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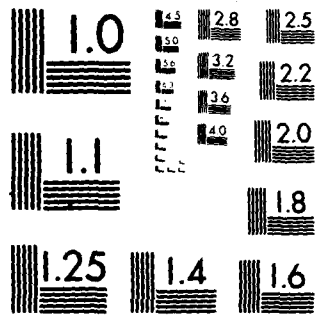
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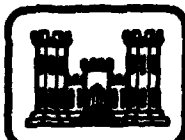
Edwin J. Chamberlain

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By



UNITED STATES ARMY CORPS OF ENGINEERS
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FOUNDATIONS OF STRUCTURES IN POLAR WATERS

by

Edwin J. Chamberlain

INTRODUCTION

This study was part of a larger project undertaken to provide guidance to the U.S. Geological Survey for evaluating the hazards of placing off-shore structures in polar waters for exploring for and producing petroleum from subsea resources. The study concentrates on the region of the Beaufort Sea off the north coast of Alaska and is specifically concerned with foundations in polar waters. Only factors unique to polar waters are addressed.

Unique conditions that affect the stability of bottom-founded structures in polar waters are primarily related to the force of sea ice, the settlement of subsea permafrost upon thawing, and frost heaving. Sea ice can impose a very large horizontal force on structures, causing their displacement. The thawing of ice-bonded subsea permafrost can cause settlement and associated failures of drilling platforms, manmade islands, and borehole casings. Frost heaving can cause the differential heaving of structures, the jacking of piles and the failure of bore-hole casings. Thus, any structure placed in polar waters must be designed to prevent damaging displacement and/or stress caused by these forces.

Several types of structures can be used in the Beaufort Sea to support exploration and production equipment. Manmade islands, drill ships, and grounded and floating sea ice have been used as drilling platforms in the Canadian Beaufort Sea. Although no tower-mounted platforms have yet been used, several designs are on the drawing board; these will probably be used in deeper water. Exploratory drilling has also been done from floating and grounded ice platforms and drill ships. However, these methods can only be considered for short term exploratory purposes¹ and cannot be used to support production facilities.

Since this report is concerned solely with foundation problems, only platforms that interact with the sea bed and subsea permafrost will be considered. Basically, three types of structures founded on or beneath the

sea bed need be considered. They are 1) artificial islands made with fill, 2) gravity steel or concrete towers founded on the sea bed, and 3) towers founded on piles driven into the sea bed.

The selection of the type of structure will be greatly influenced by site factors. These include 1) the depth of the water, 2) the type of ice cover and ice interaction, 3) the occurrence of ice-bonded permafrost, 4) the engineering properties of both frozen and unfrozen subsea sediments, 5) the availability of suitable fill, and 6) the exposure to wave action.

ARTIFICIAL ISLANDS

Many islands have been constructed in the Canadian Beaufort Sea.¹⁻⁹ Most of these islands have been built during the summer using hydraulically dredged fill. A few were built with mechanically excavated subsea fill, and others with gravel trucked over the ice from sites on land.

All of these islands were built for exploratory drilling, and none were designed to withstand the long-term force of sea ice or the effects of freezing and thawing that production facilities may encounter.

These islands have typically been 100 m in diameter at the working surface and have had a freeboard of as much as 6 m. Water depths have been as great as 13 m. These islands have performed well. The experience gained in the Canadian Beaufort Sea with these temporary islands provides a sound but limited basis for designing production islands in the Alaskan Beaufort Sea, where the long-term effects of frost action and sea ice and the deeper waters in which some of the islands will be sited may impose more severe forces.

An excellent guide to the design and construction of temporary islands has been written by deJong et al.⁴ The principal limitations of their report are that it does not consider the long-term effects of frost heaving, permafrost thawing, wave action, and ice force that permanent islands will be subjected to. Special precautions will be necessary to ensure the stability of permanent production islands.

The hazards of petroleum production from artificial islands in the Beaufort Sea can be minimized by considering the following factors: 1) sub-surface conditions, 2) site selection, 3) fill material, 4) island dimen-

sions, 5) bearing capacity and settlement, 6) effects of freezing and thawing, 7) effects of gravitational, wave and ice forces on slope stability, and 8) shearing resistance that can be mobilized by the island and its foundation to resist ice force.

Not all of these considerations are unique to the arctic environment, but because they are often interrelated with those that are, it is necessary to consider their combined effect. For instance, both ice and wave action can cause slope stability problems. Action to minimize the effects of one must allow for the effects of the other.

Site investigations are necessary to identify subsea conditions. To analyze foundation stability, quality samples must be taken for laboratory strength and consolidation tests. In addition, it is essential that ice-bonded sediments be identified and that thaw consolidation tests be conducted. The strength of frozen sediments must also be investigated. Finally, it is essential to know the frost heaving characteristics of the subsea sediments. All of these factors are discussed in another report.¹⁰

The selection of the site need not precede the site investigation. They will, in fact, be accomplished simultaneously, a general survey of the lease area being made first and a more thorough investigation being made once the general location of the site has been determined. Sites will probably be selected to avoid shallow ice-bonded permafrost if possible. Figure 1 shows that the depth to ice-bonded permafrost varies considerably from the nearshore region adjacent to the west ARCO docks near Prudhoe Bay to the deeper water region outside Reindeer Island. In the region 2-4 km offshore the depth below the sea bed to ice-bonded permafrost is estimated to be nearly 65 m. Farther offshore (9-11 km), the depth is almost 130 m. Yet at a distance of 21 km offshore, the depth of ice-bonded permafrost is less than 10 m. More recent studies sponsored by the USGS^{18,19} revealed that such variations in the depth to ice-bonded permafrost may occur over wide regions of the Alaskan Beaufort Sea.

Shallow ice-bonded permafrost should be avoided to minimize the impact of thawing ice-rich permafrost and to avoid the problems of excavating ice-bonded materials or hauling more suitable materials long distances for use as fill.

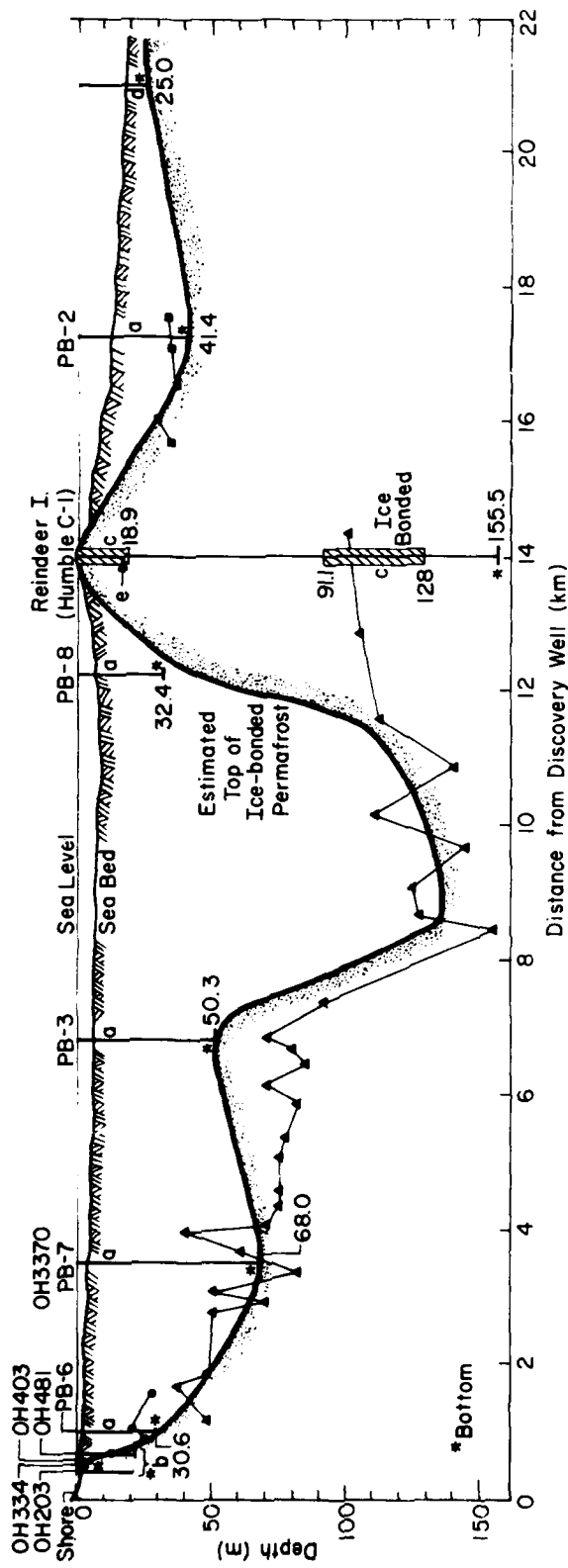


Figure 1. Top of ice-bonded permafrost near Prudhoe Bay, Alaska. (From Sellmann and Chamberlain. 11)

- Refraction data¹²
- ▲ Reflection data¹²
- Refraction data¹³
- a Drilling, sampling, temperature and chemistry data (CRREL-USGS)¹⁴
- b Drilling, sampling, temperature and chemistry data¹⁴
- c Drilling and sampling¹⁵
- d Drilling¹⁶
- e Drilling and temperature data¹⁷

Materials selected for fill must be suitable for supporting the island and the structures placed on it and for withstanding the forces of waves and ice. Sands and gravels are preferable, as they are more easily placed under water than silts and clays and they are often non-frost-susceptible.

The working surface must be large enough to accommodate the structures necessary for drilling and production, with special provisions made to accommodate wave action, ice ride-up and the principal direction of ice movement. The freeboard must be great enough to prevent ice rubble and storm waves from overriding the island and causing damage to production facilities. Experience in the Canadian Beaufort Sea has shown that a freeboard of 6 m is sufficient. According to Reimnitz and Mauer²⁰ the largest storm surge in the U.S. Beaufort Sea in the past 90-100 years was 3 m above mean sea level. Thus, a 6 m freeboard appears to be sufficient to accommodate wave action. However, little is known of the height to which ice rubble will form in the open regions of the U.S. Beaufort Sea lease area. Conservative estimates must be made and modified by experience. To minimize the forces of sea ice, the island should be oriented so that its narrowest dimension is normal to the principal direction of ice movement.

Conventional bearing capacity and settlement analyses should be made for the island and its foundations. In addition, special analyses are necessary if shallow ice-bonded permafrost is present. In the Canadian Beaufort Sea, the top of the ice-bonded permafrost has been observed to rise with time beneath an artificial island.⁷ Thus, thawing ice-bonded permafrost may not be a problem immediately beneath artificial islands because the cold arctic air is likely to promote the formation of ice-bonded permafrost. However, if heated structures are placed directly on artificial islands, ice-bonded permafrost may thaw, particularly in shallow water. Procedures such as insulating the foundations of heated buildings or elevating buildings on piles may be necessary to avoid the thawing of ice-bonded sediments.

Frost heaving may be a serious problem affecting permanent artificial islands and the sediments beneath. For this reason, non-frost-susceptible sands and gravels should be selected as construction materials. Where

these materials are not available and frost-susceptible materials have to be used, methods have to be adopted to prevent frost heave damage to structures. Possibly the surest way to prevent frost heave stability problems is to place structures on piles anchored in ice-bonded permafrost. Where this is not possible, other measures will have to be used, such as artificially heating or insulating beneath structures, providing structures with leveling devices to accommodate differential frost heave, or reducing the adfreeze bond on pilings by using coatings or double walls.

Slopes of artificial islands must be protected to resist the forces of waves, ice and frost. Islands in the Canadian Beaufort Sea are principally protected with sandbags.^{2-4,6-8} Other measures, including filter cloth, chain link fence, wire mesh, sacrificial beaches and gabion berms, have also been used.^{2-4,6,7} However, little is known of the long-term effects of these forces. It is certain that if these methods are employed for production islands, some remedial efforts will be required to maintain the integrity of the fill.

The resistance of artificial islands to the force of sea ice is certainly one of the most important considerations in their design. It is also one of the most difficult analyses to make because of uncertainties in the magnitude of the ice force and the shearing resistance that can be developed by fill materials.

According to deJong et al.,⁴ the three principal kinds of failure due to the force of sea ice (Fig. 2) are 1) slope failure through an edge, 2) shear failure through the island fill, and 3) shear failure in the sea-bed foundation sediments.

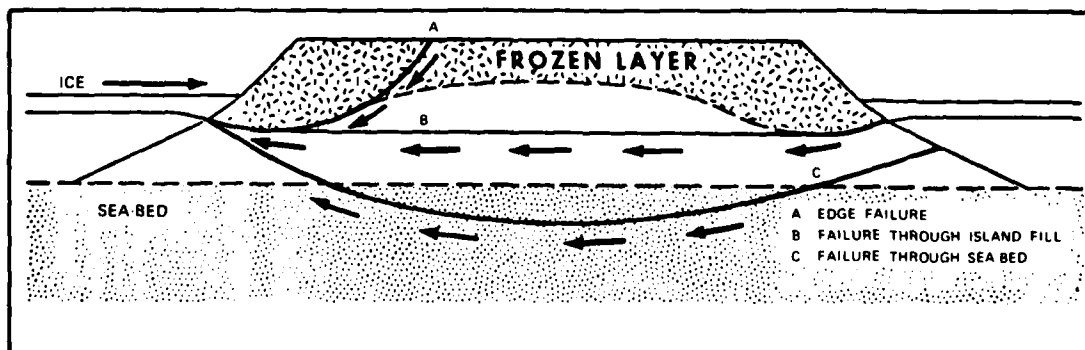


Figure 2. Potential failure planes beneath an artificial island. (From deJong et al.⁴)

DeJong et al.⁴ showed that for a sand fill placed on normally consolidated, unfrozen silty sediments the critical failure plane would be in the weak foundation sediments. They assumed that a thick frozen crust, which resists slope failure, forms in the fill before ice forces become a problem. My analysis of a sand island placed on strong, highly overconsolidated clays such as have been observed at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) site PB2¹⁹ near Reindeer Island shows that the weakest plane can be in the fill material beneath the frozen crust. In either case the factor of safety is not much greater than 1.2, which, because of the uncertainties in the calculations, is probably unacceptable for any island except those in shallow-water, fast-ice regions. Moreover, the factor of safety does not reflect the probability of failure, which is most important in the design of artificial islands. In defense of the design and construction practices used in the Canadian Beaufort Sea, it should be stated that no displacement of artificial islands has been observed for several years, even though these islands were designed for only one drilling season.

GRAVITY TOWERS FOUNDED ON THE SEABED

Many of the considerations in the design of foundations for gravity towers for open water in the Beaufort Sea are similar to those for more temperate parts of the world. However, there are two problems unique to the Arctic: 1) the force of sea ice and 2) the thawing of ice-bonded sub-sea permafrost.

Ice force is likely to be the principal cause of loading on offshore structures in the Arctic. In addition to resisting this force, foundations will have to withstand the weight of the structures, wave loading, and in some areas, seismic loading.

Ice-bonded permafrost will be a problem for the stability of structures founded directly on the seabed only if the structures or operations cause thawing. If thawing is allowed to occur, then the integrity of the tower, well casing and flow lines may be endangered.

Jazrawi and Khanna²¹ and Hancock et al.²² have proposed such structures. The Jazrawi-Khanna structure (Fig. 3) is designed to operate

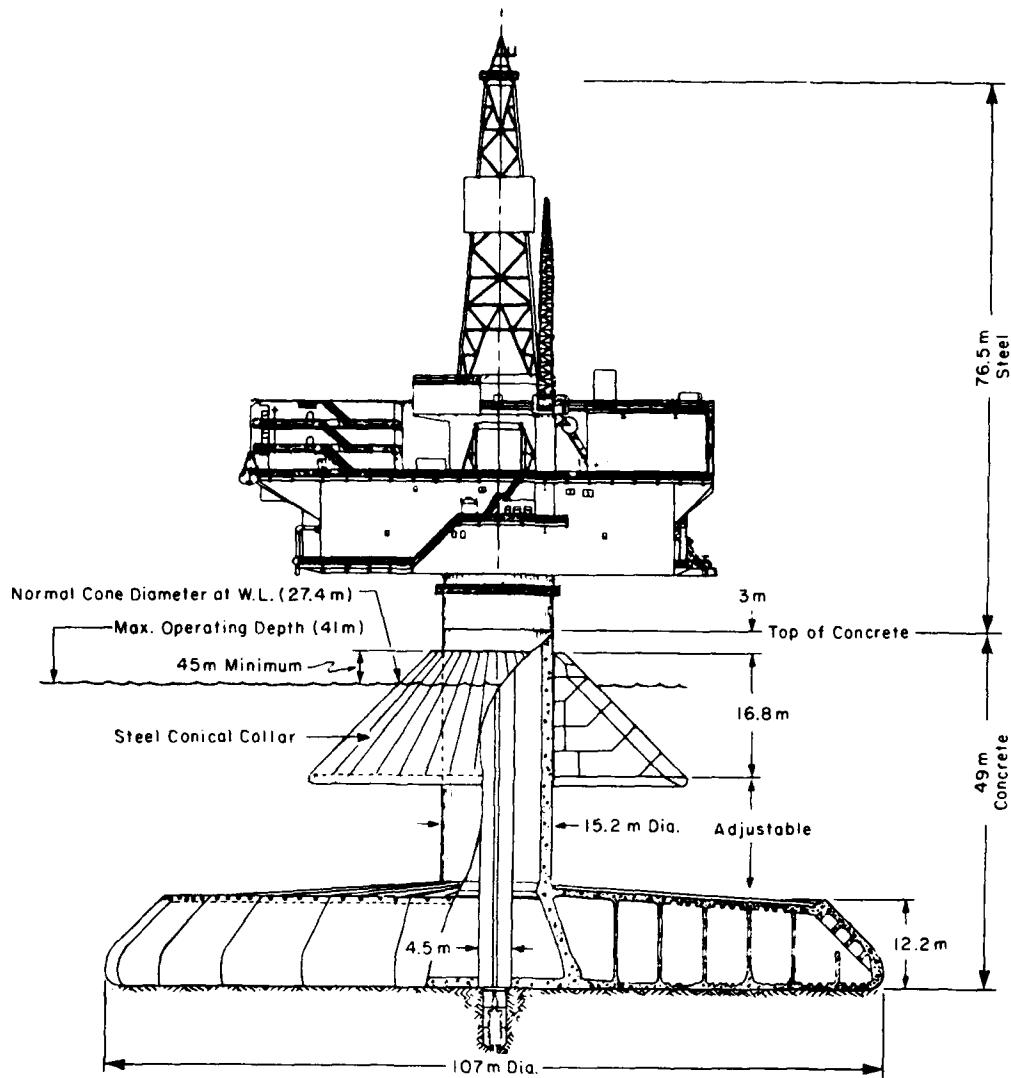


Figure 3. Gravity drilling platform for the Beaufort Sea.
 (From Jazrawi and Khanna.²¹)

in water up to 41 m deep, and that of Hancock et al. in water up to 18 m deep. Both structures cause the ice to fail in flexure by using a conical collar mounted on the central support shaft; the foundation stresses are distributed by a large diameter "lightship" base. Failure in flexure of the ice can be ensured only if adfreeze between the sea ice and the cone is eliminated; both types of structures do this by heating the cone.

According to Jazrawi and Khanna, their structure can be placed on relatively weak bed sediments (with a minimum shear strength of 21 kPa and a bearing capacity of 215 kPa). Of the seven offshore sites in the Beaufort Sea investigated during the CRREL-USGS program,¹⁹ three appear to have sufficient bearing capacity and shear strength to support such loads. And of 20 sites investigated during the USGS Conservation Division program,²³ eight appear to be suitable. To resist horizontal shear at the sea bed, Jazrawi and Khanna propose to seat their structure on a sand blanket, while Hancock et al. propose to use shallow skirts.

It is uncertain whether Jazrawi and Khanna have considered the cyclic nature of ice loading (and wave loading) in their design. (Hancock et al. have not.) This must also be considered, as cyclic loading of the foundation sediments may cause an increase in pore pressure and a reduction in bearing capacity and shear strength. The effect of cyclic loading is a major consideration in the design of gravity towers in the North Sea,²⁴ and it must be analyzed with cyclic triaxial compression and cyclic direct shear tests.

If ice-bonded permafrost occurs near the seabed, as it does in many regions of the Beaufort Sea, foundation support will probably not be a problem. However, if ice-bonded permafrost thaws under a gravity platform, the shear strength and bearing capacity of the foundation may be reduced and failure or settling may occur. Thawing will most likely occur as a result of production from the well. Unless precautions are taken, thaw will progress radially out from the well casing and downward beneath the structure. Downward thawing can be prevented rather easily by designing the submerged part of the structure to be operated at ambient, sea-water temperatures. Radial bore-hole thawing, however, will be a more difficult problem to prevent. The most effective mitigative measure would probably be to refrigerate and insulate the well casing in regions containing ice-bonded permafrost.

PILE-FOUNDED TOWERS

The same general considerations that apply to the design of foundations for gravity towers also apply to the design of pile-founded towers.

However, pile-founded towers have the advantage of providing greater bearing capacity and overturning resistance. They will probably be necessary where the sea bed sediments are too weak to support gravity structures and in the deepest waters where they will be the only practical solution to the overturning moments. In fact, Stagg²⁵ suggests that pile-founded structures, such as that shown in Figure 4, will be the general solution in arctic waters, as they can be designed to resist overturning moments and lateral shears for even the worst foundation conditions. The principal drawback is that piles may induce thawing of ice-bonded permafrost, particularly if some are used as well conductors. This problem, however, is similar to that beneath gravity towers and can be treated through proper application of insulation and refrigeration.

Piles are commonly used to support structures on land permafrost. Piles in permafrost have high support capacities, and they allow the elevation of structures to minimize the thermal disturbance of the permafrost. An excellent discussion of design and installation practices on permafrost has been prepared by Sanger.²⁶

Piles are usually designed to develop their support capacity through the adfreeze bond between the frozen ground and the pile. Point resistance is not usually added because point loads often do not develop fully until

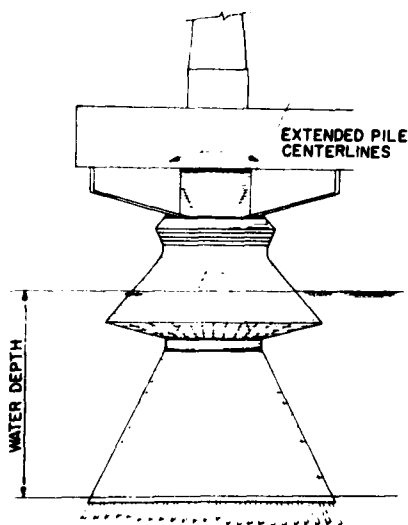


Figure 4. Pile-supported platform for the Beaufort Sea. (From Stagg.²⁵)

the adfreeze bond has broken. The adfreeze strength depends on temperature, soil type, ice content, and type of pile and surface preparation. The depth of embedment is normally calculated by determining the distribution of the maximum bond stress with depth (which varies with depth because temperature normally varies with depth) in the frozen zone and integrating over the depth to determine the maximum pile capacity. Safety factors of two for sustained loads and three for peak loads are commonly applied. To resist heave forces developing in the active zone during the winter, the length of anchorage in the ice-bonded permafrost should be equal to at least twice the active zone thickness.

This design procedure accounts for load capacity only, not for settlement. As settlement often controls the design, it also must be considered and is usually evaluated with full-scale test piles.

Piles are usually placed in permafrost by augering or steaming holes. Steaming should not be considered for the subsea setting as it induces large thermal disturbances. With little or no freezeback capacity in the relatively warm subsea permafrost, it would take a long time to refreeze and redevelop the adfreeze bond. Augered holes are preferable as they introduce little thermal disturbance. The principal thermal disturbance in augered holes in subsea permafrost will be from the intrusion of warmer sea water.

Because freezeback is slow in warm subsea permafrost, it may be necessary to induce freezeback artificially, either with mechanical refrigeration systems or with thermal piles like the Long Pile²⁷ or Balch Pile.²⁸ Thermal piles will probably be most effective when placed in shallow water or through artificial islands or embankments. They could be used both to support structures and to promote freezing of the fill and sea bed.²⁹ In deeper waters, however, heat losses along the portion of the pile extending through the water may reduce the effectiveness of the natural cooling.

Piles used to support towers on the sea bed will need special designs if the depth to ice-bonded permafrost is shallow. If ice-bonded permafrost is well beneath the bottom of the piling, however, conventional design and emplacement procedures can be used. Where piles extend into ice-bonded

subsea permafrost, artificial refrigeration may be necessary, particularly if any of the piles are used as well conductors.

Piles will not only be used to provide the necessary bearing capacity for structures, but may also be required to resist the shearing force between a tower and the sea bed and to resist the overturning uplift force imposed by sea ice. Refrigerated piles may increase shear and overturning resistances.

Piles that are placed beneath towers to provide horizontal shear resistance at the sea bed will be laterally loaded. The bending resistance of the piles must be evaluated to ensure that lateral displacement will not damage well casings or flow lines.

CONCLUSION

The design of structures for offshore exploration and production of petroleum resources in the Beaufort Sea needs to consider conditions unique to polar waters. The force of sea ice, the thawing of subsea permafrost, and frost heaving all must be accounted for to ensure the stability of bottom-founded structures.

Three types of structures are currently being considered as permanent production facilities. Artificial islands constructed of dredged or trucked earth materials have been used with considerable success for temporary exploration structures. Gravity towers founded on the sea bed and pile-founded towers founded beneath the sea bed are also being considered but none have been employed to date.

The artificial islands must be designed to resist the shearing force of sea ice and the effects of freezing and thawing. The foundations of the towers must be designed to resist the shearing and overturning forces of sea ice and settlement due to thawing of permafrost.

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