direction frequency and separates the selected class intervals of Beaufort force within which the percentage frequency for each direction and class interval of wind force is actually printed. A one-line table is printed below each rose that gives the percentage frequency of occurrence of each individual Beaufort force (2-9), all directions combined. Continuous records obtained from fixed ocean stations provide the information necessary for the graphs showing duration frequency and recurrence intervals for gales (≥ Force 8).

Revisons include wave period-height and direction-height frequency graphs and bar graphs, as well as isolines giving frequency of waves less than 1.5 and 2.5 meters and equal to or greater than 3.5 and 6 meters.

Oceanography includes seasonal presentations of prevailing surface currents and mean speed ranges (entire area and selected locations), tide types, corange lines, ice concentrations and extremes, and freeze and breakup dates.

15. U.S. NOAA, EDS, NDOC, Environmental Conditions Within Specified Geographical Regions - Offshore East and West Coast of the United States and in the Gulf of Mexico (1973), NOAA, Environmental Data Service, National Data Buoy Center, 1973, U.S. Department of Commerce.

Percentile occurrences of surface meteorological parameters in the American coastal waters are presented by month for subregions and miniregions. Included are air and sea temperatures, atmospheric pressure, wind speeds and directions, and ocean wave heights. Monthly roses of winds, seas, and swell are also reproduced.

Spectral values of ocean waves in 15 frequency bands for eight points in the western North Atlantic Ocean in the month of January 1959 are presented. These values are given as an aid to the engineering decision-making process in regard to wave sensor development and deployment. In addition, wave spectra graphics and one-dimensional wave height analogs are presented.

16. U.S. NOAA, EDS, Wind, Wave, Water Level and Air Pressure Measurements in Gulf of Mexico, (1960-1970), Ocean Data Gathering Program (ODGP) in Gulf of Mexico, as sponsored by Shell Development Co.; raw data and analysis filed at Environmental Data Service (EDS) of NOAA, Ashville, NC 28801 (also Washington, D.C. 20235).

Wind, wave, water level and air pressure as functions of time, measured at six offshore drilling and production platforms spaced along 260 miles off the coast of Louisiana during: winter storm, Feb. 1969; Hurricane Camille, Aug. 1969; tropical depression, Sept. - Oct. 1969; Hurricane Laurie, Oct. 1969; Hurricane Celia, Aug. 1970; tropical storm Felice, Sept. 1970.

EDS will provide separate reports for all six storms, as prepared by Baylor Co., Houston, Texas, on single roll of microfilm for $5, and all raw data on 252 magnetic analog tapes for $136 per tape, along with compressed time scale storm chart (direct read-out oscillograph) for additional $10 per tape (1975 prices).

Reports contain: wave power spectrum; significant wave height and period; maximum wave height and associated period; maximum gust; maximum sustained wind speed lasting for two minutes; average wind speed; significant direction of the average wind; average barometric pressure; and still-water level.

17. U.S. NOAA, NODC, Wind, Wave and Current Observations from Shipboard (1870 - date), National Climatic Center of NOAA, Federal Building, Ashville, NC 28801. (Also, National Oceanographic Data Center in Washington, D.C. 20235, which is part of NCC.)

Holdings date from 1870 and include several thousand pages of unpublished tabulations (computer-produced summaries based on older data files) and over 100 magnetic tapes containing over 100 years of wind observations and several decades of wave observations which can be provided in condensed form. Several operational programs are available for summarizing this information, and/or special programs can be prepared.

Information on over 4 million ship's sets of sea-surface current observations for the World Ocean can be provided on two highly packed magnetic tapes for $120. Files are maintained on current from drift bottles and current meters.

Visitors are welcome; staff assistance available at cost.

18. U.S. NOAA National Climatic Center (1975), Guide to Standard Weather Summaries and Climatic Services, NAVSIR-50-1C-534; available from National Climatic Center, Federal Bldg., Ashville, NC 28801. About 100 pp.

Part 1 contains descriptions of published and unpublished climatological summaries available from appropriate agencies in Federal Bldg., Ashville, NC.

Part 2 is a catalag of the "standard" summaries available, presented on a worldwide basis in continent-country-station order. Reference made to "Selected Guide to Climatic Data Sources" (key to Meteorological Records Documentation No. 4.11 of Environmental Data Service).

19. U.S. Department of Commerce and U.S. Department of the Navy, Climatological and Oceanographic Atlas for Mariners. Volume II, North Pacific Ocean, prepared by the Office of Climatology and Oceanographic Analysis Division, Washington, D.C. (1961).

Detailed historical wind data accumulated from 600-1000 ship observations is presented for each month of the year. Wind distributions are presented by means of a combination of two graphical forms, the wind rose and the circular contingency table. The circles serve as a scale marked at increments of 10% to ease reading of wind direction frequency, as represented by the length of each bar and as lines separating the selected class intervals of Beaufort Force within which the percentage frequency for each direction and class interval of wind force is actually printed. In addition, a one line table which gives the percentage frequency of occurrence of each individual Beaufort Force for all directions combined is printed below each rose.

Historical wave data is based primarily on observations compiled from 1854-1953 by the U.S. Navy Hydrographic Office and the U.S. Weather Service. The input was from ships in transit in the Northern Pacific. In addition, eight Ocean Station Vessels provided a network of regular observation records. The significant wave height data is presented in the form of isolines on charts of the North Pacific. Each season is represented by a separate chart, as is each sea state of waves 5 feet, 8 feet, and 12 feet. The isolines indicate the percentage frequency of waves at those heights. The direction of the waves must be inferred by the wind roses. This atlas may be purchased from the U.S. Government Printing Office.

20. U.S. Department of Commerce and U.S. Department of the Navy, Climatological and Oceanographic Atlas for Mariners, Vol. I, North Atlantic Ocean, Office of Climatology and Oceanographic Analysis Division, Washington, D.C. (1959).

Contains meteorological charts and historical wind data as described in Vol. II above. Oceanographic charts, seasonal roses, wave direction-height, graphics giving wave period height and period direction, and isolines of waves greater than 5 and 12 feet. Includes ice concentrations and extremes, freezeways, and breakup dates, iceberg reports, ship-structure icing, sea surface temperature, cotidal lines, types of tides, and surface current vectors.

21. U.S. Naval Oceanographic Office, Pub. No. 700, Oceanographic Atlas of the North Atlantic Ocean, Section IV, "Sea and Swell," 227 pp., Washington, D.C. (1963).

Covers the entire North Atlantic, including the Gulf of Mexico, Caribbean, the Mediterranean, and the Baltic the North Seas. Contains monthly charts giving wind roses (wind force by direction), sea state roses (sea state by direction), isolines (seas equal to or greater than 5, 8, 12 and 20 feet), predominant sea direction and constancy, swell roses (swell height by direction), isolines of swell equal to or greater than 12 feet, rose correction chart, and predominant swell direction and constancy. Contains seasonal graphs which give the persistence of waves equal to or greater than 6, 9 and 12 feet and less than 6, 9 and 12 feet for ocean weather ships and for lightships off the U.S. and European coasts. Includes seasonal graphs of wave height by period and wave period by direction. Based upon merged data from domestic and international sources, observation table is given for rose and graphic presentations. Contains bibliography.

22. U.S. Naval Oceanographic Office, Pub. No. 700; Oceanographic Atlas of the North Atlantic Ocean, Section I, "Tides and Currents," Washington, D.C. (1965).

Covers the North Atlantic Ocean, including the Gulf of Mexico, the Caribbean, the Mediterranean, and the North and Baltic Seas. Graphics cover types of tides and cotidal lines, typical tide waves for coastal regimes, tidal ranges by regions, and tidal stations by region. Graphics cover seasonal (summer and winter) vectors of prevailing surface currents, isolines of mean current speed in knots, and ocean current roses (current set by direction). Graphs are presented illustrating current profile with depth, vectorial illustrations of surface and subsurface currents for selected straits, and the Gulf stream profile and variability. Surface current vectors are presented, along with an excensive bibliography, and numbers of observations are available for each compiled current rose area.

23. U.S. Naval Oceanographic Office, H.O. Pub. No. 705, Oceanographic Atlas of the Polar Seas, Part II, Arctic, 150 pp., Washington, D.C., (1958) (reprinted 1968, 1970).

Contains charts and graphics based upon all domestic and international data available over the entire Arctic Basin in seven sections; supporting text and bibliography.

Section I: Tides and Currents - Tide type, cotidal lines, tide ranges, and general surface circulation for the entire basin and for bordering seas, straits and embayments, major vessel and ice island drift, and dynamic topography.

Section II: Physical Properties - Seasonal frequency curves of sea temperature and air-sea temperature difference; seasonal isolines of surface salinity and density; water color and transparency ranges.

Section III: Ice - Average and extremes of ice for 15-day periods, May through November; comparison of ice conditions and ice pack boundaries by season over about 5 years; freezeup dates and probability of superstructure icing by season.

Section IV: Wind, Sea, and Swell - Seasonal wind, sea, and swell roses, isolines of seas equal to or greater than 5 feet and swell greater than 12 feet wave period-height and period-direction graphs and sea heights for coastal stations.

Section V: Marine Geology - Geologic structure; rock types; bottom sediments; seismicity; volcanoes; tsunamis; gravity; magnetic variations; magnetic field intensity; daily range of intensity, and Auroral displays.

Section VI: Marine Biology - Distribution of fouling; marine algae and seagrass; distribution of marine mammals by month; and the Deep Scattering Layer.

Section VII: Distribution of Oceanographic Observations; bathythermograph and serial station observations; geographic location; and bathymetry of the Arctic region.

24. Naval Oceanographic Office, special Publications 1400, 1401, 1402, 1403, and 1404, Department of the Navy, Washington, D.C., 43 Regional Atlases, beginning in 1977.

Computerized replacement for old Hydrographic Office surface current atlases (HOP 566, 568, 569, and 570). Consists of 43 regional surface current atlases (not all completed) based on more than 4,200,000 set and drift observations. Compiled by month and by 1° ocean area giving total observations, calms, mean speed, vector resultant direction, percent frequency of and mean speed for primary and secondary direction and number of observations by quadrant. If there are more than 12 observations in an area, the data are assembled as a vectorial presentation giving persistent current, prevailing current, primary current, secondary current, bi-zonal flow, and variable current. SP 1400 - NA6, 1402 - NP6, and 1402 - NP9 cover waters off the U.S. Atlantic and Pacific coasts and the Gulf of Alaska, respectively.

25. Corps of Engineers, South Pacific Division, "Memorandum for the Record of Wave Data meeting" San Francisco, CA (1977).

Reviews a proposed Corps of Engineers West Coast Data (Wave) Collection System, including recommendations for standards. The proposal is for a 3-year wave measurement program at 100 locations covering the entire California coast. Data archiving, analysis, and monthly and yearly publication of spectral analysis, wave roses, maximum wave height, and wave height duration.

26. National Oceanic and Atmospheric Administration and University of Delaware, Proceedings of a Working Conference on Current Measurement, University of Delaware, 1978.

Conference convened to help determine need for currents, available and needed technology, and recommendations as to solutions to specific technology problems. Papers covered current measurement applications to scientific research, ocean engineering, environmental impact assessment, and operational surveys. Working sessions included opinions on the effectiveness and deficiencies of current measurement technology, specific limitations, and identification of tasks appropriate to limitations.

27. American Society of Civil Engineers, Ocean Wave Measurement and Analysis, Vols. I and II (1974).

Convened as a forum for researchers to exchange ideas on ocean wave measurement and analysis. Included sessions and papers on wave climate programs, retrieval and synthesizing wave data, remote sensing applications, instrument development, statistical analysis procedures, engineering application of wave data, wave direction measurement and analysis, application to refraction and velocity determinations, and analysis and application of wave data.

28. National Academy of Sciences, Ocean Wave Spectra, Proceedings of a Conference, Prentice-Hall, Inc. (1961).

A review of state of ocean wave spectra research, including various theoretical approaches to data measurement, analysis, and application. Participants included most scientists actively concerned with the potential of wave spectra.

29. Hoffman, D. and D. A. Walden, SSC 268 Environmental Wave Data for Determining Hull Structural Loading, Ship Structure Committee, Washington, D.C., (1977).

Reviews methods for obtaining visual and measured wave data, as well as wave hindcast techniques. Discusses theoretical spectral formulations, wave data from hindcast models (deep and shallow water models), prediction of wave loads, effect of format variation on load prediction, and wave data needs for design. Appendices include:

Index of Punched Cards with Wind and Wave Data
Sample Wave Observation Tables
Wave Measuring Systems
Catalog of References to Available Measured Spectra

Sources of Unpublished Measured Data
Catalog of Tucker Shipboard Recorded Data
Comparison of Draper and Spectral Methods of Analyses
Sample Measured Spectra
Ocean Wave Parameterization Techniques
Comparison of Wave Buoy, Wave Hindcast, Wave Spectra
Proposed South African Wave Measurement Buoy System.

30. Graham, H.E. and D.E. Nunn (1959) "Meteorological Conditions Pertinent to Standard Project Hurricane, Atlantic and Gulf Coasts of the United States," National Hurricane Research Project Report No. 33, U.S. Weather Service.

This report was prepared to provide generalized hurricane specifications that are consistent geographically and meteorologically for use in planning, evaluating, and establishing hurricane design criteria for hurricane protection works. The Standard Project Hurricane (SPH) indices were derived for use in selecting the standard project hurricane criteria for specific projects. The SPH index is the wind speed and direction pattern with specified dimension spans, and ranges of forward speed and direction of movement for a specific location. The meteorological characteristics and dimensions of the SPH indices are based on analyses of past hurricanes of record. The report presents analyses of the data which form the basis for defining the limits of the SPH indices. Various hurricane characteristics are correlated with intensity criterion, latitude, and other features. A generalized procedure for determining the SPH criteria is shown for the Atlantic and Gulf Coasts.

31. Schwerdt, Richard W., Francis P. Ho, and Roger R. Watkins (Sept. 1979), Water Management Information Division, Office of Hydrology, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, "Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Wind Fields, Gulf and East Coasts of the United States."

Criteria for determining wind fields along the Gulf and East coasts of the United States from Texas to Maine for the most severe hurricane reasonably characteristic of a region, Standard Project Hurricane (SPH), and for the hurricane that will produce the highest sustained wind that can probably occur at a specified coastal location, Probable Maximum Hurricane (PMH), are presented. A single limiting value for the meteorological parameters of peripheral pressure and central pressure was determined. Upper and lower limits were determined for the radius of maximum winds, forward speed, track direction, and inflow angle. Interrelations between the several parameters, latitude or longitude were investigated. Hurricane (through 1975) and typhoon (through 1974) data were used. An understanding of hurricane behavior through 1977 was used for studying and evaluating values of parameters for the SPH and PMH. Other necessary considerations for defining wind fields are covered in this report. These include the wind speed distribution and limits of rotation of wind fields. The study develops a meteorologically consistent set of criteria. This report is in more detail than the report by Graham and Nunn (1959) and includes about 20 years of more recent Hurricanes.

32. Wiegel, Robert L, Oceanographical Engineering, Prentice-Hall, Inc., (1964).

Basic reference for an understanding of the effects of dynamic forces on structure in the ocean, with emphasis on waves.

NOTE: Additional references not cited in the above abstracts are given subsequently.

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BACKGROUND PAPER VI

EARTHQUAKES

By P. Arnold

Introduction

A major source of uncertainty in the design of offshore platforms in seismically active regions of the world is the evaluation of the characteristics of possible future ground shaking.

While there are similarities between the methodology applied in evaluating environmental exposure for oceanographic and seismic threats, the earthquake problem has several significant aspects which distinguish it from the problem of predicting the occurrence of severe wind, wave, and current conditions offshore. One notable aspect is that the processes which govern the generation, transmission, and local modulation of earthquake ground motions at sea are such that significant differences in the severity of shaking can occur at sites which are relatively short distances apart. Thus, evaluation of earthquake risk is often best treated as a site-specific problem. This paper describes the basic elements of technology available for making a quantitative assessment of the severity of the earthquake hazard at a site of construction interest. The term "site seismicity" will be used here to imply a quantitative description of the seismic threat at a site of interest.

Site Seismicity

A site-specific approach carries with it the burden of explaining the cause and effect relationships which govern such spatial variations in the characteristics of ground motion, either theoretically or empirically. Another distinguishing aspect is that the occurrence of earthquakes is not a purely random process in either the spatial or the temporal sense. Details of the processes and conditions which lead to the generation of an earthquake are not yet well understood, but they are related to the faults and discontinuities of the earth's crust. Although it may be necessary or desirable to incorporate simplifications in the model developed to evaluate earthquake exposure, it is important to retain as many of the physical realities of the earthquake problem as possible.

The key elements in the process of selecting earthquake design criteria include the severity of the environmental hazard, the initial cost of the platform, the incremental cost associated with an increase in reliability, the nature and extent of the consequences if damage or failure were to occur, and the length of time the platform is exposed to the environment. These interactions can be balanced quantitatively to achieve the design objectives of economy and safety through the application of reliability or value analysis. The structural criteria, or design rules, employed in configuring and sizing the platform, provide the link between the severity of the environment and the reliability and cost of the platform, for they include the specification of materials, allowable stresses, analysis models, joint detailing, fitup, inspection and other construction practices which are employed. As noted in the text of this report, detailed reliability analysis may not be necessary to establish earthquake design criteria, except perhaps in instances involving a platform size or configuration or a seismically active region in which significant experience does not already exist. For a reliability analysis to be meaningful, all of the key elements of the problem must be identified and each contributing factor must be quantified in either an individual or an aggregate form.

It is essential that the type of platform be known during the process of evaluating environmental design criteria. This is especially true with regard to earthquakes. The notion of maximum oceanographic load is fairly straightforward, as it is mainly a function of the maximum combination of wave and current conditions and the geometry of the platform itself. In contrast, the maximum load experienced during an earthquake is strongly dependent on the stiffness, mass, and energy dissipation characteristics of the platform, as well as the severity of the quake itself. This contrast underscores another important difference between oceanographic and earthquake design problems. In the oceanographic case, loading is direct, whereas earthquake loading is, by its nature, indirect. An important implication of the indirect nature of earthquake loading is that the designer has the opportunity to exert more control over the actual severity of loading experienced by the platform than is generally possible under oceanographic loading conditions. This control is derived largely by varying the size and configuration of foundation elements. The foundation of pile-supported platforms generally contributes significantly to the flexibility of the overall system and can significantly effect the deformation and force transmission characteristics of the platform system.

To be useful as input to the selection of design criteria, the results of a site seismicity study must include a quantitative description of both the severity and the likelihood of occurrence of future ground shaking at the site. In addition, the characterization of the severity of ground motion must be readily translated into at least one format which is suitable as direct input to a structural design procedure.

The characteristics of earthquake-generated ground motions at a site of interest are influenced by a number of factors. Three distinct physical phenomena can be identified:

1. Source characteristics

2. Local site modulation effects

3. Source-to-site transmission and attenuation

Although this is a simplified picture of the complex energy release and seismic wave propagation phenomena associated with an earthquake, it provides a useful framework for developing a model for evaluating site seismicity. Important source characteristics include the type and geometry of faulting and the frequency of occurrence, location, and magnitude of future earthquakes. Local site modulation effects include the influences of local surface and subsurface topography and soil conditions in modifying the incoming seismic waves. Source-to-site transmission and attenuation is concerned with the characteristics of earthquake ground motions and their variation with distance from the site and the geologic conditions along the travel path.

Characteristics of Earthquake Ground Motions

In general terms, the intensity, frequency content, and duration of ground shaking significantly influence structure response. The importance of ground motion intensity should be obvious. Frequency content is important because the response of a structure is generally dictated by the amount of excitation energy at or near the structure's fundamental mode of vibration. In terms of damage potential, the response of structure and soil systems often depend not only on the amplitude of deformation but also on the cumulative number of deformation cycles, and therefore on the duration of shaking. The specific characteristics of earthquake ground motions that affect the response of an offshore platform are greatly dependent on the dynamic characteristics of the superstructure and foundation components of the system, as well as on the local soils, which both transmit to and absorb energy from the vibrating system.

A complete time history of motion for each of six degrees of freedom is required to fully describe earthquake shaking at any given point. However, even the most rigorous structure response analyses will generally be limited to three translational components of shaking. This is at least partly due to the fact that very little that is known about rotational components of shaking has been corroborated by field measurements. In numerical studies of site seismicity, the important elements of earthquake ground motions are most often approximated by parameters of acceleration time histories or by the peak response of simple structures. A variety of parameters will generally be required to develop a sufficiently detailed description of ground motion intensity. A comparison of the frequency content of ground shaking and the dominant periods of platform response can provide important insight as to the design relevance of a particular ground motion parameter. Although one parameter may provide more information than another, single-peak parameters alone (e.g., peak acceleration, velocity, and displacement) are not sufficient to completely describe the important characteristics of earthquake ground motions. Additionally, they are not generally suitable as direct input to an analysis of structural response. Since the designer is generally interested in the maximum value of some response quantity which can be related to stresses and displacements in important structural components, the earthquake response spectrum provides a more complete and useful indicator of ground motion intensity. Although these data are more cumbersome than single-valued ground motion intensity parameters, they are needed for estimating dynamic structural response when evaluating site seismicity.

Local Site Modulation Effects

Although not completely understood it is clear that local site conditions can significantly modify important characteristics of incoming earthquake motions. The influence of local soil conditions is primarily a function of the dynamic, cyclic stress-strain characteristics of the soil, the thickness of the profile (depth to bedrock), and the manner in which seismic waves arrive at the site. In some situations, the effects of local topographic and geometric features (e.g., large slopes, faults, and effects close to the edge of sediment basins) might also be important. Both analytical and empirical procedures for evaluating soil modulation effects have been developed over the past several years.

Although Kanai in Japan had conducted earlier studies of soil response using a viscoelastic representation of the soil, Seed and Idriss 1,2/ described the first technique which found wide acceptance for studying the effects of local soil conditions on ground motions. Seed and Idriss made two important assumptions to obtain a tractable solution to the problem of studying ground motion in soil deposits. The first assumption was that the horizontal motion in a soil deposit could be respresented solely by vertically propagating shear waves. This assumption is open to criticism since the pattern of wave propagation in soil deposits is certainly more complex than vertically propagating shear waves alone. The assumption, however, appears to lead to reasonable results with respect to the intensity of shaking in the few cases where observed field experience has been reconstructed.3,4/ The second assumption of Seed and Idriss was that the nonlinear strain history dependent properties of soils could be represented by equivalent linear properties. In using the equivalent linear representation of soil properties, shear moduli and viscous damping ratios are chosen for each layer in the soil profile that are compatible with the average peak shear strain induced in that layer by the earthquake motions. Laboratory cyclic loading tests of soil samples are generally used as the basis for establishing strain-compatible modules and damping values. Since the appropriate levels of shear strain are not known in advance, several iterations may be required to obtain compatibility.

A ground response analyses which assumes the vertical propagation of shear waves may produce results reflecting the effects of local soil conditions on the peak ground motion parameters that are in accord with specific observed experience. However, perhaps the greatest usefulness of such an analysis is the identification of the possibility of pronounced amplification (or deamplification) of the ground motion by a soil deposit.

Pronounced site amplification has been observed in the field. If structures founded on such soil deposits have natural frequencies similar to an apparent fundamental site period, a resonance condition may occur, with potentially damaging consequences. It is important to note that because of the nonlinearity of soil response, a fundamental period of the soil profile is not single-valued. While it may be a convenient notion, an apparent fundamental period will vary with the severity of shaking. It should be noted that the significance of the computed fundamental period of a site tends to be exaggerated by the assumption that the motions consist solely of vertically propagating shear waves. It also turns out that use of equivalent linear soil properties, which means that a single set of shear moduli and damping ratios is used throughout the record, tends to lead to overamplification of the peak surface acceleration and of motion around the fundamental period of the soil profile model.

As a consequence of the above observations, the use of equivalent linear properties in soil response analyses is now being superseded by the use of analysis models incorporating full nonlinear soil properties.5,6,7/ A variety of nonlinear soil models and solution techniques are available and additional developments may be expected.

Recent work by Seed, Ugas, and Lysmer,8/ Mohraz,9/ and others has led to the development of empirical response spectra for rock and several broadly defined categories of soil deposits. These response spectra may more correctly be referred to as "normalized" spectra because they are nondimensional and use some ground motion parameter (usually peak acceleration) as a scaling factor. These normalized spectra represent statistical averages of structural response amplification which have been computed from a group of records (generally between 5 and 25 records per group) falling into the same site classification. In practice, these spectra provide a simple means of estimating the ordinates of structural response spectra for a site of interest based on a predicted value of peak acceleration, which reflect the intensity of ground motion at the site, as well as the modulation effects of the local soil conditions. One limitation common to all the averaged soil amplification spectra described here is that since a single parameter is used for scaling, the shape (i.e., frequency content) of the resulting response spectrum becomes fixed for each site classification. Thus any influence which earthquake magnitude or source-to-site distance might have on varying the frequency content of ground motions is not reflected; these effects have been averaged out in the analysis process. Perhaps the most important limitation of empirical amplification spectra is the lack of actual field data of severe shaking (in which the nonlinear properties of soil response may be important) and on the profiles of soft, deep soil profiles which are characteristic of many offshore locations. In practice, the emphasis may vary, but it is generally prudent to combine both empirical and analytical approaches as a basis for judgment in evaluating the modulation effects of local soil conditions.

Source-to-Site Attenuation

Characterization of source-to-site transmission/attenuation effects provides the quantitative link between the earthquake source parameters and the characteristics of ground shaking at a distant site. In the intervening distance, important changes in the characteristics of shaking can occur as the result of geometric or hysteretic energy dissipation, seismic wave mode conversion, and other more complex phenomena along the travel path. Although the seismological community is developing analytical solutions for so-called dislocation models, nearly all available transmission/attenuation relations currently being applied in engineering practice have been developed empirically. Typically, these solutions are relatively simple functional relationships between earthquake size and source-to-site distance and some parameter of site ground-motion intensity. Most attenuation relations that are in common use incorporate earthquake magnitude and some distance parameter, such as epicentral distance or closest distance to the fault, as independent variables. The dependent variable is generally peak acceleration, peak velocity peak displacement, or some other quantitative measure of ground motion intensity such as the ordinates of structural response spectra. The coefficients of these empirical attenuation relationships are generally determined by regression analysis of measured data.

Since empirical attenuation relations are statistical in nature, they only provide an *estimate* of the relationship between earthquake source parameters and site ground-motion conditions. Even if the earthquake magnitude and source-to-site distance of a future event could be predicted with certainty, the corresponding site ground motion conditions are still not known deterministically. One characteristic which is common to all data used to define empirical attenuation relations is that the statistical scatter is quite large; therefore, the probability that actual ground motion parameters will be significantly different (less or greater) than predicted by the mean attenuation law is also quite large. In practical situations, the decision-maker may choose from at least two alternate ways of dealing with the large uncertainty associated with empirically determined attenuation laws: treat the uncertainty explicitly in a fully probabilistic framework or treat the mean attenuation plus 1 standard deviation or some other fractile as a deterministic relationship.

Recommendation of a particular attenuation relationship for general use in site seismicity studies is not possible at this time. A recent state of the art paper by Idriss10/ represents an excellent source for comparison and reference of many attenuation relationships which are available. The following criteria may be useful in the selection or development of attenuation relationships for site seismicity studies:

1. Select the ground motion or structural response parameters which are most relevant to the dynamic characteristics of the structure-foundation system being designed, and

2. Select or develop a relationship which is based on a data set which best matches local site conditions, the local/regional geologic and tectonic framework, the range of source parameters, and the distances of interest.

Spatial aspects of earthquake ground motions must also be given attention. Strong ground motions of engineering significance may be the result of contributions from several types of waves which arrive at a site from different directions and at different times. It is impossible to generalize as to which wave components are most significant; this will depend on many factors related to the characteristics of the earthquake source, the source-to-site distance, and the travel path, as well as the dynamic properties of the structural system to be designed. There is little doubt that the shaking at a point on the surface of the earth which results from an earthquake is truly three dimensional, involving three translational and three rotational components. There also seems little doubt that the charactristics of earthquake motions may vary significantly over relatively short distances, both on and below the earth's surface. In most cases, however, it is sufficient to describe earthquake shaking in terms of three orthogonal translational components of motion. For pile foundations, it may be desirable to account for variations in the amplitude and phase of ground motions over the length of the piles; however, to account for these variations with confidence implies a knowledge of earthquake wave forms which stretches beyond current practice. It is generally not necessary to account for variations over the horizontal extent of the platform foundation unless the horizontal dimensions of the foundation are a few hundred feet or more.

Hazard Assessment - Analysis Framework

The objective of a site seismicity study is to provide input to the process of selecting design criteria. To meet this objective, the assessment must provide a quantitative description of both the severity and likelihood of occurrence of future shaking which properly reflects important aspects of earthquake source characteristics, source-to-site attenuation, and local site modulation effects. Although details of the analysis procedures can vary widely, formal approaches to quantitative evaluation of site seismicity may be either probabilistic or deterministic, or some combination thereof.

In the deterministic approach the occurrence of one or more "critical" earthquake events is hypothesized. These events may frequently be characterized by such terms as "probable maximum" or "maximum credible." A maximum credible earthquake is generally an estimate of the largest event which can reasonably be postulated to occur on a given fault system, based on existing geologic and seismologic evidence. A precise estimate of the probability of occurrence of a maximum credible earthquake is rarely possible, but its probability of occurrence during the design lifetime of a platform is generally quite small. Ground motion at a site is estimated directly, for a value of magnitude assigned to the "critical" event, using a fixed relationship between earthquake magnitude, source-to-site distance and a particular ground motion parameter. Uncertainty in location of the seismic source and attenuation may or may not be accounted for in evaluating the corresponding characteristics of ground shaking at the site. This approach is often referred to as semi-deterministic in an effort to reflect possible inclusion of at least some elements of randomness. In its purest form, however, this approach amounts to earthquake prediction.

The fully probabilistic approach to evaluating site seismicity attempts to explicitly incorporate uncertainty in the time of occurrence, location, and magnitude of future earthquake events and source-to-site transmission/attenuation. The technique described by Cornell 11/ and conventionally referred to as "seismic risk analysis" provides a logical framework for evaluating site seismicity. The basic elements of the classical seismic risk analysis technique are described in a series of papers by Cornell 12/ and others.13,14/ Many earthquake engineering consultants and engineers have obtained or developed computerized versions of probabilistic seismic risk analysis models. A basic assumption normally made in the development of these models is that the occurrence of future earthquakes can be represented as a random process, with a constant mean rate of occurrence for events having magnitudes greater than some specified lower level of engineering interest. It is not, however, necessary to retain a fully random occurrence model in probabilistic seismic risk analysis.15,16/

Earthquake Source Model

Development of an earthquake source model is a crucial step in an evaluation of site seismicity, regardless of the analysis framework used. The degree of sophistication that is warranted in developing a source model will depend mainly on the level of seismic activity of the area, the type and amount of data which is available and the social and economic significance of the facility. Although the detailed mechanism of earthquake occurrence is not fully understood, it is known that on a global scale, most earthquakes occur within relatively narrow zones along the major tectonic plate boundaries. Earthquakes are especially frequent at boundaries where large continuous relative deformations occur between adjacent plates. Thus on a regional scale, seismic activity is generally a function of the amplitude and direction of relative movement along plate boundaries. In active regions, 80 to 90 percent of significant earthquakes are associated with identifiable geologic faults. Therefore, in evaluating site seismicity, it is generally acceptable to assume that major earthquakes occur as the result of the sudden release of accumulated strain in the earth's crust along an existing fault surface.

There are several important steps in the development of an earthquake source model. The first step is to identify and locate all faults in the vicinity of the site which are potential sources of major earthquakes. This step must include differentiation between "active" faults and inactive remnants of the geologic past. The next step is to quantify the spatial distribution of seismic activity of active earthquake sources. This amounts to estimating weighting functions which answer the question, "If an earthquake occurs, where is it likely to occur?" Finally, it is necessary to evaluate the driving parameters of the source model: answer the questions, "How often do earthquakes of engineering significance occur?" and "If an earthquake occurs, how big is it likely to be?"

There are several ways to evaluate the parameters of an earthquake source model, but they are generally based either on a numerical analysis of the historical record of earthquake occurrences or on a physical interpretation of the geologic record. Because the historical record is often quite short in the vicinity of offshore areas of interest, future earthquake activity generally cannot be confidently predicted by simply extrapolating the historic record of seismic activity. Ideally, both historic and geologic approaches should be employed and should lead to estimates of earthquake activity rate which are generally consistent with each other. As these approaches are often based on crude assumptions and use different types of data involving dramatically different time scales, the resulting rate estimates are not always consistent. Other special problems that will inevitably arise include the estimation of upper limit magnitudes and the treatment of foreshocks and aftershocks. These effects are most effectively addressed by geologists and seismologists experienced in the characteristics of the local tectonic/geologic setting.

In summary, the development of a source model for use in evaluating site seismicity should include identification of potential earthquake sources, a quantitative assessment of the level of earthquake activity in the region, the spatial distribution of activity between potential sources, and the relative distribution of earthquake magnitudes. Systematic development of a comprehensive source model permits the decision-maker to explicitly incorporate the expertise of experienced geologists and seismologists explicitly in the selection of earthquake design criteria.

Summary

The results of a site seismicity study should provide input to the design criteria selection process which includes a quantitative description of the severity and likelihood of occurrence of future earthquakes. The evaluation of earthquake hazards must recognize the important aspects of earthquake sources and mechanisms, source-to-site transmission/attenuation characteristics, and potential local site modulation effects. The development of a realistic source model is often the most difficult part of the problem; the importance of this step in developing reasonable and defensible earthquake design criteria should not be underemphasized. This is an area where the expertise of geologists and seismologists who are experienced in the geologic/tectonic environment of interest can be invaluable. The overall modeling and analysis effort should also incorporate input from platform designers and geotechnical engineers.

If modeling and analysis efforts are carefully performed, the results of a probabilistic seismicity study may be quite valuable in making quantitative assessments of risk. As in any analysis, the results are only as good as the assumptions. In seismic risk analysis, the estimates of probability are often quite sensitive to the assumptions made with regard to the parameters of the source model and the attenuation relationships used. As in any engineering study, the sensitivity of the results to key modeling assumptions should be determined.

In formulating a plan for carrying out a seismicity assessment, at least three important factors must be balanced:

1) The complexity and severity, in terms of design cost, of the earthquake hazard and the amount and type of data available.

2) The sophistication of the modeling and analysis.

3) The consequences of damage or failure of the platform system.

In order to provide self-checking and a feel for the reasonableness of the results, site seismicity assessments generally should include both semi-deterministic and probabilistic modeling and analysis techniques and a combination of empirical and analytical approaches to account for local site modulation effects.

Future Developments

It is believed that earthquake engineering technology, which exists or is currently under development will permit the prudent offshore operator to design and build platforms which will perform satisfactorily. In the face of uncertainty, safety is achieved through conservatism. Further improvements in our understanding of earthquake phenomena will provide a basis for improving the cost effectiveness of future designs. Table I briefly identifies some of the areas of technology in which improved understanding will be particularly significant to the design of safe and economical offshore platforms. Suggestions are included for focusing continued efforts in the areas of data acquisition and the development of improved analytical models and instrumentation systems.

TABLE I

FUTURE DEVELOPMENTS

DATA	INSTRUMENTATION	ANALYTICAL MODELS
Expand and maintain national strong motion instrumentation network in areas of high seismic activities and future frontier development areas where coverage is limited.	Improved power and performance reliability of strong motion instruments for long term (6-12 months) operation and hostile environments (e.g., cold regions and underwater).	Continue development and calibration of analytical models of earthquake occurrence and strong motion wave propagation) with emphasis on identifying and linking the parameters of earthquake source mechanism and wave propagation phenomena to ground motion parameters of engineering significance.
Special data needs are: -nearfield motions -horizontal and vertical arrays -offshore sites -very soft clay and saturated cohesionless sites -soil-structure interaction of structures supported on piles and large mat foundations.	Continue development of remote data acquisition hardware (e.g., marine acoustic transmission) with emphasis on data rate and reliability.	

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BACKGROUND PAPER VII

ICE RELATED ENVIRONMENTAL PROBLEMS

By W. F. Weeks and J. Ruser

Introduction

Fixed surface piercing structures have been utilized for oil production in Cook Inlet, Alaska for about 14 years. An unmarred structure safety record attests to the adequacy of the ice design considerations. Similarly, lighthouses and bridges piers constructed in ice-covered waters have generally performed satisfactorily, although there are at least two documented cases of lighthouse failure as well as numerous cases of ice-induced damage to bridges.

Design force levels for the Cook Inlet platforms represented a substantial jump in environmental force as compared to force levels for temperate climate structures being built at the time. Rather well defined ice conditions and a singular design ice-failure mode permitted the usage of temperate climate structural configurations, i.e., template type structures. Naturally, the structures were proportionately heavier to resist the higher loadings, and special provisions such as using low temperature steel and keeping all bracing below the ice line had to be made.

Although Cook Inlet has been termed an Arctic area in the past, the ice conditions there are substantially less severe than those in a truly Arctic area such as the Beaufort Sea. Without attempting to define the word "Arctic," it is fair to state that ice conditions become increasingly severe as one proceeds north through the Bering Sea, Chukchi Sea, and into the Beaufort Sea, where virtually all known ice features exist in large quantity and formidable size.

A legitimate first step in developing efficient structures for truly Arctic conditions would be to attempt to extend temperate climate technology to a level adequate to meet the Arctic environment. A number of industry studies have been directed to this end. As a result of these studies, it was soon realized that straightforward extensions of existing technology might not be adequate and that new and radically different structural configurations and design approaches might be needed. There is substantial interaction between ice as a loading mechanism and the structure it is loading. When this is coupled with other constraints, a high degree of design interrelationships results. In short, the task in the Arctic is not to design a structure to withstand the environment, but to interact properly with it.

Characterization of the Ice Environment

The primary distinguishing feature of the Arctic is its extreme cold. Subfreezing temperatures usually occur during eight months of the year, with extreme low temperatures of -40° to -45° not uncommon. Darkness accompanies the cold winter months and winter storms are frequent. Arctic summers (actually spring, summer, and fall) are short, with the period of above-freezing temperatures generally extending from June through September. The darkness, of course, is an operational nuisance, and the low temperatures must be considered in selecting construction materials that are resistant to low-temperature brittle failure However, it is the formation of the ice, an effect of the low temperatures, that causes the most concern for the designer and the operator.

An adequate description of the ice environment at any location includes many types of information. Here the discussion will be limited to major hazards limiting the design or the operation of specific systems. The hazards will be grounded in terms of the four ice-zones (open water, bottom-fast ice, floating-fast ice, and pack ice) that exist off most Arctic coasts and the specific systems that might be utilized in each zone. For instance, small fast ice movements, even if rare, are very important in protected near-shore areas because systems there may not be designed to withstand ice motions of more than a few meters. These motions are common further offshore, but relatively unimportant design-wise; there, structures must be designed for events exerting much larger forces.

A short assessment about the state of knowledge of each hazard follows. A more extensive description of ice hazards is found in the discussion of "Environmental Hazards to Offshore Operations Along the Coast of the Beaufort Sea" (Arctic OCS, 1978) and in the 1975 Alaska Oil and Gas Association Status Report on Arctic Research Requirements for Oil and Gas Operations in the Alaskan Arctic (AOGA, 1976).

Open Water

Hazards occuring in open water in arctic regions include the following:

Rapid encroachment of heavy pack ice into ice-free areas. Conventional marine transport, as well as the use of floating drilling vessels, is essentially restricted to ice-free sea conditions. If offshore pack ice were to move rapidly into an ice-free area, conventional ships would be unable to operate, could sustain hull damage, and might be pushed aground by the ice pack. The operations of floating drilling vessels are severely curtailed when ice could force a ship off its station above the drill hole. At best, the vessel would have to be prepared to rapidly disconnect from the drill-string and move off site.

Records have now been compiled of summer ice-edge locations in the Chukchi and Beaufort Seas. Operational forecasts are also made by both private and government groups of the movement of the ice edge. However, hindcast studies have apparently not been made for the "verification" of these predictive schemes (this is particularly true when the more modern ice dynamics models are considered). Moreover, satisfactory high-resolution remote sensing systems, capable of obtaining data under unfavorable atmospheric conditions such as clouds or darkness, have not been deployed in operational satellites. In addition, operational systems do not as yet exist for efficiently transmitting high-resolution real-time environmental data and ice forecasts to ship and offshore platform crews.

Thermal erosion of the coastline. Because the coastal sediments contain a large amount of ice, wave action may cause the rapid recession of exposed portions of the coast. For instance, bluff retreats of more than 60 m have been noted in a single storm. Protection of selected stretches of beach at pipeline crossings from erosion should not be difficult, although it clearly would be expensive.

Observations of coastal erosion rates based on the analysis of sequential series of aerial photographs are available as are direct measurements of headland retreat associated with individual storms. It would be desirable to develop a physical model capable of forecasting extreme erosion in order to predict the magnitude of such events from the characteristics of extreme storms.

Storm surges. Major storm surges are generated by westerly blows and generally occur near the end of the open water season, when the fetch (distance) between the land and the semicontinuous pack ice is at its maximum. The worst storm surge on record for the Alaskan Beaufort Coast occurred in September 1970. The surge height was 3 m and wave heights were also estimated at 3 m. Such extreme storm surges are believed to have recurrence intervals of between 25 to 100 years. Although these hazards are not strictly ice-caused, the magnitude of the surge is controlled both by the wind characteristics and the distance the main ice pack is located offshore. During these surges, the severe coastal erosion mentioned above occurs and all but the highest barrier islands are entirely awash and undergo considerable erosion (some small islands disappear completely.) Although these surges and the extensive ice are mutually exclusive, the strong winds invariably force old floe fragments to the shore where they "bang" against the coast with each high wave. Examples are known where ice fragments weighing several hundred tons have overridden small islands.

The times and magnitudes of several historic surges are known. As yet, however, existing numerical models of storm surge behavior have not been systematically applied to this record so that a suitable hindcast storm surge can be generated. From such a series, it would be possible to develop realistic probabilities of the frequency of occurrence of surges of various magnitudes.

Offshore permafrost. There is still question about the degree of hazard imposed by the presence of offshore permafrost. In general, at locations in the floating-fast ice zone, as well as further offshore, the top of the bonded permafrost is usually far enough below the sea floor so that pipelines and the foundations of offshore structures would be within the thawed near-surface layer. In the bottom-fast ice zone, the permafrost can extend right to the sea floor, and the presence of permafrost would definitely have to be considered in foundation and buried pipeline design. Also recent OCS studies have indicated that when the sub-sea sediments are tight (dense, highly compacted clays), permafrost may come up close enough to the sea bed to become a foundations problem, even at sites well off the coast. Whether these occurrences are common remains to be determined. Certainly site-specific checks for offshore permafrost will be necessary to assess the design and construction practices that will be utilized in various offshore areas.

When hot petroleum begins to flow from offshore wells, the heat will cause melting and produce differential subsidence within sub-sea permafrost. This is a problem that must be taken into account in the well bore design to prevent gathering system failures and serious production delays. Similar problems are taken into account in the colder "land-based" permafrost. It is probable that techniques developed for land-based permafrost will prove adequate for the sub-sea case.

Sufficient drilling has been conducted to provide a general pattern for the distribution and character of the offshore permafrost in the near vicinity of Prudhoe Bay. At other coastal locations, data on offshore permafrost are largely lacking. Present information indicates that the factors controlling the permafrost distribution are quite complex, including parameters such as the thermal history of the soil, the sediment grain size, and the porewater salinity.

Superstructure icing. Superstructure icing only occurs when high waves (spray) and subfreezing air temperatures exist simultaneously. Because a fairly continuous ice cover limits the presence of high waves, icing is usually not a problem in the Arctic. However, it can be a severe problem in sub-arctic seas because thick, very heavy masses of ice can build up rapidly on the upper portions of ships and platforms. If icing is not anticipated in the design of an offshore structure, structural failure of exposed portions of the superstructure of the platform could result.

Since superstructure icing is a severe hazard to the fishing industry, considerable efforts have been mounted to predict it. As a first approximation, the empirical icing correlations developed from these studies could be combined with statistical analysis of storm characteristics in the region of interest to make estimates of extreme icing events. Once offshore platforms are installed, they should be used as field sites to collect additional information on the problem.

Bottom-Fast Ice Zone

This zone is adjacent to the main coast and resticted to water depths under 2 m (i.e., locations where the undeformed ice becomes thick enough to freeze to the bottom.) In some locations along the coast of the Beaufort Sea, this zone may be several kilometers wide. When bottom-fast ice is discussed, it is generally assumed to be in an area where ice motions during the the winter are negligible.

Movement of thin and deteriorated fast ice. During the winter, when ice motions are small and the ice cover is thickest and strongest, systems such as grounded barges and artificial ice islands can be considered for use as platforms for both exploration and production drilling. However, as these systems are sensitive to lateral ice motions, it is important for the designer to know within well-defined limits the extent of the ice motions to be anticipated. Even though 2 m thick winter ice may be well-grounded and effectively motionless at a given location, this does not preclude the ice from moving in the fall before it is thick enough to be grounded or in the spring when it melts free from the bottom. In fact, most coastal near-shore ridges are composed of ice fragments that are less than 50 cm thick. This is an indication that the ice motions causing the ridge building occurred in the early winter. Moreover, ice motions of several tens of meters up and onto the shore are apparently fairly common in the spring, when the near-shore ice is weak and highly deteriorated. For both these cases, it is essential that the designer be able to calculate the forces exerted by the ice motion and the height of any ice pileups that would result. It is these considerations that govern whether the stability of a grounded barge or an artificial ice island should be enhanced by surrounding them with gravel berms or by other techniques.

The thin, newly formed ice of the early winter and the deteriorated ice of the spring may override gravel causeways connecting drilling sites. The forces resulting from such events must be known so that proper protection can be designed if feeder pipelines are to be built on the surfaces of causeways. At some sites openings may be provided in causeways to minimize their effects on local coastal circulation. Bridges spanning these breaks in the causeways would also have to be designed against ice override.

No data on the motions of ice within the bottom-fast ice zone exist in the public domain. However, proprietary information has been collected by company-sponsored projects. The results might well be highly site specific. For instance, significant ice motions in areas protected by barrier islands would probably be less likely than in areas where the near-shore ice can be subjected to direct pressure from the arctic pack.

Floating-Fast Ice Zone

This zone occurs just offshore of the bottom-fast ice and extends seaward for varying distances, depending upon the time of the year. Ice conditions within the fast ice zone can change dramatically from year to year, depending upon the forces and movements to which the weak fall ice is subjected. As the fall ice continues to thicken and strengthen, it becomes more resistant to deformation. Therefore, the potential for extensive deformation within the fast ice zone gradually decreases as the winter progresses. There is debate about the likely location of the outer fast ice boundary. Frequently, the boundary is assumed to be at the 20 m isobath, because often this water depth coicides roughly with the location of the edge of the fast ice during early winter. However, recent OCS studies have shown that the fast ice edge may lie well seaward of the 20 m isobath in late winter. For offshore resource development purposes, it is much safer and therefore more appropriate to select the 13 m isobath as the outer edge of the "stable" floating fast ice, since this boundary tends to separate regions where the fast ice is relatively undeformed from regions where encounters with very large moving ice masses can definitely be expected. Perhaps after more years of observation it will be safe to consider this boundary as being further seaward, especially on a site-specific basis.

Movement of thick, cold floating-fast ice. Anywhere within the floating-fast ice zone, large (100 m) movements of thick, cold sea ice are possible. Available information suggests that such movements are quite likely seaward of the barrier islands, becoming rarer between the islands and the coast. However, unless site-specific information is available to the contrary, drilling activities proposed for the floating-fast ice zone must be prepared to contend with such movements. Where such movements are known to be large, it may be desirable to utilize additional defensive structures to prevent ice from overriding sites. Also, precautions should be taken so that a blowout could be prevented if a site were to be destroyed by rapid ice movements.

Artificial gravel islands are the most likely platforms in the floating-fast ice zone; they have proven to be very effective under similar conditions north of the Mackenzie River. Other possibilities are cone-shaped gravity structures specifically designed to resist the forces which occur during ice movement and piling. Artificial ice islands or grounded barges may also be possibilities at locations where total winter ice motions are known to be small, if a "moat" is maintained or a gravel berm is built-up around the periphery of the site.

One important consideration is that south of the barrier islands large multi-year floes rarely occur, while north of the barrier islands multi-year floes of appreciable size (up to several hundred meters in diameter) may be common within the fast ice, particularly along the coast of the Beaufort Sea.

Observations of fast ice motion up to 6 km shoreward and up to 30 km seaward of the barrier islands of the Beaufort Sea have been recorded as part of the Outer Continental Shelf Environmental Assessment Program (OCSEAP). Net motions, greater than 60 m were noted, even in the vicinity of the islands. The OCSEAP field team also felt that during April 1976, if meteorological conditions had been only slightly more favorable (with stronger offshore winds of longer duration), the complete fast ice sheet north of the barrier islands could have broken off and rapidly moved out to sea (there were very few grounded ice features north of the barrier islands that year to aid in stabilizing the fast ice). Industry has carried out studies of fast ice motion during the last 3 years. Although most of their sites were south of the barrier islands in protected locations, they also obtained some data north of the barrier islands. This data is still proprietary.

Development of a model for predicting motions of the floating-fast ice from a knowledge of the state of the offshore pack and existing atmospheric and oceanographic conditions has not been attempted. The Cold Regions Research Engineering Laboratory (CRREL) at Hanover, NH which conducted the OCSEAP studies feels that this may prove possible only for large events of fast-ice motion, which fortunately are the ones of interest in designing oil-producing structures. (Small events appear to show little if any correlation with environmental conditions.) If a model could be developed, then it could be used in conjunction with past weather information to generate a time series of fast ice motions which could serve as a basis for design.

Pack Ice Zone

This zone extends seaward of the fast ice zone. For the purposes of this paper, the "southern" limit of the pack ice zone will be based on the typical ice conditions during the early winter (October-November). During this period, the fast ice forms within the barrier islands and extends north of the islands to approximately the 13 m depth contour. The extension of the fast ice to this depth is stabilized by the grounding of large masses of deformed ice. North of the fast ice edge, there is considerable crushing and shearing of the largely winter ice as the pack moves toward and along the coast. This zone, in which the ice is more deformed than the ice either nearer the coast or farther to sea, can be several tens of kilometers wide and is sometimes referred to as the "shear zone." Within the shear zone, the potential for significant lateral ice movements of more than a kilometer per day exists at all times of the year. The likelihood of movement is particularly high in the early winter and late spring. (As the thickness and strength of the ice increases during the winter, its susceptibility to deformation decreases.) During the late winter and early spring, the actual fast ice boundary may extend well seaward of the 15 m depth contour. The highly deformed landward portion of the shear zone commonly contains many large grounded ice masses and is referred to by various authors as either the "grounded ridge zone" or the "stamuki zone."

The characteristics of the shear zone are not well known because it is neither an easy nor an inviting place to visit. Its width is usually less than 100 km, and within the zone the degree of deformation of its ice is variable along the coast. Off the North Slope of Alaska, the degree of deformation appears to decrease as one moves west from Barter Island. It is the drifting and highly deformed ice of the shear zone that is found above much of the continental shelf off Alaska. A permanent structure for this ice zone would have to be designed to withstand the forces exerted by moving masses of cold, thick, first-year ice and by large first-year pressure ridges.

In the shear zone, design conditions would probably be governed by the possible interaction between offshore structures and the even larger and often more formidable types of ice masses that will be described below.

Multi-year pressure ridges. When a first-year pressure ridge is formed, the ridge is composed of a pile of ice blocks produced from the interacting ice sheets that "collided" to form the ridge. These ice blocks are poorly bonded together, and the ridge as a whole may have little structural strength. However, if a pressure ridge survives several summers, there is a gradual percolation of "fresh" water into the core of the ridge during the melting season. This water then freezes and gradually the pressure ridge is transformed into a massive, void-free, low-salinity ice body with high strength. To add to the difficulty, these ridges are commonly "embedded" in heavy multi-year floes which may have average thicknesses of as much as 5 m. These ridge-floe combinations can exert very large forces on an offshore structure.

In the last 10 years much has been learned about pressure ridges, particularly their general geometry and properties. For instance they can be very large, with reported sail heights and keel depths on free-floating ridges of 13 and 47 m respectively; their internal state is quite varied, depending upon age; their sail heights (and keel depths) exhibit negative exponential frequency distributions; and the frequency of their occurrence varies appreciably with location and season (and presumably from year to year). However, most of the laser and sonar profile data upon which these statistics are based were obtained from ice seaward of the shear zone. For the areas of the Beaufort Sea of interest here, frequency data on sail height distributions are only available for 1976 (February, April, August, December) and 1978 (March). Corresponding keel depth information is largely unavailable because the shallowness of these waters makes submarine operations difficult.

Furthermore, when ridge frequencies are tabulated from laser or sonar data, no method exists to separate first-year ridges from multi-year ridges. This is an important distinction because ablation may cause multi-year ridges to be smaller than first-year ridges. Also, ridge data are available only as a space series (ridge heights versus distance along the sampling track) as opposed to the more useful time series (the heights of ridges passing a given site as a function of time). The drift rate of the ice past the site must be known for this conversion.

Individual multi-year pressure ridges are a ubiquitous feature of multi-year ice and a definite hazard to offshore operations. However, recent studies have shown that even more decided multi-year ice hazards exist. For example, at certain shoal areas within the grounded ridge zone, large, elongated systems of shear pressure ridges form, with large ridges arrayed one after another like furrows in a plowed field. One ridge zone approximately 40 km long was observed off Oliktok Point in 1975 (see Kovacs, 1976, for the variety of imagery of such ice features). If these features survive several summers, large, thick, massive ice bodies result which can become ungrounded to drift along the coast. Although these ice bodies are not usually as impressive as ice islands (see below), they are a local product of the margins of the Arctic Ocean and must be dealt with when offshore structures are designed for this region. Moreover, when these multi-year shear ridge systems break up, they can produce large numbers of floebergs (fragments of multi-year pressure ridges), which in turn probably produce much of the ice-induced scoring of the sea floor.

It is now known that the formation of shear ridge systems is common off the North Slope of Alaska and that these features many times survive several melt seasons to become multi-year ice. Limited information is available about the geometric nature of the ice in these masses. Particularly lacking is quantitative information on the number of these ice features and their size distributions. If these data and related motion data were available, then the probability of encounters between fragments of ridge systems and offshore structures could be calculated.

Ice islands. Tabular icebergs produced by the calving of ice from the Ellesmere Ice Shelf are called "ice islands." The shelf itself is 35 to 60 m thick, and the resulting ice islands can be quite large (for instance, island T-3 had "initial" dimensions of 6 x 14 km). Once an ice island forms, it drifts southwestward along the coast of the Canadian Archipelago and northern Alaska, where it enters either the clockwise drift of the Pacific Gyral or the northward motion of the Transpolar Drift Stream. Ice islands caught in the Transpolar Drift Stream may leave the Arctic Ocean within 3 years. Ice islands in the Pacific Gyre may circulate for decades. During this clockwise drift, these ice features may pass along the coast of the North Slope many times, gradually thinning, with many ultimately breaking into ice island fragments. These fragments, with typical lateral dimensions of 30 to 100 m and thicknesses of 12 to 30 m are most commonly found off the North Slope of Alaska (Kovacs and Mellor, 1974). The ice in these fragments is quite strong. An offshore structure would probably be destroyed in the event of a collision with a large ice island, particularly if the island was imbedded in and carried along by heavy pack ice. Designs should preclude an oil spill even in the case of such an unlikely event. A much more likely event is a collision with an ice island fragment which would not necessarily produce a failure.

The general characteristics of ice islands and their fragments are known. However, considerable information that could be useful to the designer is still missing. For instance, little quantitative information exists about their size distribution, numbers, degradation rates, production rate from calving in the Ellesmere Shelf, and the break-up of preexisting ice islands compared with the rate as they leave the Arctic Ocean. In short, realistic estimates of encounter probabilities between offshore structures and ice islands cannot be made at present. Photographic missions conducted by the oil companies in 1972 indicated the presence of at least 400 ice islands along the Alaskan coast. Recently ice island sightings have apparently been much less common, although no comparable photographic search has been carried out. Pertinent questions include: When will the next major calving of the Ellesmere Shelf occur? Will a large ice island drifting offshore (such as T-3) break up, producing shallower draft fragments capable of reaching sites nearer the coast before grounding?

Icebergs. Icebergs are fragments of glacier ice (other than tabular fragments of the Ellesmere Shelf) drifting in the sea. Fortunately, they are not a problem along the margins of the Arctic Ocean. However, they do present severe operational problems at locations such as Baffin Bay, the Labrador Sea, and the Grand Banks.

As compared with our knowledge of ice islands, there is an abundance of information available on icebergs because of the data collection program of the International Ice Patrol. Encounter probabilities with offshore sites can be estimated. Also, at many locations the iceberg hazard occurs in either very open pack ice or in open water, making the towing of icebergs "around" a structure a definite operational possibility.

Scoring of the sea floor by ice. Scoring of the sea floor by pressure ridge keels and by ice island fragments is a phenomenon that also must be considered in the design of offshore structures in the Arctic. If blow-out preventers and feeder pipelines are not buried below the maximum expected gouge depth or "armoured" to protect them against the drifting ice masses, they can be plowed up by the ice. Another related but poorly investigated problem is the possibility of rapid erosion of sediment around the foundations of offshore structures by the ice debris formed when pack ice breaks against the structures. Scoring can occur in all water depths of less than roughly 50 m. However, score depths vary depending on ice zonation, bottom morphology, and sediment type. Burying an offshore pipeline so that it is always at a depth exceeding the maximum observed score (currently a value in excess of 6.5 m) would be grossly overdesigning most lines. Clearly, high resolution, site-specific information on score characteristics, bathymetry, and sediment type can result in large savings in offshore construction costs.

Ice score densities, incision depths, and dominant score trends are fairly well known for the region between Cape Halkett and Flaxman Island inside the 15 m isobath. However, information is scant for deeper water and in the eastern and western portions of the Beaufort Shelf. Data from the Chukchi Sea are also limited. Score depths are generally greater than 1 m within and seaward of the grounded ridge zone and less than this value nearer the coast. Extreme values observed so far are 4.5 m for the Chukchi Sea, 5.5 m for the Alaskan sector of the Beaufort Sea, and greater than 6.5 m north of the Mackenzie Delta. Scoring appears to occur at all times of the year. There are still major uncertainties about the frequency of scoring at different sites. For example, it is not known whether the score record "seen" on the bottom represents tens or thousands of years. Also, the available data have apparently not been tabulated so that the frequency distributions of score depths and score numbers can readily be examined as a function of location. Therefore, it is still not possible, even at sites where good data is available, to make an adequate risk analysis based on depth of proposed pipeline burial vs. the expected lifetime of the line.

Ice Forces

A number of impressive ice-related hazards to offshore development in the Arctic have been listed. Assuming that enough is known to specify the frequencies of occurrences of these different hazards, the designer must be able to confidently translate these recurrent events into ice forces that will be exerted on the structure of interest. This process is far from well understood. Sea ice is a highly non-linear material, with its mechanical properties functionally dependent on at least its temperature, salinity, crystal orientation, confining stress, and stress or strain rate. Temperature and salinity are in turn primarily dependent on the conditions of ice growth. Also, the upper portions of sea ice masses are commonly cold (and strong), while the lower portions are warm (and weak). Therefore, it is difficult to characterize a relevant strength property with a single value that can be used for design purposes. Even the limited laboratory investigations of the small scale strength of ice have drawbacks. They have commonly been limited to simple stress states; many parameters known to affect strengths in other materials have been inadequately investigated (e.g., grain size, strain rate, and precipitation of new phases); strong crystal orientations recently found to be common in coastal ice make the interpretation of many past field studies of strength uncertain and make difficult the application of measurements of laboratory-grown ice to the field situation. Also, no reasonably complete failure model is available to help define and interpret the appropriate basic ice-property tests. Perhaps even more important is the difficulty in making the transition from the forces exerted on a geometrically simple small-scale sample to the forces exerted by irregular ice masses on large diameter structures.

Sea ice forces on permanent offshore installations can be separated into two categories: (1) the force required to fail the ice cover; and (2) the force required to dispose of the broken ice once it has failed. The force required to fail sea ice is highly dependent on structural geometry. Aside from the shape of the structure at the water line, the slope of the surface-piercing elements can change failure modes from crushing to bending to combinations thereof. Moreover, the forces associated with these failure modes can be substantially different. The net result is that no single force algorithm can be developed for all types of Arctic structures or, for that matter, even a given class of structures.

A higher degree of design interdependence exists for Arctic structures than for structural design in temperate climate offshore areas. For example, the loads to be supported by the structure determine to some extent the minimum waterline geometry of the structure. This geometry affects ice force as well as the amount of volume available with which to achieve weight in the case of gravity structures. The plan of the structure at the mudline and the estimated on-bottom weight determine foundation resistance. If this resistance is not sufficient, then the design process must begin again with altered geometry, new forces, changed weight, etc.

Ice management, that is, the efficient disposal of broken ice, is the second component of the sea ice force problem. However, the same arguments presented in the discussion of breaking sea ice apply. The problem is highly dependent on structural geometry. An optimum geometry guaranteeing a smooth flow of ice on or around the structure must be sought. The iterative process applied here must operate in parallel to the breaking force problem.

Although the history is short, tradiorally the development of force algorithms has proceeded from the study of small-scale model test results. Failure modes are determined for these studies and are used in the development of analytical models. The analytical models can be calibrated against intermediate or large scale test results and then be used for system design. A different structural geometry may arise from the design study; and a reverification of fundamental failure modes would them be necessary with small-scale model studies. Thus, the development of accurate force-algorithms represents an inner iterative loop to the overall design process discussed above.

Exposure Characterization

The environmental exposure for Arctic structures can be expressed in terms of the probability of occurrence of a specific ice feature and a probablistic description of the geometry and strength of the feature. In a sense, the ice management problem discussed above can be viewed as an exposure problem, but the extent of exposure is a function of the structural type and the design process.

With regard to occurrence probability, it would appear that the permanent polar pack essentially represents, a "frozen history" of all possible design conditions. In other words, in all probability the maximum ice feature with respect to forces on a structure can be found somewhere in the pack. Theoretically, beyond a certain water depth, a structure would be exposed to the maximum feature. In reality, some locations would be more sheltered than others because of coastal boundaries, prevailing currents, etc. Hence, the encounter probability must be established by considering and surveying the exact location of the structure. Shallow water depths, of course, limit or reduce to zero the encounter probability of the maximum feature.

Geometric statistics of the ice, on the other hand, must be established by measurements of feature geometry on a regional basis. That is, there is no reason to expect that a first-year ridge created in the middle of the pack is fundamentally different from a ridge created in a coastal zone (grounded ridges, however, do have higher sails than non-grounded ridges). Thus, the establishment of a sufficiently large data base should permit the development of geometric statistics.

While the strength of an ice feature, both in a gross and a microscopic sense, is unique, a similar feature, that is, one with similar geometry, formation history, and aging history, should have the approximately the same strength. The establishment of a strength characterization then is in reality a survey of the variability associated with geometry, mode of formation, and aging history. A problem exists, however, in strength characterization because strength is usually measured on a microscopic scale, and as mentioned previously, substantial variabilities result from different test techniques and intepretation of resulting data.

Regarding environmental exposure in general, it can be stated with some certainty that structures in Arctic waters have an appreciably higher environmental exposure probability than structures in temperate climate offshore areas. As an example, a structure in the Gulf of Mexico has low annual encounter probability for the maximum hurricane-generated wave. In fact, the structure may be in operation for 20 years and never experience its design condition. On the other hand, an Arctic structure in, say, 5 m of water would be designed primarily for annual sheet ice forces. For practical purposes, the probability that sheet ice will grow in the area in any given year and load the structues is 1. Hence, the environmental exposure of the Arctic structure is high. The same can be said for deeper-water Arctic structures. However, for this circumstance a special ice feature would likely control the design, and the encounter probability for such a feature would be lessened with respect, for example, to sheet ice. But it would not be lessened, in all likelihood, to the degree of probability associated with temperate climate design, so that a high environmental exposure characteristic would still exist.

Variability and Uncertainty

The Arctic Sea ice environment has been characterized above by the occurrence, geometry, and strength of ice features. Of these, the greatest degree of natural variability is associated with geometry and gross strength of ice features. Obviously, ridges can have keel depths which range from theoretically zero to the measured maximum given previously. More importantly, gross strength can be highly variable; a prime example is a first-year ridge which is only partially congealed. The gross strength in combination with structure geometry determines failure modes, which must be faithfully modeled in force algorithms. The variability associated with microscopic strength measurements, from which gross strength must frequently be inferred, is a combination of natural variability and professional uncertainty in the interpretation of strength measurement results.

Variability associated with occurrence can be either high or low, depending on design circumstances. A case of low variability was discussed previously for an Arctic structure in 5 m water depth. For deeper water applications, ice islands may well be the controlling loading mechanism. However, with respect to other ice features, the ice island population is relatively small, which would result in a highly variable but still low encounter probability.

As mentioned above, professional uncertainty exists about ice strength. A primary source of this uncertainty lies in the difficulty of developing force prediction algorithms. This uncertainty is not a reflection on professional competence, but rather results from the high degree of design interrelationships present in Arctic design. The uncertainty can be substantially reduced when specific circumstances are considered, i.e., a given water depth, a specific location, and a specific structural type.

Research and Development and Data Needs

Many R&D data needs exist that, if met, would help solve the challenging and varied problems of offshore design for the Arctic. Several of the more important areas where increased understanding would significantly assist the practicing engineer are described below.

Ice Strength

A knowledge of the variations in the strength of sea ice as a function of ice thickness, temperature, salinity, internal structure, and loading is essential for estimating the forces exerted on offshore structures. Data on ice strength do, of course, exist. However, much of this is of questionable quality, either with respect to the testing techniques that were used or the adequacy with which the state of the ice was specified. There is need for both high quality field and laboratory studies. Also, there is a need to subject the available test data to critical analysis and interpretation, by authorities experienced in both reliability considerations and in criteria requirements for the design of offshore structures (AOGA, 1976).

Ridge Strength

The ice in ridges is composed of varying sized blocks of deformed sea ice that gradually freeze together into a cohesive mass. Studies should be carried out concerning the state of the ice in the blocks and the degree of interblock bonding and "consolidation." The purpose of this work would be to develop characteristic measures of the gross strength of the ice in ridges as a function of the type of ridge and its history. Of particular interest would be additional knowledge about the state of the ice in the lower two-thirds of large multi-year ridges.

Statistical Characterization of the Geometry of Ice Deformation Features

First-year and multi-year ridges and systems of ridges are considered to be a primary loading mechanism for Arctic structures. Statistically sound estimates of the frequency of occurrence of large ridges and their geometry are necessary for input into force prediction algorithms. While a number of first and multi-year ridges have been profiled, this data base is too limited in time to establish the effect of year-to-year variations. Also, most of the regional sampling is based upon laser and sonar data, which precludes the separation of different types of ridges. The utilization of remote sensing systems in characterizing ridges should be further developed. Such systems have the potential of obtaining sample sizes that are adequate for statistical extrapolations and can be used to verify statistical models.

Movement of Near-Shore Sea Ice

Some structural systems such as artificial ice islands and grounded barges are highly sensitive to ice movement. Even when systems relatively insensitive to ice movement, such as monopod structures, are considered, ice movement information will be necessary to convert space series of observations on ice characteristics to time series of estimates of ice forces. Because ice motions near the coast are known to change significantly from site to site, it is important to monitor these movements on a continuing basis until data can be obtained over a number of years. In addition, cause-and-effect relationships should be sought so that adequate near-shore ice movement models can be developed.

Ice Islands Occurrence

Large ice islands represent a potentially catastrophic loading mechanism for fixed structures. Good estimates of their impact probabilities are highly desirable. An annual survey of the arctic coastal zones, noting the size and location of such ice features, is recommended. Because the ice islands noted in the Beaufort Sea come from the Ellesmere Ice Shelf, further work directed toward estimating the probability of significant future calving would be useful. To obtain reliable impact probabilities, a thorough statistical characterization of existing ice islands will have to be combined with estimates of ice island drift patterns within the Pacific Gyre and in the near-coastal zone.

Geophysical Models of Limiting Ice Forces

Ice forces on offshore structures should be considered on both the local (engineering) and regional (geophysical) scale. For instance, when a large ice feature encounters a large offshore structure, the maximum force possibly may be governed by failures elsewhere within the pack as opposed to failures near or within the structure. Recent modeling results indicate that the nominal crushing strength in the pack as considered on the geophysical scale is quite low. Increased understanding of these two scales of ice deformation and their interaction should be sought because of the need for insight into the limiting values of maximum ice forces in terms of ice pack characteristics.

CONCLUSIONS

This paper has discussed the influence of the environment on offshore operations for mineral resources on the continental shelves of Arctic seas. The ice-related hazards are serious, but are not insurmountable when the initial design has been properly developed and engineered, and subsequent operation of the structure has been carried out according to the initial concept. The costs are high, but with additional experience and investigation to broaden the existing data base, progress will be made. Eventually, if a theoretically sound basis for estimating ice forces can be formulated and verified by field measurements, the development of the Arctic continental shelves can be approached with increased confidence for safe and efficient operation.

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DATA SOURCES

Studies of the applied aspects of sea ice are published in a wide variety of outlets. This is not surprising, considering the highly interdisciplinary nature of the subject. One difficulty is the fact that many papers are published in special symposia, some of which are rather obscure. Also, any thorough study of the subject must survey the large number of Soviet and Japanese contributions.

Bibliographies giving coverage of publications on sea ice include:

1. U.S. Army Cold Regions Research and Engineering Laboratory (USACRREL). *Cold Regions Bibliography Report 12.* Hanover, NH 03755. (many volumes; excellent coverage of cold regions engineering and geophysics in general and sea ice in particular).

2. World Data Center A for Glaciology [Snow and Ice]. *Report GD-2, Glaciological Data: Arctic Sea Ice, Parts 1 and 2 (1978).* INSTAAR, University of Colorado, Boulder, CO 80309 (a special report focused on recent sea ice literature).

3. Bradford, J. D. and Smirle, S. M. *Bibliography on Northern Sea Ice and Related Subjects (1970).* Marine Operations, Ministry of Transport and Marine Sciences Branch, Dept. of Energy, Mines and Resources, Ottawa (dated, but gives older literature not listed in 2).

4. *Journal of Glaciology*, Glaciological Literature Section. International Glaciological Society, Cambridge, England DB2 1ER (contains section on sea ice).

5. Arctic Institute of North America. *Arctic Bibliography.* University Library Tower, Calgary, Alberta, Canada T2N 1N4 (very broadly based bibliography; publication recently discontinued).

Recent symposia emphasizing applied aspects of sea ice include:

6. *Journal of Glaciology.* "Symposium on Applied Glaciology" *Vol. 19, No. 81, 1977*; "Symposium on Remote Sensing of Snow and Ice," Vol. 15, No. 73, 1975.

7. International Conference on Port and Ocean Engineering Under Arctic Conditions (most recent conference POAC 79, Norwegian Institute of Technology, Trondheim, Norway).

8. International Association of Hydraulic Research Symposium on Ice Problems. Most recent conference held in Lulea, Sweden, 1978.

9. Proceedings of the AIDJEX/ICSI Symposium. R. S. Pritchard, ed. "Sea Ice Processes and Models." University of Washington Press, Seattle, Washington. 1980. (heavy emphasis on modeling).

For information about the continental shelves of Arctic Alaska, the following sources should be consulted:

10. Arctic Outer Continental Shelf Environmental Assessment Program (OCSEAP). Beaufort Sea Synthesis Report. Available from OCSEAP Office, NOAA/ERL, Boulder, CO (good up-to-date synthesis of existing knowledge).

11. Alaskan Principal Investigators Annual (and Quarterly) Reports, July 1975 to present. Available from OCSEAP Office, NOAA/ERL Boulder, CO (very lengthy documentation of Alaskan OCSEAP).

12. Alaskan OCSEAP Data Bank, NOAA, Juneau, AK (repository of basic data collected by Alaskan OCSEAP).

13. Alaska Oil and Gas Association. Status of Arctic Research Requirements for Oil and Gas Operations in the Alaskan Arctic; 1975. Also: Final Report on Alaskan Beaufort Sea Floor and Soil Conditions Engineering Research Needs, 1976. Anchorage, AK

14. Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska. Vol. III. Chuckchi - Beaufort Sea, 1977. Available from AEIDC, 707 A Street, Anchorage, AK

15. Technical Reports of the Canadian Beaufort Sea Projects. Department of the Environment, Victoria, B.C.

A good starting strategy for readings in ice-related applied problems in the arctic offshore may well be items 10 and 13, with review in items 1 and 2 of the references of the following investigators who have had long-term interests in this general subject area: P. Aagaard, P. Barnes, M. Coon, E. R. Croasdale, W. D. Hibler III, A. Kovacs, D. Nevel, T. D. Ralston, E. Reimnitz, P. Wadhams, W. F. Weeks, W. Wittmann.

BACKGROUND PAPER VIII

SEA FLOOR SOILS

By E. H. Doyle, J. M. Audibert, R. G. Bea and N. T. Monney

Introduction

Sea floor soils are a unique component of offshore environmental criteria. The soils must act to support the structure and may load it as well. Marine soils are a complex and variable material composed of solids, water, and frequently gases which are under high total pressures developed by the water column. Because of this variability and complexity and the general inability to sample or test the material without introducing disturbance effects, a wide variety of tests and measurements are made to provide indices which will be indicative of the behavior of the material. The scope of these tests and measurements will be largely determined by geological and environmental conditions and by the types of structural foundations used.

There are three fundamental aspects of sea floor soils which must be considered as they impact on environmental design criteria for offshore structures:

1. Characteristics of the soils, including the geologic setting, regional and site specific, at the mudline and at depths influenced by the geologic environment and the foundation elements; and engineering properties of the soil required for evaluation of soil behavior under the strains induced by the environment and the structural foundation.

2. Sea floor soil instabilities, including determination of the possible extent of deformations or changes in support conditions during the life of the structure to be supported by the soils; a projection of loadings developed by the soils on the foundation elements; and a determination of the soil strength and stiffness during the structure's lifetime.

3. Design of the foundation elements, or proportioning the foundation for desirable strength and ductility within the context of a design process which relies heavily on empiricism and experience and characterizing the soils and assessing their response in the context of the foundation design process and objectives.

Each of these components will be discussed in later sections of this paper.

Soil mechanics and foundation engineering on land have progressed with major reliance on empiricism. Soil, by its nature, does not permit exact determination of its interaction with projected engineering structures. In general, the properties of ocean sediments are at the extreme range of terrestrial experience, and there are many important compositional differences. The difficulties are compounded by our inability to sample or even test in situ without significantly influencing the soil's properties and by the necessity of dealing with plastic deformation and failure criteria, rather than elastic deformation.

A comprehensive and accurate assessment of the geology of the region, area, and site is of primary importance for the evaluation of sea floor soils and the design of structures founded on the sea floor.

Geology provides an understanding of the environment under which the soils have been deposited, thereby providing a valuable guide for interpreting the results of soil characterization efforts and for projecting the near future responses of the soils.

Like terrestrial soils, sea floor soils may be highly variable both vertically and horizontally. There are several other significant sources of uncertainty in addition to this natural variability. Uncertainties in projected environmental conditions, their direct effects on the soils and their indirect effects through the foundation loadings or deformation, are significantly greater offshore than onshore. In addition, the variabilities added by the difficulties of marine drilling, sampling, and testing, and uncertainties about the actual performance of the foundation-soil system, result in significantly greater uncertainty in offshore geotechnical practice.

The experience of the petroleum industry in offshore operations confirms these uncertainties. To accommodate these problems, the industry has incorporated large margins of redundant reserve capacity in the structures and their foundations. This indicates that the scope of future research and development activity must extend well beyond simply improving the ability to measure the engineering properties of marine sediments. The effort must be extended to include analytical models to assess response of the sea floor soils and their interactions with the foundation elements, along with prototype field tests, which are essential both in guiding the course of future research work and in providing the empirical base required for advanced design procedures.

The objectives of the sea floor soils characterization are the identification of the various soil types and the assessment of the engineering properties. These soil characteristics, coupled with knowledge of the geology and environmental effects, provide the necessary information for analytical models to project future soil responses. A wide variety of methods and equipment are available for characterization of soils. Soil boring and sampling equipment, in situ testing devices, geophysical equipment, shallow drop cores and grab samplers, and a large variety of laboratory tests performed on retrieved samples provide a broad data base. With a knowledge of the intended application of the data, the engineer uses all of the available techniques and information to develop a rational characterization of the soils.

The purpose of assessing soil instability is to predict the possible extent of the deformation and the strength and stiffness characteristics of the sea floor soil column during the life of the structure. An evaluation must be made of: (1) the capability of the soil to support the stresses and loadings transmitted to it by the foundation elements; (2) the extent to which deformations and settlements developed in the soil will develop loadings on the foundation elements; and (3) the manner in which the soil deformations will influence the supporting conditions of the foundation elements. The response of the soils will be determined by geostatic stresses as developed by gravity, fluid pressures, and regional geologic conditions, and by dynamic stresses as induced by earthquake ground motions, passage of storm waves and currents, and ice impacts, and by the contact stresses developed by the foundation elements.

The fundamental objective of the design of the foundation elements is to proportion the foundation elements and develop an installation-construction scheme which will result in a foundation system having adequate performance characteristics. Performance refers to both the strength and deformation capacity of the foundation-soil system. Adequate performance of the foundation system can be defined as the ability of the system to support the platform structure for its intended purpose without undue expense or risk. The purpose of platforms is to support drilling and production operations, and of pipelines, to transport hydrocarbons. Because of the nature of these operations and the design of the systems, large deformations can be tolerated without adversely affecting performance.

Large deformations, or even a complete loss of strength of one component of the soil member of the system, does not in itself constitute an unacceptable situation, provided that the structural and foundation members of the system have been designed to maintain integrity under the imposed loadings and deformation. Primary engineering strategies for achieving desired performance are the optimization of the design of the strength and flexibility of the foundation elements and of the structure system siting to minimize exposure to undesirable elements of the environment.

Soil Characterization

Prediction of an offshore structure's performance is limited, as with any other manmade structure, by the ability to characterize the loading and resistance regimes. Characterization of the soil should therefore include a determination of the soil properties necessary to describe the resistance of the foundation elements to loading imparted to the structure from the water (oceanographic loading) and from the soil itself (earthquake shaking, soil slides, etc.). A well-planned site sampling program will take into consideration the platform type and algorithms to be used for the analysis and design of the structure's foundation.

The continental shelves of the United States are known to be overlaid by a variety of soil conditions. The Gulf of Mexico, for example, varies from stiff, overconsolidated clays off the coast of Texas (caused by a lowered Pleistocene sea level), to very soft clays off the Mississippi River Delta (caused by rapid deposition from the soil-laden Mississippi River), to sands immediately east of this delta. However, even with the hundreds of soil borings and many miles of high resolution profile (HRP) recording, investigators are still learning about the character of Gulf of Mexico soils.

Characterization of soils is important on both the broad geographic scale (of regional depositional extent) and the macroareal scale (small enough to define individual soil depositional or stability processes). On the broad scale, many continental shelves are still relatively unexplored, except perhaps by shallow drop coring (less than 25 feet penetration) and some HRP lines. While shallow coring may provide useful geotechnical information, deep penetration (50 feet or more) information is required for most continental shelf activities for understanding of behavior of shelf soils in relation to a variety of manmade activities. The most pressing application of deep soils information is to fixed, bottom-supported oil platforms. However, sea floor bottom structures, such as pipelines, may also require broad geologic deep-penetration soils data when, for example, subaqueous slope movements are occuring. Thus, for most offshore structures, it is important to gather geotechnical information on the broad geographic scale on both the near-bottom and deep soils.

The preceding paragraph should not be interpreted to mean that a broad geographic area must be fully investigated before man's use of the area can begin. The development process is accomplished in steps and becomes very site specific. HRP and soil-boring investigations are conducted at the specific area of interest before installing important structures on the sea floor.

Once a reasonably clear picture of a broad geographic basin is obtained, work on a macroareal scale to define the depositional and stability processes to be expected within the broad area is better able to proceed. While site-specific to a certain extent, macroareal studies need not be geared to defining every unstable location. An effective and useful program is to identify characteristic unstable features, so that other unstable areas can be recognized once commercial site-specific investigations are begun.

The only area where broad geographic-scale information is largely complete is the Gulf of Mexico. From the oil industry's viewpoint, some broad geotechnical information is available for the Baltimore Canyon, Gulf of Alaska - Yakataga Basin, and Kodiak Shelf areas and for offshore areas north and south of Los Angeles. Deep penetration geotechnical data are not available for the remaining shelf areas. Areas which are expected to be leased first and presently lack deep penetration geotechnical data should be the focus of data gathering efforts. Some areas, such as the Beaufort Sea, where permafrost conditions are expected, may dictate special soil drilling and sampling requirements. For the more normal areas, standard and existing soil boring practice and sampling tools are recommended so that engineers may meaningfully compare soil results from different borings and areas. Where soil stability is an important design consideration, special care should be taken to obtain high quality samples and/or in situ tests, using devices such as remote vanes, penetrometers, pore pressure probes, and/or measurements of in situ shear wave velocities.

Soils characterization is an interdisciplinary study involving geology, geophysics, environmental mechanics, and soil reconnaissance and testing. The following paragraphs adapted from Garrison and Bea 1/ (1977) describe in more detail the methods and their use in providing the information necessary to properly characterize soil behavior.

Geology

A careful geological analysis is the first step in the characterization of soil behavior. Properly conducted, the geological studies will determine the type, extent, and location of subsequent study elements and form a framework around which the more quantitative data can be fitted.

In better-known OCS areas, the most important geological facts are already well-known and little effort is required to complete an adequate study. In lesser-known frontier areas, however, significant gaps may exist in the geologic picture.

The geology and dynamic processes of the area should be well understood. The information sought should include geologic history, bathymetry, sediment type, and important environmental influences which affect the performance of the soil (deposition rates, exposure to river mouths and glaciers, etc.).

Geophysics

After the geological analysis is well developed, information in the vertical dimension must be obtained through high-resolution geophysical surveying. Line spacing should be sufficiently close so that significant features are not missed. Record quality must be the best possible, and navigation for this type of survey should have the greatest possible precision.

The most useful geophysical tools for investigating shallow geology belong to three classes of seismic reflection devices, as follows:

High-resolution seismic reflection systems. The first class of instruments utilizes various sources, commonly a high voltage electric discharge, to create an energy pulse in the water. Although power outputs vary, the dominant frequencies produced are usually between 50-1000 Hz. They can discriminate density layers down to about 1 m in thickness, and, depending on power output, water depth, and sediment type, penetrate up to 750 m of sediment. The resulting data are most useful for establishing the relationships between deeper structures and the deformation of upper layers, but they are useful also for examining shallow faulting, detecting the presence of shallow gas zones, locating the bases of slide zones, and delineating other sub-bottom features that directly or indirectly affect the stability of near-surface sediments.

Acoustic profiles. The second class of instruments utilize transducers that emit acoustic pulses at frequencies usually between 3.5-7.0 kHz and receive their reflections from the bottom and shallow sub-bottom. The depth of sub-bottom penetration by acoustic profilers is seldom greater than 250 m, depending on power output, water depth, and sediment type, and is generally much less. Their great value, however, is in resolving power, which ideally may discriminate layers as thin as 15 cm. This provides the detail required to correlate borehole data, analyze the internal structure of disturbed sediment mass, measure fault offsets at the sea floor, and perform a wide variety of other observations necessary for understanding unstable bottom features.

Side-scan sonar. The third, and most recently developed, of the seismic reflection devices, has two small acoustic transducers in a single, towed housing. These are made to sweep rapidly and continuously outward from each side of the vertical axis so that the sea floor is scanned through vertical angles of about 40° to port and starboard of the ship's track over the sea floor. Because sonar frequencies of 50-200 kHz are utilized, no sea floor penetration is accomplished. The resulting record, however, presents a photo-like view of "shaded" bottom relief analogous to that produced by airborne radar over land, showing features as small as 0.3 m in diameter. Side-scan sonar is becoming more widely used for bottom stability investigations, pipeline surveys, archeological surveys, and the mapping of such bold sea floor features as sand waves and rock outcrops. Sea floor mapping systems which give real time plan views of the sea floor provide the best information as to the character of bottom features.

Although each class of geophysical instrument provides a unique perspective of the problem it is often desirable to use all three together. The decision on the kind of data needed, however, will be governed largely by the possible types of bottom instability to be expected in an area, as indicated by the geological analysis.

Environmental Mechanics

The role of environmental mechanics in assessing problems of bottom instability is to describe the complex variety of stresses that might influence the performance of soils at a platform site. These environmental stresses fall into two general categories:

1. Geostatic stresses, as developed by gravity, fluid pressures, and regional geologic conditions; and,

2. Dynamic stresses, as induced by earthquake, strong ground motions, the passage of storm waves, currents, and ice.

Because of the necessity for determining both present and future states of stress deformation, combined use must be made of direct field measurements, indirect information obtained from analysis of soil properties, and analytical models.

Direct measurements (e.g., in situ fluid pressures) and indirect information from geology and soil analysis currently provide most of the information from which the existing geostatic stresses can be inferred. However, much additional work is needed to develop reliable instrumentation systems that are capable of making important in situ measurements. The viability of historical modeling depends on direct measurements of the severity of parameters of interest (e.g., wave height and period coupled to sea floor pressure amplitude and distribution). Field measurements are difficult and expensive, but they provide the analytical model with a degree of reliability and usefulness that can effect significantly later economies of time and money.

Soil Reconnaissance and Testing

The objectives of soil reconnaissance are the identification of the various soil types and the characterization of their engineering properties. These soil characteristics, coupled with the environmental effects discussed above, form the necessary input for analytical models used to predict future soil responses.

A wide variety of methods and equipment are available for soil reconnaissance. Deep penetration soil boring and sampling equipment, in situ testing devices (e.g., electric logging, penetrometers, pressuremeters, shear wave velocity, and remote vane shear), shallow drop corers, and grab samplers are among the principal methods currently in use.

Sampled soils may be subjected to a large selection of shipboard and laboratory tests to determine gradation, classification, strength, and stress-strain properties. However, the unavoidable effects of sampling provide, at best, an indirect index of the in situ characteristics of primary interest. Many, but not all, of the disturbance effects associated with sampled soil testing can be avoided by use of in situ testing devices.

The soil testing program includes the selection of the number of borings, their depth, the sampling interval, and the sampling methods. In situ testing devices are also used to complement the data that can be obtained from samples. Soil characterization is based upon the results of various soil mechanics laboratory tests. Some of these tests may be performed offshore.

The following tests are suitable for performance offshore: sample description; shear strength determination by pocket penetrometer and torvane, miniature vane, fall cone, unconfined compression tests; natural water content; density determination; Atterberg Limits determination; and grain-size distribution of granular soils.

Tests which should only be performed in onshore laboratories include: shear strength determination using triaxial testing devices, direct simple shear devices, centrifugal testing devices, torsional testing devices, consolidation testing, and relative density testing.

Selection of the test methods and parameters is influenced by several factors, including analysis and design methods, soils encountered, and the geotechnical problem being investigated.

It is recommended that the conventional soil tests (water content, Atterberg Limits, unconfined compression, miniature vane, torvane, unconsolidated triaxial tests, etc.) always be performed because they are basic to the present state of the practice in foundation design. However, special tests using more sophisticated methods of analysis and aimed at more closely exploring the in situ soil behavior and soil structure interaction phenomena should also be performed.

The modeling of foundations for offshore structures subjected to ocean wave and/or earthquake loading requires an understanding of cyclic soil behavior and the soil properties characterizing the dynamic response. The success of analytical techniques in evaluating the foundation performance depends upon an accurate assessment of these properties and behaviors.

Considerable effort has been directed toward the development or improvement of methods to determine cyclic soil properties. Laboratory techniques such as the cyclic triaxial test, cyclic simple shear test, resonant column test, and torsional shear test have the advantage of controlled conditions, thereby making the result easy to interpret. It is also desirable to make these property determinations by in situ methods, such as geophysical or plate-bearing tests, to eliminate some of the problems created by sample disturbances.

The geotechnical engineer, faced with a need to characterize soil properties under current and projected environmental conditions, therefore utilizes a combination of in situ and laboratory test data. No test is universal and all have their particular advantages, limitations, and applications. Moreover, because of the inherent inhomogeneities of natural deposits and the variability of results obtained from different reconnaissance methods, the soil parameters always exhibit considerable scatter. Therefore, experience and good engineering judgment, coupled with an understanding of the information developed by geological and geophysical studies, become the only means of determining valid soil properties to be utilized in analytical models.

Variabilities and Uncertainties

Three major sources of uncertainty, discussed below, are found in soil profile modeling. They are: (1) natural heterogeneity of in situ profile of the soil; (2) limited availability of information about subsurface conditions; and, (3) measurement errors from sample disturbances, test imperfections, and human factors. Additional uncertainty is introduced from possible errors or insufficient accuracy in the location (navigation, positioning, depth measurements) of the data obtained.

Natural heterogeneity or in situ variability. The spatial variability of natural soil is caused by variation in mineral composition, stress history, and depth of strata. When the variations are sufficiently large, the soil is divided into "layers", and a standard soil profile is produced. However, the local variation existing within a "layer" of soil can introduce significant uncertainty into any analysis which assumes a constant strength or modulus value for a layer.

Limited availability of information about subsurface conditions. A limited number of samples are usually tested. A direct relationship exists between the amount and quality of exploration/testing and the quality of the subsequent reliability analysis. The uncertainty remaining after correcting for inaccuracies in measurement of soil properties in the true value of sample mean is a statistical random error due to the small sample size.

Measurement errors. The true in situ soil properties of interest (usually strength parameters) will probably be different when measured and interpreted in the laboratory. Factors contributing to the difference are: (1) sample disturbance of mechanical or stress-release nature; (2) soil anistropy; (3) relative magnitude of intermediate principal stress; (4) rate of shearing; (5) cyclic loading and/or strain softening; (6) initial in situ stresses; (7) specimen size; and (8) correlation of index and engineering properties. Some of the differences may be attributed to errors in soil modeling, but may also be due to uncertainties in mean property values.

Natural soil variability has always confronted the geotechnical profession. Sampling and testing variations may account for most of the variability in results. High standards, consistent with good engineering practice, will tend to limit this problem to acceptable levels.

Inadequate testing techniques do not necessarily imply poor practice. Frequently, testing methods are employed which do not represent the field stress conditions or load application. However, research continues to improve testing methods. For example, the increasing use of cyclic direct simple shear devices more closely (but not perfectly) represent in situ earthquake shaking conditions than do cyclic triaxial test devices. Research efforts should continue to examine the varied soil movement types to determine testing (and sampling) requirements.

Conclusions

Characterization of the soil properties must proceed from a well-planned, interdisciplinary study of geology, geophysics, environmental mechanics and soil reconnaissance and testing. This should include taking deep soil borings, since it is not possible to infer an adequate soil characterization (one useful in the foundation design process) from only surface information (e.g., drop cores).

An optimum soil testing program must include conventional soil tests, since the present state of the practice in foundation design relies heavily on correlations with the results from such simple tests. This data may need to be augmented by special tests aimed at solving specific design problems or conditions.

Finally, in situ tests must also be used, because of certain advantages over laboratory tests performed on sampled soils. Offshore in situ testing techniques and methods of interpretation could be significantly improved through additional research.

While there is often only one test or one device to measure particular oceanographic parameters, there are often several testing methods and devices available to measure the same soil parameters, each leading to a different value. This adds to the degree of uncertainty and to the possible scatter in foundation design solutions. It is important that the appropriate test be used to characterize soil properties to be used in particular design algorithms.

Soil Instabilities

Soil instability is defined here as a subaqueous soil movement which places design restraints upon an offshore structure.

Recognition and Characterization

The recognition of soil movement phenomena and their deformational characteristics form the basis for stability studies. Ultimately, however, the most important aspect is the loading imposed on the structure by the deformational process. Many structures are inherently resistant to soil movements because they were designed for other, more severe conditions. Thus, while a deformational process may exist, its real importance is whether or not it dominates the design. Hazard exposure characterizations generally do not relate the hazard with respect to its importance to the intended use of the structure. For example, cloudy water could be considered as a hazard if submersibles were to visually navigate through it; but cloudy waters are not necessarily a hazard to large bottom-supported structures. In addition, language problems sometime result when events of geologic (i.e., extended time) proportions are intermixed with events of engineering (i.e., the life span of the specific structure). For example, evidence of soil creep is of little concern to engineers if it can be shown to have occurred in the Pleistocene era by processes no longer at play.

Thus it is important to properly categorize and rate types of soil instability and their resulting deformations to a specific site's intended use. The economic design of a structure to resist soil deformation vs. the economic and political consequences of a failure should be judged independently, and are not part of this present discussion.

Types of Soil Instabilities

One of the more complete summaries of the types of subaqueous slope movements was presented by J. M . Coleman at the Second Conference on Offshore Geologic Hazards held in Corpus Christi, February 2-3, 1978. Table I gives his summary. Five major types of soil movements are shown, of which there are 15 subtypes. Coleman has compared the occurrence of each soil movement with the soil type (grain size), slope, loading mechanism, and movement rate. An addition to Table I could include scour and gravity-driven downslope creep as distinct soil movement mechanisms.

The type of soil movement which might be expected in any given locale falls into two categories. The first is movement which is clearly observed when thorough HRP surveys and soil boring(s) are conducted. The second category is movement which is not obvious when HRP surveys and soil borings are conducted but must be analytically recognized. The first category is the easier to deal with in engineering terms. Soil movement can be gauged and, in a sense, calibrated against what has happened in the past.

Research in soil instability should concentrate on the calibration (visual and analytical) of clearly recognized movement features which can be mapped and sampled for geotechnical data input to analytical models. The USGS Gulf of Alaska program for recognizing and then hindcasting slope failures is an important program, typical of efforts which can be expanded to an even better capability in identifying possible instability conditions.

In addition to hindcasting known movements, geotechnical data taken during failure would add significantly to the understanding of the processes. To obtain such data it would be necessary to instrument areas which are clearly expected to produce future movements (in a timely, near-term engineering sense). An example would be hurricane-wave-induced motions in very soft clays like those in the Yakataga Basin or offshore of the Mississippi Delta. The result of this particular research, for example, would be to adequately bound the prediction of engineering parameters, such as time of occurrence and depth of lateral and axial motion under each ocean wave. The data collected could be used to develop analytical models for the design of structures resistant to the type of soil movement investigated.

Table 1
Subaqueous Slope Movements

Type of Movement	Grain Size		Slope		Mechanisms						Movement Rates			
	Coarse	Fine	Steep >2°	Low <2°	Sediment Loading	Wave Loading	Earthquake	Excess Pore Pressure	Gas Production	Oversteepened Slope	Slow	Rapid	Catastrophic	Episodic
VERTICAL														
Diapiric Instrusion		D	D	D	D						D			D
Mud Volcanoes		D	D	D	D		S	D	S		D			
Collapse Depressions	S	D		D		D	S	S	D				D	
Liquefaction	D		D	D			D	D					D	
Faults	D	D	D	D	D		D				D		S	
ROTATIONAL														
Arcuate Slumps	D	S	D				D			D	D			D
Bottleneck Slides		D		D		D		D				D		
Contemporaneous Faults	D	D	D	D	D						D			
TRANSLATIONAL														
Retrogressive Elongate Slides		D		D		D	S	D	S			D		D
Complex Multiple Elongate Slides		D		D	D	S	S	D	D			D		D
Quick Clay Slides		D	D	D				D					D	
FLOWS														
Mud Flows		D		D		S	S	D	D		S	D		D
Debris Flows	D		D				D						D	
Turbidity Flow	D		D				D			D			D	
COMPLEX														
Mud Wave		D		D		D		D	D			D	D	

D = Dominant S = Secondary
(Coleman, J. M. (1978) Second Conference on Offshore Geologic Hazards, Corpus Christi, Texas, February 2-3)

One of the most difficult areas of stability study is for locations where movement is thought to exist but no clear visual evidence is available. For example, earthquakes may cause a low angle slope to move a few feet without any evidence of rupture. While the recently completed EQWS* study provides some insight, additional laboratory analytical studies would be very useful. Such studies lead to the development of analytical models based on good laboratory data and help in bounding engineering soil movement problems.

In characterizing soil instabilities scientists and engineers must develop some model of the process. The first step in developing a model is to understand the process in the geologic sense (both in a time and a tectonic sense). Once this is understood, an engineering model is derived, with the physical soil parameters as input. Input parameters other than soil properties are often required in analyzing soil instability because many soil movement conditions occur as a result of another type of hazard. For example, a hurricane is required to produce hurricane-wave-induced instability, but not all hurricanes produce instability. Earthquakes also fall into this class. In addition, then, to providing analytical tools to compute the occurrence of soil instability, probabilities of occurrence must also be given for the driving mechanism. Cooperation with environmental data gatherers is essential for deriving maximum benefit. An example is the ocean wave stability area, where additional information is desirable on the dependent joint probability distributions of ocean wave height, period, and bottom wave pressure.

Four broad areas of soil conditions are of major concern: scour, faulting, sliding, and liquefaction. The state of the practice in these areas is discussed below.

Scour. Scour is the process by which large amounts of usually coarse-grained material are transported by ocean currents and waves. By itself, the scouring produces no loading against structures. The primary problem is the removal of support from around fixed structures and pipelines. Structures are usually designed for what is called general scour (removal of material over the entire extent of the platform foundation) and local scour (removal of material over one or more legs). Several fixed structures in the North Sea are located in waters where considerable soil transport occurs. These structures appear to have survived well. Data are desirable in geographic areas such as Georges Bank and Lower Cook Inlet to better define if net bottom soil losses or gains occur through scour. Designs for local scour are not of any real research concern as long as bottom currents are known.

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*Earthquake & Ocean Wave Soil Stability Study, administered by Shell Development Company for four other oil companies and USGS.

Faulting. This broadly defined category includes gravity-associated events and earthquake-induced surface ruptures. A common primary assumption used in fault analysis is that unless the existing fault is acted upon by some explainable environmental force, new faulting is not likely to occur. That is, movements will continue along existing faults. Pipelines might thus be located on faults. When they are, the design problem is usually structural and not geologic.

Fault location and activity rates are of the greatest concern. It is desirable to standardize, categorize, and place faulting in the context of its environment. The most often asked questions are: Is the fault still active? How old is it? How much will it move in the future? It would appear that analysis of faulting (in rocks generally and in soil particularly) would benefit from regional studies on a macroscale to adequately define the importance of faults to engineering design.

Sliding. Sliding is broadly defined as a mass movement of soil initiated by outside forces. Common problem areas are hurricane-wave-induced slides, slope oversteepening and/or surcharging from rapid deposition, and earthquake loading conditions. Confidence in the state of the practice is lowest in this area of soil movement. The previously discussed research efforts of hindcasting, instrumentation programs, and laboratory/analytical studies should have the most benefit in this area.

In recent years the state of practice has improved greatly as better HRP tools are developed, as more researchers investigate the problem and exchange ideas, and as field and laboratory testing methods improve.

Analysis of the hurricane-wave and earthquake-induced sliding problem is making reasonable progress. Unfortunately, more soil failures are needed to better calibrate existing models. Present analysis better calibrate existing models are more soil failures; the present emphasis is on nonlinear analyses (like, for example, the EQWS nonlinear analysis for earthquake clayey slopes and the Texas A&M equivalent linear wave-sea bottom analysis developed by Schapery). Research will continue to show improvement as better data become available.

To understand better the process of gravity-induced sliding, additional field soils data and HRP surveys are required. For bottom-supported structures, a conservative approach to depth of movement probably represents the state of the practice. These approaches vary from interpretations of HRP surveys to limiting equilibrium methods.

Liquefaction. The term liquefaction usually implies the loss of supporting capacity in sands under earthquake loading conditions. Equivalent linear analyses combined with field experience has led to a fairly reasonable yes/no predictive capability onshore. The primary drawback to its offshore use is the problem of adequately measuring sand properties. Water depth and floating drilling operations usually prevent a precise correlation with onshore testing methods. Work is needed both in this area and in furthering laboratory/analytical studies to better understand the phenomenon.

Forces Generated Against Platforms Elements by Moving Soils

The oil industry has dealt reasonably well with soil movement problems. No major pollution has ever occurred as a result of soil movement. Yet, many fixed platforms and pipeline exist in known unstable areas, off the Mississippi Delta, for example.

During periods of soil movement, lateral and axial forces are imposed against fixed structural elements. The soil pressure developed depends on both the magnitude and rate of soil movement. For lateral movements, many investigators have found the maximum lateral soil pressure against piles at depth is on the order of 9 to 11 times the soil shear strength. For axial movements, the axial pile loading is on the order of 0.5-1.0 times the soil strength.

For large mass movements with a clearly defined failure depth, designers assume full lateral loading. Several types of movements, however, produce displacements which vary with depth, such as ocean-wave-induced instability. It is important in these cases to know the degree of soil displacement as a function of depth. The ocean-wave-induced instability problem may also not have a clearly defined failure depth. Thus, soil pressures will increase from zero at the no-movement level to perhaps full load in the zone of greatest movement. While theoretical and small-scale studies are useful to define the load-displacement relationships as a function of load rate application, field data is most desirable. The types of movement which produce variations in the magnitude of soil displacement to a depth which could affect structures include: (1) ocean wave-induced stability; (2) gravity-induced creep; (3) earthquake slope stability; (4) mud wave progradation; and (5) translation gravity-induced slides.

The depth at which soil movement ceases is also important, since lateral and axial support is provided beneath the moving soil.

Design of Foundation Elements

True structural-foundation-sediment interactions are very complex. The systems are multi-dimensional and the sediment behaves in a highly non-linear fashion. To circumvent the complexities and fulfill a design need, engineers have taken an approach that calls for the following steps:

1. Select a sediment deformation or strength property likely to describe the major part of load transfer between the foundation and sediment;

2. Select a plausible empirical relationship between the sediment property selected and the foundation performance; and

3. Calibrate the empirical relationship with test data.

The design calculations for the axial capacity and lateral load capacity of pilings are examples of this approach.

The procedures given in the American Petroleum Institute RP-2A: Planning, Designing, and Construction of Fixed Offshore Platforms, reflect the generally accepted practice for evaluating the capacity of a pile. More sophisticated techniques may be in use by individual engineering groups.

The calculations outlined in RP-2A are supported by substantial test data. Although many pilings used in the Gulf of Mexico were designed with calculations differing slightly from those presented in RP-2A, the successful experience in the Gulf confirms the conservative nature of the calculations for applicable conditions. In design practice, a safety factor of 2.0 is applied to loads for normal operating environment conditions in combinations with drilling or producing operations. A safety factor of 1.5 is used for extreme design environmental conditions, with appropriate drilling or other minimum loads. The safety factors reflect the confidence of the engineer in the accuracy of characterization of the environmental factors and the reliability of the design model. The need for refinements in either area should be tied to economics, within the constraints of providing a safe and reliable structure. The goal is to provide maximum strength and flexibility with minimum expenditures. Efforts for improvements in design capabilities should be focused on aspects where significant economic returns may result. For example, the costs associated with a very conservative design to resist lateral loading of piles are relatively insignificant in the overall cost of the structure, but the design for axial loading can have a major impact on the overall cost.

A related consideration is the need for improved design models in situations where environmental factors are encountered which are not consistent with conventional design experience. RP-2A notes the importance of consistent experience with design capacity, penetration, and planned installation procedures. Measured field performance data of given pile designs are needed for proving and extending design capabilities.

Other aspects of pile-sediment interaction not specifically addressed in RP-2A also support the need for measured performance data. As an example, relative deformations of the pile and sediment are not taken into account in the axial capacity calculations outlined in RP-2A. Thus, the calculations provided are most applicable to stiff piles when deformation of the steel piling does not affect capacity. Also, the design formulas and the relationship between friction and shear strength do not account for the in situ lateral sediment pressure that activates friction between sediment and the pile. In addition, the expressions do not account for the stress state in the sediment after pile installation. This stress state and other driving disturbances can affect the available strength in the sediment near the pile.

Procedures for calculating axial and lateral capacity of piles exemplify the essential characteristics of engineering capabilities in other areas of sediment engineering. These characteristics are:

1. Rational simulation of complex sediment response with functional forms adapted from analytical solutions for similar but highly idealized problems; and

2. Calibration of the rational but empirical simulations with available test data.

Mat or gravity foundation analyses are grounded in classical solutions for the bearing behavior of plastic materials and sliding friction calculations that estimate lateral load capabilities. The design models needed for gravity structures include the cyclic response of the sediment from cyclic loads on the structure, sediment liquefaction potential, the effect of sediment layers on bearing capacity failure from inclined loading, and the potential for scour.

Installation of a structure warrants special consideration because the incurred loading can be dramatically different from that to be experienced during the operational life of the structure. The prime objective of a foundation installation is to develop full load carrying capability of the sediment. Achievement of this objective implies full depth of penetration of a driven pile. For a drilled and grouted pile, the objective requires full strength between grout and sediment and grout and the pile. For a mat or gravity foundation, the objective requires uniform contact of the foundation with the sediment and full penetration of shear skirts or other devices added to mobilize full strength of the near-surface sediment.

The problems addressed in the design and verification of platform foundations will be different for different types of soils; thus, the engineering approaches will vary. To accomplish this, sediment models based on comprehensive field performance and response data are required.

REFERENCES

1. Garrison, L.E. and R. G. Bea, "Bottom Stability as a Factor in Platform Siting and Design." Preprint OTC Paper 2893. Houston, Texas. 1977.

ENVIRONMENTAL EXPOSURE CONDITIONS TAKEN INTO ACCOUNT IN LEASE-SALE DECISIONS

Paul G. Teleki

The U.S. Government's responsibility in offshore development is threefold: to ensure orderly development of mineral resources, to provide for the safety of the environment and of operating conditions, and to obtain a fair market value for the Nation's resources. In this process, geological and geophysical data are used to estimate the resource potential of a given OCS (Outer Continental Shelf) area, followed by a study of environmental factors that may hinder development. Results from the resource and environmental studies are used in the designation of tracts considered safe to develop, which are then offered for lease. Tracts in which hazards may exist but which will support specially engineered structures are offered, with stipulations on development. Tracts not considered safe in light of existing technology are retained for future sales. Hence, the Government needs environmental data in order to reduce the probability of environmental damage.

The following is a list of exposure conditions, by geographic region, that must be taken into account by the Government in considering which tracts to lease. They are also taken into account by the industry in determining the engineering and other costs related to developing the resource of the tract, and thus affect the price industry bids for the tract. This list is an update of the following publications:

1. Environmental hazards: considerations for Outer Continental Shelf development, by P.G. Teleki, L.E. Garrison, and M.A. Hampton, 1979, Proc. 11th Offsh. Tech. Conf., Houston, TX, v. 4, p. 2579-2589.
2. Environmental hazards on the U.S. Continental Shelf, by P.G. Teleki, M.A. Hampton, and L.E. Garrison, 1979, Proc. 5th Intl. Conf. on Port and Ocean Eng. under Arctic Conditions, Trondheim, Norway, v. 1, p. 435-448.

North Atlantic

1. Sediment erosion and deposition: Predominantly sandy bottom material in shallow waters of Georges Shoal is subject to scour by currents ranging from 30 cm/sec to 100 cm/sec at bottom. Large active sand wave fields exist in the Nantucket and Georges Shoal areas (in depths less than 30 m), the bedforms are 5-15 m high and 150-750 m long.

2. Soil properties: Georges Bank contains many buried of glacial outwash (undifferentiated soils, including boulders) and pockets of clay and silt rich in organic matter.

3. Sediment instabilities: Sediments at the shelf edge, especially around canyon heads, are subject to mass downslope movement, which is accompanied locally by shallow faulting. Subsidence potential is unknown.

4. Earthquake activity: Low-level earthquake activity has been reported from scattered epicenters in the region. The 1755 earthquake at Cape Ann, Massachusetts, had a magnitude of 8 on the Mercalli scale. The silt and clay pose a potential liquefaction hazard if events similar to the 1929 Grand Banks earthquake take place.

5. Wind, waves, and currents: The area is characterized by rapid weather changes (it is in the zone of westerlies). Severe winter storms and occasional late summer to autumn (August to October) hurricanes and tropical storms affect the area. Structures must be designed to withstand wind conditions that are about the same as those for the North Sea. The maximum sustained 100-year wind is 188 km/hr. The relatively shallow Georges Bank induces rapid shoaling and consequent steepening of waves, and these may occur simultaneously with storm tides. The 100-year maximum wave height ranges from 20 to 24 m. Currents in storm surges are strong for the entire water column. A westward current on the slope opposes the northeastward movement of shelf water adjacent to the Gulf Stream. The westward drift joins the Georges Bank eddy on the southern edge of the bank. Near-bottom current speeds on Georges Bank in the summer months are approximately 37 cm/sec, but they reach 100 cm/sec in winter-storm conditions.

6. Ice and snow: Icebergs have been reported very infrequently along the North Atlantic OCS. Accretion of ice on structures is expected, however, in the winter. Coastal areas (bays, lagoons, tidal channels) usually have ice cover from December through March. Visibility in snowfalls and fog may be impaired.

Mid-Atlantic

1. Sediment erosion and deposition: On the Mid-Atlantic OCS, scour conditions in surface sand sheets of variable thickness are caused by storm waves and wind-driven currents. Large sand waves near the heads of Lindenkohl and Wilmington Canyons indicate bedload transport during winter storms in west-southwest-flowing bottom currents. Low-relief sand ridges aligned northeast-southwest on the inner shelf have been studied; determination of their origin is inconclusive.

2. Soil properties: Silt and clay of unknown thickness underlie the surface sand sheet in several areas on the shelf. Geotechnical analyses show that these sediments are overconsolidated and thus are not a geologic hazard.

3. Sediment instabilities: High resolution seismic reflection data records suggest that mass movement has taken place along the walls of many canyons, but the ages of slumped sediment masses are not yet known.

4. Gas in sediment: Scattered coring indicates high methane content in sediments near the edge of the shelf between Hudson and Wilmington Canyons.

5. Wind, waves, and currents: The area is subject to severe winter and tropical storms and attendant high sea state, strong winds, and storm-surge current near the coast. Winds in the summer average 15-22 km/hr from the southwest and in the winter average 18-37 km/hr from the northeast. During August and September, hurricanes affect the area for about 8 days, and tropical storms affect the area for about 15 days. The 100-year maximum sustained wind speed is 189 km/hr. Maximum wave heights for a 100-year recurrence interval range from 22 to 29 m.

5. Aquifer: Results of the U.S. Geological Survey's Atlantic Margin Coring Project (AMCOR) identified the presence of a high-discharge freshwater aquifer approximately 200 m below mudline.

South Atlantic

1. Faulting: Shallow faults along the Florida-Hatteras slope offset surface beds. A deep-seated growth fault has been mapped along the margin of the Blake Plateau between lat. 32°N and 34°N. Its origin is believed to be subsidence caused by salt diapirs. Displacement is normal (1 m at 10 m depth and approximately 500 m at 5 km).

2. Soil properties: Sediment properties on the South Atlantic OCS generally favorable for foundations, although dense sand may pose problems for pile driving. Patches of lagoonal mud and peat are distributed widely, particularly in the central part of the shelf. Submerged karst topography common off Florida is found from the COST GE-1 well to Cape Canaveral. Many buried sinkholes that do not breach the surface are evident in seismic data.

3. Sediment instabilities: Scattered slump features have been mapped at the base of the Florida-Hatteras slope and appear to be modern features. Slumps have not been found in the Georgia Embayment.

4. Sediment erosion and deposition: Strong bottom currents originate in Gulf Stream countercurrents and eddies, and are responsible for the sand-wave fields of inner shelf and the erosional features of the Blake Plateau.

5. Earthquake activity: There is a potential for strong-motion events in the vicinity of Charleston, S.C., where an earthquake having a magnitude of 6.8 (Richter scale) took place in 1886. Several smaller magnitude earthquakes have also taken place along the South Atlantic Coast.

6. Wind, waves, and currents: Tropical storms generate high waves and wind along the southern Atlantic coast and strong currents on the shelf. The 100-year maximum sustained wind speed is approximately 130 km/hr. Depending on location, the maximum wave height ranges from 19 to 24 m for a 100-year recurrence interval. Surface currents near shelf edge have average velocities of 180 cm/sec.

Eastern Gulf of Mexico

1. Sediment instabilities: One large area of slumping was noted on the upper slope of the Florida Escarpment; more detailed surveys in the eastern Gulf of Mexico may show others.

2. Soil properties: Discontinuous, thin, and unconsolidated sediment cover represents relict, transgressive deposits of late Wisconsinian Age, varying from quartz sands (West Florida shelf) through zones of pelletoid, oolitic, algal, and shell carbonate sands toward the south to biogenic silts and oozes along the slope. Underlying karst may pose drilling and foundation problems.

Central and Western Gulf of Mexico

1. Gas in sediments: In the central and western Gulf of Mexico, ubiquitously distributed shallow gas creates hazardous conditions, both as high-pressure accumulations and in the form of dispersed bubbles in sediment pore space that alter strength properties in sediments.

2. Sediment instabilities: Submarine landslides, slumps, and mud flows as much as 30 m thick are commonly associated with regions of rapid deposition and/or steep slopes that have caused many pipeline ruptures and a few platform failures. Many slumps coalesce to form channels of frequent debris flow. Both creep and block slumping are common.

3. Soil properties: Sediments contain a high percentage of biogenic methane. The gas may exist in solution or in bubble phase; in the latter state, it creates excess pore pressures. Undercompacted muds may fail when they are subject to cyclic loading by storm waves.

4. Active faults: Growth faults are prevalent on the shelf. Many faults are associated with diapiric features and with over-steepened depositional slopes.

5. Earthquake activity: Although the Gulf of Mexico has been considered to be historically aseismic, an earthquake of 4.6 magnitude (Richter scale) took place on July 24, 1978, at lat. 26.6°N, long. 88.6°W.

6. Wind, waves, and currents: During the summer, winds are predominantly from the southeast; during the winter, they are predominatly from the east-northeast, but vary greatly near coastal regions. Storm statistics show a probability of a hurricane affecting the area in any year is 1 in 6. The principal danger to development of the OCS are hurricane waves and winds; during Hurricane Camille in 1969, waves reached a height of 20 m and wind speeds exceeded 300 km/hr. The 100-year maximum wave heights are 20.7 m for the central Gulf and 21.9 m for the western Gulf. Storm-surge elevations are fairly well documented (6.9 m at Pass Christian during Camille, 6.7 m in Lavaca Bay during Carla in 1961). Although 200 cm/sec current velocities have been reported, actual measurements of storm-current velocities are few.

Southern California Borderland and Santa Barbara Channel

1. Earthquake activity and faulting: Earthquakes having magnitudes greater than 4.5 have taken place in eastern Santa

Barbara Channel and on San Pedro shelf. It is estimated that an 8.2 magnitude event (Richter scale) will occur every 100 years. Smaller events have been recorded on the Santa Rosa-Cortes Ridge. As recently as 1978, a 5.1 magnitude event was recorded in the Santa Barbara Channel. Shallow recent faults that offset the seafloor, are present near Tanner or Cortes Banks, on the northern part of the Santa Rosa-Cortes Ridge, and on the Santa Monica and San Pedro shelves. Major northwest-trending fault zones on the shelf include the Patton Escarpment, the west Santa Rosa-Cortes Ridge, the east margin of Santa Cruz and San Nicolas basins, the San Clemente Island Escarpment, and the Catalina Escarpment. The active Palos Verdes and NewportInglewood fault zones extend southeast from the Los Angeles Basin offshore along the shelf and into the Gulf of Cataline, respectively. In 1933, an earthquake having a magnitude of at least 6.0 took place along the offshore extension of the Newport-Inglewood fault. Potential problems include sudden fault displacement and fault creep.

2. Sediment instabilities: Slumps, sediment flows, and creep have been identified on the slope of the Santa Barbara Channel, Cortes Bank, and Tanner Bank, the flanks of major ridges such as the Santa Rosa-Cortes Ridge and on the slope between San Pedro and San Diego. Much of the mass movement evident in seismic-reflection records may have been earthquake-induced.

3. Soil properties: Expansive soils (montmorillonite) and rocks (altered volcanic tuffs) are present on many areas of the shelf.

4. Oil and gas seeps: Natural hydrocarbon seeps from thermogenic sources have been identified in Santa Barbara Channel, Santa Monica Bay, and San Pedro Bay. Some are associated with faults.

5. Wind, waves, and currents: Extratropical cyclones, generally approaching from the west, and occasional tropical hurricanes affect the area. Wind speeds average 14-26 km/hr depending on locality, but gusts may reach 148 km/hr. Waves reaching the shelf, however, originate more often in distant Pacific Ocean storms than locally. Wave periods range from 8 to 22 sec; wave heights range from 0.3 to 6 m. The 100-year maximum wave height is estimated to be 14.6 m. Velocities in the Davidson Current and the semipermanent Southern California Countercurrent average 23 cm/sec and are locally influenced by wind. The velocity of the 100-year surface current is estimated to be 150 cm/sec, and that of the bottom current is estimated to be 20 cm/sec.

6. Tsunamis: A wave originating near the coast of Chile caused severe damage in Los Angeles Harbor on May 23, 1960.

Central-Northern California

1. Earthquake activity and active faulting: Major fault zones (e.g., Hosgri, San Andreas, Sur-Nacimiento) extend offshore in central and northern California. Historical records of seismic activity of the region portend future strong-motion ground shaking and seafloor rupture. Smaller shallow and surficial faults have been mapped in the Bodega and Santa Cruz Basins. Active folds and faults in Eel River Basin suggest recent uplifting and faulting. In Washington State, most earthquakes have been centered around the Olympic Peninsula and have had intensities as high as VIII on the Mercalli scale. All Oregon's coastal counties have reported seismic activity.

2. Slope instability: Submarine slides have been identified both on the narrow shelf (average slope 3°) and on the upper Continental Slope off central and northern California. Massive slide blocks are found near Big Sur in a zone 10 to 15 km wide, and thicknesses of the slumped sediment masses are as much as 500 m. In the Eel River Basin, large slumps have been noted on the outer shelf (marginal plateau, plateau slope) and the upper Continental Slope. Other known areas of instability include Monterey Canyon and the outer edge of Santa Cruz Basin.

3. Soil properties: Sediments are rapidly accumulating offshore of river mouths, such as the Columbia and Eel Rivers. These sediments probably have weak bearing capacity like those deposited in similar conditions near the Mississippi and Copper River deltas.

4. Gas in sediments: Gas seeps associated with faults have been identified in Bodega Basin.

5. Piercement structures: Major diapiric structures, probably composed of Pliocene shale, have been recorded by seismic-reflection methods in an area extending from Mendocino, Calif., north into the Washington Continental Shelf. Diapirs may extend for as much as 20 km^2 and their relief may reach 200 m. Their morphology and physiographic expression indicate active uplift. Hazards associated with diapirs include abrupt movement, peripheral faulting, trapped gas, and slumping off their flanks.

6. Wind, waves, and currents: Winds blow from the north-northwest in the summer at speeds averaging 11-26 km/hr. Wind directions change to southwest-west in the fall, and increase in velocity in response to the relationship of the Pacific high-pressure system to the Aleutian low-pressure system. Winter wind speeds range from 11 to 18 km/hr. Gale winds, whose speeds exceed 63 km/hr, usually originate in the southern Gulf of Alaska (or at the northern boundary of the Pacific high-pressure system). Wave conditions reflect the prevailing wind conditions, as well as distant storms in the Pacific. Swell periods range from 6 to 15 sec. In summer, circulation is mainly represented by the meandering California current, whose velocities within 100 km of the coast are less than 1 km/hr. In winter, the Davidson Current dominates.

Northeastern Gulf of Alaska

1. Earthquake activity and faulting: The northwestern Gulf of Alaska is within one of the world's most seismically active areas. During the last 80 years, 40 earthquakes affected the area, among which 4 events had magnitudes equal to or greater than 8.0 (Richter scale) and 10 events had magnitudes of 7-8. In 1964, an earthquake of 8.4-8.6 on the Richter Scale was recorded in Prince William Sound. Epicenters of recent earthquakes, some having magnitudes exceeding 6.0, are concentrated near Pamplona Ridge. A concentration of smaller magnitude epicenters is in and just offshore of Icy Bay. Zones of shallow faulting, wherein some of the faults are thought to be active, exist near Middleton Island, extend toward Kayak Island, and are also found around Wessel's Reef. Hazards associated with seismic activity and faulting include fault rupture, strong-motion ground shaking, sediment mass movement, tectonic deformation of the seafloor, and tsunamis. Experience with damaged buildings on land show that structural failure is often caused by dynamic shaking or foundation failure resulting from ground rupture or soil instability. High-intensity aftershocks can also cause damage.

2. Soil properties: Rapid sediment accumulation in the Copper River prodelta and offshore of the Malaspina and Bering Glaciers is the cause of underconsolidated and low-strength seafloor soil.

3. Sediment instabilities: On the Continental Shelf, submarine slides have been mapped in Kayak Trough (areal dimensions 10 x 17 km, as much as 150 m in thickness), in the Copper River prodelta (a 5 km by 70 m zone), and off Icy Bay-Malaspina Glacier (a 8 km by 40 km zone). Records show minor slumping

into sea valleys and around Pamplona ridge. Large slumps on the upper Continental Slope are also known.

4. Gas in sediments: Broken, discontinuous reflectors indicating the presence of gas are common in seismic-reflection records from two major areas: off Kayak Island and the Copper River prodelta. Anomalous amounts of gas have been measured in surface sediments in these areas.

5. Sediment erosion and deposition: Erosional features are found in Tarr Bank-Middleton Island platform area and near islands. Along the coast in the northeastern Gulf of Alaska, the morphology has changed significantly during historical times. These changes have resulted from erosion and and deposition of sediments in Icy Bay, in Yakutat Bay, and along the barrier islands of the Copper River Delta.

6. Wind, waves, and currents: Sustained winds having speeds as high as 180 km/hr are generated by storms that commonly persist for 1 to 3 days, but average wind speeds are below 100 km/hr. The area is known to give rise to cyclones, which are frequent and intense storms accompanied by large amounts of precipitation and strong winds, especially in the autumn. Average wave height in the area is 1.2-4.8 m; the maximum wave heights are 15.6 m and 39.6 m, respectively, for the 25-year and 100-year return intervals. Extreme current speeds are estimated to be 150-200 cm/sec on the surface and 25-64 cm/sec at the bottom.

Lower Cook Inlet

1. Sediment erosion and deposition: In the lower Cook Inlet, fields of large and small bedforms have been mapped by seismic-reflection systems and side-scan sonar. Bedload movement of sand in areas of large sand waves (13 m high, 1000-m wavelength) has been documented, but displacement of large bedforms during the last 5 years appears to be negligible.

2. Winds and currents: Wind speeds of 92-140 km/hr can be expected near the inlet during the late fall and early winter. Tidal amplitudes range from 4.2 m at the mouth of the inlet to 9 m at Anchorage. At Kenai Peninsula, the highest tidal range is 7.9 m. Surface current velocities of approximately 200 cm/sec are amplified to 330 cm/sec at monthly tidal extremes.

3. Volcanism: Augustine volcano within the Lower Cook Inlet is active and locally poses a danger of lava flows, nuées

ardente, ash falls, seismic shaking, and tsunamis. Four other active volcanoes are onshore along the northwest side of Cook Inlet.

4. Earthquake activity and faulting: The area is susceptible to earthquakes having magnitudes greater than 8.0 (Richter scale) and to the attendant hazards of strong-motion ground shaking, consolidation and failure of seafloor sediments, fault rupture, and tsunamis. At least 12 earthquakes having magnitudes greater than 5 have taken place in this area since 1899.

Kodiak Shelf

1. Earthquake activity and faulting: Located within one of the world's most seismically active regions, the Kodiak shelf is affected by earthquakes having magnitudes greater than 8.0. Since 1902, at least 95 earthquakes having magnitudes greater than 6.0 have taken place in the area. Shallow faults, many of which offset the seafloor and hence are believed to be active, are distributed across the shelf. These faults are especially numerous in a zone offshore of the southeast coast of the Kodiak Islands. Hazards related to seismic activity and faulting include strong-motion ground shaking, fault rupture, sediment displacement, tectonic deformation of the seafloor, and tsunamis.

2. Soil properties: Large troughs traversing the Kodiak shelf contain fine-grained sediments. Surficial samples are composed mostly of volcanic ash. The shear strength of these deposits may be low.

3. Sediment instabilities: Numerous submarine slides, some being greater than 8 x 8 km in plane dimension and 300 m thick, have been discovered on the uppermost Continental Slope off the Kodiak shelf and may pose problems if development moves seaward from the Continental Shelf. No evidence exists of submarine sliding on the shelf.

4. Sediment erosion and deposition: A field of large sand waves having heights as great as 10 m exists in Stevenson Trough. This and other geological evidence suggests strong bedload movement in Stevenson Trough relative to other areas of the shelf.

5. Gas in sediments: Gas is known to exist in sediments of the southern and middle Albatross Banks and in Chiniak and Kiliuda Troughs because broken, discontinuous reflectors are observed in high-resolution seismic records.

6. Wind, waves, and currents: Wind, waves, and current conditions on the Kodiak Shelf are similar to those of the Gulf of Alaska and eastern Aleutians. Sustained winds having speeds greater than 140 km/hr and significant wave heights of 15+ m are expectable every year on the shelf. Wave conditions are most severe in the late autumn-winter period. Currents reach speeds of 70 cm/sec in the Alaska Stream, but velocities may be locally greater near coastlines.

Aleutian Ridge

1. Earthquake activities and faulting: The Aleutian Ridge is seismically a very active area, where several major earthquakes took place during this century. Earthquakes are caused both by tectonic deformation of the lithosphere and by volcanic eruptions. Both shallow and deep-focus shocks are common. Numerous shallow faults, many likely to be active, trend parallel and perpendicular to the ridge. Seismic hazards include strong-motion ground shaking, fault offset, and mass sediment movement.

2. Sediment instabilities: Massive slumps have been identified on sloping areas of the Aleutian Ridge, its margins, and on bench areas.

3. Wind, waves, and currents: Seasonal high winds near the Aleutian Ridge are caused by local conditions (willawas) or accompany regional storm systems. Wave conditions are probably as severe as those in the Gulf of Alaska; wave heights are estimated to be 6 m in the summer months and 8 m in the winter. Surface currents related to the Alaska Current have speeds of 30-50 cm/sec. Wind stress can intensify these currents an additional 20 cm/sec.

4. Volcanism: The Aleutian Islands contain 76 major volcanoes, half of which have been active in historic times. Volcanic eruptions can create locally hazardous conditions in the form of lava and ash flows, ash falls, fire, toxic gases, corrosive rains, flash floods, and local tsunamis.

Northern Bering Sea

1. Gas in sediments: In Norton Sound, buried gas is vented through small craters in the seafloor in an area approximately 100 km^2 in size. Sediments near vents are susceptible to liquefaction. The gas is composed of CO_2 (which is probably partly thermogenic) and methane (originating in shallow buried peat deposits).

as 5 m deep. Coastal thermal erosion takes place when relatively warm ocean water attacks frozen coastal soils, reducing soil shear strength as well as inducing coastal retreat as much as 40 m. Also, wave action on thawed permafrost can accelerate erosion.

4. Gas in sediments: Frozen gas hydrates (clathrates) are widely distributed on the slope and rise in the Beaufort-Chukchi Sea and may be trapped below permafrost caps on the shelf. The physical mechanical properties of hydrates are not known, but they are perceived as hazardous to drilling if expansion of the gas is not contained.

5. Wind, waves, and currents: Autumn and winter storms in the Bering Sea can be severe. Wind velocities in excess of 80 km/hr are common and increase to 112 km/hr in the winter, when winds blow parallel to the coast. Barrow has reported winds speeds greater than 160 km/hr in January. Winds normal to the coastline may gust to 190 km/hr as a result of Venturi effects created in valleys. Surface currents are strong between Point Hope and Point Barrow and range from 50 to 280 cm/sec. Nearshore currents are wind driven. Waves are less than 5 m high in the Chukchi Sea in the summer but heights often increase to 7 m in the fall. In the Beaufort Sea, wave heights are less than 1 m 90% of the time, although the highest recorded wave was 9 m. During storm surges, wave heights may reach 6 m in the Beaufort Sea and may be higher along the coast of the Chukchi Sea.

6. Sediment instabilities: Slumps have been identified in seismic-reflection records near the shelf break in the Chukchi Sea.

7. Earthquake activity: Earthquakes having magnitudes less than 4.0 have been registered in Camden Bay, presenting a minor seismic hazard. Seafloor faulting takes place in the Hope Basin area.