MORPHOLOGY OF A FIRST-YEAR RIDGE AND ITS INFLUENCES ON
DESIGN ICE LOAD IN THE SEA OF OKHOTSK

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ABSTRACT
To establish a rational design ice load estimating system for the Sea of Okhotsk, the morphological and mechanical parameters for ice features in the region must be data-based. However there is too little information to establish a reliable database. In the paper, the author tentatively determines morphological and mechanical parameters of a first-year ridge by literature survey. A design ice load estimating system based on the Monte Carlo simulation is developed and some sensitivity analyses are conducted. It is suggested that the thickness of consolidated layer predominantly influences on the design ice load and also concluded that the encounter rate of ridge affects remarkably on the design ice load. Those suggestions result in the recommendation that the statistical studies on the morphology and strength of consolidated layer and the encounter rate should be conducted with the highest priority.

KEY WORDS: the Sea of Okhotsk, Ice load, First-year ridge, Monte Carlo simulation

INTRODUCTION
To design an arctic structure, the rational estimation of ice load has to be performed. The design ice load is generally based on the specified load that is defined as a load value corresponding to a certain return period. Therefore the accurate estimation of the ice load-return period relation is essential to design a safe and economical arctic structure.

The author has been devoting to establish the design ice load estimating system (Kato, 1992a). The system is based on the Monte Carlo simulation that calculates a probability distribution of ice load numerically. The specified scenario allows choosing the equation to calculate the ice load deterministically (the equation is referred as the ice load model in the paper) if a shape of structure is assumed. The Monte Carlo simulations to determine the ice load-return period relation for all possible scenarios are performed. The largest ice load corresponding to a certain return period would be the specified load for the return period.

The morphological and mechanical characteristics of ice features are probabilistic. To obtain a reliable ice load-return period relation through the simulation, it is essentially necessary to know accurate probabilistic information on the ice features concerned. And a database should be established for every region concerned. However, too little information is available at the moment.
The database should be constructed with priority that may be judged by the ice load-return period relation in the region concerned.

In this study, the author tries to identify primarily important morphological and mechanical parameters of a first-year ridge in the Sea of Okhotsk for the determination of ice load-return period relation. First, the author tentatively determined morphological and mechanical parameters of a first-year ridge by literature survey. Then the Monte Carlo simulation is conducted using such parameters and some sensitivity analyses are also conducted. The sensitivity analyses allow identifying primary important parameters, which are suggested to put in the database with higher priority.

**FIRST-YEAR RIDGE MODEL IN THE SEA OF OKHOTSK**

The traditional first-year ridge model is depicted in Figure 1. Although the variation in morphology may be very large, the author tentatively determines the parameters shown in Figure 1 through a literature survey. Vast amount of papers written by Russian researchers have been available since 1990. These papers can supply a great deal of information about those parameters of a first-year ridge in the Sea of Okhotsk. In the study, the author carefully selected papers to conduct the literature survey. Data summarized by Timco & Burden (1997) for the first- and multi-year ridge in the arctic and sub-arctic was also referred.

"Average" first-year ridge model

\[
H_s = 4.7 \sqrt{h_0}, \quad (1)
\]

\[
H_k = 4H_s, \quad (2)
\]

\[
B_s = 6.3H_s, \quad (3)
\]

\[
B_k = 3.93H_k, \quad (4)
\]

\[
h_l = 1.03H_s, \quad (5)
\]

where \( H_s \) is the sail height, \( h_0 \) the average thickness of ice fragments consisting ridge, \( H_k \) the keel depth, \( B_s \) the sail breath, \( B_k \) the keel breath, \( h_l \) the thickness of consolidated layer.

**Probabilistic characteristics of first-year ridge**

Equation (1) is based on the consideration that a ridge consists of broken ice fragments generated by the failure of relatively thin ice sheet. The probabilistic characteristics of sail height are assumed to depend on these of thickness of ice fragment \( h_0 \). However there is no statistical data for \( h_0 \). The author assumes that the probabilistic characteristics of \( h_0 \) could be expressed as the normal probability density function (PDF in short). According to the report by Beketsky...
(1997), the upper limit of $h_0$ is 0.6m in the central part of the Sea of Okhotsk. The lower limit of $h_0$ is assumed to be 0.1m. Assuming that the upper and lower limit described above correspond to {the mean ± 2 times the standard deviation} value, the mean and standard deviation of sail height are 2.78m and 0.65m, respectively.

Although Beketsky (1997) reported the histogram of ratio between keel depth and sail height $H_k/H_s$, it is difficult to find out any probabilistic characteristics from his report. Timco & Burden (1997) reported that $H_k/H_s$ could be approximated by the log-normal PDF with the coefficient of variation of 0.41. The author tentatively applies it in the study.

Some data concerning the ratio between keel depth and keel breath $H_k/B_k$ was reported by Surkov (1998). Although he did not stated clearly in his report, the log-normal PDF with the coefficient of variation of 0.33 is applicable.

The thickness of consolidated layer $h_i$ is not uniform even in a ridge. According to Timco & Burden (1997), it is not uncommon that the ratio between the maximum and minimum thickness is more than two. Equation (5) is proposed by Beketsky et al. (1997) for aged ridges. It would be better to assume the interaction between an aged ridge and a structure when it comes to estimate a design ice load. Thus Equation (5) holds in the study. The author uses Equation (5) as deterministic equation. Since the normal PDF is assumed to express the sail height, then so the thickness of consolidated layer.

**ICE LOAD MODEL**

The ice load model is an equation that calculates the ice load deterministically when all the morphological, mechanical and other parameters are set. The ice load model should be specified depending on what kind of ice feature would interact with what kind of structure. In this study, the author concentrates on the interaction between a first-year ridge and a vertical structure. The author assumes that the ice load $F_i$ would be given by Equation (6) below.

$$F_i = F_c + F_{ks},$$

where $F_c$ is the failure load of consolidated layer, $F_{ks}$ the failure load of unconsolidated layer.

Equation (6) seems to be too simple. There must be some interaction between consolidated and unconsolidated layers when they fail. It has not clearly understood yet. The author assumes temporally that the layers would fail independently. The unconsolidated layer would fail the same manner as the failure of granular material. The consolidated layer would fail the same manner as the failure of the level ice sheet. Since the structure is assumed to be vertical, the failure mode of consolidated layer would be crushing.

**Failure load of unconsolidated layer** $F_{ks}$
There have been proposed many formulae that calculate the failure load of unconsolidated layer. However the difference in calculated loads is vast (Timco et al., 1999). The author employs the formula proposed by Croasdale & Cammaert (Timco et al., 1999). It does not mean that the author recommends this formula. This formula is chosen because it would give a quite moderate value among all formulae (Timco et al., 1999). The equation for failure load of unconsolidated layer proposed by them is written below.

\[ F_{ks} = \left( \frac{B_1 D_e H_k}{2} + \frac{B_2 H_k^2}{3} \right) \gamma_e \tan \phi, \]  

(7)

where \( D_e \) is the effective diameter of structure, \( \phi \) the angle of internal friction of material consisting the keel, \( \gamma_e \) the effective specific weight of material which defined as

\[ \gamma_e = (\rho_w g - \rho_i g)(1 - n_k), \]

where \( \rho_w g \) is the specific weight of water, \( \rho_i g \) the specific weight of ice, \( n_k \) the porosity of keel.

### Failure load of consolidated layer \( F_c \)

Since the author assumes that the consolidated layer thickness is uniform, then so-called a crushing formula can be employed for the calculation of failure load of consolidated layer. Kato (2001) evaluated many crushing formulae by comparing with the ice load measured at Molikpaq. Among those formulae, the equation proposed by Kato (1992) gave the ice load corresponding well to ice load measured at Molikpaq. The equation is written below.

\[ F_c = 0.3 \left( 0.54 \frac{h_i}{D_e} + 1 \right) \left( 0.58 \sqrt{1 + 1.97 \frac{h_i}{D_e}} \right) D_e h_i \sigma_e. \]  

(8)

where \( \sigma_e \) is the reference compressive strength of ice corresponding to \( \dot{\varepsilon} = 10^{-3} (1/s) \).

### MECHANICAL PARAMETERS OF FIRST-YEAR RIDGE

The ice load model requests such mechanical parameters as the angle of internal friction and porosity of keel material, and the reference compressive strength of consolidated layer.

Although many reports concerning the angle of internal friction of keel material \( \phi \) have been published, none of them were measured by the well designed test like tri-axial tests. It may be almost impossible to conduct any tri-axial tests in-situ. The author concludes that \( \phi \) is quite uncertain and there is no hope to define a PDF for \( \phi \). Therefore the author decides that \( \phi \) is deterministic being 35 degrees.

Surkov et al. (1997) proposed the empirical formula for the estimation of porosity of keel \( n_k \) as written below.
\[ n_k = 0.09051 \cdot ln\left(\frac{l}{h_0}\right), \] (9)

where \( l \) is the average length of ice fragment consisting the ridge. The mean ratio of \( l/h_0 = 3.56 \) was report by Surkov et al. (1997).

The specimen size for the compression test should be large enough to contain enough number of ice fragments to avoid any localized effects. The specimen size is presumably too large to conduct a tests neither in-situ nor in laboratory. The reported strengths were measured using either small core samples taken from an ice fragment or samples taken from miniaturized refrozen consolidated layers that were prepared in laboratory.

The author agrees that the strength of consolidated layer would be a function of the porosity as same as the geotechnical common sense. Beketsky & Astafiev (1997) conducted the measurement using the miniaturized refrozen consolidated layer. Their data are re-plotted in Figure 2 and the approximated equation is written below.

\[ \sigma_r = 1.0143 \cdot exp(-5.64n), \] (10)

where \( \sigma_r \) is the relative strength, \( n \) the porosity of consolidated layer.

The information about \( n \) is yet uncertain. Beketsky et al. (1997) reported it is basically 0. Surkov et al. (1997) recommended 0.2.

It is a kind of distress to define the compressive strength when \( n = 0 \). The author decides that the compressive strength for \( n = 0 \) is identical with the compressive strength of level ice sheet. Truskov et al. (1992) proposed the empirical formula for level ice strength.

\[ \sigma_{c0} = -7.42 - 0.1404T + 0.1458S + 11.57845\rho_i g - 0.847 \frac{S}{\rho_i} \] (11)

where \( \sigma_{c0} \) is the reference compressive strength in MPa, \( T \) the ice temperature in \(^{o}C \), \( S \) the salinity of ice in ppt, \( \rho_i g \) the specific weight of ice in \( gf/cm^3 \).

Combining Equation (10) and (11), the reference compressive strength of consolidated layer \( \sigma_c \) is expressed as below.

\[ \sigma_c = \sigma_r \times \sigma_{c0} = 1.0143 \cdot exp(-5.64n)\sigma_{c0}. \] (12)

The salinity, temperature and specific weight of ice and the porosity of consolidated layer may be different event by event. In the sensitivity analysis described later, the generated values under the assumptions that all those quantities distribute uniformly are used. The salinity distributes from 3 to 7 ppt, the temperature from –2 to -10 \(^{o}C \), the specific weight from 0.78 to 0.91 \( gf/cm^3 \).
and the porosity of consolidated layer from 0 to 0.2. The histogram obtained from the generated reference compressive strength is shown in Figure 3.

**SENSITIVITY ANALYSIS**

Using the aforementioned ice load model and PDFs for morphological and mechanical parameters, the Monte Carlo simulation was performed with \( N = 100,000 \) which is referred as Case A. The relative frequencies of ice loads are depicted in Figure 4. It is obvious that the contribution of unconsolidated layer is insignificant. Thus uncertainties involved in the morphological parameters for the keel and sail may not be significant in the calculation of ice load. The uncertainties involved in the angle of internal friction are also insignificant.

On the other hand, the thickness and strength of consolidated layer are quite significant. Three simulations were performed using three different PDFs for the thickness of consolidated layer. Since the thickness of consolidated layer is the function of sail height through Equation (5), then three different PDFs for sail height mentioned later were employed. The same mean being 2.78m was assigned to all PDFs. The standard deviation of 0.43m was assigned for Case A, 0.86m for Case B, 0.21m for Case C. The accumulated relative frequencies (probabilities) are depicted in Figure 5. The differences are pronounced at higher probability region which is referred in the estimation of specific load. Then it is obvious that the accuracy of probabilistic characteristics for the consolidated layer thickness has a distinct importance for the estimation of specific ice load.

The probabilistic characteristics for the strength of consolidated layer are also presumably important in the estimation of specific load. To clarify the difference in the probabilities of ice load...
corresponding with the difference in the probabilistic characteristics for the strength, three simulations were performed with three different PDFs for the ice temperature, which were distributed uniformly from –2 to -10°C for Case A, from –2 to -20°C for Case D, from –2 to -5°C for Case E. The histograms of reference strength are shown in Figure 6. The probability of ice load are shown in Figure 7. It is clearly seen that the probabilistic characteristics for the strength are affected the probability of ice load. And the probabilistic characteristic for the strength is presumably important in the estimation of specific load.

![Figure 6](image1.png)  
**Figure 6** Relative frequencies of reference strength for Cases A,D,E  

![Figure 7](image2.png)  
**Figure 7** Differences in the probability for Cases A,D,E

The return period $R(\text{year})$ is generally calculated by the equation written below.

$$R = \frac{1}{p(F \geq F_0)\mu}, \quad (13)$$

where $p(F \geq F_0)$ is the probability that $F$ is greater than $F_0$, $\mu$ the encounter rate in times/year. The encounter rate affects a lot in the ice load-return period relation. The resulted ice load-return period relations with four different encounter rates are shown in Figure 8. It is clear that the encounter rate is essentially important in the estimation of the ice load-return period relation.

![Figure 8](image3.png)  
**Figure 8** Ice load-return period relations for four different encounter rates

**CONCLUSION**

Although the ice load model and the morphological and mechanical parameters employed in the study are tentative, it is strongly suggested that the thickness of consolidated layer predominantly influences on the design ice load and also concluded that the encounter rate of ridges affects remarkably on the design ice load. Those suggestions result in the recommendation
that the statistical studies on the morphology and strength of consolidated layer and the encounter rate of ridges should be conducted with the highest priority.

REFERENCES