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OVERVIEW OF ICE RUBBLE GENERATORS AND ICE PROTECTION STRUCTURES IN TEMPERATE REGIONS

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ABSTRACT

This paper presents the past and present use of ice rubble generators and ice protection structures in temperate regions. Information was assembled through a literature review and discussions with national and international personnel involved in with this type of construction and research. The majority of structures investigated were designed for use in shallow water (approximately 4 m in depth). However a number of concepts show the potential to be adapted for deeper water use. Many involved an arrangement of piles designed to hold back rubble or to encourage the formation of a stable ice sheet. Structures specifically designed to generate rubble have focused on rubblemound berm or barge-based structures. The structures were studied in order to develop innovative technological concepts that hold promise for use in the Canadian Beaufort Sea.

INTRODUCTION

During the exploration of the Beaufort Sea in the 1970s and 1980s, considerable attention was paid to the large accumulations of broken ice pieces (ice rubble) that often grounded around offshore structures. Controversy ensued whether ice rubble would (a) reduce ice loads (by transmitting some of the ice load to the seabed and preventing ice crushing on the face of the structure), or (b) increase ice loads by making the "structure" wider. Analysis of ice load data has shown convincingly that rubble fields can be very beneficial for attenuating ice loads.

This is an extremely important finding for future production structures in the Beaufort Sea, especially in the shear transition zone (e.g. Amauligak site). There will be a clear

advantage for lower loads (and hence lower cost structures) if a stable rubble field could be generated and maintained at the structure. This technology would, in effect, provide a passive load-reduction technique. If crushing directly on the structure can be effectively negated, the peak ice loads would be reduced by over 30%. To effectively use this approach, innovative technology must be developed to initiate and "pin" the ice rubble around the structure. This could be done using Ice Rubble Generators (IRG) - passive devices that would initiate rubble formation in selected areas and secure the rubble throughout winter, thereby shielding the structure from direct ice contact. In summer, the IRG could act as "depth-limiters" that would restrict the thickness of isolated, multiyear, ice floes that could hit the structure. These latter types of structures are often referred to as Ice Protection Structures (IPS).

This paper forms part of an ongoing project, the goal of which is to determine the feasibility of using hybrid Ice Rubble Generators/Ice Protection Structures (IRG/IPS) in the Canadian Beaufort Sea, primarily in the shear transition zone. This could result in lower loads associated with the structure, and hence lower cost structures themselves, increasing the potential for development in this region of Canada. In the first year of the project, the technology of IRG/IPS was investigated through a literature review and discussions with national and international personnel to collect available information. For example, it is known that in a few temperate regions such as Japan, the Caspian Sea and the Great Lakes, IPS or IRG have shown the ability to generate rubble and decrease loads on structures. This paper discusses these systems and their ability to generate ice rubble. It does not deal with the load reduction issue since little information is known about the load reduction characteristics of ice rubble.

ICE RUBBLE GENERATORS (IRG)

The majority of research concerning IRG has been carried out for studies related to exploration drilling in the Caspian Sea. A number of investigations conducted at the Hamburg Ship Model Basin (HSVA) relating to ice barriers and their rubble-generating capacity have been reported. These structures were intended for use in the shallow water of the Caspian Sea, generally 4 metres of water or less. While this water depth is potentially less than that in which Beaufort Sea drilling structures will be located, some of these investigations will be useful in developing design concepts for the Beaufort and, in shallow water environments, many technologies will still be applicable. These investigations examined three general types of IRG: (1) barges; (2) piles and barges combined; (3) rubblemound berms.

Barges

Jochmann et al. (2003) describe physical model tests performed for the Agip Kazakhstan North Caspian Operating Company. In this test series, four 85 m long barges were used as ice barriers surrounding the Sunkar drilling rig, placed in a variety of configurations and with varying ice velocity and drift angle. Originally,

the Sunkar had been protected by two rows of large piles driven along the longest sides of the structure (Evers et al., 2001). The (scaled) ice thickness for this test series was 0.5 m or 1.3 m with a bending strength of 770 kPa. Two velocities were tested (0.5 and 1.0 m/s approximately) and five different ice drift directions. The gap width between barriers (0 m, 65 m or 85 m) and the angle of the ice barriers with respect to the rig (0°, 10°, 30°) were also varied. The distance between the rig and the barriers was 135 m. The barges initiated ice rubble accumulation, and the stability of the Sunkar was sufficient regardless of the ice drift angle. An angle of 10° to 15° was optimal for generating rubble and protecting the structure. A significant horizontal global load reduction was obtained by using the barriers. However, it was noted that an advanced ice management system could be necessary, with respect to problems with the downstream ice barriers, as the Sunkar needed to be accessed by supply vessels year-round.

Piles and Barges

A series of tests (Weihrauch et al, 2003; Evers and Weihrauch, 2004) investigated barriers that were designed for relatively thin ice (compared to the Beaufort Sea) of 0.1 m to 0.5 m and an ice velocity of approximately 0.5 m/s. The goal of the study was "to design modular ice barriers which catch early, thin ice, stabilize themselves by this ice and can withstand thick ice later in the ice season" (Weihrauch et al, 2003).

A number of designs were investigated:

- vertical piles in a row
- inclined piles in a row
- barge with oppositely arranged rows of vertical piles
- barge with oppositely arranged rows of inclined piles (60°)
- barge with closed, inclined sidewalls (60°)
- inclined piles with inclination against the ice direction
- two oppositely arranged rows of inclined piles
- inclined roof structure
- barge-based barrier with a roof-structure to collect thin ice.

The conclusions from the tests were that (Weihrauch et al, 2003):

- the distance between piles should be less than 4 times the pile diameter for inclined piles and less than 6 times the pile diameter for vertical piles (larger distances only generated ice rubble after the ice had grounded); however the piles only generated rubble for thicker ice
- the piles did not prevent the ice rubble from drifting downstream and significant pile-up only occurred for small distances between piles (not efficient)
- the use of a barge encouraged earlier grounding of the ice when used with piles

- significant ride-up only occurred for the barge-based structures and the inclined roof structure
- an optimal design should have a sloping angle of less than 30°, with closed sides and at least two barriers placed oppositely to collect ice.

An ice barrier based on a barge with piles, spaced at 4 times the pile diameter, that supported an inclined roof structure of pleated steel sheeting was selected as the optimal design. Nylon nets that had a mesh width of 0.3 m were arranged between the piles to catch rubble ice. One of the advantages of the ice barrier with the inclined roof was that it would not need to be anchored to the sea bottom or have an extremely large weight to withstand ice forces, as it was designed to take into account the stabilizing nature of the ice rubble. The barrier could be arranged with a variety of angular configurations with respect to the structure to be protected, and could be placed directly at the structure if necessary. This type of barrier was designed to be modular and removable for the summer shipping season. It should be noted that spray ice barriers built upon barges have also recently been tested for use in the Caspian Sea.

Rubblemound Berms

As with the laboratory tests described previously, the rubblemound barriers described in Lengkeek et al (2003) were designed for use in the shallow waters of the Northern Caspian Sea. In this paper, a finite element modelling assessment of rubblemound barriers was carried out. A number of loading scenarios were studied: thin ice interacting with a bare rock slope; thick level ice acting on grounded rubble; rafted ice acting on grounded rubble; thick ice interacting with a bare rock slope; ice acting on a frozen layer in the barrier; a pressure ridge acting on the rubblemound slope. No examination of the rubble-generating capacity of such structures was documented.

Barker and Croasdale (2004) used a numerical model to predict ice rubble pileup geometries and forces due to an ice sheet impinging on a structure protected by arrangements of rock mounds. The results compared favourably to associated full-scale data. The chosen driving force and material parameters produced the expected pileup thickness. The maximum grounded thickness was approximately 10 m, with a corresponding pileup height of 6 m in 4 m of water.

ICE PROTECTION STRUCTURES (IPS)

Ice Protection Structures have a primary goal of preventing ice from contacting a structure or a shoreline, rather than generating ice rubble. However, rubble generation was often a secondary effect of these structures' placement in environments where ice is present. The IPS that were studied fall into four broad categories: ice barriers and ice breaker frames; ice booms; rubblemound breakwaters; piles.

Barriers

A number of ice barriers have been investigated either through field trials or conceptually. A field test of a four-legged offshore ice barrier was conducted in the Sea of Okhotsk in approximately 4.0 m of water, as documented by Yamaguchi et al. (1981). The tests were conducted over two winters (1979-1980), however the structures did not encounter heavy pack ice during the period of investigation. The barriers were designed by the Nitsui Engineering and Shipbuilding Company Ltd. While a number of structure designs were developed, the final design was chosen based upon "the ability to keep off pack ice, ice and wave resistance, water permeability, ease in foundation erection, and construction costs". The barrier was placed on a rock seabed. Two alternative designs, for deep water or a soft seabed material such as sand or clay were also conceptualized. The barriers were designed for a maximum ice force (horizontal) of 16 tons (80 kN) and maximum wave force of 30 tons (150 kN), with pipes inclined at 45° to reduce horizontal ice forces. They also had the ability to prevent pack ice passing through the structure, by spacing the pipes such that that encroaching pack ice would ride up the inclined pipes and fail in bending. When pack ice encountered the structures, they formed an "effective barrier" and seemed to encourage the development of a land-fast ice cover behind the structures. The ice behind the structures was not rubbled. Ice did not freeze to the structures due to tidal variations.

Further investigation into a structure suitable for protecting shoreline areas in the Sea of Okhotsk is found in a paper by Nishizawa and Tanaka (1988). The structure that was developed was made up of three inclined pipes that were filled with concrete, attached in a pyramid shape. They were designed for a high water level of 5.25 m, with a wave height of 2.5 m. The associated ice parameters were a thickness of 0.5 m, a flexural strength of 0.5 MPa, a Young's Modulus of 500 MPa and a friction factor of 0.1 between the structure and the sea ice. The pipes were inclined at a 45° angle. The concrete within the pipes was deemed to be necessary following stress and stability analysis of the structure for ice and wave forces. This three-legged barrier was a conceptual design.

A paper by Saeki (1992) mentions another paper (Inoue et al. 1988), describing a Hybrid Ice Trap Structure (HITS) that was similar in design to the three-legged pack ice barrier. These two structures had the design advantage of being more stable than the Yamaguchi (1981) four-legged design.

Ettema et al (1983) described a laboratory study for a barrier that was developed to prevent sea ice from interacting with a harbour structure in Nome, Alaska. This involved an offshore barrier placed around the port. The purpose of the "ice breaker frames" was to limit ice over-ride, by fracturing an incoming ice sheet. The design water depth was approximately 6 m. The spacing of the frames was a function of their distance from the structure, with a greater offshore distance allowing a larger spacing between the frames. The frames had to be "well anchored to the sea bed in

order to resist both uplift forces that can be imposed when they are frozen to a rising ice sheet during water-level change, and overturning moments due to horizontal ice loads." For a 0.9 m thick ice sheet with flexural strengths between 0.50 and 0.65 MPa (73 to 94 psi), peak horizontal loads of 1.3 to 1.8 MN (300 to 400 kips) were measured on a modelled frame, with peak uplift forces of 22 to 27 MN (5000 to 6000 kips).

Some issues with ice barriers were presented in Saeki (1992). The paper points out that barriers should:

- not obstruct navigation
- not adversely affect drift and sedimentation along a shoreline
- have construction costs kept within a reasonable range
- be able to resist the simultaneous loading that may develop in locations where waves and ice floes exist concurrently.

Ice Booms

Papers by Saeki (1992) and Morse (2000, 2001) discuss the use of booms for controlling ice. Ice booms have been in used in Canada for a number of years. They have been deployed, for example, in the Rideau River for controlling spring ice break-up and in the Ottawa River and Lake Erie for controlling ice in the vicinity of hydropower stations. In the St. Lawrence River, three booms were originally deployed downstream of Montreal, in Lac St. Pierre in order to minimise the risk of ice jams in the navigation channel.

Morse (2000, 2001) expanded on some previous studies that examined ice forces on these booms. The booms were cylindrical steel pontoons, from 61 to 76 cm in diameter and approximately 914 cm long. Depending on their location, the booms were designed to encourage ice bridging or a stable ice cover between the boom and artificial and/or natural islands (discussed in the following section) and to hold back ice floes from entering the navigation channel. The incoming ice during the study generally consisted of large sheets of thin 0.02 to 0.06 m ice, not ice rubble. The study found that the peak annual load was on average 6.4 kN/m, with a maximum line load of 10.9 kN/m.

Rubblemound Breakwaters

Lac St. Pierre often traps ice that is moving downstream in the St. Lawrence River. This causes a problem for the seaway navigation channel, which can become choked with broken ice. Four artificial islands were installed to help control ice movement by retaining an intact ice cover (Danys, 1980). The islands were designed to stop early winter small ice floes that would then freeze together and initiate the formation of a solid ice cover upstream of the island. The islands rest on a clay riverbed, in approximately four metres of water, 6 km from shore. The footprints of the islands ranged from 45 m to 80 m with an above-water width of 10 m. Three of the islands

were built to a height of one metre higher than the winter high water level (4.8 m), while the fourth island, designed to accommodate a light pier, came to 3.7 m higher than this water level.

The island with the light pier was designed as a berm structure to minimize ice ride-up, and proved to be very effective in generating large ice pile-ups that did not impinge on the light pier structure. The remaining islands were not designed as berms and initially no armour stone was placed on the slopes of the structures. This was amended two years later, as the quarry-run rock was insufficient for resisting both waves and ice action, and the islands were redesigned with a berm configuration. The islands required continuous maintenance work due to the large volumes of moving ice and primarily as a result of strong waves and swell generated by passing ships. Due to the clay seabed, the islands experienced a great deal of settlement after ten years – in some places, double the predicted settlement of 1.2 m for the island with the light pier, and even larger for the other three islands. Overall, while the islands were effective in holding back the ice and creating a stable ice cover, they were only economical in shallow water due to the poor clay foundation. It should be noted that many exploration drilling, and hence production, locations in the Canadian Beaufort Sea also have clay seabeds.

Piles

Alaskan projects carried out by PND Inc. (D. Nottingham, personal communication) have involved a variety of techniques, often pile-based, to break-up incoming ice floes. These projects did not generate rubble specifically, however they demonstrate the ability of piles to break up incoming ice, often the first step in generating ice rubble.

One project, the Endicott Causeway Breach Bridge, owned by BP Exploration (Alaska), is used for providing access for oil field service traffic and also supports the Endicott oil field pipeline. The overall bridge length is 213 m, with a 198 m breach opening contained within this. The breach opening in the causeway bridge was designed in order to accommodate fish passage along the Alaskan North Slope shoreline. The high water velocities through these openings can cause scour in the order of 9 m in a single storm and sea ice applies major forces to the foundations. The Endicott Bridge is supported by piles and has two conical piers. These piers have bevelled sides to reduce ice forces. The piles within the piers consist of six 0.76 m-diameter steel pipe piles that are covered by a pier cap. The cap has top and bottom plates, radial stiffeners and face plates to make the cap rigid enough to withstand ice forces. Over this cap is an outside steel cone. The piers are designed for a maximum ice force of 2.5 MN (250 tons) horizontal (design ice load of 2.2 MN (500 kips)).

The Kuparuk River Crossing bridges cross two river channels in a flood plain along the Alaskan North Slope. They are owned by Phillips Petroleum Company. They

were designed to be submersible during flood events and to be able to carry large vehicle weights. River ice in the area can be 1.5 m thick. Figure 1 shows this thick, strong ice impacting with one of the bridges.

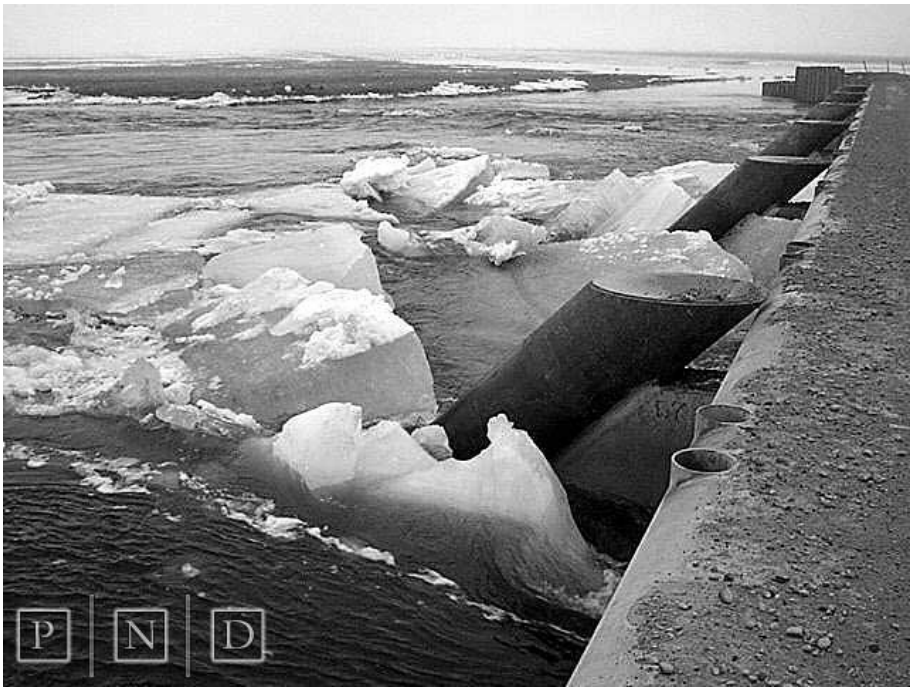

Figure 1: Kuparuk river module breaking up thick river ice (photo courtesy of PND Ltd.)

Additionally, spin-fin piles were developed by PND Ltd. in the mid-1980s and have been used for a variety of structures and soil conditions (Nottingham, 1994). These piles have steel fins welded onto the bottom of the pile and were designed to resist high loads (over 100 tons). The piles are suitable for use where anticipated uplift loads would normally cause pile failure. Through their use of such piles, PND have found them to be a more predictable and reliable tension pile and an economical option for driven pile foundations. Another advantage to this type of pile is that they allow substantial pile movement without catastrophic failure. One of the main criteria for their use is the need to define what is the tolerable deformation for a given scenario.

An example of the ability of such piles to resist high impact loads even though deformation has occurred was given in Nottingham (1994) and in an accompanying video recording. The paper describes a 35 100 ton-displacement, 245 m tour ship at Skagway, Alaska being pushed into the terminal dock by wind. The approach velocity of the ship was approximately 0.18 m/s and the estimated contact energy was 59 ton-m. This event severely damaged or destroyed two of the steel pile dolphin moorings (12 and 6 piles, respectively) along the dock. Another dolphin, constructed using spin-fin piles, stopped the ship. It was estimated that a light-duty outer fender

absorbed approximately 14 ton-m prior to collapse, with the remaining energy absorbed by movement of the dolphin. The spin-fin pile dolphin had 0.2 m of horizontal movement and 0.1 m of pullout movement for the main pile. The ultimate tensile load was calculated to be 299 tons or 67 kPa average shaft friction.

IMPLICATIONS FOR ICE RUBBLE GENERATION AND ICE PROTECTION IN THE CANADIAN BEAUFORT SEA

Table 1 summarizes some of the key features of the structures presented in this paper. It is clear that some of the structures described are more applicable for use in the Beaufort Sea than others. Of the structures covered in this paper, rubblemound barriers, submerged barges (such as concrete caissons) or piles would seem to be the most suitable to function as a hybrid IRG/IPS. For example, the scenario of the cruise ship that ran into the spin-fin dolphins could be comparable to a summer ice floe impacting a pile-based IRG/IPS surrounding an offshore platform. In this case, it would be desirable to slow down the floe's velocity, while not necessarily attempting to stop it completely. A pile-based structure would aid in energy absorption thereby protecting the platform from the full-impact of the floe. Deformation of the piles to a certain extent would be acceptable, as the piles could be re-driven if need be at a later time, unless critical failure had occurred. Whether such piles would generate sufficient rubble throughout the winter to dissipate loads on a platform would need to be investigated. A rubblemound barrier or a submerged barge would both have the ability to generate rubble throughout the winter, while also providing a depth-limiting factor for summer ice floes. Most IPS that are in use today do not appear to have the necessary strength and stability required to withstand the impacts of summer ice floes. While many IPS have generated rubble in the field, their ability to do so in deeper water and on a regular basis may not match the capabilities of typical IRG configurations. Of course, there are many factors besides those listed in Table 1 that need to be considered in order to develop IRG/IPS concepts that would be suitable for the Beaufort Sea. Some of these considerations are indicated in Table 2.

The information presented in this paper is derived from a report (Barker and Timco, 2005) that describes the IRG and IPS structures in considerable detail with photographs. It also summarizes the rubble generation that occurred around Beaufort Sea exploration structures. The report is available on the CHC website (www.chc.nrc.ca). This research is part of a four-year research program to investigate the feasibility of using hybrid IRG/IPS around production platforms in the Canadian Beaufort Sea.

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Table 1: Comparison of IRG/IPS key parameters for use in the Canadian Arctic

	Applicable water depth? (disregarding cost)	**Generate grounded rubble?**	**Slow/stop summer floes?**	**Presently in use as IRG or IPS?**
IRG				
Barges	Shallow/intermediate/deep	Yes	Maybe	Yes
Piles and Barges	Shallow/intermediate/deep	Yes	Maybe	Yes
Rubblemound Barriers	Shallow/intermediate/deep	Yes	Yes	Yes
IPS				
Barriers	Shallow	Maybe	No	Yes
Ice Booms	Shallow	No	Maybe	Yes
Rubblemound Breakwaters	Shallow/intermediate	Yes	Maybe	Yes
Piles	Shallow/intermediate	Maybe	Maybe	Yes

Table 2: Hybrid IRG/IPS concept considerations for the Canadian Arctic

Factor	**Considerations**
Construction Logistics	Is the support infrastructure (access vehicles, heavy machinery, supply vessels) available in the Arctic for the development of the IRG/IPS? Are the required supplies (fill, piles, concrete) accessible? What environmental constraints are there with respect to construction timing?
EER Logistics	How will the IRG/IPS affect EER logistics, such as the location of EER facilities on the platform, deployment of EER vessels or lifeboat manoeuvrability?
Maintenance	What type of upkeep will the IRG/IPS require over the lifetime of the platform? What actions would be necessary if an allowable amount of failure occurs?
Supply access	Is there access for supply vessels throughout the year?
Cost	Is a concept feasible for a certain location, but cost prohibitive?
Seasonality	Is the concept reliant upon a technology that is seasonally-dependent, such as spray ice? If so, how will this affect summer performance of the IRG/IPS?

REFERENCES

Barker, A. and K. Croasdale (2004). Numerical Modelling of Ice Interaction with Rubble Mound Berms in the Caspian Sea. Proc. IAHR Symposium on Ice, IAHR'04, Vol.2, pp 257-264, St. Petersburg, Russia.

Bastian, J., Standberg, A.G., Graham, W.P. and D. Mayne (2004) Caspian Sea Sprayed Ice Protection Structures. Proc. 17th International Symposium on Ice (IAHR'04) Vol.2, pp.58-67, St. Petersburg, CIS.

Danys, J.V. (1980) Artificial Islands in Lac St. Pierre to Control Ice Movement. Proc. 1st Canadian Conference on Marine Geotechnical Engineering, pp. 366-379, Calgary, Canada.

Ettema, R., Kennedy, J. and M. Horton (1983) Ice Study for the Port Development at Nome, Alaska. Proc. 7th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'83), Volume 2, pp. 865-874, Espoo, Finland.

Evers, K. and A. Weihrauch (2004) Design and model testing of ice barriers for protection of offshore structures in shallow waters during winter. Proc. 17th International Symposium on Ice, IAHR'04, Vol. 2, pp 124-131, St. Petersburg, CIS.

Inoue, K., Ohnuma, Y. and M. Tatsuta (1988) Design method of hybrid ice trap structure (HITS). Proc. 7th Cold Region Technology Conference, p.299-304.

Jochmann, P., Evers, K. and W.L. Kuehnlein (2003) Model testing of ice barriers used for reduction of design ice loads. Proc. 22nd International Conference on Offshore Mechanics and Arctic Engineering (OMAE'03), OMAE2003-37385, pp.815-821, Cancun, Mexico.

Lengkeek, H.J., Croasdale, K.R. and M. Metge (2003) Proc. 22nd International Conference on Offshore Mechanics and Arctic Engineering (OMAE'03), OMAE2003-37411, pp.831-837, Cancun, Mexico.

Morse, B. (2001) Dynamics of Ice Forces on Booms. Cold Regions Science and Technology. Volume 33 pp.29–43.

Nishizawa, S. and S. Tanaka (1988) Structural Design of New Type Three Legged Ice Barrier. Proc. 9th International Symposium on Ice, (IAHR'88), Volume 1, pp. 591-600, Sapporo, Japan.

Nottingham, D. (1994) Spin-Fin Pile Performance. Proc. U.S. FHWA In. Conf. on Design and Construction of Deep Foundations, Orlando, U.S.A.

Saeki, H. (1992) Ice Control in Northern Harbors. Proc. 11th International Symposium on Ice, International Association of Hydraulic Engineering and Research (IAHR'92), Volume 3, pp. 1211-1241, Banff, Canada.

Weihrauch, A., Berger, J. and M. Bartels (2003) Design of self-stabilzing ice barrier. Proc. 22nd International Conference on Offshore Mechanics and Arctic Engineering (OMAE'03), OMAE2003-37163, Cancun, Mexico.

Yamaguchi, T., Yohida, H, Yashima, N and M. Ando (1981) Field Test Study of "Pack Ice Barrier". Proc. 6th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'81), Volume 1, pp. 313-322, Quebec City, Canada.