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Ice Load Estimation Methods for LNG Jetty Design in Various Ice-Structure Interactive Conditions

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Abstract

In this study, the authors proposed the ice load estimation methods for LNG jetty design in the southern coast of Sakhalin Island by building scenarios of ice forces exerted on the structures, e.g. i) driving ice force with geographical features considered, ii) ice force with jamming effects considered, iii) ice force with jamming effects and non-simultaneous ice failure considered, and iv) ice force with no jamming. The possibility of ice jamming cannot be ignored when consideration is given to the geometrical configuration of the close proximity of the jetty supports. However, using the mechanisms that consider the failure of ice around a single support, it has been demonstrated that the predicted ice loads are larger than those resulting from ice jamming occurring between a series of closely spaced supports.

Introduction

Sea ice is generated every winter in the Okhotsk Sea and drifts southward to the coastal area of Hokkaido, Japan's northernmost island. Within this environment, the Sakhalin Oil & Gas Project, undergoing continuing development offshore Sakhalin Island, has greatly increased oil transportation in the Okhotsk Sea. Offshore fields in the north of Sakhalin are situated in the subarctic zone where the sea is covered by ice during the winter months which significantly complicates access to the facilities located there. To make exports possible throughout the year, crude oil and gas are transported by pipelines to Aniva Bay in the south which remains largely ice-free during winter time. Ice environment data reports provided by the Japan Coast Guard indicate that the mean ice appearance ratio in Aniva Bay (the percentage of days with ice entering Aniva Bay during the observation period) is 57%, and the mean ice coverage ratio (the percentage of Aniva Bay covered with ice) is 82%. Therefore, although it remains largely ice-free during winter timw in Aviva Bay, ice force have to be considered for the design of horbor facilities such as jetties, trestles, bridge piers, etc. This study intended to recommend an ice loading condition for the design and construction of the LNG Jetty using the state-of-the-art techniques for achieving a high level of functional reliability and acceptable levels of safety that takes into consideration the environment and sea ice condition in Aniva Bay. The scenarios proposed in this study would be useful for the design of structures to be built in the sea with sea ice presence. The locations of Sakhalin Island and Aniva Bay and LNG jetty in Aniva Bay are shown in **Fig. 1** and **Fig.2**, respectively.

Fig.2 LNG jetty in Prigorodonoye, Aniva Bay.

Fig.1 Schematic of the Sakhalin I and II Project elements and Aniva Bay.

Ice Load Calculations

Scenarios of Ice Forces Exerted on the Structures

The indentation ice force is defined as the ice force resulting from ice crushing/bending failure against the structures. This force can be simply expressed as follows:

Ice force = (ice compressive/bending strength) x (structure shape factor) x (structure width) x (ice thickness)

In addition, the ice forces on structures when ice accumulates in front of the structures (hereafter, ‘driving force’) have to be considered in some cases; the force is induced by the water flow and wind. In this case, the accumulated ice will not fail or be crushed by interaction with the structures.

The following scenarios determine the ice force in these cases:

- Scenario 1: The design force is equal to the ice indentation force. This means that the ice will fail (crush/bend) when the environmental force becomes as large as the ice indentation force and
- Scenario 2: The design ice force is equal to the environmental force if the environmental force is smaller than the ice indentation force.

Calculation of the environmental force involves defining the accumulated area of ice perpendicular to the structure line. This information is usually difficult to accurately determine because it is affected by the ice velocities, ice block size, current direction, wind direction, etc. Because the ice will fail when the driving force becomes as large as the ice indentation force, the ice indentation force is the maximum ice force. As a result, the design ice force is usually estimated by the ice indentation force because this gives a conservative value.

Driving Ice Force with Geographical Features Considered

The jamming ice forces acting against the set of structures (MD4-MD5) are the wind driving force and the current driving force, as shown in **Fig. 3**, and can be calculated by the equations proposed by Sanderson (1988). When taking into consideration the geographical features of Aniva Bay, it is remotely possible that the ice in front of the set of structures, i.e. MD4 to MD5 including six strucutres between them, might accumulate up to the length of 45 km, as shown in **Fig. 4**. Under this extreme and highly unlikely condition, the wind and current driving forces developed from the drag of flows over the rough top and bottom surfaces of the entire ice cover would become 2.45 MN per support, as calculated below.

$$\begin{aligned} A &= 45 \times 10^{3} \times 156.8 \\ &= 7{,}056 \times 10^{3} m^{2} \end{aligned}$$

$$\begin{aligned} Fa &= 2.5 \times 10^{-3} \cdot 7{,}056 \times 10^{3} \times 20.4^{2} \\ &= 7{,}341{,}062\ N \\ &= 7{,}341\ kN \end{aligned}$$

$$\begin{aligned} Fw &= 4.1 \times 7{,}056 \times 10^{3} \times 0.65^{2} \\ &= 12{,}222{,}756\ N \\ &= 12{,}223\ kN \end{aligned}$$

$$\begin{aligned} Ftotal &= 7{,}341 + 12{,}223 \\ &= 19{,}564\ kN \\ &= 19.56\ MN \end{aligned}$$

$$\begin{aligned} F &= 19.56 / 8 \\ &= 2.445 \\ &\fallingdotseq \underline{\underline{2.45\ MN}} \end{aligned}$$

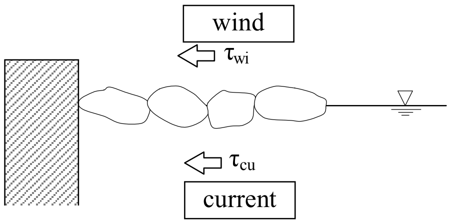


Fig. 3 Wind and current driven ice forces.

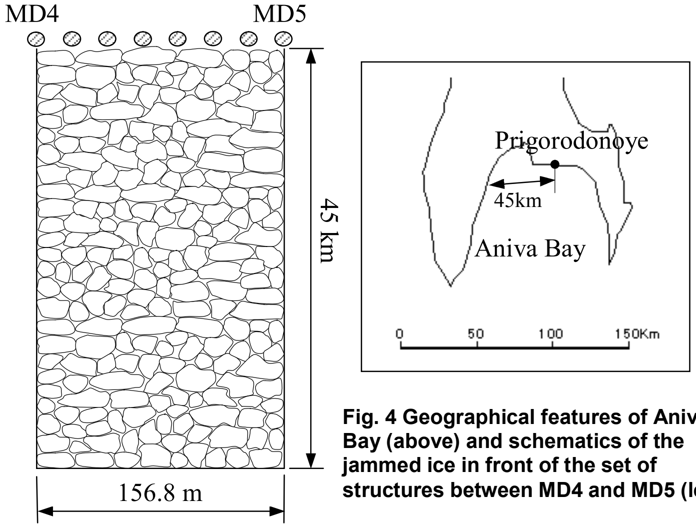
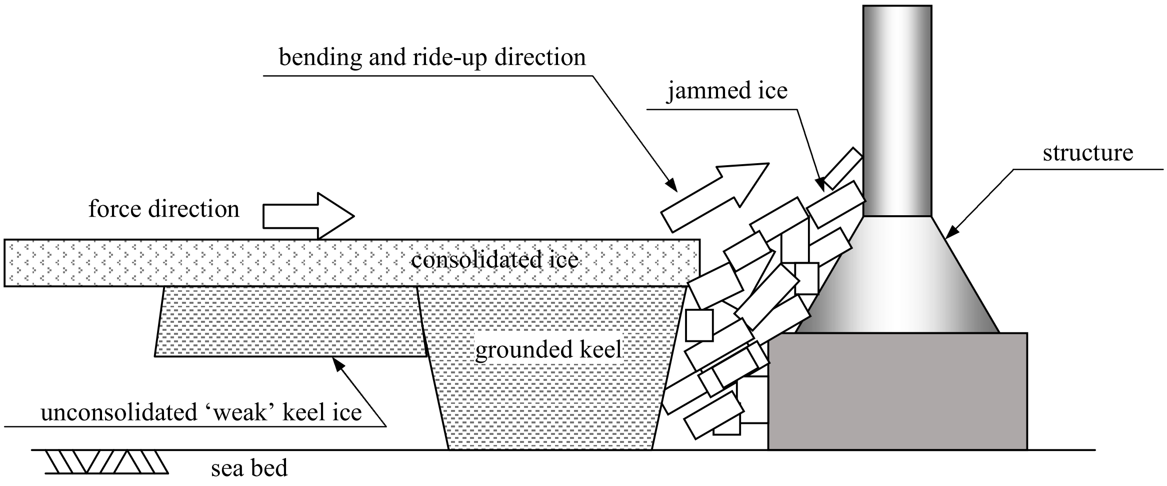


Fig. 4 Geographical features of Aniva Bay (above) and schematics of the jammed ice in front of the set of structures between MD4 and MD5 (left).

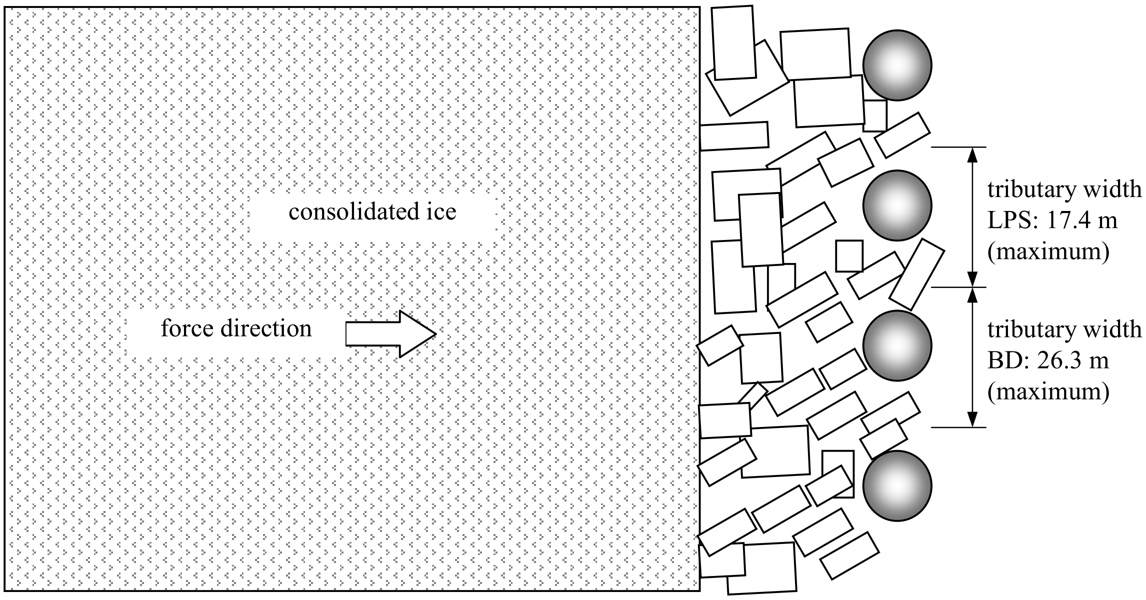
Ice Force with Jamming Effects Considered

Geometry of jamming effect

The close proximity of the supports in the central part of the jetty will cause ice jamming, and the jamming increases the contact area for oncoming ice. In the event of ice jammed in front of the set of structures with an ice cover comprised of both consolidated and unconsolidated keel layers formed behind the jammed ice, the ice forces on the structures would be generated by the bending and the ride-up motion of the consolidated layer and the unconsolidated keel force. Both of these forces would interact with the structures through the jammed ice existing between the ice cover and the structures, as shown in **Fig. 5**.



a. Cross-sectional view



b. Plan view

Fig. 5 Schematics of ice-structure interaction with ice jamming effects considered.

Jamming effect force

Croasdale (1980) developed a two-dimensional analysis model for ice interaction with a sloping structure as expressed in the equation below. The first term gives the horizontal force generated at the first instance of ice failure. Once the ice has failed, the broken pieces start to ride up the face of the structure (the sloping face of the jammed ice in the present study), and an additional force is experienced by the sloping face. The second term gives the ride-up force. Although this is a two-dimensional analysis, it is appropriate for very wide structures. Thus, the bending and the ride-up force generated by the consolidated layer can be calculated by the following equation with the values listed below. The load is calculated over a tributary width larger than the width of a support. The tributary widths are defined as the contact length of the ice-structure interaction. The tributary widths for the supports are defined in **Fig. 6**.

$$\frac{H}{b} = \sigma_f \left(\frac{\rho_w g h^5}{E} \right)^{1/4} C_1 + Zh\rho_i g C_2$$

$$C_1 = 0.68 \left(\frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha} \right)$$

$$C_2 = (\sin\alpha + \mu\cos\alpha) \left(\frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha} + \frac{\cos\alpha}{\sin\alpha} \right)$$

where,

symbol	*parameter*	*SI value*
H	*the horizontal ice force per unit width*	-
b	*the width of the structure*	*1 m*
σ_f	*bending strength*	*0.4 MPa*
$\rho_w g$	*the weight density of water*	*0.0101 MN/m*^{3}
h	*the ice thickness*	*1.3 m*
E	*the elastic modulus of ice*	*1,400 MPa*
Z	*the maximum ride-up height*	*5 m*
$\rho_i g$	*the weight density of ice*	*0.0090 MN/m*^{3}
α	*the angle of the slope from the horizontal*	*45 degree*
μ	*the coefficient of friction between ice and ice*	*0.3*

Using the two-dimensional analysis model and the values listed in the table above,

$$\begin{aligned} C_1 &= 0.68 \left(\frac{\sin 45° + 0.3\cos 45°}{\cos 45° - 0.3 \times 45°} \right) \\ &= 0.68 \left(\frac{0.707 + 0.3 \times 0.707}{0.707 - 0.3 \times 0.707} \right) \\ &= 1.2629 \fallingdotseq 1.263 \end{aligned}$$

$$\begin{aligned} C_2 &= (\sin 45° + 0.3\cos 45°) \left(\frac{\sin 45° + 0.3\cos 45°}{\cos 45° - 0.3\sin 45°} + \frac{\cos 45°}{\sin 45°} \right) \\ &= (0.707 + 0.3 \times 0.707) \left(\frac{0.707 + 0.3 \times 0.707}{0.707 - 0.3 \times 0.707} + \frac{0.707}{0.707} \right) \\ &= 2.6260 \fallingdotseq 2.626 \end{aligned}$$

$$\begin{aligned} \frac{H}{100} &= 4 \left(\frac{1.03 \times 10^{-3} \times 130^5}{14{,}000} \right)^{1/4} \times 1.263 + 500 \times 130 \times 0.918 \times 10^{-3} \times 2.626 \\ &= 193.216 \end{aligned}$$

$$H = 19{,}322 kgf / cm = 19.32 tf / m = 0.19 MN / m$$

$$LPS : 019 MN / m \times 17.4 m = 3.306 \fallingdotseq 3.31 MN$$

$$BD \;: 0.19 MN / m \times 26.3 m = 4.999 \fallingdotseq 5.00 MN$$

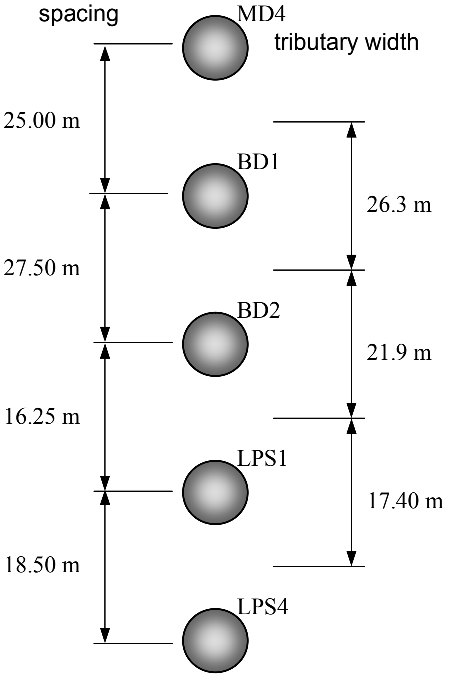


Fig. 6 The definition of the tributary width.

Keel effect of the unconsolidated layer

The keels are quite deteriorated due to the warm Tsushima Current from the Soya Strait (LaPerouse Strait) in March. Thus, the keel is weak and does not produce significant forces; in addition deeper keels will ground and then transmit force directly into the seabed, providing relief for the jetty supports. In addition, in the case of jamming and the associated wide loaded width, it is reasonable to consider the keel clearing effect on the support to be negligible.

Ice Force with Jamming Effects and Non-Simultaneous Ice Failure Considered

In the event of ice jammed in front of the set of structures with an ice cover comprised of both consolidated and unconsolidated keel layers formed behind the jammed ice as shown in Fig. 5, it can be assumed that the ice forces on the structures would be generated by the crushing of the consolidated layer although the bending failure of the consolidated ice have been likely observed in this situation. In this case, the failure mode of the consolidated ice, the associated wide loaded width 70 m, connected to the jammed ice is assumed to be non-simultaneous. The ice force calculation method for the non-simultaneous failure of the ice against the structures has been proposed by Takeuchi et al. (2002) as shown below.

V/h > 3 x 10^{-3} (1/s)

$$Ft = 0.40\left\{57.6\left(\frac{h}{h_m}\right)^{0.4}\right\}\times\left\{\frac{2.75}{(W/h)}+2.18\right\}\times\left\{0.46+\left(\frac{0.54}{(W/h)^{0.3}}\right)\right\}\times Wh\sigma_c$$

V/h < 3 x 10^{-3} (1/s)

$$Ft = 0.90\times 0.92\left\{\frac{1.00}{(W/h)}+1.09\right\}\times 1\times Wh\sigma_c$$

where,

symbol	parameter	value
F_t	global ice force	
W	structure width	70 m
V	ice velocity	0.1 to 0.15 m/sec
h	ice thickness	1.3 m
h_m	$E_c/\rho g$	refer to Fig.9 in Takeuchi et al. (2002).
σ_c	uniaxial compressive strength of the consolidated ice	0.4 MPa

- *V/h > 3 x 10^{-3} (1/s) from the values; v=0.1-0.15 m/sec and h=1.3 m,*

$$Ft = 0.40\left\{57.6\left(\frac{h}{h_m}\right)^{0.4}\right\}\times\left\{\frac{2.75}{(W/h)}+2.18\right\}\times\left\{0.46+\left(\frac{0.54}{(W/h)^{0.3}}\right)\right\}\times Wh\sigma_c$$

$$= 0.40\left\{57.6\left(\frac{1.3}{2.7\times 10^4}\right)^{0.4}\right\}\times\left\{\frac{2.75}{(70/1.3)}+2.18\right\}\times\left\{0.46+\left(\frac{0.54}{(70/1.3)^{0.3}}\right)\right\}\times(70)(1.3)(0.4)$$

$$= (0.4)\times(1.08)\times(2.23)\times(0.62)\times(36.40)$$

$$= 21.74MN$$

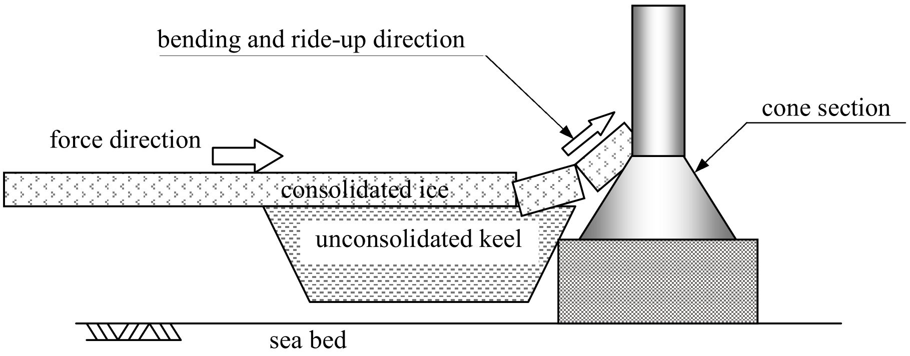
$$H = 21.74MN \div 70m = 0.31MN/m$$

$$LPS : 0.31MN/m\times 17.4m = 5.39MN$$
$$BD \ : 0.31MN/m\times 26.3m = 8.15MN$$

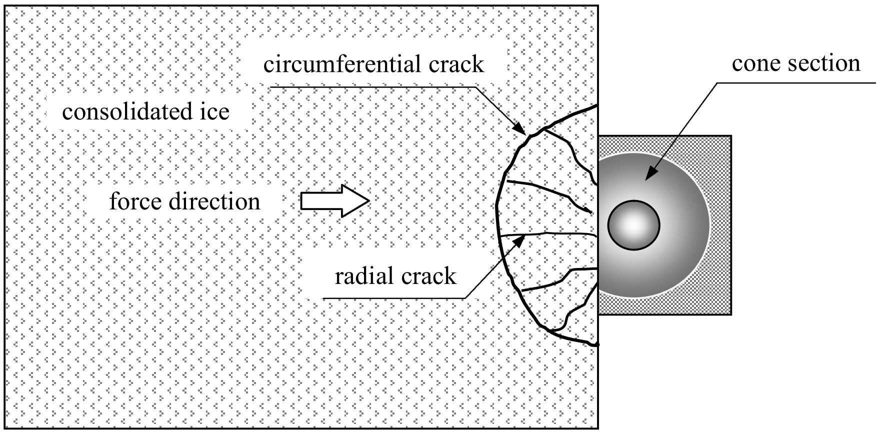
Ice Force with no Jamming Using API Recommended Equations

Geometry of individual ice-structure indentation

In case with no ice jamming considered, the ice-structure interaction can be assumed as an individual ice indentation on the structures. The ice forces on the structures would be generated by the bending and the ride-up motion of the consolidated layer and the unconsolidated keel clearing force. Both of these forces would directly interact with the structures, as shown in **Fig. 7**.



a. Cross-sectional view



b. Plan view

Fig. 7 Schematics of individual ice-structure indentation.

Bending failure and ride-up force

Using the original Ralston's equation (1977), the ice forces on a cone structure caused by a flat ice plate can be expressed as shown below. A schematic diagram of the cone-type structure is shown in **Fig. 8**.

$$F_h = \left\{ A_1 \sigma_f h^2 + A_2 \rho_i g h D_w^2 + A_3 \rho_i g h (D_w^2 - D_T^2) \right\} A_4$$

where,

symbol	*parameter*	*value*
F_h	*total ice force*	
A1, A2, A3 and A4	*refer to Ralston (1977)*	
σ_f	*flexural strength*	*= 0.4 MPa*
h	*ice thickness*	*= 1.3 m*
ρ_i	*ice unit weight,*	$\rho_i g = 0.0089\ MN/m^3$
D_w	*diameter at structure waterline*	*= 3.76 m*
D_T	*diameter at top of cone*	*= 2.50 m*
the first term	*force caused by ice bending failure*	
the second term	*gravitational force caused by broken ice blocks on the cone*	
the third term	*ice ride-up force*	

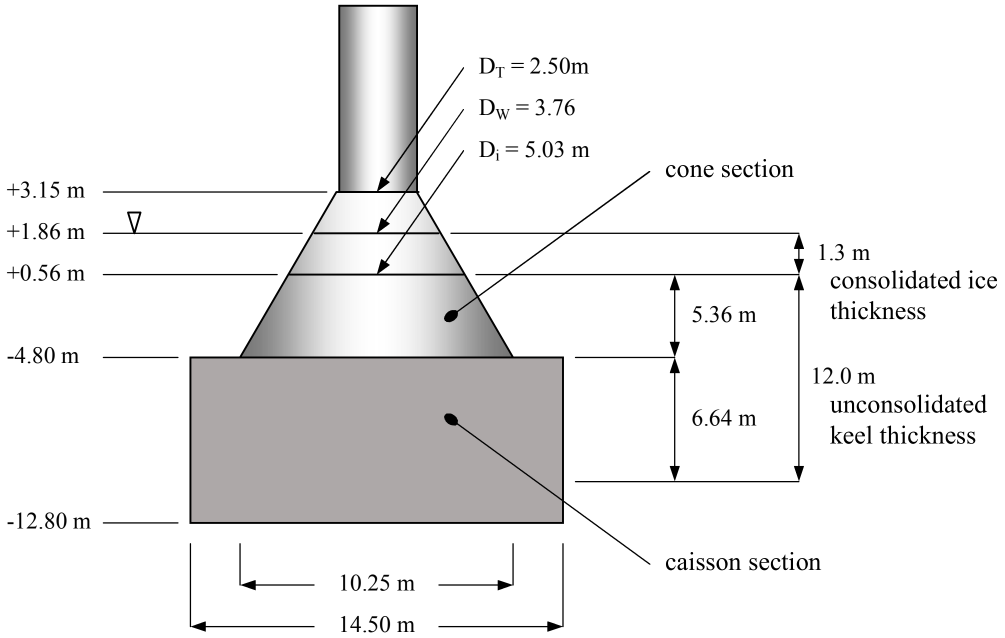


Fig. 8 Schematics of the cone type structure.

$$\begin{aligned} F_h &= \{(1.6)(0.4)(1.3)^2 + (0.25)(0.0089)(1.3)(3.76)^2 + (0.5)(0.0089)(1.3)(3.76^2 - 2.50^2)\}(3.1) \\ &= (1.082 + 0.041 + 0.046)(3.1) \\ &= 3.62MN \end{aligned}$$

Keel clearing force

Using Prodanovic's equation, which API (1995) recommends, the ice forces on the structure caused by the unconsolidated keel can be expressed as shown below.

i) keel clearing force on the cone section

$$F_1 = \sigma_p\left\{1 + a\frac{t}{D}\left(1 + b\frac{t}{D}\right)\right\}Dt$$

$$= 0.02\left\{1 + (0.69)\left(\frac{5.36}{7.64}\right)\left(1 + 0.33\frac{5.36}{7.64}\right)\right\}(7.64)(5.36)$$

$$(5.03 + 10.25) \div 2 = 7.64$$

$$= (0.02)(1 + 0.60)(7.64)(5.36)$$

$$= 1.31MN$$

ii) keel clearing force on the caisson section

$$F_2 = 0.02\left\{1 + (0.69)\left(\frac{6.64}{14.50}\right)\left(1 + 0.33\frac{6.64}{14.50}\right)\right\} \times (14.50)(6.64)$$

$$= (0.02)(1 + 0.36)(14.50)(6.64)$$

$$= 2.62MN$$

iii) total keel clearing force

$$\begin{aligned} \Sigma F &= F_1 + F_2 = 1.31 + 2.62 \\ &= 3.93MN \end{aligned}$$

Total force on a single support using API recommended equations

$$\begin{aligned} F_{total} &= 3.62 + 3.93 \\ &= 7.55\ MN \end{aligned}$$

Summary: Ice Load Calculations

i) Scenarios of Ice Forces Exerted on the Structures

The indentation ice force is defined as the ice force resulting from ice crushing/bending failure against the structures. In addition, the ice driving forces on structures when ice accumulates in front of the structures have to be considered in some cases; the force is induced by the water flow and wind. In this case, the accumulated ice will not fail or be crushed by interaction with the structures.

ii) Driving Force

As shown in the calculation results for the driving force, the simple, straight line driving force of 2.45 MN is markedly smaller than the ice failure forces.

iii) Ice Force with Jamming Effects Considered

The ice forces per structure affected by the presence of the jammed ice in front of the set of the structures were calculated. A two-dimensional analysis model for ice interaction with a sloping structure was used to calculate the bending and the ride-up forces of the consolidated ice (3.31 MN for LPS and 5.00 MN for BD). In addition, a non-simultaneous failure model was used to calculate the crushing forces of the consolidated ice (5.39 MN for LPS and 8.15 MN for BD).

iv) Ice Force with no Jamming

The ice loads on the individual support for the case of no ice jamming were calculated by using API recommended methods. In this case, the ice forces generated by the consolidated ice and the unconsolidated keel were considered. The result of calculations using API was 7.55 MN.

v) Design Ice Force

It has been demonstrated that the ice loads that incorporate the failure of ice around a single support are larger than those resulting from the ice driving force and the ice forces with jamming effects considered.

Acknowledgements

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