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Sea Ice Engineering for Arctic Oil and Gas Development

Concepts structuraux pour l'exploration de gisements dans les régions arctiques

Bauwerkskonzepte für die Erdöl- und Erdgas-Gewinnung im arktischen Meer

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SUMMARY
A general overview is presented on sea ice engineering concepts for oil and gas development. Several design concepts for oil and gas exploration and production platforms are discussed, and structural design alternatives for the internal framing and exterior walls for these ice-resisting structures are presented. Use of composite steel-concrete and concrete concepts for the exterior icewalls is also discussed. Recent reports on the behavior of these structural elements are reviewed and their benefits are compared.

RÉSUMÉ
Un aperçu général est donné sur les innovations technologiques concernant le développement de sources de pétrole et de gaz naturel en milieu arctique. Plusieurs concepts pour l'exploration des gisements de pétrole et de gaz naturel ainsi que les plateformes de production sont présentés. Les différents éléments de structure qui s'opposent aux efforts exercés par la glace, et qui constituent l'ossature interne et les parois externes, sont présentés. L'emploi du béton ainsi que d'un mélange béton-acier pour la réalisation des parois externes est discuté. Des articles récents traitant du comportement de ce type de structures sont examinés et les résultats les plus significatifs en sont dégagés.

ZUSAMMENFASSUNG
Der Beitrag gibt eine allgemeine Übersicht über die neuesten Entwicklungen der Bautechnik im arktischen Meer. Verschiedene Entwurfsideen für der Erdöl- und Erdgas-Suche und -Förderung dienende Plattformen werden beschrieben. Verschiedene Möglichkeiten für die Aussteifung und die Ausbildung der Wände dieser, grossen Eisdrücken ausgesetzten, Tragwerke werden vorgestellt. Die Verwendung von Stahl-Beton-Verbund-Konstruktionen für die Ausbildung der Wände wird diskutiert. Neuere Berichte über das Verhalten dieser Bauteile werden, Vor- und Nachteile abwägend, miteinander verglichen.

1. INTRODUCTION

The search for oil and gas in the arctic regions of the world over the last 15 to 20 years has resulted in great advances in sea ice research, and a proliferation of structural design concepts which enable the exploration of these mineral resources. With the discovery and production of oil in Cook Inlet, Alaska, during the mid-sixties, followed by the discoveries of oil at Prudhoe Bay and gas in the MacKenzie Delta, the interest in the arctic regions has grown rapidly. More recent discoveries in the northern arctic island regions of Canada and off the eastern coast of Labrador and Newfoundland have reinforced the need for new design concepts for most-effective recovery operations in resources in these environmentally harsh regions.

Building in part on significant technological advancements of oil and gas activities in the North Sea, Baltic Sea, and arctic offshore areas of the USSR, exploration and production activities are progressing in all likely potential and demonstrated reserve regions of the North American arctic.

This paper presents a general overview of state-of-the-art sea ice engineering concepts for arctic offshore oil and gas development in North America. Design concepts for exploration and production platforms are presented along with detailed discussions focusing on the structural design of the exterior ice-resisting walls. Principal regions of attention are the Bering, Chukchi, and Beaufort seas off Alaska and Canada; the Canadian arctic islands region; and the offshore east coast of Newfoundland and Labrador (see Fig. 1). As an aid to understand the evolution of this industry, some of the unique environmental, geotechnical, geographical, and economic characteristics which have influenced and continue to influence the design of structures for these regions are also discussed.

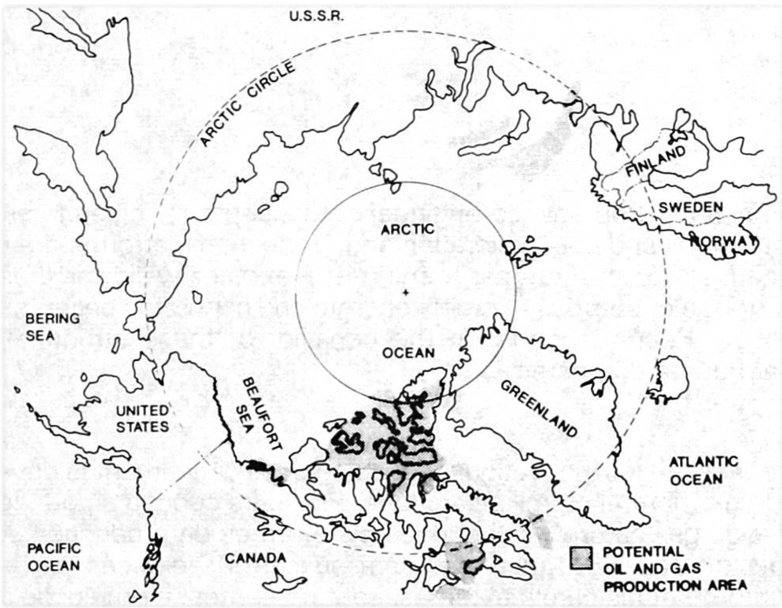

Fig. 1 Areas for Potential Oil and Gas Production

2. ARCTIC OIL AND GAS REGIONS -- DESIGN REQUIREMENTS

2.1 Cook Inlet

The early arctic offshore exploration and production activities were conducted in the relatively mild environment and shallow water of Cook Inlet in the

Gulf of Alaska, a tidal marine estuary lying at about 60°N latitude. Ice is present in the region for up to six months of the year and is generally less than 1 meter thick. Due to tidal ranges of as great as 10 meters and currents of 3 meters per second, the ice can form ridges several meters thick as the edges of broken ice floes ride over one another and freeze together. Propelled by the tidal currents, these ice features exert considerable force on stationary oil drilling and production platforms [1, 2].

Development of the Cook Inlet oil and gas resources began in the early 1960s using conventional drilling rigs during ice-free months. Later, production was accomplished using bottom-founded platforms designed to resist the ice forces. Even though the environment in this region is not as severe as that encountered in the Beaufort, the experience gained with these pioneering ice-encountering structures has advanced the understanding of ice/structure interaction, and paved the way for structures to be designed and deployed in the more rigorous arctic extremes to the north.

2.2 Alaskan and Canadian Beaufort Sea

Following development of the on-shore Prudhoe Bay oil deposits, interest shifted to the vast offshore tracts of the Beaufort Sea, and more recently to areas of the Chukchi and Bering seas.

The Beaufort Sea is almost completely ice-covered for much of the year except for the shallow, near-shore region which generally clears to varying degrees for approximately 90 days each summer. The sea ice cover may be thought of as consisting of three zones, as illustrated in Fig. 2. The ice within each zone has unique characteristics which need to be considered in the design of offshore structures [3].

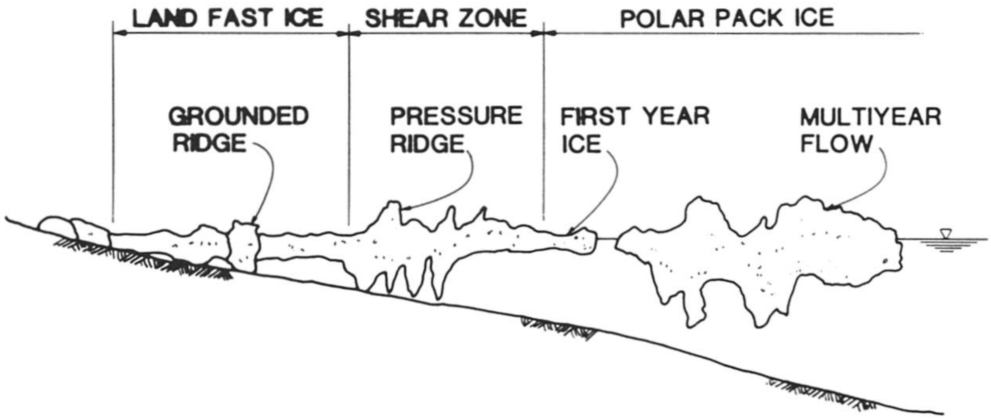

Fig. 2 Arctic Sea Ice Zones

The near shore zone is characterized by land-fast ice out to about the 20-meter isobath. This ice is typically seasonal first-year ice which may be as much as 2 to 3 meters thick. Only the very near-shore region of this zone is smooth ice, however. Beyond, the ice is continually broken and ridged by the wind. These pressure ridges may have thicknesses of as great as 20 meters and often scour the sea bottom and become grounded within this zone. This extends the zone of land-fast ice to increasingly deeper water as the winter freeze-up progresses [3].

During the short summer season, the near-shore regions thaw and break up under the influence of warmer temperatures, southerly winds, and the flows of warmer waters from rivers that empty into the sea. The open-water season in this zone varies, depending on meteorological conditions; however, it generally extends from mid-July until mid-October. Even during this time, large multiyear ice floes may be present and may be driven by the wind into the shallow-water regions near shore.

Furthest from shore is the zone of permanent polar pack ice which rotates in a counterclockwise direction about the pole. This ice is composed of seasonal and multiyear floes and ridges. The velocity of its circumpolar drift averages about 3 kilometers per day at its periphery [4].

Between the drifting polar pack and the land-fast ice zones is the transition or shear zone. The ice in this region is being continuously fractured, forming pressure and shear ridges. These ridges may have keel depths to 50 meters, as evidenced by the scours and gouges they create in the sea floor as they are carried by the currents [5].

2.3 Canadian Arctic Islands

Several commercial oil and gas discoveries have been made in the Canadian arctic islands since drilling began in the early 1960s. This region, while environmentally as severe as the north slope of Alaska and Canada, has not proven to be as difficult to develop. Although covered with ice most of the year, the sea ice is for the most part land-fast because of the maze of channels, the protection afforded by the islands, and the low tidal influence. This unique combination of climatological, meteorological, and geographical features makes it possible to drill for oil and gas directly from the ice. Some drifting of the ice can be accommodated in the drill string riser with the deeper water sites withstanding the greatest drift due to the increased length of the riser. Grounded ice "islands" have also been used as platforms for drilling operations.

2.4 Canadian East Coast

Petroleum exploration off the east coast of Labrador and Newfoundland began in 1966 with two major discoveries occurring in 1979. Like Cook Inlet, this region is not actually an "arctic" zone; however, its rather unique combination of geographic, oceanographic, and environmental features make the area particularly challenging to the structural designer.

The principal ice feature associated with oil and gas development off the east coast of Canada are icebergs. Even before the tragic sinking of the Titanic after striking an iceberg in 1912, the hazards of these sea ice features were appreciated. Icebergs are a common occurrence in the oil and gas regions of the Labrador Sea and Davis Strait and, to a lesser degree, on the Grand Banks of Newfoundland. The majority of icebergs are formed by calving off from glaciers on the west coast of Greenland and are carried by the Labrador current southward along the coast of Labrador and Newfoundland.

The frequency of occurrence of icebergs varies from year to year and, while most numerous in the northern extremes, they decrease in both size and number to the south. It is estimated that as many as 20,000 icebergs calve off Greenland glaciers in a year; yet, on the average, only about 400 a year reach the 48°N parallel of latitude [6], the region of most oil operations. Icebergs may weigh as much as 120 million tonnes or more, and travel at speeds as great as 1 nautical mile per hour [3]. Obviously, the structural design implications associated with dissipating that much kinetic energy are formidable. In fact, current practices for iceberg management involve accurate, early detection and tracking; towing them to prevent collision with oil and gas drilling structures when it is necessary and possible; and, in some cases, disconnecting and moving the drillship to prevent collision. Only recently have drilling or production module structural concepts been proposed that resist iceberg impacts.

3. SEA ICE CHARACTERISTICS AND DESIGN REQUIREMENTS

3.1 Sea Ice Characteristics and Properties

Sea ice is a crystalline material whose properties depend upon many variables, such as orientation of the crystals, salinity, temperature, density, and impurities. Sea ice grows as a sheet on the ocean surface with ice crystal growth being influenced by the presence of impurities and currents. Entrapped salt is concentrated in brine pockets within the crystalline structure. Subsequent remelting and freezing tend to expel the entrapped brine through drainage channels and this progressively strengthens the ice.

The mechanical properties of sea ice likewise depend upon many variables including crystallographic structure, temperature, brine content, confinement, and strain rate. Various studies have been conducted to establish the strength and other engineering properties of sea ice. Guidance for establishing the design loads from sea ice features are contained in standards such as API RP-2A [14], Bulletin 2N [15], and DnV [16]. For design purposes, ice features most likely present in a particular area dictate the ice loads imposed on the structure. Ice feature types such as ice ridges, rafted ice, rubble, multiyear floes, pack ice, and ice islands, each with unique characteristics, may need to be considered for a particular site.

Icebergs differ from sea ice in that they are composed of fresh water and are usually highly consolidated due to the large pressures accompanying the transformation to glacial ice at their source. It is the engineer's responsibility to determine the maximum force that the iceberg can exert on the structure. The tremendous energy associated with large moving icebergs requires the designer to develop concepts which limit the magnitude of the load transmitted directly to the structure and mobilize the resistance of the foundation material. Such concepts promote crushing, splitting, and deformation of the iceberg as a means of dissipating energy; the dynamic interaction of the structure, iceberg, soil, and water is a crucial consideration in the analysis of the iceberg impact event [7].

Generally, arctic exploration and production structures must operate safely and exhibit no permanent damage under all service load conditions. Under extreme loads, the structure should maintain its structural integrity and provide a reasonable factor of safety against catastrophic failure. Some important parameters which influence the design under these limit states are ice and soil conditions, operating water depth, draft requirements, ease of construction, and simplicity of installation.

3.2 Design Ice Loads

The prediction of ice loads for a structure requires solving a variety of complicated ice/structure interaction problems. The magnitude and distribution of forces are functions of many variables, including (1) the mechanical properties of the ice, (2) the geometry of the ice feature, (3) the failure mode induced in the ice feature, (4) the continuity between the ice and the structure, (5) the velocity of the ice feature, (6) the environmental driving forces such as wind and current, and (7) inertial effects of the ice feature and the structure.

Methods for predicting ice loads are presented in standards such as API Bulletin 2N [15]. However, in general, the loads are highly dependent upon structure geometry and the assumptions used regarding both the ice properties and the failure mechanisms. Therefore, while approximations may be developed using readily available references, a detailed study of all factors which may influence a particular structure should be undertaken. Project criteria may thus be developed which relate structure parameters to a well-defined understanding of site-specific ice interactions.

4. DESIGN CONCEPTS FOR ARCTIC OIL AND GAS DEVELOPMENT

Several different structural systems for arctic North American gas and oil development have been proposed and deployed. The remainder of this paper will focus on structures designed for the Beaufort Sea. Generally, Beaufort Sea structures can be divided into two service categories: exploration and production. Exploration structures have a shorter required service life and should be as mobile as possible, allowing reuse at a variety of drilling sites. Production structures are intended for longer service periods and virtually permanent installation at a single location.

Both production and exploration structures can be further subdivided into different types as shown below.

Exploration Structures	Production Structures
Artificial Gravel Islands	Artificial Gravel Islands
Caisson-Retained Islands	Caisson-Retained Islands
Mobile Gravity Structures	Mobile Gravity Structures
Drillships and Floating Structures	

4.1 Artificial Gravel Islands

These man-made islands are generally constructed of gravel obtained from a nearby borrow source and placed in shallow offshore waters in sufficient amount to clear the water surface and prevent wave overtopping. The drilling rig and necessary supplies are then placed on the island.

Generally, there are two types of artificial gravel islands: sacrificial beach and sandbag-retained. Issungnak Island, the largest sacrificial beach type island to date, has operated successfully in waters 23 meters deep. Mukluk and Seal islands are sandbag-retained and have operated in water depths of 18 and 14 meters, respectively. The overall cost of both of these types of islands can vary, but the average cost is in the area of $3 million per meter of water depth [17]. The primary factor influencing this cost is the proximity to the borrow source, as a tremendous amount of gravel must be transported to the site, typically 750 thousand cubic meters or more.

Sacrificial beach islands use shallow side slopes, typically around 1:15. These shallow slopes act like a beach causing waves to break and dissipate energy. In winter, the beach promotes ice sheet failure, creating a protective rubble field around the island. Secondary slope protection, using sandbags and filter cloth, is provided at the beaches and around the drilling surface.

Sandbag-retained islands, as shown in Fig. 3, offer a substantial increase in slope, thereby significantly reducing the amount of fill required. Slope protection is typically supplied over the entire island through the use of polypropylene bags filled with 1.5 to 3 cubic meters of gravel placed over a synthetic filter cloth. Side slopes for these islands can be as steep as 1:3. Design for wave attack is typically achieved by providing sufficient freeboard to reduce wave overtopping. Design for ice forces is based primarily upon the shearing strength of the gravel fill and the seabed material beneath this fill.

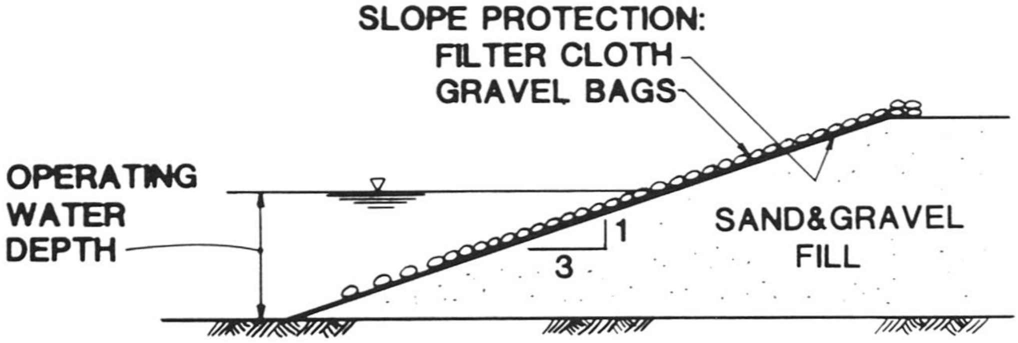

Fig. 3 Typical Cross-Section,
Sandbag-Retained Artificial Gravel Island

Through the early stages of offshore oil and gas exploration in the offshore Beaufort Sea, artificial gravel islands provided a sound and reliable solution for drilling in relatively shallow water. These islands could also be used year-round, which was often not possible using floating structures or drillships.

Toward the end of the 1970s, offshore exploration proceeded into deeper waters and the economic feasibility of artificial gravel islands began to be scrutinized. Very large amounts of fill are required in deep water and suitable sites were restricted to areas of abundant borrow material.

Other factors which weigh against gravel islands include (1) no capital expenditure reclamation since they cannot be reused; (2) excessive length of time required to mobilize operations; (3) susceptibility to damage from storms and ice features, especially during construction; and (4) continuous repair work required on the slope protection. These problems led to the next generation of arctic offshore drilling platforms for the 1980s.

4.2 Caisson-Retained Islands (CRI)

As the economic viability of gravel-only islands in deeper water grew doubtful, the concept of a gravel-filled reusable perimeter structure, known as a caisson-retained island (CRI), was developed. The perimeter structure is floated to the site and ballasted down onto a prepared underwater sand and gravel berm. Additional fill is placed inside the perimeter caisson structure and drilling operations take place on top of this interior fill or core (see Fig. 4). The berm is simply a scaled down and submerged

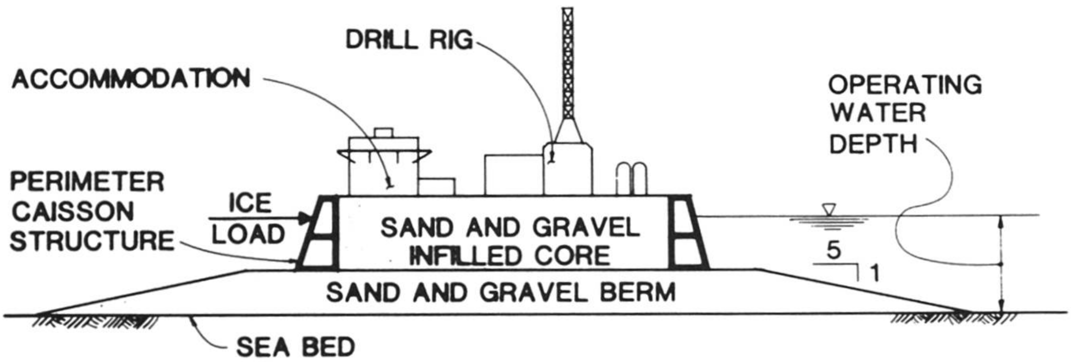

Fig. 4 Typical Cross-Section, Caisson-Retained Island

artificial gravel island. The perimeter caisson and core top off the berm, giving the island the sufficient height for drilling operations

Constructed either of steel or concrete, the caisson both retains and armors the sand and gravel core. Ice-load resistance is achieved by efficient load transfers from the ice feature through the core and to the foundation [11]. Provided quality control programs can be implemented that control the silt content of the fill, the dead weight of the structure will densify the berm so that it exhibits the necessary shear strength [8].

Berm construction is required to reduce the height of the caisson and to provide flexibility in terms of usable water depths. The berm also provides a grounding area for ice rubble during the winter. This rubble can become an effective ice barrier for the caissons [9]. Advanced placement techniques for the borrow material have allowed steeper overall underwater side slopes and, therefore, less fill quantities.

The use of CRIs in the Beaufort Sea has led to a substantial reduction in the amount of fill required per a given water depth when compared to artificial gravel islands. This concept also allows recovery of a substantial amount of the exploration investment because the caissons can be deballasted and moved to another drilling site. Additional problems associated with artificial gravel islands such as slope protection and lengthy construction periods are overcome by the use of the perimeter caissons.

Three CRI systems have been deployed in the Beaufort Sea for exploratory drilling. They are Tarsiut Island, Esso stressed steel CRI, and the Gulf mobile arctic caisson (MAC).

4.3 Mobile Gravity Structures

While the use of CRIs substantially increased the working water depth for oil and gas exploration, their substantial fill requirements hindered the ability to mobilize these structures in increasingly deeper waters. The response was development of the concept of mobile gravity structures (MGS) which are highly mobile, self-contained structures that can operate in deeper waters and be rapidly relocated. These structures would typically be constructed at a shipyard in a more temperate climate, outfitted with topside equipment, floated to the drilling site, and ballasted into position. Though the initial cost of MGSs can be high, their mobility allows the capital to be amortized over multiple exploration wells.

Several MGSs have been proposed, each incorporating a different concept to mitigate global ice forces. However, only Global Marine's Concrete Island Drilling Structure (CIDS) is currently deployed in the arctic (see Fig. 5). It is a completely self-contained MGS, and can be deployed in water depths between 10 and 27 meters. CIDS is composed of four modules, a concrete caisson or brick, two deck barges, and a steel mud base. Ice loads are resisted by the lightweight concrete brick and are then transferred to the soil through the concrete internal framing system and the mudbase.

Stability of CIDS against sliding at the base depends upon the nature of the soil at the site. While no base preparation is required where good soils are encountered, some site modification is anticipated when weak cohesive type soils are prevalent. Further protection against ice overloads is achieved through a rubble generation system, which uses high-pressure water cannons to create an artificial rubble berm a distance of 100 to 200 meters from the edge of CIDS. These grounded rubble berms can considerably reduce the ice load intensity on the structure [10].

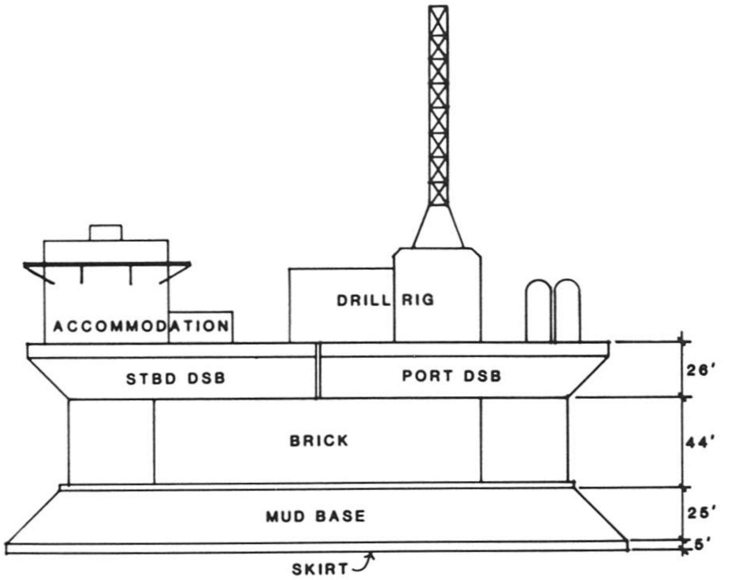

Fig. 5 Global Marine's Concrete Island Drilling Structure (CIDS)

Another water-ballasted gravity structure currently in use is the Canmar Single Steel Drilling Caisson (SSDC). It is basically an oil tanker segment reinforced to withstand ice loads. This structure has held up successfully during several winters in moving ice packs. However, the SSDC requires an underwater berm constructed to within 11 meters of the water surface, thus requiring the construction of a sometimes substantial berm for deeper watersites.

Other MGSs which have been proposed include monocones, stepped structures, and vertical-sided structures similar to CIDS. Whereas vertical-sided structures resist ice flow by brute force crushing of the ice, conical structures are designed for reduced ice forces because (1) the conical shape of structure creates a reduced effective ice contact area at the water plane, and (2) the sloping sides of the cone force the ice to ride up and around the structure, thereby failing it in bending rather than in compression (see Fig. 6).

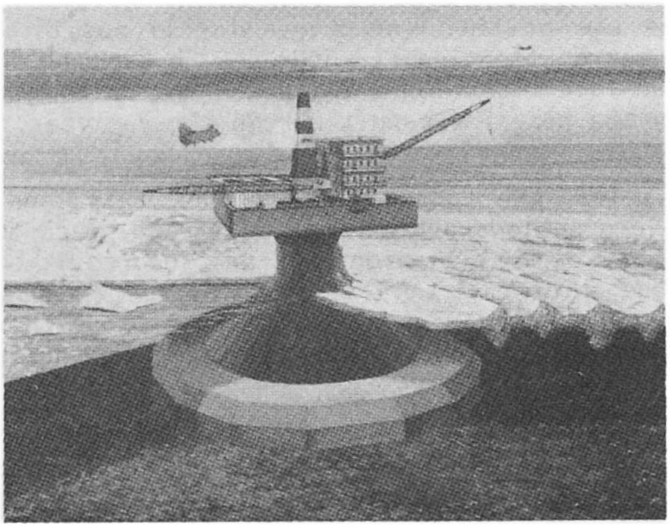

Fig. 6 ABAM's Arctic Drilling Structure (ADS)

The lifting of the ice also transfers kinetic energy within the ice pack into potential energy, which effectively reduces ice loads that are governed by a maximum driving force. Furthermore, vertical loads from the uplifted ice acting on the leading edge of the cone can add to the structure's stability against sliding. Mobile conical drilling structures have been proposed which can be deployed in water 55 meters deep. These structures will probably be deployed during the 1990s.

One of the primary failure modes investigated in the design of MGSs is resistance against sliding at the base. This capacity depends on several factors but is generally governed by the nature of the soil at the site. Several methods have been proposed to deal with this failure mode, among them

- Removal of weak soil and replacement with improved soil
- Accelerated consolidation with wick drainage
- Strengthening of weak soil by freezing with thermopiles
- Enlarging the base structure to increase contact area for cohesive soils
- Using sand fill to increase vertical force for cohesionless soils
- Using sheet piles or skirts to penetrate the weak soil layer and mobilize the underlying stronger soil
- Using retractable steel piles or spuds, driven by a vibratory hammer, to act as dowels in the soil

4.4 Floating Structures

Structures which float and resist ice floes have also been deployed in the Beaufort Sea. Gulf Canada's Kulluk is towed to its location and then stabilized against ice forces by a 12-point, radially deployed mooring system. Kulluk, with its inverted truncated conical hull, can resist ice up to 1.5 meters thick by forcing it under the structure, thereby failing it in flexure. The vertical loads associated with pushing the ice down are substantially less than those encountered in conical MGSs, since one is pushing against the bouyant force rather than uplifting the dry weight of the ice. Large ice features cannot be resisted by Kulluk, so permanent ice management support must be provided by icebreakers. This limited load resistance precludes use of such structures in all possible ice cover conditions. Hence, moored floating structures such as Kulluck or drillships are typically limited to exploration drilling during rather narrow drilling windows, dictated by the peak ice conditions in a given year.

Dynamically positioned drill ships and semisubmersibles have been successfully used in Cook Inlet, the Labrador Sea, Grand Banks, and other areas where sufficiently long periods of ice-free water are present. The design ice loads in these areas are still high, but are the result of impact from large ice features and icebergs. Further ice management support is therefore required for these mildly ice-resistant structures from either icebreakers or tugboats which deal with thickened ice features and the deflecting of hazardous icebergs.

5. ICEWALL DESIGN

Structures must be designed to resist high-intensity ice pressures in arctic waters and high impact forces in the North Atlantic. Local ice intensities on small areas can be substantially higher than those associated with global ice loads. However, a critical component of the artic structures previously discussed of key interest is the exterior wall or "icewall" which is designed to transfer these high local loads to the internal framing of the structure. Because icewalls typically constitute a large and important portion of the structure, their design has significant cost, draft, and safety implications. The following paragraphs will discuss the philosophies of three types of icewall design.

5.1 All-Steel Icewalls

All-steel icewall designs can accommodate large deflections because stiffening ribs, webs, bulkheads, internal framing, and membrane action give multiple load paths and allow for a great redundancy within the structure. Therefore, designs for a steel icewall can be based on lower bound ice load criteria with the understanding that some damage may occur. Further ice loads can still be transferred because of the redundant nature of the structure and repairs can be made, if required, at some other time.

Risk studies have been conducted on steel structures with icebreaker-type framing. These studies have shown that ice loadings significantly larger than the design values could be tolerated without loss of overall structural integrity or risk to personnel or environment [11]. Steel designs offer a reduced weight-to-strength ratio and this allows for a shallower transit draft. A gravity-based structure fabricated entirely of steel, however, requires a great deal of dead load ballast to offset its bouyancy. This ballast is necessary to maintain sufficient vertical gravity loads to stabilize the structure against global ice forces.

Steel icewall designs typically require relatively closely spaced support webs and stiffening ribs on the flange plates to preclude crushing or buckling from external ice loads. These factors significantly affect the economics and constructability of steel icewall structures. Significant cost savings can be realized if the weight of the webs and number of flange plate stiffening ribs can be reduced. In addition, special low temperature steels and coatings are often required for the arctic environment.

5.2 All-Concrete Constructions

Concrete icewalls have been developed which have proven very efficient and offer advantages of high strength and durability in marine environments, high thermal resistance, low maintenance and cost, and high sliding resistance once the structures have been placed and ballasted. Drawbacks are low tensile strength, low freeze/thaw resistance, and low ductility. In addition, membrane cracking can lead to a loss in water tightness. However, these drawbacks can be overcome through proper reinforcing and prestressing and selection of suitable concrete mix designs.

Design of concrete icewalls using conventional code techniques typically results in large wall thicknesses, which have highly impractical implications on draft. More efficient designs utilizing a haunched or arched shape have been designed which enhance the formation of an internal arch within the wall [12], thereby obtaining a high strength-to-weight ratio. These icewalls are typically prestressed by post-tensioning in both directions. The magnitude of prestressing is set to account for thermal effects and to reduce principal tensions associated with shear transfer. Longitudinal tendons can be straight since the shape of the icewall can introduce the desirable secondary moments and substantial transverse distribution of load can be ensured due to the high torsional resistance of the icewall at the supports.

Nonlinear finite element analyses have indicated that these concrete icewalls exhibit ultimate strengths within design requirements, as well as satisfy serviceability limit states [12]. Failure is typically controlled by compression at the crown, due to combination of bending and arch behavior. This happens because the support bulkheads for the icewall are generally not rigid enough to provide the necessary horizontal reactions to develop the full arch action thrust.

5.3 Composite Construction

Combining steel and concrete within the same structure takes advantage of the beneficial properties of both materials to provide a "composite icewall." This concept reduces or eliminates the disadvantages of either material when considered separately and provides both high ductility and resistance to high intensity loading.

Composite icewalls are basically sandwich structures. They consist of two flange plates separated by a concrete infill. This two-dimensional composite plate is supported by either steel or concrete bulkheads. Shear connection devices and plate stiffeners are usually incorporated to provide the necessary composite behavior and stabilize the structure for construction loads.

A composite design has a number advantages over a design utilizing steel alone. The load distribution capability afforded by the injected concrete fill makes the icewall relatively insensitive to high local pressures. The concrete fill may totally eliminate the tertiary or plate bending stress in steel plate forming the outer wall. The ice pressure simply transfers through the outer steel plate into the concrete by bearing, and diagonally through the concrete in compression where it is reacted by the inside flange plate and support bulkhead (see Fig. 7). This can lead to a considerable increase in the stiffener spacing and a possible elimination of the webs. In addition, buckling of the steel plates within the icewall is prevented by the concrete encasement. Finally, the overall cost of the

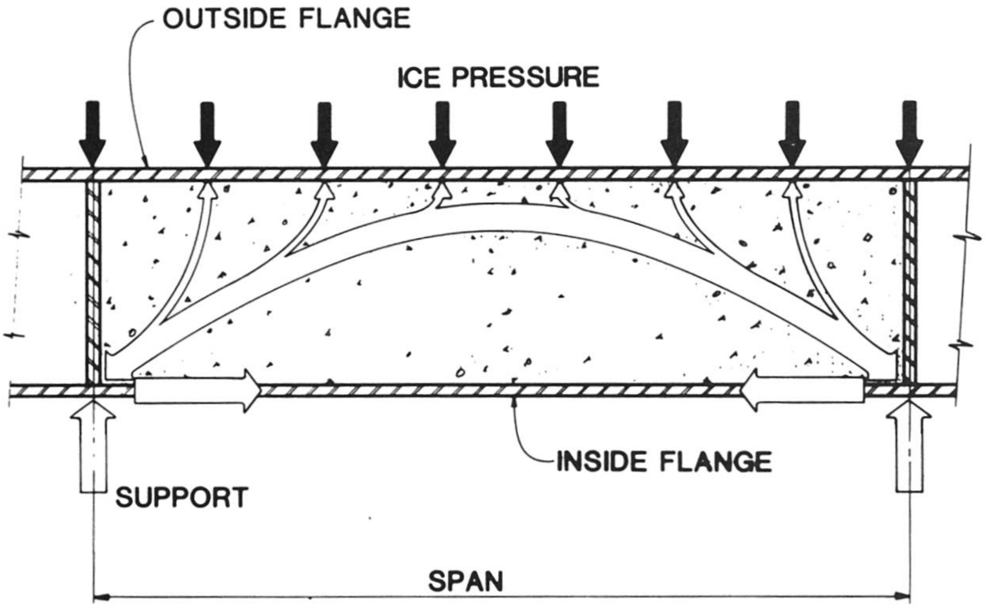

Fig. 7 Structural Design Concept for Composite Icewalls

icewall can be reduced since the strength improvements achieved by injection of concrete in the composite is relatively inexpensive in relation to the increased internal framing required in steel structures.

When compared to an all-concrete design, a composite design exhibits significantly increased strength and energy absorbing capability. The interior flange plate provides a tension tie for the internal concrete arch, which increases its effectiveness. Because the composite wall is thinner than an all-concrete wall, the overall structure draft is reduced. The composite wall is less costly because the double-wall steel plating serves a variety of purposes, e.g., concrete reinforcement, formwork for the concrete, three-dimensional confinement, and a watertight membrane. In addition, there is potential for reduced global loads on conical structures since the friction coefficient for an ice/steel interface may be less than for an ice/concrete interface.

One of the earliest sources of experimental work on composite icewalls is a series of tests sponsored by Hitachi Shipbuilding and Engineering Company [13]. These tests, while conducted at relatively low load intensities, nevertheless demonstrated that composite structures offer advantages over concrete or steel structures alone. Research is currently being conducted within the United States to determine the response of composite icewalls at load levels representative of arctic structure design requirements. Though the data is for the most part proprietary, it is acknowledged that the results of these programs confirm the viability of the concept.

Fig. 7 illustrates the load-resisting mechanism for ice forces as they encounter a composite structure. It is evident that composite behavior is desirable between the outside or compression flange and the concrete; this serves to lower the concrete stress and increase the internal lever arm. However, it is not necessary for the inside or tension flange to be composite with the concrete except at the support where it reacts against the horizontal thrust of the internal arch. In fact, interpretation of the results of the Hitachi test by the authors of this paper indicate that it was more practical to allow slip between the tension flange and the concrete. Full shear connection between the tension and concrete typically resulted in excessive flexural cracks in the concrete, which tended to deteriorate the diagonal compression arch capability in the specimen.

Another advantage of composite icewalls is that they utilize a very simple load transfer mechanism, as indicated in Fig. 7. This means that a relatively simple design approach based on static equilibrium rather than on strain compatibility can be utilized to obtain estimates of load-carrying capability. Such a method would use a "compression field" theory to analyze stresses in the concrete, and a corresponding "tension field" approach to analyze stresses in the steel. Furthermore, because of the confinement of the concrete by the steel plate, surrounding structure, and the ice itself, enhanced performance of the concrete is anticipated.

Further research developing finite element analytical models for composite icewalls would be highly useful to the implementation of this design concept. This research would define a theoretical basis for design which would accurately predict composite icewall behavior at all limit states and load conditions. Additional large-scale, two-dimensional panel tests are also desirable as the results from these tests can further the data base for composite behavior and benchmark the analysis procedure.

6. NEW TECHNOLOGY

Massive bulkheads of steel or concrete are typically required to brace icewalls capable of resisting large local ice loads. Although there is only one major concentrated load acting on the structure at a time, all bulkheads must be designed for this load since the ice may strike from any direction. These closely spaced bulkheads can represent a substantial portion of the structure's cost.

One proposed solution to this problem has been to eliminate the support bulkheads altogether, causing the icewall to behave as a conical or cylindrical shell. In such a shell, the concentrated load is supported primarily by plate bending in the vicinity of the load, which produces relatively large bending moments. At greater distance from the load, the curvature of the shell becomes more important and a greater proportion of the load is supported by membrane compression. Composite steel/concrete ice walls appear well suited to provide the required strength and toughness to withstand these loads. The membrane compressive forces also enhance the bending strength of the composite icewall in the same manner that compressive loads increase the bending strength of a concrete column.

7. CONCLUSIONS

Advancements in sea ice engineering technology have helped make the North American arctic oil and gas development of the last 20 years possible. Research in the areas of composite structural systems, lightweight concrete, sea ice forces, and soil conditions has paved the way to the next generation of arctic structures. With this experience, the industry is ready for the design and deployment of these exploration and production structures which will unlock the resources of the severe arctic offshore environment.

REFERENCES

1. HULL, T.L., The Replacement of a Major Submerged Structural Brace on MGS Platform A, Cook Inlet, Alaska. Offshore Technology Conference, OTC 2165, May 1975.
2. NOAA, Tide Tables, West Coast of North and South America. U.S. Department of Commerce 1985.
3. CROASDALE, K.L., Sea Ice Mechanics: A General Overview, Marine Technology Society Journal. Volume 18, No. 1, 1984.
4. HNATIUK, J., Results of an Environmental Research Program in the Canadian Beaufort Sea. OTC 2445, May 1976.
5. ROJANSKY, M., Arctic Exploration and Production Structures, Marine Technology Society Journal. Volume 18, No. 1, 1984.
6. HNATIUK, J., Current and Future Offshore Activities in Canada. OTC 4707, May 1984.
7. GERWICK, B.C., POTTER, R.E., ROJANSKY, M., Development of a Structural Concept to Resist Impacts from Multiyear Ice Floes, Ridges, and Icebergs. OTC 4799, May 1984.
8. STEWART, H.R., JEFFERIES, M.G., GOLDBY, H.M, Berm Construction for the Gulf Canada Mobile Arctic Caisson. OTC 4452, Volume 2, May 1983.

9. FITZPATRICK, J., STENNING, D.G., Design and Construction of Tarsuit Island in the Canadian Beaufort Sea. OTC 4517, Volume 2, May 1983.

10. WETMORE, S.B., The Concrete Island Drilling System: Super Series (Super CIDS). OTC 4801, Volume 3, May 1984.

11. BRUCE, J.C., ROGGENSACK, W.D., Second Generation Arctic Platforms: Lesson From First Generation Design Experience. OTC 4798, Volume 3, May 1984.

12. SCHLECHTEN, J.R., FERNANDES, R.L., DOLAN, D.K., BIVENS, H.R., Analysis and Design of an Icewall Framing System for an Arctic Drilling Structure. OTC 4691, Volume 1, May 1984.

13. SUHARA, T., NISHIMAKI, K., MATSUISHI, M., IWATA, S., On the Strength of Composite Steel - Concrete Structures of Sandwich System, Nav. Archit. Ocean Eng. Volume 18, 1980.

14. API RP 2A, Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms. American Petroleum Institute, January 1982.

15. BUL 2N, Bulletin on Planning, Designing, and Constructing Fixed Offshore Structures in Ice Enviornments. American Petroleum Institute, January 1982.

16. DnV Rules for the Design, Construction, and Inspection of Offshore Structures, Det norske Veritas, Oslo 1977.

17. AGERTON, D.J., Construction of an Arctic Offshore Gravel Island in 39 Feet of Water During Winter and Summer. OTC 4548, Volume 2, May 1983.