The seventh international conference on port and ocean engineering under arctic conditions

Volume 4

VALTION TEKNILLINEN TUTKIMUSKESKUS
STATENS TEKNISKA FORSKNINGSCENTRAL
TECHNICAL RESEARCH CENTRE OF FINLAND
ESPOO 1983
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Volume 4

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Organized by
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Laboratory of Structural Engineering

VALTION TEKNILLINEN TUTKIMUSKESKUS
STATENS TEKNISKA FORSKNINGSCENTRAL
TECHNICAL RESEARCH CENTRE OF FINLAND
Espoo 1983
PREFACE

POAC 83 was the seventh in the series of international conferences dealing with various theoretical and practical aspects of arctic technology in navigation and coastal engineering. The first conference was held in 1971 in Trondheim at the initiative of Professor Per Bruun and the Norwegian Institute of Technology. The following conferences were subsequently held in Reykjavik in 1973, in Fairbanks, Alaska in 1975, in St. John's, Newfoundland in 1977, a second time in Trondheim in 1979, and in the City of Québec in 1981. It was an honour for the City of Helsinki to host this conference in 1983.

Ice problems in polar marine areas and harbours, as well as ice loads on coastal structures, have traditionally formed the basic subject of the POAC conference. Since 1975, more and more attention has been focused on the utilization of arctic energy resources and the problems associated with the increasing industrial activities onshore and offshore. At most meetings, some local questions related to the field of interest of the POAC conference have also been discussed. Thus, at this conference, there were papers on various aspects of navigation in the Baltic and in the Gulf of Bothnia.

The papers were published in four volumes. Volume 1 and Volume 2 came out before the Conference. Volume 3 and 4, including the discussions on the papers, came out in autumn 1983.

The POAC 83 conference was organized with the financial support of The Ministry of Trade and Industry, The National Board of Navigation, The Technical Research Centre of Finland, and a group of eleven Finnish enterprises. The administrative responsibility was taken by The Technical Research Centre of Finland. Many other Finnish organizations have worked with us in preparing the conference. We should like to give special mention to The
University of Oulu, The Helsinki University of Technology, and
the industrial associations of Finnish Shipbuilders and Building
Material Industry.

Finally we wish to acknowledge various working groups and many
individual persons for their help, the authors of the papers
presented for their important contribution, and all the
participants who have helped us to make the PDAC 83 conference a
success.

We look forward to seeing you in Greenland in 1985.

August, 1983

Pauli Jumppanen
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THE PRESENT STATE AND FUTURE DEVELOPMENT OF ARCTIC OFFSHORE STRUCTURES

Abstract

The major difference between offshore structures in the arctic compared with more temperate zones is that they have to withstand ice of one form or another. The petroleum industry, particularly in Canada, has gradually developed an ability to explore for oil and gas in the offshore arctic. A significant aspect of this development has been the use of artificial islands for drilling in the Beaufort Sea. By 1982 over 20 islands had been built in water depths out to 30 m. The early islands were simple dredged sand mounds in 2 to 3 m of water. The latest islands incorporate steel or concrete retaining structures to minimize fill and ease construction through the water-line. This paper reviews the history of island technology in the Canadian Beaufort Sea and also speculates on the design of future production platforms which may be built. The paper also reviews the special requirements of offshore structures for areas such as the Canadian East Coast where exists pack ice, icebergs and a severe wave climate. Similarities and contrasts with the Beaufort Sea are discussed and possible platform configurations are presented.

1 INTRODUCTION

Five and a half years ago I addressed this conference in St. John's Newfoundland. I spoke on the progress that had been made in ice engineering to support offshore petroleum activities in ice covered waters. I described how artificial islands had been developed and used for offshore drilling in the Beaufort Sea. I reviewed our progress towards understanding ice
forces. Various types of offshore structures such as islands, steel and concrete monopods and cones were described. I was enthusiastic about progress /6/.

In this talk I intend to describe the even more exciting achievements which have taken place since then. I will also discuss future structures for the hostile environments of the deeper arctic waters and Canadian East Coast, which are now being considered and designed. I will be focusing mainly on the Canadian scene, but perhaps this is appropriate as it is in Canadian waters that the most progress has been made to date, (at least in terms of the actual installation of facilities).

2 SUMMARY OF PROGRESS SINCE 1977

In 1977, 16 exploratory drilling islands had been built in the Canadian Beaufort Sea. The deepest island was Isserk in 13 m of water. Since 1977, although only an additional six island locations have been drilled, they have generally been in much greater water depths. (See Figure 1) The Issungnak Island completed by Esso in 1979 was the first island in 20 m of water. It took more than two summers to build and required about 5.0 million cubic metres of dredging.

In contrast, the Tarsiut island, in 22 m of water built by Canadian Marine Drilling (Dome) on behalf of Gulf Canada Resources, utilized concrete caissons, and the dredging was reduced to under 2.0 million cubic metres. This reduction was achieved partly by the use of caissons and partly by achieving steeper dredged slopes.

Another recent major advance has been the installation by Canadian Marine Drilling (Dome) of a steel caisson drilling system at Uviluk in 31 m of water. This caisson is a modified VLCC hull with additional steel and concrete reinforcement to resist ice loads. The drilling rig and equipment are permanently mounted, and the system is ballasted onto a submerged berm by adding 186,000 tonnes of water.
In addition to these installations, new drilling systems have either arrived in the Beaufort or are under construction. Such systems as the Esso Caisson Retained Island which is currently wintering in Tuktoyaktuk, and the Gulf Mobile Arctic Caisson, under construction in Japan, will be described in more detail later in the paper.

A number of promising oil and gas discoveries have been made in the Beaufort and there is a high degree of confidence that the area will be a commercially viable oil producing province. For this reason an Environmental Impact Statement (EIS) has recently been filed describing development scenarios and potential impact /11/. The EIS was jointly prepared by Dome Petroleum, Esso Resources Canada, and Gulf Canada Resources.

Off Canada's East Coast, summer drilling with ships has continued off Labrador, and year-round drilling is taking place off Newfoundland. A promising oil discovery has been made at Hibernia. This discovery has led to designs for structures to withstand both severe wave climates and iceberg impacts. I shall discuss such designs later in the paper.

3 PHYSICAL ENVIRONMENTAL INFLUENCES ON DESIGN AND OPERATIONS

Numerous articles and papers have been written describing the physical environment of the arctic offshore areas, and therefore in this paper, I shall only give an overview of this topic. The over-riding influence on the design of structures for Arctic regions, is the presence of ice in one form or another. Clearly, if the ice was not present, then arctic offshore structures would be no different from those in use in more temperate zones. On the other hand, even though a particular form may be chosen to best resist ice, the effects of waves can have a significant influence on design and/or construction. For example, it is ironical that in the Beaufort Sea most operators will tell you that their biggest problem in terms of islands is the damage due to waves. But of course this is because islands are good at resisting ice but not at resisting erosion due to waves.
Obviously a better concept would optimize the effects of the two environmental forces, ice and waves.

Similarly off the East Coast of Canada, structures will have to be very massive to resist impact by icebergs. Such designs are not good from a wave point-of-view and this can lead (in a non-optimized configuration) to the extreme wave forces being greater than the iceberg impact loads.

In the Beaufort Sea, the ice is present for about nine months of the year nearshore, and is a permanent feature as one goes north into the polar pack. The ice restricts normal offshore construction operations (and also floating drilling operations) to about 100 days per year on average, and much less in bad ice years.

In the nearshore areas of the Beaufort Sea, the usual winter ice environment is composed of first-year ice which grows to a maximum thickness of about 2 m. The ice usually becomes landfast by the end of the winter out to about the 20 m water depth. Further offshore, although one is in the mobile pack which can move several kilometres per day, the predominant ice type is first-year, but with extensive ridging. For nearshore temporary winter islands, it is usual to design only for first-year ice.

As one goes deeper and installs more permanent facilities, then the multi-year ice of the permanent polar pack has to be designed-for. Even so, experience has shown that in most winters, the occurrence of multi-year ice interaction with arctic structures is rare, at least off the Canadian coast. In fact, it is the summer months, when there is no buffer of first-year ice, that collision from large multi-year floes is most serious. In the Beaufort Sea, multi-year ice will be on average about 5 to 6 m thick, but with extreme thicknesses in the form of ridges and hummocks up to 30 m thick. The average diameter of floes greater than 500 m is about 1.2 km, however floes up to 14 km across have been observed /20/. Permanent
production islands or structures in the deeper Beaufort waters will have to be designed for such multi-year features.

Ice islands, which are calved from the ice shelves of Ellesmere Island have been observed in the southern Beaufort Sea /26/. These features can be several km across and 50 to 60 m thick when calved. Knowledge of existing numbers, past calvings and current growth of the ice shelves indicates that present and future occurrence of ice islands is very low. Furthermore, recent work by De Paoli et al /10/ on likely drift paths of these features, indicates very low probability of collision between ice islands and offshore structures in the Beaufort Sea. The estimated return period of a collision between a large ice island and structure in 60 m of water is about 1500 years (see Figure 2). Such a low risk suggests that ice islands may be discounted as a design feature, especially as it will usually be possible to see these features days in advance and action can be taken to secure wells and evacuate people.

As I mentioned earlier, structures built for ice are often susceptible to damage from relatively small waves. So it is very important to be able to define wave conditions. This is not easy in the Arctic because the fetch is governed by the ice edge, which is quite variable. Furthermore, there is limited historical data. In general, waves in the Arctic are much lower than say in the North Atlantic or North Sea. For example, the largest significant wave height measured during the past five years at the Beaufort Sea drill sites was only 3.6 m /11/.

Off the East coast of Canada, structures will have to be designed for much larger waves. For example on the Grand Banks, the 100 year design significant wave is about 15 m. In addition, sea ice and impacts by icebergs and bergy bits have to be considered. On the Grand Banks sea ice is quite rare but the design iceberg is currently estimated to be 12 million tonnes/21/. Figure 3 summarizes typical environmental criteria for the Beaufort Sea and Grand Banks.
4 USES FOR ARCTIC OFFSHORE STRUCTURES

To date all arctic offshore structures (that I know about) have been built to explore for oil and gas. Future offshore structures will also most likely be used for hydrocarbon exploitation. In this context, there are three broad uses for arctic structures; exploration drilling, production operations and tanker loading.

4.1 Exploration Drilling

It is the nature of uncertainty in hydrocarbon exploration that on average only one wildcat well in ten is a discovery. For this reason, exploratory drilling structures at any one location can be regarded as temporary. This is the major design influence, and economic constraint. It has led to two types of solutions for bottom-founded arctic structures. One solution is to use temporary dredged islands for winter drilling only. These are allowed to erode away after the rig has been removed. All the Esso islands built to date in the Beaufort Sea have been of this type. The other solution is to use a mobile structure which can be ballasted down onto the sea floor for the period of drilling and testing.

For exploratory drilling, a surface about 100 m in diameter is needed for the rig, camp, equipment storage, etc. Because of the temporary nature of exploration islands, they are often designed for loading events associated with a 25 year return period. If the load event is site-specific, this is probably a logical design philosophy. However, if the event is area specific, and islands are being built and used every year over a period of years, then higher return-period events should be considered.

4.2 Production

Structures and islands for production have to allow for the drilling of perhaps up to twenty producing and/or injection wells. In addition, space for primary processing of produced fluids is needed. Storage of produced oil may be needed, as well as equipment for reinjection of produced gas. In addition, space
is needed for accommodation of personnel and storage of consumables. All this adds up to greater space requirements than exploration structures and a typical production island will have a diameter of about 200m. A concrete or steel structure will require the same total area, but may have several levels to achieve a more compact design.

Production structures will usually be built for a life of between twenty and thirty years. This will require designing for more extreme loading events than in the case of exploration islands. The normal practice in other offshore areas is to design for a 100 year event. However the risk level chosen for a particular system should be qualified by the type of event, the safety factors used, the consequences of failure and especially by the ability to predict extreme events in time to evacuate the platform, drain-down storage and close-in the wells.

4.3 Tanker Loading

In some areas, tankers may be used instead of pipelines for the transportation of hydrocarbons to market. In this case a means of loading a tanker is needed. In ice-covered waters special designs are required. One solution is to create an enclosed harbour which protects the tanker from the moving ice. Another solution is to have a special single point mooring structure which allows the tanker to "weather vane" in the protected ice of the structure. Both of these approaches require special consideration of ice management, and tanker operations in ice.

5 STRUCTURAL OPTIONS FOR ARCTIC OFFSHORE STRUCTURES

To fulfill the requirements just described, and to accommodate the severe environmental factors of the Arctic, many different configurations and types of offshore structures have been proposed.

It is of interest for example to look back to ten years ago at what solutions were being considered. Figure 4 shows exploratory drilling concepts then considered possible for ice covered
areas. Various solutions were thought appropriate for each type of ice zone and water depth. Since Figure 4 was drawn some concepts, notably artificial islands, drillships and ice platforms have all been used successfully. Designs for steel or concrete cones and monopods have been made, but none have yet been built (largely because of their high capital cost).

Figure 5 shows possible production concepts being considered about a decade ago. No production has yet occurred from the arctic offshore areas, but designs do exist for production islands and concrete gravity production structures.

Some specific examples of these generic types of structures will now be described.

5.1 Conventional Islands

As already mentioned, about twenty so-called conventional dredged islands have been built to date in the Beaufort Sea for exploratory drilling. ("Conventional" islands are those which don't use special retaining structures or caissons in their construction). Typical beach configurations are shown schematically in Figure 6. The sacrificial beach island is usually only possible at those locations where abundant local sand or gravel is available for construction.

Conventional islands have been used out to the 20 m water depth and have proven their capability to withstand normal ice conditions (mostly first-year ice) in the nearshore zone. Furthermore, no instances of serious ice ride-up have occurred.

In the nearshore zone the ice eventually becomes landfast, however in the early winter it is mobile and extensive grounded rubble fields usually occur around the islands (Figure 10). The rubble fields provide protection against ice ride-up, provide additional sliding resistance, but also increase the effective width of the islands to ice loads. The rubble field phenomenon has been discussed by several previous authors and research on grounded rubble fields continues/1/7/12/19/.
As mentioned earlier, although dredged islands can easily resist the ice, they are susceptible to damage by waves. Two effects are of concern, wave run-up, and erosion. The sacrificial beach design helps to mitigate both effects. For permanent production islands maintenance of the sacrificial beaches will be needed, probably on an annual basis. Also higher freeboards will be required to avoid extreme wave run-up and ice ride-up events. An alternative production island design uses armour blocks to prevent wave erosion (Figure 7).

Conventional dredging techniques result in island slopes of about 1 in 15. As water depths increase the volumes of granular material increase dramatically (see Figure 8). This is why for deeper locations, steeper island slopes are desirable.

5.2 Islands With Concrete Caissons and Steeper Dredged Slopes (I.e. Tarsiut)

To alleviate the problems of erosion and large fill volumes, a new design of island was installed at the Tarsiut location in 22 m of water. (Tarsiut was designed and constructed by Dome/Canmar on behalf of the operator Gulf Canada).

The cross-section of the Tarsiut island is shown in Figure 9. Four concrete caissons were built to 7 m below water level. The concrete caissons provided a means of rapid water-line penetration and formed retaining structures for the interior fill. A vertical wall design was used to simplify construction and also to discourage ice ride-up (no ice deflectors were installed). The four concrete caissons were sandfilled and resisted outward pressures from the interior fill without being connected to each other at the corners. This feature considerably simplified the structural design of the caissons, and they were built in Vancouver in less than six months.

Another major advance at the Tarsiut location was to build the berm with steeper slopes than had been achieved before. The target slope was 1 in 5 compared to the usual underwater dredged slope of about 1 in 15. By this means, the aim was to keep the dredged fill volume to less than 2.0 million cubic metres. This
was necessary because the nearest large deposit of good quality sand was at Ukalerk 120 km from the Tarsiut location. The target slope of 1 in 5 was achieved by controlled placement of the fill, which had been brought from Ukalerk by the Geopotes X, a large trailer hopper dredge. The Tarsiut story will be told in more detail by others at this conference and elsewhere /15/23/.

The caisson system at Tarsiut has worked quite well. Two wells were drilled from the island, one in winter and one in summer. The island was originally conceived as a winter drilling system only, and for the summer operation the island was upgraded to provide better resistance to waves. This upgrading consisted of adding one metre rock at the toe of the caissons, and adding large gabions above the wall of the caissons to protect against wave-run up.

Tarsiut was extensively instrumented for ice forces and measurements are still being taken. An extensive rubble field formed around the island. See Figure 10. As predicted, it grounded on the slopes of the berm to about the -20 m water depth. To achieve relief well capability, a grounded ice pad was built on the rubble, on the north side of the island. This was planned in advance, and the underwater berm was extended in this area and brought to about -4 m before freeze-up. The ice pad was built by collecting ice from the naturally formed rubble using bulldozers, and also by daily flooding. The ice pad was raised to about +7 m by January and was stable through the winter. /24/.

One of the major drawbacks with the Tarsiut type design is that the rig and equipment have to be placed after the island has been constructed. This often results in the rig-up occurring during freeze-up at large expense and with considerable uncertainty because of variation in freeze-up dates. To eliminate this problem, the single caisson design on which the rig is already mounted has evolved.
5.3 The Single Steel Drilling Caisson (SSDC)

The SSDC was conceived and brought into the Beaufort by Canadian Marine Drilling, a Dome subsidiary. It is presently drilling at the Uvilkuk location in 31 m of water (Figure 11).

Its design is aimed at providing a system with the rig already mounted so that rapid deployment and removal can be achieved. It is a water ballasted system with a freeboard of 16 m, it sits on a prepared berm built up to -9 m (Figure 12). It is designed for initial use as a winter drilling system, but can be used during the summer if the berm is protected against erosion, and extreme multi-year ice is not in the area.

As can be seen from the photograph, the SSDC is the converted forebody of a 230,000 dead-weight ton oil tanker. It was converted by Hitachi Zozen of Osaka during the first half of 1982. Extensive ice strengthening with 7,000 tonnes of steel and 14,000 m³ of concrete was installed during conversion. 186,000 tonnes of water ballast is added to achieve sliding resistance on the berm, and the base of the tanker hull has been treated with 'shotcrete' to improve sliding friction. The system is described in more detail by Janson, /15/ and Mitchell /23/.

The SSDC's first location at Uvilkuk in 31 m of water is the first location which is outside the landfast ice for the whole of the winter. Even so, that area of the Beaufort, in a normal winter, sees only first-year ice. This has been the case at Uvilkuk during the past winter. Routine aerial reconnaissance flights were undertaken however, to ensure that advance warning of any large multi-year ice floes could be given. In addition, a large ice pad has been constructed to provide relief well drilling capability and additional sliding resistance.

The SSDC will be moved next summer to the Nerlerk location in 45 m of water, where berm is 70% complete following the 1982 construction season.
5.4 The Esso Caisson Retained Island (CRI)

Design on the Esso retained island began in about 1974. It was realized then that conventional dredged islands would get more and more difficult to build as water depths increased and if local fill was unavailable. The major aim of the CRI design is to reduce fill requirements and provide quick water-line penetration and wave protection. The eight steel caissons forming the retaining structure each contain about 1000 tonnes of steel they are linked together by stressing cables into a ring 117 m across, which contains the inner sand fill (see Figure 13). Each caisson is 12 m high and the whole caisson ring is water-ballasted down onto a berm built to within 9 m of the water level. The caissons have a 60° face and a wave-ice deflector adds another 4.5 m to the height of the caissons. After a winter drilling season the caisson ring can be raised, split into two halves and towed to a reassembly area in preparation for lowering at a new location /9/25/.

5.5 The Gulf Mobile Arctic Caisson (MAC)

The Gulf Mobile Arctic Caisson (MAC) was conceived to provide the most desirable characteristics of a shallow-water arctic system, namely; rapid deployment, minimum dredging, and good resistance to both waves and ice. As can be seen from Figure 14 it consists of a symmetrical monolithic steel structure which sits either directly on the sea floor on a berm at -15 m. The system is sunk onto the berm by water ballast (its light ship draft is 5 m) and overall sliding resistance is provided by interior sand fill (of 115,000 m³). The height from the water line to the top of the ice/wave deflector is 12.5 m. The sides of the caisson have a slope of about 75° from the horizontal. The MAC is designed for multi-year ridges up to 21 m thick /4/. The MAC is presently under construction in Japan and is expected in the Beaufort Sea in the summer of 1984.

5.6 Other Ballasted Caisson Systems at the Design Stage

With increased activity related to offshore Alaska, a number
of other organizations have recently disclosed their designs for mobile arctic drill systems.

Standard Oil of Ohio (Sohio) have a design for a monolithic ballasted caisson system. It is an octagonal barge structure with a reinforced, prestressed concrete base supporting steel drilling modules. It is known by the acronym SAMS (Sohio arctic mobile structure). A unique feature of SAMS is the provision for 56, 2 m diameter steel spuds which can be driven as much as 12 m into the mudline to provide enhanced horizontal resistance /13/.

Brian Watt Associates have also designed a monolithic water ballasted system (known as BWACS). This a honeycomb cellular concrete structure with vertical sides. It is designed primarily for the landfast ice zone (i.e. mainly first-year ice) but it has significant capability to resist multi-year floes /30/.

Swan Wooster Engineering in association with Anglo Energy have developed a design for a monolithic steel exploration structure rather like the SSDC. It is rectangular, has slightly sloping sloping sides (25° from the vertical) and is partially sand filled.

There are probably other exploratory caisson systems under development which have not mentioned. It is of interest to note that all recent designs benefit from the Canadian Beaufort experience, and they strive to achieve rapid deployment and minimum dredging.

5.7 Gravity Conical Structures for the Beaufort Sea

For the deeper Beaufort waters where multi-year ice is common, and lengthy ice cover restricts dredging and floating drilling, organizations have developed designs for concrete or steel conical shaped structures. The narrow cone structure has significant advantages in reducing ice loads from multi-year floes and ridges.

Cone designs go back to 1970 (and probably further) when Esso as operator of APOA Project 12 looked at various designs for
arctic offshore structures /2/. Subsequently, numerous model tests were done to establish ice loads; and monocone designs were developed for various water depths /17/. Dome also developed a monocone design in the late 1970's /27/.

More recently, a study is being conducted for the Alaskan operators by Brian Watt and Associates of an arctic cone exploration structure (ACES) /30/. To date, the major inhibition to actually constructing a conical exploration structure has been the high capital cost, and the progressively achieved success of islands and drillships.

5.8 Beaufort Sea Production Structures

As already discussed, production structures need to be larger than exploration structures, they also are more permanent and should therefore be designed for more extreme load events. On the other hand, production structures will only be installed once a particular deposit of oil or gas has been found and proved commercial. Therefore because there is more certainty about the potential revenues, it is usually possible to commit larger sums of money to install a production structure than an exploration structure. This is why island-type structures for the Beaufort Sea are being considered for significantly deeper water than they are used in for exploration.

Shallow water production islands would use the same technology described for exploration, but would be larger and have higher freeboards. For example a conventional dredged production island would have a diameter of about 200 m, a freeboard of +20 m, and have armoured 1 in 3 slopes down to -8 m, see Figure 7. The choice of armour size obviously depends on the selected design wave condition. For a location with a maximum design significant wave of 6 m, an armour size of 10 tonnes is suggested /28/.

Hybrid island-caisson systems have also been designed which in some cases are similar to scaled-up Tarsiat-type designs, (see Figure 15). Other approaches use a monolithic caisson system, which either sits on a berm or the sea floor and is protected against extreme ice features by the surrounding berm.
Calculations based on the ice load models discussed by Croasdale and Marcellus /8/ indicate that such designs can probably cope with the most extreme ice features expected in the Beaufort Sea.

In places where sea floor conditions are not suitable for large dredged structures, it may be possible to use steel or concrete conical-shaped structures piled into the sea floor. Such designs have yet to be developed.

5.9 Beaufort Sea Loading Terminals

Two types of tanker loading terminals have been proposed in the recent Beaufort Sea Environmental Impact Statement /11/. One approach is to allow the tanker to enter an enclosed harbour where it will be protected from the moving ice (see Figure 17). The other design requires the tanker to be moored in the lee of a caisson type structure /28/. Both systems can be designed to resist ice and wave loads. The critical issues are related more to tanker manouevering and ice management and are beyond the scope of this paper.

5.10 Production Structures for the Canadian East Coast

Bottom-founded structures are being considered for the development of the Hibernia field in 85 m of water off Newfoundland /16/21/. The area is usually free from extensive sea ice and the critical ice feature is the iceberg. Structures are currently being designed for impact by an iceberg of 12 million tonnes moving at 0.5 metre per second. The most effective design will be one which will stop the berg over the longest distance, hence reducing the peak impact force. For example, the kinetic energy of the berg just described is 1.5 GJ. If this energy is dissipated by the work done of a linearly increasing force over a stopping distance of 1 m, then the peak force is $3 \times 10^6$ KN (approximately 300,000 tonnes-force). (This simple calculation neglects the added mass of the berg). Clearly if the stopping distance is doubled to 2 m, the peak force is reduced to $1.5 \times 10^6$ KN (or 150,000 tonnes).
For a rigid structure the actual stopping distance will be governed by the external geometry of the structure and the crushing strength of the ice. The energy absorbed by structural deformation, may reduce the peak force; however the stresses in the structure may also be magnified by its dynamic response. Special energy absorbing devices such as deformable or sliding outer structures might be incorporated in order to provide additional energy sinks (as suggested by Norwegian Contractors). The justification for, and cost-effectiveness of, such devices can only be determined by in-depth technical studies.

Several structural geometries to extend the distance of penetration of an iceberg crushing against a structure (and hence reduce the peak load) have been suggested. One such design using a "gear-tooth" cross-section is shown conceptually in Figure 17.

Other energy absorbing approaches have been suggested. One is to incorporate a subsea berm into the structural configuration as suggested by Jarlin /16/, see Figure 18. However the height of such a berm would have to be kept quite a way below sea level in order to prevent erosion by severe storm events. An optimum design would balance ice loads, wave loads and erosion of the berm.

Another way of dissipating the kinetic energy of a colliding iceberg is to have a sloping structure which raises or rotates the iceberg and gives it potential energy. Calculations show that a blocky iceberg needs to be raised less than a metre at its leading edge to dissipate its kinetic energy. Figure 19 shows a concept for a conical structure to resist iceberg impacts.

6 ICE INTERACTION

6.1 Beaufort Sea General

Recent Canadian Beaufort Sea accomplishments have demonstrated that structures can be installed to withstand the forces of
moving first-year arctic pack ice. To date these structures (which have been described in this paper) incorporate a subsea berm which leads to the creation of a grounded rubble field. The grounded rubble field usually protects the water-line portion of the structure from direct ice action. Furthermore this phenomenon suggests that for winter ice conditions, there is little point in incorporating sloping sides on the structure because the active zone moves to the edge of the grounded rubble.

Except for temporary winter drilling locations, the governing ice design criteria for the Beaufort Sea is the impact of large multi-year floes, usually in the summer or autumn. Critical parameters governing these ice loads are floe diameters, average thicknesses, edge thicknesses and speeds. Statistics for these quantities in the Canadian Beaufort were recently compiled by Marcellus and Morrison /20/. Careful consideration of these data is required before specifying ideal production structures. Especially when determining optimum berm height to give protection against extreme ice features, and whether or not to incorporate a sloping side on the structure.

Little experience has yet been gained in the Beaufort Sea with extreme multi-year ice interaction. However recent work at a natural island (Hans Island) has allowed measurement of gross forces generated by large-scale multi-year ice collisions. /22/.

Global loads are also governed by the driving forces in the polar pack, which in turn are probably limited by ridge building forces. (Croasdale and Marcellus, /8/; Vivrat and Kreider, /29/.

In addition to global load considerations, local ice pressures have to be designed for. It is these which are likely to govern wall thicknesses and local framing, and may well govern the cost of a structure. Local ice pressures are not well understood, especially in terms of the influence of loaded area, geometry of confinement, and type of ice. Recent papers by Bruen et al
6.2 Iceberg Impacts

As discussed, the global loads caused by iceberg impact are related to the distance over which the berg is brought to rest. For an iceberg colliding with a vertical structure the load will be a function of the ice crushing strength and the area of contact versus penetration. Cammaert and Tsinker /5/ presented equations for a structure of circular cylindrical form and a blocky berg. These are of the form.

\[ F_m = 2t_1 \sigma (2r x_m - x_m^2)^{1/2} \]  
(1)

where \[ x_m = \left( \frac{0.27 \sigma r^2 t_2}{t_1} \right)^{3/2} \]  
(2)

where \( F_m \) is the maximum force, \( x_m \) is the maximum relative penetration, \( t_1 \) is the local iceberg thickness, \( t_2 \) is the average iceberg thickness, \( r \) is the local structure radius, \( \sigma \) is the average ice crushing strength, \( l \) is the iceberg length and width, \( \rho \) is the ice density, and \( V \) is the initial velocity of the iceberg.

As an example look at a typical impact scenario of a very large iceberg of 12 million tonnes moving with an initial velocity of 0.5 m/s. Further assume that \( l = 350 \) m, \( t_2 = 100 \) m, \( t_1 = 50 \) m, \( r = 10 \) m, \( \rho = 1000 \) kgm\(^{-3}\) and \( \sigma = 7 \times 10^6 \) Nm\(^{-2}\) (1000 psi).

Substituting gives a relative penetration of 0.8 m and a maximum horizontal force of 2.74 \times 10^6 \text{ kN} (or 274,000 tonnes force).

It is of interest to look at the sensitivity of the global force to the average ice crushing strength. This is shown in the following table.
Work is presently underway to refine these simple impact models and to address the uncertainty in the crushing strength of iceberg ice. To date most data on the strength of iceberg ice comes from small scale tests. There is a need to obtain strengths which relate to real-scale situations. We are currently preparing plans for field simulations of iceberg impact phenomenon.

Sloping-faced structures do offer a potential for lower loads as also discussed by Cammaert and Tsinker /5/. An additional energy sink with a sloping structure is the gain in potential energy of the iceberg as its leading edge is raised and the berg rotates. The vertical component of the normal ice crushing force, plus any inertial forces, will also help to stabilize the structure by acting downwards to increase its frictional sliding resistance. A conical structure of the type shown in Figure 19 could also be designed for an optimum balance between wave and ice forces. A conical structure may however be more expensive than a simple cylindrical shaped platform. Further work on the design of conical structures to resist icebergs is underway.

7 CONCLUDING REMARKS

Recent activities in the Canadian Beaufort Sea have seen routine use of artificial islands for exploratory drilling out to 20 m of water. For deeper water, caisson systems at Tarsiut and Uviluk have already been successfully used. The combination of caissons and steeper dredged slopes has enabled island systems to be used effectively for exploratory drilling in ever-increasing water depths.
New caisson systems will soon be operating in the Beaufort. All the new caisson designs attempt to achieve rapid deployment and to minimize dredging. Some caissons use water ballast and some use sand ballast.

To date, experience with ice has indicated force levels lower than designed for. On the other hand extreme multi-year ice interactions have not yet been experienced. Research at Hans Island however indicates that even extreme multi-year ice events can be predicted and resisted.

Wave erosion and run-up continue to be a problem, although no catastrophic failures have occurred. The newer designs incorporate features to minimize wave problems.

Production structures conceived for the Beaufort are based on experience with exploration structures. Designs with subsea berms are considered to be capable of resisting the worst ice features such as ice islands and multi-year hummock fields.

Off the Canadian East Coast, designs for bottom-founded structures have been prepared which are considered capable of resisting impact by large icebergs. Work continues to optimize these designs and extend their application into deeper water and for more severe conditions. Plans are being prepared to obtain large-scale iceberg crushing strengths.

The technology to install offshore structures to exploit existing and future hydrocarbon discoveries in ice-infested areas is well in-hand.

8 ACKNOWLEDGEMENTS

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Figure 1

BEAUFORT SEA
ICE ISLAND RETURN PERIODS
(After DefTran et al. 1982)

Figure 2

TYPICAL PHYSICAL ENVIRONMENTAL DESIGN CRITERIA

ICE
- PRESENT 9 MONTHS OF YEAR
- FIRST-YEAR SEA ICE UP TO 2m THICK WITH RATTING & RIDGING
- LARGE SHEETS & FLOES MOVING OVER 10km PER DAY

BEAUFORT SEA
- MULTI-YEAR FLOES UP TO 1km ACROSS, 8m XL THICKNESS WITH LOCAL THICKENING UP TO 10m SPEEDS UP TO 10kn
- LARGE ICE ISLANDS GREATER THAN 500 YEAR RETURN PERIOD

CANADIAN EAST COAST
- GRAND BANKS
- ICEBERGS MAX CREDIBLE MASS OF 12 MILLION TONNES MOVING AT 0.5kn
- FIRST-YEAR SEA ICE SMALL FLOES ABUNDANT ACROSS 10kn W-T WAVES
- BERG-BITS DRIVE BY WAVES

WAVES
- SHALLOW LOCATIONS UP TO 25kn MAX SIGNIFICANT WAVE HEIGHT
- DEEPER LOCATIONS UP TO 10kn MAX SIGNIFICANT WAVE HEIGHT
- 100 YEAR MAX SIGNIFICANT WAVE HEIGHT OF 15m

Figure 3
EXPLORATORY DRILLING CONCEPTS FOR ICE INFESTED WATERS

Figure 4

PRODUCTION CONCEPTS FOR ICE INFESTED WATERS

Figure 5
TYPICAL SHALLOW DREDGED ISLAND CROSS-SECTIONS

Figure 6

Figure 7

ARMOUR SLOPE ISLAND
GENERAL WAVE CONDITIONS WITH $H_s = 6.0m$

Figure 8
The Tarsiut Island Cross-Section

Figure 9

The Tarsiut Island in Winter.

Figure 10

The Single Steel Drilling Caisson.

Figure 11

Figure 12
Figure 13

Figure 14

Figure 15

Figure 16

ARCTIC PRODUCTION AND LOADING ATOLL (APLA)
Figure 17
The Proposed Norwegian Contractors Ring Gravity Structure.

Figure 18
The JARLIN* Production Concept for Grand Banks

Figure 19
Possible Production Concept for Canadian East Coast Designed to Resist Icebergs
A.B. Cammaert, Manager, Arctic and Offshore Services
T.T. Wong, Engineering Systems Analyst
D.D. Curtis, Engineering Systems Analyst

Acres Consulting Services Limited
Calgary, Canada

IMPACT OF ICEBERGS ON OFFSHORE GRAVITY AND FLOATING PLATFORMS

Abstract

The potential collision of icebergs with floating or bottom-fixed structures remains one of the most serious obstacles to the production of oil from the Hibernia field, offshore Newfoundland. Various analytical techniques are presented for the calculation of impact loads. For gravity platforms the influence of the contact face and the effect of variable ice crushing strength as a function of strain rate and penetration depth are investigated.

A simple one-degree-of-freedom model is formulated for the case of a berg bit colliding with a semisubmersible. Several typical case studies are analyzed and motion characteristics are presented. The basis of development of a three-degrees-of-freedom iceberg-structure interaction model is also described. Such a model incorporates plastic deformation of the iceberg, elastic/plastic deformation of the structure, platform excursions, and flexibility of the mooring system.

1 INTRODUCTION

The presence of icebergs poses the greatest threat to offshore oil production from the Hibernia field [8]. The field is approximately 300 km southeast from St. John's, Newfoundland and
is in the general path of icebergs drifting south from Greenland under the influence of the Labrador Current.

The present study outlines a number of analytical procedures to give preliminary estimates of impact loads on both floating and gravity-base structures. A sensitivity analysis which includes the effects of variations in structural configurations and iceberg crushing strengths is carried out for impact loads on gravity platforms. A one-degree-of-freedom system is formulated for bergy bit impact with semisubmersibles, and a range of loading cases and mooring characteristics are analyzed. A numerical procedure is proposed for a three-degree-of-freedom iceberg/semisubmersible interaction model, which takes into account iceberg and structure deformation, vessel excursions, and the overall flexibility of the mooring system.

2 LITERATURE REVIEW

Kivisild [5] has calculated the forces resulting from the collision of a growler with a drillship, moored or dynamically positioned. The size of the growler and its velocity at impact were varied in order to define critical conditions for ice impact on the drillship. Camaert and Tsinker [2] used an energy balance approach for preliminary estimates of the impact of icebergs on cylindrical and conical gravity-base platforms. The analysis assumes that when an iceberg collides with a massive structure, the contact zone will fail by crushing, and will increase in size as the resisting force is steadily increased. The kinetic energy of the berg is then decreased until an equilibrium is reached.

The most recent work on the impact of bergy bits with semisubmersibles has been published by Reddy et al [10]. This work describes initial studies on motion and structural response to wind, wave, current and bergy bit impact forces. The authors perform a time-history analysis of a single-degree-of-freedom
model for independent surge and pitch motion. The impact force/time history is obtained from analytical considerations of conservation of momentum and energy during impact.

3 IMPACT SCENARIOS

Two possible impact scenarios are assumed. Mobile drilling and production units can be designed to move away from approaching icebergs which are detected under extreme environmental conditions. However, such units must be designed for impact with ice features that cannot be detected. While the limit of existing radar systems has not yet been established it is assumed that hergy bits ranging in size from 5,000 to 50,000 tonnes may be a collision hazard. The second scenario is that of a gravity-base structure which, since it cannot be moved easily, must be designed to withstand all iceberg impacts.

4 INFLUENCE OF ICEBERG CRUSHING STRENGTH

One of the least defined parameters which affects iceberg/structure interaction is iceberg compressive or crushing strength. Very few iceberg ice samples have been retrieved and tested. Recent work carried out by the oil companies is still proprietary; however, one testing program was carried out recently by the Newfoundland Petroleum Directorate [4]. Samples used in the study came from five grounded icebergs in various Newfoundland coastal areas. It was observed that iceberg ice is a more deformable fracture-resistant material than freshwater ice at similar temperatures. The bubbles present in icebergs (air trapped during the glaciation process) likely inhibit fracture formation. Iceberg ice failed at mean failure stresses approximately 35% higher than lake ice tested at the same time. For a total of 11 samples, the test results are summarized as follows:
Mean uniaxial crushing strength: 5.33 MPa
Mean Young's modulus: 6.09 GPa
Test temperature: -3 to -6°C
Strain rate: 1.1 x 10^{-3}/s

It is interesting to compare these results with Michel's universal curve (Figure 1) for uniaxial crushing of S2 ice (representative of most types of sea ice). At a strain rate of $10^{-3}/s$, the comparable strength of S2 ice at a temperature of -10°C is approximately at its highest level of 7.5 MPa. When modified for a higher test temperature of -4°C [7] the expected crushing strength of S2 ice is approximately 3.7 MPa. Hence iceberg crushing strength, as observed from this testing program, is about 50% higher than sea ice for comparable temperatures and strain rates. Unfortunately, there are no data available on temperature profiles for icebergs. If it can be assumed that the mean ice temperature in the contact zone is about -10°C, then an approximate maximum uniaxial crushing strength ($\sigma_{cm}$) for icebergs is about 50% higher than the maximum strength of sea ice, or about 11 MPa.

![Figure 1. Michel's Uniaxial Crushing Curve [7].](image-url)
No information is available on the behaviour of iceberg ice at high strain rates, and it is assumed that failure processes are comparable to other ice types. Since it is expected that most iceberg collisions will occur at high strain rates, iceberg ice will likely fail in pure brittle fracture. From Michell's universal curve, it is seen that brittle crushing strength is virtually constant with variations in strain rate. This is also observed in tests carried out by Exxon [3]. Although some tests indicate a reduction in crushing strength after strain rates of about 5 x 10^{-4}/s, it is assumed here that crushing strength remains constant after this point. Hence, for the transition and brittle failure zones:

\[ \sigma_c = \sigma_{cm}. \]  \hfill (1)

The strain rate \( \dot{\varepsilon} \) is calculated as

\[ \dot{\varepsilon} = \frac{V}{4D} \]  \hfill (2)

where \( V \) is penetration velocity and \( D \) is the width of the contact face.

There may be instances, however, where the initial velocity is low and ductile failure could occur. In this zone ice crushing strength can be expressed as [7]

\[ \sigma_c = 11.4(\dot{\varepsilon})^{0.32} \sigma_{cm} \quad (\dot{\varepsilon} < 5 \times 10^{-4}/s). \]  \hfill (3)

The overall effective crushing pressure \( p \) may be written as

\[ p = C \sigma_c \]  \hfill (4)

where \( \sigma_c \) is the appropriate crushing strength for the applicable strain rate range. \( C \) is the indentation coefficient which has a value of 2.97 for ductile behaviour and 1.57 for brittle conditions [7]. The factor \( k \) is a contact coefficient (0.6 for ductile conditions and 0.30 for brittle conditions). The value \( m \) is a form coefficient (0.9 for a cylindrical indenter). Hence for brittle behaviour the average crushing pressure for iceberg ice (at \(-10^\circ\text{C}\) and for a cylindrical
structure) will be approximately:

\[ p = 1.57 \times 0.30 \times 0.90 \times 11 = 4.7 \text{ MPa} \]  \hspace{1cm} (5)

After initial impact, and as the structure penetrates the iceberg, ice crushing stresses increase with the degree of penetration. Vivatrat [11] has analyzed deformation patterns, strains and strain rates in sea ice indentation problems and their application to ice load prediction. From a variety of field and laboratory tests, he has developed pressure-displacement curves (Figure 2), and he has observed that the initial load build-up is similar for a number of tests. The indentation pressure \( p \) is related to indenter width \( D \) and indenter displacement \( x \) by:

\[ p = 300x/D \text{ MPa}. \]  \hspace{1cm} (6)

Such a relationship, however, does not take into account indenter shape, ice type, temperature, strain rates, scale ratio and other effects.
5 PRELIMINARY ANALYSIS OF ICEBERG IMPACT WITH A GRAVITY PLATFORM

A simplified analysis of a 'blocky' iceberg colliding with a cylindrical gravity-base platform (Figure 3) was presented by Cammaert and Tsinker [2]. The analysis is extended here to include the sensitivity of various factors influencing iceberg loadings.

It is assumed that the collision is central; hence the full kinetic energy \( E_k \) of the iceberg, is absorbed in the collision. With an added mass of \( (7.5 \text{ m}) \) the total kinetic energy is:

\[
E_k = 1.5(mV^2/2) \tag{7}
\]

For a uniform cylindrical platform the contact width \( D_x \) for a penetration distance of \( (x) \) is

\[
D_x = 2 (2Rx-x^2)^{0.5} \tag{8}
\]

where \( (h) \) is the iceberg depth and \( (R) \) is the platform radius.
If the exterior of the platform consists of wedge-shaped walls, then the width of the contact face is

\[ D_x = 2x(\tan \alpha) \]  

(9)

where \( (2\alpha) \) is the cone angle.

The impact load is then defined as:

\[ F_x = D_x h p. \]  

(10)

With the assumptions discussed in reference [2'], the maximum impact force and penetration distance are found by equating the kinetic energy of the berg to the energy absorbed in crushing:

\[ E_k = \int_{0}^{x_m} F_x dx \]  

(11)

where \( (x_m) \) is the maximum penetration distance.

This equation is solved numerically and a sensitivity analysis is presented in Figures 4A to 4G for the following reference design:

- Iceberg mass, \( m \) : 15 x 10^6 tonnes
- Iceberg depth, \( h \) : 75 m
- Iceberg velocity, \( V_0 \) : 1.0 m/s
- Iceberg crushing pressure, \( p \) : 5.0 MPa
- Platform radius, \( R \) : 60 m

The effect of varying the radius for a cylindrical platform is shown in Figure 4A. For a structure of radius 60 m (reference design), the impact loading is 10,400 MN and the penetration distance is 1.6 m. If the exterior walls of the platform are constructed of interconnected cylinders of smaller radius (Figure 3) the penetration depth is increased, and for a radius of 7.5 m the total load is reduced by 55 percent to 4,700 MN. The impact loads can be reduced even further by the use of wedge-shaped exterior walls (Figure 4B). For a wedge angle of 60° the impact
FIGURES 4A-4G. PARAMETRIC ANALYSIS OF ICEBERG IMPACT WITH GRAVITY STRUCTURE.
loading is 5,400 MN; and for 30°, the loading is 3,100 MN (72 percent less than the reference design) and the penetration distance is 7.2 m.

If average crushing pressures are higher than those assumed (5 MPa), the general effect is an increase in impact loadings (Figure 4C). For example, the impact force is 16,500 MN for an average crushing pressure of 10 MPa (constant with depth). If the crushing strengths is assumed to vary with strain rate (Figure 4D) as per equation (3), the impact loading is 14,800 MN. For crushing strengths which vary with penetration depth as in equation (5), the loading is increased to 22,800 MN.

It is of interest to note the variation in contact time and strain rate with penetration depth (Figures 4E to 4F). The total contact time is 4.8 sec. Within 1.0 sec. after initial contact the strain rate is less than 2x10^{-2}/s, which is in the brittle failure range. The average strain rate is approximately 1.2x10^{-2}/s.

6 PRELIMINARY ANALYSIS OF BERGY BIT IMPACTS WITH SEMISUBMERSIBLES

The potential collision of a bergy bit with a semisubmersible can be idealized as a single-degree-of-freedom (SNOF) system. This allows a preliminary sensitivity analysis of platform motions and provides a basic aid in understanding iceberg/structure interaction.

Consider the system shown in Figure 5. The mass M represents a platform, which includes an added hydrodynamic mass. The damper represents the viscous drag caused by the relative motion of the platform and the surrounding water. The spring, which can be nonlinear, represents the mooring system for the semisubmersible, with restoring force R.
The basic equation of motion is

\[ M \ddot{x} + c \dot{x} + R x = F \]  

(12)

where \( F \) is the impact force acting on the platform due to the bergy bit impact.

A Fortran program to solve the equation for irregular force/time histories and nonlinear springs is given in reference [6]. Three combinations of assumed forcing functions (Figure 5) and mooring stiffnesses are analyzed, and the results are represented in Figure 6 for the following reference design:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bergy bit mass, ( m_b )</td>
<td>50,000 tonnes</td>
</tr>
<tr>
<td>Bergy bit velocity, ( V_b )</td>
<td>1.2 m/s</td>
</tr>
<tr>
<td>Semisubmersible mass, ( m_s )</td>
<td>20,800 tonnes</td>
</tr>
<tr>
<td>Viscous damping/critical damping</td>
<td>0.01</td>
</tr>
<tr>
<td>Mooring cable stiffness (stiff)</td>
<td>78 MN/m</td>
</tr>
<tr>
<td>Mooring cable stiffness (less stiff)</td>
<td>21 MN/m</td>
</tr>
</tbody>
</table>

The impact force/time histories computed by Arockiasamy and Reddy [1] were input into the SDOF model (Figure 6A). The forcing functions were obtained by considering the momentum transfer of the lumped mass of the bergy bit, semisubmersible and added mass moving at a common velocity \( V_{bs} \). The forcing functions and resulting surge displacements are plotted in Figures 6A and 6B respectively.
FIGURES 6A-6D. ANALYSIS OF BERGY BIT IMPACT WITH SEMISUBMERSIBLE.
For the forcing function in Figure 6C, the damping was arbitrarily increased to 0.10 times the critical value, and the surge displacements are plotted in Figure 6D.

The SDOF model has a number of shortcomings including: knowledge of the impact force is required for the analysis; only constant values of hydrodynamic added mass and damping can be considered; and only head-on collisions can be modelled. It was decided to improve the SDOF model to account for true collision simulation, improved hydrodynamic behaviour and to increase the number of degrees of freedom for the system.

7 DEVELOPMENT OF NEW ICEBERG/STRUCTURE INTERACTION MODEL

A three-degree-of-freedom (TDOF) iceberg/structure interaction model is under development by Acres and funded by the Newfoundland Petroleum Directorate. The model is being developed first for bergy bit/semisubmersible interaction, but it can also be modified to describe the interaction between icebergs and gravity-base platforms. The impact model proposed is based largely on the work of Petersen and Pedersen [9]. The motions analyzed are sway, surge and yaw (Figures 7 and 8).

The kinetic energy of the iceberg is dissipated by a combination of the following:

- local plastic deformation of the iceberg by crushing
- local deformation (elastic and plastic) of the structure
- tension change in mooring cables
- vibration (global and local).

The forces exerted during iceberg crushing vary primarily with contact area and crushing strength, and are derived in the same way as for gravity structure impact.
The drill rig absorbs energy due to impact in the form of local denting of elements, development of plastic hinges, membrane tension, and buckling of braces. Local denting of individual elements will be evaluated using analytical techniques. A nonlinear analysis of the structural system is carried out using a standard structural analysis program, modified to account for plastic hinges.

The mooring cables introduce a geometric nonlinear stiffness into the system. As the platform translates, the catenary shape changes and a new secant stiffness is computed. Simplified methods are available which allow the equivalent stiffness of mooring cables to be computed. The strain energy absorbed by the cables is readily computed when the rig translation with time is known.

Energy absorption through structural vibration is expected to be very small, since the moored semisubmersible represents a rather "soft" structure, and is ignored in the analysis.

The equations of motion for the iceberg are as follows:

\[ [M_1] \ddot{X}_1 + [C_1] \dot{X}_1 = F_1, \]  

(13)
The mass matrix of iceberg and the added mass of water

The damping matrix, a function of the berg mass

Local berg acceleration vector

Local berg velocities vector

Forces vector due to impact.

The linearized equations of motion for the moored drillrig are as follows

\[ [M_2] \ddot{X}_2 + [C_2] \dot{X}_2 + [K_2] X_2 = F_2 \]  

(14)

where \([M_2], [C_2]\) and \((F_2)\) are similar to the definitions given above except that they relate to the semisubmersible and the \([K_2]\) term represents the nonlinear secant stiffness of the mooring system.

The equations of motion of the iceberg and drillrig are coupled using load-penetration relations. These relations at the impact zone are modelled by four nonlinear springs (Figure 9) to model movements in two orthogonal directions in the plane of impact for the two structures. The equations of motion for the impact system are then given by the following

\[ [M] \ddot{X} + [C] \dot{X} + [K] X = F_C \]  

(15)

where \([M]\) is a partitioned mass matrix containing the mass of the iceberg and the semisubmersible.
The collision force vector \( F_c \) is proportioned via equilibrium of the four spring system. The resultant forces on the iceberg are in equilibrium with the resultant forces acting on the platform. The coupled equations of motion are then solved using the Newmark time-integration procedure, and if required, numerical stability will be improved using Wilson's \( \theta \)-method. The time-integration analysis is continued until the kinetic energy of the iceberg has occurred (i.e., mooring cable rupture, drillrig collapse). Upon completion of the analysis drillrig excursions and mooring cable forces will be known throughout the time of impact.

The analysis of iceberg impact with a gravity-base platform can be performed in a similar manner. The generalized mass and stiffness matrices are computed from an eigenvalue analysis. Once the generalized mass and stiffness matrices are established, the analysis proceeds as outlined for the bergy bit/semisubmersible impact analysis.

8 CONCLUSIONS

For the case of iceberg impact with a gravity structure, the analysis presented is very simplistic, but it does reveal the significance of the assumptions made regarding crushing strength and the contact face. The wedge-shaped walls, for example, can achieve a major reduction in impact loads but at the same time allow a much higher penetration. Mechanical properties of iceberg ice need to be investigated in greater detail, because of their sensitivity in the analysis.

A one-degree-of-freedom model for bergy bit impact with semisubmersibles can give motion characteristics, but a complex analysis is needed to determine realistic impact loads. A more appropriate interactive model is proposed, which would yield both impact forces and platform motions for surge, sway and yaw motions.
REFERENCES


ON ESTIMATING LARGE SCALE ICE FORCES FROM DECELERATION OF ICE FLOES

Abstract

Ice forces on Hans Island were obtained in 1981 from measurements of the mass and deceleration of four colliding multi-year ice floes. The theory behind the analysis, including the estimation of environmental drag forces and hydrodynamic added mass is presented. The techniques of data acquisition as well as some of the characteristics of the data are outlined. Qualitative results of the project are discussed and recommendations are made for future research.

1 INTRODUCTION

With the discovery of hydrocarbons in ice infested waters, there has been a dramatic increase in the development of ice resistant offshore structures. Some of the most important parameters affecting structure design are the magnitude of ice loads and ice behavior during failure. These issues have been the focus of a large number of field and laboratory investigations. Out of practical considerations, most of the research to date has been restricted to small scale measurements which through theoretical interpretations were applied to the larger scale processes occurring in nature. Because of the potential drastic consequences of poor structure design, this rather indirect estimate of ice loads on
structures has tended to leave design engineers with an uncomfortable degree of uncertainty.

The ice loads on a structure will be dictated by the particular ice conditions to which it will be exposed. One important loading scenario in the Beaufort Sea is the impact of large, fast moving multi-year ice floes with a structure in open water. Multi-year ice invasions in the southern Beaufort Sea are fairly irregular and impacts are virtually impossible to predict.

At Hans Island however, these conditions recur almost annually and it is an ideal natural laboratory for monitoring this type of collision. Hans Island is situated midway in Kennedy Channel between Canada and Greenland at about 81°N. During most of the year it is in landfast ice but for a few weeks in July and August it is surrounded by open water. During this season large multi-year ice floes drift southward from the Arctic Ocean. As Hans Island is one of the first obstructions these floes encounter, it is subjected to numerous collisions.

During the open water seasons of 1980-81, Dome Petroleum Limited (through its subsidiary of Canadian Marine Drilling) conducted field investigations of multi-year ice floe collisions at Hans Island. The purpose of these investigations was to calculate the ice forces on the island from measurements of the mass and deceleration of the colliding floes. Measurements of the contact area reduced these loads to the effective strength of multi-year ice during failure. Metge et al (1981) describe a number of data acquisition systems utilized in the 1980 study including accelerometers, an electro-optical distance meter, theodolites and photogrammetry. The 1980 calculations yielded surprisingly low values of effective ice strength but as this was the first time that some of the equipment had been used for this type of application, a high level of uncertainty was associated with the results. The 1981 field programme was initiated to examine...
the validity of the earlier data and to attempt to resolve some of the fine structure of the failure process.

A great deal had been learned from early experience and significant improvements were made to the data acquisition systems. The 1981 project yielded high quality data for four multi-year floe impacts. Force calculations were based on deceleration data gathered at a sampling rate of about 3 Hz. when these measurements were combined with aerial and ground based time lapse photography of the contact zone, it was possible in some cases to associate certain predominant failure mechanisms with specific load signatures.

The results of both studies still remain proprietary to participants of APOA (Arctic Petroleum Operators Association) Project Numbers 180 and 181 and this paper is therefore restricted to a discussion of experimental design and qualitative observations.

2 METHODOLOGY

During any single open water season, Hans Island is probably subjected to hundreds of ice impacts but only a handful of these events lend themselves to the extraction of a practical amount of ice load data. To calculate a reliable force level during a floe collision, the effective mass of the colliding floe needs to be reasonably apparent. This is only practical when the floe remains separated from other floes during the interval of the deceleration. This restriction severely reduces the number of impacts potentially useful for analysis but several practical considerations reduce this number even further. To yield an acceptable quantity of data, a floe should possess sufficient kinetic energy to support a prolonged deceleration. The floe should be large enough not to be significantly affected by the current perturbation around the island and small enough to undergo a detectable deceleration on impact. Naturally, the collision should occur during a period
when the instrumentation is ready and the weather is suitable for its deployment. Finally, the trajectory of the floe, should be relatively simple and easily anticipated. Several of the floes during both projects that had been instrumented changed course and missed or just grazed the island while unlikely (and therefore uninstrumented) floes collided.

At any instant, the net force on a floe failing against an obstruction is determined by the vector sum of the ice load \( F_i \), air drag \( F_a \), water drag \( F_w \) and coriolis force \( F_c \). The net force can be calculated from the effective floe mass \( M \) and its deceleration \( a \).

\[
P = M \dot{a} = F_i + F_w + F_a + F_c
\]

The effective floe mass is the sum of the actual ice mass of the floe and the hydrodynamic added mass. One of the authors, Dunwoody, has derived an estimate of this added mass per unit area in terms of water density \( \rho \) and the effective amplitude and wavelength of the undulations of the bottom surface of the floe \( \varepsilon \) and \( \lambda \) respectively:

\[
m = \frac{\rho \varepsilon^2}{\lambda}
\]

Hydrodynamic added mass can make a significant contribution to the effective mass of thin new ice floes characterized by uneven surfaces. For most large multi-year ice floes however, it makes little difference. The characteristic amplitude and wavelength of the underside of floes at Hans Island were estimated to be about 1 and 50 metres, respectively. As the average floe thickness was greater than 5 m, the added mass calculated from equation (2) accounted for less than 1% of the total ice mass and it was therefore ignored.

The air and water drags on a floe can be expressed as functions
of the respective drag coefficients \(C\), densities \(\rho\), floe area \(S\), and net velocity of the fluids with respect to the floe \(\Delta V\).

\[
F_a = \frac{1}{2} C_a \rho_a S (\Delta V_a)^2 \\
F_w = \frac{1}{2} C_w \rho_w S (\Delta V_w)^2
\]  

At the ambient wind and current velocities at Hans Island (usually near 10 m/s and .5 m/s, respectively), it was found that these forces were sufficiently small compared to the calculated ice forces that they could be ignored.

Coriolis force on a floe always acts to the right of the direction of motion and as such never contributes to energy calculations. The force only affects the direction in which a floe moves. The magnitude of this force was also found to be insignificant especially in that it falls to zero as the floe comes to rest.

Disregarding the environmental forces on the floe, equation (1) can be rewritten as:

\[
F_1 = Ma
\]  

Since \(F_1\) is the product of the effective ice strength during failure and the area over which failure is occurring, the equation becomes

\[
F_1 = cW_h' = Sh_i a
\]

where:

\(c\) is the effective ice strength
\(W\) is the width of the contact zone
\(h'\) is the thickness of the failing ice
\(S\) is the floe area
h is the mean floe thickness
\( \rho_1 \) is the density of ice
\( a \) is the deceleration of the floe

The maximum temporal resolution of the ice force at the contact zone based on measured decelerations some distance away is dictated by the dimensions of the floe. A floe will react rigidly to a force only if the wavelength of the force exceeds the dimensions of the floe. For typical floe diameters between one and two kilometers, the 1500 m/s stress velocity implies a maximum temporal resolution of the ice force of about one second.

If the mean thickness of the floe equals the ice thickness at the contact zone, then equation (6) can be written as:

\[
c = \rho_1 \frac{S}{\rho} a
\]  

(7)

In other words, the only data required for calculations of ice strength are the floe area, the width of the contact zone and the rate of deceleration of the floe.

If a floe impacts the edge of an island and shearing occurs, it is possible to obtain the effective coefficient of friction of ice undergoing large scale failure. The only data required are the magnitude of the ice force and its orientation relative to the contact zone. The force vector can be separated into components normal and parallel to the contact. The normal component represents the effective ice pressure, the parallel component represents the effective ice friction. The large scale friction coefficient of ice has not yet been obtained but it is felt to be an extremely important parameter in the transfer of pack ice loads to structures.
3  DATA AQUISITION

For all of the monitored impacts, floe areas were determined from independent theodolite fixes of their perimeters before and after the collisions. The data agreed surprisingly well and the error was estimated as 5%.

The contact zone was photographed from a helicopter hovering about 100 m away. The time was recorded on each frame by the camera. The width of the zone was measured from the photographs with respect to a grid of previously deployed markers. Probably the greatest uncertainty in the data stemmed from the assumption that the thickness of the failing ice was equal to the mean thickness of the floe. This assumption was necessitated by practical consideration. It was virtually impossible to predict which section of the floe would contact the island until minutes before the collision. By this time it was considered too dangerous to ground truth the ice thickness. It should be pointed out however, that old ice is generally characterized by smooth features and it is unlikely that abrupt thickness variation existed within the short distance between the failed ice and the location of subsequent level ice measurements.

Floe decelerations were measured with accelerometers sensitive to $10^{-5}$ m/s$^2$. The signals were low pass filtered and recorded at 3 Hz on a digital tape. Most of the records exhibited a drift of the baseline not encountered during laboratory tests. This drift was attributed to minute settling of the instrumentation on the floes at the near freezing temperatures. Fortunately this drift appeared relatively uniform over the duration of the recording interval. As this interval extended for well before and after the collision, a new baseline selected to account for the drift was fairly unambiguous.
RESULTS

Of the four events monitored during the 1981 field program, two floes failed against the island directly while two failed against a smaller floe trapped against the island. During the direct impacts, ice failure occurred primarily along the shore of the island while during the indirect impacts, the predominant failure was between the two floes with little failure evident at the island interface. Ice forces associated with the direct impacts were significantly higher.

The magnitude of the ice force during a direct impact also showed dependence on the predominant mode of failure is illustrated in Figure 1. The force generally increased steadily with increasing floe contact while the ice failed in crushing and flaking. As this process continued, a ridge was being formed at the contact zone. When the ridge reached a sufficient height, flexural cracks became evident along the surface similar to those described by Parmeuter and Coon (1972). The appearance of flexural cracks was associated with a reduction in the total ice force. If floes were small or of low velocity, their kinetic energy was often expended in the early stages of the collision prior to the development of flexural failure.

CONCLUSIONS

The effective strength of ice during failure can be calculated from measurements of the mass and deceleration of a floe colliding with an island. For most large multi-year ice floes, the hydrodynamic added mass can be neglected. Under normal conditions, the wind and current drags on a floe colliding with an island are far less than the ice force. There is a reduction in the effective strength of ice with the commencement of flexural failure.
Only a handful of floe collisions with Hans Island have been satisfactorily monitored to date but already a number of important determinants of ice loads have been identified. More collisions need to be monitored to isolate the effects of various contact zone parameters such as contact area and geometry, strain rate, depth of penetration etc. One or more well-monitored impacts against the edge of the island which result in shear ridge formation, could lead to important discoveries regarding the large scale coefficient of friction of ice. With a little luck, future studies will be able to establish the threshold criteria for the massive failure (splitting) of some floes on impact. This could lead to a significant re-assessment of the present approach to ice load prediction and result in a safer and more cost efficient offshore development in future years.
REFERENCES


ICE LOAD SENSORS FOR OFFSHORE ARCTIC STRUCTURES

Abstract

Ice loads generally govern the design of offshore structures in the Arctic as they may be orders of magnitude larger than other environmental loads. Field measurements are needed for comparison with the results of theoretical work so that better design criteria can be developed. Three caisson type drilling structures, now operating in the Canadian Beaufort Sea, have had sensors installed on them to collect such data. This paper discusses the development of two of the sensor designs used on these structures and the development of a third, more recent design. This latter design is suitable either for attachment to a structure or for embedment in the ice. Test results are presented for all three designs.

1 INTRODUCTION

The move of the resource extraction industries into the offshore Arctic regions has given considerable impetus to studies of the behaviour of the thick ice that dominates that environment. The loads that the ice can impose on the facilities needed for exploration and production are of the most interest, as they may be orders of magnitude greater than other environ-
mental loads, such as those due to waves or currents. Ice loads are easily the governing factor in the design of most exposed facilities and, as such, have a major influence on cost.

This interest in loads has led to very significant advances in the field of ice mechanics, with respect to our understanding of the physical and mechanical properties of ice, the mathematical modelling of its failure processes, and the physical modelling of these processes. There is, however, very little field performance data available which might be useful in validating the results achieved.

Measurements of the loads on icebreakers provide the largest data base, but they are not of direct use in studying fixed structures because of fundamental differences in the failure processes involved in each case. Loads on structures have been measured in Cook Inlet [1], and loads on bridge piers and lighthouses have been measured directly or estimated, as summarized in [4]. These latter measurements, however, generally involve freshwater ice, while the ice conditions in Cook Inlet are very light; level ice thicknesses generally do not exceed 0.6 m and ridges have keel depths of about 3 m. In situ measurements of the internal pressure in the ice surrounding artificial drilling islands have been made in the Canadian and Alaskan Beaufort Seas to allow estimates of the forces on the structures, but no direct measurements were possible. (See, for example, [2], [5], [6]).

An opportunity to augment the field measurement data base was presented in 1981 with the construction of the Gulf Canada Resources – Dome Petroleum Tarsiut caisson island in the Canadian Beaufort Sea. The caissons provided the means for mounting direct load measuring devices which had not been possible to do with the previous artificial islands. This paper discusses the development of two types of load sensors for installation on the Tarsiut caissons and the more recent development of a third design suitable either for installation on a structure or for
embedment in the surrounding ice. Sensors of the type used at Tarsiut have also been installed on the Esso Resources Canada caisson and on the Dome Petroleum SSDC tanker conversion.

2 DESIGN CONSIDERATIONS

The factors discussed in this section received the most weight in the development of the three designs.

2.1 Sensor Effective Modulus

The general problem of measuring ice pressures with an embedded sensor has been discussed by Metge et al [2] and Templeton [6], and many of the same considerations apply to the case of measuring pressures (loads) at the interface of the ice with a structure. The solution to the sensor inclusion problem presented in [2] was slightly modified in [6] to give:

\[
\frac{\sigma}{\sigma_1} = \frac{E_1/E + H/2D}{(E_1/E)(1 + H/2D)}
\]

where

- \( \sigma \) = undisturbed stress
- \( \sigma_1 \) = measured stress
- \( E \) = elastic modulus of the ice
- \( E_1 \) = elastic modulus of the sensor
- \( H \) = thickness of the sensor
- \( D \) = width of the sensor.

Templeton concludes from examining this equation that the sensor should be thin and wide. As the sensor thickness-to-width ratio decreases, the ratio of undisturbed-to-disturbed stress approaches unity over a widening range of values for the ratio of the two elastic moduli. Due to the wide variation in the properties of sea ice, it is very difficult to select a design value for the ice elastic modulus and minimizing the
thickness-to-width ratio minimizes sensitivity to any variations. Minimizing this ratio also reduces creep effects and plastic yield effects, as can be shown by letting $E$ approach zero in Equation 1. A recommended value for the sensor modulus was given as 2.0 GPa, based on an assumed range for the ice modulus of 1.0 to 4.0 GPa.

Taking the interface problem into consideration, this analysis can also be applied, if the sensor is assumed to be embedded in the ice face bearing on the structure. Another approach would be to treat the sensor as a component of the structure. This would require that the sensor, including its support members, and the structure have the same modulus (or stiffness) to prevent "arching" across the sensor or load concentration at the sensor. However, the choice of a stiffness value for the structure is not straightforward since the deflections of the loaded surface will vary with the placement of stiffening and support members. The effects of differences in moduli can, no doubt, be reduced by increasing the width of the sensor, but the requirements are not well understood. For soils, Weiler and Kulhawy [7] cite criteria for diaphragm type pressure sensors which specify that the sensor diameter-to-diaphragm deflection ratio should exceed 2,000, and criteria for rigid plate type sensors which suggest a diameter-to-deflection ratio of at least 10,000. To our knowledge, similar criteria have not yet been developed for ice.

2.2 Sensor Area

In addition to the dimensional considerations already discussed, a second consideration in sizing is the selection of a loaded area which might be most useful in developing structural design criteria. For many of the designs which have been developed or are currently being proposed, component sizes for analysis are usually a minimum of 0.3 - 0.4 meters wide and a maximum of 2 - 5 meters wide. The depth of interest would generally be the thickness of the contact zone or a maximum of
about 5 meters.

If a measurement of the total load on the structure is needed, a large number of sensors may be required to provide a good estimate of the pressure distribution over the ice interface. As sensor cost usually increases substantially with increasing size, this consideration tends to limit size in order to provide more coverage.

### 2.3 Differential Thermal Expansion

For a structure-mounted sensor, the effect of differential thermal expansion on measurement accuracy is probably not as important as for an embedded sensor, and might be reduced significantly by closely matching the sensor and structure materials and material thicknesses. Templeton [6] concludes that for an embedded sensor, it is impractical to correct for this effect because of viscoelastic and plastic yield considerations, but the error can be minimized by minimizing the sensor thickness-to-width ratio. He also notes that the greatest thermal strains are likely to occur close to 0°C where the elastic modulus of sea ice is smallest.

### 2.4 Sensor Performance Characteristics

Since long-term measurements are one goal of most field installations, the sensor response should be insensitive to the effects of temperature changes and should be stable and repeatable. Temperature changes can affect response through changes in the elastic properties of the materials the sensor is constructed from, or through changes in the "zero reference" or the sensitivity of the method used to measure the deformation of the sensor. For example, sensors which use fluid pressure change or volume change methods can be susceptible to zero drift and changes in sensitivity because of the inevitable differences between the thermal expansion coefficients of the fluid and the other construction materials. Zero drift can be corrected for,
if temperature is measured at the sensor location, but the correction becomes rather more complicated if the sensor sensitivity is also affected by temperature change.

The sensor should give a stable and repeatable response because of the difficulty involved in conducting calibration checks in the field, and the increased laboratory calibration testing and data reduction time that results, otherwise. Also, a linear response is an advantage in data reduction.

Dynamic response is another consideration, if the application will include measurements of high strain rate events. Frequencies of interest may be as high as $5 - 10$ Hz. [3], thus the sensor should be capable of tracking events in this range and should have a resonant frequency of at least $30 - 50$ Hz.

Cross-sensitivity also needs to be considered. Since a structure-mounted sensor will, in general, be subject to shear loads across its face, it is important that it be insensitive to this condition along its measurement axis, (usually normal to the face). For an embedded sensor, cross-sensitivity to in-plane loads and to bending in the plane of its face are of concern.

2.5 Summary

These considerations, together with requirements for corrosion resistance and submerged operation, formed the guidelines for the designs discussed in the following sections.

3 SHEAR-BAR LOAD SENSOR

This sensor was developed to measure loads generated either by floe impacts, or transmitted through a surrounding rubble field or ice sheet. It can either be recessed into the face of the structure or fastened directly to the surface.
The gauge elements can be wired, (i) firstly, to form a full bridge for the entire cell, (ii) secondly, to form a full bridge configuration for each bar or (iii) thirdly, to bring each arm of the full bridge per bar configuration separately to a junction box or another location where the bridge can be completed for each bar, or for the cell as a whole. The gauges are positioned to remove the effects of any torsional and in-plane shear loads on the bars, and to average effectively over the length of each bar. Self-temperature-compensated gauges are used, in addition to the full bridge wiring, to minimize temperature sensitivity.

The high strength steel used for the bars, combined with the support they provide to the plates, allows for a low profile of the assembled unit. This type of construction also allows for an effective stiffness of the unit of about 2.0 GPa, so that inclusion effects might be minimized.

Special consideration has been given to the design of the sealing details. The primary seal is provided by a thin gauge steel diaphragm welded around the periphery of the sensor between the face plate and back plate. Each gauge rosette is protected after installation by a coating suitable for extended use underwater. For the final step of assembly, the sensor is filled with a dielectric fluid compound.

A typical calibration curve for a Shear-Bar sensor is shown in Figure 3. This plot is of a static calibration done at room temperature and contains data points from three successive test runs. This particular sensor contained four bar elements, and the ordinate of the plot is the sum of the outputs from each bar.

A more extensive series of tests was conducted on a prototype to measure temperature sensitivity, cross-sensitivity, frequency response, and sensitivity to point loads. Table 1 summarizes the performance of the design as measured in these
The design consists of rigid, load-carrying front and back plates fastened to an instrumented core; a configuration which measures the total load applied to the face plate rather than the average pressure. The core comprises two or more long, strain gauged square bars, machined from high strength steel. Figure 1 shows a photograph of a sensor during assembly and Figure 2 shows an assembled unit.

FIGURE 1. Interior of a Shear-Bar Load Sensor (circular configuration).

FIGURE 2. Assembled Shear-Bar Load Sensor (prior to application of the coating).
tests and in the static calibration. The response is characterized by very good linearity and sensitivity, low threshold load, insensitivity to the effects of shear and point loading, insensitivity to thermal effects, and a high effective modulus. Actual values are expected to exceed those stated, as the response characteristics of the hydraulic apparatus used for the tests are expected to be of the same order. Although frequency response could not be tested above 4 Hz because of the limitations of the available test apparatus, it should easily exceed the range of interest because of the sensor's strain gauge-based design and high natural frequency.

Fig. 3. TYPICAL SHEAR-BAR SENSOR CALIBRATION PLOT.

Sizes constructed have ranged from 0.25 m² to 2 m² in sensing area, and thicknesses have ranged from 100 mm. to 190 mm. Design capacities have ranged from 1.75 MN for the smallest units to 22 MN for the largest. The design is flexible enough to allow a wide range of size and design load combinations to be selected without changing the effective modulus of the sensor.
TABLE 1
SHEAR-BAR SENSOR PERFORMANCE TEST RESULTS.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RATED OUTPUT:</td>
<td>&gt;1.75 mV/V/bar</td>
</tr>
<tr>
<td>NONLINEARITY:</td>
<td>&lt;± 1% R.O.</td>
</tr>
<tr>
<td>HYSTERESIS:</td>
<td>&lt; 3% R.O.</td>
</tr>
<tr>
<td>REPEATABILITY:</td>
<td>&lt; 3% R.O.</td>
</tr>
<tr>
<td>ZERO RETURN:</td>
<td>&lt; 0.5% R.O.</td>
</tr>
<tr>
<td>TEMPERATURE EFFECT ON ZERO BALANCE:</td>
<td>&lt; 0.04%/°C R.O.</td>
</tr>
<tr>
<td>TEMPERATURE EFFECT ON SENSITIVITY:</td>
<td>0.05%/°C R.O.</td>
</tr>
<tr>
<td>SHEAR LOAD EFFECT ON SENSITIVITY:</td>
<td>&lt; 1% R.O.</td>
</tr>
<tr>
<td>POINT LOAD EFFECT ON SENSITIVITY:</td>
<td>&lt; 3% R.O.</td>
</tr>
<tr>
<td>EFFECTIVE MODULUS:</td>
<td>Est. 2200 MPa</td>
</tr>
<tr>
<td>FREQUENCY RESPONSE:</td>
<td>Est. &gt;20 Hz</td>
</tr>
</tbody>
</table>

4 HYDRA COIL LOAD SENSOR

This design, like the Shear-Bar, was initially developed for installation on the Tarsiut caissons and is also intended to be recessed into the face of a structure or mounted on the exterior. Figure 4 shows a photograph of one of the sensors installed at Tarsiut. The design comprises two face plates separated by a small diameter, fluid-filled conduit arranged in the shape of a coil. The conduit is compressed between the plates under load, pressurizing the fluid, and this pressure is measured with an electrical transducer.

Figure 4. Hydracoil Load Sensor (circular configuration).
The design has been improved recently by the selection of a new type of high pressure conduit with thermal expansion properties that match those of the fluid used. This minimizes the effect of temperature changes on the accuracy of the sensor and very good thermal response characteristics result in comparison with many fluid type designs.

Figure 5 shows a typical calibration plot for the design. Because this particular design had a precompression load applied to the coil, the sensitivity is reduced at loads below approximately 150 KN, (300 kPa uniform load). Beyond this point the response becomes quite linear. More recent designs have not incorporated precompression which has reduced this nonlinearity.

![Typical Hydracoil Sensor Calibration Plot](image)

Table 2 summarizes the measured performance characteristics of the prototype. Because of its slow response time and its low effective modulus, this design is best suited to applications for which high strain rate events are not a concern or time-averaged loading is wanted. These conditions are most likely to occur when the structure is located in landfast ice, or is
surrounded by a rubble field protecting it against direct floe impacts.

TABLE 2

HYDRAOIL SENSOR PERFORMANCE TEST RESULTS.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATED OUTPUT:</td>
<td>70 MPa</td>
</tr>
<tr>
<td>SENSITIVITY:</td>
<td>10 kPa/kPa uniform</td>
</tr>
<tr>
<td>load (nominal)</td>
<td></td>
</tr>
<tr>
<td>NONLINEARITY:</td>
<td>≤±4% R.O.</td>
</tr>
<tr>
<td>HYSTERESIS:</td>
<td>&lt;4% R.O.</td>
</tr>
<tr>
<td>REPEATABILITY:</td>
<td>&lt;6% R.O.</td>
</tr>
<tr>
<td>TEMPERATURE EFFECT ON SENSITIVITY:</td>
<td>≤5% R.O.</td>
</tr>
<tr>
<td>TEMPERATURE EFFECT ON ZERO BALANCE:</td>
<td>&lt;0.1%/°C R.O.</td>
</tr>
<tr>
<td>EFFECTIVE MODULUS:</td>
<td>170 MPa</td>
</tr>
<tr>
<td>FREQUENCY RESPONSE:</td>
<td>1 Hz (0.1 - 0.08 Hz</td>
</tr>
<tr>
<td></td>
<td>at -30°C</td>
</tr>
</tbody>
</table>

The design lends itself to construction in a range of sizes and various shapes. Thicknesses can be as small as 15 to 20 mm. Since it is capable of withstanding pressures approaching the burst strength of the conduit forming the coil, a very wide range of design loads can be specified from 2.5 MPa to 20 MPa, uniform load.

5  HEXPACK LOAD SENSOR

This design was developed either for attachment to a structure, or for embedment in the ice. Figure 6 shows a photograph of an assembled unit. The sensor is comprised of a large number of small, button-like, metal elements, each capable of acting as an individual sensing unit, sandwiched between two thin metal plates. The button elements are arranged in a close-packed hexagonal array, resembling a honeycomb, to maximize support for the thin envelope plates and maximize resistance to bending. The envelope is welded around the periphery to form a watertight seal.
Load is measured by means of strain gauges attached to a number of the button elements. As for the Shear-Bar design, the strain gauges used are the self-temperature-compensated type and are wired into one or more full bridges to give very low sensitivity to temperature changes. The position and number of the instrumented elements is selected to minimize edge effects and to provide a representative sampling of the pressure distribution over the face of the sensor. The sensor, in effect, then acts as a pressure-averaging device, unlike the Shear-Bar sensor which measures total load. Because of this characteristic, it can also be configured to sample pressure over subdivisions of its face area. For example, pressure could be measured over two or more horizontal strip segments to provide data on the vertical distribution of stress within the ice.

The height, width, and shape of the sensor can be varied readily because of the modular nature of the internal button elements. A typical thickness is on the order of 15 mm. so that
the width-to-thickness ratio can be made quite small. A wide variation of design parameters can be selected for the button elements and the envelope - button and membrane thickness, button size, material, array packing density - so that both design load capacity and the effective modulus of the sensor can be specified for a particular application.

A laboratory calibration plot for a prototype sensor is shown in Figure 7. It contains the data from three successive tests covering about a third of the range for this particular unit. The results of a more extensive test series are summarized in Table 3. The design exhibits very good linearity, repeatability, and hysteresis, and is insensitive to temperature effects as expected for an all-metal, strain gauge type construction. One of the sensors is currently installed at the edge of the rubble field at Dome Petroleum's Uvilik drilling location and is undergoing field tests.
TABLE 3
HEXPACK LOAD SENSOR PERFORMANCE TEST RESULTS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity:</td>
<td>$1.164 \times 10^{-3}$ mV/V/kPa</td>
</tr>
<tr>
<td>Nonlinearity:</td>
<td>0.34% R.O.</td>
</tr>
<tr>
<td>Hysteresis:</td>
<td>0.5% R.O.</td>
</tr>
<tr>
<td>Repeatability:</td>
<td>0.87% R.O.</td>
</tr>
<tr>
<td>Zero return:</td>
<td>0.1% R.O.</td>
</tr>
<tr>
<td>Temperature effect on zero balance</td>
<td>0.05%/°C R.O.</td>
</tr>
<tr>
<td>Temperature effect on sensitivity:</td>
<td>0.02%/°C R.O.</td>
</tr>
<tr>
<td>Creep:</td>
<td>0.12% R.O. (18 hr. test)</td>
</tr>
<tr>
<td>Effective modulus:</td>
<td>1540 MPa (nominal)</td>
</tr>
<tr>
<td>Frequency response:</td>
<td>Est. &gt;10 Hz</td>
</tr>
</tbody>
</table>

6 SUMMARY AND CONCLUSION

Three new ice load sensor designs have been described. The Shear-Bar and Hexpack designs are characterized by very good linearity and insensitivity to temperature effects. Also, both have effective elastic moduli which minimize elastic inclusion, creep, and plastic yield effects on the measured load. Because of this, they are well suited to measuring loads over the entire range of strain rates which are generally of interest. The Hexpack can also be used as an embedded sensor and satisfies all the requirements for minimizing measurement errors in this application.

The Hydracoil design is less accurate than the others, but has acceptable performance characteristics for many applications. Also, it inherently provides a large sensing range and a high overload capacity. The effective modulus and frequency response characteristics of this design make it best suited for low strain rate measurements.
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Geophysical Institute, University of Alaska
Fairbanks, Alaska, USA

P. Bruun, Professor
Norwegian Institute of Technology
Trondheim, Norway

J. Widdis, Asst. Planning Manager
Alaska Dept. of Transportation and Public Facilities
Fairbanks, Alaska, USA

WAVE AND ICE DESIGN CRITERIA FOR A TERMINAL AT NOME, ALASKA

Abstract

Future offshore oil activities in Norton Sound, together with growth in commercial and mining operations, are expected to require a supply base at Nome for small cargo vessels with drafts not exceeding about 6.5 to 7.0 meters (22 to 23 ft.).

Presently, marine cargo at Nome is unloaded onto shallow draft barges which use an existing harbor in the estuary of a tidal river. This harbor is subject to considerable siltation and is dredged annually to a depth of 2.4 meters (8 feet). The general region is covered with shifting annual sea ice from November until mid-May, and is subject to severe storm tides and waves during the open-water season. The new offshore terminal is planned for a possible availability of up to 12 months, depending upon ice conditions and the ice-penetrating capacity of the vessels serving the terminal. The terminal will be located at 9 meters (30 ft.) water depth about 1200 meters from shore, connected with a rock-ound causeway to shore, and is expected to be in ice-free waters for about 6 months of the year.

Data needed for the planning of this facility has included the extent of the anticipated offshore activities; ice coverage, thickness, physical properties, and velocity of movement; waves, currents and sediment transport.

A review of the available data is given and its use in the design and projected operation of the new facility is shown. The new terminal must survive both ice and wave attack, and its
design is based on physically well-justified principles in order that it may provide for possible year-round port operation in the ice-infested northern Bering Sea.

1 INTRODUCTION

The proposed port facility at Nome, Alaska, is subject to sea ice for about seven months each year, as well as the possibility of substantial waves from the southwest during the summer months. These two categories of environmental hazards were considered to be most severe from the outset, and early in the design process it was recognized that criteria for ice and wave protection designs should be established. A general discussion of the port design is given by Perdichizzi et al. /30/.

1.1 Ice Design Criteria

A review of available satellite imagery of ice in the vicinity of Nome revealed that the slightly concave shoreline geometry extending from Cape Nome (22 km east of Nome) to Sledge Island (38 km west of Nome), as shown in Figure 1, served to collect drifting ice which became shorefast ice in many instances during winter. The presence of Sledge Island seems to enhance this trend. Very little ice is in the area during October and November, as illustrated in Figures 2a-c. Consideration of the average number of freezing degree days at Nome and sea ice thickness calculation based upon the relation given in Zubov /35/ suggests that some floes of 30 cm thickness may be found at the end of November (Figure 2d). However, the winds in Norton Sound cause substantial ice activity well beyond this date, and it is in December (Figure 3a) and January (Figure 3b) that the drifting floes tend to form shorefast ice at Nome. The Nome causeway will probably intercept drifting ice floes in November and December, however, and the possibility exists that shorefast ice such as is usually found in February (Figures 4a-f) may begin to be formed earlier in the winter, perhaps even in late November. Ice floes
Figure 1. Map of vicinity of proposed Port of Nome.

Figure 2(a). Landsat photo of 4 November 1976 showing ice near Nome.

Figure 2(b). Landsat photo of 9 November 1976 showing ice-free region near Nome with ice floe formation in central Norton Sound.
Figure 2(c). Landsat photo of 19 November 1980 showing ice-free region near Nome.

Figure 2(d). Landsat photo of 30 November 1973 showing approximately 50% ice floe coverage adjacent to Nome.

Figure 3(a). Landsat photo of 7 December 1982 showing approximately 60% ice floe coverage adjacent to Nome.

Figure 3(b). Landsat photo of 12 January 1983 showing nearly continuous ice coverage adjacent to Nome, with open water both east and west of Sledge Island suggesting that longshore ice sheet movement has taken place recently.
Figure 4(a). Landsat photo of 8 February 1974 showing Nome fast ice.

Figure 4(b). Landsat photo of 13 February 1973 showing Nome fast ice.

Figure 4(c). Landsat photo of 18 February 1979 showing Nome fast ice.

Figure 4(d). Landsat photo of 16 February 1981 showing Nome fast ice.
restrained by the causeway would quickly form a sheet of shorefast ice, the seaward boundary of which is likely to coincide with the end of the causeway initially, and with the normal Cape Nome/Sledge Island boundary later, in mid-winter. Severe storm conditions with winds from the southeast, the west, or the south could drive loosely-packed ice floes onshore in early winter, before this shorefast ice sheet forms a frozen and consolidated buffer zone for the region around the causeway. The problem of ice floes riding up onto the causeway from the southeast or northwest, and rideup onto the seaward face of the end of the causeway due to ice movements from the south, was thus identified, and a model study was initiated, the results of which are reported elsewhere /14/.

In the absence of severe storms, it was felt that slowly-drifting ice floes accumulated adjacent to the causeway would freeze together to form a sheet of fast ice, and although winds from the north could carry that ice sheet out into Norton Sound, there was a possibility that the fast ice sheet could be driven up onto the causeway by southeast or northwest winds. Some attention has been given to calculations of the threshold for
this type of ice sheet movement, and its probability. From the number of freezing degree-days /1/, the ice thickness may be calculated using the relation of Zubov /35/:

\[ h = -25 + \sqrt{(25 + h_0)^2 + 8\Delta R} \]  

(1)

where \( h \) is ice thickness (cm), \( h_0 \) is initial ice thickness, and \( \Delta R \) is the number of degree-days below 0°C, beginning when the ice thickness is \( h_0 \). Results are presented in Table 1. Ice buckling and flexural failure depend upon the characteristic length \( L \) in the ice sheet; the expression /24/:

\[ L = \left[ \frac{Eh_0^2}{12(1-v^2)K} \right]^{1/2} \]  

(2)

may be used, where one may assume \( K = 10.1 \text{ kN/m}^3 \), \( v = 0.33 \), and \( E = 10^6 \text{ kPa} \). The wind stress and water stress together are taken to represent the total environmental force on this sheet of shorefast ice; the assumption may be made that the drifting pack ice in Norton Sound beyond the shorefast zone does not apply appreciable forces to the fast ice. Currents beneath shorefast ice have rarely been measured, but data from Stefansson Sound in the Beaufort Sea /27/ suggests that average currents are small, of the order of 1-2 \text{ cm/sec}, directed away from the coast. No measurements of currents under the shorefast ice in Norton Sound near Nome have been reported. They have been neglected in our calculations. According to Coo5 /12/ the air stress \( \tau_a \) is:

\[ \tau_a = \rho_a C_a \frac{U^2}{g} \]  

(3)

where \( U \) is the geostrophic windspeed, \( \rho_a \) is air density, and \( C_a \) is the air drag coefficient. Experiments in the AIDJEX program /31/ suggested that reasonable values for these constants were \( \rho_a C_a = 1.1 \times 10^{-3} \text{ kg/m}^3 \) and \( \left( \frac{U_{10}}{\rho_a g} \right)^2 = 0.36 \), where \( U_{10} \) is the windspeed measured at 10 meters height. Assuming the shorefast ice is of dimensions 1.100 \text{ m} \times 25 \text{ km} to the west of the causeway, and 1.1 \text{ km} \times 22 \text{ km} to the east of the causeway, the
Table 1. Summary of ice thickness, extreme winds, and resulting ice stresses including stress levels needed for buckling or for flexural failure. Flexural failure and rideup initiation is possible for ice thickness of less than about 30 cm.

<table>
<thead>
<tr>
<th></th>
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<tr>
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<td>0.30</td>
<td>0.57</td>
<td>0.77</td>
<td>0.96</td>
<td>1.07</td>
<td>1.14</td>
<td>1.14</td>
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<td>NW Winds 1% Level (m/s)</td>
<td>9-11</td>
<td>6-9</td>
<td>9-11</td>
<td>6-9</td>
<td>6-9</td>
<td>6-9</td>
<td>9-11</td>
<td>6-9</td>
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<tr>
<td>SE Winds 1% Level (m/s)</td>
<td>11-14</td>
<td>11-14</td>
<td>21</td>
<td>21</td>
<td>25</td>
<td>21</td>
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<td>21</td>
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<tr>
<td>NW or W Winds Most Extreme (m/s)</td>
<td>25</td>
<td>25</td>
<td>28</td>
<td>28</td>
<td>25</td>
<td>28</td>
<td>21</td>
<td>21</td>
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<tr>
<td>SE or E Winds Most Extreme (m/s)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
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<td>21</td>
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<tr>
<td>Ice Pressure (NW) 1% Level (kPa)</td>
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<td>3.8</td>
<td>3.4</td>
<td>1.5</td>
<td>1.2</td>
<td>1.1</td>
<td>1.7</td>
<td>1.0</td>
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</table>

<table>
<thead>
<tr>
<th>Month</th>
<th>Ice Pressure (SE) 1% Level (kPa)</th>
<th>Ice Pressure (NW or W) Extreme (kPa)</th>
<th>Ice Pressure (SE or E) Extreme (kPa)</th>
<th>Far Field Buckling Pressure (kPa)</th>
<th>Rideup Initiation (kPa)</th>
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<td>62.5</td>
<td>3100</td>
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<tr>
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<td>4.0</td>
<td>3.4</td>
<td>77940</td>
<td>32.6</td>
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</table>
total windshear force on the shorefast ice may be calculated as a
function of windspeed by multiplying the air stress by the ice
area upon which it acts. Monthly variation in windspeed at Nome,
taken from the Climatic Atlas /1/, is presented at the one
percent occurrence level, and also at the most extreme level, in
Table 1. In that table, internal ice pressure due to the wind
loading is also shown. Calculated far-field stress $\sigma_{ff}$ for ice
sheet buckling failure /25/ is found from the equations:

$$
\sigma_{ff} = \left( \frac{2R}{L} \right) \sin \left( \frac{\alpha}{2} \right) \frac{P_b}{\lambda}
$$

(4)

and

$$
P_b = KL \left( \frac{L}{h} \right)^f
$$

(5)

where $\lambda$ is the radius of each element in a linear array of
circular obstacles at the ice sheet boundary, $\lambda$ is the spacing of
these elements (in units of $L$), $\alpha$ is the angle of ice contact
around each element ($\alpha = 180^\circ$ in our case), $K$ is the specific
weight of water, and $f$ is a computed non-dimensional buckling
load function /25/ which varies with $R/L$, $\lambda$, and the choice of
fixed, hinged or frictionless boundary condition. We assume that
the presence of a tidal crack implies a hinged boundary
condition, and that the causeway rocks at the ice boundary are as
closely-spaced as possible ($\lambda = 2R/L$). Then,

$$
\sigma_{ff} = \frac{KL \frac{Z}{h}}{f}
$$

(6)

and since $K = 10.1$ kN/m$^3$, $R = 0.76$ m, the factor $f$ may be
obtained from the curves of Kovacs and Scsh /25/ and the
far-field stress for buckling may be computed. Results are shown
in Table 1 for the several ice thicknesses. Rideup initiation may
be calculated from the relationship due to Crossdale /13/,

$$
\frac{H}{b} = \sigma_f \left( \frac{Kb^5}{\lambda} \right)^{0.25}
$$

(7)

in which $\sigma_f$ is the flexural strength, $H/b$ is the horizontal force
per unit width, $E$ is elastic modulus, and $C_1$ is a function of slope angle and friction. For the Nome causeway, the slope angle is $33^\circ$. It is difficult to justify an appropriate choice of friction coefficient between the ice sheet and the sloping structure, because the details of the interface will be variable from point to point along the causeway, both geometrically and with respect to materials in contact. Croasdale shows that $C_1 = 0.5$ if $\mu = 0.1$ and $C_1 = 1.2$ if $\mu = 0.5$; in our calculations we have arbitrarily assumed that $\mu = 0.3$ and $C_1 = 0.8$. Taking $E = 10^6$ kPa and $\sigma_f = 700$ kPa one can compute the internal ice pressure required to initiate flexural failure; the results are shown in the last column of Table 1. Additional internal ice pressure is required to move broken ice up the slope and to build ice rubble.

### 1.2 Discussion: Ice Design

An examination of Table 1 shows that the environmental driving forces during the more severe storms of October and November may be sufficient to initiate rideup of a continuous ice sheet, if one has formed. Buckling failures are not likely to take place because the high stresses required cannot be provided by wind shear loading of the shorefast ice. (If there are partially-frozen thin, weak boundaries between ice floes, however, buckling there may still be observed). The maximum ice thickness for which ice rideup is expected on the side of the causeway is about 30 cm. Judging from accounts of locally-observed winter movements of ice at Nome, the ice also can move away from the shoreline as seen in Figure 4e, from 19 February 1979. Newly-frozen, thinner ice may subsequently form and be driven back to the shoreline in mid-winter. If the thickness of that ice is less than 30 cm, rideup of that ice may occur during extreme storms anytime during the winter. From the standpoint of ice management around the causeway during the winter, it is clear that ice movements are likely to occur, and thus the model studies reported by Ettema et al. /14/ were undertaken. The movement of broken ice floes of 1 meter thickness during spring
breakup is also of interest, but has not been the subject of our calculations. A review of winter satellite photos for the past decade for the Norton Sound region usually shows broken ice conditions, implying that winter navigation in ice-strengthened ships is possible. Winter use of the Port of Nome thus depends upon economic factors, and upon local ice rubble management.

2 WAVE ACTION BASIC CRITERIA

The design of the breakwater will be based on the most recent experience available on waves/structure interaction. Basic criteria for design include data on waves, tides (including storm surges), soils, ice conditions, availability of materials and construction equipment, and finally costs—which are highly influenced by Nome's remote location. This section deals with waves versus structures. Tides are known from tidal computations. Storm tides will be up to about 2 meters at 11 meter depths during a severe storm from SSW to WSW. Along the causeways, where waves break, wave set-up $S$ has to be added as: $S = 0.3 \frac{\gamma_b}{H_b}$ where $\gamma_b = H_b/D_b$ and $H_b$ is the breaker height. For $\gamma_b = 0.75$ and $H_b = 5.5$ meters, $S = 1.3$ meters. Close to shore $\gamma_b$ could be almost one which for $H_b = 4$ meters gives $S = 0.3 \times 1 \times 4 = 1.2$ meters. This gives a maximum total tide of about 3.3 meters. In the beach zone, uprush must be added which could be (0.6) $H_b = 2.5$ meters at most.

Consequently total water level could reach as high as 6 meters to 7 meters, thereby causing floodings as also experienced at Nome.

3.1 General Discussion on Stabilities of Mound Breakwaters

Presently available experiences have demonstrated that in order to be assured of adequate stability for a mound breakwater, three different kinds of stability requirements must be fulfilled:

1. overall stability of the mound;
2. stability of units in the mound. They must not
leave or move appreciably.

(3) Structural unit stability of single members of the mound.

Furthermore, the toe structure, the wave screen, the crown and inner slope must remain stable. The foundation must be able to carry all loads, as well as provide protection against erosion in front of and behind the mound, to avoid danger to the stability of the toe structure /6,7,9/.

An earlier tendency has been to define stability as "unit stability" only, as it was expected that such stability include "everything." Experience however, has demonstrated that stability must be considered in a much broader sense.

2.2 Overall Stability

Overall stability is mainly concerned with /6,7,8,9,10/:

(1) Sliding of the armour layer as a whole or as mass slides penetrating deeper in the mound;
(2) Mass departure of blocks from the armour layer by jumping and/or rolling;
(3) Toe failures causing breakdown of the lower slope, expanding upwards, then causing a mass failure of the armour. Such incident may start as a failure of the mattress below the toe.
(4) Mass breakdown by heavy overwash of the crown of the mound, peeling off layer after layer and then washing most of the material down on the inside of the mound.

Sliding of the armour layer as a whole is usually a result of lifting of the armour, decreasing or cancelling entirely the friction forces between the armour and the first sublayer. The lifting may be a combination of forces by up- or down-rushing waters, plus hydrostatic pressures from the water standing in the mound, which varies highly with the permeability of core and sublayer materials. It is counteracted by gravity, including friction forces /4,6,7,9,10/.
Mass departure of blocks may take place as a result of such combined forces, which first force a single unit out. Neighboring units which are resting on (exert pressures on) said unit may then start moving too, in a kind of "attempt to close the gap." The result of such movements will, however, in most cases not only be a "healing of the wound", but a decrease of ties between blocks, making them more vulnerable to extraction by external forces. The departure of one unit may therefore be followed by the departure of a great many other units.

The failures are often hard to observe because severe toe damage usually expands upward in the mound, leaving no direct evidence of its occurrence. The reason for the failure is either scour by currents or by deep downrushes or by both. Such scours may be prevented by a proper mattress, which could be built of rock, willow (Holland) or of synthetic materials, in all cases loaded down with rock. The magnitude of the mattress depends upon the local bottom condition. The softer is the bottom, the larger and the stronger the mattress should be. Model experiments may be of guidance on design of a proper mattress.

Mass failures of the upper part of the mound by overwash are sometimes the reason for massive failure of mound breakwaters /6,9,10/. It has been a habit to try to save materials in the crown and in the inside slope. This often proved to be a poor practice. Storm waves are in most cases augmented by high tides. Together they cause high uprushes and possibly overwash, which could be fatal to the breakwater if crown and inside slope blocks are too small. To improve such situations, still using blocks of more modest size, grouting by asphalt may be used avoiding the rigidity of cement mortaring. Concrete caps on the top of crown blocks sometimes fail due to uplift pressures. Vent holes may mitigate the problem, but they are seldom kept clean and fail to work when critical situations arise.

2.3 Stability of Units in the Mound

Forces on the unit include impact and moment forces,
exerting pressures and shear forces on the unit which try to push it out of the mound /4,5,10,16/. Wave period is an important, often ignored, factor /5,6,8,9,10,16,17,18,22/.

The ability of units to stay in place in the mound first of all depends upon gravity forces. Gravity forces are exerted directly on the unit and by friction forces on a unit by neighboring units. A unit's ability to stay in place highly upon their geometry. For the same slope, blocks may show a great variety in being extracted by hydraulic forces, because their ability to "interknit" or "intertangle" varies greatly /7,9,10,26/, as do the "squeezing forces" by gravity, depending upon friction forces in all directions /4,5,8,10/. While intertangling is "a geometrical condition" that does not depend upon slope the squeezing forces are highly slope-dependent. One may, therefore, present the stability in its single components as a function of slope and the three components of stability: Gravity directly, squeezing and intertangling. Gravity is responsible for squeezing by friction forces. The three components make up "stability of the unit" disregarding all structural aspects. Various block materials, however, have strongly varying characteristics /8,9,10,25/. Intertangling is not necessarily an advantage because it introduces "fragility" of elements /8,9,10,26/.

The "stability", however, should not only be looked upon "statically" because this only gives "static information." A rock mound structure under wave attack becomes dynamic, and may include numerous moving parts. It possesses a certain "brittleness" and is subjected to tear and wear /2,3,9/. The "stability", therefore, cannot be defined adequately without consideration of the ability of the structure and its units to stand up to certain "shocks" as well as to "tear and wear" by rocking and exposure. The structure must neither be too "brittle", nor should it be allowed to wear out too soon, which in this respect means during the next 100 to 200 years or more. Fort structures should be built to last. They are neither supposed to suffer short range breakdowns, nor long range wear and degradation, making them inept to fulfill their purpose.
Rock mound breakwaters built 100-200 years ago are usually functioning well in 1983. Examples are found at many northwest European countries.

2.4 Structural Unit Stability

Unit stability may be considered not only as the ability of the unit to stay in place in the mound but as the structural stability of the unit, which must not rupture, crack or break under any load, static, dynamic or both, to which it will be exposed.

The forces working for stability of a unit include gravity forces directly, and friction forces. These forces may (in blocks of special geometrical shape) be assisted by joining of blocks in an interlocking or intertangling, making the armour a kind of a "mattress." This, however, may be a very dangerous practice if the single elements (leg or arm) of a block are not strong enough to resist the forces of pressure, momentum, shear or combined, to which they are exposed. The numerous failures of breakwaters with armour of multilegged blocks have proven the inadequacy of the structural stability of such blocks, which simply was not considered in the design. In those cases, blocks were simply too fragile /2,3,9/.

It has happened that in mounds of multilegged blocks the largest number of broken blocks were found in the lowest part of the mounds. Comparing rock to concrete blocks, including box and multilegged, the damage experienced in numerous cases was that for the multilegged blocks, damage developed rapidly. The breakdown in relation to duration of storms is fastest for steep slopes like the multilegged, and slowest for more gentle slopes, like rock mounds /7,9,10/. In between the cases of multilegged concrete mounds and rock mounds, one may place cubes or parallelopedic blocks of concrete on relatively gentle slopes. Experience with such blocks has been relatively good (e.g. in Europort in Holland, and this may further improve if units are grooved on four sides, releasing inside pressures, as the
Antifer-blocks used at several places in France, Belgium, Italy and as planned in Mexico.

2.5 Damage to Mound Structure

Heavy damage often occurs when the armour is completely soaked or fluidised in wave uprush. The breakdown pattern therefore, may be disastrous and capable of moving large masses /7, 8, 10/.

Common reasons for breakdown of rubble mound breakwaters, whether the mound is composed of natural or artificial blocks, are depicted in Fig. 5 /8, 9, 10/. They include:

1. Knock-outs by plunging wave when

\[ \xi = (\tan \alpha) \sqrt{H_d/L_o} < 2.0 \]  

2. Liftouts (by uprush - downrush) usually resulting from combinations of uprush and downrush and toe velocities in an arriving plunging wave. Professor Koutitas /23/, (in press) has made extensive theoretical studies of this subject.

3. Slides of the armour as a whole. This happens in particular at steep slopes, which are subjected to high waves of

![Figure 5. Common reasons for damage to or breakdown of mound breakwaters /6/.](image-url)
periods close to resonance (i.e. uprush-downrush period is close to wave period), see refs. /5,16,18/.

Failure is caused by combinations of buoyancy, inertia and drag forces supported by the effect of hydroacoustic pressure from the core of the breakwater. These forces all seem to reach their maximum value for lowest downrush which occurs at resonance or for:

\[ \xi = (\tan \alpha)\sqrt{\frac{g H_b L_o}{c}} \geq 2.0 \quad /5,10,16,18/ \quad (9) \]

Experience, however, has shown that large single or double waves (Fig. 6a) may be particularly dangerous. This has been observed directly in the field and some of the large failures of multilegged blocks may be attributed to the occurrence of such waves or groups of waves /6,9,10,17/. On the other hand groups of waves have caused rapid breakdown by "fatigue" /2,3,9,10/. Grouping of waves has been subject to extensive studies /2,3,15,16,32/.

4. Gradual breakdown or failure due to "fatigue." Fatigue starts with smaller movements of the blocks, which steadily increases, and by which the blocks are gradually moved out of intimate contact with neighboring units or from the first sublayer, and perhaps simultaneously suffer from tear and wear due to their rocking or bouncing, thus impacting other blocks and causing damage. This process is particularly important for multilegged blocks, when such damage may be directly observed or heard. Occurrence of resonance, making the uprush/downrush period equal to the wave period for groups of waves (Fig. 6b), has particularly damaging effects due to the constant rocking motion which partly breaks down friction and interknitting between blocks, and partly cause structural ruptures due to bending stresses and other fatigue forces /3,9/. Other types of wave trains (e.g. wave series with deep troughs) (Figs. 6c and 6 d) causing deep rundown (Fig. 6e), and therefore high downrush velocities as well as higher hydrostatic pressures from the water table in the core, are very dangerous /4,7,16/. Natural rock is
Figure 6. (a) Mammoth (freak) wave; (b) group of waves; (c) wave series with a deep trough; (d) wave series with a deep trough followed by a high crest; (e) a deep trough causing a deep down-rush at breakwater /5,6,9,10/. 

(a) \[ T_1 - \Delta T \quad T_1 \quad T_4 + \Delta T \quad T_4 \] 
(b) 
(c) 
(d) 
(e) 

TIME (Sec) 

SWL 

ARMOUR FILTER 

CORE
a compact mass and its resistance against movement is based on its weight and friction against other blocks. When useful weight is decreased due to buoyancy, the resistance against movement decreases to about half. The wave situation depicted in Fig. 6 d, therefore, is very dangerous, because the slope meets wave No. 2 in a submerged condition. It is the most dangerous wave trains, hydrodynamically speaking, that determine the stability or failure.

It is a too-often repeated mistake to base tests on "spectra" without regard to the sequences of waves, and laboratories have claimed that they were included in the spectra, but after the fact, and without delivering sufficient proof of this. In fact, they most likely were not included simply because generators could not produce them. On occasions it has been claimed that such waves do not exist, but this postulate has been based on a limited time recording at only one place. It is also argued that waves as shown in Fig. 6 are shallow water phenomena, but experience shows that this is incorrect for they have been observed in the middle of oceans during storms, and are generally known as 'freak waves' among sailors. The local wave mode or pattern varies along the breakwater and it is of course the local wave situation which determines the local forces, and may include concentrations of wave energy. For a long breakwater it is, therefore, necessary to know the wave situation for the entire distance along the breakwater. Breakwater failures often happen in areas where wave action, possibly owing to the bottom topography or wave interaction, is concentrated. Conventional head geometry, by turning the end inward, creates such concentrations. It is, therefore, much better for stability as well as for reasons of navigation and sediment transportation, to curve the head outward /8,10/. This is based on long established Scandinavian experience and is now being increasingly utilized elsewhere (Fig. 7).

5. Often, based on old Mediterranean practice, the breakwater is provided with a large wave screen on the top. The latest years experience with such "mammoth" wave screens (Sines, Arzew el Djedid, Tripoli, Bilbao, Akranes) is that they are
Figure 7. Stabilization of breakwater at Sorvaer harbour, Troms, Northern Norway [3, 10, 21].
harmful when wave uprush during extreme storms is allowed to hit them, thereby generating strong reflection and high pressures, causing erosion of blocks in front of the wall and ultimate collapse of the wall /6,8,9,10/.

6. Overwash which could damage the interior slope of the mound as well as the crown, lowering it and thereby increasing damage.

7. Uplift pressures on the crown slope. If such pressures are not relieved they may cause severe damage to the crown as well as to the interior slope and to the area inside (Tripoli). Measures against such damage include a tight core, prohibiting pressures from penetrating the crown, and/or vent galleries installed in the crown. They must be kept clean.

8. Toe erosion caused by deep downrushes combined with currents. The toe must be solid but it must not "invade" erosion by being built too high so that it faces deep downrushes. It must rest on a mattress, protecting it against scour by downrush and currents.

9. The foundation must be adequate to carry the mound. Slip circle failures have occurred.

10. Construction and workmanship must be up to reasonable standards. The mound shall be built as designed /22/.

2.6 Testing

Special attention should be paid to wave groupings, particularly when periods are close to resonance /4,5,10,17,18/ and/or the \( \xi = (\tan \alpha)\sqrt{H_o/L_o} \) value is near the dangerous value of 2.

Wave groups are important for fatigue failures of blocks caused by rocking. This is particularly important for concrete blocks /3,9/. Rocking should, therefore, be observed carefully in the model. It is also of importance to know the failure mode when the mound is subjected to wave action beyond its capacity.

With respect to wave data it could happen that they are available from records, but in most cases they usually refer to a short time period, making them less useful for extrapolations.
Usually wave data is interpreted using its spectra and in spectral geometries /20,21,32/. The danger of simulating spectra from the prototype to the laboratory, however, is that regardless of full spectral similarity the detailed wave geometry, including groupeness, may differ greatly /32/. It is, therefore, necessary to imitate wave sequences--including wave groups correct in the model--regardless of spectral shape. Certain properties of wave groupeness seem to be related to the spectral peakness, p. The quantity p is defined as:

\[
p = \frac{1}{m_0^2} \int_0^\infty S(ft)^2 \, dt
\]  

(10)

Goda /16/ and Rye /32/ studied wave groupeness in relation to a variety of \( Q_p \)'s and found that groupeness and \( Q_p \) were related, since \( Q_p \) and the mean length of runs of \( H > H_{1/3} \) show a clear dependency. The higher \( Q_p \), the longer "mean runs" (more waves in the group). The peakness parameter \( p \) has proven to be practical for the description of wave groups in relation to various group parameters including the \( Q_{HH} \)

\[
Q_{HH}(1) = \frac{1}{Q_{HH}(0)} \cdot \frac{1}{N_z-1} \sum_{i=1}^{N_z-1} (H - \overline{H})(H_{i+1} - \overline{H})
\]  

(11)

\[
Q_{HH}(0) = \frac{1}{N_z} \sum_{i=1}^{N_z} (H_i - \overline{H})^2, \quad N_z = \text{number of waves in sample}
\]

Model tests should, therefore, include all necessary considerations to detailed wave geometries and particularly to those which are most dangerous to stability.

Regular waves do not imitate nature correctly. They may be used solely for introductory experiments comparing block geometries, different kinds of concrete blocks and dangerous periods related to resonance effects. Such periods will, however, usually be known beforehand from numerous other experiments, as are block geometries as related to stability. Regular wave tests, therefore, are of less use with advanced design programs. Table 2 shows the type of wave data which are needed for model experiments and the nature of the experiments.
It is obvious that scale effects have to be accounted for in the model study /29,33/.

Table 2. Wave data needed for experiments.

<table>
<thead>
<tr>
<th>Wave Description</th>
<th>Spectra</th>
<th>Spectra with correct sequences</th>
<th>Wave Rays Groups</th>
<th>Waves of solitary type</th>
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<tbody>
<tr>
<td>Available as</td>
<td></td>
<td>Time series</td>
<td>Observed or Calculated</td>
<td>Observed Designed</td>
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<tr>
<td>Records</td>
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<td></td>
</tr>
</tbody>
</table>

2.7 Nome Project Breakwater

Experiments as described are in progress. Waves are limited by depth to about 0.7 $D_b$. Figure 8 shows schematically cross sections naming the various layers by a figure and describing properties in the Legend below. At the same time numbers describe sequence of construction.

![Figure 8. Mound structure. Schematics. Various layers. Sequence of construction.](image)
(1)Mattress - to protect against scour and penetration of fine material up in the mound if the bottom is silty.

(2)Toe structures of material size (5) and (6) possibly covered with larger armour on the outside toe.

(3)Core 1 - Quarry waste material, lowest grade but without sand. Most material is < 1.0 kg.

(4)Core 2 - Quarry material fulfilling the requirement of no content or sand, pebble or gravel. Material size 10-100 kg.

(5)2nd Sublayer - material of size W/100 with tolerances where W is the average weight of the armour.

(6)1st Sublayer - usually of size W/5 - W/10 where W is the weight of armour.

(7)Armour of weight W in top layer; slightly < W in the second layer.

(8)Interior slope armour protection which could be of size (6) or perhaps (5) for milder conditions.

(9)Crown block layer which could be of size (6) or lower depending upon overwashes. It may be a slab (12 below).

(10)Wave screen of piled (placed) rock or concrete blocks.


It should be noted that the armour layer does not necessarily need to be composed of one-size blocks. The most exposed section is located between +Hb at high tide and -Hb at low tide and blocks may be largest in this area. If rock of adequate size is not available for this area it may be replaced by concrete blocks (e.g. of the Antifer type) which are slightly coned shaped and have half-circular grooves on four sides which will be placed about perpendicular to the slope. With respect to layout, the head of the breakwater will be turned outward following the principles outlined by Bruun in reference (FOAC-83).

Blocks in the causeway are attacked by waves under angles < 25 degrees which decreases block size to about half of the weight.
for perpendicular attack referring to rock only.

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BERGYBIT IMPACT FORCES ON A MOORED SEMISUBMERSIBLE

Abstract

The transient responses of and the forces developed on a moored semisubmersible due to collision with a bergybit are presented in this study. Two approaches, one using the total energy of the system, and the other using the conventional structural dynamics method of initial velocity conditions, are presented. Numerical solutions are obtained only for the latter. The local structural response is also considered. Numerical results are presented for impact with two bergybits of mass 5,000 t and 10,000 t.

1 INTRODUCTION

In view of the considerable hydrocarbon resources in the offshore regions of Labrador and the recent discovery of oil at Hibernia in the Grand Banks region (offshore of Newfoundland), the need has risen for year-round operations. Since Hibernia waters are infested with ice-floes, ice-ridges, and occasional icebergs and the attendant bergy-bits/growlers, it becomes essential to investigate the design safety of semi-submersibles against transient ice forces generated by the impact of bergy-bits and growlers. The present study is an analytical study of this problem.
Iceberg impact on a drillship of the 'Pelican' type was examined by FENCO, GERMAN and MILNE [5]. The effect of the size of the growler and its drift velocity on the impact forces were examined and the critical conditions determined. Hull resistance to impact, and the splitting strength of the growler were also examined. The collision between a ship and a platform was investigated by Larsen and Engseth [10]; they also proposed fendering systems to protect the offshore platforms from damage. Allowable velocities to minimize impact damage were estimated. Furness and Amdahl [7] carried out theoretical and experimental studies on the damage due to collision of small ships on large steel/concrete platforms.

Collision probabilities of ships with other offshore structures were examined by Larsen and Engseth [10], and Furness and Amdahl [7] using simulation procedures. Using Monte Carlo simulation, the probability of iceberg impact with an offshore structure was investigated by Reddy, Arockiasamy, Cheema and Riggs [12].

The dynamic response of a four-column-supported semisubmersible vessel was determined by Whitney [15]. He also examined the possibility of optimizing the structural motions by the use of active displacement control on heave, pitch and roll motions. The local static/dynamic responses of the plating and the supporting frames of a semi-submersible, subjected to ice floe impact, were described in a report of FENCO [6]. Four types of load application, i) gradual, ii) transition between gradual and sudden, iii) short duration, and iv) high velocity impacts, were examined in detail, and expressions formulated for the generated forces. Momentum-energy relationships were used along with the exact differential equations of motion. Ice failure patterns were also examined. The plastic energy absorption capacity of steel tubular members of offshore structures was examined by de Oliveria [4]. Arockiasamy and
Reddy [1] and Reddy et al [13] investigated the dynamic response of moored semisubmersibles to bergy-bit impact, irregular wave, wind, and current forces. The experimental motion responses to irregular waves were found to correlate well with the theoretical predictions. Also, it was pointed out that the impact forces and responses depend mainly on the stiffness of the mooring cables; forces were found to be very large for high cable stiffness. The transient added masses due to a collision process have been described by Blok and Dekker [2]. Hydrodynamic forces associated with the icebergs in motion were investigated by Chirivella and Miller [2], White, Spaulding and Geminbo [14], and Hsiung and Aboul-Azm [8].

In the present paper, the following studies are reported:
1) the global response of a moored semisubmersible to the impact forces generated by the impact of a bergy-bit, and
2) the local indentation of an adequately reinforced column of the semisubmersible.

3 IMPACT RESPONSE OF A SEMISUBMERSIBLE TO BERGYBIT COLLISION

When a bergy-bit collides with a moored semisubmersible, part of its kinetic energy is absorbed by rigid body rotation (in pitch and roll only) of the semisubmersible, and elastic/plastic deformation of the impacted and other parts of the semisubmersible. Another part is dissipated by rigid body rotation (in pitch and roll only) of the bergy-bit and local crushing or splitting of the bergy-bit, and the rest by the linear/nonlinear deformation of cables. As a result of the collision, one of the following actions will take place:
1) The impact forces produced are so small that the semisubmersible resists them with slight denting of some regions, and the bergy-bit sustains slight local spalling but remains intact as a whole body. The cable deformations may or may not be significant (depending on cable stiffnesses).
ii) The impact forces and the impact strains generated are such that the bergy-bit deforms extensively or is split apart by the semisubmersible, and the semisubmersible is damaged significantly. The cable deformations are extensive and if the anchor is not capable of resisting the pullout forces, the anchors are dragged over the seabed till the impact energy is dissipated.

iii) The bergy-bit is so large that it does not break apart on impact, but causes extensive damage to the semisubmersible and cables.

In this study only the first two cases are investigated with the following assumptions; (1) the anchors are designed to withstand the transient pullout forces; (ii) the cables do not snap, and iii) the impact is plastic (i.e. common interactive velocity is attained). The justification for the assumption (iii) is obtained from the equation given by Hunter [9], where the duration of impact, $t_d$, is given by

$$ t_d = \frac{K_1 V_{bo}}{-1/5}, $$

in which

$$ V_{bo} = \text{initial velocity of the bergy-bit}, $$

$$ K_1 = 2.94 \left( \frac{15}{16} \frac{m'_b m'_s}{m'_b + m'_s} g \right)^{2/5} R^{-1/5}, $$

and

$$ g = \frac{1-\nu_b^2}{E_b} + \frac{1-\nu_s^2}{E_s}, $$

where

$m'_b$ and $m'_s =$ virtual masses of the bergy-bit, and the semisubmersible, in the direction of motion of the bergybit

$R =$ radius of the semisubmersible component hit by the iceberg,

$\nu'_b$, $\nu'_s =$ Poisson's ratios of bergy-bit and semisubmersible material,
\( \text{Ed, Es} = \text{corresponding Young's moduli.} \)

In the study under consideration the impact durations were found to be approximately 1.421, 2.0769 and 2.972 sec respectively for the front and side of the pontoon, the columns and braces. Eqs. (1) and (2) assume very large rigidity for the impacting faces; for elastic structures these impact durations are bound to be much higher, implying plastic collision.

In all the three modes of behavior listed above

\[
\frac{1}{2} m' v_o^2 = E_d + E_{\text{member}} + E_{\text{system}} + E_{\text{elast}} + E_{\text{bergy-bit}}
\]

(3)

where

- \( E_d = \text{energy absorbed in local denting,} \)
- \( E_{\text{member}} = \text{energy absorbed in member bending,} \)
- \( E_{\text{system}} = \text{energy absorbed in rigid-body motion of the semisubmersible and bergy-bit,} \)
- \( E_{\text{elast}} = \text{energy absorbed by the elastic structural deformation of the semisubmersible} \)

and

- \( E_{\text{bergy-bit}} = \text{energy absorbed in elastic/inelastic deformation of the bergy-bit.} \)

3.1 Local Structural Damage

When the bergy-bit impacts either a horizontal brace or a vertical column, three types of behavior can be observed, i.e., local denting, local denting and beam bending, and structural collapse depending on the \( D/h \) and \( \delta/r \) ratios, where \( D(r) = \text{diameter (radius) of the tubular member, } \)
\( h = \text{thickness and } \delta = \text{deflection. Following de Oliveira (4), the energy absorbed in local denting is given by} \)

\[
E_d = 2M_o \left( 4L\Delta/L + 2L\Delta/k + 2L \right)
\]

(4)

where
\[ M_o = \frac{\sigma_o h^2}{4} \]

\[ \sigma_o = \text{uniaxial yield stress (in steel)} \]

and

\[ l, L, L, \Delta \text{ and } \alpha \text{ are defined in Fig. 1.} \]

Since the member collapse is the end result of large bending, the second case is not considered separately. The load causing structural collapse is determined considering perfectly rigid plastic behavior; the yield conditions are as follows [Ref. 4]:

\[ p = \alpha + \pi N \omega + \frac{1}{2} dw \left( \frac{L}{L_1} k_{r1} + \frac{L}{L_2} k_{r2} \right), \]

\[ w = \frac{1}{2} \sin \left( \frac{\pi}{2} n \right) \pm \left[ \left( \frac{1}{2} \sin \left( \frac{\pi}{2} n \right) \right)^2 + 2 \frac{e}{k_e} \right]^{1/2}, \quad (5) \]

where,

\[ d = \frac{D}{L}, \quad L_1 = \frac{L_1}{L}, \quad L_2 = \frac{L_2}{L}, \quad p = \frac{PL_1 L_2}{2L M_o}, \quad m = \frac{M}{M_o}, \quad n = \frac{N}{N_o}, \quad w = \frac{d}{D}, \]

\[ k_{r1} = \frac{K_{r1}}{M_o}, \quad k_{r2} = \frac{K_{r2}}{M_o}, \quad \frac{k_e}{k} = \frac{L}{L_1 + L_2}, \]

\[ k_1 = \frac{K_1 d}{\pi \sigma_o}, \quad k_2 = \frac{K_2 d}{\pi \sigma_o}, \quad (6) \]

and

\[ N_o = \pi D t \sigma_o, \]

where

\[ P \text{ and } M = \text{transverse load and bending moment at the point of application of the load,} \]

\[ N = \text{axial force acting on the member,} \]

and

\[ W, L, L_1, L_2, K_{r1}, K_{r2}, K_1, \text{ and } K_2 \text{ are defined in Fig. 2.} \]

When the bergy-bit hits the front or sides of the pontoon, similar phenomena will take place; the stiffened flat plate replaces the tubular member. The stiffened plates acting as orthotropic plates get dented first due to impact, and then the transverse closed frames are deformed before the overall deep
beam action of the pontoon, in between the columns, sets in. A small part of the energy is also transmitted to the cables. According to Xirouchakis and Shortstrom (16), the impact load sustained by the longitudinally reinforced hull is given by

$$P = \frac{3T^2EI_{LG}}{a^{2.5}(T-a)^{2.5}} \Delta$$

where

- $T$ = spacing of transverse frames,
- $a$ = distance from the transverse frame at which the impact load acts,
- $EI_{LG}$ = stiffness of the longitudinal girder with plating

and

$$\Delta = \text{transverse deflection.}$$

The energy absorbed in the local deformation of the plate girder is

$$E_d = \frac{1}{2} \sum_{i=1}^{n} P_i \Delta_i \ldots \text{for elastic deformation}$$

and

$$E_d = \sum_{i=1}^{n} P_i \Delta_i \ldots \text{for plastic deformation} \quad (8)$$

where

- $P_i$ = impact force acting on the $i^{th}$ plate-girder combine

and

- $\Delta_i$ = consequent elastic or plastic deformation of the plate-girder combine.

The energy absorbed in the deformation of the member is given by

$$E_{\text{member}} = \frac{1}{2} P \dot{\epsilon} \ldots \text{for elastic deformation}$$

and

$$E_{\text{member}} = P \delta \ldots \text{for plastic deformation} \quad (9)$$
3.2 Local Deformation/Failure in Bergybit

As mentioned earlier, during the impact of a bergybit with a semisubmersible, part of the kinetic energy of the bergybit (before impact) is transformed into the energy required for the crushing/deformation of ice at the zone of contact. Upon impact, a bulb of crushed ice forms beneath the impact surface due to the unevenness of the surface and the high local stress concentrations. As the contact pressure increases, the area of contact increases due to local elastic deformation and crushing of surface unevenness. If the impact force at the contact area is large enough, failure of ice occurs and dissipates part of the kinetic energy of the bergybit.

\[ E_{\text{bergybit}} = \frac{1}{2} P \delta_1 \text{ .... for elastic deformation} \]

and

\[ E_{\text{bergybit}} = P \delta_1 \text{ .... for inelastic deformation} \quad (10) \]

where

\[ \delta_1 = \text{the deformation in ice}. \]

3.3 Global Motion

The moored semisubmersible behaves as an elastically restrained rigid body when it is impacted by a bergy-bit. If the semisubmersible is impacted by a bergy-bit in a general direction (angular impact) at any general point on its front or sides, the equations of motion are given by

\[
\begin{align*}
(a_{11}D^2 + b_{11}D + c_{11})\zeta + (a_{13}D^2 + b_{13}D)\theta &= F_1(t) \\
(a_{22}D^2 + b_{22}D + c_{22})\eta + (a_{24}D^2 + b_{24}D)\phi &= F_2(t) \\
(a_{33}D^2 + b_{33}D + c_{33})\zeta &= 0 \\
(a_{24}D^2 + b_{24}D)\eta + (a_{44}D^2 + b_{44}D + c_{44} + c_{44})\phi &= F_1(t)z_1 \\
(a_{15}D^2 + b_{15}D)\zeta + (a_{55}D^2 + b_{55}D + c_{55} + c_{55})\theta &= F_2(t)z_1 \\
(a_{66}D^2 + b_{66}D + c_{66})\phi &= F_1(t)y_1 - F_2(t)x_1 \quad (11)
\end{align*}
\]
where

\[ D = \frac{\partial}{\partial t}, \]

\[ F(t) = F_1(t)i + F_2(t)j \]

is the impact force with components \( F_1(t) \) and \( F_2(t) \) in the x and y directions, respectively, 

\[ (x_1, y_1, z_1) = \text{point of impact with respect to the centre of gravity}, \]

\( \xi, \eta, \zeta = \text{translatory motions of surge, sway and heave respectively} \)

and

\( \phi, \theta, \psi = \text{rotational motions of roll, pitch and yaw respectively} \)

The terms \( C_{ij} \) correspond to the contributions from the cables.

Since the heave motion is not influenced by impact, it can be neglected from any further considerations. Eqs. (11) are solved to determine the transient responses of the semisubmersible.

The impact force, \( F(t) \), is determined in an iterative manner by the considerations of energy, Eq. (3), and the solutions of Eqs. (11).

The energy absorbed in impact is obtained by the use of Eq. (3), where \( E_d \) is given by Eq. (4) or Eq. (8), \( E_{\text{member}} \) by Eq. (9) and \( E_{\text{hyd}} \) by Eq. (10). Since \( E_{\text{elas.}} \) is small, it is neglected (energy absorbed by parts other than the impacted face). The \( E_{\text{system}} \) is obtained as follows: Assuming the impact to be plastic,

\[ E_{\text{system}} = \frac{1}{2} m' \left[ \omega_{bs}^2 + \frac{1}{2} \left( I_{b\psi} + I_{ab\psi} \right) \right] + \frac{1}{2} m'_b \left[ \psi_{bs}^2 + a_{66} \right] \omega_{bs}^2 - E_{d} - E_{\text{member}} - E_{\text{hyd}} \]

where
$$b_{E_{hyd}}$$ = hydrodynamic (drag and inertial) forces acting on the bergy-bit due to its sudden deceleration, and

$$v_{b_s} = \frac{m_b v_b}{[a_{11} + m_b]}$$

$$\omega_{b_s} = \frac{[(I_{b\psi} + I_{ab\psi}) + m_b r_{b\psi}^2] \omega_{b\psi}}{[(I_{b\psi} + I_{ab\psi}) + m_b r_{b\psi}^2 + a_{66}]}$$

(13)

and

$$\omega_{b_o} = \frac{v_{b_o}}{r_1}$$

(14)

in which

$$I_{b\psi} + I_{ab\psi}$$ = virtual yaw moment of inertia of the semisubmersible,

$$r_{b\psi}$$ = distance of the center of gravity of the bergy-bit from the center of gravity of the semisubmersible,

and

$$r_1$$ = perpendicular distance of the center of gravity of semisubmersible from the drift path of the bergy-bit.

$$E_{system}$$ can be computed from

$$E_{system} - E_{hyd.} = \int_o^u \text{Audu} + \int_o^u \text{Budu} + \int_o^u \text{Cudu} + \int_o^u \text{Dvdv}$$

(15)

where,

$$\begin{bmatrix} a_{11} & 0 & 0 & a_{15} & 0 \\ 0 & a_{22} & a_{24} & 0 & 0 \\ 0 & a_{24} & a_{44} & 0 & 0 \\ a_{15} & 0 & 0 & a_{55} & 0 \\ 0 & 0 & 0 & 0 & a_{66} \end{bmatrix} = [A]$$

and

$$\begin{bmatrix} b_{11} & 0 & 0 & b_{15} & 0 \\ 0 & b_{22} & b_{24} & 0 & 0 \\ 0 & b_{24} & b_{44} & 0 & 0 \\ b_{15} & 0 & 0 & b_{55} & 0 \\ 0 & 0 & 0 & 0 & b_{66} \end{bmatrix} = [B]$$
The coefficients $d_{ij}$ are the inertial properties of the bergy-bit determined at the centre of gravity of the semisubmersible, for the $\phi$ and $\theta$ motion.

When the impact is plastic, Eqs. (11) can be solved in another way. Since the denting, the bending of impacted member, and the local crushing (due to unevenness) of ice are almost short-time phenomena (because their stiffnesses are comparatively larger), the system could be idealised as a system subjected to initial velocity conditions: i.e., $V_{bsx}$, $V_{bsy}$, $\omega_b$ in the surge, sway and yaw-directions respectively, where

$$V_{bs} = V_{bsp} + V_{bsn}$$

Eqs. (11) are to be modified taking into consideration the inertial, damping and restoring properties of the bergy-bit-semisubmersible system. These can be written as

$$(a_{11} \dot{D}^2 + b_{11} \dot{D} + c_{11}) \xi + (a_{15} \dot{D}^2 + b_{15} \dot{D}) \phi = 0$$

$$(a_{22} \dot{D}^2 + b_{22} \dot{D} + c_{22}) \eta + (a_{24} \dot{D}^2 + b_{24} \dot{D}) \phi = 0$$

$$(a_{24} + b_{24}) \eta + (a_{44} \dot{D}^2 + b_{44} \dot{D} + c_{44}) t = 0$$
\((a_{15}'D^2+b_{15}'D)\xi + (a_{55}'D^2+b_{55}'D+c_{55}'+c_{55})\theta = 0\)
\((a_{66}'D^2+b_{66}'D+c_{66}')\psi = 0\)  \(\text{(18)}\)

where

\[ a_{11}' = m_b' + a_{11}, \quad b_{11}' = b_{11} + \text{damping in bergybit, etc.,} \]
\[ a_{22}' = m_b' + a_{22}, \]
\[ a_{44}' = (I_{b\phi}^2 + I_{a\phi}) + m_b'^2 + a_{44}, \]
\[ a_{55}' = (I_{b\theta}^\phi + I_{a\theta}^\phi) + m_b'^2 + a_{55}, \]

and,

\[ a_{66}' = (I_{b\phi}^\phi + I_{a\phi}^\phi) + m_b'^2 + a_{66}. \]  \(\text{(19)}\)

Eqs. (18) are solved subject to the initial conditions given by Eqs. (13), (14) and (17). Reduction of Eq. (18) leads to

\[ \begin{array}{cccc}
A_{11} & \xi + A_{12} & \xi + A_{13} & \xi + A_{14} & \xi + A_{15} = 0 \\
A_{21} & \eta + A_{22} & \eta + A_{23} & \eta + A_{24} & \eta + A_{25} = 0
\end{array} \]

and

\[ \begin{array}{cccc}
a_{66}' & \psi + b_{66}' & \psi + c_{66}' & \psi = 0
\end{array} \]  \(\text{(20)}\)

where

\[ A_{11} = a_{55}'a_{11} - a_{15}'^2, \]
\[ A_{12} = a_{55}'b_{11} + a_{11}'b_{55} - 2a_{15}'b_{15}, \]
\[ A_{13} = a_{55}'c_{11} + \tilde{c}_{55}a_{11}' + b_{55}'b_{11}' - b_{15}'^2, \]
\[ A_{14} = b_{55}'c_{11} + b_{11}'\tilde{c}_{55}, \]
\[ A_{15} = c_{11}\tilde{c}_{55}, \]
\[ A_{21} = a_{44}'a_{22} - a_{24}'^2, \]
\[ A_{22} = a_{44}'b_{22} + a_{22}'b_{44} - 2a_{24}'b_{24}' \]
\[ A_{23} = a_{44} c_{22} + \tilde{c}_{44} a_{22} + b_{44} b_{22} - b_{24}^2, \]
\[ A_{24} = b_{44} c_{22} + b_{22} \tilde{c}_{44}, \quad A_{25} = c_{22} \tilde{c}_{44} \]
\[ \tilde{c}_{44} = c_{44} + c_{44}, \quad c_{55} = c_{55} + c_{55} \]

and

\[ a_{44} \ddot{\xi} + b_{44} \dot{\xi} + \tilde{c}_{44} \dot{\xi} = -a_{24} \ddot{\eta} - b_{24} \dot{\eta}, \]
\[ a_{55} \ddot{\eta} + b_{55} \dot{\eta} + \tilde{c}_{55} \dot{\eta} = -a_{15} \ddot{\xi} - b_{15} \dot{\xi}. \]

The \( a_{ij} \) coefficients are those of the semisubmersible-bergybit system. Eqs. (20) are first solved for the transient response \( \xi, \eta \) and \( \psi \) subject to the initial velocity conditions. Then these values of \( \dot{\xi} \) and \( \dot{\eta} \) are substituted into Eqs. (22) and solved for \( \ddot{\xi} \) and \( \ddot{\eta} \). The impact forces \( F_1(t) \) and \( F_2(t) \) are determined using Eqs. (11) as

\[ F_1(t) = (a_{11} \ddot{\xi} + b_{11} \dot{\xi} + c_{11} \dot{\xi}) + (a_{15} \ddot{\eta} + b_{15} \dot{\eta}) \]
\[ F_2(t) = (a_{22} \ddot{\xi} + b_{22} \dot{\xi} + c_{22} \dot{\xi}) + (a_{24} \ddot{\eta} + b_{24} \dot{\eta}) \]

and

\[ F(t) = F_1(t)i + F_2(t)j \]

4 RESULTS AND DISCUSSION

Fig. 3 shows a number of bergy bits, probably calved out of the larger iceberg observed in and around Hibernia. In this study, bergybits of masses 5,000 t and 10,000 t are assumed to impact a corner column of the semisubmersible drifting at an angle of 60° to the direction of surge. Figs. 4 to 6 describe the salient features of the semisubmersible considered in this study. The mass, inertial and other properties of the semisubmersible are given in Table I. The added mass and damping coefficients were computed according to the method indicated in Price and Bishop [11] and transformed to the centre of gravity of the vessel.
The semisubmersible vessel is moored by 3 cables at each of the four corners, inclined at 30°, 45° and 60° to the x-axis. Individual cable stiffness is determined with a horizontal cable tension, \( T_0 \) of 200,000 N, using the cable formula (in an incremental manner),

\[
y = \frac{T_0}{2d} \left( c_1 e \frac{\mu X}{T_0} - c_1 e - \frac{\mu X}{T_0} \right) - \left( c_1 + \frac{1}{c_1} \right),
\]

where

\[
T = \frac{T_0}{2} \left( c_1 + \frac{1}{c_1} \right) + \frac{2 \mu y}{T_0},
\]

\[
c_1 = \tan^2 \theta_0 + \sqrt{1 + \tan^2 \theta_0},
\]

\( u = \) buoyant self-weight of cable per unit length,

\( \theta_0 = \) angle the cable makes at the anchor,

and

\( x, y = \) the horizontal and vertical distances of the point under consideration.

For the whole semi-submersible, the stiffnesses are determined as follows:

\[
K_{ij} = \sum_{j=1}^{4} \sum_{i=1}^{3} k_{h_{ji}} \cos \theta_{ji} \cos \theta_{ji},
\]

\[
K_{n} = \sum_{j=1}^{4} \sum_{i=1}^{3} k_{h_{ji}} \sin \theta_{ji} \cos \theta_{ji},
\]

\[
K_{u} = \sum_{j=1}^{4} \sum_{i=1}^{3} \sin \theta_{ji} \cos \theta_{ji},
\]

\[
K_{v} = \sum_{j=1}^{4} \sum_{i=1}^{3} k_{v_{ji}} \sin \theta_{ji} \cos \theta_{ji},
\]

\[
K_{h_{ij}} = \sum_{j=1}^{4} \sum_{i=1}^{3} \sin \theta_{ji} \cos \theta_{ji} + k_{h_{ij}} \cos \theta_{ji} \cos \theta_{ji},
\]

\( k_{h_{ij}} = \) coefficients

and

\[
K_{v} = \sum_{j=1}^{4} \sum_{i=1}^{3} k_{v_{ji}} \sin \theta_{ji} \cos \theta_{ji} \cos \theta_{ji} + k_{v_{ji}} \sin \theta_{ji} \cos \theta_{ji},
\]

\( \mu = \) proportionality constant

\( \theta_{ji} = \) angle between the cable and the x-axis at point \( i \)

\( \theta_{ji} = \) angle between the cable and the y-axis at point \( i \)

\( x_{ji}, y_{ji} = \) horizontal and vertical distances of point \( i \) from the anchor

\( c_1, c_2, c_3, c_4, c_5 = \) coefficients

(27)
where,
\[ k_{hji}, k_{vji} \] = horizontal and vertical cable stiffnesses of the \( i^{th} \) cable at \( j^{th} \) corner,
\[ \alpha_{ij}, \beta_{ij} \] = inclination of each of the cables to the surge and vertical directions,
and
\[ a_j, b_j, c_j \] = \( x-, y-, \) and \( z- \) distances of the cable attachment points (from the centre of gravity of the vessel) at \( j^{th} \) corner, respectively.

In this study, the cable attachment points of each cable are assumed to be \( x=163.6 \) m and \( y=84.0 \) m from the anchor; the diameter of each cable is taken as 8.90 cm.

Since the impact is assumed to be plastic, the combined properties of the semisubmersible-bergybit system are computed in the \( x, y \) and \( z \) directions (of the semisubmersible) according to Eq. (18). The size of the bergy-bits were computed as \( 30 \times 14.57 \times 13.50 \) m and \( 39 \times 17.39 \times 16.2 \) m with free-boards of 1.5 m and 1.8 m, respectively. The solutions of Eqs. (20), (22) and (23), subject to the initial velocity conditions, are given by
\[ \ddot{z} = \dot{z}_0 e^{-a_1 t} \sin a_2 t, \]
\[ \ddot{\theta} = \dot{\theta}_0 e^{-a_1 t} (\beta_2 \sin a_2 t + \beta_3 \cos a_2 t), \]
\[ \ddot{\psi} = \beta_4 \dot{\psi}_0 e^{-a_1 t} \sin a_4 t, \]
and
\[ F_1 = \dot{q}_0 e^{-a_1 t} \left[ \beta_5 \sin a_2 t + \beta_6 \cos a_2 t \right], \]  
(28)
where
\[ \dot{q}_0 \] = speed of the bergy-bit,
\[ \beta_4 \] = initial, common interactive angular yaw speed of the semisubmersible-bergybit system,
and

and

$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, a_1, a_2, a_3$, and $a_4$ = numerical coefficients.

The global surge, sway, roll pitch and yaw motions of the semisubmersible are given in Figs. 7 to 9; the speed of the bergy-bit is assumed as 1.0 mps. At this speed the impact forces shown in Fig. 9 are found to be 1.3% and 2.47% of the weights of the bergy-bit (5,000t and 10,000t). If the speed of the bergy-bit is assumed to be 1.5 mps, the impact force is found to be 1.90% and 3.70% of the respective weights of the bergy-bits. It is also observed that when fluid drag forces are included in the calculations, the impact force increases.

The local damage suffered by the column under the ice impact load is determined using Eqs. (4) and (5), and it is observed that the column remains integral as a structural member without undergoing overall failure. Considering the failure mechanism stipulated in Fig. 1, the local denting takes place at a load of 249.66 kN. Under the impact load of 3.629 MN (10,000t bergy-bit at 1.5 mps), the sizes for the local mechanism were found to be $2l=30.25$ cm, $L = 21.40$ cm, $L = 40$ cm, and $a = 0.033611$ rad (Fig. 1 and Eq. (4)). In these calculations, the failure stress in ice was taken at 30 MPa.

5 CONCLUSIONS

It is observed that for the given semisubmersible and bergy-bit, the maximum ice impact load could reach a maximum of 3.7% of the weight of the bergy-bit (for 10,000t bergy-bit). Local denting of the column will take place under an initial impact load of 249.66 kN.
ACKNOWLEDGEMENTS

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### TABLE I. Mass and Inertial Properties of the Semisubmersible.

<table>
<thead>
<tr>
<th>Mass (kg)</th>
<th>Distance of c.g. from the center of the vessel in the water-plane</th>
<th>Mass moment of Inertia (10^6 x kg.m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.868 \times 10^6</td>
<td>x=0.0089m  y=0.0061m  z=1.1141m</td>
<td>I_{xx} = 190.699  I_{yy} = 0.681  I_{zz} = 284.723</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I_{xy} = -0.262  I_{yx} = 174.256  I_{yz} = -0.575</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I_{zx} = 0.681   I_{zy} = -0.575   I_{zz} = 284.723</td>
</tr>
<tr>
<td>Draft</td>
<td>GM_T = 18.50m  GM_L = 2.6185m  GM_L = 2.6691m</td>
<td>CX_RADIUS = 30.2166m  GY_RADIUS = 28.8847m  GZ_RADIUS = 36.9220m</td>
</tr>
</tbody>
</table>
REFERENCES


Fig. 1. Mechanism for local denting.
Fig. 2. Mechanism for local structural failure.
Fig. 4. Elevation of the semisubmersible.
Fig. 5. Plan of semisubmersible.
Fig. 6. Sideview of Semisubmersible.
Fig. 7. Surge time history.
Fig. 8. Time history of pitch and yaw motions.
Fig. 9. Time history of impact force on semi-submersible.
DAVID E. MITCHELL, SENIOR GEOTECHNICAL ENGINEER
WILLIAM E. BERZINS, SENIOR GEOTECHNICAL ENGINEER
CANADIAN MARINE DRILLING LTD., CALGARY ALBERTA, CANADA

DESIGN, CONSTRUCTION AND MONITORING OF A MARINE
FOUNDATION FOR AN OFFSHORE OIL EXPLORATION STRUCTURE
IN THE BEAUFORT SEA

ABSTRACT

A submarine berm-caisson system was commissioned on November 9, 1982 by Canadian Marine Drilling Ltd. to explore for oil in the 31 m waters of Uviluk P-66 in the Canadian Beaufort Sea. The Uviluk structure is unique in two main aspects: it constitutes the first mobile Arctic drilling caisson and it is the first offshore oil exploration facility to be located in the Beaufort Sea ice shear zone. In contrast to the Tarsliut concrete caisson system, the Uviluk penetration structure is a monolithic, ice-reinforced, steel structure created by modifying the forward section of a very large crude carrier. The structure has been acronymically termed the SSDC, for Single Steel Drilling Caisson. The composite geotechnical work packages included field investigations, design, construction supervision and testing, cone penetration testing, instrumentation and long-term monitoring. The majority of the field-related programs were both practical and research oriented and, as a group, represent the most comprehensive documentation of Arctic island construction and performance to date.

1 INTRODUCTION

The energy crisis of the early 1970's caused an acceleration of hydrocarbon exploration efforts in the Canadian Beaufort Sea and a rapid evolution in the design and construction of structures required to undertake such activities in a harsh, offshore Arctic environment. The initial structures were
pioneered by Esso Resources Canada Ltd. and comprised waterline-penetrating, sacrificial beach islands with gentle side slopes. Economic and construction schedule considerations generally preclude the use of such systems in water depths greater than 20 m and, therefore, Canadian Marine Drilling Ltd. (CANMAR) commissioned the first hybrid Arctic exploration systems to assess subsea hydrocarbon reserves in the 21 m waters of Tarsiut N-44 (1981) and the 31 m waters of Uviluk P-66 (1982).

The concept of an artificial waterline penetration system resting on a steeply-sided submarine berm was integral to both the Tarsiut and Uviluk structures. However, the Uviluk topside unit is a monolithic, ice-reinforced, steel structure while that at Tarsiut comprises a multiple, concrete caisson system. Both approaches are a quantum leap from the sacrificial island in terms of reduced fill volumes and minimizing the effects of wave and current erosion, and the steel unit betters the multiple caisson system with regard to mobility, freeboard, and pre-placement assemblage of the drilling rig package. The seabed foundation and berm components of the Uviluk system, and their impact on the design of the topside facilities, are discussed herein.

2 PROJECT DESCRIPTION

The Uviluk P-66 site lies approximately 90 km northeast of Tuktoyaktuk and 50 km northwest of McKinley Bay in the Canadian Beaufort Sea (Figure 1). It is characterized by a 31 m water depth, and a competent seabed foundation. The exploration structure consists of a Single Steel Drilling Caisson (SSDC) resting on a submarine berm.

The site was drilled for geotechnical purposes in August of 1981, using Canmar's coring vessel the Supplier V. The borehole extended through early berm material dumps to a depth
of 130 m below sea level, and penetrated four basic material units: a surficial 5 meter thick stratum of interbedded sands and gravels, overlying a 35 m thick deposit of fine uniform sands, which was underlain by a frozen clay layer, and in turn by a frozen silt and sand unit.

Construction of the submarine berm was initiated during the summer of 1981 and was completed two million cubic meters later, in late August of 1982, after a winter-induced hiatus. The prime borrow source was located 20 km west of the site and contained a uniform, subangular sand with a median grain size of 350 microns and less than 5 percent material passing the No. 200 US sieve. Borrow exploitation, haulage, and dumping was effected with two large hopper dredges. Controlled pipeline discharge was used to create the steep side slopes and to place the protective gravel layer. A 24 hour material
inspection watch was maintained on both dredges to ensure adherence to gradation specifications. The finished berm possessed nominal 6H:1V side slopes and provided a caisson setdown surface area approximately 85 m wide and 210 m long at elevation - 9 m (Figure 2).

The SSDC was created by modifying the forward section of the WORLD - SAGA, an unrestricted ocean-going VLCC built in 1972. The primary modifications were performed in Japan between April and August of 1982 and involved lower level structural ice reinforcing, and cantilever and drilling facility additions. The structure is 162 m long, 53 m wide, and 25 m high, although the deck has been cantilevered over both the bow and stern to provide 40 additional meters of deck length storage. The sliding stability of the system under ice loading was provided by filling the original oil cargo tanks with seawater.

3 GEOTECHNICAL DESIGN

3.1 General

The geotechnical design and construction of the Uviluk structure was heavily influenced by the excellent performance of Tarsiut N-44. The design detailing was finalized on the basis of state-of-the-art geotechnical engineering using both laboratory-derived and Tarsiut performance-derived geotechnical parameters. The conceptual and preliminary geotechnical design was performed by Canmar geotechnical personnel. Detailed laboratory and design studies were
subsequently initiated to address the identified areas of concern, and EBA Engineering of Calgary was commissioned to undertake a complete design review of the project.

Cursory limit equilibrium and deformation analysis of the system for the end of construction and operational design conditions revealed three areas of concern: sliding stability of the SSDC under the design ice load; basal contact stresses and deformations of the SSDC during setdown and subsequent ballasting; and liquefaction potential of the berm.

3.2 Sliding Stability

Horizontal sliding of the SSDC under the design ice load was the critical failure mode for the Uviluk system. In contrast to Tarsiut, any slip surfaces below the caisson-berm interface possessed higher factors of safety due to the excellent foundation conditions.

Initial analysis produced factors of safety against sliding which were lower than those of conventional design practice. As a result, shotcrete was applied to the base of the caisson to raise the angle of frictional contact above that of steel on sand, and a protective ice-bumper pad system was introduced into the design to augment the sliding resistance of the waterline penetration system (Figure 3). Large scale laboratory testing performed to measure the frictional resistance between lightly 'marine-fouled' shotcrete and the berm sands indicated a friction angle of 30 degrees. The viability of the ice pad-augmentation approach was supported by field data from the Tarsiut relief well ice pad. In light of the unconventionality of the design, however, extensive ice and geotechnical alert level instrumentation was installed in and around the SSDC/berm/ice pad system to monitor loads and displacements, and thereby provide early warning of any deviations from the stress-strain assumptions inherent in this approach.
3.3 Contact Stresses And Tanker Deformations

Aside from the ice - strengthening issue, the prime structural concern for the SSDC pertained to the berm contact stresses and related deformations. The SSDC, with its VLCC background, was not ideally suited to act as a gravity structure because of its local rigidity. A great amount of effort was therefore devoted to modelling the caisson-berm interaction during setdown, ballasting, and long term operation. Superimposed on the need to limit cantilevering or non-uniform differential settlement was a desire to put the caisson into a minor sagging mode to minimize brittle fracture concerns in the deck region.

A hyperbolic finite element modelling (FEM) study was commissioned to investigate the sensitivity of predicted settlements to setdown and ballasting sequence, and to account for tanker stiffness. Soil deformation input parameters were selected on the basis of published data, material-specific laboratory testing and back-analysis of the Tarsiut N-44 performance data.

The initial FEM study task addressed the case of direct placement of the caisson on a level berm. The predicted total settlements for a homogeneous berm approached 200 mm, and the differential settlements and stresses were negligible due to the stiffness of the caisson. The latter conclusion was supported by case histories of similarly stiff and loaded structures on granular foundations. A statistical analysis of
cone penetration testing (CPT) results from Tarsiut to assess the accuracy of the assumption of berm sand homogeneity indicated little density variation; the measured variation translated to a maximum predicted differential settlement of 5 percent of the total settlement, or 10 mm.

The direct setdown of the caisson was the most attractive placement option, but there was concern over our ability to achieve the very stringent berm screeding tolerance set by the structural designers. As a result, a second setdown scenario, involving artificial, stress-limiting, end support pads in conjunction with sand slurry underfilling of the tanker was developed parallel to the direct placement option (Figure 4). Finite element modelling of this setdown method revealed that: the total settlement would increase by that attributable to pad overstressing (approx 400 mm); a sagging deformation could easily be induced in the SSDC with controlled ballasting and underfilling; the amount of "sag" was not appreciably affected by ballasting sequence; and the use of stress-limiting foam pads would keep contact stresses within tolerable limits.

3.4 Liquefaction Considerations

The influence of earthquake loading on earthen structures has often been addressed through pseudostatic analysis wherein the disturbing effects are represented by a horizontal force of
magnitude, $m \times a$ ($m =$ mass of structure, $a =$ earthquake acceleration). A more realistic treatment of the problem involves the inclusion of the excess pore pressures or undrained shear strengths created by dynamic and monotonic loading in conventional stability analysis. The latter approach was used for the SSDC design analysis.

Laboratory analysis of the borrow sand was performed to define its steady state flow line (void ratio vs $\sigma_{ss}'$) and thereby facilitate prediction of potential excess pore pressure ($u_e$) at any depth in the berm-foundation system by comparing the minor in situ effective principal stress ($\sigma_{3}'$) at any depth with the steady state stress ($\sigma_{ss}'$) for that location, i.e. $u_e = \sigma_{3}' - \sigma_{ss}'$. In situ void ratios were estimated from maximum and minimum density tests of the sand and the CPT - derived relative densities obtained from the Tarsliut berm. Subsequent stability analysis produced acceptable factors of safety against SSDC sliding and global failure of the SSDC berm system.

4 CONE PENETRATION TESTING (CPT)

4.1 General

Cone penetration testing was undertaken upon completion of the berm in mid-August, 1982 as part of the quality assurance programme. Test results were analyzed to determine the lithology of the berm and estimate in situ densities and strengths. Particular attention was given to the identification of weak/soft zones within the berm, and zonal heterogeneity which would lead to significant differential settlements.

A total of 19 tests were completed. Tests were performed with a 30 tonne shallow water testing platform, and an electric cone which measured tip resistance, pore pressure and sleeve friction. Test results were tabulated during penetration, and a graphical output was produced on site.
4.2 Berm Stratigraphy

Berm stratigraphy was inferred using standard classification charts (5) and tip resistance versus material type correlations derived from previous Beaufort island studies. Piezometric data were used to confirm general soil types. The use of weekly bathymetric surveys and detailed dredging records permitted the accurate reconstruction of the fill placement sequence.

A typical berm cross section is shown in Figure 5. CPT profiles and dredge information have been superimposed, and highlight the remarkable consistency of the test data with known differences in fill borrow sources.

![Figure 5: Berm Cross Section with CPT Profiles](image)

The most significant finding of this portion of the analysis was the identification of a thin clay zone in the south east quadrant of the berm. This clay was attributed to one of the poorer borrow sources, and while limited in extent, did result in minor modifications to the positioning of the tanker and the installation sequence.
4.3 Berm Densities

Berm densities were estimated on the site using correlations considered to be conservative given the grain size distribution and mineralogy of the berm sands (1). The average relative density was in excess of 50% and therefore met or exceeded the specifications derived from the dynamic stability analyses. Differences in placement method and depositional history were also reflected in the sand density.

5 SSDC PLACEMENT AND BALLASTING

Upon completion of the CPT programme, the berm was screeded and final bathymetric surveys were carried out. These surveys indicated that the stringent screeding tolerances had not been met, and it therefore was decided to use the pao/sand underfill setdown method. The innovative nature of this installation sequence placed considerable emphasis on the ability to make field decisions during key phases of setdown. The success of the installation depended upon the achievement of uniform contact stresses and sufficient deck compression; hence a comprehensive construction monitoring program was designed to provide real-time data on the above to the on-site personnel.

Contact stresses were measured using a grid of 65 pressure cells located on the base of the tanker. These cells incorporated sensors measuring both total and piezometric pressures. Global tanker stresses arising from tanker flexure and differential settlements were estimated from frequent deck level surveys and structural back-analysis.

The tanker was setdown on October 9, 1982 and partially ballasted. Subsequent to sand underfilling, ballasting was completed in two stages, separated by a period of 30 days to confirm that there was no damaging settlement related to the consolidation of the southeast quadrant clay layer. The
installation sequence can be best summarized through a condensed record of total pressures and settlements, as shown in Figure 6. Review of these and other data confirmed the success of the placement sequence: shear stresses in the tanker were kept within the design limits, and the sand-underfill provided uniform support for the caisson. The measured settlements also agreed remarkably well with those predicted from the FEM analyses.

6 POST SETDOWN TESTING AND INSTRUMENTATION

6.1 In Situ Testing and Sampling

Geotechnical testing and sampling was undertaken to evaluate underfill densities, provide detailed stratigraphic logs for instrument placement, and to verify the interpretation of earlier CPT results. Three additional CPT tests were performed with a tip friction and resistivity probe through access tubes installed in the tanker. Continuous soil sampling was undertaken with a vibro core rig preparatory to
the installation of berm instrumentation.

The most significant finding of the post-setdown testing was the apparent increase in sand density after placement of the tanker. Figure 7 shows adjacent CPT profiles taken before and after tanker placement. These highlight an apparent increase in soil resistance above that attributable to the change in stress state alone. The additional densification component is the result of dynamic wave loading after tanker setdown.

![CPT Profiles Before and After Caisson Setdown](image)

6.2 Berm Geotechnical Instrumentation

Geotechnical instrumentation was installed through the SSDC into the berm to measure the lateral deformations and settlements resulting from winter ice loads. A total of eight inclinometer casings were installed, four for continuous monitoring at discrete depths in the berm and four to permit manual profiling over the full depth of the berm. Two of the latter installations also facilitate settlement profiling. Monitoring during this winter will define the hysteretic response of the composite berm/caisson structure to ice loading.
As mentioned in section 3, an extensive geotechnical, ice, structural and environmental monitoring system was installed in and around the Uviluk structure. Composite instrumentation included basal total and pore pressure cells, vertical inclinometers, settlement gauges, tanker and rubble field ice pressure panels, internal thermistors and strain gauges, and a meteorological station. The majority of this equipment is remotely sensed and recorded by a central data acquisition system, as shown in Figure 8. Monitoring and rig personnel are alerted to major events or variations in structural performance by a 24 hour audible alarm system. Graduated alert level reaction directives have been set by design personnel to ensure safe operation throughout the drilling season. A multi-disciplinary team is always present on the SSDC to monitor island stability and alert level status (Figure 9).
8 CONCLUSIONS

The Uviluk/SSDC operation has afforded Canmar the opportunity to monitor the performance of an offshore structure in the severe and often unpredictable Arctic environment. Canmar has thereby confirmed and extended the offshore Arctic data base with regard to: optimal construction procedures; the use of marginal construction materials; geotechnical design parameters and procedures; ice features and pressures; and ice sheet, ice rubble, and structure interaction.

Canmar has also demonstrated the successful use of an ice/soils/weather stability alert and monitoring system to facilitate safe operation of a major structure in ice-infested waters. These systems and the data collected will allow engineers to reduce the design conservatism necessitated by lack of experience and consequently move closer to the design of the optimal offshore Arctic production facility.

ACKNOWLEDGEMENTS

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J. Vaughn Barrie, Leader - Seabed Group
C-CORE, Centre for Colo Ocean Resources Engineering
Memorial University of Newfoundland
St. John's, Newfoundland Canada

SEDIMENTARY PROCESSES AND THE PRESERVATION OF ICEBERG
SCOURS ON THE EASTERN CANADIAN CONTINENTAL SHELF

ABSTRACT

Iceberg scours, the physical evidence of grounding icebergs, are observed over much of the eastern Canadian continental shelf. The degree of preservation or degradation of these scours (which can define scour age) depends on the type of sediments, their physical and geotechnical properties and the hydrodynamic regime that the sediments are exposed to. Evidence drawn from sediment textures, mineralogical analyses, submersible observations, acoustic geophysical surveys and from the hydrodynamic environment demonstrate that the rate of scour degradation is determined primarily by wave-induced oscillatory motion and to a lesser extent, by unidirectional currents at the seabed and the sediment available for deposition. Assuming that the hydrodynamic processes can be quantified, then scour frequencies and rates of scour degradation can be determined more accurately; these quantititative parameters are based on scour morphology as interpreted from the existing scour data base. Three defined scoured environments are compared, including examples from the Davis Strait, the Labrador Shelf and the Grand Banks of Newfoundland.
INTRODUCTION

Iceberg scours, which are the physical evidence of grounding icebergs, are observed over much of the Canadian Atlantic continental shelf. Iceberg interaction with the seabed to create linear scour marks was hypothesized as early as 1858 by Charles Darwin /7/ and has been identified in the offshore by the development of sidescan sonar technology. Icebergs were recorded in the process of disturbing the seafloor and gouging out a scour on the Labrador Shelf on Saglek Bank and Main Bank in August 1979 /17/. Iceberg scour marks appear in the form of linear to curvilinear furrows and as pits, and occur over the entire eastern Canadian continental shelf from Baffin Bay to the Grand Banks of Newfoundland down to water depths of greater than 400 m. These marks vary markedly in size and morphology and can occur as furrows on the seafloor up to 200 m wide, 17 m deep and over 10 km in length /2/. Although many scour marks are modern, many more are interpreted as relict, dating from an earlier geological period. Their longevity is clearly apparent from studies of ancient (Pleistocene) scours found in the Norwegian Trough /4/, in the Laurentian Channel and western Grand Banks /11/, in the Beaufort Sea /15/ from ridge-heel scouring, on Saglek Bank in the Labrador Sea /2/, off the west coast of British Columbia /19/ and in the southern hemisphere on Chatham Rise off New Zealand at 43°S (H. Kundress, pers. comm., 1982). These studies clearly demonstrate that scour marks can persist for several thousands of years. Evidence presented in this paper, however, will show that scours may last only a few years in
areas of the continental shelf exposed to dynamic sedimentological environments.

The analysis of change in scour morphology is important for several fundamental reasons. First, the dimensions of many scour marks are used in statistical analysis for determining the mean and extreme scour penetrations and for iceberg scour return periods. Morphologic dimensions, such as depth and width, determined from acoustical geophysical records, will be in error due to degradation unless the processes can be quantified. Second, scour marks can act as benchmarks against known processes or sediment erosion. This may be undertaken by examining the interrelationship of scour marks and sedimentary bedform features and, subsequently, the age of a scour can be determined based on the age of the bedforms. Alternatively, the amount of sediment transport can be determined if the scour mark is of a known age. These techniques are useful in examining both the modern scouring and the modern sediment dynamic regime. Third, ancient scour may degrade to such an extent that only residual features are left, and these are a key to their origin. Without a thorough knowledge of the various degradation processes no valid and useful interpretation of such features can be made in the geological record. All these aspects are related to iceberg scour age, the most important factor in scour analysis.

2 SCOUR ENVIRONMENTS

Three distinctive environments of iceberg scour have been defined from regional geophysical surveys and submersible observations for the eastern Canadian
Atlantic shelf (Fig. 1). These environments reflect different soil types which are partially a result of different surficial sediment origins.

FIGURE 1. The eastern Canadian continental shelf. Bathymetry is in metres.

2.1 Scours in Stiff Clays

Scour marks in stiff clays have steep rirs (berms or embankments) with slope angles up to 60° and scour
penetration depths up to 6 m and greater. Submersible observations off Cumberland Sound in Baffin Bay /20/ demonstrate the nature of these steep sided deeply penetrated scours. Another area where similar geomorphological scour relief occurs is southern Sagleka Bank in the Labrador Sea (Fig. 1). Here iceberg scours, seen on the Bedford Institute of Oceanography (BIO) sidescan sonar /9/ reach a maximum of 12 m penetration depth with slope angles of up to 45° (Fig. 2).

Sediments from the Southern Sagleka region consist mostly of poorly sorted silts (Fig. 3). No active sedimentary bedforms can be interpreted from the sidescan sonograms collected from this area. Evidence from mineral hydraulic equivalence relationships /22/23/ also suggests that little reworking of the surficial sediments has taken place. Heavy mineral distributions for Sagleka Bank are distinctly bimodal with the mean grain size of the heavy minerals being consistently coarser than the light (quartz) mineral mean grain size. This trend is inconsistent with that expected in normal sorting hydrodynamic conditions. Consequently, it can be concluded that the surficial sediments has not been hydraulically reworked since deposition.

2.2 Scours in Bouldery Till

Scour marks developed in bouldery material are characterized by concentrations of large boulders in the rims associated with a finer matrix of gravel and sand in the troughs, reliefs or 1 to 4 m and slope angles of up to 15o /18/. Submersible observations in this type of environment have been made in areas of
FIGURE 2. A sidescan mosaic of an area of south-central Sagleq Bank showing the distinctive iceberg scours in plan and cross-section.

the northeast Newfoundland Shelf /24/ and from areas of Hamilton Bank on the southern Labrador Shelf /5/ (Fig. 1). Typically, the sediments in these regions are silty sands that are poorly sorted and contain a high percentage of boulders, cobbles and pebbles.
FIGURE 3. Plot of sediment mean grain size against standard deviation (sorting) for bottom grab samples collected on Saglek Bank (in area of Fig. 2), Makkovik Bank and on the northeastern Grand Banks.

2.3 Scours in Thin Surficial Cover.

Scour marks developed over areas of thin surficial cover overlying semi-consolidated or consolidated bedrock show concentrations of boulders, cobbles, pebbles and sand in their rims and have a relief of only 1 to 2 m with slope angles of 60° or less. Three areas of this type of environment ranging in water depth from 80 to 400 m, will be described briefly. These areas are the Davis Strait region...
southeastern Baffin Island, central Nakkovik Bank in the Labrador Sea and the northeastern Grand Banks of Newfoundland (Fig. 1).

The Hekja survey area in Davis Strait is located in the 325 - 375 m water depth range. Here the typically shallow scours (approximately 1 m in depth) are found in a sediment of fine sand that is moderately sorted and which unconformably overlies Tertiary bedrock /21/. Waves would have no effect in these water depths but the area is affected by strong diurnal tides. Mean spring tidal current velocities measured 1 metre from the seabed average 25 cm/sec with peak velocities averaging 30 cm/sec. Megaripples within the troughs of the scours can be seen throughout this environment.

Nakkovik Bank, in 80 - 150 m water depth, has a fine sand sediment cover which is again moderately sorted (Fig. 3) in the densely scoured environment. When compared to Sagiekr Bank, the mineral hydraulic equivalence relationships for this area indicate complete reworking of the sediment. The heavy minerals mean grain size is between 0.5 phi to 1.0 phi finer (3.0 - 3.5 phi) than the light host minerals (2.5 phi). The reworking of the surficial fine sand has formed a lag of heavy minerals with an average of 7.3% of the total sample being heavies. Normal heavy mineral concentrations in marine sands range from 0.1 to 0.5% /10/. The indication here is that during the Holocene period the reworking process built up a heavy mineral lag. Though no sedimentary bedforms exist, except in the shallowest areas (above approximately 100 m), sediment transport is evident (e.g. lag deposits around boulders) as can be seen from submersible observations /10/.
Finally, another example of a thin Quaternary deposit unconformably overlying Tertiary bedrock can be seen on the northeastern Grand Banks of Newfoundland in the Hibernia hydrocarbon discovery area in a water depth of 60 m. There is evidence that sediment transport of the surficial sands has occurred. This is based on the identification of modern sedimentary bedforms such as ripples, megaripples and sand waves /3/. The sediments are moderately well sorted medium to coarse sands (Fig. 3), the decrease in sediment grain size being proportional to depth. Similar to Makkovik Bank, the mineral sands of Hibernia are in hydraulic equivalence.

3 SCOUR DEGRADATION PROCESSES

From these three scoured sedimentary environments a qualitative classification of degradation is presented. The categorical breakdown is based on the hydrodynamic forces acting on the seabed as they are the most significant factors in scour degradation.

3.1 Low Hydrodynamic Regime

Normally areas of both low current and wave influence are areas in which sedimentation or suspended fine-grained sediments (silt and clays) are found, such as central Sagleek Bank (Fig. 3). Therefore scour obliteration is mainly by infilling and disturbance rather than by erosion. Over central Sagleek Bank where sedimentation is minimal, scours will last indefinitely. Repetative sidescan surveys over the same site in 1978, 1979 and 1981 (see Figure 2) reveal that the scours have not changed noticeably in their
morphology since they were first acoustically detected.

This explains the existence of Pleistocene scours found in numerous areas, such as those described earlier. In scoured areas where degradation is slow, a cross-cut network of scours will exist. The chronological sequence of scour events is determinable by an analysis of cross-cutting relationships /25/ and subsequently a relative dating sequence for the scours can be determined. Where the cross-cutting is intense and degradation slow, older scour morphologies will eventually be obliterated by overscouring or succeeding iceberg scours.

3.2 Moderate Hydrodynamic Regime

In areas influenced by unidirectional currents that at peak periods are above the threshold of sediment transport for sand and therefore consistently too high for fine grain sedimentation, winnowing of the finer fraction is constantly at work. This results in well-sorted, surficial sediments of fine sand with a heavy mineral lag much like that of Makkovik Bank or Hamilton Bank on the Labrador Shelf. Iceberg scour marks formed in these sediments are affected by this winnowing mechanism. Winnowing of fine sediment leaves berm consisting of exposed boulders and cobbles with diminished relief associated with finer well-sorted sediment in the troughs. Josenhans and Barrie /10/ used this criteria to distinguish relict (older) scour marks from fresh (younger) scour marks on Makkovik Bank. Sidescan sonar records confirm these interpretations by revealing evidence of scour mark obliteration by reworking and transport of the surficial sediments (Fig. 4). In areas of bouldery
tills under moderate hydrodynamic conditions, the residual seabed features left over time are parallel linear boulder ridges.

FIGURE 4. Iceberg scour degradation due to sediment transport in an area of Nakkovik Bank as seen on a sidescan sonogram. Notice the mottled seabed morphology on the upper left hand corner of the sonogram.

3.3 High Hydrodynamic Regime

In areas of strong wave (oscillatory) motion and high current velocities at the seabed, the mobile surficial sediment is generally well sorted sand (see Figure 3). Sediment erosion and transport is frequent and sedimentary bedforms are well developed.

In this type of regime scour marks are obliterated rapidly, in terms of years. Only large cobbles and
boulders remain after scour degradation. An example of bedform migration into a scour trough from the northeastern Grand Banks area can be seen in Figure 5. Here megaripples generated by currents greater than 50 cm/sec \cite{6} have migrated into the scour.

High resolution sonograms from the northeastern Grand Banks show examples of scours that have been transgressed by megaripples (Fig. 5). Examples of scours cutting megaripple fields are also evident. Using the Law of Superposition it is assumed that the ice scours cutting the megaripple fields were formed since the last sediment transport event which led to bedform migration. Using this concept the scour frequency can be determined by the following relationship:

\[
S_f = S_n \times B_f
\]

where:  
\(S_f\) = scour frequency  
\(S_n\) = scour number  
\(B_f\) = bedform migration frequency

The scour number is the total sum of scours which appear to cut megaripple fields over the area of study. Scour obliteration by bedform migration can then be used as a scour frequency dating technique.

In areas of strong unidirectional currents, such as the Hekja survey site in the Davis Strait and on the tops of the Labrador Banks, scours aligned with the current direction may act as channels at the seabed. This channelling effect would increase the threshold stress for sediment transport and tend to keep the scour troughs open. The presence of megaripples in the troughs of scours in the Hekja area and
submersible observations from Labrador of increasing current flow in scours, support this conclusion.

FIGURE 5. Negaripples obliterating an iceberg scour on the northeastern Grand Banks in 80 m water depth as seen on a sidescan sonogram.

On the eastern Canadian continental shelf in areas where the seabed is frequently scoured by grounding icebergs, and the water depth is generally shallower than 100 m, the seabed morphology becomes complex and mottled. Mounds of coarse material are the only physical evidence of cross-cutting scours left after erosion. This feature can be seen in sidescan sonograms from the shallowest part of both Makkovik Bank (Fig. 4) and Nain Bank (Labrador Shelf; Fig. 1). The same seabed morphology is seen on the northeastern Grand Banks but was probably produced during the early
Holocene /3/. This mottled morphology forms above wave base so the oscillatory reworking of surficial sediments has an important effect in degrading the scour morphology. Wave-base is near 110 m for the northeastern Grand Banks or Newfoundland /3/ and it is postulated that wave base for most of the Labrador Shelf is this depth, or slightly less.

Lewis and Barrie /17/ report a significant drop in scours per unit area in water shallower than 100 - 120 m in the northeastern Grand Banks area. Normally iceberg scour density increases up slope /15/. Lewis and Barrie /7/ noted, however, that sediment reworking may be partially responsible for this unusual distribution. Recent work completed by Barrie et al. /3/ clearly shows that increased wave and periodic current forces occur above 110 m in this area. This is clearly evident when the linear Airy wave equation combined with the critical threshold equation for sediment transport under unidirectional flow /12/13/14/ for medium sand (the predominant size in this area (Fig. 3)) is compared to waveider buoy data collected at eight drilling sites in the Hibernia - Bonneville exploration area during 1980 and 1981. Figure 6 demonstrates the control that average near oscillatory energy has on the reworking of surficial sediments during the winter months above 100 m water depth. For both years, in December, at a 70 m water depth, sediment was being reworked nearly 70% of the time (Fig. 6). Wave energy at the seafloor in this area, therefore, seems to be the dominant factor in iceberg scour degradation. It is combined with periodic high unidirectional currents and continuous low velocity unidirectional currents. A similar hypothesis can be argued for the shallowest portions of the central Labrador Banks (i.e. Main and
Makkovik). Barnes and Reimnitz \cite{1} also observed the significance of wave base in conjunction with currents in eroding ice ridge scours in the Beaufort Sea. Above wave base this oscillatory motion would work against the channel effect noticed in linear scour marks from areas with a strong and persistent unidirectional flow.

![Figure 6](image)

**FIGURE 6.** Percent exceedance of sediment threshold for transport of medium sand on the northeastern Grand Banks of Newfoundland during 1980 and 1981.

4 SUMMARY

It has been shown that the magnitude of hydrodynamic forces acting on the seafloor exert a significant control on the sedimentary environment in which iceberg scouring takes place. The principal agent of
scour degradation is wave-induced oscillatory bottom currents. Consequently, knowledge of wave base is important when analysing iceberg scour statistics. In any area under the influence of hydrodynamic reworking, scour penetration depths and widths may not represent the actual amount of iceberg disturbance of the seabed, no matter how recent the scours are. This has to be taken into account in using scour analysis methods such as 1) the deepest scour in an area, 2) cross-cutting analysis, 3) scour equilibrium analysis, and 4) statistical analysis of regional iceberg scour distribution. For example, at Hibernia the scour frequency cannot be determined solely by the present scour distribution as seen on acoustic records, whereas on Saglek Bank the modern scour record is complete. If hydrodynamic and sedimentation processes can be quantified for the area of interest, the expected iceberg scour frequencies and maximum seabed disturbances can be determined more effectively.

ACKNOWLEDGEMENTS

This work forms a part of the ongoing iceberg scour research undertaken jointly with Dr. C.F.M. Lewis of the Geological Survey of Canada at the Atlantic Geoscience Centre. His assistance and guidance is warmly appreciated. The manuscript was reviewed by Dr. C.P.G. Pereira and C.F.T. Woodworth-Lynas who offered valuable suggestions.
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Austin Kovacs, Research Civil Engineer  
U.S. Army Cold Regions Research and Engineering Laboratory  
Hanover, New Hampshire, U.S.A.

SEA ICE ON THE NORTON SOUND AND ADJACENT BERING SEA COASTS

Abstract

Recent observations and historical accounts of sea ice on the shores of Norton Sound and the adjacent Bering Sea are presented. The movement and accumulation of sea ice on the shores was found to be a common event, as were massive icebergs on island surfaces. Sea ice was found to have been pushed inland over 150 m and to have moved over 15 km inland during high storm seas.

1 INTRODUCTION

In the design of arctic and subarctic coastal facilities, marine terminals, and offshore structures, major consideration is being given to the phenomenon of sea ice movement onto the shore. This phenomenon includes ice ride-up and pile-up resulting from offshore stresses and ice driven ashore during high seas caused by storm surges. Sea ice has destroyed boats, piers and wharves, and crushed houses and their inhabitants /3,6,17/. Stefansson /13/ stated: "houses which stand one or two hundred yards from the sea are in danger" of sea ice movement onto the shore. There is concern today about the safety of personnel and facilities on arctic and subarctic shores and offshore structures.

This paper discusses sea ice incursions of more than 5 m onto the Norton Sound and northern Bering Sea coasts of Alaska observed during reconnaissance flights in spring 1981 and 1982 and others reported in the literature. The paper augments previous reports /6,13/ that include historical and recent observations and theoretical analyses of the processes and forces of shore ice ride-up and pile-up. It provides a record of the severity of these events along the Bering Sea and Norton Sound coasts.

2 SEA ICE

In Norton Sound and the Bering Sea ice exists from about November to mid-May. Shore-fast ice extends out to about the 10-m isobath. It is most extensive in southern Norton Sound, where it extends up to 30 km offshore and is anchored in place by large ground ice formations /8/. Along the northern coasts of Norton Sound and the Bering Sea, exclusive of cays, fast ice extends from a few tens of meters to about 1 km from shore.

Tides, long-period ocean swells or waves, and storm surges coupled with shifting currents and winds keep the pack ice in constant motion /1,6,12,14, 15/. The changing conditions can cause sudden breaks in the shore-fast ice and major changes in the velocity and direction of movement of ice floes. When strong onshore winds are coupled with a rise in sea level, the fast ice can be lifted free of the shore and, along with the offshore pack, move far inland.
The thickness of the ice is highly variable. Stable fast ice may grow to about 1.2 m thick in Norton Sound and 1.4 m thick near Bering Strait. Within the highly dynamic pack, thickness can vary from a few centimeters in new growth in leads to over 3 m in rafted ice.

3 OBSERVATIONS

Reconnaissance flights were made in late March 1981 and early April 1982 using both a fixed-wing aircraft and a helicopter. The former could not land to allow inspection of pile-ups and ride-ups. Nor could the helicopter land where there was rough terrain, where only a narrow beach existed between steep bluffs and the sea, or where high winds were encountered near bluffs. The coastline examined ran from Stewart Island on the south side of Norton Sound north to Bering Strait (Fig. 1). St. Lawrence Island and King Island (Fig. 2) were also visited, as were Fairway Rock and Little Nome Island. Ice conditions at the last two islands were reported on by Kovacs et al. /8/.

At least some ice pile-up and ride-up were seen along much of the coastline. The most severe cases are listed in Tables I and II; their sites are given in Fig. 1 and 2. Photographs of the ice at some of the sites are shown in Fig. 3-12.

Figure 1. Map of Norton Sound and the adjacent Bering Sea.
<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Ice Block Height</th>
<th>Maximum Dist.</th>
<th>Type of Shore</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 March</td>
<td>1</td>
<td>0.2 to 1.5</td>
<td>15</td>
<td>Boulder beach</td>
<td></td>
</tr>
<tr>
<td>29 March</td>
<td>1</td>
<td>0.25</td>
<td>5</td>
<td>Boulder beach</td>
<td></td>
</tr>
<tr>
<td>2 April</td>
<td>A</td>
<td>0.22</td>
<td>5</td>
<td>Boulder beach</td>
<td></td>
</tr>
<tr>
<td>7 April</td>
<td>-</td>
<td>0.25</td>
<td>5</td>
<td>Boulder beach</td>
<td></td>
</tr>
</tbody>
</table>

**Table I. Ice ride-up and pile-up observations along the Norton Sound and adjacent Bering Sea coasts.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Ice Block Height</th>
<th>Maximum Dist.</th>
<th>Type of Shore</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 March</td>
<td>1</td>
<td>0.2 to 1.5</td>
<td>15</td>
<td>Boulder beach</td>
<td></td>
</tr>
<tr>
<td>29 March</td>
<td>1</td>
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<td>5</td>
<td>Boulder beach</td>
<td></td>
</tr>
<tr>
<td>2 April</td>
<td>A</td>
<td>0.22</td>
<td>5</td>
<td>Boulder beach</td>
<td></td>
</tr>
<tr>
<td>7 April</td>
<td>-</td>
<td>0.25</td>
<td>5</td>
<td>Boulder beach</td>
<td></td>
</tr>
</tbody>
</table>
Table II. Observations of ice ride-up and pile-up along the coast of St. Lawrence Island.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Ice Block*</th>
<th>Maximum*</th>
<th>Height (m)</th>
<th>Type of Shore</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 1981-1982</td>
<td>1</td>
<td>&lt; 1/2</td>
<td>10</td>
<td>25</td>
<td>Low-lying beach</td>
<td>Ice piled on beach in front of camp Kulove, nearly reaching one building which was reported, by Matthew Iya of Iya Village, to be located 35 m from the water; he reported the water near shore to be deep.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>&lt; 1/2</td>
<td>10</td>
<td>5</td>
<td>Low-lying bluff 2 m high</td>
<td>Ice piled up on top of bluff.</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Stabilized Rocks - two vertical walled rocks about 20 m in plan and 30 m high</td>
<td>These rocks are surrounded by shallow water; ice rubble piles time each year away from the rocks; thick icings were observed each year up to 15 m high on the rock walls.</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>&lt; 1/2</td>
<td>10</td>
<td>2</td>
<td>Low-lying beach</td>
<td>Ice overrode 2 m high and 30 m from water.</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>= 1</td>
<td>10</td>
<td>7</td>
<td>Low-lying beach</td>
<td>Ice moved inland up to 30 m.</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>50</td>
<td>Low-lying beach</td>
<td>Old ice-pushed sand-gravel piles 1/2 m high along 300 m of beach; ice moved inland up to 30 m.</td>
</tr>
</tbody>
</table>

*Estimated values as no landing could be made at sites to make measurements.

The sea ice ride-ups and pile-ups typically consisted of ice about 1 m thick (Tables I and II). Only at 4 of the 30 sites where ice blocks were measured was the ice over 1 m thick. The inland movement was generally under 10 m. Theoretical expressions /6,8/ allow calculation of the distributed force in an ice sheet required to overcome the gravitational potential energy and friction forces active during shore ice pile-up and ride-up. For the features observed the distributed force was typically less than 140 kPa (20 psi). Where
The ice pile-up is estimated to be over 7 m high and is formed of ice about 1 m thick. No landing was made at this site.
Figure 7. Ice pile-up against isolated shoreline rock formation at site 8, Fig. 1.

Figure 8. Ice piled against vertical side of 20-m-diameter, 20-m-high rock island at site G, Fig. 1.

Figure 9. Ice pile-up and ride-up on talus beach and mountain slope at site 13, Fig. 1. Arrow points to person.

Figure 10. Northeast side of King Island at site R, Fig. 1, where ice pushed through a shear ridge (arrow 1) and then on over the ice rubble of the icefoot and up the side of the steep bedrock slope (arrows A and B). Note the thick icing covering the rock surface to a height of about 30 m.
the ice sheet may have been crushed during ice piling, as at site location G, the local crushing force may have been around six times as large, depending on the effective strain rate and the ice temperature.

Ice was seen farthest inland at site location 13 (Fig. 1). Here a wedge of sea ice 0.95 m thick moved inland an equivalent horizontal distance of 42 m. It traveled over a rough boulder-gravel beach surface and then advanced about 11 m up a 25° rock talus slope (Fig. 9), gouging into it about 0.1 m.

The most spectacular ice ride-up, and the one which must be given highest consideration in the design of coastal or marine structures, was at site location R on the northeast side of King Island. Here the sea ice was driven against the island icefoot, pushed through the high shear ridge outer boundary, overrode the icefoot rubble for about 25 m, and then pushed up the steep rock surface of the island (Fig. 10). This occurred at sites A and B, which are within about 150 m of each other (Fig. 10). The ice reached a height of about 20 m above sea level as indicated by the radar altimeter on the helicopter. A landing at this site was not possible due to air turbulence close to the island.

Information on icefoot morphology similar to that at King Island and the failure processes and relative forces active during ice sheet failure can be found in Kovacs /8/.
In addition to the sites listed in Table II, massive icings were observed covering many of the small rock islands off the southwestern coast of St. Lawrence Island, between Singkipak Pt. and Bunnell Cape, and on the surface of the steep bedrock cliffs on the island to a height of 15 to 20 m. Some small islands were also partially or totally covered with sea ice rubble as a result of ice ride-up or pile-up (Fig. 12). Some of the rubble may have been set in place during high seas.

4 HISTORICAL ACCOUNTS


In January 1907 The Nome Daily Gold Digger reported that during the first week of January winds over 160 km/hr caused a high tide and drove ice against the shore. Timber piling offshore (Fig. 13) and on the beach was snapped off by the ice, which was moving westward along the coast. The ice piled up to a height of 7 m at several places along the beach (Fig. 14). The ice did considerable damage, crushing vessels, scows and barges. Seven schooners were totally destroyed. The steamers Seddoll and Grayhound were pushed about 9 m, turned over on their sides, and then covered with ice. (In an article 'Ice Records for Years' in the 19 Dec 1981 issue of The Nome Daily Nugget, it is stated that the Grayhound ended up being crushed by the ice during this storm.) The steamer Saidle, blown ashore east of Cape York (see Fig. 1) during an early fall storm, was moved 30 m further inland by shore ice ride-up during the same January storm.

At Solomon (Fig. 1), ice and water driven into the town on 4 January 1916 removed boats and damaged homes (The Nome Daily Nugget, 5 Jan 1916).

The Daily Nome Industrial Worker of 7 January 1916 reported that during the 4 January storm winds piled large ice fragments up on the beach in the area

Figure 13. Nome rail dock destroyed by ice in January 1907. (Photo by Dobbs, courtesy of Carrie M. McLain Memorial Museum and Archives, Nome, Alaska.)
Figure 14. Ice pile-up against the end of a Nome dock. (Photo by F.H. Nowell, courtesy of Carrie M. McLain Memorial Museum and Archives, Nome, Alaska.)

Figure 15. Sesnon Caisson. The caisson's top section with wooden tower was reported by The Aurora in 1911 to weigh 83 tons and was towed out from shore on the ice using 32 horses in April 1906. (Photos by Loman Brothers [1916], courtesy Carrie M. McLain Memorial Museum and Archives, Nome, Alaska.)

of Nome and in many places far inland on the tundra. A photo by Dobbs, on file in the Carrie M. McLain Memorial Museum and Archives in Nome, shows the ice pushed far inland. The caption reads "Ice hummocks forced 600 ft (about 180 m) back on tundra, 4 miles (6 km) west of Nome."

This storm apparently caused much damage along the coast. One structure destroyed by the ice was the Sesnon Caisson, \( \frac{1}{2} \) km offshore in about 3 m of water. It was part of a tramway system used to transfer material to shore from barges (Fig. 15).

In The Nome Daily Nugget of 7 January 1916 a person who was interviewed provided the following information: "There is a Russian record, made before
the Alaska purchase, which is now in the possession of the government, that the ice at one time came up during the Russian occupancy and covered the coast for a depth of five miles (8 km) along the entire coastline. [We suspect this refers to a high storm surge condition, during which ice was more easily driven inland or was transported inland by the high water and winds.] The ice had come up on shore along hundreds of miles of coastline and practically every coastal village was obliterated and the inhabitants compelled to flee for their lives. So sudden was the intrusion [sic] of the ice that the majority of the people lost practically all of their food and clothing and thousands perished of starvation and exposure before the arrival of spring. ' ' This report may seem exaggerated but we shall see that it is reasonable.

Another account of the same or a similar event is given by Harrison /4/, who writes: "The natives tell a story of a storm which probably occurred in the early part of the last century. This storm destroyed several of the villages. A great many Eskimo perished from being force out into the inclement weather with insufficient food and clothing." (The water and ice which entered their dwellings froze, making the homes uninhabitable.)

Thomas /16/ writes that the elders of Shaktoolik tell an old story of the destruction of a village near the mouth of the Shaktoolik River (see fig. 1 for the present location of Shaktoolik). "The story relates that one winter when the sea ice was about two feet (.6 m) thick, the conditions were such that the ice shot up over the tundra and bulldozed the village flat, carrying the igluts [remainder of the dwellings] a considerable distance onto the flats. The people drowned in the high water which accompanied this ice action... There was a similar occurrence about 40 to 50 years ago, when Shaktoolik was located at its old site a few miles [about 4 km] down the coast." During this event sea ice about .6 m thick thrust to the top of the steep 4-m-high shore. No account of damage is given by Thomas.

The following account /5/ is by Regina Andrews, who was fishing about 7 km upriver from the village of Kotlik (see fig. 1) on the coast of the Yukon Delta in the fall after the ice had formed. "When I looked out toward the sea I saw a huge wall of water and ice coming, or a big wave, and the ice was cracking and breaking. I ran to shore and had the family turn the boat up and by the time we had it upright the water had already risen knee high. We all got in the boat. We looked around and all the land was covered by water."

During the severe storm which struck Norton Sound and the adjacent Bering Sea during the second week of November 1974, flood waters and moving ice caused over 12 million dollars in damage at Nome alone. Kitlutsitstl /5/ reported that this storm's flood waters and moving ice caused significant damage, including the loss of two dwellings at Snelid's Point (Fig. 1), and much damage at Chevak, a village about 20 km inland.

An early winter storm of 1924 appears to have been the worst of this century. Flood waters moved inland along the Yukon Delta about 50 km. Families living at Black (Fig. 1) were drowned and ice was driven inland up to 26 km, gouging the tundra in many areas /5/.

At Yankiakleet (Fig. 1), in fall 1963, a storm with high seas drove sea ice into the town. Four or five houses were moved and several sheds were destroyed by ice (Fig. 16). Two-thirds of the town was flooded (Dr. W. Ryan, pers. comm.). This storm also did considerable damage to the Nome waterfront.
Figure 16. Sheds damaged by storm-driven ice in Unalakleet, fall of 1963. (Photo by W. Ryan.)

Figure 17. Ice piled on Nome jetty, spring 1980 (top) and 1981 (bottom).

At Nome two jetties about 2 m above sea level extend about 75 m offshore. Their seaward surfaces are armored with rocks up to 1½ m across. Nearly every year the seaward ends of the jetties are overridden by sea ice to a depth of 2 m or more (Fig. 17). However, no damage appears to occur. This suggests that wharfs, piers, etc. along the Norton Sound coast could be adequately protected from the effects of sea ice push, ride-up or pile-up by the use of armor stones of similar size. Larger armor stones, on the order of 6 to 8 tons, would undoubtedly be necessary to protect similar structures built in deeper waters from the effect of storm waves. Such armor should be adequate to resist displacement by the sea ice forces which can be expected in the Bering Sea.
Matthew Iya (pers. comm.) of Savoonga, St. Lawrence Island, reported that in mid-1950 he observed sea ice 1 to 1.1 m thick that had been pushed up a 6-m-high bluff near Savoonga (Fig. 2) and then inland another 20 m. He also mentioned that one year at hooookoolik (Fig. 2) ice about 1 m thick was thrust inland over 40 m right into a native's tent.

5 SUMMARY AND DISCUSSION

The data in this report show that sea ice along the Norton Sound and adjacent Bering Sea coasts has moved inland significant distances, over gentle, sloping terrain and rough boulder beaches, and up steep bedrock surfaces. Accounts are presented of sea ice having been thrust inland 180 m and carried or pushed inland many kilometers during high storm surges.

Shore ice ride-up and pile-up can be a destructive phenomenon. Accounts of ships, piers and other structures being crushed by ice ride-up or pile-up are given. Shore ice pile-ups or ride-ups were observed along much of the Norton Sound and adjacent Bering Sea coastline. These features typically extended less than 10 m from the sea. This distance, however, was often controlled by the severe roughness of the terrain over which the sea ice advanced or by very steep bedrock surfaces against which it was pushed.

Many engineers believe that marine structures should be built with steeply sloping, highly irregular or very rough surfaces to avoid the hazard associated with sea ice ride-up or pile-up on the working area. For causeways, terminals or other structures on which people will not reside, the added cost of defenses against ice ride-up or pile-up may not be justified. Should sea ice move onto these working surfaces or travel-ways, it would be easy to do it off. To avoid sea ice damage to utility systems, or even a walkway, they should be placed in buried utilidors or other recessed structures.

The phenomenon of sea ice driven ashore during high tides or carried inland during high storm seas is a devastating one. Economic losses of life and property has resulted from such events. It is clear that this phenomenon must be fully addressed in the design of coastal and marine facilities.

Thick icings form on offshore islands in the Bering Sea, and icings on Fairway Rock and the Diomede Islands have been described /8/. This type of ice formation can be extremely hazardous to semi-submersibles and other floating structures /10/. Existing drill ships and semi-submersibles have not been designed to limit ice accretion and related instability. This became evident during operations in December 1979 in Lower Cook Inlet, Alaska, when the semi-submersible Ocean Bounty began to list under differential ice loading /11/. Clearly, floating structures need to incorporate anti-icing technology, including icephobic coatings, utilization of waste heat, elimination of protruberances and dangling cables, and use of water jet ice removal systems. Emergency evacuation systems must also be designed to be fully deployable and operable under icing conditions. For semi-submersibles, this may ultimately necessitate development of an on-station submersible evacuation system.

6 ACKNOWLEDGMENT

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DESIGN, CONSTRUCTION AND MONITORING OF THE
TARSIUT RELIEF ICE PAD.

Abstract

Gulf Canada Resources Inc., the operator of the Tarsiut N-44 well in the Beaufort Sea, was required to have relief well capability when drilling beyond a certain potential hydrocarbon threshold depth during the winter months of 1981/82. It was decided that an artificially built, grounded ice pad would provide the most economical means to support a helicopter transportable drilling rig for relief well drilling in the event of a blowout. With predominant wind directions from the north or north-west and north-east, the ice pad which provided relief well drilling capability was constructed about 150 m north of the caisson retained island on grounded ice accumulations that had formed on the caisson island's berm.

In this paper, a unique ice structure is discussed which is the first of its kind in the Canadian Beaufort Sea. The ice pad was designed to withstand similar ice pressures to the Tarsiut caisson retained island. During and after the construction, the ice pad was continuously monitored with regard to global and internal movements, temperatures, strains and stresses, degree of consolidation, extent of grounding and strength. A total of about 10 weeks were required to construct the pad on the caisson's dredged sand berm.
An analysis of the data showed that substantial ice pressures from the surrounding ice cover were effectively resisted and transferred to the sand berm by the ice pad.

The ice pad proved to be a successful structure which could be utilized as a relief well drilling platform and as an evacuation location for the island personnel in case of an emergency. It was also used as a helicopter pad and storage platform. No attempt was made to prolong the integrity of the structure by protecting it from erosion with the onset of open water during the summer.

2 INTRODUCTION

In November, 1981, the drilling of the first well off a caisson retained island commenced in the Canadian Beaufort Sea at the Tarsiut N-44 location. As shown in Figure 1, Tarsiut lies within the Gulf Canada Resources Inc. (GCRI) acreage. GCRI as operator of the Tarsiut N-44 well was required to obtain the necessary government approvals for exploratory drilling. One of the requirements called for a relief well contingency plan which requires for the winter drilling season a stable structure - independent of the caisson retained island - suitable for supporting a helicopter transportable rig which in turn could be utilized to drill a relief well in the event of a blowout. Fenco was retained as a consultant to build a grounded ice pad on top of a previously grounded ice rubble field. The initiation and formation of the rubble was substantially enhanced by the presence of a berm extension or bathymetric high dredged to the north of the caisson island during the construction phase.

Construction of the ice pad commenced at the end of November, 1981, was ready in January, and the ice pad was completed by the end of March, 1982 (see Figure 2). The ice pad had a surface area of approximately 6300 m² and a freeboard of more than 8 m. The ice pad centre was located about 150 m north of
the N-44 well bore.

During construction and post-construction phases, instrumentation - such as ice movement stations, thermistors, strain gauges and ice pressure sensors, were installed in and around the ice pad for monitoring purposes.

This paper describes the design, construction and monitoring of the first ice pad located at the edge of the landfast ice in the Beaufort Sea.

3 DESIGN

The three main design criteria for the ice pad were:

a) limited horizontal and vertical movement of the ice pad;

b) capability to carry and accommodate a specified helicopter transportable rig including consumables and drilling equipment, and;

c) ability to withstand horizontal ice forces due to movement of the surrounding ice cover.

The ice pad design was based on a circular shape with a diameter of 90 m. This maximized the surface area while minimizing the cross section exposed to ice forces. However, the final shape (see Figure 3) was controlled primarily by the configuration of the existing rubble field once the majority of the high rubble features in the pad vicinity were incorporated into the ice pad.

The vertical stability of the ice pad was conservatively determined by assuming no grounding but rather a floating ice sheet on an elastic foundation. The required ice thickness to provide the bearing capacity was about 5.5 m. However, the horizontal stability requirement against ice loading controlled the ice pad thickness.
The horizontal stability of the ice pad was determined by considering three different failure planes, one through the ice rubble, the second at the sand-ice interface and the third through the berm itself. A failure plane through the sand was considered to be the most critical one.

The magnitude of the total ice force to be resisted by the ice pad is a function of the thickness of the surrounding ice cover and the assumed global ice pressure. The ice thickness of landfast ice increases at a decreasing rate to a maximum of about 2 m as shown in Figure 4. The required ice pad thickness was based upon the mechanical properties of the supporting sand berm and the properties of the ice comprising the ice pad above and below the water level. A minimum ice pad freeboard of 5.65 m and 6.5 m was required for drilling purposes by January 4 and January 16 respectively (see Figure 4) in order to ensure a safety factor of at least 1.5 against horizontal forces (see Figure 5) by March 2 at which time the sea ice thickness was estimated to be 1.7 m as shown in Figure 4. Stability calculations were based on an internal friction angle of $33^\circ$ for sand, an average ice density of 0.8 and a maximum void content of about 15% for the rubble comprising the ice pad below water level.

4 CONSTRUCTION

Construction activities began at the end of November, 1981 with a field survey of the ice rubble field which had developed to the north of the Tarsiut caisson island over the dredged sand berm. At this time, a layout for the relief ice pad was staked to locate and identify the design surface area (see Figure 3).

Construction of the ice pad required the use of several different types of equipment and procedures. The main source of ice material for pad construction was the rubble formation comprised of naturally formed ridges and hummocks. Heavy
equipment, D6 Caterpillar bulldozers and Caterpillar 966 front-end loaders were used for bulk ice rubble movement into the design area and for levelling and building up the ice pad. Use of the D6 CAT was principally during the initial phases of construction when the natural rubble piles were redistributed to form a level design pad area. The 966 loaders were used throughout the construction for hauling ice rubble from further afield and for building dykes around the perimeter of the ice pad to contain flood water.

In the second phase following the utilization of rubble as building material, ice buildup was achieved by flooding the ice rubble with 15 hp - three submersible pumps capable of 21 l/s. These pumps were installed at the periphery of the design ice pad area (see Figure 3). Water was carried to the relief ice pad location using heat-traced insulated lengths of piping. Coverage of the ice pad area was achieved by using fire nozzles typically used for municipal fire fighting. The combination of submersible pump, insulated pipes, and fire nozzles was capable of flooding up to 40 m from the nozzle location.

Spray flooding using fire nozzles was a very effective method for ice buildup as the high heat transfer affected by the travel of spray droplets through the air promoted rapid freezing of the flood water.

Ice buildup is a function of ambient air temperature and wind velocity and varied daily. At Tarsiut, the temperature remained between -9°C and -33°C over the construction period. The overall average ice buildup rate was about 70 mm/day.

As shown in Figure 4, the minimum average design freeboard of 5.68 m was reached by January 4, 1982, which was based on ice forces generated by 1.7 m thick sea ice. For 2 m thick ice, a minimum freeboard of 6.5 m was required which was obtained by free flooding on January 16, 1982. By March 17, the ice pad was completed with an average freeboard of 8.0 m.
5 MONITORING

In order to evaluate the performance of the ice pad, monitoring began during the early stages of construction in December, 1981 and continued through until the end of June when the structure deteriorated. The various instruments used were survey pins, strain gauge rosettes, thermistor banks, inclinometer casings, a tide recorder station and ice pressure panels. Locations of the instruments are shown in Figure 6. Furthermore, in-situ ice strength and consolidation tests were done, as well as crack monitoring and ablation measurements. The outline of the monitoring procedures is given as follows:

Positional surveying was done from the caisson island on a daily basis from December 15, 1981 until the end of June 1982 to monitor horizontal movement of the ice pad. A series of survey pins, 50 mm steel pipes 6 m long, were placed in the design area and these pins were checked daily with the aid of an Electronic Distance Meter (EDM) for movements from a base line on the caisson island. On two occasions, small ice pad movements relative to the caisson island were observed. The movements were substantiated by high ice pressure values recorded by the ice pressure panels, change in crack pattern on the ice pad and large increases in strain gauge readings. The ice pad stabilized immediately after the movement occurred.

Strain gauges were installed in the ice pad on March 9 and 10, 1982, in four rosettes of three gauges each, by flooding them into the ice. At the completion date for ice pad construction, March 17, 1982, the strain gauges were about 0.3 m below the ice surface. The gauges were 1.5 m long and made of 3 m long, 0.127 mm Teflon coated constantan wire capable of monitoring strains of ± 6000 με (1). Readings were taken daily manually with the aid of a strain indicator. The strain gauge data indicated initially principal compressive strains in the order of -350 με. When the ice pad underwent a small movement in late March, all rosettes showed a change in principle strain.
to $+1700 \mu \varepsilon$. At that time also, small cracks appeared on the surface of the pad which, however, did not affect the integrity of the pad and also quickly stabilized. Following the movement, the principle tensile strains decreased to approximately $+1000 \mu \varepsilon$.

Three thermistor banks were installed, two in December and one in January, to monitor ice temperatures in the ice pad. Thermistors were of a resistance type measured bi-weekly with a multimeter. Ice temperatures varied linearly with depth, showing an average temperature of approximately $-10^\circ C$ between December and March.

Ice pressures on the ice pad were measured by using several MEDOF type sensors (2). The MEDOF panel is basically a hydraulic system consisting of a porous elastic medium between two steel plates which are welded to form a leak proof container. As loading is applied to the panel, fluid is displaced in proportion to the applied loading and is measured.

Four of these ice pressure panels were installed adjacent to the north side of the ice pad and another one at the edge of the caisson island in the area between the ice pad and the caisson island. Peak ice pressure readings indicated that the forces on the edge of the ice pad were roughly four times the force measured at the caisson island indicating a considerable resistance to ice forces by the ice pad.

Inclinometer casings were installed late in April for determining motion and shear strains within the ice mass itself. Inclinometer readings were taken periodically with an accelerometer probe to determine the change of shape. Unfortunately, the casings were installed too late in the season to yield any useful results and, in addition, the bottom of the casings could not be adequately secured in the sand bottom as the necessary equipment was not available.
The tide recorder at Tarsiut yielded a complete set of data for the period of February through June. The tides were between 10 and 35 cm in magnitude, and the height of the tide cycle was variable depending on lunar position, atmospheric pressure, and storm surge.

Ice strength testing was done in-situ with the aid of the FENCO borehole jack, a hydraulic piston jack which measures the confined compressive strength of ice in a 150 mm (6 inch) borehole.

The borehole jack tests showed reasonable quality ice with average strengths of 8.0 MPa, 10.5 MPa and 17.0 MPa for the three tests done in December, March and June, respectively. These values compared favourably with ice testing done previously in flooded ice. The elastic modulus values found were estimated at 680 MPa and 950 MPa for the March and June testing respectively. These values also were similar to those found in previous testing.

The degree of consolidation of the ice pad was assessed by drilling more than thirty 50 mm test holes through the ice pad. It was found that the ice pad consisted of hard ice, soft ice, rubble, slush and voids. In December, the average degree of consolidation was about 85%. Generally, the degree of consolidation increased with time.

The ablation of the ice pad was monitored for the period of June 3 to June 26 after which the ice pad became inaccessible. The average ablation rate was found to be about 7 cm/day. Final deterioration of the ice pad took place on July 3, 1982 when the ice pad broke up into several pieces which moved off site. Deterioration was not initiated by impinging ice but by wave attack in addition to ice ablation.
6 SUMMARY

The Tarsiut Relief Ice Pad was the first of its kind being built at the edge of the landfast ice in the Beaufort Sea. With a construction time of about 10 weeks a relatively cheap structure was built to serve as drilling relief platform for the period of January through June, 1982. Measurements within and around the ice pad indicated that the structure withstood substantial ice forces. Minor horizontal movements of the pad were observed during major ice events. These small movements would not have affected relief well drilling activity. Monitoring of the ice pad continued until its destruction on July 3, 1983. Ablation wave undercutting and calving were the primary deterioration mechanisms. The ice pad did not become unstable at any time due to excessive horizontal ice forces.

7 ACKNOWLEDGEMENTS

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FIG. 1. GULF OPERATED AREAS AND DRILLING LOCATIONS.

FIG. 2. TARSIUT ISLAND.
FIG 3. PLAN AND X-SECTION OF ICE PAD.

FIG. 4. THICKNESSES OF SEA ICE AND ICE PAD.
FIG. 5. LATERAL ICE PAD FORCES AND RESISTANCE.

FIG. 6 INSTRUMENTATION OF ICE PAD.
ARCTIC SLOPE PROTECTION DEVELOPMENT

1 INTRODUCTION

Artificial islands have proved to be both a safe and economic support for offshore exploration and production facilities in the ice-infested waters of the Beaufort Sea. Although it is envisioned that while structures will probably replace exploration island technology, the extremely high costs of Arctic operations have indicated a major need to develop or modify innovative systems for the Arctic that will reduce installation time and material, labor, and equipment costs. An Arctic slope protection development program has been under way at Sohio since 1978. This paper discusses our progress to date.

2 ARCTIC SLOPE PROTECTION PROBLEMS

The provision of slope protection in the Arctic is complicated by two primary factors: (1) harsh environmental conditions and (2) labor cost and material availability and supply.

Slope protection devices in the Arctic must withstand ice impact, ice abrasion, extremely low temperatures (-50°F), and repeated freeze-thaw cycling. In particular, the severe storms experienced in the Alaskan Beaufort Sea during the 1982 open-water season indicated the particular hazards posed by the combination of drift ice with high wave and current conditions.

The remoteness of the area, short open-water season, or work off the ice combine to make labor and equipment costs extremely high. Due to the seasonal nature of work in the Arctic, an experienced labor force is not usually available unless similar projects are performed annually.

To guide the development of our Arctic concepts, the following general design objectives were adopted:

1. Resistance to Arctic weather elements
2. Suitability for rapid deployment
3. Minimization of labor requirements during installation
4. Minimization of the use of nonnative materials, except for sand and gravels
3 SLOPE PROTECTION CONCEPTS

There are many types of revetments, as identified by B. McCartney /7/. Those considered desirable for Arctic slope protection are discussed below.

3.1 Sandbags

At present, the most widely employed means of slope protection for Arctic exploratory islands is large sandbags.

3.2 Test Sections of Sandbags, Grout-Filled Bags, and Longard Tubes

Endeavor Island and Resolution Island, designed for a multiyear service life, incorporated a number of test sections that have been monitored over the last 2-1/2 years. The sections consisted of 2-cubic yard ultraviolet-stabilized polypropylene sandbags, Longard tubes, grout-filled bags, and an articulated concrete mat.

Since their construction, the islands have experienced relatively mild winter ice conditions, with a maximum significant wave height of 3.2 feet and associated period of 3.8 seconds recorded in the project area. Moderate storm activity occurred in September and October of 1982, however, subjecting the islands to more severe wave conditions and impact from drift ice.

Based on periodic monitoring inspections conducted since the time of construction, the following conclusions about the slope protection test sections on Endeavor and Resolution Island have been derived:

Sandbags

- The 2-cubic-yard sandbag armor system has successfully protected the island slopes against wave and ice attack, although some damage has been observed in the form of ruptured bags and failed bag closures.

- Of the damage sustained to date, a large percentage has resulted from human-related activities rather than environmental factors.

- Of the natural causes, drift ice impact during the open-water season has initiated the largest number of bag ruptures. During the moderate easterly storms of September 1982, large ice floes limited in size only by the water depth were observed to ground against the island armor under the influence of storm winds, waves, and currents. Once grounded, the floes were oscillated by wave action, and they easily chafed through contiguous sandbags, creating areas of concentrated bag damage.

- A lesser, but significant, source of armor deterioration is wave-induced bag closure failure. The inclusion of double drawstring closures has resulted in markedly reduced closure failures.
The above damage observations indicate that a periodic inspection and maintenance program is essential to preserve the functional utility of soft armor systems.

- Ultraviolet deterioration has not noticeably affected bag performance.

- The single-ply bags evidenced significantly greater resistance to damage from both construction handling and ice impact than did the comparable four-ply bags.

**Grout-Filled Bags**

- The grout-filled bags have successfully withstood wave and ice attack.

- Inspection of the bags after two years in place indicated that the hardened fill material had chafed through the bag fabric in numerous locations in the zone of wave impact.

- If the cemented fill retains its integrity after deterioration of the bag fabric, then grout-filled bags may provide an effective solution to the problem of drift ice impact.

In areas that are not subject to severe ice impact, however, the use of grout fill material does not appear necessary.

**Longard Tubes**

- The hydraulic filling apparatus used in the in-situ filling of the Longard tubes performed successfully, indicating the feasibility of hydraulic filling techniques for Arctic gravels during the summer construction season. The potential advantages of in-situ filling include reductions in both manpower and heavy equipment requirements.

- Damage propagation has been experienced to a larger degree than with sandbags, due to the continuous nature of the tubes.

### 3.3 Articulated Concrete Mats

An articulated mat test section composed of reinforced square blocks measuring 4 feet per side and 8 inches thick was placed in prefabricated panels up to 6 blocks long and 2 blocks wide at a rate of approximately 500 square feet per hour. It is anticipated that considerable improvement in the placement rate can be achieved after more specialized equipment is available and construction personnel gain additional experience.

Since its installation in September 1980, the mat has performed effectively in stabilizing the island slopes against wave and ice attack. Because of the promising performance of the initial test section, second-generation mats were installed in 1981 as toe protection for a concrete dock on Endeavor Island and a concrete seawall on Alaska Island (Figure 1). To reduce costs, the linkage for the second-generation mats
was provided by galvanized wire rope instead of chain, as discussed in greater detail by Leidersdorf, et al. /6/. As with the initial test section, the two toe protection sections have functioned effectively and have required no maintenance.

To evaluate the hydraulic performance characteristics of the mat concept under controlled conditions, a large-scale model study was undertaken at Oregon State University during April and May of 1982 (Figure 2). Performed at a 1:4 scale and for water depths of approximately 20 and 40 feet, the tests were conceived to investigate not only the stability of articulated mat armor, but also the performance of various compound or "benched" profile configurations.

The basic incentive to test compound slope profiles is provided by natural beaches and failed rubble-mound structures, both of which typically incorporate a flattened region or bench in the wave impact zone connecting upper and lower slopes of greater steepness. In terms of hydraulic performance, improved armor stability is achieved with a properly designed bench by virtue of three factors: (1) reduced backwash velocities, (2) reduced resonant interaction between backwash and wave breaking, and (3) reduced wave impact. An additional potential benefit of benched profiles is a reduction in wave runup engendered by destructive interference between runup from an arriving wave and backwash from the preceding wave /2/.

For Arctic application, the concept of a compound profile is expected to offer greater resistance to ice rideup as well as improved hydraulic performance relative to a more conventional straight slope.

To quantify the effectiveness of various bench geometries in reducing wave runup and improving armor stability, three compound profile configurations were subjected to both regular and irregular waves ranging from 4- to 10-second periods and up to 17 feet in height at the prototype scale. Bench widths of 40 to 80 feet (prototype scale) were tested. Articulated concrete mat armor composed of blocks 4 feet square and 1 foot thick (prototype scale) was used throughout the test.

Although the relative effectiveness of the various configurations varied somewhat according to bench width, bench elevation, and wave period, the following general conclusions were derived from the model test results:

- The articulated concrete mat provided effective protection for the model slope for the range of wave heights and periods tested. Uplift of the individual blocks on the bench was noted when wave heights reached approximately 9 feet for wave periods of 6-8 seconds (prototype scale). Because the blocks were linked together, however, significant armor displacements did not occur, and the underlying slope sustained virtually no damage. The linkage concept thus appears to contribute significantly to improved armor stability and to render a conventional stability analysis using Hudson's Equation inappropriate.

- For a bench width of 40 feet, reductions in wave runup on the order of 20%-30% were typically achieved, as compared with predicted runup elevations for straight 1:3 slopes. This reduction in runup
suggests that the incremental increase in island fill material volume engendered by a compound profile may be partially or totally offset by reduced island freeboard.

- Armor stability was markedly increased by the provision of a flattened bench in the wave impact zone. When the model water level was lowered to induce wave impact on the lower 1:3 slope, however, armor uplift was observed at wave heights of 5 to 6 feet for comparable wave periods. The provision of a flattened slope in the zone of direct wave impact thus offers the potential for reducing the weight of the armor units required for stability.

Because of the model results and favorable performance of the prototype test sections, the concept of articulated concrete mats warrants consideration for both production facilities and exploratory facilities in exposed locations. As with grout bags, concrete mats offer increased resistance to ice-inflicted damage relative to sandbags. Besides their superior stability relative to bags, as demonstrated in the model tests, mats offer the potential for modular removal and reuse at other locations.

The primary disadvantage of the articulated concrete mat concept is cost, which was considerably higher than the cost of sandbag armor for the test sections installed in 1980 and 1981.

3.3.1 Proprietary Articulated Revetment Blocks

An additional phase of the program, conducted by J. Fluet of J.E.F. Associates, consisted of a detailed review of existing block systems and existing test data, together with an attempt to determine whether current proprietary block types can be extended for economical use under the higher-wave environment ice conditions and the problems unique to the Arctic.

A second phase of this study is currently under way, but initial results indicate that one or two of the proprietary products may be extended and will be cost-competitive with the Sohio-developed articulated block.

3.4 Filled Fabric Mattresses

The concept of filled fabric mattresses has been employed on a limited scale in Europe, Africa, and Japan over the last 15 years for slope and toe protection in sheltered environments /4/. Sohio is currently engaged in further development and testing to determine whether mattress designs and filling techniques appropriate for the Arctic environment can be devised.

The basic mattress concept employs prefabricated fabric panels tailored to accommodate a desired slope configuration; the panels are filled in-situ or filled adjacent to the site before being placed by a lay barge or crane. Applications for slope protection of offshore islands and causeways and for toe protection of vertical-walled caisson structures are envisioned. Typical features of the mattress concept are illustrated in Figure 3.
Two mattress fill materials currently receiving study are native sand and gravel, and grout. For areas not subject to severe drift ice impact, sand and gravel appear to be the more economical. Because of the successful application of hydraulic filling techniques to the Longard tube test section on Endeavor Island and previous Japanese experience, a hydraulic filling system that uses a submersible pump and hopper to produce a sand-water slurry is currently under development. An alternative sand filling system, a modified reciprocating grout pump that delivers a relatively dry slurry containing 90% sand and 10% water, is also under consideration. Preliminary testing of the latter system indicates that the dry slurry will not flow readily down a 1:3 slope and must be delivered to each tube of the mattress by a discharge pipe that is withdrawn as the tube fills. Despite this limitation, however, the modified grout pump system appears promising for small mattress installations and emergency repairs, in which its ability to be transported by helicopter and operated by a small field crew is particularly beneficial.

In areas subject to severe ice impact, grout rather than sandfill may be required to prevent the rupturing and subsequent loss of granular fill material already experienced with sandbags and Longard tubes. Conventional grout pumping techniques are envisioned for this application, although the problems associated with underwater filling in exposed environments and grout propagation through elongated tubes require additional study.

In light of the deterioration of the bag fabric in the grout bag test section on Resolution Island (see Section 3.2), it is assumed that the fabric panels employed in grout-filled mattresses will serve primarily as a formwork and will not contribute materially to the long-term integrity of the armor. Therefore, currently under consideration is an array of grout-filled compartments linked by preinstalled cables such that the grout mattress will function in analogous fashion to an articulated concrete block mattress.

On the basis of the preliminary analytical studies performed to date, the filled fabric mattress concept appears to offer the following potential benefits:

- As with sandbags, the fabric mattress concept employs native fill materials and requires the importation of only relatively lightweight, inexpensive fabric panels. However, filling is accomplished by hydraulic rather than mechanical means, thus offering the promise of reduced labor and heavy equipment requirements.

- As with articulated concrete block mattresses, the fabric mattress concept employs large-scale, modularized elements that may reduce placement time and provide more complete slope coverage.

- Composite mattress designs may be feasible, in which the zone most susceptible to ice impact is filled with grout, while the upper and lower slopes use less expensive sand-filled panels. Such a design would resist ice damage without incurring the high cost currently associated with articulated concrete blocks.
When applied as toe protection for mobile caisson drilling structures, inexpensive sand-filled mats may be hydraulically filled in place by divers or lowered from a filling barge. Because the raw material cost is low and filling time is anticipated to be relatively brief, the mats may be slashed and removed when the structure is moved, and new mats will be installed at the next drilling site.

It should be noted that, although promising, the filled fabric mattress concept requires considerable development and testing before its suitability for Arctic application can be fully evaluated. To provide a basis for further research, a prototype test section is under development for installation on the southern California coast in mid-1983. Current plans call for installation and performance monitoring of eight mattress designs: two proprietary grout mattress products, two composite grout-sand designs conceived specifically for Arctic applications, and four sand mattress designs with varying tube diameters, permeabilities, and geometries. A representative cross-section of the proposed test section is shown in Figure 3. Various filling techniques for sand and grout will also be evaluated to develop a realistic assessment of production filling rates and equipment requirements. After installation, performance monitoring will be conducted over an extended period to evaluate the stability and durability of the mattresses when exposed to moderate wave conditions.

### 3.5 Scrap Tire Mat Revetment System

One system that was shown to have potential for Arctic use is the scrap tire mat revetment (STMR). This appears to have the potential for extremely low cost and long life, but of greatest importance, it appears to have the potential for energy absorption from ice floes.

Although discarded tires have outlived their usefulness for automotive use, they retain tremendous strength and flexibility—characteristics that make them potentially attractive as a construction material.

The modules for the STMR developed for Arctic use are envisioned to be built offsite and delivered to the shore area, where they are connected with minimal labor into a continuous mat.

#### 3.5.1 Wave Tank Tests of Scrap Tire Mat Revetment

A series of wave tank tests were conducted by J. Armstrong of The Traverse Group, Inc. at the wave research facility of Oregon State University (OSU) in Corvallis, Oregon as part of Sohio's low-cost slope protection project. The purposes of these initial tests were as follows:

1. To examine the response of the STMR under scaled conditions of water depth and waves
2. To initially examine some anchoring systems proposed (method and forces) for the system
3. To obtain data on engineering and hydraulic characteristics of the system.
The two basic test conditions were as follows:

1. A 13-foot prototype depth: a scale factor of 4.5:1, waves exceeding the 100-year wave and random waves.

2. A 60-foot prototype depth: a scale factor of 5.5:1 and a 15-year wave

3.5.2 Test Results

A preliminary review of the test results shows that the system performed well. Our preliminary review indicates that the normal range of run-up coefficient was between 0.5 and 0.9.

3.5.3 Forces

The distribution of forces within the STMR can be obtained (approximately) only by experiment, due to the system's complexity. The test results were encouraging. The average maximum forces (scaled up to prototype) range between 900 pounds and 5.2 tons on the anchors and 46 pounds and 100 pounds on the STMR interconnection belts.

Although the system was developed for shallow-water applications in the Arctic, tests at a 60-foot prototype depth were run to see whether the system could be extrapolated to deeper-water locations. The tests at the 60-foot prototype depth indicated that the initial anchoring pattern was not as effective at these deeper-water locations. After a number of tests at the 60-foot water depth, it was observed that the mat's motion up and down and along the slope (both upslope and downslope) was of a magnitude greater than desired.

3.5.4 Prudhoe Bay Field Test, Full-Scale

After the preliminary screening of low-cost slope protection structures, it was decided that actual field information on the construction costs, the onsite field problems, and the actual response of the structure to shallow-water ice conditions was required. A full-scale test section was designed and manufactured in Anchorage and then shipped in sections to Prudhoe Bay, where it was assembled onsite at the West Dock (Figure 4). The test's objectives are as follows:

1. To identify critical construction factors to be considered with a full construction scenario, including cost information and Arctic productivity, using actual onsite labor

2. Full-scale testing to both wave and ice conditions in a typical mild ice environment in relatively shallow water (20+ feet)

3. To provide a section of armor for an actual installation

The tires for the modules were collected in Anchorage and shipped in small modules to Prudhoe Bay. Approximately 1,500 tires were assembled into 72 modules plus 201 connector tires.
Our initial assessment of the costs of the test section is approximately $28 per square foot of area covered. It is believed that for a major project these costs could be reduced substantially.

3.5.5 Future Testing

One of the major advantages of the scrap tire concept appears to be its potential to absorb the energy of ice floe impacts. A Sohio program currently under way is attempting to assess the following areas, which we consider potential problems:

1. The long-term life and fatigue resistance of the connector belts and the connections

2. The overload capacity of the connector belts and the connections, and if necessary the development of a new type of connection that can satisfy substantial overload requirements

3. The STMR system's ability to absorb the impact from ice floes impinging on a deep-water structure

3.6 Asphalt

In 1982 Sohio initiated a number of office and field reconnaissance studies to locate, if possible, adequate native materials that could be used for riprap associated with both exploration and production facilities in the Beaufort Sea. The studies have shown that the only native materials available within a reasonable haul distance to the Beaufort Sea coastline are sand, gravel, and highly fractured stone that is not acceptable for large riprap. Because extensive R&D programs have been undertaken in the Netherlands for many years to develop techniques for efficiently using sand, gravel, and small stone for coastal protection /11/, we have initiated a program to assess the Dutch experience and investigate in greater detail the applicability of bitumen for coastal protection under the unique requirements of an Arctic facility.

3.6.1 Sand-Asphalt

Sand-asphalt consists of local sand mixed with 4%-4.5% paving grade asphalt. This mixture can be dumped underwater in lifts to form an annulus that is then filled with dredged sand.

Three Sohio-sponsored test series are in progress at the University of California at Berkeley under the direction of Professor C. Monismith. The creep testing program was developed to assess the creep modulus to determine the strength characteristics of sand-asphalt under sustained loading. The fatigue testing program was developed to assist the fatigue strength for evaluation of sand-asphalt's ability to withstand cyclic wave loading. The freeze-thaw testing program was developed to determine the effect of cycles of freezing and thawing on material strength.

An asphalt mixing plant combines the sand with bitumen at elevated temperatures (250°-300°F); the mixture is barged to the site and then placed underwater while still hot and workable.
The advantages of the concept are as follows:

- It is a good filter layer.
- The slope can be steepened to 1:2, if stable.
- Sand slopes may be steepened substantially.
- The sand-asphalt layers may last 2-3 years in mild-to-moderate wave conditions. This duration would be suitable for exploration structures; for a production facility, armor would have to be added.

A full-scale test under maximum wave conditions is envisioned for this concept.

3.6.2 Stone-Asphalt

Stone-asphalt consists of a mixture of asphalt-mastic or asphalt-rubber with gravel or crushed rock. This material has potential use as an armor coat on an exposed sand asphalt surface at critical points.

Creep and fatigue testing programs are in progress at the University of California at Berkeley to acquire structural design information for this type of armor. If the testing is satisfactory, a test section may be placed on the California coast.

Asphalt-mastic binder consists of asphalt plus filler material, such as local sands and very fine limestone dust, or Portland cement in a weight ratio of about 25:75.

The binder may also consist of asphalt-rubber material, whose adhesion, in our opinion, is better than that of asphalt. Asphalt-rubber consists of asphalt blended with reclaimed rubber material in a weight ratio of 50:20. Some anticipated advantages of asphalt-rubber are as follows:

- Easier handling and shipping
- No onsite mixing of filler with asphalt
- Lower cost, since no limestone dust is available onsite
- Better adhesion to stone surface
- Better low-temperature properties

Questions still exist about the handling, shipping, equipment, and manpower, together with corresponding cost factors in the Arctic. These questions exist because we have not proceeded as far with asphalt erosion protection as we have with some of the other concepts. The main advantage of using asphalt in the Arctic is that it allows the use of a wide range of local materials, including seafloor materials. Also, dredging is definitely an option, and only the asphalt and asphalt filler materials (i.e., limestone dust, cement, or asphalt-rubber) must be imported.
Asphalt is easily blended with other materials; only a mixing unit and heater are needed.

Asphalt, and particularly asphalt-rubber, may be more durable in cold weather with respect to cracking and the effects of freezing and thawing.

The costs are potentially lower, if the concept is proven.

Our review has shown that asphalt does not appear to have any major disadvantages for Arctic use. One possible problem may be the handling of asphalt in cold temperatures. A second possible problem might be high mobilization costs and high equipment costs if an asphalt plant is not used frequently after assembly in the Arctic.

4 CONSTRUCTION EQUIPMENT STUDY

Due to the extremely high cost associated with the mobilization of highly specialized equipment, a portion of our low cost slope protection study concentrates on modifying existing barges that might have dual use for handling prefabricated concrete block or asphalt mats or handling mattresses or other prefabricated units. This work is currently being performed by A. Miller of Earl and Wright.

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Fig. 1. Second-generation articulated blocks at toe of test wall section, Alaska Island, Beaufort Sea.

Fig. 2. Articulated concrete block mattress model tests—Oregon State University wave tank.
Fig. 3. Proposed fabric mattress test section—profile.

Fig. 4. Scrap tire mat revetment test section, Prudhoe Bay.
S.B. Shinde, C.V. Mancini, I.M. Fraser
Esso Resources Canada Limited
Calgary, Canada

R.C. Joshi
University of Calgary

SLOPE PROTECTION FOR BEAUFORT SEA
ARTIFICIAL ISLANDS USING SOIL CEMENT

Abstract

Artificial islands have been used as exploration drilling platforms in the shallow waters of the Canadian Beaufort Sea since 1973. Typically, sandbags underlain by filter cloth provide erosion protection for these temporary islands. This paper presents the results of laboratory tests and a field trial, conducted at Issungnak island during the summer of 1980, to investigate compacted soil cement as shore protection above the waterline. Fabric mats filled with soil cement grout have been proposed below the waterline to prevent erosion and consequent undercutting of the compacted soil cement. The results of laboratory tests on these fabric mats are also presented.

1 INTRODUCTION

The locations of the islands in shallow water which Esso has built since 1973 are shown in Figure 1. These islands were generally constructed by dredging sand from the seabed during the summer. Since the rock and gravel, normally used for shore protection, are not readily available in the Beaufort, sandbag retained and sacrificial beach islands with a shore protection of sandbags underlain by filter cloth have been used. Past experience has shown that maintenance, which adds to costs, is required for sandbag slope protection after every major storm. As a result, based on its use on river banks and
dams, compacted soil cement for slope protection was considered to be a good possible alternative to sandbags.

The experience with dams indicates that seven day compressive strengths of 1.8 to 2.6 MPa are required to achieve long term durability. For short term durability, required for exploration islands, seven day compressive strengths of 0.6 to 1.0 MPa are considered sufficient.

Since soil cement relies on in situ mixing and compaction, it is only appropriate in the beach zone above water level. Below that elevation, some method must be employed which will exclude excess water and retain the protection material. For this application, fabric mats laid in place and filled with plastic soil cement or soil cement grout appeared appropriate as they have also been used successfully for river banks and dams.

To test the applicability of these forms of protection, a series of laboratory tests and a field trial were designed and carried out.

2 THE ENVIRONMENT

The open water season in the Beaufort Sea extends from mid July to mid October. Wind velocity and fetch have a direct effect on wave heights. The fetch is generally restricted by
the proximity of summer ice cover, hence the most severe wave conditions are generated when the polar pack ice is at its extreme northerly position. The general wave climate, based on the results of a statistical analysis of exceedance frequencies for significant wave heights /5/ is shown on Figure 2.

![Figure 2: Deep Water Wave Climate - Beaufort Sea](image)

Air temperatures are variable throughout the July to October period but, generally, range from 0°C to +15°C. The sea temperature during most of this period is about +1.5°C, but it crops to -1.5°C late in the season, as freeze-up occurs.

3 LABORATORY TEST MATERIALS

The laboratory tests were carried out using uniformly graded, fine sand from the Issungnak Island./3/ Class 'G' oilwell cement, which was available at the site, and sea water were used in the preparation of soil cement samples. The effectiveness of chemical grade calcium chloride and pozzolith 122HE as accelerators for reducing the hardening time were tested. Soil cement strengths were measured at temperatures ranging from 3°C to 10°C to cover the expected field conditions.
during mixing and curing. No appreciable variations in strength were noted.

4 LABORATORY TESTS AND RESULTS

4.1 Compacted Soil Cement

The strength of soil cement is dependent on its cement and moisture contents and its in-place density. As is the case with soils, there is an inter-relationship between the moisture content of the mixture and the density which can be achieved with a given amount of energy. The moisture content at which the maximum density is achieved is known as the optimum moisture content.

In the laboratory, the optimum moisture content was obtained using the procedures from ASTM D558-57, for mixtures with a cement content varying between 10 and 20% of the dry weight of the sand. In all cases calcium chloride weighing 3% of the cement weight was added to the mixture.

After curing at 10°C, the samples were subjected to an unconfined compression test using the procedures from ASTM D1633-63 after 24 hours and after seven days. Figure 3 shows the results of these tests. At 24 hours, strengths varied

![Figure 3](image_url)

**FIGURE 3.**
Compressive strength of laboratory prepared compacted soil cement cured at 10°C.
between 0.15 and 1.20 MPa. After seven days, the strengths increased significantly and varied between 0.56 and 3.80 MPa.

Additional tests were run with the calcium chloride content increased from 3% to 6%. The resulting accelerated rate of curing substantially increased the 24 hour strengths but did not appreciably affect the seven day strengths. Pozzolith 122HE was also used, in some mixtures, to accelerate curing but, in combination with the sea water used for mixing, resulted in samples too brittle to test.

4.2 Plastic Soil Cement

In fabric mats, early setting of the cement is important to minimize loss of cement fines through the fabric due to current and wave action. As a result, normal Portland cement was used in laboratory mixtures as it sets more rapidly than Class 'G' oilwell cement. Calcium chloride was used as an accelerator to further reduce the setting time.

Plastic soil cement samples were prepared with sand and added cement weighing 10, 20, 30 and 40% of the dry weight of sand. The water:cement ratio of each mix was gradually increased until fluidity tests showed that it was pumpable. Mixes containing 10 and 20% cement were highly segregated and could not be used as pumpable grouts even when bentonite was added in an attempt to reduce segregation. Mixes containing 30 and 40% cement showed little segregation and the fluidity tests indicated good pumpability, for both mixtures, at a water:cement ratio of 0.86:1.

Compressive strength tests of both these soil cement grouts, cured at 8°C are presented in Figure 4. Some tests were carried out on mixtures with varying amounts of bentonite and calcium chloride. Strengths ranged between 0.25 MPa and 1.25 MPa at 24 hours and between 4 MPa and 9 MPa after seven days. The latter strengths substantially exceed the criteria for durability mentioned in Section 1.
The applicability of both synthetic and natural fibre jute bags was assessed by filling bags 300 mm x 200 mm x 50 mm with grout and testing them for loss of cement fines in a water flume. The tests indicated that the maximum losses, which occurred with jute bags, did not exceed 10% for currents up to 3.0 m/s. Curing of the soil cement continued under these currents.

5 FIELD TESTS

In Section 4.1 the three parameters of cement content, moisture content and in-place density, which are important to soil-cement strength, are listed. Practical limitations, in the field, made control of the moisture content and in-place density impossible and control was limited to variations of cement content.

The test section was prepared on Issungnak on the east beach. It covered 1 200 square meters and was 250 mm thick.
The laboratory tests showed that 12% cement content was sufficient to achieve the required minimum compressive strength in seven days. However, it was decided to evaluate the performance of varying cement contents in sections of the field test to verify that the minimum strength specified was adequate for a relatively thin layer of soil cement in the Beaufort.

The area was divided into ten equal sections. Cement concentrations were varied from 10 to 20% by weight of sand and the accelerator (calcium chloride) concentrations were varied from 4-1/2 to 12% by weight of cement. The ambient temperature at the test site ranged between 6°C and 13°C.

A front-end loader was used, initially, to spread Class 'G' oilwell cement and calcium chloride over the test sections and the task was completed by hand. A rotovator was then used to mix the sand, cement and calcium chloride to a depth of approximately 250 mm. The test areas were immediately compacted by the front-end loader. Visual inspection indicated that the mixing with the available equipment was not satisfactory.

Thin-wall cylindrical tubes were pushed by hand or were driven into the soil cement to obtain relatively undisturbed samples for density and strength tests. The density tests measured the saturated unit weight of the samples between 16.5 to 18.63 kN/m³. After density testing, the specimens were wrapped in plastic, left at the site to cure for four days and were then flown to the laboratory for testing. The moisture content of these samples varied between 5.5% and 17.5%. The compressive strength test data on samples from the test sections are presented in Figure 5.

The average of the five day compressive strengths varied from 0.6 MPa with a 10% cement content to 3.3 MPa with a cement content of 20%. These strengths are similar to those of the compacted samples prepared in the laboratory during the initial investigation.
Visual observations indicated that the test sections hardened within twelve hours of compaction and subsequently did not yield under the pneumatic tires of construction equipment.

![Figure 5](image)

**Figure 5.**

Compressive strength of field-cured compacted soil cement at 5 days (curing temperature 6°C - 13°C) compared to 7 day compressive strength of laboratory cured soil cement.

The field test section was exposed to 330 hours of storm conditions during September and October with maximum wave heights from the east ranging from 1.5 m to 2.4 m. The soil cement sections with cement content greater than 15% were successful in resisting wave erosion, however, the hardened layer was undercut by waves at the water line. This led to cracking and burial of the pieces in the sand. Even under these conditions, the test section provided sufficient resistance to wave action to limit its erosion to about 15 m from the water line prior to freeze-up in late October. The test sections above the 15 m line were intact throughout the winter and served as temporary helipads and drill pipe storage areas until spring break-up.

6 COST ESTIMATES

Cost estimates and the relative effectiveness of various techniques used for erosion protection of artificial islands are given in Figure 6. The cost estimates are based on current material, labour and installation costs. The assessment of the
relative effectiveness of each of the shore protection methods is qualitative and is based on visual observations of field tests conducted during 1982.

The soil cement method costs about $25 per square meter, in place, compared with $33 per square meter for sandbags. An additional, substantial advantage of using soil cement is the elimination of the clean-up costs associated with the use of synthetic filter cloth and sandbags.

Pre-formed fabric mats filled with soil cement grout are more expensive than the formation of soil cement in the beach zone. Some very limited testing of this concept was carried out.
at Alerk during the summer of 1981 and it appeared to be effective.

7 CONCLUSIONS

The field test indicated that soil cement, prepared with sea water, protected the beach zone from wave erosion better than sandbags. A section thicker than 250 mm or a cement content greater than 14-1/2% will be required to resist beach erosion for waves greater than 2 m. Erosion protection of beaches below the water line may be achieved by pre-formed fabric mats filled with plastic soil cement.

ACKNOWLEDGEMENTS

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D. J. Goodman, Project Co-Ordinator,  
New Technology Division,  
Production Department,  
BP Petroleum Development Ltd.,  
London EC2Y 9BU, UK

ICE LOAD INSTRUMENTATION FOR ARCTIC OFFSHORE STRUCTURES AND VESSELS

Abstract

The designer of an Arctic offshore structure or vessel seeks the answers to three important questions. First, what is the extreme load the structure will experience during its life, or more precisely what is the likelihood of a given load being exceeded? Secondly, what is the maximum local pressure the wall of the structure or the hull plate must sustain without yield. And thirdly, what level of cyclic loading may be expected. Difficulties have been experienced in extrapolating model data to the full size, and therefore the designer will turn to measurements made on existing structures to find the answers to these three questions. Observations have been made on a wide range of structures such as bridge piers, lighthouses, gravel islands, causeways, supply vessels, cargo vessels, and even an oil tanker (the S.S Manhattan). If results are to be extrapolated from an existing structure to a new site, care must be taken to ensure the same failure mechanism will be operating at both sites.

The paper examines the instrumentation which is available for the measurement of total loads, local pressures, and fatigue loads. The advantages and weaknesses of each device is discussed.
For some structures (for instance a gravel island surrounded by a rubble pile) it is only possible to measure the stress distribution in the surrounding ice. The total load must be deduced by integrating the local stress times the area element around a path round the island. In practice only spot measurements of local stress can be made. These must be in positions where the stress is varying slowly, and sufficient in number to account for non-simultaneous failure around the periphery of the island.

Load panels have been used to observe local stresses in the ice but suffer from the disadvantage that they must be placed exactly perpendicular to the maximum compressive principal stress otherwise small tensile stress zones at the edge of the panel could cause cracks to form. These cracks may locally disturb the stress field.

The ice itself may be used as a load cell. Even under very small stresses (\(1 \mu \text{N} \cdot \text{m}^{-2}\)) detectable creep strain rates are observed. Measurement of surface strain rates can be used to deduce the directions of the principal stress axes (if the ice is horizontally isotropic), and the magnitude of the principal stresses if the salinity, temperature and crystal structure are known at the site. Where no bending is observed, the strain rate must be uniform through the thickness; this determines the vertical stress distribution.
Abstract

In March/April 1981, Communications Research Laboratory and Department of Fisheries and Oceans personnel conducted an experiment on Borden Peninsula, northern Baffin Island, in which three marine radars were operated from the shore, overlooking an area of landfast ice. The radars were about 30 metres above sea level, a height typical of a ship-mounted antenna. Radar parameters were varied and the corresponding analog radar video was recorded for later analysis. The variable radar parameters included: frequency, pulse length, antenna beamwidth, antenna height, and polarization. Aerial photography of the area around the radar site was taken.

This paper reports data collected with the antenna stationary, transmitting outward along a radial line. The line chosen contained several different ice features. Two Luneburg lenses (calibrated radar reflectors) were deployed. Graphs of radar signal versus range are presented for various radar parameters, showing their effects on the radar return. A typical graph is compared with the aerial photography to show the radar return/surface topography correlation.

1 INTRODUCTION

The increasing requirement for year-round navigation in the Arctic dictates the need for a reliable method of monitoring the ice conditions around a ship. Shipborne radar, with its all-weather all-light operational capability, will be an important surveillance device. Present marine radars, however, were not designed for ice detection, and design improvements can be made.

To provide basic research into the possible improvements, the Communications Research Laboratory (CRL) of
McMaster University and the Canadian Department of Fisheries and Oceans (DFO) have begun a program to evaluate the effect of various radar parameters on the detection of sea ice, with the final aim of developing a design for a radar specifically for use in detecting and monitoring sea ice conditions around a ship or a drilling platform.

The experimental radars whose parameters are given in Table 1, permitted comparison of the following parameters:

i) pulse length, e.g. Decca X-band: 810, 220, 70 ns.

ii) antenna azimuthal beamwidth, Decca X-band: 9-foot (0.8°) vs. 4-foot (1.9°)

iii) frequency, S-band (3 GHz) vs. X-band (10 GHz)

In addition, scaffolding was used to raise the 4-foot X-band antenna for operation at 120, 125, 130 and 135 feet above sea level. The effect of polarization was examined by transmitting horizontally using the Decca X-band and receiving the desired polarization using the Furuno X-band receiver fed by a rotatable-feed parabolic dish antenna. The radar recordings were made over a six-day period. Details of the experiment are given in /1/.

Table 1. Important Parameters of Experimental Radars.

<table>
<thead>
<tr>
<th>Model</th>
<th>Decca RM 1229</th>
<th>Decca RM S1230</th>
<th>Furuno FRM 64W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>9.415</td>
<td>3.052</td>
<td>9.380</td>
</tr>
<tr>
<td>Transmitter:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak power (Kw)</td>
<td>25</td>
<td>30</td>
<td>8.8</td>
</tr>
<tr>
<td>Pulse length (ns)</td>
<td>810</td>
<td>870</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Pulse repetition frequency (Hz)</td>
<td>825 (for long pulse)</td>
<td>825 (for long pulse)</td>
<td>800</td>
</tr>
<tr>
<td>Receiver:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>logarithmic</td>
<td>logarithmic</td>
<td>logarithmic</td>
</tr>
<tr>
<td>MDS (dbm)</td>
<td>-96</td>
<td>-96.5</td>
<td></td>
</tr>
<tr>
<td>Antenna:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aperture (ft)</td>
<td>4</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Beamwidth (az) (degrees)</td>
<td>1.9</td>
<td>0.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Gain (db)</td>
<td>24</td>
<td>31</td>
<td>27</td>
</tr>
<tr>
<td>Rotation rate (rpm)</td>
<td>28</td>
<td>28</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24</td>
</tr>
</tbody>
</table>
Four major aspects of a surface-based radar monitoring surface targets bear on this work: (i) radar resolution, (ii) grazing angle, (iii) radar cross-section, and (iv) the multipath effects of the ice surface. For further radar information, see /2/ or standard radar texts.

i) The radar resolution cell size is defined as \( c t/2 \) units in range by \( R/2 \) units in bearing, where \( t \) is the radar pulse length, \( c \) is speed of light, \( R \) is range, and \( b \) is the antenna azimuthal beamwidth. Targets within the same resolution cell cannot be distinguished. Note the range dependence of the cell size in bearing.

ii) Grazing angle, the angle between the radar signal and the horizontal at the target, can be approximated as

\[
\theta = \sin^{-1} \left( \frac{h_a}{R} - \frac{R}{2r_e} \right)
\]

where \( h_a \) = antenna height
\( R \) = range
\( r_e \) = 4/3 actual radius of earth

It is important to note that for the ranges of interest here, 0.5 nmi to 5.5 nmi, the grazing angle is less than 2.5\(^\circ\), and is less than 1.0\(^\circ\) for ranges greater than 1.3 nmi.

iii) Radar cross-section (RCS), \( \sigma \), is a measure of the radar reflectivity of a target. Reference /3/ gives the radar equation for a point target in free space. When the radar illuminates the earth's surface, the point target \( \sigma \) term is replaced with an area RCS, given by the surface area illuminated within the radar resolution cell times the normalized radar cross-section, \( \sigma_0 \), the reflectivity per unit area. That is,

\[
\sigma = \frac{c t}{2} R/2 b \sigma_0
\]

This changes the received power's range dependence in the radar equation from \( R^2 \) to \( R \).

iv) For a surface-based radar detecting surface targets, the radar illuminates and receives an echo from the target along at least two paths: the direct path and an indirect path reflected off the earth's surface. This multipath causes lobing in the vertical antenna beam pattern, as discussed in /3/. Reference /3/ gives the radar
equation for received power from targets whose height is below the lowest lobe. Substituting for \( \phi \) from equation (2), this equation's range dependence goes from \( R \) to \( R' \). The height of the maximum of the lowest lobe occurs for range

\[
R = \frac{4 h_a h_t}{\lambda} \tag{3}
\]

where \( h_a \) = antenna height

\( h_t \) = target height

\( \lambda \) = radar wavelength

A similar relation, by Lord Rayleigh, suggests that a surface appears smooth if \( h_t \sin \phi < \lambda/8 \). Using (1) with \( R/2r_e = 0 \) for short ranges,

\[
R > \frac{8 h_a h_t}{\lambda} \tag{4}
\]

Equations (3) and (4) show the importance of increasing antenna height \( h_a \) and decreasing wavelength \( \lambda \) to improve the detection of low-lying targets.

3 RESULTS

3.1 Radar Recording

The analog radar signal was recorded using an RCA Adviser wideband video recorder. The recorder has 6 MHz bandwidth, and 36 db dynamic range. The detected video from the transceiver was recorded before any display signal processing circuitry. The recorded video was later digitized to 8 bits at a sampling rate of 7.68 MHz (arbitrary).

3.2 Calibration

For recording, the radar video amplitude was shifted and adjusted to suit the recorder, and again during replay to suit the analog-to-digital converters. Therefore the digital samples are arbitrarily scaled versions of the original absolute radar receiver voltage. The only record of these absolute voltages is a series of oscilloscope photographs taken in the field during the experiment. The voltage of selected points was noted, then used to scale the digitized data to produce similar traces. The accuracy of this scaling process is not high. The conversion from receiver output voltage to received power is given by the radar calibration curve which is approximately linear for both X-band radars.
The next possible step is to calculate the normalized radar cross-section. The radar equation can take multipath into account but requires knowledge of the target height. For the area covered by the antenna beam, the assignment of a target height is meaningless. Thus, one must use the free-space radar equation, with the area RCS term. Rewritten and converted to decibels (db) by taking $10 \times \log ( )$, the equation is of the form

$$\sigma_0 = 10 \log (C) + P_r + 30 \log (R)$$

(5)

with $\sigma_0$ in db, $P_r$ in dbm, $R$ in m, and $C$ is a constant which depends only on the parameters of the radar.

Because of the difficulties encountered in the data scaling, the reader is cautioned to use the curves in this paper for qualitative comparisons only. Similarly, because of the dubious merit of calculating the normalized radar cross-section $\sigma_0$ with a possibly less than faithful form of the radar equation, the graphs in this paper will be shown as return power versus range. Since the scaling from digitized data to receiver voltage to received power is linear, the form if not the scale of the original radar video is preserved. Readers who want $\sigma_0$ values can use the graph values and the appropriate radar equation to determine $\sigma_0$.

3.3 Radar/Photography Correlation

Figure 1 is part of an aerial photograph mosaic showing the radial line which was illuminated by the antenna. Indicated are the radar, several ice features, and the two Luneburg lenses. Also shown is a graph of the radar return versus range for the Decca X-band radar, plotted with the same range scale. There is good correlation between the large surface features and the radar return amplitude. The range resolution of the radar for $r = 810$ ns is 121.5 metres. The same labelling of the features by number as used in Figure 1 is shown on all subsequent graphs for comparison.

3.4 Radar Pulse Length

Figures 2 and 3 compare the X-band received power vs. range for pulse lengths of 810 and 220 ns, and 810 and 70 ns. The range resolution increases with decreasing pulse length. Feature 3 (lens #1) return is narrower, and the two-peak nature of feature 10 is resolved.

3.5 Antenna Beamwidth

Figure 4 compares the return power versus range for
the Decca X-band using the 4-foot antenna, $\theta = 1.9^\circ$, and the 9-foot antenna, $\theta = 0.8^\circ$. Features 3, 6, and 12 have larger returns and their leading edge occurs slightly closer in range. For a ridge at an angle to the radar, a wider antenna beam will illuminate the closer part of the ridge sooner (i.e. at closer range) than the narrower beam. The wider beam also illuminates a larger area, possibly containing strong reflectors.

3.6 Radar Frequency

Figure 5 shows sample amplitude versus range for the S-band radar, antenna beamwidth of $2.0^\circ$, and the X-band radar, antenna beamwidth $1.9^\circ$. (The S-band radar calibration curve was unavailable, so the graphs show sample amplitude). The wavelength dependence of some reflections is indicated by the virtual disappearance of feature 6 and the appearance of 5A and accentuation of 6A. The partial or complete absence of features 8, 9, 12 and 14 seems related to the antenna lobing, i.e. these features appear "smooth" to the S-band radar. Even though the S-band radar transmits 30 Kw, it cannot detect low-lying targets as well as the 25 Kw X-band.

3.7 Radar Polarization

The Decca X-band (9 foot antenna at 120 feet) transmitted horizontal polarization, while the Furuno receiver was fed with a parabolic dish antenna, whose feed was rotated to receive the desired polarization. Figure 6 compares the Furuno return for horizontal (like) polarization and vertical (cross) polarization. Although the cross-polarized return power is obviously reduced, some features (e.g. feature 8) disappear completely while others (4, 5, 6, 7, 10, 11) are reduced in varying degree. Features beyond feature 11 are absent due to lack of sufficient transmitted power. The use of cross-polarized returns for feature identification deserves further study.

3.8 Antenna Height

As the antenna height was altered over the physically limited range of 120 to 135 feet, the basic shape of the return remained the same, with changes in detail. The changes in the return are due to changes in the geometry of the radar and the ice, i.e. different multipaths, and changing radar shadowing. Figure 7 compares the return with the radar at 120 and 135 feet. Lens 2 was not deployed for the 135-foot recording.
4 CONCLUSIONS

Increased range resolution is desirable, but to maintain the range of detection, the transmitted signal energy must be maintained, either through higher peak transmit power, or pulse compression techniques. The use of a lower frequency results in decreased detection of low-lying targets. Therefore, the higher radar frequencies are favoured. Decreasing the wavelength has the additional advantage of reducing the antenna beamwidth, hence increased bearing resolution, for the same physical aperture size.

Calibration of the radar returns is not a straightforward matter. The use of calibrated radar reflectors on the ice is subject to error due to multipath effects, and the reflector cross-section may not be constant for differing geometries.

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3. Lewis, E.O. and Currie, B.W., Investigation of the effect of multipath interference on the detection of low-lying targets on the ice surface. The 7th Int. Conf. on Port and Ocean Engineering under Arctic Conditions (POAC). Helsinki, Finland, 1983.
Figure 1

Comparison of aerial photograph of radial line and radar return from Decca X-band radar with 9-foot antenna.
Radial line is between arrow heads.
Radar is located at tip of left arrow head.
Return is shifted slightly inward in range to centre the echo on its corresponding ice feature.
Large feature top-centre is Adam's Island.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubble</td>
<td>&lt;1 m</td>
</tr>
<tr>
<td>Flat ice</td>
<td></td>
</tr>
<tr>
<td>Luneburg lens #1</td>
<td>1 m</td>
</tr>
<tr>
<td>Light rubble</td>
<td>1 m</td>
</tr>
<tr>
<td>Pressure ridge</td>
<td>2-3 m</td>
</tr>
<tr>
<td>Very light rubble</td>
<td></td>
</tr>
<tr>
<td>Light rubble</td>
<td>&lt;2 m</td>
</tr>
<tr>
<td>Pinnacle</td>
<td>4 m</td>
</tr>
<tr>
<td>Intermediate rubble</td>
<td>&lt;2 m</td>
</tr>
<tr>
<td>Heavy ridging + single</td>
<td>2 m</td>
</tr>
<tr>
<td>Intermediate rubble</td>
<td>2-3 m</td>
</tr>
<tr>
<td>Luneburg lens #2</td>
<td>3-5 m</td>
</tr>
<tr>
<td>Ridge</td>
<td>2-3 m</td>
</tr>
</tbody>
</table>
Figure 3: Comparison of radar return for pulse lengths of 6, 10, and 14 ns when the 4-foot and 10-foot antennas were used with the X-band radar. 

Figure 4: Comparison of radar return for pulse lengths of 8, 10, and 14 ns when the 10-foot and 14-foot antennas were used with the X-band radar.
Figure 4. Comparison of radar return for each wave, taken from antenna beam at 45°.
and the beam from an antenna at 90°.

Figure 5. Comparison of radar return for horizontal and vertical receive collection of a vertical, collimated, L-band transmission.

Figure 6. Comparison of radar return for each wave, taken from a VHF antenna at heights of 120 and 135 feet above sea level.
Abstract

In March/April 1981, Communications Research Laboratory and Department of Fisheries and Oceans personnel conducted an experiment on Borden Peninsula, northern Baffin Island, in which three marine radars were operated from the shore, overlooking an area of landfast ice. The radars were about 30 metres above sea level, a height typical of a ship-mounted antenna. Radar parameters were varied and the corresponding analog radar video was recorded for later analysis. The variable radar parameters included: frequency, pulse length, antenna beamwidth, and antenna height. Aerial photography of the area around the radar site was taken.

This paper deals with the display of the sampled radar images using a raster scan (TV) system. The topic of scan conversion from $R^2$ to $XY$ coordinates is discussed. The images are first presented in grayscale with 256 levels of intensity. There is a brief discussion of image processing techniques such as histogram stretching for contrast enhancement, and two-dimensional filtering for image enhancement, with examples of their use.

The radar image is compared to the aerial photography. An example is presented of a radar image in which the intensity levels are mapped onto colours, producing a pseudo-colour image. Comparison of the grayscale and colour-coded images shows the increase in the information conveyed in a single image when using colour. Issues involved with colour perception and selection are mentioned. Finally, radar images are presented in grayscale for a variety of radar parameters to show their effect on the display.
1 INTRODUCTION

The parameters of the radars used in the experiment and their variation are described in /1/ and will not be repeated here. Indeed the reader is well advised to read /1/ before proceeding further.

It should be noted that all the display work here was done "off-line"; our purpose at this time is not to design a real-time display, but rather to identify useful features to be used in the display of radar images.

2 SCAN CONVERSION

The raster display system used for the image display has 1280 pixels per line by 1024 lines with 8 bits per pixel. For round images, a 1024 pixel by 1024 line format was used for the radar image. The recorded radar video was sampled at 8.00 MHz, using an 8-bit analog-to-digital converter, to give 512 samples per sweep for radar range 0.3 nmi to 5.5 nmi. Sweep refers to the radar return for one pulse repetition interval. The position of the radar sampling point is given by its range R and its bearing θ. Each sampled sweep was tagged with a 12-bit bearing value. For a typical radar pulse repetition frequency (PRF) of 825 Hz and an antenna rotation rate of 28 rpm (2.14 sec per rev), there are about 1766 sweeps per radar scan. Radar scan refers to one complete rotation of the antenna. Scan conversion refers to the process of taking each radar sample, coordinates (R,θ), and assigning it to the raster pixel, coordinates (x,y). Two problems are encountered in doing this. First, for smaller R, many radar samples are assigned to the same pixel; how should these samples be combined? Second, for large R, since the sweeps diverge, there may be pixels to which no radar samples are assigned. This occurs even for 4096 sweeps per scan, producing a Moiré pattern near odd multiples of 45°.

The sweeps are scan converted one at a time directly to the raster display memory. The x and y addresses for each sample are generated using software versions of binary rate multipliers. For multiple assignments to the same pixel, two techniques were compared: running average versus replacement. For these images, replacement was satisfactory and faster.

Regarding the second problem, there is additional data filling required. The digitizing system sampled only one scan, giving 1700-1900 sweeps per full scan image, to be assigned over 4096 possible sweep bearings. Obviously about half the bearings were assigned no
sweeps. To fill in these bearings, sweeps were replicated at the next bearing position. After the complete image was built up, remaining holes were replaced with their nearest non-hole neighbour.

3 AERIAL PHOTOGRAPHY

Figure 1 shows an aerial photo mosaic of part of the area around the radar site. The photo has been scaled to match the radar image shown in Figure 2. The same PPI-style range-bearing overlay has been put on the photograph and the radar images for position identification. Several targets are labelled by number on the X-band radar image for correlation with the photography. Note the radar shadows behind the larger single targets and the ridging (feature 15) to the north. The feature 19 area is a lead, either open or recently frozen over.

4 IMAGE PROCESSING

The basic purpose of image processing is to increase the desired information content of an image. This definition presupposes that the "desired information" has been defined for a given image. The first image "improvement" step is to ensure that full use is being made of the dynamic range of the display device. This is done by taking the histogram of the image values, then spreading the range of values to match the range of the display device. This stretches (enhances) the contrast. Histogram equalization or modification involves the reassignment of image values in order to make the histogram approximate a desired shape. The shape is usually the uniform distribution, to use all display levels equally, but other shapes are used depending on the data and the desired image.

Most image processing algorithms are oriented for Cartesian coordinates, accessed by row-column or x,y indices. Many operations can be done first on rows, then on columns, because of the orthogonality of the axes. For radar, the natural orthogonal coordinates are range and bearing, Ro. If a row operation is applied to a scan-converted radar image, it impacts a different range at each bearing. However, if the image processing is applied before scan conversion, with the radar sweeps taken sequentially, a row operation corresponds to a range operation and a column operation corresponds to a bearing operation. Once the image processing is complete, the radar data can then be scan converted. Image processing operations used in this paper were applied to a radar image displayed in B-scan format (sequential sweeps
displayed on sequential lines), then the result was scan converted.

Another image improvement operation is signal integration for noise reduction. In the radar (and the sampling system) the noise on each sample is uncorrelated with that of the next. By the definition of radar resolution, (see /1/), a point target will produce an echo on each sweep of duration equal to the pulse length, for as many sweeps as occur within the beamwidth of the antenna. Therefore the sampled data can be smoothed for noise reduction by averaging the corresponding number of samples in range and bearing. Note that smoothing involving more samples could be used to simulate radars of lower resolution.

Keeping in mind the calibrated difficulties discussed in /1/, Figure 2 was converted to normalized radar cross-section. The resulting image is shown in Figure 3. This range normalization of the returned power is what the sensitivity time control (STC) of the radar display attempts to do.

Another radar display function normally available is some sort of high pass filter, the idea being to detect targets while adapting to the local noise level. This is the basis of constant-false-alarm-rate receivers. In the case of image processing, the local background level is estimated by creating a smoothed (low-pass) version of the image, and subtracting it from the original to leave the high-pass result. The resulting difference image is bipolar, and for display purposes a constant offset of half intensity is added. Figure 4 shows such an image based on Figure 2, with the smoothing done by averaging a 9 range by 9 sweep neighbourhood. Additionally as a form of image sharpening, the difference image can be added to the original, with the result shown in Figure 5.

Future analysis will include possible texture analysis for classification of surface roughness. There are some major obstacles. Feature classification based on synthetic aperture radar (SAR) has been fairly widely applied. SAR offers high resolution, typically 10-25 metres, independent of range; therefore many pixels per feature. The marine radar, as shown in this paper, has poorer resolution, which is range dependent, yielding relatively few samples per feature. Therefore, it is difficult to obtain sufficient samples for one type of texture to use to develop a texture classifying feature.
Almost every colour can be produced from red, green, and blue components; hence the use of red-green-blue (RGB) monitors for colour displays.

One problem in using colour is how to specify a given colour and how to control the RGB monitor to obtain a desired colour. This leads to the idea of colour space, in which colours are specified by coordinates. The obvious colour space is the RGB cube in which the red, green, and blue gun intensities are normalized from 0.0 (off) to 1.0 (fully on) to provide the axes. The drawback here is the difficulty of intuitively arriving at the RGB coordinates of a desired colour.

Subjectively, colour can be ascribed three properties: hue, saturation, and brightness. Hue distinguishes the basic colour, e.g. red from green and blue. Saturation refers to purity, that is, how little the colour is diluted by white, and determines how pastel or strong a colour appears. Brightness embodies intensity, such as in the gray scale. These three properties can be varied independently and are therefore used to determine a three-dimensional colour space.

For specifications of computer-generated colours, the HLS (hue, lightness, saturation) colour model was used in this work. The term intensity can be used synonymously with lightness. The colour model consists of a double cone, as shown in Figure 6, with intensity ranging vertically from 0.0 to 1.0, saturation radially from 0.0 to 1.0, and hue meridionally from 0° to 360° with blue at 0°. All colours are specified in HLS coordinates, which are software transformed to RGB values for use in the display colour tables.

There are two criteria which should be met by the colour tables: dark colours should be used for small data values so as not to draw undue attention to the background noise, and the error in mistaking one colour for another should be small in terms of the data values. Because each pixel corresponds to an individual radar resolution cell, the area of a given colour can be as small as one pixel, making the distinguishing between shades very difficult. For 8-bit data, 8–32 colours may be more practical than 256.

Grayscale is one dimensional, the axes of the HLS model, whereas colour is three dimensional. Therefore 256 points in 3-D colour space can be further separated (distinguished) than in 1-D grayscale, but the ordering of the points is lost. For grayscale
images, the brain subconsciously integrates the shading effects created with the direct sample-value-to-brightness relationship, giving a three-dimensional appearance to the display. With pseudo-colour, the brain does not do this subconscious integration. Thus grayscale and pseudo-colour radar image displays serve different but complementary purposes. Grayscale gives the operator a qualitative feel for the sea ice environment, similar to a PPI but with more dynamic range. Pseudo-colour allows the operator to make quantitative evaluations of the ice conditions since colour makes data value identification much easier. For example, Figure 7 shows a colour-coded version of Figure 2. Here, the operator can more easily determine the radar return level of various features. Colour can also be overlayed on the grayscale image for highlighting, e.g. to level slice the image as in Figure 8.

6 RADAR PARAMETER VARIATION

This section presents radar images for various operating parameters. The brightness and contrast of the images were adjusted to allow a fair comparison of the parameter change effects. Figures 9 and 10 show the Decca X-band radar, 9-foot antenna, on medium and short pulse length. The range resolution increases but the range of coverage decreases. Figure 11 shows the Decca X-band with the 4-foot antenna. Comparison with Figure 2 shows the decreased bearing resolution of the 4-foot antenna. Figure 12 shows the S-band radar image. This radar picks up the large discrete targets but lacks the "texture" of the X-band. The lack of detection of low-lying roughness in the southeast is evidence of the multipath phenomenon described in /1/. Even the modest antenna height variation performed in this experiment showed noticeable changes in the image. Figure 13 shows the image with the X-band 4-foot antenna at 135 feet above sea level (asl). Shadowy low relief areas at 120 feet (Figure 11) show more detail on the 135 foot image, indicating more power on the surface, as predicted in /1/. Figure 14 shows the image for the X-band 9-foot antenna at 95 feet asl. Note the marked increase in the berg radar shadow lengths, and the loss of detection of area roughness.

REFERENCE

1. Currie, B.W. et al., Effect of radar parameters on the ground-based radar return from landfast sea ice - I: Radial line analysis. The 7th Int. Conf. on Port and Ocean Engineering under Arctic Conditions (POAC). Helsinki, Finland, 1983.
Figure 1. Actual aerial photo mosaic was digitized in parts using TV camera digitizer, then scaled to match radar images.

Figure 2. Radar image with same feature number locations as figure 1. (Bright radial line is injected radar heading flash.)
HLS colour model.
Vertical dimension is lightness.
Central vertical axis is grayscale.
Figure 7
Example of colour-coded radar image.

Figure 8
Example of use of colour to level-slice a grayscale image.

colour slice level

Figure 9

Figure 10
Abstract

Full scale ice breaking trials of innovative vessel designs are an essential part of the development of commercial ice-going shipping capable of year-round operation in the Arctic. The ice breaker CANMAR KIGORIAK, designed by Dome Petroleum Ltd. of Calgary to support its Beaufort Sea oil exploration activities, was the object of an extensive program of full scale tests, spanning the winter of 1979-1980. The purpose of these tests was to measure the effectiveness of this vessel under the conditions that must be met by ships capable of year-round operations in the Arctic, with special emphasis on evaluating its unique design features and its structural response to ice loads in all modes of operation. The results of this program have been used to support Dome's continuing development of marine systems for use in the ice-covered waters of the Canadian Arctic.

The objectives of the shipboard instrumentation program for the Kigoriak's trials are presented, and the nature of the data collection problem is compared with other examples of experimental measurements involving extensive use of automatic instrumentation.

The analytical, technical and operational constraints upon the designer of instrumentation for icebreaker trials are developed, and summarized with emphasis on those that are unique to icebreaking operations and the Arctic environment.
The full scale test instrumentation for the kigoriak is described, outlining the overall approach to the measurement problem and particular responses to the various design constraints. The instrumentation system is discussed with reference to four basic classes of measurements: propulsion machinery output, ship motion, hull structural response and hull temperatures; and with reference to seven functional subsystems; transducers, analog recording and reproduction, digital real-time data processing and display, long term statistical recording, low speed data logging, closed circuit video recording and the timing and data annotation subsystems.

The operational experience with this instrumentation system is summarized and the validity of the original design approach is examined in the light of this experience. Several design principles for such instrumentation are suggested and the impact of rapidly advancing technology upon the problem is discussed.
INTRODUCTION

The Canmar Kigoriak is an icebreaking, anchor handling supply vessel of 7000 tonnes displacement, designed by Dome Petroleum Ltd. of Calgary to support the Company's Beaufort Sea marine drilling program. As discussed by Arno Keinonen in his paper (Ref. 1), also presented at this conference, the design of the Kigoriak is a unique one, incorporating many innovative features and departures from previous icebreaker design practice.

Concurrent with the design and construction of the vessel, which was initiated in late 1978, Dome also began planning a program of full scale research and development to be carried out with this ship during the first winter following its arrival in the Beaufort Sea. The purpose of this program was to determine the operational capabilities of the vessel and to provide data on the performance of its various special features that could be used to support the development of future designs for year-round operation in the Canadian Arctic.

Arctec Canada Ltd. was selected as a consultant to Dome Petroleum having overall responsibility for developing and implementing a research data collection system for the vessel in accordance with objectives and criteria set by the Dome project management team. Numerical work was carried out at Arctec during the early part of 1979 to determine the locations of strain gauges to be placed in the hull structure to measure its response to ice loads. Instrumentation work was initiated while the vessel was under construction at St. John Drydock Co. in St. John, New Brunswick. Cabling, engine room transducers, closed circuit video equipment, a suitable speed log for use in ice and much of the strain gauging was installed during the construction phase.
The vessel was delivered in August of 1979 and made its maiden voyage through the Northwest Passage to the Beaufort Sea in September of that year. Installation and commissioning of instrumentation continued throughout this voyage and in October of 1979, the ship was taken to the edge of the permanent polar pack near 72 degrees 30 minutes North Latitude and five days of ship testing and data collection were obtained, primarily in ramming operations in massive multi-year ice floes.

In December, following the conclusion of the 1979 late season drilling operations, final instrumentation installations were made on board the Kigoriak, including the installation and testing of a digital ship performance data logging system. In early January, 1980, the first winter test period of the ship, spanning some 17 days and including a navigation of some 160 nautical miles, was carried out. A second series of winter tests were carried out from late February until mid-March, and a final series of tests were conducted during the early breakout operations of the vessel between late May and mid-June.

During the testing, Arctec Canada Ltd. provided instrumentation engineering and technical support, while test management and ice data collection was carried out by Dome personnel. Software development were initiated at Arctec Canada Ltd. and continued by Dome during the course of the winter test program. Analysis of the test data was conducted by Dome personnel following completion of the tests.

2 MEASUREMENT OBJECTIVES

The purpose of the shipboard instrumentation system installed for the Kigoriak's full scale icebreaking trials was to provide an automatic means of recording the
large amount of information, available from measurements onboard the ship, required to evaluate the vessel's icebreaking performance and its structural response to ice loads, and to process and display a part of this information in real time. This data was supplemented with measurements collected by an on-ice team to characterize the size, geometry and strength of the ice features that the vessel was transiting. The output of the system was intended to support three categories of analysis.

2.1 Determination of Icebreaking Performance

Fundamental to this analysis are measurements of ship speed, developed shaft power, and the parameters of the controllable pitch propeller sufficient to estimate the developed thrust of the propulsion system. From these quantities, the speed-power and speed-resistance relationships may be determined for various ice conditions. In addition, time histories of the transient behavior of the propulsion system under ice-propeller interaction loads and manoeuvring loads were considered to be important to gaining an understanding of how the ice environment affects the ability of the propulsion to develop thrust.

In order to better control the testing of the vessel, it was recognized that it would be valuable to process as much of the ship performance data as possible in real time. It would then be possible to detect important anomalies or performance characteristics during the actual testing and thereby adapt the testing program to check or further study such effects while the opportunity was at hand.
2.2 Measurement of Structural Response to Ice Loads

A major objective of the program was to study the mechanical response to ice loads imposed, under various ice conditions and modes of operation, upon the hull, the propulsion system components and the steering gear. Two types of analysis of this data were envisioned; statistical treatment of the records to produce strain versus frequency histograms that would be useful in checking the adequacy of the design; and causal analysis of a series of events, for each of which the structural response, ship speed, and ice data are measured in order to detect any relationships that might exist between these variables.

It was also considered important to compare the response of different structural elements such as plating, frames, webs and stringers in highly loaded parts of the hull in order to gain an understanding of how loads are transmitted into the structure under various conditions.

2.3 Real Time Monitoring of Structural Response to Assess Operational Safety of the Vessel

Although closely related to item 2.2, above, it was considered an important objective of the instrumentation system design to provide for continuous real time indication of the levels of strain being experienced in certain highly loaded parts of the structure such as the stem waterline area, and vital parts of the ship's machinery such as the gearbox, propeller shaft and steering gear.
3 COMPARISON WITH OTHER EXPERIMENTAL MEASUREMENT PROBLEMS

A rough index of both the cost and the power of a data acquisition system is given by the product of the number of channels, the bandwidth per channel, and the maximum time window for uninterrupted data collection, provided by the system.

In order to control the cost of such systems, it is common to attempt to minimize as many of these three factors as is compatible with the experimental objective.

For example, in laboratory measurements it is often possible to fix many of the physical parameters affecting an experiment so that only one or a few quantities have to be measured to determine the outcome of the experiment.

By contrast, in a process control system, many tens or even hundreds of temperatures, pressures, flow rates, etc., may have to be monitored, essentially indefinitely. Fortunately, most industrial processes proceed slowly enough that only one, or a few, readings per channel per second is usually adequate to detect any important changes.

In the case of measuring the effects of shock loading of structures, such as military aircraft, both the total number of data channels and the required bandwidth per channel may be high but the data acquisition system need only store data spanning a relatively brief period of time if the triggering of the data collection can be synchronized with the application of the load.

An important problem for the designer of icebreaker trials instrumentation is the measurement of hull structural response to ice impact loads. A large number of strain gauge signals are frequently required to
monitor a complex icebreaker structure. The required bandwidth to resolve local response to ice impacts may be several to many tens of cycles per second, and it may be important to acquire data for hours or even days of operation in order to detect the extreme events of greatest interest.

4 DESIGN CONSIDERATIONS FOR FULL SCALE ICEBREAKER TEST INSTRUMENTATION

The constraints that must be satisfied in the design of test instrumentation for icebreaker full scale trials will usually include the following:

4.1 Adequate Channel Bandwidth

This constraint is most important to observe in the case of digital acquisition of strain gauge signals which are responding to hull-ice impact events. Until recently, digital processors fast enough to acquire such events continuously in real time on more than a few channels simultaneously were not available in configurations and at costs feasible for shipboard installations. For purposes of statistical treatment of multiple strain signals in real time by digital techniques, analog front end processors have been designed to detect and hold extrema of the analog waveform for counting by the processors. Such techniques, however, do not support detailed analysis of particular ice-impact events.

4.2 Adequate Time Windows for Various Types of Observations

For certain types of tests such as the recording of hull response during a ramming impact with an ice floe, a relatively short data acquisition window well localized in time can be defined. By contrast the statistical processing of data to determine the shape of amplitude-frequency characteristics of ice impact
response over a given ship mission profile may require continuous acquisition of data for many hours or even weeks of vessel operation. In each case, the recording/analysis equipment must be designed to have sufficient storage to receive the necessary volume of data and acceptable stability over the duration of the measurement.

4.3 Adequate Numbers of Channels on Common Time Base

where it is intended to analyze complex events in some detail, time histories of multiple channels of data may be required on a common time base. Sufficient channels to contain all signals essential to the analysis of the event must then be provided with an inter-channel time base error that is small compared to the period of the data's upper band edge frequency.

4.4 Verifiability of the Collected Data

Suitable facilities to control the quality of the data must include a proper means for frequently checking the calibration of all data channels, and wherever possible, multiple measurements of the same quantity by two or more independent systems, preferably utilizing different physical principles. Multiple measurements will rarely be possible for all quantities, but can be extremely valuable for important quantities such as ship speed and power. In addition, automatic annotation of the data and the ability to correlate the output of all recording systems in time can greatly assist in verifying and analysing the data.

4.5 Real Time Data Analysis and Display Capability

In order to support real time monitoring of critical or highly loaded parts of the structure for response
approaching unsafe regimes, and for detection of test results that can be used as feedback to help guide and adapt the testing procedure so as to enhance the quality of the collected data, it is very useful to have the capability to present at least certain key measurements scaled in engineering units, or plotted graphically in real time.

4.6 System Flexibility

Because the prevailing ice conditions largely determine the types of testing that can be carried out as well as the amplitude, frequency and location of ice loads and thus, the characteristics of the various signals and the combinations of channels on which useful data will appear, and because it is frequently difficult to predict the ice conditions that the ship will encounter more than a few hours in advance, it is important that the instrumentation can be readily configured to properly record whatever information of value the ship is able to generate at any point in its deployment. This means that the allocation of channels to various recording devices and the ranging, filtering, and calibration of such channels be readily selectable. The alternative would be to provide a complete measurement/acquisition chain for each type of test that involves a unique combination of data channels.

4.7 System Reliability

Lastly, overall system reliability is a primary concern in such testing. Because of the very high cost of the vessel's deployment, it is of great importance that this time be efficiently utilized gathering the desired data. Also, the remote locations in which such tests are frequently done may preclude the timely replacement of a failed piece of equipment. Even if the time to replace
such equipment is as little as a day, the cost in lost ship's time for data collection could be large compared with the cost of duplicating major parts of the instrumentation system.

An important part of system reliability is the ability to 'degrade gracefully' rather than 'fail catastrophically'. In a large data acquisition system of one hundred or more channels, the loss of several channels will usually not significantly reduce the value of the collected data, and the loss of even a high percentage of these may still permit the acquisition of much valuable data while the remainder of the system is being restored to serviceable condition. For this reason, splitting the workload at all levels of processing of the incoming data amongst multiple identical units has much to recommend it.

5 THE KIGORIAK INSTRUMENTATION SYSTEM

The instrumentation system installed onboard the Kigoriak for its 1979-1980 winter trials comprised some 120 signals available for input to six different data recording and display systems (Ref. 2). Figure 1 indicates the locations of the major categories of transducers. The location of the ship's instrumentation room is also shown. All of the data recording and display equipment was situated in this room, immediately beneath the ship's bridge. During controlled tests, the system was operated from this location by two members of the test team. For monitoring of general navigation, ship performance and hull strain data could be collected for long periods of time with only occasional operator intervention to replenish recording media. Audio communication to test personnel on the bridge and on the ice was provided using VHF walkie talkies.
5.1 Ship Power and Motion Measurement System

In Figure 2, the instrumentation sub-system used to measure the Kigoriak's icebreaking performance, and to store the data from which the vessel's powering and resistance characteristics were subsequently obtained, is represented schematically. The signals processed as part of this system are listed in Table 1. These include signals that determine the output of the propulsion system and those that define the state of motion of the vessel.

5.1.1 Propulsion Machinery and Steering Gear Measurements

The propulsion system of the Kigoriak consists of a single, ducted, controllable pitch propeller driven through a reduction gear by two medium speed diesel engines. Steering is provided by a single rudder centred in the slipstream of the propeller. To monitor the outputs of this plant, thirteen signals were available.

The propeller shaft torque and thrust were measured with strain gauge bridges installed on the intermediate shaft aft of the main reduction gear. These signals were telemetered from the shafting as FM signals, then demodulated and transmitted by cable to the instrument room as analog data with a measurement bandwidth of 900 Hz.

Magnetic proximity switch pickups were used to sense the rotational speed of the intermediate propeller shaft and the engine output shafts. The pulse train outputs of these pickups were conditioned in frequency-to-voltage circuitry to provide analog data signals with an effective bandwidth of 5 Hz.
A signal proportional to the pitch angle of the c.p. propeller blades is available as a mechanical displacement of a feedback linkage connecting the main hydraulic cylinder in the hub with the oil distribution box from which actuation of the c.p. mechanism is controlled. This displacement is converted to an analog electrical signal by a potentiometer in the o.d. box and is made available to both the ship's electronic control system and to the data recording instrumentation. In addition, a strain gauge type pressure transducer was provided to measure the oil pressure in the supply to the pitch actuation mechanism.

The instantaneous positions of the fuel racks on the two diesel engines were measured with linear variable differential transformer displacement transducers. These provided highly stable position indication with a measurement bandwidth of 250 Hz.

The bridge telegraph order was also available for recording as a pickoff from the ship's control electronics, while the angular position of the rudder was measured with a potentiometer driven by the movement of one of the linkages in the steering hydraulic control system.

The telegraph order and rudder position were normally set at the direction of the test manager according to the type of test being performed, but were monitored automatically to allow the data analysts to verify that the specified settings were indeed obtained for any given test.

5.1.2 Ship Motion Measurements

Ship motions were measured both with a navigation speed log and with accelerometer instrumentation. The object
of the former was to provide the basic output for ship performance measurement while the purpose of the latter was to provide information on the nature and magnitude of vessel rigid body motions in ice impact events such as occur in ramming manoeuvres.

Ship speed was measured with a doppler microwave speed log of a type that has been developed especially for use on ice-going vessels in the Baltic. When properly installed and calibrated, this log was found to give reliable and accurate data for all ship speeds above approximately 1.5 knots in continuous motion in an unbroken ice sheet. This greatly simplifies the procedures for carrying out ice breaking performance tests. In certain areas where testing was carried out, it was also possible to make use of a shore-based precise radio positioning system of the microwave tellurometer type. This system provided ship speed, heading and position at frequent intervals.

For purposes of calibration and checking of the speed log, and to measure low speeds at which the log was not reliable, two additional methods were used. Timed visual observations of the vessel's transit of a known length indicated by markers along its bulwarks, and timing of motions in the field of a calibrated video display were made manually.

In order to measure the strong rigid body motions associated with impact of the vessel with unbroken ice in ramming operations, accelerometer instrumentation was installed. Near the ship's centre of gravity, a two-axis gyro-stabilized accelerometer platform was located. This unit measured the three orthogonal components of the acceleration of the C of G in a reference frame fixed with respect to gravitational vertical. In addition, signals proportional to the instantaneous pitch and roll
angles were available from this platform.

In the forepeak, just aft of the stem waterline, three uniaxial ship-fixed accelerometers were located. These were oriented to measure accelerations in the longitudinal, transverse, and vertical ship directions. Their purpose was to contribute additional information to help determine the rotational components of the rigid body motion of the vessel by detecting high amplitude motions at a point far from the centre of rotation.

3.1.3 Digital, Real Time, Vessel Performance Data Logging

Any combination of the twenty signals listed in Table 1 could be fed to the analog instrumentation tape recording system used to store strain gauge data. Because of the important wide band information related to transient ice impact loads contained in the outputs of the accelerometer signals, these were normally recorded on tape with a bandwidth of DC to 300 Hz.

For purposes of measuring vessel performance, however, the first eight signals in Table 1 were fed through 0.5 Hz low pass anti-aliasing filters to a digital data logging/processing system based upon Hewlett Packard's model 9845 desk top computer.

Because the filtered shaft torque and thrust waveforms are essential to ship performance and resistance analysis, while the unfiltered waveforms contain important information regarding transient ice-propeller impact loads, these two signals were normally recorded simultaneously both in the digital data logging system and, wide band, on analog tape.

The digital measurement system consisted of a programmable scanning multiplexer and a high speed
A digital voltmeter, both capable of being controlled, via an IEEE 488 instrument bus, by real time software running in the 9845. Timed interrupts, generated by a hardware real time clock, produced an end-of-line branch to the instrument control routine every 250 ms. Within this routine, a burst of eight readings, 1 ms between successive channels, was input to the 9845 from the voltmeter. The voltage readings were processed to remove offsets and to correct for certain transducer non-idealities present on the ship speed and shaft thrust signals. All signals were then scaled in engineering units using a table of calibration factors stored in the routine, and the total shaft power was computed from the shaft torque and shaft speed readings. All of the measured values, plus the calculated power, were summed into accumulators for the purpose of building averages of each quantity and the processor would then go into an idle state to await the next interrupt.

Upon entering the real time routine, the operator could specify the number of successive scans to be averaged. The system was designed to sample the data continuously at four scans per second, accumulating engineering unit averages for the specified number of scans, then displaying them as a line of output in a tabular form as they were completed. With the use of program defined soft keys, the operator could at any point re-set the number of scans to be averaged, insert test titles into the display form, re-direct the display form to the CRT screen or to the computer's built-in high speed printer, or cause the displayed information to be copied onto 8 inch flexible disk media to form a permanent machine readable record of a test. At the end of a test, when logging of data into a disk file was halted, a set of global averages of all the records written to disk for that test would then be printed in a test summary line.
If high speed data logging was required, the user was able to request signal averages consisting of only one scan. This would result in four lines of output being printed and four records being written to disk every second and this could be sustained indefinitely, limited only by the available form in the printer and storage space on the disk. This time resolution was found useful in logging the deceleration of the vessel in ridge ramming events, and the changes in propulsion output during propellor pitch reversal.

The principal advantages of this system were twofold. The ship's speed-power relationship could be determined immediately in engineering units by conducting tests at successive power levels in a given thickness of level ice. Any anomalies in the resulting characteristic curve would then be noted as they occurred and could be checked, if necessary, by repeating the test.

Secondly, all of the test data were stored in machine readable form, scaled in engineering units. Subsequent analysis to determine the dimensionless propulsion coefficients, the ship resistance, and to analyze the large amount of transient data for vessel performance in ramming, were transformed from laborious manual procedures into automatic procedures carried out in specially developed software.

5.2 Strain Gauge Measurement System

The measurement system used for recording, reproduction and display of strain guage data is shown in the block diagram of Figure 3. Two separate recording and display sub-systems were used; one comprising 52 channels of data recording on analog magnetic tape, the other consisting of ten single channel micro-processor based histogram recorders.
5.2.1 Strain Gauge Signals

Of the 120 signals available within the instrumentation package, 90 were strain gauge signals. Sixty different locations within the structure were instrumented for strain measurements. Most measurements were of bending strains measured on the flange tops of frames or stringers in the forebody. For this application, temperature-compensated half bridges consisting of two active foil adhesive gauges were used. These were mounted at right angles to each other and measured the bending strain with an effective number of active arms equal to one plus Poisson's ratio.

For determination of the biaxial state of stress in the shell plating in the forebody, and in bulkheads and plates within the kort nozzle foundation structure, rosettes consisting of three independent strain gauge half bridges were used. In this case, the half bridges consisted of one active gauge and one 'dummy' gauge for temperature compensation, the dummy gauge being mounted in thermal contact with the specimen, but in such a way that no strain was transmitted to the gauge.

Most of the gauges were installed in dry void tanks, though a number of the rosettes on the kort nozzle foundation structure had to be located within a ballast space and were thus, subject to immersion in salt water. All gauges, however, were installed and protected for immersion in water.

In addition to the strain gauges on hull structural members, a strain gauge torsion bridge was mounted on the rudder stock beneath the steering yoke. The output provided data on the loads transmitted to the steering gear as a result of hydrodynamic and ice impact forces acting on the blade of the rudder.
To monitor the stresses experienced in the main reduction gear, this unit was procured with a tooth root stress monitoring system supplied by the manufacturer. This system uses strain gauges to monitor the stresses on four of the gear teeth on the bull wheel. These are inductively transmitted from the rotating piece and are continuously processed by an alarm and display unit. The analog waveform from this system was conditioned and made available as an output to the data recording instrumentation.

All strain gauge signal conditioning, with the exception of that for the gear tooth stress monitoring system and the shaft torque and thrust measuring systems, was centrally located in the ship's instrument room. Bridge excitation and signal connections between the strain gauges and the signal conditioning were made via individually-shielded conductor triplets installed as far as practicable in continuous runs.

5.2.2 Analog Recording and Reproduction System

The primary data storage system used for strain gauge and other wide band signals, such as the accelerometer outputs, consisted of two 28 channel, IRIG compatible, instrumentation tape recorders. On each machine, two channels were allocated for the recording of timing information. The remaining 52 channels were configured for frequency modulation recording of analog data. This system offered the advantage of providing economical storage of a large number of channels of data on a common time base, at a bandwidth of at least DC to 300 Hz per channel, and was capable of accepting this data flow for relatively long scans of time.

For each distinct type of ship test, an appropriate combination of 52 signals were selected from the
available schedule of some 116 analog data lines available in the ship's instrument room. Certain important signals such as ship speed and shaft torque were always recorded on one of the machines. Other channels were allocated to record combinations of signals that depended upon the mode of operation of the vessel. In tests in ahead operation, many data channels were allocated to strain gauge signals in the forebody and relatively few to those in the stern area. In certain ramming tests, fewer strain gauge signals were recorded and channels were allocated to accelerometer signals instead. In general, each recording system configuration was selected to provide data in support of a particular set of experimental objectives related to the type of ship testing for which it was used.

In order to reproduce and display the waveforms of selected signals being recorded on tape, 28 channels of data reproduce electronics were installed. These could be configured to permit reproduction of any group of fourteen channels on either tape recorder in either real time (i.e. while recording) or in play back. The reproduced analog signals were displayed on an 18 channel CRT oscillograph recorder together with the timing information. In this way, the amplitude of impact peaks in key strain gauge waveforms could be monitored while testing was in progress, and the wide band variation in the shaft torque, shaft thrust, and rudder stock torque signals could be observed.

By operating the oscillograph recorder at slow paper rates, a compact record of a large span of data could be created on which significant events could be readily identified. These individual events could then be analyzed in detail by reproducing the appropriate segments of tape in a second pass, displaying selected channels with optimal gains and paper speeds to yield an
easily interpreted record.

Following completion of the Kigoriak tests, the analog data tapes, together with the manually generated calibration tables and channel assignment logs, formed the core of the test data archive. These tapes were further processed by reproducing selected channels and events into analog to digital conversion equipment and transmitting the data into a digital computer system. In this environment, digital signal processing and statistical analysis tools could then be applied to the data.

A further important use of these tapes was to provide realistic 'live data' for the development and testing of real time digital computer software intended for subsequent ship board data collection programs.

5.2.3 Digital Histogram Processor/Recorders

A useful analysis to perform on strain gauge data from a structure experiencing random dynamic loading is to obtain the strain amplitude-frequency distribution. This can then be used, either to estimate long term extreme response by extrapolation of this distribution, or to estimate the service life of the structure by applying materials test data to the distribution to calculate accumulated damage as a fraction of that required to initiate failure.

For the Kigoriak test program, ten single channel histogram recorders were installed, capable of counting and accumulating frequency-amplitude statistics on strain gauge waveforms in real time. Ten key strain gauge signals were identified, representative of various parts of the structure, and were fed to these recorders for processing throughout the Kigoriak tests.
Each recorder consisted of a strain gauge signal conditioner, an analog-to-digital converter which sampled the output of the signal conditioner at a maximum of 800 readings per second, and a microprocessor. The software counting routine was contained in a plug in read-only-memory (ROM) module. Several different statistical counting programs were available in this format. The routine selected for most of the statistical recording on Kigoriak was based upon the so-called 'real time rainflow' algorithm. This routine partitions the processor's read/write memory into a two dimensional array. Each time the software detects a complete cycle of the input strain waveform, a memory cell in the array is incremented that corresponds to the range and mean of the detected strain variation. Strain cycles having a range less than a user-selected hysteresis setting are not counted. The unit is capable of continuous, unattended operation for up to three months. As many as 65280 counts can be accumulated in each cell of a 32 x 32 band histogram.

During the ship's deployment for icebreaking tests, the current histogram in each processor's memory was read out onto a printing data terminal in tabular form at the end of each test day. The operator then had the option of continuing the counting of the histogram or of clearing the memory and beginning a new histogram.

Software was developed for the HP9845 computer to provide for the permanent storage and retrieval of the histogram data on flexible disk, and for the display of the data using the 9845's graphics capabilities.

5.3 HULL TEMPERATURE MEASUREMENT SYSTEM

The hull temperature measurement system is shown in Figure 4. In order to measure the range of temperatures
to which the structural steel of the vessel is exposed during the course of operations throughout an Arctic winter, two arrays of temperature transducers were located in unheated forebody spaces. Within one of the port forward water ballast tanks, seven transducers were mounted in a vertical line on the side shell at various distances from the waterline. Another array of five transducers was located in one of the forebody dry void tanks, similarly distributed with respect to the waterline. The temperature sensors used were thermistor-based thermilinear networks providing an output voltage linear with temperature over the range -50 to +50 C.

Excitation and signal transmission for these transducers was provided using the same type of shielded multi-core cable as was used for the strain gauge signals. Excitation was from DC supplies, and data readout was on low speed printing data loggers, all centrally located in the ship's instrument room.

5.4 VIDEO IMAGING SYSTEM

Figure 5 is a block diagram of the Kigoriak's video recording system. Four low light level monochrome TV cameras were installed to provide visual documentation of the ice conditions in which the vessel was operated during testing. Three of these were fitted in environmental housings equipped with heaters and remotely operated wipers to keep the viewing plates free of snow and ice. The most frequently used image was obtained from one of these mounted looking forward from the bridge top, providing a view of the ice cover extending from the ship's bow to the horizon.

The second unit was mounted over the port side bulwarks looking down at the point where Kigoriak's side reamer
meets the waterline. Flood lamps were installed to illuminate this area so that the passage of broken ice around the reamer could be observed. With this image it was possible both to estimate the ice thickness when blocks were turned up on edge in the field of view of the camera, and to gauge the speed of the vessel by timing the passage of ice features across the picture.

A third television camera, also mounted in an environmental housing, was installed on the bow bulwark on the ship's forecastle deck. It provided a more detailed image of the ice features immediately in front of the ship's bows than could be obtained from the much higher forward looking camera on the bridge top. On one occasion this third unit was moved to a mounting on a welded steel frame extending out over the bow, and oriented so that it could provide a picture of the stem waterline area and thereby image the icebreaking pattern across the bow as well as the action of the Kigoriak's hull water lubrication system.

The fourth television camera was mounted in one of the windows of the starboard wing of the bridge and provided an aftward view over the ship's cargo deck and the broken track astern to the horizon.

The video recording equipment consisted of four time lapse helical scan video tape recorders, each equipped with its own date and time generator which wrote timing annotation onto the recorded image. Any one of a number of recording speeds from approximately 30 frames per second down to one frame every four seconds could be selected on each unit. By selecting a low recording speed up to 108 hours of data could be recorded on a single 2400 foot reel of tape and this could later be viewed in as little as one hour. At higher recording speeds, it was also possible to annotate the tape with
the test manager's voice via a microphone installed on the bridge.

Of the four VTR's, three were used to record the fore, aft and over the side low light camera images. The fourth was used to record either the image from the bow bulwark mounted camera or the video display information from the ship's dual channel satellite navigator.

6 OPERATIONAL EXPERIENCE WITH THE KIGORIAK INSTRUMENTATION

The design of the data acquisition system for the Kigoriak's icebreaking trials was based upon a division of tasks between analog and digital instrumentation.

Bulk acquisition and storage of multi-channel, wide band data was handled using powerful analog equipment capable of accepting a very high data rate on a quasi-continuous basis.

Real time reduction and processing of a limited amount of particularly important data was performed using digital techniques.

Each system presented its own combination of advantages and drawbacks.

The principle disadvantages of the analog instrumentation were two fold. The set up, calibration, and maintenance of this equipment imposed a large ongoing workload on the limited available manpower during testing. Secondly, the extensive analog tape records that were obtained proved to be expensive and time consuming to reproduce and analyse compared with the digital data stored in engineering units representation.
In compensation, however, the analog recordings provided some of the most valuable information obtained from the tests. The capability to continuously record many channels of data at bandwidths sufficient to resolve fast transients permitted the capture of numerous important events that would not otherwise have been detected.

To have provided the same capability to store multi-channel transient data in an all-digital system would have been many times more expensive in the 1979-80 state of the art.

Unlike the analog equipment, the digital instrumentation required relatively little set up or maintenance. This was partially offset by the major initial effort required to develop appropriate software. As the software was put in place, however, the power of real time digital techniques for processing vessel propulsion and motion data quickly became apparent.

The printed HP9845 ship performance data log provided invaluable documentation of each ship test, while greatly reducing the requirements for manual record keeping and enhancing the uniformity and reliability of the data. Annotated with timing information to the nearest second, it served as an index, not only to the data stored on the digital media, but also to that stored on the analog tapes which were similarly time stamped.

The ability to view the results of the performance testing in engineering units in real time also contributed to the prompt identification of instrumentation system problems, and to improvements in testing procedures.

In a similar way, the CRT oscillograph unit proved both reliable and extremely useful as a means of verifying the
quality of the signals being stored on the analog tapes.

Because of the limited size of the test team and the relatively high workload during testing, the decision to centralize as much of the instrumentation as possible in a single location was seen to have been appropriate. While use of distributed strain gauge signal conditioning placed as near to the gauges as possible can result in significant reductions in signal noise from EMI and RFI sources, this must be weighed carefully against the extreme difficulty of maintaining such instrumentation during vessel deployment.

Finally, the overall flexibility of the system proved valuable on two counts, firstly, in allowing for rapid re-configuration for different types of ship tests, and secondly, to permit re-configuration to minimize the impact of the failure of any system component upon the value of the data being acquired. The use of multiple identical pieces of equipment, as in the case of the two 28 channel tape recorders, also contributed to the field maintainability of the system due to the interchangeability of parts.

SUMMARY AND CONCLUSIONS

Careful matching of instrumentation characteristics to various data acquisition and processing tasks must be the chief concern of the designer of large scale automatic data collection systems of the type required for full scale icebreaking tests.

Currently available micro-computing systems are highly suited to real time processing of powering and motion data for icebreaker performance measurement. The only factor significantly limiting this application appears to be the cost of software development which must be
justified in each case for only one or a few major projects.

Processing of a limited number of channels of strain gauge data from hulls subject to impact loading can also be handled by micro-processor based systems if nothing more than a statistical summary of the data is required as the output and the appropriate processing algorithm can be specified beforehand.

Until recently, however, continuous digital recording of very large numbers of channels of strain waveform data with sufficient bandwidth to reproduce mechanical impacts of the type experienced by icebreaker hulls has not been cost competitive with analog recording.

With the advent of very high speed 16 and 32 bit processors (Ref. 3) this situation is now changing. Some of these new processors have sufficient computational throughput to continuously acquire and inspect vast numbers of data points per unit time, and to recognize and store waveform segments containing important information.

Such processors should speed the development of very powerful multi-channel transient recording systems suitable for field measurement of structural response data.
FIG. 2. SHIP POWER AND MOTION MEASUREMENT SYSTEM.
FIG. 3. STRAIN GAUGE MEASUREMENT SYSTEM.
FIG. 4. HULL TEMPERATURE MEASUREMENT SYSTEM.

FIG. 5. VIDEO RECORDING SYSTEM.
<table>
<thead>
<tr>
<th></th>
<th>Ship Propulsion &amp; Motion Signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Ship Speed (Microwave Log)</td>
</tr>
<tr>
<td>2.</td>
<td>Shaft Torque</td>
</tr>
<tr>
<td>3.</td>
<td>Shaft Thrust</td>
</tr>
<tr>
<td>4.</td>
<td>Shaft Speed</td>
</tr>
<tr>
<td>5.</td>
<td>Propeller Pitch</td>
</tr>
<tr>
<td>6.</td>
<td>Port Engine Fuel Rack</td>
</tr>
<tr>
<td>7.</td>
<td>Starboard Engine Fuel Rack</td>
</tr>
<tr>
<td>8.</td>
<td>Rudder Angle</td>
</tr>
<tr>
<td>10.</td>
<td>Port Engine Speed</td>
</tr>
<tr>
<td>11.</td>
<td>Starboard Engine Speed</td>
</tr>
<tr>
<td>12.</td>
<td>Telegraph Order</td>
</tr>
<tr>
<td>13.</td>
<td>C of G Surge (Accelerometer)</td>
</tr>
<tr>
<td>14.</td>
<td>C of G Sway (Accelerometer)</td>
</tr>
<tr>
<td>15.</td>
<td>C of G Heave (Accelerometer)</td>
</tr>
<tr>
<td>16.</td>
<td>C of G Pitch (Gyro Tilt)</td>
</tr>
<tr>
<td>17.</td>
<td>C of G Roll (Gyro Tilt)</td>
</tr>
<tr>
<td>18.</td>
<td>Bow Surge (Accelerometer)</td>
</tr>
<tr>
<td>20.</td>
<td>Bow Heave (Accelerometer)</td>
</tr>
</tbody>
</table>
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Lennart Fransson, Research Engineer
Div of Structural Engineering
University of Luleå
Luleå, Sweden

ICE FORCE MEASUREMENTS ON A BRIDGE PIER IN THE LULE RIVER

Abstract

Ice pressure has been measured in four directions around a bridge pier in the Lule River during the winter of 1981/82. Ice pressure and temperature were recorded every hour and the ice thickness was observed in drilled holes. A maximum pressure of 200 kPa and a lowest air temperature of -33°C were found during the winter. The ice thickness was increasing to 1.90 m close to the pier in the end of March compared with 0.35 m beside the bridge.

Measured ice pressure is assumed to be mainly caused by thermal expansion. A function is presented which makes it possible to calculate the ice pressure if the rate of change of temperature in the ice is known. Effects of changes in the water level are also discussed.

1 INTRODUCTION

The development of hydro power in the Lule River has partly changed the ice conditions. Shore cracks, flooded water and flooded ice, caused by large water level variations, have become common. There are also reasons to expect increasing ice forces on structures such as bridge piers.
An investigation was started in order to make comparisons between ice loads on structures where the water level is constant during the winter and ice loads in a river developed with hydro power /1/.

2 ICE CONDITIONS IN THE LULE RIVER

Ice thickness

In the middle of December the ice cover was thick enough for our gages which means 0.30 to 0.40 m close to the bridge pier. Changes in the water level caused rapid growth of the ice under the bridge. In the end of the winter the ice thickness reached 1.90 m compared with 0.35 m beside the bridge.

Fig. 1. Ice conditions close to the bridge over The Lule River (Day no.22).
Fig. 2. Section showing ice growth between pier no. 1 and the shore.
The ice thickness shown in fig 2 was observed in drilled holes with a distance of 2 metres.

Cracks

Day no. 352-355 the water level dropped 0.70 m. When the level rose (day no. 8) large cracks occurred around all the piers and along the shore. Fig no. 1 shows these cracks and the flooded ice close to the pier.

Fig. 3. Water level versus time upstream the bridge.

Ice Displacements

The positions of targets on the ice cover were determined with a theodolite standing on the shore. The vertical displacements, $z$, show the level of the primary ice.
Fig. 4. Vertical displacement of the ice cover.

Fig. 5. Horizontal displacement of the ice cover.

Fig. 6. Pier displacements versus time.
**Pier Displacements**

With the same method as above, the pier displacement at a point, showed in fig 6, was measured. The stiffness of the pier is mostly depending on the piled foundation and could be determined theoretically and experimentally. The drawbacks are that the displacements are small and the effects of thermal expansion of the construction are hard to separate from the ice load.

**3 MEASUREMENTS OF ICE PRESSURES**

**Instrumental set up**

Ice pressures were measured in four directions around the bridge pier marked no. 1 in fig 1. Oil filled transducers with a diameter of 300 mm were placed in 6·ts in the ice approximately 3.0 metres from the pier. The transducers were originally embedded 24 cm below the ice surface, but when the ice was growing the depth to the ganges gradually became deeper and reached 0.8-1.0 m in the end of the winter. The temperature at the center of each transducer and the air-temperature were recorded with copper-constantan thermoelements.

**Results**

Temperatures and pressures were recorded every hours. An example of these tapes are shown in fig 7 and 8 where the gauges were placed upstream the bridge pier.
Fig. 7. Recorded ice temperature close to a bridge pier in the Lule River 1982.

Fig. 8. Recorded ice pressure close to a bridge pier in the Lule River 1982.
Fig. 9. Showing the regression line of the measured ice temperature.

Fig. 10. Showing measured and calculated ice pressure (smooth curve=calculated)
Empirical formula

Under the following circumstances ice pressure may be satisfactory represented with the used transducer:
- small rates of increase of the ice temperature
- ice temperatures close to the freezing point
- long term loads.

If the recorded pressure is assumed to correspond with the termal expansion the rate of change of pressure can be calculated as

\[ \dot{p}(\theta) = a \dot{\theta} - b p^c \]  

(1)

where \( p \) = current pressure
\( \dot{\theta} \) = ice temperature
\( a = b = c = \text{const} \)

Eq (1) is written on difference form as

\[ P_{k+1} = P_k + a \Delta t \dot{\theta}_k - b \Delta t p_k^c \]  

(2)

where \( P_k \) = pressure at \( t=k\Delta t \)
\( P_{k+1} \) = pressure at \( t+\Delta t = (k+1) \Delta t \)
\( \dot{\theta}_k \) = rate of change of ice temp at \( t=k\Delta t \)

At day 12 flooded water, slowly warmed the ice cover between the bridge pier and the shore. In fig 9 measured ice temperatures 3 m from the pier towards the shore were replaced with spline functions and its time derivate. With this input the ice pressure has been calculated according to eq (2). The time step was 1 hours and the constants \( a, b \) and \( c \) were determined by curve fitting. The obtained values were
\[ a = 45 \text{kPa/°C} \]
\[ b = 2 \cdot 10^{-4} \text{kPa}^{-1} \text{°C/tim} \]
\[ c = 1.8 \]

The results are shown in fig 10.

4 DISCUSSION

Embedded oil filled transducers have turned out to be temperature dependent due to oil expansion /2/. Some efforts have been made to estimate the magnitude of this overloading in the ice cover and in casted specimen in the laboratory /3/. Uniaxial tests have indicated decreasing consequences at small rates of temperature changes in the ice. However, these results are very uncertain, mainly because of influences of nonconstant applied load.

As seen in fig 9 there is a time difference between calculated and measured ice pressure when it starts to raise. This can be explained by the fact that the ice near the gages was warmed by flooded water while the rest of the ice cover still was cold. And later when the flooded water covered the whole area the pressure increased.

So far the nature of the investigation has been "trial and error". Increasing ice thickness and repeated temperature loads caused by flooded water can be mentioned as negative effects of the water level variation. But still quite too few ice force measurements have been carried out to make conclusions about the design loads.
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J.R. Hawkins, D.A. James, C.Y. Der
Research Department, Esso Resources Canada Limited
Calgary, Alberta, Canada

DESIGN, CONSTRUCTION AND INSTALLATION OF A SYSTEM TO MEASURE ENVIRONMENTAL FORCES ON A CAISSON RETAINED ISLAND

Abstract

In the late summer of 1983, Esso Resources plans to install a Caisson Retained island (CRI) on a dredged berm in the Canadian Beaufort Sea. The performance of this caisson will be monitored by a suite of instruments on the caisson face, bottom, and inner walls: on key structural members: in the sand fill, berm, and seabed: and in the surrounding ice sheet, ice rubble, or waves. The design of this instrumentation and the associated data collection system is described in this paper.

1 INTRODUCTION

In the last twelve years, exploration for hydrocarbons in the Canadian Beaufort Sea has been conducted either from drillships, operating during the open water season in water depths greater than 30 m, or from artificial islands, constructed during the open water season and drilled during the winter in water depths less than 30 m. Exploration in water depths between 15 and 35 meters, in the western half of the Canadian Beaufort Sea where good sandfill is scarce, has prompted the construction of a new generation of drilling system -- the caisson island.

Canmar, Gulf, and Esso have all built caissons for Arctic use. Esso's has eight steel units, which can be strung together in a ring. The ring is filled with dredged sand to create a working surface. Details of construction and operation are described by Comyn 12/. Although these caisson structures were thoroughly tested and conservatively designed, all Beaufort Sea operators installed comprehensive instrumentation systems to measure the environmental forces on the caissons, record them, and sound alarms if warranted. This paper describes the philosophy behind, and the design of, the instrumentation system for Esso Resources' Caisson Retained Island.
1.1 CRI Locations

Two of the CRI wells shown in Figure 1 are in the western Beaufort, where subsea soil conditions are generally poor. The top 20 m of the seabottom is made up of layers of soft clays and sandy clays, which have shear strengths ranging from 10 kPa to 120 kPa, so that the berm designs require allowance for 5% to 10% settlement during a year.

The nearest site of good quality sand is 75 km away at Ukalerk. When the berm material is dredged and dumped, most of the silt (D < 0.075 mm) is removed with the result that the sand in place has a D_{10} of 0.15 mm and a permeability greater than 10^{-2} cm/s.

Early winter storms, with winds up to 80 km/h, will typically drive 200 to 300 km of first-year ice past these locations. By the end of December, the landfast ice reaches out to the 20 m isobath. Except for a few rare exceptions /4/, ice movement is then restricted to tens of metres until breakup in late June.

Significant wave heights at Kadluk and Minuk are limited by the water depth to 7.1 m. Currents in the area are low, less than 2 km/h. They are primarily wind driven, but are influenced by the Mackenzie River outflow /1/.

1.2 Description of the Caisson Retained Island

Esso’s Caisson Retained Island, shown schematically in Figures 2 and 3, is described in detail by Comyn /2/. Structurally the caissons are designed to resist global ice loads of 1700 kPa and local ice loads of 4800 kPa. The caissons will withstand the impact pressures from peak waves up to 10 m high without
damage. The caisson ring is also strong enough to withstand severe undermining. Once the ring is ballasted onto the berm, a single completely undermined caisson can be entirely supported by the two adjacent caissons.

2  OBJECTIVES OF THE INSTRUMENTATION PROJECT

Despite a confidence in the CRI design based on extensive testing and Arctic experience, this was to be Esso's first steel structure in the Beaufort, so it was important to thoroughly record the caisson's response to environmental forces in the fill, the berm, the seabed, and the surrounding ice and wave environment. Our overall objectives were threefold:

1. Safety - to provide early warning of approach to any design conditions
2. Design Optimization - to gather data necessary for the design of safe, cost-effective production facilities
3. Field Experimental Verifications - to use the island as a research platform from which we could conduct a number of different studies.

2.1 Safety

Although the caisson was designed to resist the environmental forces as we understand them, there is always the remote possibility that many factors could coincidentally conspire to produce loads on the caisson which approach design conditions.
We wanted to have warning in the event that any of the measured parameters exceeded 60% of the design value. This would give us time to take whatever corrective action is warranted. For example, increasing ice stresses on the caisson face could be countered by artificially building up more ice on the rubble or by cutting slots in the ice sheet. The most likely failure, however, is slight, repairable damage to the caisson skin caused by high local ice forces. Advance warning of such an event would enable us to secure any pumps or instruments within the caisson and/or relieve the excess stress in the ice.

2.2 Design Optimization

Earlier exploration structures, like sacrificial beach islands or sandbag-retained islands, were purposely designed to be temporary. However, caisson islands are clearly the precursors to offshore production platforms, and information from the caisson instrumentation systems will be invaluable in optimizing their design. The following table illustrates some of the measurements which will be used to improve the design criteria for future permanent structures.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Potential Design Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Ice Forces</td>
<td>Increase frame &amp; stringer spacing</td>
</tr>
<tr>
<td>Local Ice Forces</td>
<td>Decrease skin plate thickness</td>
</tr>
<tr>
<td>Wave Height</td>
<td>Reduce erosion protection size</td>
</tr>
<tr>
<td>Soil Pore Pressures</td>
<td>Reduce minimum quality sand fill</td>
</tr>
<tr>
<td>Soil Temperature Profiles</td>
<td>Reduce flowline burial depth</td>
</tr>
<tr>
<td>Foundation Settlement</td>
<td>Modify foundation treatment</td>
</tr>
</tbody>
</table>

2.3 The CRI as a Research Platform

An Arctic caisson is an ideal platform from which to conduct research. Of particular interest is the role played by the ice rubble surrounding the caisson in propagating and attenuating the forces generated by the moving ice sheet. Part of the instrumentation was designed to coincidentally measure the stresses in the ice sheet, the rubble, and on the caisson face
during the rubble building process. This data will be correlated with radar imagery of the ice movement and changes in the rubble geometry to serve as a field verification of the mathematically predicted ice rubble growth.

Three relief well pads, constructed of ice on the rubble surrounding islands and caissons, demonstrated that the pads can be constructed quickly, have sufficient compressive strength to support a rig, and are stable enough to drill a relief well. Esso plans to build a relief well pad beside its first CRI well at Kadluk, and the CRI instrumentation system will be used to monitor the performance of the Kadluk relief well pad.

3 INSTRUMENTATION SELECTION, DISTRIBUTION AND INSTALLATION

3.1 Ice Force Sensors

Measurement of the ice forces exerted on the caisson will be performed by 33 sensors of three different types and sizes. The smallest of these, the microcells, have a load surface 165 mm in diameter and are temperature compensated strain gauge diaphragm cells. They are mounted on the caisson in machined inserts and are welded flush with the shell plate.

They measure the "point" loads exerted by the ice as it crushes against the hull, or waves as they hit the caisson face. As shown in Figure 2, these sensors are mounted in groups of four, spanning the water line, to accommodate variability in set-down depth. These groupings are located in the quadrant from which the greatest ice forces are expected.

The 815 mm diameter maxicells are supported by the structural stringers inside the hull plate and are mounted on the caisson skin. The applied pressure is calculated from the increase in fluid pressure in a spiral of reinforced elastic tubing sandwiched between two bearing plates. Since they are less responsive to rapidly changing loads, the eight maxicells are concentrated on the southern faces of the caisson where loads are not expected to fluctuate as rapidly or as dramatically.
The largest of the ice sensors are the shear-bar sensors with a load surface of 2100 mm x 500 mm. They measure normal loads due to uniformly distributed pressures. These nine sensors, mounted on the stringers, are concentrated on the north-facing caissons. The larger size will allow the examination of the reduction in average unit pressure with increasing size when loads are compared with those experienced on the microcells.

3.2 Wave Sensors

The wave climate 2 km from the caisson will be monitored with a wave rider buoy. However, since the geometry of the caisson and its berm will substantially change the wave pattern, three wave probes will be attached to the caisson on the north, west and east faces. Radar imagery will be used to determine the direction from which the waves approach.

3.3 Structural Sensors

The strain gauge installation is aimed primarily at measurement of the reaction of the structure to external loads from both ice and waves. A finite element analysis determined the most critical locations on four frames shown in Figures 2 and 3 for the 156 weldable steel strain gauges. Readings from the strain gauges will be used to determine both the response to known loadings and, in some cases, will be used to calculate the loads which have been applied.

3.4 Geotechnical Sensors

In responding to loads placed upon it by ice and waves, the caisson will react with its internal fill and the material upon which it is founded. In addition, the waves and ice will have a direct impact on the berm and the seabed outside the caisson. These reactions are measured by a suite of geotechnical instruments, which include total stress cells, pore pressure cells, deflectometers and settlement gauges. A correlated set of 26 Carlson Total Pressure Cells and 26 Carlson Pore Pressure Cells has been installed in inserts in the caisson concentrated along the centerline of the caisson, along the base and up the inside vertical face. With this distribution, it will be
possible to measure varying pressures under the caisson for differing loads and the reaction of the retained fill.

Pore-pressure buildup in the foundation and horizontal movements in the island will be monitored with electric piezometers and deflectometers. Outside the caisson, two strings of four piezometers in the berm will be used to examine the relationship between wave action and pore pressures.

Three thermistor strings to measure frost penetration and three settlement gauges will be installed in the caisson fill. The location of this instrumentation is shown in Figure 4.

1 DESIGN OF DATA ACQUISITION SYSTEM

The event durations for the different transients range from fractions of a second for the ice forces to hours and days for pore pressures. The data acquisition system will selectively and automatically collect data, adapting the collection rate and processing to the characteristics of the data being measured. Uneventful data will be compressed or averaged before recording. The key element is the provision of distributed intelligence - a network of computers allows the data acquisition to be efficiently subdivided. This has the additional advantages of:

- placing subsystems inside the caissons to conserve island surface space,
- reducing cable centralization for greater reliability,
- building in redundancy and flexibility, and
- providing the capability for parallel processing of tasks for increased data throughput.

4.1 Collection Rates

As shown in Figures 5 and 6, the CRI data acquisition system is an interconnected network of data collection nodes. Each node
contains a scanner, located in the caisson control rooms, which is connected to a block of sensors. Associated with each group of two or three nodes is a local computer which processes the digitized sensor data provided by the node scanners. A magnetic tape drive in an instrumentation trailer is backed up by tape units with the local computers.

The high-speed subsystem captures transient events with a relatively high frequency information content. Peak forces or structural stresses are sampled at 10 samples/sec per sensor. For the strain gauge complement, this is a burst sample rate of 1560 samples/sec. The low-speed subsystem measures parameters having much lower information bandwidths such as soil temperatures and pore pressures. It samples at a maximum rate of approximately 1 sample/sec per sensor. The data recording rate is independent of the sampling rate. The local computers also optimize the recording rate, compressing and averaging the uneventful data.

Two special remote units collect data on off-island measurements of waves and ice forces at preset scan rates without local processing.

The operator interface to the instrumentation system is a separate computer monitor in an above-deck trailer which eases operation and data tape maintenance. It monitors the data transmissions from the other computers and is primarily used to alert, in real-time, events that may affect the safety of the
island operations. It also provides on-demand, real-time data summaries, graphical displays and system status reports.

4.2 Computer Hardware and Sensor Linkages

Hewlett Packard HP9826A computers are used in the data acquisition system. An HP2250 Measurement and Control Processor complements this computer in the high-speed subsystem. This combination was chosen for its powerful parallel processing capability allowing it to operate independently. In contrast, the low-speed subsystem uses an HP3497 data acquisition unit controlled by a host computer.

A set of communication cables encircles the entire caisson ring, using jumper cables between pedestals at the joints between caisson sections. All of the sensors are direct-wired to a central control room located in each caisson. Penetration through the caisson hull and intervening bulkheads utilizes standard marine cable glands. The sensor cables are low temperature, grease-blocked, marine cables specified for the Arctic environment. More detail on the computer hardware has been recently published by Der [3].

5 CONCLUSIONS

This instrumentation and data collection system for Esso Resources' CRI incorporates a number of features designed to ensure that the significant events are captured and recorded, yet the total volume of information is minimized. The ice, structural, and geotechnical instruments are concentrated on the north caissons. The sensors with small sensing areas have been arranged in clusters to increase the probability of picking up peak local loads, and the data collection system has been assembled and programmed to allocate its resources in an optimum fashion as needs change. This array of instruments and sensors will provide warning of extreme events, refine our design criteria for offshore structures, and monitor the progress of our Arctic research projects.
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INVESTIGATION OF THE EFFECT OF MULTIPATH INTERFERENCE ON THE DETECTION OF LOW-LYING TARGETS ON THE ICE SURFACE

ABSTRACT

It is a well-known phenomenon that radar returns from targets on or near the surface of the sea can be severely attenuated due to multipath interference, sometimes known as the "Lloyd's Mirror Effect." It was anticipated that this phenomenon would also occur over relatively smooth sea-ice. To confirm these suspicions, personnel from the Canadian Department of Fisheries and Oceans (DFO) carried out an experiment at a site overlooking Lancaster Sound in the NWT, in May of 1982.

During the experiment a Luneberg lens target of known constant radar cross-section was deployed on the ice at a range of three nautical miles. A conventional X-band (10 GHz) marine radar was used to illuminate the lens and measurements of the returned signal amplitudes were made as the lens was raised from the ice surface to 4.2 m. The radar equipment was operated at a height of 30 m above sea level, resulting in a grazing angle at the target of less than 0.4°.

In addition, utilizing a continuous wave (CW) transmitter at the same frequency as the radar, the actual power received at two sites on the ice was measured from the surface to a height of 2.5 m.

Results from the experiment show that signal returns from the lens when it is within approximately 0.75 m of the surface of the ice are significantly reduced from the value predicted by the free space radar equation and from the signals received from the lens at heights greater than this. Also, the CW energy measured within 0.75 m of the surface of the ice is significantly lower than that received further above the ice. The results are compared with theoretical results predicted by the modified radar equation for propagation over a plane earth.

The results indicate that multipath interference must be taken into account when predicting the detection of small, though significant targets near the surface.
INTRODUCTION

The Canadian Department of Fisheries and Oceans, working together with McMaster University and Canadian industry, has been carrying out a series of studies to gain an understanding of the interaction between signals emanating from a surface-based radar, and Arctic sea-ice. The objective of this program is to develop techniques and equipment capable of classifying sea-ice features and type from a surface vessel. The Department has constructed a research facility on Baffin Island in the Canadian Arctic (Figure 1) overlooking the Northwest Passage. The facility provides an effective base for carrying out radar and ice-related research studies. The facilities have been and will be made available for other researchers involved in radar or ice research programs.

A view of the camp with the 6.5 x 8 m laboratory building on the right and two accommodation buildings on the left is shown in Figure 2. The camp has a cleared and barrel-marked 1500 ft runway suitable for Twin Otter aircraft traffic.

This site was chosen for the wide variety of ice types normally located within close range. In addition to first and multi-year ice, there is also a good selection of icebergs within view of the site, which also overlooks relatively smooth, fixed ice in Navy Board Inlet, heavily ridged and rafted ice at the junction with Lancaster Sound, and mobile ice in Lancaster Sound itself. The site was selected to provide a height of 30 m above sea level to simulate the mast height of proposed Arctic tankers.

During March and April of 1981, a major experiment was carried out to evaluate how changing various radar parameters affected the ability to classify ice features and type. During this experiment the parameters examined included radar frequency, transmitted power, antenna beam width, transmitted pulse length, elevation above sea level and antenna polarization. The results of this work are presented elsewhere in these proceedings.

BACKGROUND

As a result of findings from this experiment and a general interest in confirming the presence of multipath interference over an ice surface, a follow-up experiment was performed.

As shown in Figure 3, multipath interference (also known as the "Lloyd's Mirror Effect") occurs when a direct signal transmitted from a near surface radar is interfered with by a signal reflecting off the surface. This is a well-known phenomena over the sea surface and was strongly suspected of occurring over a smooth ice surface. This interference results in destructive or constructive interference, depending on the phase between the direct and reflected signals.
The radar equation for propagation of a signal in free space is:

\[ P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} \sigma_t \]  \[1\]

where:
- \( P_r \) is the power received
- \( P_t \) is the power transmitted
- \( G \) is the antenna gain
- \( \lambda \) is the wavelength of the transmitted signal
- \( \sigma_t \) is the radar cross-section of the target
- \( R \) is the range to the target.

However, for propagation over a plane reflecting surface (the earth, the sea, ice, etc.), the basic equation has to be modified for multipath interference. This modified equation takes the form:

\[ P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} \sigma_t \cdot 16 \sin^2 \left( \frac{2\pi h_t}{\lambda R} \right) \]  \[2\]

where:
- \( h_a \) is the antenna height
- \( h_t \) is the target height.

In Equation [2], the normal free-space returned power (Equation[1]) is modulated by the

\[ 16 \sin^2 \left( \frac{2\pi h_t}{\lambda R} \right) \]

term, which cycles from a maximum of 16 (in decibels, 12 dB) to a minimum of zero.

For small angles where \( \sin X \approx X \), Equation [2] becomes:

\[ P_r = \frac{4\pi P_t G^2 \sigma_t (h_t h_a)^4}{\lambda^2 R^8} \]  \[3\]

A plot of the modulating lobes as a function of the height of the target above the surface can be drawn. Figure 4 is such a plot of the first three interference lobes for an X-band (3 cm) radar operating at a height of 30 m at a range of 5600 m.

We can see that the lobe maxima occur at 1.4, 4.2 and 7.0 m and the minima occur at 2.8 and 5.6 m. Equations [2] and [3] are based on the assumption of a perfectly reflecting surface. Since this is seldom the case, the theoretical maxima will not be realized and the nulls (minima) will be partially filled in.

Equation [3] shows that by increasing the height of the antenna \( (h_a) \) and decreasing the wavelength \( (\lambda) \) of the transmitted signal (increasing its frequency), the power returned from a given low-lying target can be increased.
3 EXPERIMENTAL PROCEDURE

The multipath interference experiment was carried out at the Borden radar site during May of 1982. The experiment had two objectives; (i) to measure the radar returns from a constant radar cross-section target as it was raised from the surface of ice, (ii) to measure the power received on the ice as a function of height above the ice surface.

For the first experiment a Luneberg lens was deployed on the ice at a range of 5600 m (2 nm) from a small marine radar mounted on the laboratory building. The ice between the radar and the target was relatively smooth, with the ice within a mile of the target being very smooth. The experimental set-up is similar to that shown in Figure 3 where the height of the radar was 30 m, the height of the target was up to 3 m and the range from the radar to the target was 5700 m. The grazing angle at the target was less than 0.4°.

A standard Furuno 7 kW (68.5 dbm) marine radar was used to illuminate the target as it was raised from the surface of the ice to a height of approximately 4 m, utilizing the raising rig shown to the left in Figure 5. The raising rig was constructed of plastic pipe with no measurable radar cross-section.

The radar antenna was stopped and carefully aligned on the target to give a maximum return signal from the radar's video amplifier. The video output was displayed on an oscilloscope. Once a maximum signal had been received, the radar antenna was locked in that position for the balance of the experiment.

The Luneberg lens was then systematically raised in 6-in (~15-cm) increments from the ice surface to approximately 12 ft (~4 m). The return signal at each height was measured and recorded.

In the second experiment, the Furuno radar was replaced with an X-band CW signal source (Travelling Wave Tube) with an output power of 10 W continuous (40 dbm). The output of the signal source was connected to a 1-m dish antenna with a gain of 35 db. On the ice, the Luneberg lens was replaced with a microwave average power meter fed by a 22 db standard gain horn.

The power measurement system (on the right of Figure 5) was set up next to the Luneberg lens and the transmitting dish antenna was adjusted in azimuth and elevation to give a maximum reading on the power meter.

The standard gain horn was then raised from the ice surface to a height of 8 ft (~2.5 m) in 6-in increments. The received power was measured and recorded for each increment. These measurements were then repeated at eight other locations on a 3 m x 3 m grid around the Luneberg lens.
The power measurement system was then moved to a new site 3700 m (2 nm) from the transmitter in a patch of rougher ice which extended approximately 1 km towards the transmitter. This patch of ice consisted of random slabs of ice 2 to 4 ft in thickness thrown haphazardly up on end at a spacing of 2 to 3 ft between pieces. Power measurements from the surface to a height of 8 ft were repeated at the site on a grid of five locations in an L-shaped pattern, 3 m between locations.

4 DISCUSSION OF RESULTS

In Figure 6 we can see the results of the lens-raising experiment. The solid line is a plot of the return power from the Luneberg lens as a function of the height of the lens above the surface. Although the Luneberg lens has a constant radar cross-section, the return power varies over more than 30 db as the lens is raised from the surface to a height of 4 m. As a reminder, a signal increase of 3 db represents a doubling of power. The 30 db increase in power from weakest to strongest signal represents a one thousand times signal increase. The dotted curve of Figure 6 is a plot of the signal level as a function of height, as predicted by Equation [2], while the solid line at -72 dbm is the return power predicted by the free space radar equation. The measured return power agrees favourably with theoretical predictions of the modified equation and deviates substantially from the free space prediction. The maximum signal level received is only 7 db stronger than the free space prediction, not 12 db as predicted by Equation [2], while the null is a substantial 25 db down, but not zero. However, as indicated earlier, the maxima and minima are predicted on the basis of a perfect reflecting surface, which the ice is not.

In Figure 7, the results of the on-ice power measurement at a typical station near the Luneberg lens are presented. The solid line is a plot of the actual power received as a function of height above the surface. The dotted line is a plot of the predicted power using a modified form of Equation [2] for a one-way transmission path, while the solid line at -30 dbm is the power predicted by the free space equation. Note that because of the one-way transmission path, the maximum expected signal level increase over the free space prediction is 6 db, rather than 12 db.

As Figure 7 shows, the actual signal maximum is exactly that predicted by Equation [2]. Also, the maximum and minimum occur at greater heights than anticipated; otherwise there is good agreement on the shape of the curves.

In Figure 8, the results of the power measurement at the second site 3700 m (2 nm) from the transmitter are shown. This site is in an area of rougher ice and has rougher ice between it and the transmitter. The solid line is a plot of the actual power received as a function of height, while the dotted line again
represents the power as estimated by Equation [2]. The solid line at -26 dbm is the free space power prediction.

Again there is excellent agreement between the actual and predicted power levels, with the maximum having a value of 5.8 db greater than the free space prediction. The null, however, has been reduced to only 8 db below the free space prediction, undoubtedly due to the rougher ice at this location. As in the case of the measurement near the Luneberg lens, the peak signal at this site also occurs at a greater height than predicted, although the null occurs where predicted.

CONCLUSIONS

Figures 6, 7 and 8 show that multipath interference has had a significant effect on the level of radar signals transmitted over the ice surface. From these results it can be seen that the application of the free space radar equation for estimating the detectability of targets near the ice surface will result in significant errors. The modified radar equation (Equation [2]), on the other hand, produces a good estimate of the reflected energy or the energy received on the ice.

It is interesting to note that the power received at both the 5600 m station and 3700 m station was heavily influenced by multipath interference, even though the 3700 m station was in, and preceded by, rougher ice. It is estimated that at the approximate 0.5° grazing angle at this station, ice features in the 0.5 m range would appear rough to the radar signal, and thus should have broken up the multipath interference. Other than the more substantial filling in of the null, this did not appear to be the case.

However, the variation between the five measurements taken at the site in the rough ice was substantially greater than that of the smooth ice site, possibly indicating that the rough ice was indeed beginning to break up the multipath interference.

It is also interesting to note that, although the one-way transmissions had a peak signal that agreed with the predicted level to within 1 db, the two-way transmission resulted in a maximum signal 5 db less than predicted. This is possibly due to the broad angular response of the Luneberg lens, and interference from other azimuthal paths which did not affect the narrower beamwidth standard gain horn.

Referring again to Equation [3] (the approximation to Equation [2]), we can see that the power received back at the transmitting site is directly proportional to the height (h2) of the transmitting antenna and inversely proportional to the wavelength (\lambda) of the transmitted signal. The results of the experiment show that with a transmitter height of 30 m and a range of 5600 m, signal levels begin to fall below the free space prediction at approximately 0.75 m. However, as Figure 9 shows, if the
height of the radar antenna is lowered to 10 m, the first lobe maximum moves up significantly to 4.2 m. Signals from targets at a height of 1.25 m or less will begin to fall off rapidly below the free space prediction.

The power received at the transmitter is also inversely proportional to wavelength, hence directly proportional to the frequency of the transmitted signal.

In Figure 10, we can see that as the frequency is increased (S-band - 3 GHz, X-band - 10 GHz, K_a-band - 35 GHz), the height at which the signal return from a target falls below the free space prediction is increasingly reduced.

In summary, there are three points which warrant emphasis.

1) When concerned with detecting targets near the ice surface, the radar antenna should be as high as possible, and the radar frequency should be as high as is practical, bearing in mind that radar frequencies above X-band suffer increasing atmospheric attenuation.

2) When performing calculations to determine the detectability of targets near the ice surface, it is essential that the modified radar equation (Equation [2]) be utilized.

3) When performing radar evaluation or detection experiments with artificial or real targets, care must be taken in positioning of the targets above the ice surface to avoid significant distortion due to multipath interference.

Fig. 1. Location of Experiment.
Fig. 2. Radar Research Facility.

Fig. 3. Diagram of Multipath Interference.
Fig. 4. Modulating Lobes vs Height

Fig. 6. Signal Returns from Luneberg Lens
FIG. 7 RECEIVED POWER VS HEIGHT AT SITE 1

FIG. 8 RECEIVED POWER VS HEIGHT AT SITE 2

FIG. 9 EFFECT ON LOBES OF LOWER RADAR ANTENNA

FIG. 10 EFFECT ON LOBES OF CHANGING RADAR FREQUENCY
A NEW SENSOR FOR MEASURING ICE FORCES ON STRUCTURES:
LABORATORY TESTS AND FIELD EXPERIENCE

ABSTRACT

The basic concept of the ice pressure instrument described in this paper is similar to the one developed several years ago by Esso Resources Ltd., i.e. two large (1m x 2m) flat plates separated by rubber-like buttons which are compressed under ice pressure. Several important improvements have been made to the original concept which make the new ice pressure sensor more reliable, more sensitive, stiffer, less temperature sensitive, easier to read, and less expensive than the original sensor. The main innovation consists of filling the holes between the rubber buttons with a fluid which is expelled when a load is applied to the sensor. The quantity of fluid expelled is proportional to the load and can be read using a simple graduated transparent tube. Other improvements have been made in manufacturing particularly in the curing and bonding of the buttons.

The resulting new sensor has a linear calibration curve up to about 10 MPa. The effect of temperature is small, less than 7 kPa /°C. The sensor is not sensitive to the distribution of stress over its measuring surface, only to total load. The effect of creep in the buttons cannot be neglected, but it is relatively small: 10% in 24 hours at 1 MPa.

Because it is thin and wide, this type of ice pressure sensor functions well when embedded in an ice sheet as its "stress
concentration factor" is close to unity (1.09). However, these sensors have also been welded and bolted to hard surfaces such as ships, wharves, and concrete structures. Because of their low profile, their installation is easy, inexpensive and rugged. In addition to normal loads, the sensors can be instrumented with strain gauges to measure shear loads exerted on them by the ice. Tests have shown that the cross sensitivity between normal and shear load measurements is small (less than 6%).

1 INTRODUCTION

Measurements of the loads on arctic offshore drilling platforms are essential: for the monitoring of actual platform safety during operation, for the forecasting of impending ice loads and for the design of improvements to platforms which can make them more economical and safer.

The complex nature of the ice loading mechanisms and the magnitude of the forces involved make the development of suitable instruments very difficult. Also the varying nature of the ice properties such as creep, Young's modulus, temperature, salt content, and air content must also be considered in the design of any instrument for measuring ice pressures.

Since the stiffness of the instrument is not generally equal to that of ice, an 'inclusion factor' or 'stress bridging effect' must be taken into account. This has been described in detail by Templeton III (1). Also, the instrument is exposed to wide temperature ranges, and this may cause spurious stresses to be recorded.

In 1981, Gulf Canada Resources Inc. retained Canmar Ltd. to design, construct and install the first caisson retained island in the Beaufort Sea on the Tarsiat wellsite in 23 m of
water. Being beyond the landfast ice Tarsiut was exposed to more dynamic ice conditions than any other Beaufort Sea platform had been in the past. Thus, the need for ice load measuring systems was even greater than before.

In response to this requirement Dr. M. Metge, Dome Petroleum Ltd., and FENCO Consultants Ltd., cooperatively developed a new ice load measuring sensor: the MEDOF panel (the name MEDOF stands for Metge, Dome, Fenco).

2 GENERAL PANEL CHARACTERISTICS

The MEDOF panel basically consists of two large flat steel plates separated by ball buttons of a rubber like material which compresses under ice pressure. The metal plates are welded at the edges and the envelope formed is filled with a non-freezing fluid. (Preferably the fluid should have a low thermal expansion coefficient). An open tube, partly filled with fluid, extends upward from the top of the sensor.

To measure ice forces, the MEDOF panel is either inserted in a slot in the ice and frozen in place or bolted or welded to the walls of the structure being monitored.

As ice forces are exerted on the panel, the buttons compress and the fluid is expelled into the vertical tube at atmospheric pressure. The amount of fluid expelled into the tube is proportional to the total load on the panel, since the panel response is linear. Knowing the fraction of the panel embedded in the ice, the average stress on the panel can be determined.

MEDOF panels constructed to date have varied considerably in size and weight to fit the requirements of various projects. For manual installation, where the use of equipment is restricted, a 100 kg, 1 m x 2 m panel has typically been
used. Where MEDOF panels have been welded to structures which are to be used in the Beaufort Sea, panels of up to 650 kg and 1.2 m x 2.8 m have been constructed. These larger panels are installed while the structure is under construction in a dry dock. The outer plate of the 1.2 m x 2.8 m MEDOF panel was made of 12.5 mm plate steel. This thickness is sufficient to keep the plate from being dented by extremely high local ice stresses (up to 20 MPa on 0.05 m²). An example of a MEDOF panel constructed for use on a Beaufort Sea structure is shown in Figure 1.

3 MEDOF PANEL LABORATORY CALIBRATION

3.1 Load Versus Fluid Level and Temperature

Each MEDOF panel is calibrated in a laboratory press before being shipped for use in the field. This ensures that any changes in properties due to differences in bonding or in the rubber mix are accounted for. The response of a typical 1 m x 2 m MEDOF panel to pressures ranging from 0 to 1.3 MPa is shown in Figure 2. The response is very close to linear. To illustrate that temperature has little effect on the stiffness of the panel, two calibration curves are shown which correspond to -2.5°C and -12°C. The origin of the two curves have been shifted to start at zero, their actual origins would have differed by the amount shown in the temperature calibration curve (Figure 2, top left), but their slope is identical.

The actual effect of differential expansion between ice and sensor has not been measured under controlled conditions, but calculations indicate that the average expansion coefficient of the steel, rubber, and fluid combination is very close to the expansion coefficient of ice. The actual effect of temperature on a sensor embedded in sea ice is therefore much less than the 7 kPa/°C indicated by Figure 2, which is already
very small.

The temperature of the panels has been routinely recorded in the past, to allow a temperature correction to be calculated. However, this has generally not been necessary.

3.2 Response Time

Since the read-out of a MEDOF panel is dependent on fluid level, the response is not instantaneous. In particular during a decrease in stress, a small portion of the fluid will take a few seconds to drain from the walls of the indicator tube. However, for practical purposes, over 90% of the elastic response is obtained within one second.

The delayed response due to creep in the button material is of greater significance. Illustrated in Figure 3 is an example of MEDOF panel response to a 960 kPa (139 psig) constant load held for 8 days and then released for a 2 day period. The long-term creep effects have been found to be approximately 10% of initial elastic deformation for 960 kPa pressure. Creep response for the MEDOF panel is measured as a change in structure fluid height, over time, under a constant load. Figure 4 shows a typical creep plot against log (time) for 3 days. The creep behaviour of the panel is linear with log (time) and thus can be predicted. Essentially, it can be concluded from Figures 3 and 4 that the panel creep response after 24 hours is negligible and therefore the panel need only be creep calibrated for 24 hours.

3.3 Partial Panel Loading

Figure 5 illustrates the response of a typical MEDOF panel to a given load applied to one quarter, one half, or three quarters of the full panel area. The loading pattern for each load case was as illustrated in the left corner of Figure 6
with the width of loading \((w)\) varied to generated the desired area. The agreement of the four curves illustrates the ability of the MEDOF panel to measure total load, independently of area of application.

3.4 REPEATED LOADING

Figure 6 illustrates the response of a MEDOF Panel to repeated loading. In the test, the panel was loaded six times to a constant pressure of 0.97 MPa, held at this pressure for one hour and then released to zero pressure for one hour; then loaded to 0.97 MPa for one hour, etc., until six cycles were completed. This curve illustrates that only after the first loading cycle was there a shift in the curve. This was due to the initial creep of the panel over the first hour of loading. When measuring loads over periods greater than 1 hour, allowance should be made for this initial creep and this can be done by using the 24 hour-creep calibration curve (Figure 2). The fact that the curves are parallel indicates that eventually there is no effect of cyclic loads on the measured stress.

4 MEDOF PANEL SHEAR MEASUREMENTS

Ice forces on the face of a structure will in general include a shear component. Ice-structure friction can be in the order of 0.2 to 0.3, and the shear component can be 30% of the normal load. This has implications when considering potential rotation of a structure.

By chance, MEDOF panels are well suited to measuring shear. Since the rubber buttons are relatively soft in shear; all the shear load is carried by the steel cover plate. Strain gauges can therefore be bonded to the front steel plate, to measure its elastic strain under shear loads. In order to prove this and to ensure that there would be no cross-correlation between
shear and normal stress measurements, a test was performed in the laboratory. Eight strain gauges were placed along the edges of the plate, halfway through the thickness of the steel (the neutral axis) to minimize bending effects.

The results of one test are shown in Figure 7. In this test the vertical load on the panel was held constant at 285 tonnes for a normal panel pressure of 1320 kPa, while the horizontal load was increased from 0 to 89.5 tonnes.

Figure 7 illustrates that the strain gauges are quite sensitive to shear load (170 microstains for 89.5 tonnes); that their response is close to linear at high shear stresses; and that the fluid level, which indicates normal stress, is little affected by the application of a shear stress. The maximum change in fluid level was 40 mm or 5% of the total change due to the normal load and some of this change is attributable to creep.

5 PANEL EFFECTIVE MODULUS & STRESS CONCENTRATION FACTOR

The effective modulus of elasticity of the panel can be calculated from the pressure calibration curves as $E = PV/dv$

where $P$ pressure on the panel
$V$ total outside volume of the panel (1m x 2m x 0.012m)
$dv$ volume of fluid expelled

In the case of Figure 2, $E = 200$ MPa.

Typical values for the elastic modulus of sea ice range from 1 to 5 GPa. Using Chen’s formula (1), the stress concentration factor for this MECOF panel in ice, with a 3 GPa modulus, would be 1.09. In other words, the ice stress measured by this panel would be 9% lower than the undisturbed stress in the ice sheets. This 9% discrepancy would disappear as creep
takes place in the ice and the effective modulus of ice decreases.

6 BENDING TESTS

when a panel is embedded in an ice sheet, it is conceivable that the ice might deform in such a way as to bend the panel. This might cause a spurious reading of ice pressure. It would occur when, for instance, the panel is located in an active crack or ridge. To determine the extent of this effect, tests were performed in which panels were deflected in the center while panel fluid output was recorded. These tests indicated a reading of about 1 cm of fluid (in at 12.7 mm tube) per centimeter of central deflection. This shows that the effect of bending on fluid level is relatively small unless the panel is grossly distorted.

7 FIELD EXPERIENCE AT TARSJUT ISLAND

Twenty MEDOF panels were used at Tarsiut Island to supplement other ice load measuring devices installed on the caissons. These were "portable" panels designed to be embedded in the ice sheet. They were particularly useful in the following ways:

- to measure ice loads on the two caissons that were not instrumented otherwise.
- to measure ice loads exerted by the level ice sheet on the outside of the rubble field.
- to give a measurement of ice load which was easily (visually) recorded, independently of any electronic equipment.

Installation was simply in a slot cut through the ice with a chain saw or by drilling several holes next to each other. The panels are light enough to be handled over ridges and rubble by two men. Under good conditions four panels could be
installed by two men in one day. Within one week the panels were well frozen in and started giving reliable readings.

The panel readings were monitored two or three times a day by visual inspection of the fluid level in the tubes. In addition, pressure transducers were installed which measured the height of fluid in the tube and were monitored continuously. Figure 8 shows a typical plot of the daily visual readings for one of the MEDOF panels. The scales are arbitrary to protect proprietary data.

Calibrations of some of the panels were performed in-situ by using a "flat-jack" to load the MEDOF panel. The flat jack was made of two steel plates larger than the MEDOF panel itself. A slot was out in front of the panel about 15 cm away, the flat jack was inserted and it was then expanded using a hydraulic pump. The result of this calibration is shown in Figure 9 which illustrates the good performance of the panel.

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FIG 1 TYPICAL MEDOF PANEL

FIG 2 TYPICAL PRESSURE CALIBRATION CURVE FOR MEDOF PANEL

FIG 3 TYPICAL MEDOF PANEL RESPONSE INCLUDING CREEP AND HYSERESIS

FIG 4 TYPICAL 8 DAY CREEP TEST AT 0.98 MPa AND 150°C FOR MEDOF PANEL
FIG. 9. ON SITE CALIBRATION OF A MEDOF PANEL
THE PRELIMINARY ANALYSIS OF THE M.V. ARCTIC DATA
COLLECTED DURING THE 1980 AND 1981 SEASON

Abstract

The M.V. Arctic is a 28,000 ton deadweight ice breaking bulk carrier designed to meet Class II requirements of ASPPR and trades regularly from Nanisivik, N.W.T. to Antwerp, Belgium. M.V. Arctic is equipped with a data acquisition system for recording the performance of the ship in ice. This paper presents the preliminary analysis of the data collected on board M.V. Arctic during 1980 and 1981 voyages.

During the 1980 season, data was collected during four trips and a dedicated trial north of Saffin Island. Twenty-one magnetic tapes were recorded in conditions ranging from open water to thin first-year ice to multi-year ice floes. Data collected during early part of 1981 arctic shipping season stems from a two day ramming test series in Admiralty Inlet as well as two subsequent voyages between Antwerp and Nanisivik. A total of 11 magnetic tapes were recorded between July 5 and July 16.

1 INTRODUCTION

The M.V. Arctic is a 28,000 ton deadweight ice-breaking cargo vessel capable of commercial operation in the Arctic and is

* Present Address: Gulf Canada Resources Inc.,
   Calgary, Alberta, Canada
designed to meet the Class II requirements of the Arctic Shipping Pollution Prevention Regulations (ASPPR). Since M.V. Arctic is a forerunner of this new generation of ice-breaking cargo vessels, its design entails certain technical and economic uncertainties. At the suggestion of the Transportation Development Centre (TDC) a data acquisition system was installed aboard the M.V. Arctic with the hope that the data pertaining to ship's performance in ice during the Arctic shipping season will prove useful and will assist in the design of future ships.

The data acquisition system was in operation during the 1979 to 1981 shipping seasons. Data was collected during regular voyages as well as during four periods of dedicated ship trials being conducted in ice infested waters in Quebec, Labrador and north of Baffin Island. During the ice trials data such as speed/power runs, turning circles, break-out tests, etc., on board data and on ice data was collected.

According to the ASPPR, for vessels of Arctic Class II type, the permitted dates of operation in the Arctic zone 13 are June 25 to November 15. Since 1978, the M.V. Arctic has regularly traded from Antwerp, Belgium to Nanisivik, N.W.T. (see Figure 1), between the permitted dates and its earliest arrival at Nanisivik had been July 25 until 1980. In 1981, a successful attempt was made to extend the shipping season by entering zone 13 in early July. Based on the results of aerial photography and a ground truthing survey in June 1981, it was obvious that a passage through Admiralty Inlet, with its large areas of up to two metres thick level first-year ice, can only be accomplished by extensive ramming. It was suggested to, and accepted by TDC, to conduct a series of ramming tests. During two days of continuous ramming, a considerable amount of valuable data was collected.

In this paper we present the results of preliminary analysis of the data gathered by M.V. Arctic's data acquisition system during

2 THE ON BOARD DATA ACQUISITION SYSTEM

The data acquisition system was designed to monitor and collect data from three major areas: the hull structure, the propulsion system and ship performance. In all, 212 channels were monitored at sampling rates of one sample every 10 seconds to 1000 samples per second with the limitations of a total sampling rate of 1765 samples per second. A detailed description of the individual sensors and their functions as well as a documentation of the data acquisition system can be found in (1).

3 HULL-ICE INTERACTION

The magnitude and distribution of ice forces acting on an ice breaking vessel depend on particulars related to the ship as well as characteristics of the ice it travels through. Thus, in order to quantify hull-ice interactions, it is essential not only to collect and analyze on board data, but also to determine the type of ice, its thickness and lateral dimensions and the mechanical properties of the ice to be broken by the ship.

3.1 The Bow Structure

The hull structure of the M.V. Arctic had been designed in accordance with the recommendations given in the ASPPR, which call for design pressures ranging from 1.41 MPa at the upper transition area to 4.22 MPa at the bow area. As shown in Figure 2 the outer skin consists of 19 mm or 27 mm thick plates which are supported by a grid of 12.5 mm thick wall frames at 1.22 m c/c, angle shaped frames at 0.30 m c/c and 12.5 mm thick stringers spaced at about 1.3 m. The hull structure of the Arctic basically consists of a single skin except for a 10-frame
area between frame 178 and 188 (see Figure 3) which was reinforced by a 10 mm thick inner skin. Grade A steel with a minimum yield stress of 230 MPa was used throughout as specified by Lloyd's Register of Shipping.

As described in Section 2, weldable strain gauges were attached at strategic places to frames and plates with the intent to reduce the gauge data to ice forces. It can be seen in Figure 3(b) that as a result of the experience gained during the 1980 season, the strain gauge array used in 1980 season (Figure 3(a)) was extended by 26 additional gauges. The ice forces can effectively be approximated with the aid of the finite element method. This is particularly true in case of a complex three-dimensional ship structure in which the basic structural components (beams and plates) are extensively being used. Discretizing was done by employing plate and beam elements. The plate element had 20 degrees of freedom (DOF) namely three translational and two rotational ones at each mode. The 12 DOF beam element had three rotational and three translational DOF's at each mode. The analysis was based on linear elastic theory.

3.2 Ice Characteristics

During ice trials, in each test area the ice thickness was measured at regular intervals along the ship's track and core samples were taken to determine the vertical temperature and salinity profiles, grain size and crystal orientation. Confined compressive strength and modulus of elasticity of ice were determined in situ by using FENCO borehole jack, the unconfined compressive strength was determined by in situ flaking tests and uniaxial tests were conducted in the laboratory.
4 RESULTS

4.1 Overview

The M.V. Arctic conducted four trips during the 1980 shipping season as well as one dedicated trail north of Baffin Island. During the four voyages, 21 magnetic tapes were recorded in conditions varying from open water to 3 m thick multi-year small size ice floes. A total of 22 tapes were recorded during the six day trial period primarily in level first-year ice varying from 19.5 cm to 45 cm in thickness. Attempts to locate thicker level ice north of Baffin Island failed. Data collected during the early part of the 1981 arctic shipping season stems from a two day ramming test series (in Admiralty Inlet) as well as two subsequent voyages between Antwerp and Nanisivik. A total of 11 magnetic tapes were recorded between July 5 and July 16.

Data from strain gauges placed at the starboard side were used to monitor the hull-ice interaction. According to Major et al (2) the magnitude of ice impacts on the ship's hull depend on: ice thickness, ship speed, position of the ice impact on the hull, ice strength. In case of the Arctic data, it was decided to include two additional parameters, namely a distinction between single and double skin structure as well as separation of plate and frame gauge readings.

In order to evaluate the quality of the enormous amount of gauge data collected, it was decided to do a statistical analysis by incorporating the various parameters mentioned above. Figure 4 shows typical histograms of plate and frame strains recorded over a period of 30 minutes while the vessel traveled through 1.5 m thick first-year level ice at a speed of 2 knots. It can be seen that the percentage occurrences of plate and frame strains are very similar and that strains greater than 100 μ ε occurred only during 2% of the time.
Frame gauges located in the single skin area showed slightly higher strains than those placed in the double skin area. However, similar plate gauge strains were recorded on both areas because the inner skin does not contribute to the stiffness of the outer skin.

4.2 Distribution of Ice Impacts

From the experience gained during the 1980 season it became obvious that the majority of ice impacts were recorded below the loaded water level. Examples of the distribution of plate and frame strains are shown in Figure 5(a) and 5(b) and were recorded during September 1980 in unconsolidated pack ice and in multi-year ice, respectively. In each case it can be seen that all significant impacts occurred between 0 and 2.5 m below the water line. The "D" in Figure 5(b) depicts a dent in the outer skin which is the result of an ice impact which occurred when the Arctic hit a 3 m thick multi-year floe at about 7 knots. During the impact a maximum strain of 1550 με was recorded at plate gauge 126. Following the impact a permanent strain of 347 με was recorded by the same gauge.

4.3 Dynamic Response

Following the identification of areas with a high probability of impacts several strain gauges were connected to low pass filters with a corner frequency of 25 Hz in order to obtain the dynamic characteristics of typical ice impacts. Strain reading of two adjacent gauges are shown in Figure 6 during an impact with a multi-year floe on September 8, 1980. It can be seen that the plate responds about twice as fast as the stiffer frame with impact durations of 0.15 seconds and 0.30 seconds, respectively. The rise times are about half the impact duration and the peak strains occur within 20 milliseconds. The plate gauge also shows a negative strain after the main impact due to rebounding of the
plate. The faster response and the rebound of the plate are consistent with its greater elasticity compared to the frame. Similar impact times were recorded in loose first-year pack ice but the strains were considerably smaller than those produced by multi-year impact and no rebound of the plate was dedicated.

4.4 Estimate of Ice Loads

Methods to convert strain data to ice loads are based on principles related to structural analysis. Magnitude and distribution of ice loads can only be estimated from strain gauge data because the moment-curvature relationship is not known. The accuracy of the estimate increases with increasing strain data available. Examples of ice load calculations are given in (3) and are based on a methodology proposed by Iyer (4). We suggest to do the analysis in two phases; namely, first determining ice loads from particular strain gauge patterns, and secondly, use the calculated loads in a finite element model which in turn will determine the resulting strain values. The accuracy of the ice load calculation can then be judged by comparing strain patterns.

The relationship between externally applied loads and the resulting strain patterns had been established with the aid of calibration tests (5). The results of the tests are so called sensitivity coefficients which were found to be $1.8 \, \varepsilon /\text{ton}$ and $4.4-6.0 \, \varepsilon /\text{ton}$ for plates and frames, respectively.

5 SHIP PERFORMANCE

One of the objectives of the 1980 and 1981 trials was to evaluate the performance of the ship and its auxiliary equipment while transiting ice. During the Baffin Island Trials of 1980, the ship was able to make continuous progress through ice and the ship's performance was judged by performing the speed/power and turning circle tests. The speed/power relationship is the pri-
mary measure of the ship's capability to move through ice whereas the measurement of the turning circle provides information on the vessel's capability for avoiding obstacles.

During the Admiralty Inlet trials of 1981, the thickness of ice precluded continuous headway by the vessel and all the testing was carried out with the vessel in the ramming mode of operation. Ramming of the ice was carried out at various speeds and each test was repeated several times to form a test series. In general, 12 rams were made for each series of tests, six rams with the bubbler system in use and six without. To separate the effect that the momentum and thrust components have in ramming, certain rams were carried out with zero propeller thrust prior to striking ice. Full details of the ramming tests are given in (6).

5.1 The Speed/Power Relationship

The speed/power tests were carried out with and without the bubbler system in Navy Board Inlet, Lancaster Sound and Strathcona Sound in ice varying in thickness from 18 to 50 cm. Figure 7 depicts the variation of power with speed for various ice thicknesses without the bubbler activated. A general relationship between ice thickness and power requirement can be noted. Figure 8 depicts the speed and power relationship in level ice of 33 cm thickness with and without the bubbler system in use. It is seen that the bubbler system does not seem to show any advantage. Speeds below 2.48 knots were, however, not recorded and it is possible that the use of bubbler system may be advantageous below this speed.

5.2 Maneuvering Capabilities

Figure 9 is a plot of turning circle in ice of 33 cm thickness and offers a comparison of maneuverability with and without the bubbler. It is seen that the turning circle diameter reduces
from 1.7 nautical miles without the bubbler to 1.42 nautical miles with the bubbler.

5.3 Ramming Measurements

The ramming cycle consists of three phases: backing, acceleration and deceleration as shown in Figure 10. The impact speed was regulated by backing the vessel away from the ice edge a particular distance determined from the acceleration tests of the ship in broken channel (Figure 11) and allow the ship to accelerate to impact at full power. When it came to a stop after the impact, the ship was returned to the start point for the next ram. The speed of advance, which gives a measure of the overall performance of the ship when ramming ice, can be calculated from the measurement of penetration distance \( S_3 \) and ram cycle time \( t_c \).

Figure 12 shows a plot of mean speed of advance for rams carried out both with and without the bubbler in use at various impact speeds and in approximately 1.5 m level ice. The number of data points used for this plot are few and there is considerable scatter for those with the bubbler system in use, still it is apparent that there is an improvement in the speed of advance with the bubbler system and there is an optimum ramming speed that will maximize the overall speed of advance.

6 CONCLUSIONS

1. Almost all ice impacts were recorded up to 2.5 m below the loaded water line.

2. In the ice conditions encountered in 1980 and 1981, 98% of the frame and plate strains recorded were less than 100 ~.
3. Duration of impact times were 0.15 and 0.30 seconds for plates and frames, respectively. The associated rise times amounted to about half the impact times.

4. With a maximum impact time of 0.3 seconds it is adequate to record strains at a rate of 1 sample per second in the peak holding mode without encountering a possible superposition of two or more impacts at a particular gauge.

5. From the limited data available, the bubbler system does not seem to have any effect on the ship speeds for speeds greater than 2.5 knots in level ice of thickness 33 cm. In 1.5 m thick ice, however, the bubbler system gives a higher speed of advance. It is possible that in thinner level ice the bubbler system is effective below the speed of 2.5 knots.

6. The turning circle diameter in 33 cm thick ice was 1.7 nautical miles and reduced to 1.4 nautical miles with the bubbler system in use.

7. Comparison made between the speed of advance achieved with and without the bubbler system in 1.5 m thick level ice at various impact speeds indicated that the maximum average speed of advance was achieved by use of impact speed of 4.25 knots.

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REFERENCES


FIG. 1. TYPICAL ROUTE OF MV ARCTIC.

FIG. 2. BASIC STRUCTURAL COMPONENTS OF SHIP HULL.
FIG. 3(a) LOCATION OF STRAIN GAUGES USED FOR 1980 READINGS.

FIG. 3(b) LOCATION OF STRAIN GAUGES USED FOR 1981 READINGS.

FIG. 4 HISTOGRAM OF FRAME STRAIN AND PLATE STRAIN OCCURRENCE FOR PASSAGE THROUGH 15 m LEVEL ICE AT 2 KNOTS.
FIG. 5(a) DISTRIBUTION OF PLATE AND FRAME STRAINS GREATER THAN 300 µE IN UNCONSOLIDATED PACK ICE.

FIG. 5(b) DISTRIBUTION OF PLATE AND FRAME STRAINS GREATER THAN 300 µE IN MULTI-YEAR ICE.

FIG 6. ICE IMPACT AT 01:24 GMT ON SEPT 8, 1980 BETWEEN FRAMES 120 AND 122 AND STRINGS 4A AND 5
FIG. 7 POWER/SPEED IN VARIOUS ICE THICKNESSES.

FIG. 8 POWER/SPEED PLOT IN LEVEL ICE OF 33 cm MEAN THICKNESS.

FIG. 9 TURNING CIRCLES OF THE MV ARCTIC IN 33 cm OF ICE.
FIG. 10 CHARACTERISTICS OF RAMMING CYCLE

FIG. 11 ACCELERATION TEST JULY 8, 1981.

FIG. 12 SPEED OF ADVANCE-IMPACT SPEED (In Level Ice).
FULLSCALE MEASUREMENTS OF ICE FORCES ON AN ARTIFICIAL ISLAND

ABSTRACT

This paper describes the philosophy and design of instrumentation used to measure ice loads on Tarsiut Island, which was instrumented to ensure safety against ice loads and to provide data for future island design. Several types of sensors were used to test different measurement techniques and to provide information on the scale effect of ice loads. The scale of the measurements varied from 5 cm diameter microstuds to global loads (100 m wide).

Embeded strain gauges, flatjack panels, microstuds, and "MEDOF" panels worked well and provided useful ice load data.

INTRODUCTION

In 1980 Gulf Canada Resources Inc. retained Canmar to design and construct a caisson retained island at Tarsiut in 23 metres of water. Figure 1 shows a cross section of this island. It consists of a sand berm from the sea floor to -6 metres, with four identical caissons set in a square on the berm and infilled with sand to a freeboard of +7 metres. The role of the caissons was to provide instant water line penetration and slope protection to the sand core of the island. For the first time in the history of the Beaufort Sea, a structure with vertical walls could be instrumented to measure ice forces.

The Tarsiut caissons were thus instrumented to measure ice loads and geotechnical parameters. This paper discusses the
philosophy for the ice instrumentation and the instruments themselves; the paper by Mitchell in this conference covers the geotechnical instrumentation.

**NEED FOR ICE-FORCE MEASUREMENT INSTRUMENTATION**

All artificial islands prior to Tarsiat were in the landfast ice zone of the Beaufort Sea. Thus no measurements were available for 2 metre thick first year ice failing against the structure or a rubble field in a dynamic mode.

The effect of the rubble field around the structure was not known; would it absorb the load or enhance the load due to its width which may be several times that of the structure itself? Kry (1977) calculated that the rubble diameter must be four times the island diameter before the rubble will absorb a part of the load (Fig. 2b). However, he concluded that this needed verification.

The "frozen-in" condition was thought to be the most serious ice condition in the winter (Fig. 2a). In this condition the ice sheet is frozen solidly to the structure and extreme loads may be generated before the ice fails. Once it has failed, loads are expected to decrease significantly. This needed to be verified. The structure was not designed for a direct impact by a large thick multi-year ice floe, however, should such an event occur, ice load measurements would provide invaluable data.

Ice loading safety factors used for this structure were considered adequate based on the limited life of the structure, economy and reasonable civil engineering standards. Measurements were to provide verifications of the validity to the design criteria used.

In summary monitoring of ice loads on the structure was
considered necessary to:
1) monitor and ensure the safety of the island
2) provide design data for future islands.

INSTRUMENTATION DESIGN

The design of ice load monitoring instrumentation has been discussed previously by Metge et al (1975), Templeton III (1979), Chen (1980). However, until now, instruments had been designed to be frozen in the ice sheet surrounding the island as the islands had no vertical faces that could be instrumented. At Tarsiut two types of measurements of loads were used: caisson instrumentation and in-ice instrumentation. Caisson instrumentation was felt to be necessary to obtain the ice loads in early winter and in summer in the event of an ice floe impact.

The presence of a sensor in ice disturbs the stress field in the ice, due to the different stiffness of ice and sensor. The problem is further complicated by the presence of the structure being monitored. Theory indicates that a sensor to measure stress in a continuous, elasto-plastic material such as ice should be large in area, thin, or have a stiffness equal to or greater than the ice (Metge et al (1975) and Chen et al (1980).

Figure 3 shows the ratio of measured to actual stress, versus ratio of ice and sensor stiffness for different sensor thickness to size ratios using elastic theory. For a large thin panel, the measured stress is equal to ice stress provided the stiffness of the panel is greater than that of the ice. For a small sensor, (i.e. \( H/D = 1 \)), the stiffness of the sensor must be several times that of the ice (\( E_s/E_I \)), before the measured stress is independent of ice or sensor stiffness and then the measured stress is less than the stress in the ice. Clearly a large, thin, stiff sensor is preferable.
Unfortunately, the elastic theory does not take into consideration the effect of creep in the ice on the undisturbed stress. Many authors have discussed this problem without resolving it. Metge et al concluded that for a very wide and thin sensor "the creep has little effect on the sensor response. In fact, creep can only bring the stress concentration factor closer to unity". Templeton III, 1979, considered the creep by using a "reduced" ice modulus, using the secant stress-strain modulus instead of the instantaneous tangent modulus in case of unlimited viscoelastic creep. The author concluded by analogy that both the viscoelastic behaviour of ice at low strain rates and general plastic yielding at high strain rates can be minimized by reducing the sensor thickness-to-width ratio.

Bridging caused by the stress concentration at the sensor edges tends to be reduced eventually by the creep of the ice. However, when a sensor is emebead in a concrete wall instead of in an ice sheet, the interaction of a third medium with its different stiffness introduces more complications in the analysis of the measured stress. Thus the elastic theory has to be modified for these two problems. Work in these subjects has been conducted by Hamza and Blancnet for Dome Petroleum Limited (to be published).

Many other effects on the measured stress have been considered by Chen et al. (1980) and Templeton III, (1979). Internal shear in the ice cover, cross-sensitivity, edge effects and rate of loading can disturbo the normal measured stress up to 10%. The rate of loading isn't a problem when a thin flat panel is emebead in the ice sheet, but is very important when the panel is emebead in the wall of a structure.

SIZE OF SENSOR

Not withstanding the problems discussed above, it is desirable
to measure ice loads over different areas as the failure pressure of ice depends on the sample size and on the aspect ratio (size of structure to thickness of ice), Figure 4. This problem is known as scale effect. The instrumentation on Tarsiut was chosen to provide information from very small scale (5 cm diameter) loads to global loads (100 metres). The instruments were designed for up to 35 MPa for the very small sensors, 4.2 MPa for the sensors of about 1 metre dimension, to 3 MPa for global loads.

TIME RESOLUTION

Model tests, ice impacts with bridge piers, and results presented by Stenström et al (1970) indicated that a time resolution of several Hertz was necessary to resolve ice crushing and rubble-forming interactions. Thus it was decided to construct instruments and a data acquisition system capable of resolving 10 Hz. It was expected that during most of the winter when grounded rubble was frozen to the island that a time resolution of the instruments of several minutes would be adequate; however, this was not the case, as peak loads occurring over less than 1 minute were observed.

PHILOSOPHY USED IN SENSOR PLACEMENT

Tarsiut consists of 4 identical caissons placed to form the 4 sides of a square and filled in the centre with sand. The caissons are not joined except by doors to prevent loss of the sand; no load is transferred from one caisson to those behind.

When the island monitoring program was set up, it was not felt to be necessary to measure loads on all 4 sides of the island, but to measure loads on the sides most likely to experience most ice pressure; the north and east sides in the case of Tarsiut. Instrumentation was designed to measure the vertical and horizontal distribution of the load, the uniformity of the
load under different pressures, and rate of loading.

INSTRUMENTATION

Strain gauges were embedded into the concrete in the north and east caissons to measure global loads. The caissons consist of a concrete box (Figure 5) with 25 cm thick diaphragms separating front and back walls to transfer ice loads from the front to the back wall and subsequently to the sand backfill.

Finite element calculations indicated that the strain gauges should be located as close as possible to the front of the caisson so that the gauges would measure the load in the diaphragms before it is transferred to the caisson base. The gauges should also be far enough from the front wall to avoid the irregular shaped section of the diaphragms. The calculations suggested that 3 gauges were desirable at different heights in the diaphragms. However, as experience indicated that a large number of gauges would fail, it was decided to put in 8 gauges in pairs at 4 different heights.

The finite element calculations also indicated that the calibration factor for the strain gauges would change for highly local or uniform loads (1.1 and 1.4 respectively). Thus the load distribution could be obtained from the strain measured along the caisson and the appropriate factor (depending on width of load), applied to the data to get global loads. In any event the spread in values of the calibration factor is not large and using of a constant factor of 1.2 results in a relatively minor error. Particular attention was paid to protecting the gauges and cables during emplacement. The gauges, Alitech weighable gauges, were welded to a small flat ground at the centre of a 1 metre length of 1.2 cm (1/2 inch) re-bar. After the cable was adequately strain relieved to the bar the area of the strain gauge was potted with a silicone rubber splicing kit, and the bar tied
into the re-bar cage. Two strain gauge assemblies were located at each of 4 different heights in all 14 diaphragms in both the east and north caissons (Figure 6).

Due to the high loads required to do a useful calibration (approximately 10 tonnes per microstrain measured in the diaphragms), and the difficulty of applying a horizontal load, no physical calibration was conducted. Theoretical calibrations indicated a sensitivity of 1 microstrain measured per 7KPa (1 psi) over the front wall area supported by a diaphragm (5 metres width by 10 metres height). This was felt to be an adequate calibration considering the other unknowns.

"Test" beams were positioned in the sand fill in the caissons to determine the effects on the caisson concrete of the temperature and moisture environment to which they were exposed. The beams were 2 by 1 by 0.25 metres and of similar construction to the caisson diaphragms. These test beams indicated that a variation of only a few microstrains occurred due to environmental effects on the concrete and rebar.

Despite the efforts to protect the strain gauges and cables (by running them through plastic pipe) the attrition rate of the gauges was high. After installation, tests showed that about 98% of the gauges indicated reasonable values. After setdown of the caissons this dropped to 80% in each caisson but after hookup and monitoring, it became evident that only 35% of the gauges would provide useful information. Fortunately the functioning gauges were distributed within the caissons.

Despite the problems, the strain gauges that were operating did provide useful data. Figure 7 shows a time history plot of one of the gauges (without scale). The short term variations are due to ice loads which became larger throughout
the winter as the ice thickened. Figure 6 shows the distribution of the load measured across the front face of the caisson. The low load is due to the presence of the dilution ditch. The stiffness of the caisson should be deconvolved out of the data; this has not been done in the data presented here.

**FLATJACK PANELS**

Due to the expected problems with embedded strain gauges, load measuring systems were attached on the outside of the caisson. One such system consisted of four 4 X 4 metre plates supported on flatjacks. Ice pressure on the plates was transferred to the flatjacks where it could be measured by a pressure sensor.

As flatjacks can be "bottomed out" by local pressure it is necessary to use a thick steel front plate supported on several flatjacks. The front plate was designed such that 2800 kPa (400 psi) applied in the worst possible way would not cause the jacks to bottom out. Calculations indicated that an 8.9 cm (3 1/2 inch) thick plate was needed. Sixteen flatjacks were attached to the 4 by 4 metre front plate and then covered by a 3 mm (1/8 inch) back plate. All hydraulic hoses extended to the top of the panels where the pressure sensors were located in a waterproof compartment. Microswitches were mounted between the front and back plates to indicate "bottoming out". The panels were attached to the caisson by four lugs. (see Figure 9).

These sensors worked well, figure 10 shows an example of the results.

**CIRCULAR CELLS**

Circular cells were mounted in 0.88 metre inserts on the north caisson. Two types of cells were employed (both suggested and
constructed by Arctec Canada Ltd., see Graham et al., 1983). One type consisted of two thick, circular steel plates supported on "shear bars", which are long, high capacity load cells (Figure 11). The devices have good temperature characteristics, do not creep, and are very stiff (effective modulus of 2.14 GPa). The second type of cell, referred to as a "spiral coil" cell, consists of a spiral coil of hydraulic hose sandwiched between two steel plates. These devices are inexpensive, but are soft (0.16 GPa), non-linear and temperature sensitive (Figure 11).

These circular cells were located at and below water line on the north caisson to indicate the horizontal and vertical distribution of ice load. Unfortunately following a storm in October 1981 it was found that water had got into the devices and many were useless.

MICROSTUDS

To obtain ice pressures over extremely small areas, eight 5 cm diameter cells were mounted in the front plate of the flatjack panels. These "microstuds" (suggested by Arctec Canada Ltd.) consisted of a steel cylinder with thin front face onto which a strain gauge rosette was welded (Figure 12). After repairs in early winter most of these devices worked well.

DATA ACQUISITION SYSTEM

All signals from the various sensors (ice as described above and geotechnical sensors, see paper by Mitchell in this conference) were conditioned, digitized, and stored on 9 track magnetic tape. The data acquisition system was controlled initially by an Accurex data logger and later by an H.P. 9845B computer. Scan rates of 7 scans per second to one scan per several hours could be set; scan rates of 1 to 3 minutes were generally used during the winter, and 7 per sec during a first
year ice floe impact in mid-July. At several times during the winter, scan rates of at least one scan per second were required to resolve the ice load characteristics.

IN-ICE PANELS

To measure pressures in the ice rubble around the caisson structure a new ice panel was constructed referred to as the MEDOF panel. This panel, described in detail in the accompanying paper by Metge et al., 1983, was frozen into the ice at various locations to measure the distribution of loads in the rubble field, including ice pressure near the boundary of the field and pressures on sides of the island not monitored by the instrumentation discussed above. These panels worked well.

LEVEL-ICE MEASUREMENTS

During this program, British Petroleum measured loads in the level ice surrounding the island by means of strain meters (see paper by Goodman in this conference).

RESULTS

Figure 13 is a photograph of the Tarsiut Island in March 1982. Note the large rubble field around the caisson structure and the ice pad constructed on the north side to provide a location for a relief well in the event of a blowout and loss of the main island. (see paper by Neth et al in this conference).

Some general conclusions from the measurements are:

1) The embedded strain gauges, flatjack panels, and MEDOF panels provided the best ice load information, and
generally reasonable agreement was noted between these instruments where they could be compared.

ii) In winter 1982, the ice forces increased steadily during events from December to early April.

iii) It appeared that significant ice pressures were transferred to the caissons through the rubble field.

iv) There is some evidence of plucking loads on the caisson walls.

v) The ice loads generally have a small high frequency content (i.e. less than 0.1 Hz), except during ridge formation.

CONCLUSION

The Tarsiut ice instrumentation has provided a wealth of information on ice loads and so helps to verify the design criteria used. However, many more such measurements are needed before definitive design criteria can be established for seasonal ice loads.

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REFERENCES


Fig. 1. Cross-section of Tarsuit Island and Ice Instrument Placement

Fig. 2(a). Frozen-in Condition

Fig. 2(b). Dr. is 3 to 4 times of possible enhancement of load
FIG 3 UNDISTURBED-TO-MEASURED STRESS RATIO

FIG 4 PRESSURE VS ASPECT RATIO FOR ICE

FIG 5 LAYOUT OF STRAIN GAUGES

FIG 6 TYPICAL CAISSON SECTION SHOWING STRAIN GAUGES
FIG 7. EXAMPLE OF STRAIN GAUGE OUTPUT ON TARSUIT

FIG 8. VERTICAL DISTRIBUTION OF THE LOAD USING THE STRAIN GAUGE DATA

FIG 9. HORIZONTAL DISTRIBUTION OF THE LOAD USING THE STRAIN GAUGE DATA
FIG. 9. FALSE FRONT PANELS

FIG. 10. HISTORY DIAGRAM OF THE PLAT JACK 5-8

SHEAR BAR TYPE LOAD CELLS

SPIRAL HOSE LOAD CELL

FIG. 11
FIGURE 12 MICROSTUD

FIG 13 PHOTO SHOWING TARSIUT IN MID-WINTER
IMPROVING MARINE RADAR PERFORMANCE FOR ICE-HAZARD DETECTION

Abstract

A simple model to evaluate the performance of a marine radar in detecting ice features is discussed. The effect of antenna height and performance in the presence of sea clutter are studied. A computer-based, data-acquisition system, which interfaces to a marine radar, and some results from the data collected on a drill ship are discussed.

1 INTRODUCTION

With the increase in shipping in ice-infested waters associated with arctic petroleum exploration and transportation, demands are being made on marine radars for detecting and tracking ice. Radar is the only means of obtaining information on potentially hazardous conditions under the adverse conditions often encountered in shipping. Thus, there is an incentive to improve the performance of these radars for the detection and tracking of ice hazards. Dome Petroleum Limited, as part of its Ice Management System, has been supporting both theoretical and experimental studies including the gathering of calibrated radar data from both the sea and sea ice.

While considerable work has been done on measuring the radar cross-section of ships of various sizes /1/, little work has
been done on measuring the radar cross-section of floating sea ice. The difficulty of making such measurements is large, since, in addition to the normal multi-path and atmospheric propagation losses, sea ice exhibits a bewildering range of shapes, sizes and reflectivities. It is, therefore, not only difficult to measure the radar cross-section of ice, but difficult to parametrize the ice to make that measure meaningful. Fortunately, the problem of target motion during beam dwell does not exist, as ice motions are typically slow.

The nature of the problem of ice detection varies from season to season, and the seasons vary from year to year. In summer the problem is to detect low-lying pieces of ice floating on water; in winter, it is to find the notion of different ice features around the ship. In the former case, targets may look like holes amidst sea clutter; in the latter, they may appear as bright features surrounded by ice clutter. It is not yet possible to estimate the size or nature of these targets from the radar receiver output, because of the non-standard target shape, as well as the multi-path effects and the presence of ice or sea clutter combined with the atmospheric effects. Thus, it is necessary to conduct a series of measurements at different conditions, to develop a set of statistics for ice detection.

2 MODEL FOR SMOOTH ICE AND CALM SEA CONDITIONS

For a monostatic radar, the power received from a point target, is given by \( P_r \):

\[
P_r = \frac{P_t G^2 \lambda^2 \sigma^2 F^4}{(4\pi)^3 R^4 L}
\]

where \( P_t \) is the peak transmitter power; \( G \) is the antenna gain; \( \lambda \) is the operating wavelength; \( \sigma \) is the radar cross-section of the target; \( F \) is the propagation factor taking into account the Lloyd's mirror effect, earth's curvature and the antenna
pattern; \( R \) is the range; and \( L \) is the sum of all system and atmospheric propagation losses. \( F \) is defined as:

\[
F = \left| \frac{E}{E_0} \right|
\]

(2)

where \( E \) is the electric field intensity of the transmitted wave impinging on the target, and \( E_0 \) is the intensity that would exist at the same range under free space conditions in the maximum-gain direction of the antenna /2/. In the following analysis, the antenna pattern effect is ignored, since the antenna has a broad vertical beam width.

The magnitude of the field intensity, at the antenna, of a wave reflected by \( n \) point targets located at the same range within the beam, may be expressed as:

\[
|E_r| = \sum_{i=1}^{n} E_0^i \left( 1 + p e^{-j \alpha_i} \right)^2
\]

(3)

where \( \alpha_i \) is the phase difference between the direct wave and the ground-reflected wave at the "ith" target, and \( p \) is the magnitude of the reflection coefficient of the earth's surface.

\[
\alpha_i = \frac{2 \pi \delta_i}{\lambda} + \phi
\]

(4)

where \( \delta_i \) is the difference in the path length between the two waves, and \( \phi \) is the additional phase difference introduced by the ground reflection. The path difference is given by the approximate relation:

\[
\delta_i \approx \frac{2 \frac{h_1}{h_2}}{d}
\]

(5)

where \( h_1 \) is the height of the antenna, \( h_2 \) is the height of the target, and \( d \) is the distance between them. If \( \phi \) is assumed to be equal to \( \pi \) radians for the horizontal polarization case /3/, the result is:
If the target is assumed to be a plane reflector of square cross-section with a side of length $2a$, positioned vertically at a height $h$ above the ground, then:

\[
\alpha_i = \frac{4 \pi h \lambda^2}{\lambda d} + \pi \quad (6)
\]

In equation (7), $K$ equals $F^2$.

For the case of horizontal polarization, for practical purposes $f$ can be assumed to be equal to unity ($/3'$). The radar cross-section of the target is given by the equation:

\[
\sigma = G A \quad (8)
\]

where $A$ is the area of the reflector equal to $4a^2$, and $G$ is the directive gain of the target, given by:

\[
G = \frac{4 \pi A}{\lambda^2} \quad (9)
\]

If the target is a point reflector, then:

\[
|E_r| = \left| E_c^2 \left( 1 + f e^{-j\alpha_i} \right)^2 \right| = E_c^2 \left[ 4 \sin^2 \left( \frac{4 \pi h \lambda^2}{\lambda d} \right) \right] = E_c^2 K \quad (10)
\]

which produces the familiar Lloyd's mirror effect.
By considering a hypothetical target of square cross-section, positioned vertically on the ground, we have the centre of the target at height $h$, equal to $a$ from the ground level, and the height of the target equal to $2a$. Using equation (7), a family of curves is plotted for the derrick-top radar mounted on a drill ship at a height $h_1 = 71$ m, indicating $P_r$ versus $\sigma^-$, with range as a parameter in Figure 1, and $P_r$ versus range $r$, with the target height $h_2$ as a parameter in Figure 2. From Figure 2, it is seen that $P_r$ varies approximately as $r^{-4}$ in the near range, and as $r^{-3}$ at far range. The transition occurs at approximately $r = 8 h_1 h_2/3 \lambda$. Similarly from Figure 1, $P_r$ varies as $\sigma^{-2}$ for small values of $\sigma^-$ (small $h_2$) and as $\sigma^-$ for large $\sigma^-$ (large $h_2$). The transition region is, again, approximately given by $h_2 = 3 r \lambda/8 h_1$. In this case, the factor $K^2$, due to interference, is seen to be proportional to $\sigma^-$, for low $\sigma^-$ and at far range.

![Figure 1](image_url)

**Fig. 1.** $P_r$ versus $\sigma^-$ for derrick-top radar: flat earth case; square target.
Fig. 2. $P_r$ versus range for derrick-top radar: flat earth case; square target (target height $h_2$ varies in steps of 0.5 m).

The reason for this is as follows. The returned power is proportional to $\sigma^{-2}$ and $K^2$. The value of $\sigma^{-2}$ varies as the square of the target surface area; i.e., as $h_2^{-4}$ for the assumed square target. The interference factor $K^2$ varies as $h_2^{-4}$, as seen by equation (10) for small $h_2$ or large $d$. Hence, for the region in which interference is dominant, $P_r$ is proportional to $\sigma^{-2}$ and $r^{-3}$.

To obtain a solution for the spherical earth case, the effective antenna height $h_1'$ and the effective target height $h_2$ are found from their actual heights $h_1$ and $h_2$ and the range $r$ [2, 4]. Comparing the performance of the derrick-top radar with that of the bridge-top radar mounted at a much lower height ($h_1 = 19$ m), it is seen that the derrick-top radar displays an increased sensitivity, especially for small targets at large distances, due to interference effects. The roll-off at far range becomes more pronounced for the spherical earth case.
Instead of assuming the target as a square reflector, it may be considered as a beam-filling surface of height $2a$, which is more realistic for beam-filling ridges. If the ridge is assumed to lie along the arc of a circle with radius $r$, then the value of $K$ remains the same as in (7) and $P_r$ can be computed from (1) and (9). The value of $P_r$ will, however, be much lower in practice, because the directive gain, and hence $\sigma$ of the target will be quite low.

For comparison purposes, both the radars are assumed to be identical in all respects but the antenna height. The following values are used:

Transmitter Peak Power $P_t = 11$ kilowatts
Antenna Gain $G_t = 30$ decibels
Wavelength $\lambda = 0.032$ m
3 decibel Azimuth Beam Width $\phi_b = 0.5^\circ$ (one way)
Antenna Height $h_l = 19$ m bridge-top radar and $71$ m derrick-top radar

3 SEACLUTTER PERFORMANCE

While it is clear that a higher antenna gives better ice detection at far range, in the absence of sea clutter the near-range response is less obvious. Sea clutter falls off as $R^{-3}$, and is a very strong function of angle of incidence. Therefore, in the near range the detection performance of the lower radar may be superior. To examine this effect, a well-known sea-clutter model /5/ was used to estimate sea returns. Various wave and target conditions were examined. The calculation of target response used the full interference model, which overestimates the reflected term, since the sea is assumed calm. A rough-sea, forward-scatter model was not evolved because it was felt that the problem did not justify the effort.
Using the target and sea returns, signal-to-clutter ratios were calculated for both radars and compared. The results showed a trend of the bridge-top radar to have up to 5 decibels better performance out to 2 nautical miles. The exact details of this result are not reliable, due to the assumptions made. It is clear, however, that if it is at all possible, the combination of two radars, spaced widely apart in height, is very desirable.

4 INTERACTIVE DIGITAL RADAR IMAGING SYSTEM

The data-acquisition and imaging system used for data collection consists of an LSI-11 central processing unit with 64 kilobytes of memory, a 7.5 megabyte WINCHESTER disk, a KENNEDY 9100 tape drive, a VT-100 terminal, and an NCW-10, red-green-blue colour monitor that displays the 256 by 245 pixel, 4 bit data stored on MATROX video memory boards.

The system can select one of two radar inputs for data acquisition, select the pulse width of operation (0.25 or 1 microsecond) and average the returns for one, two, or four pulses. It can also schedule logging of the raw data to tape, or the processed image to disk, and the tracking of selected targets with operator assistance, at regular intervals. The system can display either a direct plan-position-indicator image or a scan-to-scan averaged image with a capability for zoom. Other features include the display of two images in a flicker mode, indication of range and bearing at a cursor location, and replay of images stored on disk or tape.

5 SYSTEM CALIBRATION AND DATA ANALYSIS

The on-site calibration of the system consisted of: 1) receiver calibration; 2) measurement of the transmitted power; pulse width and pulse repetition frequency; and 3) Lloyd's mirror
experiment, using LUNEBURG lenses of known radar cross-sections. The photograph in Figure 3 shows the image with ice clutter, as seen on the colour monitor.

Fig. 3. Image showing ice clutter.

6 CONCLUSION

The detection of ice features and estimation of their size with a marine radar is complicated because of several factors, such as propagation, interference, and the reflectivity of the targets. A simple theoretical model shows that the performance of the radar can be divided into two zones: the interference-free zone at near range, and the far-range interference zone. Increasing the radar height improves the performance at far range, but has a tendency to increase sea clutter even more than target returns at short range.
REFERENCES


A NEW HF DRIFTER BUOY TRACKING SYSTEM TO MEASURE SURFACE CURRENTS

Abstract

A knowledge of ocean surface currents is required to determine the fate of potential oil slicks. Examination of the various techniques used to measure these phenomena indicated a gap for acquiring this data at relatively short time intervals within a range of 100 km. This led Esso Resources Canada Limited to support the development of a High Frequency (HF) radio tracking system, aimed at reliable, accurate, short range movement measurement.

Such a system has been built by Orion Electronics Ltd. of Nova Scotia. The system measures the range and bearing from a central base station to drifting transponder buoys up to distances of 60 km. The base station is designed to operate unattended in remote locations. The unattended base station is programmed to make the measurements automatically at pre-selected time intervals and record the data on a data logger.

The system was deployed during the summers of 1981 and 1982 at locations in the Mackenzie Bay in the Canadian Beaufort Sea. Typical results from these programs are presented in this paper.
INTRODUCTION

The use of satellite tracked drifter buoys to measure ocean surface current patterns is a proven and demonstrated technique, valuable for obtaining information over large distances and time periods in the open ocean. However, studies of various techniques to acquire surface drifter information over shorter distances and in coastal regions indicated they all had limitations. For example, the use of drifter cards only gives end points rather than the actual patterns of surface drift. Also, the tracking of radio transmitter equipped buoys from aircraft provides only a limited amount of information. Logistics costs entailed in the use of aircraft can be considerable if buoys are tracked for extended periods.

This led Esso Resources Canada Limited to support the development of a High Frequency (HF) radio tracking system. The system, named the Orion 4800 Tracking System, was built by Orion Electronics Ltd. of Nova Scotia [1].

The difference between the Orion 4800 Tracking System and other commercially available radio direction finding equipment lies in the fact that both range and bearing measurements are obtained from one central station. Normally positional determinations made with radio directional finding equipment entail the use of one or more base stations since triangulation techniques are used to compute positional information. Depending on the geographical location, this is not always practical. Also, operational costs significantly increase. The Orion 4800 system was first deployed in the summer of 1981 at a location in Mackenzie Bay in the Canadian Beaufort Sea. Results and experiences acquired from using this system in 1981 and 1982 are described in this paper.
2 SYSTEM DESCRIPTION

The Orion 4800 system is designed for unattended operation at remote locations. Range and bearing measurements between the base station and drifting buoys are made automatically at pre-selected time intervals. Data collection is accomplished by recording it on magnetic tape. Periodic visits to the site are only required to launch buoys and change tape cassettes.

The design specifications called for the base station to track buoys up to distances of 100 km. However, it must be remembered, range is line-of-sight dependent, which in turn is related to base station antenna height. As long as the drifter buoy is within radio range, the base station is designed to automatically determine range and bearing of up to 15 drifter buoys.

The system can be broken down into two component units, the base station with antenna assembly, and the remote drifter buoys.

2.1 Base Station

The base station controls and measures the co-ordinates to the drifter buoys. The direction or bearing between the base station and drifter buoy is determined by conventional VHF/DF techniques, while the range is found by measuring the modulation delay in the retransmitted signal.

The base station consists of the following components:
- The main control unit
- The data logger
- Transmitting and Direction Finding (DF) antenna assembly

The main control unit (Figure 1) contains the electronic circuitry necessary for the measurement and control functions. Controls which allow the system to run in both manual and automatic modes, along with calibration circuitry, clock and
digital display, are housed in this unit. An Intel 8748 single chip microprocessor is the heart of the system. It carries out the timing and control functions, as well as data averaging and the conversion into engineering units. The base station can keep track of up to fifteen buoys at one time, as each buoy responds to an individual tone code. To select a particular buoy, the base station pulses the modulation in an eight-bit code. A decoder board in the buoy detects this code and, if it receives four consecutive correct codes, activates the buoy. When the base station is operating in the automatic mode, it interrogates each buoy in sequence and records the information on tape. The automatic interrogation sequence can be repeated at pre-set intervals between 15 and 240 minutes.

The base station requires a 12 volt DC power supply for operation. At the remote locations in the Mackenzie Delta, this has been supplied through using lead acid batteries charged by solar panels.
A Memodyne data logger (Figure 1) records the measurements on a cassette. The information is recorded with a month, day, and time preceding the measurements. Three range and bearing measurements, which consist of averages of 100 readings, are logged for every measurement determination.

The antenna assembly consists of directional finding and transmitting elements (Figure 2). The DF antenna is the multi-element one, while the transmitting antenna consists of a single whip with ground plane elements.

2.2 Drifter Buoys

The remote units (drifter buoys) consist of a radio receiver, transmitter, filtering circuitry and decoder timer along with batteries housed in a waterproof hull (Figure 3). Attached to the outside of the hull are two smallwhip antennae. The hull is 28 cm in diameter and 28 cm in height.

2.3 Operating Principles

When the system is measuring range, the base station transmits a VHF radio carrier frequency modulated by a 2.5 KHz sine wave. The remote unit detects this signal, demodulates the wave and filters the resulting output to remove transmission noise. It then generates another carrier on a separate VHF frequency, which it sends back to the base station, frequency modulating it with that sent out to measure the range.
For Bearing Determination, the base transmitter is switched off. A 2.5 KHz sine wave is applied to the Direction Finding antenna. This has eight vertical antenna elements and the outputs of each are amplitude modulated by the sine wave (phase shifted by 45° per element). When the signals are combined, the net output is an FM signal phase modulated by an amount equal to the bearing angle.

The base station measures the delay between the reference signal and the DF antenna output exactly as it measures the range. By changing to a clock frequency 360 times the reference, the output is automatically scaled to degrees.

3 MEASUREMENT PROGRAM RESULTS

In the summers of 1981 and 1982, the base station was located on Garry Island in Mackenzie Bay (Figure 4). The base station was housed in a communications repeater building at the site. The system antenna was situated 118 m above sea level on the existing communications tower.

The objective of both year's programs was to obtain information on surface currents in the nearshore region of the Mackenzie Bay for oil spill contingency planning. In order to obtain drift information throughout the summer under a variety of meteorological conditions, buoys were released at weekly intervals.

3.1 Drift Tracks

The range and bearing measurements are recorded on the data logger with the associated time and date. These cassette tapes are read by a Memodyne Reader connected to a Hewlett-Packard 9825 desk top computer. Programs have been written to calculate the geographic position of the drifting buoys, along with hourly drift rates. Typical drift tracks obtained from the plotting of this positional information for two buoys released in late July 1981 are illustrated in Figure 4.
Buoy #7 was released on 81 07 27 during a period when calm wind and sea state conditions prevailed. After initial westerly drift, it became more northeasterly. This northeasterly to northerly drift continued until the buoy drifted out of range.

Buoy #1 (Figure 4) was released one day later on 81 07 29. It drifted north around Garry and Pelly Islands, eventually coming ashore on a sand spit around 0900 hours on 81 07 30. The buoy was recovered from the estimated position in Figure 4 nine hours later. At the time of recovery, the buoy was lying on its side approximately 0.75 m above the water line. It can be seen there is a difference between the last reported position and the estimated recovery position. This was determined to be caused by an error of 10° in the initial system calibration.

The drift of buoy #3, released on 82 07 15 (Figure 5), is much more intricate. It completes two loops, passing close to its launch point, before drifting ashore at the entrance to the Mackenzie River Middle Channel, from where it was recovered. The recovery of the buoys from the locations indicated by the system confirm its reliability. The differences exhibited in the drift tracks of these three examples are due to the surface currents responding to changing wind conditions.
3.2 Wind/Drift Correlation

Observations indicate that surface currents in the Mackenzie region respond rapidly to changing wind conditions. The objective of this program is to improve our understanding of the regional wind/current coupling to aid in the development of oil spill trajectory prediction models. In considering the correlation between surface drift and the wind, it is important to remember that there are a number of processes at work besides the action of the wind. The Mackenzie River outflow influences the surface circulation directly, by river currents which are strongest close to the delta, and indirectly, by its effect on density. Inertial and tidal currents also have an effect along with the role played by bathymetry and topography in redirecting currents.

Given these variables and others, a preliminary comparison of the drift information indicated a qualitative relationship between wind and buoy motion. Work was undertaken to devise a quantitative relationship by correlation of averaged wind and buoy velocity data over three hour periods.

Examination of buoy and wind velocity time series information for varying time lags between 3 to 12 hours indicated little variation in results. This may be in part due to the short length of the records. Preliminary results showed significant correlation between direction of buoy movement and wind direction (Figure 6). Here the regression line indicates, where buoy drift lags winds by periods of 6 and 9 hours, buoy drift will be within 45° to the right of the wind direction. Reducing wind/drift lag times to 3 hours reduces the wind/drift angle to approximately 30°.

There is a less definite correlation between buoy speed and wind speed (Figure 7). Regression lines indicate current speeds are up to 5.5% of the wind speed. This is higher than the normally accepted 2 to 3% of wind speed, but again, it is emphasized that
other mechanisms which influence the flow have not been removed from the overall motion. Another factor which may influence the speed relationship, and which has not been accounted for, is a possible change in lag time with the wind for each buoy as it moves from the nearshore to offshore regions.

As with all measuring systems, there are two types of limits to accuracy: first, those inherent in the electronics and, second, those associated with the measurement strategy. Our development targets were to achieve range accuracies within ±0.1 km, and bearing accuracies within ±2°. The range error remains constant with distance, but bearing inaccuracies increase with range. For example, at distances of 10 and 50 km, a ±2° bearing error translates into a lateral displacement error of ±0.4 km and ±1.75 km respectively.

As this is a new system, an effort has been made to try and quantify what the actual system range and bearing errors might be. Initial system calibration was carried out through placing
reference buoys at surveyed bench marks. Secondly, buoys were placed on a survey tug equipped with Syledis and Mini Ranger survey systems. The vessel sailed in an arc around Garry Island at distances up to 40 km from the base station. Simultaneous Orion and Syledis range and bearing measurements were obtained for every 10° arc.

Comparison of the survey measurements with the Orion 4800 readings indicates RMS Deviation for the range readings varied between 0.12 km and 0.33 km. For the bearings, RMS Deviations varied between 1.8° and 4.6°. To gain some estimation of the system repeatability and accuracy, reference buoys were left at surveyed locations for varying periods of time. The data again indicates the range readings show less variability than the bearing measurements. This is illustrated in Figure 8, where statistics on range and bearing measurements to a reference buoy located 7.5 km from the base station in a direction 242°T are presented. Statistical analysis of these reference buoy measurements (Figure 8) indicates good agreement between surveyed and measured distances. The RMS deviation for the range measurements is 0.1 km, but for the bearing the RMS deviation is 2.6°. Comparison of the Orion positional determination with the actual surveyed position shows that, in this case, the Orion positions are on average within 120 m of the actual location.

![Histograms of range, bearing and survey/Orion positional differences for a reference buoy located 7.525 km 242°T from base station](image-url)
From an examination of the data, it is concluded that positional accuracy of the buoy is dependent on range, and the data indicates it is around 2.5% of the range at the extreme range of 60 km. The greatest source of error in positional determinations is due to system fluctuations in making the bearing measurement.

CONCLUSIONS

Results from the past two summers' field programs indicate the Orion 4800 tracking system is a viable method for obtaining information on surface currents through the tracking of free drifting buoys. Buoys have been successfully tracked up to distances of 60 km, and positional accuracies are comparable to those determined from satellite buoy tracking systems.

ACKNOWLEDGEMENTS

The design and system development was carried out by H. Roddis of Orion Electronics. Without his pioneering effort and unstinting work, the development of this concept could not have taken place. The author would also like to express his appreciation to Esso Resources Canada Limited for permission to publish this paper. Valuable assistance in the field was provided by H. Kruger, and assistance with data analysis was provided by K. Birch and M. MacNeill, all of Esso Resources.

REFERENCES

"STATISTICAL ANALYSES OF PRESSURE RIDGE KEEL DEFINITIONS AND DISTRIBUTIONS"

BY L.D. BROOKS

Vol. 1, page 69

DISCUSSION

By:
P. Wadhams, Scott Polar Research Institute, Cambridge, England

I would like to comment on the "independent event" criterion. We did not propose it as a criterion for the identification of pressure ridges in Lowry and Wadhams (1979), but simply drew attention to a problem in the interpretation of ice profiles by computer, i.e. that closely spaced keels may not be perceived as independent, whatever the criterion. This is a universal problem with unidirectional transects of three-dimensional surfaces. We would not recommend this as a criterion since pressure ridges can be created in a sequence of events and can be arbitrarily close together. When it comes to extreme value prediction, there are ways of doing it which are independent of any pressure ridge-identifying criterion (e.g. P. Wadhams, Cold Regions Sci. & Technol., 6 257-265, 1980).
"ICE FIELD OBSERVATIONS AROUND TARSIUT ISLAND IN THE BEAUFORT SEA"
By: S. Depoali and G.R. Pilkington

DISCUSSION
By:

J.R. Hawkins, Esso Resources Canada Ltd., Calgary

In your paper on the very comprehensive measurements you made on the rubble field surrounding Tarsiut in the winter of 81-82 you showed a profile through the rubble. In this profile, none of the ice was firmly grounded; the ridges were all underlain by "slush, blocks and voids". I believe that you implied a number of things;

1. The layer of "slush, blocks and voids" has no bearing capacity; it cannot transmit loads.

2. None of the ice sheet load incident on the outer edge of the rubble is/can be transmitted to the underwater berm.

3. All of the load is transmitted through the solid ice in the rubble to the face of the Caisson.

For many years some researchers have believed that rubble fields protect structures within them by transmitting forces to the berms and seabottom through the grounded keels of individual ridges in the rubble. Could you please comment on whether the observations you made at Tarsiut are common around offshore drilling islands in the Canadian Beaufort? Also, under what conditions could one expect the creation of a rubble field without the ability to transmit forces to the berm or seabed beneath it?

.../2
1. I said that the keel of the rubble we measured was composed of slush, blocks and voids but I never said that this does not transfer load to the sea bed. There may, of course, be areas in the keel that we did not measure that were more solid, however, this appears unlikely considering the number of measurements made.

2. It is impossible to say if the measurements we made are common around other offshore structures, but I imagine they probably are.

3. The ice pressure measurements we made indicated substantial forces were transmitted to the caisson walls on the east side, but not on the north side where we had the artificially built-up ice pad.
"UNIAXIAL COMpressive STRENGTH AND DEFORMATION OF BEAUFORT SEA ICE"

By R. Frederking and G.W. Timco

Vol. 1 page 89

DISCUSSION

By:
R.D. Hudson, Polar Tech Ltd, Sydney, B.C., Canada

Given that sea ice has a low fracture toughness, and is very susceptible to cracking during coring and specimen preparation, would you comment on the different surface quality of your confined compression tests (in the last paper) and uniaxial unconfined tests, and whether this affects the scatter of your data.

AUTHORS' REPLY

By:
R. Frederking¹ and G.W. Timco², ¹Division of Building Research, ²Division of Mechanical Engineering, National Research Council of Canada, Ottawa, Canada

We do not believe there was any significant difference in surface quality between the two sets of tests. At the temperature and loading rates for which the uniaxial compression tests were carried out, failure could be described as being by yield. There was no evidence that crack propagation, and thus fracture toughness, was a direct factor in failure. The variability in the test results is most likely due to horizontal variations in the grain structure of the ice cover. For confined compression, the failure is related to deformation in a direction normal to the ice surface, in which direction the grain structure may be more uniform.
"PROPOSED STANDARD METHODS FOR MEASURING AND REPORTING ARCTIC RIDGES"
BY F. A. GEISEL

Vol. 3

DISCUSSION
By:
D. Dickins, DF Dickins Associates, Ltd., Vancouver, BC, Canada

In response to Mr. Austin Kovac's comments regarding the accuracy of a rotating head sonar transducer, I would like to refer to results obtained with such a system in the High Arctic (Dickins 1981). We conducted scans from two distinct depths (say 15 and 30 m) and then matched the resulting ridge keel profiles. Correspondence was extremely good and led to increasing confidence in the rotating head system. In each case the sonar was directed vertically for an additional check. In conclusion, a rotating head system can provide reliable profiling results without the necessity of adding a new support length for each reading. The sonar beam is more closely perpendicular to the ice target than a horizontal system, resulting in a reduced footprint and improved definition of the keel shape. Like all sonar profiling systems, the hinged head is also subject to offset errors from current drag.

AUTHORS' REPLY
By:
F. A. Geisel, ARCTEC, Incorporated, Columbia, Maryland, USA

I thank Mr. Dickins for his comments and agree completely with his conclusions. During our field work we have also used the sonar system at two depths to confirm its operational accuracy. Additionally, we always use the sonar to profile a known feature such as an unbroken level ice sheet as a test of
measurement reliability. Mr. Dickins is also correct in pointing out possible errors due to water current drag. Other errors may be incurred by not "aiming" the sonar head exactly along the profile line across the pressure ridge. Particularly when profiling first-year ridges, for which unconsolidated keel shapes can be quite random, it is conceivable that an error in sighting the sonar head profile direction could result in a sonar profile which is different than measured data. Despite these possible errors, the rotating head sonar device remains a valuable tool for underwater profiling of pressure ridge keels. We would also hope that other more advanced tools may be developed in the near future.
"MODEL TESTS OF WAVE ATTENUATION IN ICE"
BY O. GRANDE, V.M. ARUNACHALAM, D.B. MUGGERIDGE

DISCUSSION
By:
P. Wadhams, Scott Polar Research Institute, Cambridge, England

As one who has done both field and laboratory experiments on wave propagation in sea ice, I find that field experiments tell you a lot more. The problem with laboratory experiments is that there is a different scaling law for body effects (heave, surge, diffraction, scattering), flexure effects, and viscous effects (skin friction drag on the ice underside). The result is that however you try to do a model experiment, you are very likely to find that the dominant mechanism for wave decay is not the same on the model scale as on the full scale. I have found that in real ice fields the dominant mechanism is scattering in the case of finite floes, and creep in the case of a continuous ice sheet, but I suspect that in a model icefield the dominant mechanism is viscous drag of the oscillating wave field on the ice underside.

AUTHORS' REPLY
By:
O. Grande, V.M. Arunachalam, D.B. Muggeridge, Memorial University of Newfoundland, St.John's, Canada

Quite naturally, the best method to study any naturally occurring phenomenon is to observe the phenomenon in-situ. However, this may not always be possible for different reasons and in such cases physical modelling of the phenomenon in the laboratory may be very useful, provided that the various physical phenomenon involved are properly modelled.
It is true that a set of scaling laws have to be satisfied to model the propagation of flexural gravity waves in ice covered seas, and they are:
1. Froude number scaling to simulate body effects
2. Cauchy number scaling to simulate flexural effects
3. Reynolds number scaling to simulate viscous effects

Unfortunately, it is almost impossible to satisfy all three scaling requirements simultaneously. However, for large Reynolds numbers the viscous effect is small compared with the gravitational effect in free surface flow problems. The fluid Reynolds number at the plate - fluid interface based on an average particle orbital velocity for all the experiments was $10^5 > \text{Re} > 10^4$. In this range of Reynolds number, the viscous effects are not likely to dominate the overall energy dissipation process. For this reason scaling satisfying the first 2 criteria was used.

To obtain a quantitative description of the energy loss, an energy loss balance equation between different locations inside the ice sheets was set up. The total energy loss was assumed to be made up of the three components:
1. Dissipation due to wave motion in a viscous fluid.
2. Dissipation at fluid/ice interface
3. Dissipation in the ice sheet

The energy loss due to 1 and 2 were calculated as described by Ofuya and Reynolds (Ref. 3 in paper), while the total energy loss, $\Delta E_T$, between location $i$ and $i+1$ into the ice cover was obtained as:

$$\Delta E_T = \frac{1}{2} \rho \omega g C_g (A_i^2 - A_{i+1}^2)$$

where $C_g$ is the group velocity of the flexural gravity wave and $A_i$ and $A_{i+1}$ are measured wave amplitudes at location $i$ and $i+1$ in the ice sheet. It was always found that the combined energy loss due to 1 and 2 was much less than 1% of the total energy loss. This should imply that the viscous loss was not the dominant mechanism for the wave amplitude attenuation in this laboratory study. The only energy loss that is of significance is the loss in the ice sheet as stated by the discusser. However, the energy loss due to creep in the model ice will probably differ from that in real ice.
"REAL TIME SURVEILLANCE OF THE BERING SEA ICE EDGE USING AIRBORNE RADAR"
BY D.R. INKSTER, J. CRAWFORD, D. GRANT

DISCUSSION
By:
P. Wadhams, Scott Polar Research Institute, Cambridge, England

Some of your imagery shows a network of ice edge bands. This demonstrates the value of imaging airborne radar (with downlink) to shipborne scientific experiments. In February of this year we were aboard NOAA ship "Discoverer" at the Bering Sea ice edge studying the properties of these selfsame bands, and would have greatly benefited from having the bands mapped out for us in such a clear way.
"FIELD STUDY ON MECHANICAL STRENGTH OF SEA ICE AT EAST COAST OF HOKKAIDO"
BY Y. KAYO et al.

Vol. 1 page 109

DISCUSSION
BY:
R. Frederking, National Research Council Canada, Ottawa, Canada

(1) In your cantilever beam test you showed an example when the beam broke about 300 mm from the root. Was this typical? If not where did break usually occur?

(2) For your impact tests you indicated that both acceleration and load cell measurements were made. Which measurement was used for calculating impact stress? Also, how did the two measurements compare?

AUTHOR'S REPLY
BY:
Y. KAYO, Mitsubishi Heavy Ind. Ltd., Nagasaki, Japan

(1) The example which I showed you was not a typical but an exceptional case. Other beams broke at points within 5 to 10 cm from the end.

(2) In calculating impact stress both measurements were used. However, the stress derived by the load cell was lower than that obtained by deceleration. The load cell was not designed for that measurements and we found that the response was not high enough to measure the impact phenomenon.
"WATER STRESS ON PACK ICE IN THE VICINITY OF THE NORTH POLE"
BY M.P. LANGLEBEN

Vol. 1 page 128

DISCUSSION
By:
P. Wadhams, Scott Polar Research Institute, Cambridge, England

Have there been any good measurements of ice-water drag coefficient in the marginal ice zone? Would you expect it to be higher or lower than in the interior pack?

AUTHORS' REPLY
By:
M.P. Langleben, Department of Physics, McGill University, Montreal, Canada

To the best of my knowledge, no measurements of the water drag coefficient have been made on ice in the marginal zone. I have never worked on ice in the marginal ice zone but, from descriptions of the ice, I would anticipate drag coefficients falling between the values given in my paper for first year ice and multiyear ice.
"USE OF SHIP'S RADAR TO OBSERVE TWO-DIMENSIONAL RIDGING CHARACTERISTICS"

BY: M. LEPPÄRANTA, E. PALOSUO

Vol. 1 page 138

DISCUSSION
By:
P. Wadhams, Scott Polar Research Institute, Cambridge, England

An additional problem with laser measurements in heavy ice conditions might be that the ship's helmsman steers to avoid heavy pressure ridging, so that the laser gives a biased view of the frequency of ridges.

AUTHOR'S REPLY
By:
E. Palosuo, University of Helsinki, Helsinki, Finland

Of course, this affects slightly on the laser observations, but not on the radar observations. This effect is probably important in the arctic sea areas, where heavy ridges must be avoided. However, in the Baltic Sea the icebreakers are able to penetrate small and medium size ridges, and when assisting merchant vessels they try to maintain their course inspite of the ridges.
"ARCTIC OCEAN ICE DEFORMATION CHART USING SONAR DATA recorded FROM NUCLEAR SUBMARINES"

BY L.A. LE SCHACK

SESSION A2

DISCUSSION
By:
Dr. Peter Wadhams, Scott Polar Research Institute, Cambridge CB2 1ER, England

I wish to make the following points:-

1. The use of r.m.s. draft and standard deviation is unfortunate since such parameters are of real use only to acousticians. The probability density function of draft is far more informative.

2. I doubt the validity of figure 2 in coastal regions of the Arctic, since it was derived from a mixture of winter and summer cruises. The southern Beaufort Sea, for instance, seems to be weighted by summer cruise data and shows no shear zone.

3. Data collected by me aboard HMS "Sovereign" in 1976 was used without acknowledgement or reference (e.g. R.T. Lowry and P. Wadhams, 1977, Proc. 4th Canadian Symp. on Remote Sensing, 407-423; P. Wadhams, 1981, Phil. Trans. Roy. Soc., A302, 45-85 etc.)

AUTHOR'S REPLY
By:
Leonard A. LeSchack, LeSchack Associates, Ltd.
Long Key, Florida, USA

1. Dr. Wadhams' points are all well taken, and firstly, I must apologize for the clear oversight in not acknowledging the HMS SOVEREIGN data that he so graciously provided to me, as well as the
papers that he quotes in his discussion. By the same token, I neglected to acknowledge with many thanks the efforts of Dr. Waldo K. Lyon, Director of the U.S. Naval Arctic Submarine Laboratory, San Diego, California, and Dr. Huon Li of the U.S. Naval Ocean Research and Development Activity, Bay St. Louis, Mississippi, for providing the major portion of the data used for this paper. My only excuse is in the rush to edit and submit the paper, I simply overlooked these important acknowledgments.

2. With respect to Dr. Wadhams' technical comments, I wish to reiterate what I said in the paper: I recognized at the time of writing that there were inadequate data to rigorously substantiate the construction of a composite chart, and especially in the coastal regions. The reader should be aware of this caveat, but also has the option of obtaining the data used (Reference 5) and conducting his own analysis. In short, the deformation chart is a first attempt, and I have no doubt that if further data ever become available, the contour patterns may well change. RMS and standard deviation values were used because they are simple indicators of ice deformation. I agree that the probability density function is more valuable for certain applications, however, I have observed increasing evidence that there may be direct mathematical correlations among these parameters.
From your figure showing cruise tracks of submarines under the Arctic ice, it would appear that only a limited cover is achieved. Yet, from your standard deviation figure, the red curves are smooth, implying considerably more data points. Would you comment please on the grid size you were using to plot them?

AUTHOR'S REPLY

By:
Leonard A. LeSchack, LeSchack Associates, Ltd.
Long Key, Florida, USA

1. A grid size of 280 km, as discussed in Section 5 of the paper, was used.
"CORRELATION OF SHEAR BEHAVIOR OF ICE WITH BIAXIAL STRESS RESPONSE"
BY L. W. MORLAND AND E. N. EARLE

DISCUSSION
By:
T. J. O. Sanderson, BP International, Britannic House, Moor Lane, London EC27 9BU

You implied that ice behaves differently under tension and compression. Under continuum conditions I do not think this is true, though, of course, it is true under fracture conditions. Do you have evidence for this?

AUTHORS' REPLY
By:
E. N. Earle, Shell Development Company, Houston, Texas, USA

We note first that the comment to which Mr. Sanderson refers was made only in passing. No assumption regarding tensile behavior was made in the paper.

The comment that stress-strain relations may be different in tension and compression is based in part on the work of Hawkes and Mellor and on more recent, as yet unpublished, measurements by G. F. N. Cox and W. F. Weeks at the U. S. Army Cold Regions Research and Engineering Laboratory. These show higher values for "initial tangent modulus" in tension as compared to compression. This is a fairly difficult quantity to determine experimentally, and it is possible that this apparent difference is not real. However, they may be real, perhaps resulting from differences in response of pre-existing fractures. We would expect fractures to be present in naturally grown ice. The differences are also present at higher strains, where it is more difficult to explain them away on the basis of experimental technique.
REFERENCE

"PREDICTION OF ICE DISTRIBUTION AND MOVEMENT IN THE OUTEP MARGINAL ICE ZONE"

BY R.D. MUENCH, G.R. STEGEN, L.E. HACHMEISTER, S. MARTIN

Vol. 1, page 190

DISCUSSION

By:
P. Wadhams, Scott Polar Research Institute, Cambridge, England

One of your slides, showing a boat crew marooned in the ice, is an example of an additional phenomenon which we observed during this same Bering Sea cruise. This is that there is an internal circulation within ice bands, so that floes (also buoys and boats) initially at the downwind end are incorporated within the ice and move upwind through the band at some 50 m hr\(^{-1}\). This is one of the many surprising aspects of ice edge bands which will require explanation in a complete MIZ model. For instance, there are several separate classes of band: wind-wave herded bands (Wadhams, P., J. Geophys. Res., 88, C3); atmospheric roll vortex bands, and others which have not been explained.
ANALYSIS OF THE PRIMARY FLEXURAL CREEP OF SEA ICE
by J.R. MURAT and G.A. DEGRANGE
Vol. 1 page 200

DISCUSSION
by T.J.O. SANDERSON, B.P. International, Britanic House,
Moor Lane, London, U.K.

Thank you for an excellent paper. I have two questions:
(i) What was the grain-size of the ice?
(ii) Is there some critical percentage strain at which primary creep may be said to be established?

AUTHOR'S REPLY
by J.R. MURAT, Ecole Polytechnique de Montréal, Montréal, Canada

The authors wish to thank the discusser for his interest.
(i) A completed description of the ice used in the reported experiment can be found in reference /7/ with pictures of thin sections cut normal and parallel to the freezing direction. The S2 type sea-ice which is 70 mm in thickness includes a top layer (around 3 mm thick) of small (1 mm) and randomly oriented crystals due to the seeding process. After a transition zone of about 10 mm, ice grows in the form of vertical columns with the c-axis randomly oriented but parallel to the plane of the ice-cover. The average grain size 6 cm below the top surface is 5 mm.

(ii) Primary creep is considered to initiate immediately upon application of the load. Even if the loading of the beams was completed within one second, it can't be considered as instantaneous. Furthermore, the creep rate in the beginning of the primary creep period is very high. It is
thus difficult to estimate the instantaneous strain. For these reasons, the first deflection measurement accounted for in the analysis of the results is taken 5 minutes after the load application.

The only critical strain which is established in this paper concerns the transition between primary and secondary creep and is found to be equal to ten times the elastic strain (deduced from an equivalent elastic modulus of about 4 GPa/7/).
I was very surprised to see no data points on any of your slides. It is well known that mechanical property tests result in a large degree of scatter. Were all your results within the widths of the lines you have plotted? Did you do any statistical significance tests to determine whether the curves you have drawn are a significantly better explanation than, say, a straight line? Please give some indication of the precision of your data.

AUTHORS' REPLY

By:
A.M. Nawwar, Arctec Canada Limited, Kanata, Ontario, Canada

The authors are in full agreement with Mr. Sanderson on the fact that mechanical testing of ice is usually associated with varying levels of scatter. The degree of scatter would depend on several factors including the test temperature, the ice sample orientation relative to the loading direction, the type of ice, and others. In attempting to present a significant amount of data in a limited space and by necessity small size graphs, it was not realistic to include all data points and it was our preference to present the data by abstract lines and curves. This was done to place an emphasis on the trends observed rather than on curve fitting. The lines which appear in Figure 1 through 6 in the text of the paper represent median curves faired through the data points. This ensures the exclusion of outliers and extreme cases. No statistical analysis was conducted nor warranted in view of
the small number of observations (sample size) under any given set of experimental conditions. In such cases, it is better to exercise some level of judgement in fitting a representative line through the data points than to rely on statistical means. However, if one has a proven model that relates the various physical quantities involved, e.g. strength, temperature, strain rate, etc. it is then possible to apply statistical techniques to produce a probably better representation of the data.

To demonstrate the quality of data and give some information on the scatter in strength measurements, two figures are presented. Figures 1 and 2, reproduced from the original report (ref [3] in the paper) present the effect of strain rate and confining pressure on the ultimate strength of 3 ppt salinity ice at -2°C and -20°C. Each figure presents the data for slant, vertical and horizontal orientations denoted s, v and H; respectively. The data covers the strain rate range from $10^{-5}$ to $6 \times 10^{-3}$ s$^{-1}$ (0.01 to 6 mm/m/s). The confining pressure data are presented in solid circles for the highest confining pressure $p_1 = 2.753$ MPa, slashed circles for the lowest confining pressure $p_3 = 0.689$ MPa and a circled 'x' for uniaxial strength data.
FIGURE 1 EFFECT OF STRAIN RATE AND CONFINING PRESSURE

FIGURE 2 EFFECT OF STRAIN RATE AND CONFINING PRESSURE
"FORMATION AND PROPERTIES OF FRAZIL FORMED IN SEAWATER AT DIFFERENT SUPERCOOLINGS"
BY G. TSANG

Number of Session: A8

DISCUSSION
By: P. Wadham, Scott Polar Research Institute, Cambridge CB2 1ER, England.

An interesting phenomenon occurring with frazil ice slicks in the open sea is the fact that they are herded by wave radiation pressure. Theoretical work done at New York University in the 1950s (summarized by P. Wadham in The Geophysics of Sea Ice, Plenum Press, ch.14) shows that there is a low period cut-off for wave propagation in such a slick. This means that very short waves are totally reflected at the upwind edge and produce a radiation pressure which keeps the slick coherent and propels it along. This may even produce enough compressive force on the slick to stimulate the transition to pancake ice observed by S. Martin in the laboratory under certain conditions (S. Martin and P. Kauffman, J. Glaciol., 27, 283-314, 1981).

AUTHOR'S REPLY
By: G. Tsang, National Water Research Institute, Burlington, Ontario, L7R 4A6, Canada.

Dr. Wadham's comment is a welcome one because it shows that wave pressure is an important contribution to the herding of frazil ice at sea. While the wave pressure is important in herding the frazil together, its continuation is not necessary for the formation of pancake ice once the interstices of the frazil pack are frozen and a strong bond is developed. The word "stimulate" used by Dr. Wadham thus seems to be very appropriate.
"SUBMARINE PIPELINE CROSSING OF M'CLURE STRAIT"
BY:
O.M. Kaustininen, Polar Gas Project, Toronto, Canada
A.C. Palmer, R.J. Brown and Associates, Rijswijk, The Netherlands

Vol. 1 page 289

DISCUSSION
By:
D.F. Dickins, 3732 West Broadway, Vancouver, B.C. Canada

I am interested to know how small ice movements may interfere with the proposed construction method of through/ice pulling. M'Clure Strait ice is thought to be in motion between August and early December. Mid-winter ice movements are not known, but could be expected to exceed movements commonly associated with the more land-locked ice cover of the Queen Elizabeth Islands.

AUTHOR'S REPLY
By:
A.C. Palmer, R.J. Brown and Associates, Rijswijk, The Netherlands

During the construction of the Drake F-76 flowline system at Melville Island, an ice movement of 1 m occurred over several months. It caused no difficulty with ice-based construction. M'Clure Strait is very much deeper, and ice movements of the order of 10 m could be accepted with only minor effects on construction procedures. If necessary, procedures could be modified to accept larger ice movements.
"SUBMARINE PIPELINE CROSSING OF M'CLURE STRAIT"
By O.M. Kaustinen
    R.J. Brown
    A.C. Palmer

Vol. 1 page 289

DISCUSSION
By:
D.V. Reddy, Department of Ocean Engineering, Florida Atlantic University, Boca Raton, Florida 33431 U.S.A.

Did you consider the effectiveness of fiber reinforcement for the lightly-reinforced concrete coating of the pipe?

AUTHORS' REPLY
By:
O.M. Kaustinen, Polar Gas Project, Toronto, Canada

At this stage in the design sequence, Polar Gas has established the feasibility of applying a technically-satisfactory coating to the crossing using existing technology, but has not carried out a detailed optimization study. There are a number of interesting new developments in submarine pipeline concrete coatings, of which the fiber reinforcement mentioned by Professor Reddy is one. Other new developments include various combinations of polymer-modified cement and reinforcements of different types: some of these materials are highly promising. Two recent papers on the subject of pipeline concrete are:

"ICE SURVEILLANCE PROGRAM TO SUPPORT THE NORTH ALEUTIAN SHELF
C.O.S.T. WELL NO. 1"

BY: S. F. GRITTNER
 J. M. KARISH
 A. STEWART

Vol. 3

DISCUSSION

By:

Per Lindgren, Gotawerken Arendal, Gotenburg, Sweden

1. What would your program for fast disconnect, due to sea ice during exploration drilling look like?

2. What are the possibilities, according to your opinion, to minimize the required time? This is with respect to both operating programs and rig design.

3. Would it be an advantage to leave the BOP on the wellhead during the ice season?

AUTHORS’ REPLY

S. F. Grittner, ARCO Oil and Gas Company, Dallas, Texas, USA

1. The primary difference between a C.O.S.T. well and an exploratory well is that we would be willing to temporarily abandon an exploratory well. However, in the case of a C.O.S.T. well, we want to permanently abandon the well. Thus, in the case of an exploratory well, if it were decided to leave the site for the season (in the event of ice), we would probably set temporary cement plugs, retrieve the riser and anchors (leave the BOP on the sea floor) and move off-site. The time required to accomplish this would probably be 4-5
days, as opposed to 12-15 days in the case of a C.O.S.T. well. For the C.O.S.T. well this is the time required to conduct final logging and permanently abandon the well.

2. It should be noted that our work on this project was based on using a conventional moored semisubmersible rig. To cut disconnect time to a minimum it would probably be advisable to use a dynamically positioned rig (eliminating the requirement to retrieve anchors) and temporarily abandon the well by closing the BOP rams. This would cut disconnect time into the range of 6-12 hours. Prior to selecting this strategy, a complete economic trade-off analysis would be required.

3. I believe it would be highly advantageous to leave the BOP on the sea floor in the event of an ice intrusion. However, this decision must be based on sound engineering and economic criteria. That is, ensuring the BOP is not hit by grounded ice and that multiple BOPs are economically justified.
"ALL-YEAR DRILLING OFFSHORE NORTHERN NORWAY"
BY O.G. HOUMB

Vol. 3 and Vol. 4

DISCUSSION
By:
F.G. Bercha, 938 - 2 Avenue N.W., Calgary, Alberta, Canada, T2N 0E6.

1. As a basis for your simulation model, why did you use Markov Processes instead of a random draw process such as Monte Carlo?

2. What was the time resolution of your simulation?

AUTHORS' REPLY
By:
O.G. Houmb, The Ship Research Institute of Norway, Trondheim, Norway

1. Simply because we have good experience using Markov Processes for simulation of environmental variables, mainly because of the "memory" inherent in this technique.

2. 3 hours.
"REAL-TIME ICE FORECASTING IN SUPPORT OF WINTER DRILLING OPERATIONS IN THE BEAUFORT SEA"

BY E. LEAVITT, E. KRAKOWSKI, B. MERCER, K. SCHUBERT

DISCUSSION

By:
F.G. Bercha, Calgary, Alberta, Canada

The finite element fine-scale model you discussed can be characterized as operating in two modes: free-drift and ice stress. In its current developmental stage, the fine-scale model operates better in those situations which more closely resemble free-drift than in cases where ice stress is a critical factor. However, the FSM is limited in all cases including free-drift by insufficient accuracy in the input data.

In ice stress mode, as you said, forecast results are dependent on ice constitutive theory. However, evaluation of ice constitutive coefficients on the forecast scale is necessarily a very inaccurate process. Stress strain law of ice on that scale is a function of so many parameters, including ice type, ice concentration, size distribution, temperature, convergence or divergence, current stress, wind stress, ice thickness, and numerous factors as to be rendered virtually indeterminate. Accordingly, forecast to results in situations where ice stresses are often predominant show large deviations when compared to observations. Do you have any comments on how you could improve evaluation of constitutive coefficients of ice for finite element predictions on an operational scale?

F.G. Bercha and Associates have had experience with both stress strain and kinematic modelling. We have found that media
characterized by highly indeterminate constitutive laws, such as operational scale continuous or discontinuous ice cover can be modelled relatively easily with good predictive results utilizing kinematic modelling or mimicking of dynamic morphology. Such kinematic models generally include a statistical predictor component and a stochastic element generator. Do you think that kinematic modelling, because of its independence of constitutive theory, might provide a better solution to modelling of ice on an operational scale than finite element modelling?

AUTHOR’S REPLY

By:
E. Leavitt, Intera Environmental Consultants Ltd., Calgary, Alberta, Canada

Dr. Bercha's comments cover a wider range of concerns than can be addressed completely here. The following are a few limited remarks.

In the discussion by Dr. Bercha, the major assumption appears to be that the constitutive law relating internal stress to strain rate is too complicated to be modelled deterministically, therefore one should develop stochastic or kinematic models.

Obvious if one's understanding of the relevant processes is incomplete because of a lack of data or because the physical processes are so complicated that it is not possible to devise a practical deterministic model than the kinematic approach may be the more suitable approach. Intera in fact, has applied such statistical models to the problems of forecasting iceberg motion in Lancaster Sound and ice edge motion in the Bering Sea.
However, statistical models have a basic limitation in that they cannot be used to forecast an event that has not previously occurred in the data set used to generate the coefficients. In contrast, deterministic models, if formulated correctly, have the potential for producing forecasts in such situations.

It is important when considering ice models such as the ice forecast model, to not confuse the ice stress calculated by the model with the actual stress which might be exerted on a structure by the surrounding ice. This latter stress is a very complicated function of the driving forces and such parameters as salinity, ice thickness, block orientation, temperature, etc.

Results from other studies (i.e., Aidjex) suggest that the appropriate internal stress can be related to the work done to build pressure ridges during deformation. This work can be related to the change in potential energy that occurs as ice is piled up or down in the pressure ridge and the internal stress can be calculated rather straightforwardly from the ice thickness distribution. Thus, computation of the internal stress is not believed to be as intractible as Dr. Bercha suggests.

We believe that the data set collected over this past winter will provide the basis for improving the calculation of model internal stress and improving further the accuracy of the forecasts.

This is not to say that further research into the formulation of the internal stress term would not enable further improvements to be made in ice models such as the finite element model described in our paper.
"TECHNICAL AND ECONOMIC ASPECTS OF ARCTIC MARINE TRANSPORTATION"
BY K. TAKEKUMA

Vol. 1 page 335

DISCUSSION
By:
D. Aldwinckle, Lloyd's Register of Shipping, London, U.K.

In your presentation you indicated that very thick plate scantlings would be required for your proposed arctic tanker. Have you and your company considered yet the possible alteration in the mechanical properties of the hull structure during the construction process? If so, can you say what steps must be taken in shaping and welding these structural components in order that the mechanical properties are not impaired as this is an area, in my opinion, which requires careful study.

At Lloyd's Register we have carried out simulation analyses for ice-breaking cargo vessels along the lines shown in Fig. 1. There are many advantages in carrying out investigations of this type. Has this been done for your design proposals?
AUTHOR'S REPLY
By:
K. Takekuma, Mitsubishi Heavy Industries Ltd., Nagesaki, Japan

The discussor pointed out the alteration in the mechanical properties of high tensile steel plate about 70-80 mm in thickness during shaping and welding process and requested to explain what steps must be taken during and welding process. The author's reply is as follows. As explained at the time of presentation, application of controlled rolling process in steel manufacturing made it possible to realize high tensile steel for low temperature use characterized by low level of impurity content, low level of equivalent carbon content and fine grain size with high uniformity together with no deterioration of grain size during welding. As the results, reliable weldability of high tensile steel plate of about 50-60 mm in thickness for
use below -60 C has been confirmed and applied to some marine structures for Arctic use. And improvement of high tensile steel material has been pursued by application of accelerated cooling process in rolling, addition of proper content of nickel and so on. This will make it possible to apply steel plate of 70-100 mm in thickness for Arctic use in the near future. Detail of investigations of fabrication technology of steel structures for Arctic use made in Japanese ship building companies and steel mills will be published shortly in some conferences concerned.

The discusser kindly showed the lines of design procedure used for his conceptional design of ice-breaking cargo vessels. The author and his colleagues have also carried out a conceptional design of Arctic tanker and INGC along such design procedure as the discussor recommended.

Thank you very much for your valuable discussion.
"PERFORMANCE OF A NEW AIR CUSHION ICEBREAKING BOW
BY R. ABDELNOUR
J. DUBOIS

DISCUSSION
BY:
D.F. Dickins, D.F. Dickins Associates Ltd.,
3732 W. Broadway, Vancouver, B.C. Canada,
V6K 2C1

In your presentation you described a variation in cushion pressure with surface condition at a constant ballast weight. Unless the all up weight of the ACV platform is varying, average cushion pressure within the cushion must be a constant. Could your pressure variations be a local dynamic effect related to position of the pressure pick-up instrument?

Another graph showed a decrease in hover height with increasing ballast weight. Does this behaviour indicate that the ACV platform is being loaded to a cushion pressure approaching the fan shut off pressure (i.e. are the fans undersized in this application)?

AUTHOR'S REPLY
BY:
R. Abdelnour, J. Dubois and J. Laframboise

The cushion pressure at a constant ballast weight remains constant if the area under the cushion surrounded by the ACIB finger tips is constant. This was not the case since the area was influenced by the height of the ACIB. This in turn was influenced by the degree of air losses between the skirt and the water or the ice. Over water, this air loss was greater than over ice, due to better air seal. Thus a smaller area was under the ACIB which provided better seal.
We do not believe there is any dynamic effect since both electronic and water column pressure meters were used.

In reply to your second question, the fan shut off pressure is designed to provide 10 kPa cushion pressure; however, the ACIB was never loaded to reach the 10 kPa cushion pressure. The decrease in hover height with increasing ballast weight is a normal behaviour of the ACIB and most other air cushion platforms.
"FULL SCALE TESTS OF CANMAR KIGORIAK IN VERY THICK ICE"

BY G.A.M. GHONEIM, A.J. KEINONEN

VOLUME 3

DISCUSSION

By:

I. GLEN, Arctec Canada Limited, Ottawa, Canada

I would like firstly to thank the authors for their paper and for making available some results from the much-tested Kigoriak. I believe the limitation on the length of POAC paper has not allowed you to do justice to this project and I have a number of points to note which will permit the authors to expand a little on their paper.

1. With respect to the use of a finite element model with which to relate measured strains to loads, it is understood that a full scale calibration was performed? If so, how and what correlation with the model was achieved and what error bounds should be put on the correlation with the model was achieved and what error bounds should be put on the 'measured' loads? Did either the F.E. model or the measured strains move into the non-linear range?

2. Referring to Figure 2, would not the dynamic response of the hull in bending cause the normal velocity to oscillate somewhat during 'slide-up' and is it not possible that the deck stress due to quasi-static bending during 'slide-up' plus hull bending response exceed the peak stress in the impact phase.
3. Referring to Figure 3, would the authors comment on the fact that the slope of the pressure/area relationship approaches almost exactly with the line of constant force 
\((p \times a = K)\).

4. Finally, with respect to the formula for global load in the hull we are pleased to see clarification of the dependence in the original formula on the specific geometry of Kigoriak, in fact, introducing the effective properties. It is stated that the equivalent beam formula rendered a 'stress coefficient Cs' of one-third that anticipated, indicating a highly damped response. This coefficient Cs incorporates the dynamic load factor which is of course a function of the ratio of load application period to ship natural response period. Could the authors indicate the range of Cs valves noted in the tests, and whether or not the mean from the August ten differed significantly from that in the October tests.

Once more, congratulations to the authors for introducing a paper to promote further discussion on this topic.

AUTHORS' REPLY

By:

G.A.M. Ghoneim, Canadian Marine Drilling, Calgary, Alberta, Canada.

The authors would like to thank the discusser for his interest in the paper and his valuable remarks. The following is our response to the four questions raised in the discussion:

1. Full scale calibrations were carried out for the local ice pressure measurements and the results agreed very closely with the Finite Element prediction. No full
scale calibrations were done however for the intermediate area forces. The accuracy of the measured forces are therefore dependent on the accuracy of the finite element analysis. It should however be mentioned that the shear strain measurements were designed together with the finite element idealizations in such a way that the resulting errors were minimized. The accuracy of the measurements are expected to be in the range of 5 to 10 per cent. The effect of getting into the non-linear range of the behaviour of the structure did not significantly affect the results due to the fact that no permanent deformations of any significance were encountered. In the very few rams where yielding was exceeded, the areas affected were very local and the resulting permanent strains were almost negligible.

2. We agree that depending on the dynamic response of the vessel, the peak deck stress encountered during the 'slide-up' phase can be larger than that occurring during the impact phase. The data confirms this fact.

3. The results shown in Figure 3 do not confirm that "the slope of the pressure/area relationship approaches almost exactly the line of constant force ($p \times a = k$)". Only the envelope to the October data is close to such a relationship.

4. The mean values of the Cs coefficients estimated from the August and October data were 0.051 and 0.066 with standard deviations of 0.009 and 0.028, respectively.
Carbamide ice, as a model ice, has better mechanical properties than any other known materials. However, according to my experience in CRREL, it is still difficult to obtain \( \sigma_f = 12.5 \) kPa with \( E/\sigma_f = 2000 - 5000 \). Could you describe how you measure the flexural strength and strain modulus? Also I would like to have a brief description of your model ice structure and warm-up procedure for ice tempering.

AUTHORS' REPLY

By:

A. Nakamura Kawasaki Heavy Industries, Ltd. Japan
M. Kano Hitachi Zosen Corporation Japan
K. Nozawa Kawasaki Heavy Industries, Ltd. Japan
T. Kitazawa Hitachi Zosen Corporation Japan

(1) Measurement of the flectural strength:

The flectural strength of the model ice was measured by cantilever beam tests. Simple load spring testers were used to measure the breaking load applied at the free end.
of the beam. The flexural strength of the ice was calculated by using the following beam equation.

$$\sigma = \frac{6FL}{bh^2}$$

where

- \(F\) = failure load
- \(l\) = length of beam
- \(b\) = width of the beam
- \(h\) = thickness of the ice

(2) Measurement of the elastic modulus:

The elastic modulus was established by measuring the deflection under defined loads in the middle of the ice cover. The elastic modulus was calculated by the following equation.

$$E = 0.1375\left(\frac{F}{w}\right)^2 \frac{1 - \nu^2}{\sigma_w g h^3}$$

where

- \(\sigma_w\) = density of water in kg/cm³
- \(g\) = gravity constant = 9.814 m/s²
- \(\nu\) = Poisson's number
- \(h\) = ice thickness in mm
- \(F\) = load in N
- \(w\) = deflection in mm
- \(E\) = elastic modulus in MPa
(3) Warm-up procedure and ice structure:

The air temperature in the ice tank was raised to a little above zero degree just after the target ice thickness was reached and the model ice was exposed to this temperature as long as required for obtaining properly scaled strength values.

Authors did not take photomicrograph of ice structure for their model ice but it was observed to be the fine grained columnar ice.
"OUTLINE OF A NEW ICE TANK FOR ICE-GOING VESSELS AND POLAR OFFSHORE STRUCTURES"

by M. Sudo, N. Yoshimura, S. Narita, N. Koma and K. Kamesaki

Vol 2, page 644

DISCUSSION

by K. Hirayama, Iwate Univ., Japan

It is my great pleasure to hear that Japan's second ice model test basin is just completed. In your test basin, how do you fulfill the uniform distribution of temperature and concentration of urea solution in the tank? And how are the uniformities of ice thickness in the tank?

AUTHOR'S REPLY

by N. Yoshimura, Tsu Research Lab., NKK, Japan

We use three sets of portable under water pumps to fulfil the uniform distribution of temperature and concentration of urea solution in the tank. The maximum deviation of ice plate thickness is less than ±1MM along the center part of 15M length, when the average thickness is 50MM.

Transverse thickness deviation is also very small, and the ice thickness near the side wall is nearly same as that of central passage.
"STRENGTH STANDARD FOR ARCTIC SHIPS"
BY A. TUNIK

Vol. 2, page 664

DISCUSSION
By:
I.F. Glen, Arctec Canada, Ltd., Ottawa, Canada

Mr. Tunik's equations (3) for ice pressure are based on some recent Soviet work. Could he state to what extent the formulations depend on measured full-scale data or on laboratory work.

We note that bending strength of the ice is a parameter required to define load when ice bending results from the impact. In view of the dependence of ice strength properties on strain rates, what statistical values does he envisage being incorporated into regulations?

I applaud Mr. Tunik's proposals for reducing the number of classes of high Arctic ships and believe that this is the feeling of other Societies (i.e. Lloyd's) and a possible direction to be taken by Transport Canada.

AUTHOR'S REPLY
By:
A. Tunik, American Bureau of Shipping, New York, USA

The equations (3) were developed by Kheisin and Kurdyumov [7,9]. The formulations can effectively work up to the extent where the base assumptions used are valid. Numerous full-scale trials and laboratory tests are in an agreement with the formulations. The most recent evidence supporting the model are your, Arctec Canada's, tests reported earlier at today's sessions ("Ice Impact Pressures and Load" by I.F. Glen and G. Comfort). Your
direct measurements of distribution of pressures, forces and contact areas during the impacts are in very good agreement with those predicted by the theory.

The formulations can become incorrect for impacts at a very low speed (less than several knots) or with small ice pieces which can be easily moved in water rather than crushed or broken. For other real conditions of navigation the model works good enough.

For real ship/ice impacts the bending failure of ice occurs within a respectively narrow range of strain rates and out of the zone where the bending strength depends strongly on the strain rate. Therefore, we can use values of the bending strength of ice corresponding to maximum ice conditions for a particular ice class.

Let me express appreciation of your interest in the presentation and your comments.
"MATERIAL PROBLEMS IN ARCTIC CONSTRUCTION"
BY P. JUMPPANEN, E. RÄSANEN, K. SÖDERLUND

DISCUSSION
By:
G. Fotinos, Ben C. Gerwick Inc., San Francisco, USA

I complement the professor on presenting the clear advantages and disadvantages of steel and concrete materials. In our studies of arctic structures we have used both steel and concrete in a single structure using the advantages of both materials and thus eliminating the disadvantages. These hybrid structures offer advantages of lower cost and lighter draft during tow.

AUTHOR'S REPLY
By:
P. Jumppanen, Technical Research Centre of Finland, Espoo, Finland

I fully agree with the opinion of the inquirer. The use of concrete and steel together in a single structure would offer some technical and economic advantages e.g. in the cases of caisson type structures as well as of terminal and harbor structures. These possibilities have not been sufficiently utilized, because the structures have been developed and built in general by shipyards or building companies. Also this paper has been prepared by the representatives of steel industry and concrete industry, separately, so that the hybrid structures have not been discussed.
FULL SCALE TESTS OF THE BARING CAPACITY OF A FLOATING ICE SHEET
BY L. FRANSSON

Vol. 2 page 687

DISCUSSION

By
J.R. Murat, Ass prof Ecole Polytechnique of Monteriol, Canada.

I would like to compliment the author for a very interesting and valuable paper. Well documented full scale results are always very welcome. The reported tests seem to have been performed at a constant deformation rate (fig 4). Did the author made any recording of the evaluation of vertical deflections with time (under a constant load)? Also, could the author comment the results presented on the last slide of his presentation where the wood reinforcement is shown to have a strong effect on the creep behaviour of the plate and on its permanent deformations.

AUTOR'S REPLY

By:
L. Fransson, University of Luleå, Sweden.

No creep tests were done the first winter. Later, tests under a constant load during 5-10 minutes were performed. The results from the reinforced plate tests have not been analyzed. The positive effect on the creep behaviour indicates that a proper reinforcement on the top of the plate can take up both tensile and shear stressed before the ice cracks.
DISCUSSION

By:
D. V. Reddy, Florida Atlantic University, Boca Raton, Florida

The flexibility of the soil can have a considerable effect on the dynamic response of a structure in the ice environment. The fluctuating ice loading will change the soil properties and, therefore, the response. Swamidas and Reddy [1] found a significant change in the dynamic magnification factor in a study on dynamic ice-structure-soil interaction of a monopod type platform. In the work of Montgomery and Lipsett [2], the filtering out of the flexibility of the structure was, in fact, a filtering out of the effect of the foundation rotation and translation as the structure was sufficiently rigid. The discusser would like to congratulate the speaker [3] on his contribution to 'deconvolution' studies for ice-structure interaction.

AUTHOR'S REPLY

By:
M. Määttänen, University of Oulu, Oulu, Finland

The author appreciates the point raised on the importance of soil effects on the dynamic response of a structure in the ice environment. The soil structure interaction is a nonlinear phenomenon and, if strictly observed, it greatly complicates the dynamic response calculations. Experiences learned from structures under wave loads can be utilized also with structures under dynamic ice loads. The references mentioned by Dr. Reddy are valuable and I should like to add one more, [4].
REFERENCES


"SIZE EFFECTS IN ICE AND THEIR INFLUENCE ON THE STRUCTURAL DESIGN OF OFFSHORE STRUCTURES"

BY: S.H. IYER

DISCUSSION

BY:

F.G. Rercha, President, F.G. Rercha Associates, Calgary, Canada.

I would like to applaud your progress toward solution of the critical problem of scale effect in ice mechanics. Although your expressions are of a relatively approximate nature, a first order approximation based on a relatively poor data set, the agreement is promising and the fact that you are continuing to pursue this important problem is personally gratifying to me. I look forward to seeing incorporated in your analysis the results of the large scale measurements which should become available as a result of the caisson instrumentation programs discussed this morning by Esso and Dome.

AUTHOR'S REPLY

BY:

S.H. Iyer, Gulf Canada Resources Inc., Calgary, Alberta, Canada

Let me first thank the audience and Dr. Rercha in particular for the renewed interest shown in the scale effect problem in ice. Dr. Rercha is one of the few earlier investigators who strongly feel that the problem is worth pursuing.
I have to mention at the outset that this paper just makes an attempt at quantifying the scale or size effect and is no doubt a first order approximation, based on the existing data set. However, as pointed out by Dr. Bercha the results seem to indicate an encouraging trend and I feel there is considerable incentive in looking at this trend semi-analytically, considering both brittle and ductile failure modes. No doubt, the current large scale measurements of Gulf, Dome and Esso may shed light on this problem. However, it may so happen that most of these measurements turn out to be strictly for first year ice and rubble and lacking the more vital pieces of information related to thick multi-year ice. It is this latter information that is most important for the design of offshore structures for local loads from ice in deep waters. Unless and until we get these data for multi-year ice, analytical means corroborated by or incorporating all actual tests data, both laboratory and field, with appropriate adjustment for size and type of ice seem to be the only solution. I hope Dr. Bercha will agree with me on this.


"CENTRIFUGAL MODELING TO DETERMINE ICE/STRUCTURE/GEOLOGIC FOUNDATION INTERACTIVE FORCES AND FAILURE MECHANISMS"
BY T. VINSON

Vol. 2 page 845

DISCUSSION
By: Vitoon Vivatrat, Brian Watt Associates, Inc., Houston, TX, U.S.A.

You mention consideration of stress-history in modeling soil shear strength. My first question is about your approach for soil deposits whose stress history were influenced by freeze-thaw or other processes such that the soil has a stiff crust near the mudline with decreasing strength with increasing depth for, say, 30 ft. Would this create any complication in modeling the shear strength profile?

The second question is regarding the ice behavior when some vertical deformation occurs i.e., buckling, ridging, ride-up. What is the effect of the centrifugal force in this case?

AUTHOR'S REPLY
By: T. Vinson, Oregon State University, Corvallis, OR, U.S.A.

The author appreciates the questions offered by Dr. Vivatrat. In response to the questions raised: (1) Duplication of a stiff crust would be difficult, but not impossible to model in a centrifuge. It would undoubtedly require successive "spin-ups" in the centrifuge. Duplication of decreasing strength with increasing depth would most likely not be possible. (2) The inertial force produced in the centrifuge replaces the gravitational force in the field and, therefore, allows the physical dimensions associated with a field structure/geometry to be reduced by the
ratio of inertial field strength divided by \(1 \text{ g}\) (termed "n"). Vertical deformations observed in a centrifuge model study associated with buckling, ridging and/or ride-up would reflect field deformations when multiplied by "n".
"INTERACTION BETWEEN ICE AND STIFFENED PANEL"
BY T. WATAMOTO, K. YAMAMOTO, N. YOSHIMURA

DISCUSSION
By:
D. S. Aldwinckle, Lloyds Register of Shipping, London, UK

There is one question I would like to ask concerning the differences between the finite element results and the experimental values for the plate panel stresses, as shown in your Table 3. What were the central lateral deflections of the plate panel and did they exceed half the thickness of the plate? If so, may I suggest that membrane stresses could be one reason for the difference. If this has not been allowed for in the modelling of the finite element work.

AUTHOR'S REPLY
By:
K. Yamamoto, Nippon Kokan K.K., Yokohama, Japan

Dr. D.S. Aldwinckle has pointed out that membrane stresses could be one reason for the difference between the experimental and calculated stress values in plate as shown in Table-3.

That is a good suggestion. Certainly the influence of membrane stress should be taken into consideration, in case the lateral deflection of plate is very large.

Although we did not measure the actual deflections in our experiment, the deflection is considered to have not been so large as compared with the thickness of plate. Because the
average of central lateral deflections in plate was 0.6 mm for 6 mm plate and 0.18 mm for 10 mm plate respectively according to the results of fem calculation where membrane stress was taken into consideration.

Therefore we consider that membrane stress is not so dominant factor in this case, but further study would be required on this subject as Dr. D.S. Aldwinckle has suggested.
"THE PRESENT STATE & FUTURE DEVELOPMENT OF OFFSHORE ARCTIC STRUCTURES"
BY K. R. CROASDALE

DISCUSSION
By:
R. D. Hudson, Polar Tech Ltd, Canada

During your presentation, you frequently indicated that a simple relationship exists between the mass of an extreme ice feature and the energy it is likely to transfer to a fixed structure. Yet there is observational evidence to indicate that ice islands or very large floes will likely split or break-up during a grounding collision on a berth. This implies that there must be some naturally occurring maximum floe area/thickness which will remain intact and therefore transfer all its energy to the structure.

Are you aware of any work being done in this field, to determine whether such limits exist, and if so, what their boundaries are likely to be?

AUTHORS' REPLY
By:
K. R. Croasdale, Petro-Canada, Canada

Dr. Hudson makes a good point. In many real situations, the deformation, fractures and motion which occur are much more complex than the simple models used in calculations. Furthermore, these phenomena will usually mitigate the forces acting during a collision. The simple models which I have referred to can therefore be regarded as conservative, which is a good starting point. Certainly I agree there are many examples of floes splitting during impact, but on the other hand I believe there are cases of floes of similar size not splitting. Recent work by Ralphor addresses the floe splitting...
issue (POAC 1981, Quebec), also the recent paper by Palmer et al (Applied Glaciology Symposium, Hanover 1982) uses fracture mechanics theory to predict the occurrence of radial cracks, which could initiate splitting.

In the case of features such as ice islands grounding on a sub-sea berm, the models which Marcellus and I developed (IAHR, 1981) did take into account the flexural failure of the ice during ride-up.
I was interested to hear your discussion of how a wedge-shaped defence system may decrease iceberg impact loads. But I'd like to stress that the loads are still extraordinarily high - of the order 3/4 to 2 million tons, for those of us who have difficulty with meganewtons. Would you comment on the feasibility of building a structure with foundations which could resist such a force?

AUTHOR'S REPLY

It is correct to state that the impact loads are very high; they vary from 3,100 MN (0.34 x 10^6 ton-force) to 10,000 MN (1.1 x 10^6 ton-force) depending on the assumptions given in the paper. We have not carried out any feasibility studies of the resistance of gravity-base structures to such loads, so we cannot reply to this comment in detail. However, if you consider that typical structures for Hibernia may have a total displacement of the order of 9,000 MN (1.0 x 10^6 tons), these loads represent approximately 34% to 110% of the weight, which indicates potential problems with overall stability against sliding. Again, it should be pointed out that the assumptions inherent in this simplistic analysis are very conservative - a more detailed
assessment of other energy absorption mechanisms, and a consideration of the loading on probabilistic terms may well reduce the iceberg loading by as much as one order-of-magnitude. If this were the case, then we consider that gravity platforms could be designed to withstand iceberg impact.

DISCUSSION
By:
K.R. Croasdale, Petro-Canada, Calgary, Canada

Tim Sanderson makes the point that even with the "geartooth" or wedge-shaped structure geometry, the calculated loads are very high. It is important to recognize that the assumption made for the iceberg geometry in the impact calculation is very conservative and probably unrealistic. The calculation assumes a "blocky berg" with constant thickness of 75 m. This means immediate contact over the full thickness of 75 m (for a vertical structure). In reality icebergs at Hibernia can be expected to be of more random geometry, and the probability of having contact over the full thickness is virtually impossible.

Design of real structures should be based on iceberg profiles generated statistically from field measurements. At this stage, the sensitivity of load to a variety of edge profiles would be a useful addition to the authors' work.

AUTHOR'S REPLY
By:
A.B. Carmaert, Acres Consulting Services Limited, Calgary, Canada

These comments are certainly valid. As we stated in the paper, and in our response to Mr. Sanderson, our analysis is very conservative, and much more work needs to be done to refine the assumptions and develop more realistic design procedures.

At the present time we have very little data on typical iceberg profiles. In response to this discussion we ran the computer
program for a variety of iceberg profiles and the results are presented below. The first case (Figure 1a) relates to an initial vertical face, which increases in height by the relationship,

\[ h_x = h_0 + x \]

where \( x \) is the penetration distance. The contact width varies as given in equation (8) of the paper; all other parameters are constant as given in the "reference design". This has the result of reducing the impact load by up to 69% (from 10,400 MN to 3,230 MN) as seen in Figure 2a.

The second case relates to an iceberg shape which has a spherical profile at the contact point (Figure 1b), where the contact area is derived from the relationship

\[ A_x = 4\pi x D_s D_b / (D_s + D_b) \]

where \( D_s \) is the diameter of the platform, and \( D_b \) is the diameter of the spherical profile. This may be a more realistic description of a fairly smooth keel shape, and the load is reduced by as much as 75% (from 10,400 MN to 2,610 MN) as seen in Figure 2b. The load would be reduced even further when these profiles are combined with wedge-shaped platform walls. This points out the tremendous sensitivity of the analysis to shape-related parameters of both the iceberg and the structure, and a statistical treatment of iceberg loads would certainly be more appropriate.
1A WEDGE-SHAPED PROFILE (CASE 1)

1B SPHERICAL-SHAPED PROFILE (CASE 2)

FIGURE 1. ICEBERG PROFILES.

2A EFFECT OF WEDGE-SHAPED PROFILE (CASE 1)

2B EFFECT OF SPHERICAL-SHAPED PROFILE (CASE 2)

FIGURE 2. ANALYSIS OF ICEBERG IMPACT WITH VARIATION IN ICEBERG PROFILES.
"SELECTION OF DESIGN ICE PRESSURES AND APPLICATION TO IMPACT LOAD PREDICTION"
BY S. SLOMSKI AND V. VIVATRAT
Vol. 2 page 909

DISCUSSION
By:
B. GRAHAM, ARCTEC CANADA, LTD., CALGARY, CANADA

Your paper proposed a Monte Carlo technique to develop a statistical prediction of the ice load during impact.

Dr. P. R. Kry with Esso Resources Canada has proposed, in previous work, a statistical model that predicts ice loads for an ice sheet against a wide structure.

1. Assuming full penetration, how do the results of your method compare with his earlier results?

2. What are the advantages of going to the Monte Carlo approach?

AUTHORS' REPLY
By:
V. Vivatrat, Brian Watt Associates, Inc., Houston, Texas

1. We have tried to relate the impact pressure to indentation tests so that the statistical data from these tests can be used. Conceptually, Kry's approach for wide structures and the method we proposed for selecting the impact pressure are very similar.

2. The Monte Carlo simulation procedure allows the consideration of the variability inherent in the floe parameters (diameter, thickness), impact velocity, and ice strength.
DISCUSSION

By:

T. RALSTON, EXXON PRODUCTION RESEARCH COMPANY, HOUSTON, TEXAS

1. In Fig. 1b, the laboratory strength curve looks like the distribution of peak stress values from individual ice samples. The "effective ice pressure" curves appear to be distributions of instantaneous values. Wouldn't it be more appropriate to make this comparison with the distribution of instantaneous stress values from the stress-time history of the laboratory data?

2. Fig. 2, from Blenkarn, presents data on "Steady Ice Loads". The ice force time histories of Fig. 3 are certainly not "steady". Would you define what is meant by "Steady Ice Loads"?

3. Fig. 5 gives the CDF for instantaneous ice pressure. Since there are infinitely many instantaneous values in any finite time period, how do you keep your computed results for maximum forces from being totally dependent on the time step (or penetration step) that you use in the calculation?

AUTHORS' REPLY

By:

V. VIVATRAT, BRIAN WATT ASSOCIATES, INC., HOUSTON, TEXAS

1. Ice load on structure has traditionally been predicted on the basis of comparison with the peak ice strength. The comparison in Fig. 1b reflected this practice.
2. Blenkarn defined "steady ice load" as the load magnitude associated with uniform floe (i.e., excluding peak loads due to embedded ridges). The ice in Cook Inlet deformed in continuous crushing and shearing, and the ice loading approached something approximating a steady state condition. The subject of this paper is on estimating the continuous deformation behavior from a regular indentation test (Fig. 3) which is indeed not a steady state problem.

3. The penetration interval for selecting the instantaneous pressure was chosen from the indentation load time history as 3 to 6% times ice thickness. If only one independent contact zone is assumed, then it is true that the maximum force from each impact event will depend somewhat on this assumption on the time step. In the paper, we showed the effects of allowing multiple independent contact zones. This significantly reduces the effect of the peak pressure (see Fig. 5). In our more recent work, we allowed the number of independent contact zone to vary with the contact width. Thus peak pressures can occur during the initial contact when the contact area is small but not during the later stage of impact.
"REPORT ON VERTICAL ICE LIFTING OF PILES IN A NUMBER OF DANISH MARINAS WITH A DESCRIPTION OF THE LIFTING MECHANISM"

BY P. TRYDE

DISCUSSION

By:
D.V. Reddy, Department of Ocean Engineering, Florida Atlantic University, Boca Raton, Florida.

Can the empirical formula given by Eqn. 3 be improved by incorporating the effects of the soil, the cross-sectional shape and the material of the pile?

AUTHORS' REPLY

By:

Formula (3) should only give the external pulling ice force. The pulling resistance of the pile should be calculated by use of the pile and soil parameters and well-known formulas of pulling resistance of piles. If $P_{ice} > P_{soil}$ the pile will be lifted.
DISCUSSION

By: K.R. Croasdale, Petro-Canada, Calgary, Canada

I congratulate the authors on a very thorough examination of the mechanics of ice ride up. They refer to the paper by myself and my co-authors written in 1978, and suggest the equation for forces in the ride up condition is incomplete. This is not true for the limit to ice ride up which we were examining - that of downward failure of the ice due to the weight of blocks on the slope. However for islands, the downward failure of advancing ice is unlikely, and I agree with their analysis which examines the limit to ice ride up due to ice crushing.

I should however also suggest extreme caution in the use of both analytical and physical modelling of ice ride up and pile up events. In our experience, both approaches indicate ice ride up to be more likely than it seems to be in real situations around islands. Also some of the mechanisms seen in model tests, such as repeated ramping, and rubble building toward the structure, don't seem to occur in real life. One problem with saline model ice, is improper scaling of modulus which allows the ice to bend too much before failure.

AUTHORS' REPLY

By: J. Cox, ARCTEC, Incorporated, Columbia, Maryland

I fully agree with all of the comments Mr. Croasdale has offered, particularly with the extrapolation of model test results
using "real" i.e. saline or carbomide ice as the test medium. Properties such as too low elastic modulus or too high crushing strength will tend to enhance ride up on a model slope as is suggested in Figure 10. Laboratory experience using synthetic ice and with thin brittle saline ice sheets demonstrate less of a tendency for progressive ride up.

The generation of rubble piles around islands rather than ride up mentioned by Mr. Croasdale as being typical experience, may be in part due to a limited data base of operation. Virtually all rubble fields observed in the field have been generated in the early freezeup season when the ice is thin. The analogous case for model tests is shown in Figure 6 where thin ice almost always results in pile generation regardless of slope roughness. Therefore the model and prototype are consistent. Where the question arises is what happens with thick ice as in a massive spring breakup ice movement. Here there is little or no experience to draw from. The model tests suggest that ride up is inevitable. For conservatism in the design of production structures, the possibility must therefore be considered.

Finally, the model tests conducted to date, have for the most part, ignored the compounding of ice movement effects. Whether an existing grounded rubble pile will prevent ride up by a thick ice sheet or even if an unsteady advance of the ice sheet will induce pile up remains to be demonstrated in both model and prototype.

I would like to indicate errors in the text of this paper. A sign error occurs in equation (10) and should be correctly given as:

\[ N = Zbh_0 \gamma \cot \alpha (\sin \alpha + \mu \cos \alpha) + \rho_v \frac{\sin \alpha + \mu \cos \alpha}{\cos \alpha - \mu \sin \alpha}. \]  (10)

Also Figure 4 has been drafted incorrectly. The slope reaction and friction forces \( F_N \) and \( \mu F_N \) should be applied at the point of contact of the floating ice sheet with the slope.
"ASSESSMENT OF ICE RIDE UP/PILE UP ON SLOPES AND BEACHES"
BY J. COX, J. LEWIS, R. ABDELNOUR, D. BEHNKE

Vol. 2, page 971

DISCUSSION
By:
D. Nevel, M/PO Offshore Engineering, Farmers Branch, Texas 75234

The authors state that Croasdale, Metge, and Verity (1976) failed to take into account the reaction force at the point of ice contact with the slope. Croasdale, etc. did recognize this and stated that the analysis is for ice sheet failure in downward bending and subsequent pile up at the water line which inhibits ride up. Later Croasdale (1980) considers the contact force between the floating ice sheet and the slope.

The authors' equation 6 represents the horizontal force on the floating ice sheet at the instant the sheet begins to slide up the slope. At this time the floating ice sheet has not been bent in flexure. Hence, equation 6 is not a limiting condition. This also means that equation 8 is not the limiting criteria for buckling instability to occur.

In equation 9, the authors have neglected to add the direct compressive stress to the bending stress. This can be corrected by replacing \( \sigma \) with \( \sigma - N/bh \). Equation 9 must be evaluated at some position \( x \). The position \( x \) should be chosen which makes the stress a maximum.

It appears that there are two typographical errors in equation 10. The first term should be identical to equation 6, and the second term should have \( \cos \alpha - \sin \alpha \) in the denominator rather than \( \cos \alpha + \sin \alpha \). Note that the \( P \) in equation 10 is defined by equation 9. To obtain the slope angle \( \alpha \) for which the least
horizontal force is required, equation 10 should be differentiated with respect to $x$ and set equal to zero. Equation 11 does not give the correct angle since equation 6 is not a limiting condition.
SHORE ICE PILE-UP AND RIDE-UP IN NORTON SOUND
AND ALONG THE ALASKA BERING SEA COAST
By A. Kovacs

DISCUSSION
By:
F. G. Bercha, 933 - 2 Avenue N.W., Calgary, Alberta,
Canada, T2N 0E6

The variety and hierarchy of pile-up and ride-up mechanisms may be classified in accordance with the degree of randomness associated with their incipience and progress.

Following the relatively deterministic pure mode initial failure, numerous optional mechanisms may take place: clearing, ride-up, pile-up, override, pile-up growth, or pile-up penetration. Ride-up would appear to be the least stochastic; three dimensional pile-up, the most stochastic or random. Can you comment on such a classification within the context of your observations?
SHORE ICE PILE-UP AND RIDE-UP IN NORTON SOUND
AND ALONG THE ALASKA BERING SEA COAST
By A. Kovacs

AUTHOR'S REPLY TO BERCHA
By:
A. Kovacs, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, U.S.A.

I would agree that ice ride-up appears to occur frequently after the initial failure of an ice sheet. This may be illustrated by the large number of ice rafted features which are found in all drifting pack ice. More ice rafted features would exist, except that when the ice ride-up process reaches some critical resistance, another failure mode occurs. The result is that the initial ride-up morphology is destroyed or obscured by the subsequent failure process.
SHORE ICE PILE-UP AND RIDE-UP IN NORTON SOUND
AND ALONG THE ALASKA BERING SEA COAST
By A. Kovacs

DISCUSSION
By:
K. R. Croasdale, Petro-Canada, P.O. Box 2844.
Calgary, Canada

Once again, Austin Kovacs has presented us with a
very interesting paper describing real ice ride-up
and pile-up events. These give designers very sobering
eamples of potential ice encroachment on off-
shore structures (despite the favourable experience
to date).

Could you comment on Jack Cox's remark that ice pile-
up tends to advance shoreward? The experience at
artificial islands to date indicates the reverse.
SHORE ICE PILE-UP AND RIDE-UP IN NORTON SOUND
AND ALONG THE ALASKA BERING SEA COAST
By A. Kovacs

AUTHOR'S REPLY TO CROASDALE

By:
A. Kovacs, U.S. Army Cold Regions Research and
Engineering Laboratory,
Hanover, New Hampshire, U.S.A

Mr. Coff's comment is based upon his observations of
ice movement and failure during model studies. It is
my belief that model tests tend to favor shore ice
pile-up and ride-up rather than rubble field formation
seaward of the shore line. In these tests the model
ice sheet will at times either override the previously
formed ice block rubble on the shore or actually drive
under or through the ice block rubble and then contin-
ue shoreward.

These tendencies are believed to be due to the large
model scales generally used, >1 to 30, and to the uni-
versal inability to "brev" an ice model material which
behaves as sea ice does when it fails against an off-
shore structure. Model tests of shore ice pile-up and
ride-up are useful nevertheless as they tend to pro-
vide information on worst case events. In short,
model ice studies appear to be good for evaluating the
ice pile-up and ride-up defense capabilities of a
given offshore structure design.
"DESIGN, CONSTRUCTION AND MONITORING OF THE TARSIUT RELIEF ICE PAD"

By V.W. NETH, T. SMITH, B.D. WRIGHT

Vol. 3

DISCUSSION

BY:
K. Eriksson, VBB-SWECO, Box 5038, 10241 Stockholm, Sweden

The ice-pad islands have been designed and made for the exploration phase of the development of the oil and gas field. Do you have any idea how the system is going to be for the production phase?

AUTHORS' REPLY

BY:
V.W. NETH, Gulf Canada Resources Inc., Calgary, Alberta, Canada.

The ice pad at Tarsiut was designed and constructed for relief well purposes during the winter period of 1981/82 only. The type of structure suitable for offshore production purposes in the Beaufort Sea will be most likely a gravity type one such as Monopod, Monocone or Dom's APAL concept. Gulf reviews presently several conceptual designs of production structures for Tarsiut which at this time have to be treated as confidential information. As an alternative to steel, concrete and sand, the use of ice as construction material for large offshore structures had seriously been considered provided the structure can be protected from wave erosion and melting during the short summer season.
"DESIGN, CONSTRUCTION AND MONITORING OF THE TARSIUT RELIEF ICE PAD"

BY V.W. METH, T. SMITH, R.D. WRIGHT

Vol. 3

DISCUSSION

BY:
T.J.O. Sanderson, BP International, Britannic House, Moor Lane, London EC2Y 9BU, U.K.

I believe there was a problem with a major crack through the ice pad in early spring 1982. Would you describe this and how it happened?

AUTHORS' REPLY

By:
V.W. METH, Gulf Canada Resources Inc., Calgary, Alberta, Canada

On February 4, 1982 a wedge type crack running in the NE-SW direction separated the NW corner of the ice pad from the main body of the pad.

The NW corner area was the last to be constructed and had less time to consolidate than the remainder of the pad. Furthermore the area was in deeper water and was presumably not fully grounded. The separated portion amounted to about 10% of the surface pad area, it subsided and was 25-40 m below the level of the main pad.
Strong SE winds generated substantial stresses within the ice cover surrounding Tarsiut which at that time was located within fast ice. The presence of high stresses was reflected in high ice pressure measurements registered by the caisson island instrumentation.

The combined action of settlement and movement of the ice cover caused the development of the crack whereby most likely bending stresses due to differential settlement initiated the crack. Stresses generated by the surrounding ice cover then caused the crack to open up in a wedge type fashion. The crack stabilized in less than 18 hrs., after its initiation. Monitoring of the crack clearly showed that the two crack faces had only separated but had not moved in a shearing motion.

In conclusion it can be said that during the February 4th event a small portion of the pad separated from the main pad but the overall stability and useability of the relief ice pad was not affected.
"ARCTIC SLOPE PROTECTION DEVELOPMENT"
BY R.E. POTTER AND J.H. SUN

DISCUSSION
By:
D.V. Reddy, Department of Ocean Engineering, Florida Atlantic University, Boca Raton, Florida

Would fiber reinforcement be practical for the concrete panels?

AUTHOR'S REPLY
By:
R.E. Potter and J.H. Sun, Sohio Petroleum Company, San Francisco, California

Due to its ability to inhibit freeze/thaw cracks and crack propagation, fiber reinforcement appears to have potential for use in the concrete panel slope protection devices currently under development for Arctic application. The use of fiber reinforcing has been reviewed by Sohio during preliminary evaluations of alternative slope protection systems and was shown to have promise for Arctic applications. Additional work to optimize the panels is currently underway and will include a detailed evaluation of fiber reinforcing.
"MODEL STUDY OF FREEZING FRONT PENETRATION IN OFFSHORE GRANULAR FILL STRUCTURES"

By T. VINSON, R. WILSON and L. MAHAR

Vol. 2 page 1025

DISCUSSION

By:

H.L. Jessberger, Ruhr-Universitat Bochum, Universitatsstrabe 150, Germany

Solute rejection during freezing is a phenomenon which can be observed not only in freezing saline soil water mixtures but also by freezing soil saturated with "normal" ground water. Increases of salinity or content of other freezing temperature reducing chemicals can cause isolated fields of reduced strength inside the frozen soil mass. But referring to your test results, I would like to ask you whether or not you have tested the freezing process in the soil together with the change of pore water properties in connection with cyclic frost penetration. This could simulate in a saline sand the in situ conditions during a number of frost periods.

Secondly, I would like to ask you if you have ever thought about the use of artificial freezing for strengthening artificial sand or gravel islands. I am quite sure that artificial ground freezing in sand or gravel islands can be used very effectively as it was indicated by recent feasibility studies.

AUTHORS' REPLY

E.: T.S. Vinson¹, L.J. Mahar², P. Wilson¹

¹ Oregon State University, Corvallis, OR, U.S.A.
² EPTEC Western, Inc., Long Beach, CA. U.S.A.

The authors appreciate the comments and questions offered by Prof. Jessberger. In response to the questions raised: (1) we have not investigated solute redistribution and freezing front penetration associated with freeze/thaw cycles. We agree, however, that this would be interesting to consider. (2) We consider the use of artificial freezing techniques to strengthen soil islands or foundation berms. We concur with your belief that artificial freezing techniques can be used effectively in arctic offshore structures.
"ICE LOAD INSTRUMENTATION FOR ARCTIC OFFSHORE STRUCTURES AND VESSELS"
BY D. J. GOODMAN

Vol. 3

DISCUSSION
By:
Y. S. Wang, Exxon Production Research Co., P.O. Box 2189,
Houston, 77001, USA

I would like to make two comments.
1. The philosophy of deriving stress magnitude from strain rate measurements in the paper requires that the ice is in the secondary creep range. In field applications extreme ice loads often develop during storms where the global ice strain rate may be in a non-steady state. A stress calculated from a non-steady strain rate could be significantly inaccurate.
2. The author commented that the stress state through the thickness of the ice sheet may be non-uniform due to the variation of temperature and salinity profiles and the panel type pressure sensors may not be able to obtain accurate pressure measurements due to this vertical non-uniformity. For the Exxon pressure sensor the stiffnesses in both transverse directions are much greater than that in the sensing direction. The non-uniformity of the pressure through the thickness direction may generate some shearing stress between the ice and the face of the sensor but this should not have any significant effect on the measurement of the normal pressure.

AUTHOR'S REPLY
By:
D. J. Goodman, New Technology Division, Production Department,
BP Petroleum Development Ltd., London EC2Y 9BU, UK

I am grateful to Dr. Wang for his two comments.
Interpreting primary creep as secondary creep will always lead to an overestimate (i.e. a safe one) of the local stress, and since the stress is proportional to the cube root of the observed strain rate, any error is cube rooted. The problem identified by Dr. Wang applies equally to a load panel particularly in the stiff transverse directions since it is necessary to understand how the load panel (an elastic object) perturbs the ice (a creeping solid) as the load fluctuates. No published analysis of a load panel has examined the effect of primary creep on the panel response. This would not be a problem if the panel were exactly perpendicular to the maximum compressive principal stress but this cannot be guaranteed.

Installation of a pressure panel disturbs the ice local to the panel, and it may be several days before the stresses are again representative of the stresses prior to the panel installation. A surface strain rate measurement causes the least disturbance to the ice, and provides an immediate indication of the principal stresses and their direction (assuming three independent strain rate measurements are made).
"A NEW SENSOR FOR MEASURING ICE FORCES ON STRUCTURES"
By: M. Metge, G.R. Pilkington and A.G. Strandberg

DISCUSSION
By:

B. Graham, Artec Canada, Calgary

Your data shows that the sensor, itself, can creep as much as 20-25% over a relatively short 7-day period.

1. Is this effect on accuracy also temperature dependent?

2. How do you correct for it when the applied load also becomes a function of time as it is in the field?

AUTHOR'S REPLY
By:

G.R. Pilkington, Gulf Canada Resources Inc., Calgary

1. We have not investigated the creep effect at different temperatures but it probably is temperature dependent.

2. In the ice the temperature is fairly stable. However, as the ice pressure variations occur over relatively short time periods (hours), it is possible to draw a baseline to the data by hand. Although, tests and calculations have been done that indicated that the observed baseline shift is due to creep, no theoretical corrections are made to the data. We feel that the above hand correction to the creep is adequate and results in a relatively small (less than 10%) final error to the pressures obtained, which we feel is acceptable considering the other problems in measuring ice pressures and the costs and other merits of these panels.
Peter Wadhams, Dr.
Scott Polar Research Institute
Cambridge, England

SUMMARY OF THE MAIN RESULTS OF THE CONFERENCE

I would like to give my personal impressions of the results of the "A" sessions on 'sea ice properties and conditions in cold regions'.

To be able to say whether these sessions have been successful or not, we have to ask "what is POAC for?" There are many answers to this question, apart from the obvious one of giving us all a nice trip to Finland. My answer would be that progress in engineering design for Arctic ports, offshore and deep ocean regions depends on progress in understanding the basic properties, distribution and behaviour of sea ice. Thus POAC is, or should be, a creative interaction between ice scientists and Arctic engineers.

Speaking as an ice scientist, what I would hope to learn from the engineers in this interaction is:-

1. What kinds of applications are there for which this basic knowledge is required? We have heard about many of them at this POAC: submarine pipelines; offshore platforms of all kinds which must either withstand ice forces or (in the case of the C.C.S.T. no. 1 well on the Aleutian shelf) must be kept clear of ice by a suitable safety margin; and novel designs of icebreaker including air cushion vehicles.
2. What ice properties do we need to measure to give the engineer the information he requires?

3. How well do we need to measure these properties?

I will now try to estimate how adequately the ice science papers at this conference have helped to answer the questions of the engineer.

I will begin with ice dynamics, which attempts to predict how ice moves and deforms under environmental forcing, including how its thickness distribution develops through ridging. We have not heard anything at POAC about basin-wide dynamics, perhaps because in the Hibler model we now have a numerical model which is reasonably good at describing the behaviour of the Arctic Ocean ice cover as a whole. Moving down to the regional scale, we have heard from Heralla and Venkatesh about the Atmospheric Environment Service's regional ice model for the Beaufort Sea, which uses the Hibler formulation on a smaller grid scale, i.e. is a finite difference scheme on a Eulerian grid with a viscous plastic constitutive law for ice. We have also heard about Leavitt et al's model, designed to cover a smaller domain in the southern Beaufort Sea in direct support of drilling operations. In contrast to the AES model this is a finite element scheme on a Lagrangian grid with a plastic constitutive law, i.e. it resembles the AIDJEX model. McKenna et al have discussed how important the constitutive law is for the correct description of ice motion, and in particular how the Hibler scheme does not permit a coherent ice mass with anomalous properties to remain coherent, but forces it to diffuse into the surrounding pack. We have heard from Muench et al about the shape of future models for MIZ (marginal ice zone) dynamics, which are of increasing importance because of offshore developments in MIZ areas (Bering, Labrador and Greenland Seas). In this zone, where floe sizes, wave interactions, lateral heat fluxes and oceanographic interactions are significant, a whole new
approach to modelling is necessary. In this area we heard an 
interesting paper by Grande and Nuggeridge on model tests of 
wave attenuation in ice. Wave-ice interaction, in the form of 
wave-induced flexural failure, is the process controlling floe 
size distribution in the MIZ, and must be incorporated in MIZ 
models. The apparently simplest problem in MIZ dynamics is the 
prediction of ice edge position, and here, for short term 
predictions, we are on reasonably firm ground with free drift 
models and the Hansen rule. But even here, for predictions 
many days ahead, a more subtle probabilistic approach is 
necessary, as we heard today, from Hansen and Grittrner. The 
purest form of free drift is the drift of icebergs, and it was 
shown today by El-Tanen et al that this drift can be well 
predicted if adequate environmental information is available, 
particularly the distribution of ocean currents with depth. 
The normal operational problem is that such information, 
especially on currents, is not available and that predictions 
based on inadequate data can be severely in error.

This brings us to the essential feature of all models, that 
they are only as good as the data which support them. There 
are two sorts of data required: firstly, the coefficients 
necessary for the formulation of the basic physical equations; 
secondly, the environmental forcing data needed to run the 
model. One might have thought that the basic coefficients 
would be known by now, but Langleben has shown us that there 
is still a large range of observed variation in something as 
fundamental as the ice-water drag coefficient; we can choose 
from a range of possible values, giving radically different 
results, and it is certain that different values should be 
used for different ice regimes. The same is true for the 
air-ice drag coefficient.

Coming on to the environmental data, we begin with the 
question of the large-scale measurement of ice distribution 
and properties in the Arctic. On the largest (basin-wide) 
scale, we have LeSchack’s paper on mean thickness and
roughness over the Arctic culled from a number of submarine sonar profiles. This is an unusual paper in that the roughnesses are expressed in a form which is useful mainly to acousticians, but there is a basic need for such basin-wide thickness surveys. The distribution of ice thickness and of pressure ridge depths can be used to assess the performance of ice models, and to predict extreme values of ice draft for estimating ice forces on structures and the probabilities of ice scour. Some aspects of this problem were discussed by Brooks and the analogous problem of iceberg scour and extreme iceberg depth prediction was discussed in papers by Barrile and by Green et al.

Still on the subject of thickness, how do we measure it without a submarine? This is still an unsolved problem. We have had a paper on eddy current methods, which may hold some promise, and another by Lepparanta and Paoluss on laser profiling, in this case from a ship. Laser profiles give surface roughness, and some inferences can be made about ice thickness distribution as a result of co-operative laser-sonar experiments which have been carried out using aircraft and submarines acting together. But there is still no reliable direct method of sounding ice from above. Perhaps, in the end, ice as a material, with its variable properties and brine content, will defeat our efforts and we will have to depend on interpreting results from a suitable combination of remote sensing methods which have been adequately calibrated by ground truth experiments.

Going from thickness to extent, we have heard from Ahlnäs and Jayaweera of how useful NOAA satellite data is to the measurement of extent, drift and deformation of sea ice in relatively cloud free areas such as the Antarctic. The fact that her case study concerned a crushed ship is a telling argument for having satellite APT receivers aboard all ice-going ships, together with somebody on board competent to interpret the images. What limits the use of satellites for
directly supporting ice operations is the cloud and darkness problem. This will not be solved until we have routine SAR (synthetic aperture radar) data from satellites, although microwave radiometers are valuable were it not for the processing time and poor resolution. We must wait for ERS-1 in 1987. In the meantime a most valuable tool is SAR or SLAR (side looking airborne radar) flown from aircraft. We have heard from Bullock of how valuable and flexible this has been in tracking the Bering Sea ice edge position in support of a drill snap that had to be kept free of ice, and from Sutton and Mudry of how SLAR imagery can provide useful information on the distribution of icebergs.

Going on to ice properties, the review paper by Weeks, as usual, tells us most of the story. Two of the recent advances in sea ice physics of which he reminded us are the demonstration that c-axis orientation in ice sheets is a response to preferred current direction - which may be of importance in giving an anisotropy to ice strength - and the discovery that frazil ice is of more general occurrence than hitherto supposed, making up some 50% of the structure of Antarctic ice floes. We heard a paper by Tsang on laboratory experiments of frazil ice; such ice is also of importance in fresh water, for instance because of its effect in blocking water intakes. On the larger scale of ice deformation features, we heard a very interesting paper by Kovacs on multi-year pressure ridges, which are perhaps the most fearsome ice type from the point of view of impact on structures, and a second paper on observations of ice pile-up. Hudson discussed the ice extrusion which has been observed to occur during some pressure ridge formation events, while Nevel analysed pressure ridge forces and showed that the predicted slope of 20 - 25° agrees well with Kovacs' field observations.
Finally we come to what is a somewhat frustrating aspect of this and of other POACs, the field of basic mechanical properties of sea ice - its creep and strength properties. There have been a large number of papers on various kinds of creep and strength test, including uniaxial, plane strain and triaxial compressive strength, shear strength and fracture toughness, but no clear picture emerges except one of disagreement. On the experimental side, Frederking drew our attention to the vital importance of an exact description of the ice sample being tested (crystal size and orientation, salinity, strain history and method of machining for the test) as well as careful measurements of the stiffness of the mounting system (which may contribute to a spurious creep rate) and the way in which the loading is applied to the ends of the specimen. On this basis many earlier papers ought to be discarded, and there is a case for a critical review of all ice creep test work to determine what body of results should be regarded as acceptable. In a discussion, Palmer drew attention to the fact that "compressive strength" tests at low strain rate are really creep tests, and vice versa, so there is even disagreement on terminology. On the theoretical side there have been some elegant treatments, such as that of Murat and Degrange on fitting equations for the primary and secondary stages of flexural creep. However, in the theoretical analysis of fracture, there is still much disagreement about the fracture mechanisms which occur under different circumstances of impact, shear of flexure, so that application of basic physical equations is of uncertain validity. The main conclusion in this field is that the time is ripe for a general agreement on acceptable experimental methods and theoretical frameworks.

While on a critical note one must mention the failure of many authors - by no means all of them Soviet - to have their submitted papers presented at POAC. This upsets schedules, and if such papers could have been weeded out we might perhaps
have had two parallel sessions instead of three, so that participants could have listened to a greater fraction of their favourite papers. There have also been a number of papers featuring graphs with no numbers on the axes, on the grounds that the information concerned is confidential. Such contributions do not increase knowledge.

In summary, I am impressed by the vigour of the research and development projects presented at this POAC. It is clear that the race in the Arctic is hotting up, and POAC serves an immensely valuable function in bringing together Arctic scientists and engineers in a true creative partnership.
O. M. Kaustinen, Vice-President, Engineering
Polar Gas Project
Toronto, Canada

SUMMARY OF THE MAIN RESULTS OF THE CONFERENCE

I am pleased to have the opportunity of giving some of my personal comments in summary form on the proceedings and results of conference POAC 83. Particularly pleased since this conference is here in Finland. I consider it a great honour.

I have personally been involved in Arctic related projects since 1969 and in this interim period there has been a noticeable increase in the information and data available on our northern environments. It has been conferences such as POAC that have greatly assisted in the dissimulation of this knowledge so that we, who have to work in this harsh and often hostile environment, have been able to not only overcome the many obstacles but often optimize our methods of operations.

For instance, the first attempts at operating in the north have mainly relied on brute force and pure guesswork whether it was pushing ships through the ice or drilling offshore wells in ice-infested waters.

After these initial and often crude attempts, many of us come to the conclusion that there must be better methods for undertaking the work and accomplishing our objectives. This has resulted in numerous studies, investigations and modelling of the environmental conditions and methods of operation. And in turn, a tremendous amount of data and knowledge has been accumulated on northern conditions such as ice strengths and roughness, currents, ice floes, ice ridges, sea bottom and sub-bottom conditions, ice islands and ice bergs and many other related aspects.
This has given us more confidence in our ability to predict working conditions and the environment, to design, construct and operate northern Arctic drilling and exploration equipment and to design, construct and operate safely, transportation systems including pipelines and docking facilities.

POAC 83 has shown that there has been a seemingly remarkable difference in the priorities placed by the various countries as to what aspects should be investigated and developed.

As an example, Finland as well as some of the other Scandinavian countries appeared first interested in developing methods of ship transportation year-round in ice-covered waters during the winter months. This is quite understandable for this seems vital to their economic well-being.

They have pioneered ice-breakers and ice-breaking tankers and carriers and developed technology in this area which is now used or adapted to specific needs by many other countries including Canada and the United States of America. I am also pleased by their current programs regarding refinement of these techniques which include:

- development of larger and stronger vessels
- model-testing facilities to initially simulate and try new methods and designs
- full scale testing to relate these preliminary results from the model-testing to actual conditions.
- and finally, the development by Wartsila and others in air-cushion vehicles that could have an enormous benefit economically in certain parts of the Arctic and at certain times of the year. In particular, this would have an impact on the ability to transport materials, supplies, equipment and personnel across ice-infested waters during the break-up or ice formation period.
This is not to say that Finland and the other countries have not addressed or developed methods for drilling offshore wells, installing pipelines or other transportation methods for offshore development of oil and natural gas reserves. But, these investigations and developments appeared to have come at a later stage.

On the other hand, Canada and the USA, in particular Alaska, have not had the transportation methods as their main theme initially. The trust of these countries has been to first find ways of exploring and developing the tremendous potential of the offshore reserves to meet the seemingly insatiable energy needs of North America.

Many methods have been developed to contend with the harsh environment which is often very sensitive during certain times of the year. Operations in the Arctic have been refined considerably as a result of the research and investigations undertaken in the last few years.

Some of the methods adopted at this time include but are not limited to:
- flooded or reinforced ice platforms for drilling in deep waters in Canada's high Arctic (a very cost effective method)

- artificial sand islands in shallow waters in the Beaufort Sea

- specially reinforced steel and concrete platforms in medium deep waters in the Beaufort Sea

- ice-strengthened drill ships and support by special ice-breakers in deeper waters in the Beaufort Sea

- semi-submersible drill ships south of Alaska and methods to predict when moving ice could endanger operations
- semi-submersible drilling operations off Canada's east coast and methods of predicting the occurrence of ice bergs and the towing of ice bergs that may endanger operations

- designing, constructing and operating large diameter pipelines in waters that may be ice-covered for most of the year

- designing, constructing and operating the offshore pipelines in the shore approach zones, protecting them from potential danger from ice-scouring due to ice movements, ice-ridging and/or ice islands.

POAC has been instrumental in bringing much of this information to the attention of individuals in many disciplines that could benefit from all these studies, investigations and actual operations.

Here are a few examples:

- the academics and research institutions have had an opportunity to learn what their counterparts have studied, concluded and as to their plans, as well as determining how well or badly actual operations have gone, and potential areas for new research.

- operators in the private sector have had an opportunity to determine the latest developments by others and assess the applicability of the latest research and investigations to optimize their methods of operations.

In summary, I believe this conference and others before it can be of great importance to all sectors and all countries that have to contend with operations in offshore Arctic and sub-Arctic conditions. One only needs to look for their particular area of interest, it is here.
As a final note, I would like to thank herra Jumppanen, Sirpa Suomela and all the very capable assistants who have been outstanding in organizing this conference and making sure that everything ran smoothly. And, of course, you have especially made me feel at home. Kiitos.

And should you ever want me to give another paper here in Finland, I shall make the utmost efforts to catch the first available flight here.

Kiitos oikein paljon kaikesta.
Jan-Erik Jansson, Director General
The National Board of Navigation
Helsinki, Finland

SUMMARY OF THE MAIN RESULTS OF THE CONFERENCE

I have been asked to review the main results of sessions 3 l...B 7. It is a pleasure to comply with this request because I have worked for very long periods with related problems in shipyards, in design, in universities and for the last six years in administration at the Finnish Board of Navigation. This government agency incidentally covers a large field and is a.c. responsible for hydrography, chart production, piloting, fairways, navigational and ship safety, environment protection at sea, maritime legislation, some transports and icebreaking.

Generally speaking a tremendous development has taken place during approximately the last 15 years in science and engineering affected by arctic conditions. We are now able to achieve in the arctic field what we could not dream about in the 60's. Part of this in result of conferences, where exchange of ideas can take place. The POAC conferences, starting in 1971, and especially this last have contributed significantly to our knowledge, and this seventh POAC conference is in dissemination of knowledge in some of its fields challenged only by the seventh WEEMENT seminar on ships and structures in ice conducted here in our subarctic country during the elever last days of March this year. It is a pleasure to see, that several authors and participants of the WEEMENT seminar also have honoured the POAC conference with their presence.
It is not easy in less than 10 minutes to summarize the results of 29 papers prepared by 53 authors with more than 1,000 slides and over 100 discussers. Therefore I have to restrict myself to the most essential generalities and I apologize for not being able even to mention all the authors.

Sessions B 1 - B 3 dealt with technical and commercial aspects of navigation in cold regions. They got a fine start with the invited general lecture by Katsuyoshi Takekuma from Nagasaki. He presented a fundamental comparison between pipeline systems and marine transportation of arctic products. He stated that pipelines are at advantage with large quantities, but he did not estimate the fraction - 10% has sometimes been mentioned - at which marine transportation may be profitable. On the role of ships in the arctic he mentioned all the services expected in the total cycle of activity. They are: survey of resources, construction of facilities, exploration, production, transport and supply. Mr. Takekuma then went on to discuss ship types for arctic transportation of crude oil and liquefied natural gas. He recommended independent ice-transiting ships and not icebreaker assisted strengthened cargo liners. He did not express an exact opinion regarding the preferable size of these cargo ships, but mentioned a propulsive power of 60,000 - 70,000 hp. Analysing some other POAC papers I get the impression that feasible maximum icebreaking cargo ship sizes may be around 200,000 tdw with propelling power in the order of magnitude of 150,000...200,000 hp.

Mr. Takekuma in a fundamental way discussed the severe navigational hazards in the arctic regions and in that connection the nuclear powered large cargo carrying submarine, which has been proposed from time to time.

The arctic regions are extremely sensitive to oil pollution and the very strict Canadian approach in this respect was emphasized during the conference.
Air-cushion vehicles are a challenging alternative for short range arctic transports, and these were discussed in a Canadian and a Finnish paper. In the latter Mr. Korppoo and Mr. Mustamäki showed, that it is possible in air-cushion vehicles design and construction to apply simple shipbuilding technique and components. So far in this field only aeronautical type engineering has been applied. The authors also under certain assumptions compared relative transportation costs for different modes of transportation. Not surprisingly the helicopter is the most expensive. If its costs are put at 100 % the air-cushion vehicle could be 14 % and normal ship transportation costs only 0.2 %.

It is interesting to note that, as shown in some other papers, the air-cushion concept also has been used in icebreaking both at low and high "critical" speed. Sometimes unfortunately this is in conflict with the transportation capability. This may, if not properly taken care of, result in operational problems.

In session B 2 a Canadian and a Finnish approach to extending ice navigational seasons were highlighted. Air bubbling systems can be used here to advantage provided that the thermal reserve is sufficient. An interesting parallel with icebreaking can also be made here since as shown in other papers, airbubbling at the forebody of icetransiting ships do reduce the frictional ice resistance. In general one can say that the use of compressed air has several advantages in many arctic engineering applications.

The four papers of session B 3 highlighted mainly the difficult problems in arctic port design and construction. In the Canadian papers of this session an example was given of a real problem. A 300,000 tdw ship under certain arctic ice condition was estimated to require a 12 km turning diameter!
Sessions B 4 - B 7 all dealt with icebreaking technology including model testing. It was started already at the opening ceremony by the presentation and film of Dr. Landman, eminent Finnish shipbuilder. He showed a.o. that development in ice operation is at its best only if theoretical research is supported and confirmed with realistic model testing and full scale ship measurements. It is no longer possible to rely on slowly accumulated experience at sea. Gone are the days, when shipowners were convinced that a skilled navigator always could cope with any situation arising. Now we have to give the navigator both the tool, the good ship, and information regarding how best to operate it!

Session B 4 was devoted to icebreaking model testing. The difficulty - or rather impossibility - of producing model ice with correctly scaled down physical properties were elaborated on. Dr. Erkvist, head of the icebreaking laboratory visited yesterday by many conference participants, in his paper explained the main icebreaking resistance components, breaking, sub-emption and velocity resistance all including friction, which actually is the dominant part. He showed how it is possible by using presawn ice fields to separate the components and he also presented a new expression for the submersion resistance (that is sliding and turning the floes). It is interesting to note, that all the existing ice model testing laboratories in the world apparently are using different techniques and full scale prediction methods. This is not surprising since the number of variables are of course much larger than in open water model testing.

In sessions B 5 - B 7 several new concepts in icebreaker design and operation were discussed. In a film the surprisingly impressive performance of the experimental icebreaker CALMAR KIGORIAK was revealed. Part of its success may be due to the high thrust of the shrouded propeller in relation to the relatively narrow beam. In two papers from the
Federal Republic of Germany the application of a new icebreaking method using combined shear and bending was demonstrated. This has been successful in certain conditions.

LCDR Brigham of the USCG showed how economy and operational efficiency may be achieved by operating two small icebreakers in tandem in place of one large in the Great Lakes.

Some papers dealt with operational icebreaking problems such as ice coned channels. In the paper of Mr. Tsoy from Leningrad perhaps for the first time the convoy speed of an icebreaker followed by an assisted ship was discussed. In other papers ice pressures and impact loads of ice were treated. The paper of Mr. Tunik from American Bureau of Shipping was instructive because it compared ice strengthening classes of different classification societies and authorities. The invited lecture in session 6.10 by Dr. Varsta on impact between ship hull and ice also would have had to be included in the sessions I have reviewed here.

It is a pleasure for me to notice that many of you have accepted our invitation to make a trip in the flagship of the Finnish icebreaker fleet, the UPHO (we operate 10 big icebreakers). Here in Helsinki it already feels like spring, but in the Gulf of Bothnia, where the ship now operates there is at present about 60 cm thick level ice and interesting ridges of several meter thickness! For those of you, who in this connection are interested in developments of Finnish government icebreakers I would like to refer to my recent lecture at the WECERMT seminar.

At the moment world shipping experiences a severe crisis manifested by the fact that half of the transport capacity of the world merchant fleet is not in use and more than 100 million tons are without employment. This economic situation together with the downward trend in hydrocarbon prices may not
look encouraging from the point of oil and gas development in the arctic. However I am confident that conditions will improve again so that the resources of the arctic areas can be put at the disposal of mankind to the common benefit of all. In this work the POAC conferences can give good contributions. I look forward with great expectation to the 8th POAC conference.
SUMMARY OF THE MAIN RESULTS OF THE CONFERENCE

1. In the C sessions there were 47 papers covering the following topics:

   Arctic Structures (Drilling Islands in Beaufort Sea, Port at Nome, Buoys, Lighthouses in the Baltic),

   Ice Forces on Structures in Ice Infested Waters (Due to pack ice, multi-year ice, icebergs, river ice.),

   Measurements of Ice Forces on Ships in Full Scale (Sisu, MV Arctic, Kigoriak),

   Ice Load Sensors (For Arctic Structures, Ships, Lighthouses),

   Behaviour of Ice on the Coast and Around Arctic Structures,

   Instrumentation and Systems for the Arctic Regime (Ice Detection Radars, Meteorological Stations, Telemetry Systems, etc.).

2. The technology we are developing is really a means to an end, and in my case the end is drilling and producing oil in the Arctic Ocean. As a result of the exchange of ideas at conferences such as PCAC we have seen, over the past 2 years, very significant advances in Arctic drilling
technology. Islands have been constructed in shallow waters of the Beaufort Sea by Esso over the past decade. In the past 2 years we have seen 2 instrumented caisson structures in the moving pack ice region of the Canadian Beaufort Sea and several very well instrumented icebreakers.

In the summer of 1983, Esso will be installing their Caisson Island and Gulf will commence using their Round Drillship. In 1984 Gulf will be bringing their Mobile Arctic Caisson into the Canadian Beaufort Sea.

This has two important implications:

i) We now have enough confidence in our knowledge of ice loads that we can go ahead with structures in ice infested waters. The structures may not be optimal but they are operating well.

ii) That technology will advance tremendously over the next few years in this area as we can now get full scale data.

It is clear from this conference that the supporting technology to allow the operations to proceed safely is also moving ahead.

3. Full scale global ice design loads are being measured, but we need more work on the ice load "scale effects". I was surprised to see only one paper on this topic in this conference in session B 12. We desperately need ice design pressures for areas of 3 x 3 to 10 x 10 metres. Full scale measurements being made now on structures should help to resolve this problem.
4. From papers presented in C 9 a fundamental issue remains unresolved; what is the best method of measuring ice loads on structures? Should we be measuring stress or load directly or should we measure strain rate in the ice? Direct comparison of these two techniques could help to resolve the problem.

5. Finally a comment that a colleague made to me recently. Over the past 10 years ice design pressures for the Beaufort Sea have been decreasing due to a better understanding of the failure mechanisms and larger scale measurements, whereas wave loads have been increasing. It will be interesting to see what happens over the next 2 years.
P. Jumppanen, President of POAC
Technical Research Centre of Finland
Espoo, Finland

CLOSING OF CONFERENCE

The four very busy conference days are over now. We have just heard the summing up and concluding remarks on the basic subjects of the conference. Before my closing words, we have a certain matter to deal with. Recommendations made today at the official meeting of the POAC International Committee should be dealt with and, I hope, accepted at this meeting. The proposals made by the International Committee are as follows:

The next POAC conference will be held in Narsarsuak, Greenland, in September 1985. The ninth POAC conference in 1987 will be organized in Fairbanks, Alaska. The next president for the period 1983 - 85 will be William Sackinger, Professor at the University of Alaska, Fairbanks. The next vice-president for the same period will be Professor Per Tryde from the Technical University of Denmark. There will also be some changes in the International Committee. New members are Mr. Takekuma from Mitsubishi Heavy Industries, Ltd., Japan, and Dr. Enkvist from the Wärtsilä Arctic Research Centre, Finland. Retiring members are Mr. Mäkinen from Finland, Professor Määttänen from Finland and Dr. Horikawa from Japan. The International Committee has also decided to call two new members, one from the Soviet Union and one from the Federal Republic of Germany. May I ask for your reaction to these proposals ... Motion carried.
We have been very fortunate in preparing this conference to get financial support both from governmental and industrial sources. I should like to address my special thanks to the Ministry of Trade and Industry, to the National Board of Navigation and to the Finnish companies participating in the exhibition.

Our national organizing committee and several subcommittees have been very active and did an excellent job in preparing the meeting. The organization of a symposium also depends very much on all kinds of small details to make things run smoothly. These are the responsibility of the secretariat. We have had the good fortune to obtain a competent secretary general for this conference. I should like to express my sincere thanks to Ms. Sirpa Suomela who has done an enormous amount of work before and during this conference. I also extend my thanks to the technical staff of Finlandia Hall, to the personnel of Area Travel Agency Ltd., to the personnel of my own institute and to all who have worked with us during this conference and in preparing it.

The success of every conference depends to a large extent on the active contribution of the authors and the session chairmen and on the active participation in the discussions. I therefore should like to extend my warmest thanks to all the participants of the conference POAC 83. You, Ladies and Gentlemen, have made this conference a success. I wish you all good luck in you very important work, a pleasant trip home and I look forward to seeing you in Greenland in 1985, if not before. Ladies and Gentlemen, I declare the conference closed.
POAC 83, which was held in Helsinki, Finland, was the seventh in the series of international conferences dealing with various theoretical and practical aspects of arctic technology in navigation and coastal engineering. Ice problems in polar marine areas and harbours, as well as ice loads on coastal structures were the basic subjects of discussion in the conference. Other subjects were the utilization of arctic energy resources and the problems associated with the increasing industrial activities onshore and offshore. As a local question, various aspects of navigation in the Baltic and in the Gulf of Bothnia were discussed. The papers of POAC 83 have been published in four volumes.

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