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IMPROVING QUALITY OF 2D ICE LOAD ESTIMATION ON FREEZED PILES

Abstract: *Nowadays a lot of projects are being constructed in the Arctic regions with ice cover. Ports, offshore platforms, satellite stations, lighthouses, and other scientific and environmental constructions are often located in such areas due to economic reasons. Ice loads are important for structure calculation. A number of possible actions from the ice can exist. Ice loads are vitally important; however, there are some gaps in the knowledge and methods. One of the factors to be taken into account is freezing into the ice and developing of ice collars around the structure. This factor leads to an increase of the load from the level ice on the structure. Freezing into the ice is important factor to be considered to improve quality of ice load estimation. The paper presents method to calculate horizontal load on the vertical cylindrical pile by using 2D models in vertical and horizontal plane. Combination of two 2D solutions increases quality of load estimation. The result shows bigger load on structure freezed in the ice comparing to the load on structure in moving ice.*

Keywords: *Quality of load estimation, ice collar, arctic engineering, adfreeze, ice load, numerical analysis.*

1. Introduction

Today scientists work on improving quality of normative recommendations for engineers who work in Arctic with cold-climate constructions. Necessity of developing new Arctic areas is constantly growing. Arctic region is important due to many reasons: huge carbon deposits (offshore platforms), necessity to build new waterway structures, superior position of the observatories and satellite equipment, environmental demand. Special engineering solutions are needed to make constructions in the areas with cold Arctic conditions. Ice loads can overcome all other environment actions and usually is considered to be the main factor. Ice is highly heterogeneous material (K Shkhinek et al., 2007), (KN Shkhinek, Jilenkov, Blanchet, & Thomas, 2008) and can form different formations and influence by many ways. For example sloped structures can significantly reduce ice loads. Meanwhile, significant gaps in the recommendations for the estimation of the ice loads on the structures exist (Timco & Croasdale, 2006), (Frederking, 2012). In addition, freezing in the ice during constant water level is one important factor which is weakly described in the norms (ISO-19906, 2010), (SNiP-2.06.04-82, 1989), (SP38.13330.2012, 2012), (VSN–41.88, 1988), (API-RP-2N, 1995), (RMRS, 2008). Ice bustles occur during the tides (Loset & Marchenko, 2009). Ice collars occur during constant water levels (relatively to a structure) (Sharapov, Shkhinek, & DelValls, 2016). Ice collar is a thick thermo-developed ice at the ice-

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structure contact. It develops due to high thermal conductivity of the structure. Ice collars were described in recent papers, (Sharapov, Shkhinek, & DelValls, 2015). Fig.1 presents underwater view of ice collar.

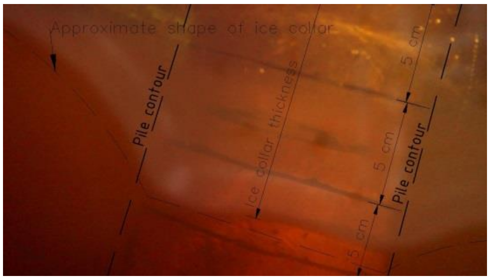

Figure 1. Underwater photo of ice collar on the steel pile

A scholastic approach was suggested for modeling of the ice matter due to high ice heterogeneity (Strub-Klein & Høyland, 2012). High amount of resources is required for the stochastic numerical calculation. 2D models are often used for simplification. It is necessary to combine 2D solution with other data sources to obtain the reliable result for 3D environment for the estimation of total load on the structure.

2D vertical and horizontal models are considered in this paper and possible combination of them is described. *Combination of two 2D solutions in horizontal and vertical plane can significantly increase the quality of ice load estimation without resource intensive computing.* Vertical 2D case is represented by rigid wall with adfreezed ice. Ice starts to move and crashes near the structure or at the structure surface. Horizontal 2D case is represented by vertical pile surrounding by ice, where ice is thicker at the contact. Ice starts to move and breaks around structure. The load on the structure increases from the beginning of the movement until maximum load occurs. Maximum load occurs before the first failure of the surrounding ice. Stresses and failures around the structure were observed. Experiments were conducted for the different sizes of the ice collars. Estimation of the horizontal ice load from the level ice on the freezed in the level ice cylindrical structure is presented. The result could be useful for improving quality of ice load estimation.

2. Load calculation in vertical plane on vertical wall

2.1. Task statement

Two-dimension vertical model consists of the rigid vertical wall and adfreezed ice collar to the wall.

The principal scheme is presented in the Fig.2.

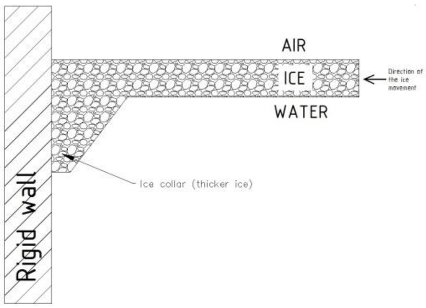

Figure 2. Principal scheme of the vertical 2D model

Ice collar grows on the structure wall surface during cold air temperatures because of the structure high thermal conductivity. Ice growth calculation and the development of the ice collars is explained in (Sharapov et al., 2015).

Ice with prescribed thickness (according to the amount of freezing degree days – FDD) moves towards rigid wall and crashes during calculation process. Failure can occur at the structure-ice collar contact or at some distance to the wall. Failure in the real conditions is highly stochastic due to the high heterogeneity of the ice matter (K Shkhinek et al., 2007), (KN Shkhinek et al., 2008). Ice matter is presented as scholastically distributed disks with different diameter and prescribed interaction loads between them in the program for numerical calculation. Such approach is highly reliable in representing of the ice as it includes fragile and viscous behavior at the same time. Also it allows monitoring the deformations and developing of the cracks before failure.

2.2. Numerical calculation

Calculation is based on two dimension finite difference method. Level ice, thicker ice (ice collar) and structure (structure wall) interaction is considered in the model (Fig. 2). Sizes of the ice collars and level ice can be changed. Ice starts to move towards structure at the first moment of the calculation. Ice collar and then level ice become destroyed due to compression during the movement. Main parameters of the experiment are presented in the Fig.3.

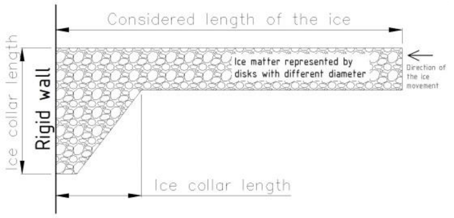

Figure 3. Principal scheme of the vertical 2D model

Ice behavior peculiarities (including failure mechanisms) are taken into account in the calculation. Ice is modelled by disks with different diameters. Such model is widely used for the numerical simulation of the different geo-materials during compression. All of the parameters (compression strength, shear strength, tensile strength, etc.) are determined from the comparison of the calculation results with the real physical experiments for the identical sample. Shear strength determination is based on the Mohr-Coulomb law. Sample of the matter model is presented in the Fig.4. Disks with different diameters fully fill the matter area. Method allows considering progressing failure of the matter, which is an important advantage.

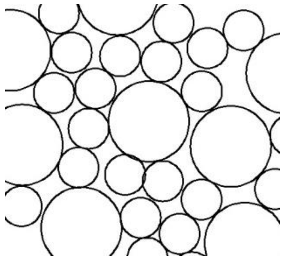

Figure 4. Ice matter by disks

The calculation can be divided into two steps: During the first step all the geometry is organized in the closed contour (closed volume for 3D case), and then this limited space is filled up with disks depending on the prescribed density (porosity) of the ice material. Porosity should exceed 15-20% for such approach. Scholastic algorithm is used for the filling of the prescribed area and therefore the result is also scholastic. Number of experiments with equal prescribed geometry and material property is needed to obtain stable result. The developed ice moves towards structure and crashes during second step. Ice starts to deform during loading, when load increases, failure could occur after some time. First failure leads to reduce of the load, however, ice in the contact area changes it’s shape; following the movement of the ice. This can lead to a significant increase of the load above previously recorded. The load on the structure is being fixated during the calculation. Typical dependence of the load from the time is presented in the Fig.5.

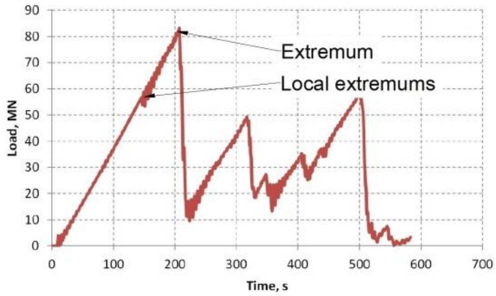

Figure 5. Typical load dependence on the time

Ice load is highly dependent on the moment of time as it is seen from the Fig.5. Normally, load is increased until the part of the ice breaks off (Fig.6), and significant drop in the load is observed. Extreme load is observed before the destruction moment (when ice collar failure occurs). The extreme load is fixated for the following consideration.

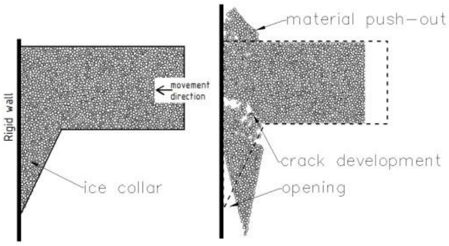

Figure 6. Crack development and deformation of the matter

2.3. Scholastic approach

The result is stochastically dependent and therefore the number of experiments is needed to be carried out. Statistical approach was used to estimate the relative mistake and the required number of the experiments. The relative mistake δ of the series of the experiments was calculated according to the Eq. 1.

$$\delta = \frac{t(\alpha,n)\cdot\frac{\sigma}{\sqrt{n}}}{\langle x\rangle} \qquad (1)$$

where n – number of the experiments,

$\langle x\rangle$ – average value of the target value x (Eq. 2),

σ - Standard deviation (Eq. 3),

$t(\alpha,n)$ – Student's coefficient depends on the number of the experiments n, and prescribed value of the confidence probability α.

$\frac{\sigma}{\sqrt{n}} = \sigma_{\langle x\rangle}$ – correlation between mean-square deviation of the final result and mean-square deviation σ of the particular experiment.

Average value $\langle x\rangle$ of the measurable value x points out the centroid of distribution, and the individual measurements groups around it:

$$\langle x\rangle = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (2)$$

Standard deviation characterizes the distribution of the particular measurements around the average value. Average value is obtained after proceeding of the data from multiple experiments. Exact values σ and $\langle x\rangle$ are limit values, and they can be obtained when number of the experiments is high $n\rightarrow\infty$.

$$\sigma = \sqrt{\frac{n}{n-1}\left(\langle x^2\rangle - \langle x\rangle^2\right)} \qquad (3)$$

Student's coefficient can be found in the literature. The 95% confidence probability was assign for the series of the experiments.

The calculation for the estimation of the relative mistake was conducted simultaneously with the experiments to define the number of the experiments needed. This approach allow save time and calculation resources. The graph in the Fig. 7 shows the typical distribution of the relative mistake from the number of the experiments. Each curve represents certain input data.

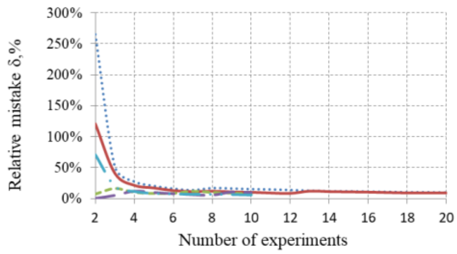

Figure 7. Relative mistake of the load estimation depending on the number of experiments for the different input data

Six experiments in most cases provide stable solution with relative mistake less than 15% as it is seen from the Fig.7. The relative mistake gets decreased when the number of experiments is increased. However more than six experiments in the series was conducted for the essential accuracy, and then experiments were continued until the relative mistake become lover than 10%. Maximum number of the experiments in the series is 20.

2.4. Calculation results

Ice collars shapes and level ice thicknesses depend on freezing degree days (FDD). The relative mistake of the series is below 10%. Loads were considered in relation to the load from the flat level. For the estimation of loads from the level ice a number of the experiments were conducted. The results are presented in the Fig.8. The graph shows that the ratio of the load from the level ice with certain thickness to the level ice with unit (1 m) thickness - F/F_{1m} depending on the level ice thickness - h_{ice}. The confidence probability is 95%.

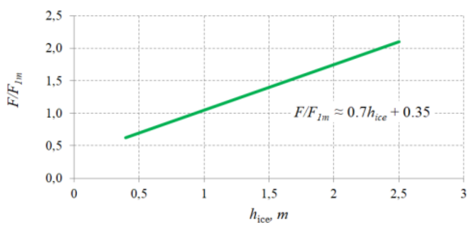

Figure 8. Ratio of the load - F from level ice (with different thickness), to the load from level ice with unit (1 m) thickness - F_{1m}, depending on the level ice thickness h_{ice}

The following scheme for the calculations is realized:

- Level ice thickness was calculated for the certain values of FDD;
- The parameters of the ice collar (k, α) were determined according to the recommendations (Sharapov et al., 2015) and level ice thickness and FDD are taking into account;
- Level ice thickness and parameters of ice collar allow introducing full geometry into the calculation model.
- Statistical approach was used after series of calculation for the determination of the probabilistic values;
- Final loads were presented as a ratio of the load when ice collar exists to the load from flat level ice of the corresponding thicknessF/F_{ice}. Graph representing F/F_{ice} from FDD is presented in the Fig. 9.

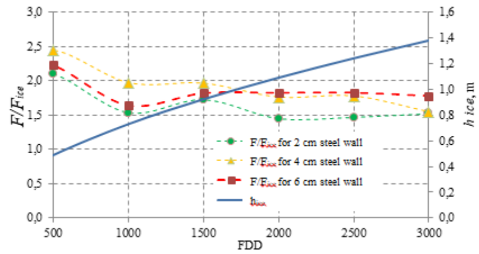

Figure 9. Dependence of the relative load F/F_ice and the level ice thickness h_ice from the amount of FDD

Load from the ice collar normally 1.5-2.0 times higher than the load from the level ice for the corresponding FDD as it is seen in the Fig.9.

3. Calculation of the load on the vertical pile in horizontal plane

Calculation in vertical plane is normally suitable for long length constant profile shore constructions. However, calculation in vertical plane is not enough for the vertical cylindrical piles (legs of the platforms). Such constructions are surrounded by ice and the interaction on the whole ice-structure surface (including back of the structure) is important. Additional pulling forces will appear behind the structure if structure freezes into the ice. Numerical calculations of the ice interaction with such structures should be conducted in 2D horizontal plane if 3D calculation analysis is not applicable.

Above described model (ice represented by disks) is possible to use for the calculation of the ice-structure interaction. Simple 2D horizontal model is based on the finite difference method on the generated around the structure net; the area around the structure should be modelled with the material having higher strength than surrounding ice. Such approach allows include ice collars into consideration. Melting of the ice (due to structure heating) can be modelled if the strength of the material in the model around the structure is lower than surrounding level ice.

The scheme of the 2D horizontal model is presented in the Fig. 10.

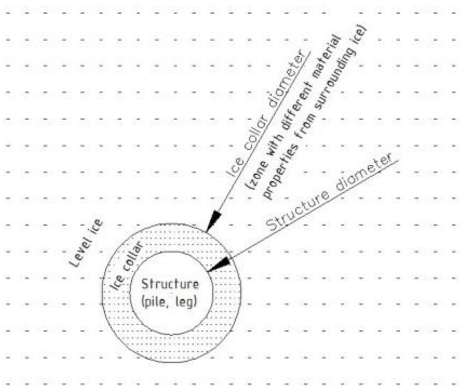

Figure 10. Scheme for the calculation of the ice loads on the cylindrical structure in the horizontal plane

Size and properties of ice collar (zone with different material properties from surrounding ice) can be modified in the program. Ice collar size can be determined by using recommendations (Sharapov et al., 2015), or by thermodynamical calculation. The properties of the “zone with different material” can be determined accordingly to the calculation in vertical plane from the following consideration: required flat level ice should transfer the same load on the structure as level ice with ice collar (see next chapter).

The structure is incorporated in the ice. Ice field starts to move when the calculation begins, and ice starts to break at the structure surface or near it. Shear strength in the considered model is determined by Mohr-Coulomb law (Li & Shkhinek, 2013), (Li & Shkhinek, 2014). Calculation net was tested for the convergence. A version with minimum calculation mistake and acceptable speed of the calculation was chosen. The calculation mistake is estimated below 5%. Number of cells in the model: about 10^4.

Load on the structure is increasing until the ice failure occurs during the calculation process. Typical graph is presented In the Fig.11. Maximum load in the calculation should be used for the following considerations.

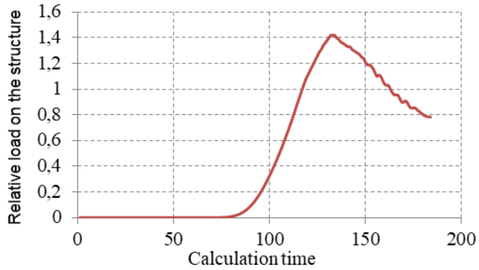

Figure 11. Maximum during calculation of the load on the cylindrical structure in the horizontal plane (the maximum is related to the failure of the ice collar)

4. Combination of the 2D vertical and 2D horizontal solutions

Special method to determine parameters of the zone near the structure is needed to conduct calculations in 2D horizontal plane as described above. The key parameters are “Length of the zone with modified properties” (X zone) and new “relative strength of the zone”. All the parameters should be obtained from the information about the ice collar properties and shape. Illustration of the transformations is presented in the Fig.12.

New strength (R_c - compression strength, R_t – tensile strength) of the zone around the structure has to be calculated. New strength of the zone should provide the same increase in the load as ice collar provides compare to the level ice (2D task in vertical plane, above). According to the ISO 199062 (ISO-19906, 2010), the strength of the level ice should be increased proportionally to the increase of the load. Using this we obtain a new strength of the zone around the structure. The length of the zone around the structure X_{zone} assumed to be equal to the length of the ice collar.

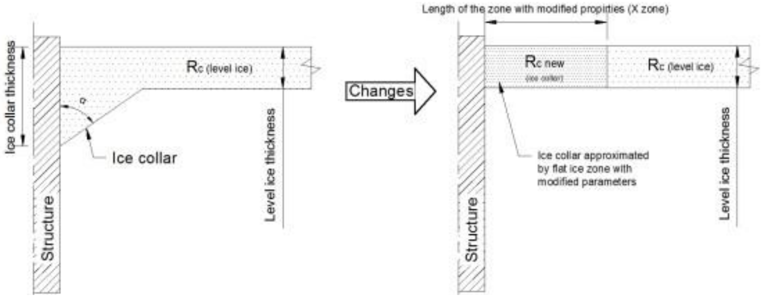

Figure 12. Full task reduction to the 2D horizontal task

According to the ISO 199062 and the above mentioned considerations:

$$\frac{C_{R(zone)}}{C_{R(ice)}} = \frac{F}{F_{1m}} \quad (4)$$

where

$\frac{C_{R(zone)}}{C_{R(ice)}}$ – ratio shows how many times the strength coefficient of the zone around the structure is higher than the strength of the surrounding level ice; (relative strength coefficient);

$C_{R(zone)}$ – coefficient of the strength of the zone around the structure, MPa;

$C_{R(ice)}$ – coefficient of the strength of the ice, MPa ($C_R \approx 2.4$, according to the ISO 19906);

$\frac{F}{F_{1m}}$ – relative load, which is obtained from the calculation of the interaction between vertical wall, level ice and ice collar; (F – absolute load from the level ice and the ice collar; F_{1m} – absolute load from the level ice);

The relative strength $\frac{C_{R(zone)}}{C_{R(ice)}}$ can be recalculated depending on the FDD (Fig.13).

Strength coefficient of the area around the structure should be 1.5 to 2.4 times bigger than the coefficient of the level ice strength, as it is seen from the Fig.13.

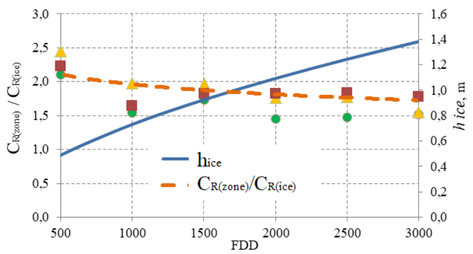

Figure 13. Relative strength coefficient C_(R(zone))/C_(R(ice)) dependence on the FDD and level ice thickness dependence on the FDD

Length of the zone around the structure is chosen accordingly to the length of the ice collar. Ice collar thickness is decreasing with increasing of the distance to the structure; therefore the assumption, that length of the zone is equal to the length of the ice collar can lead to some reserve in the load estimation. Length of the zone around the structure can be rewritten depending on the level ice thickness (Sharapov et al., 2015):

$$X_{zone} = (h_{ice} \cdot k - h_{ice}) \cdot tg(\alpha) \quad (5)$$

where

X_{zone} – desired length of the zone around the structure (material properties is different from the level ice properties), m

h_{ice} – thickness of the level ice, m;

k – coefficient of the ice collar shape, the ratio of the ice collar thickness to level ice thickness;

α – angle of the ice collar shape (to the vertical).

X_{zone} is depending on the level ice thickness h_{ice}. Level ice thickness h_{ice} depends on the amount of FDD. Therefore Length of the zone X_{zone} can be presented depending on the FDD (Fig. 14).

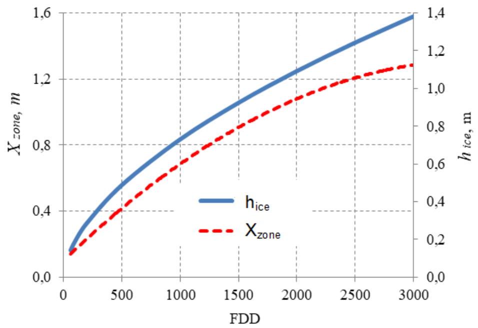

Figure 14. Length of the zone X_zone dependence on the FDD, and h_ice dependence on FDD

5. Results and conclusion

Combination of vertical and horizontal models was used to improve quality of ice load estimation. Numerical models were analyzed during the present work. Vertical and horizontal models estimate the dependence of the load on the cylindrical structure freezed into the ice on the diameter of the structure and amount of FDD. The load on the freezed into the ice structure (with ice collar presence) F_{collar}, and the load on the structure in the moving level ice (no ice collar) $F_{moving\ ice}$ were considered. The target load is the ratio of F_{collar} to $F_{moving\ ice}$ which is non-dimensional load, which is showing the increase of the load on the freezed in the ice structure to the conventional case (structure cuts the moving level ice, and no pulling forces exist behind the structure). Non-dimensional load $\frac{F_{collar}}{F_{moving\ ice}}$ is presented in the Fig.15 for the different diameters of the structure and different thermo-transfer ability of the construction depending on the amount of FDD. The minimum values correspond to the biggest diameter of the structure (40 m), the maximum values observed for small structure diameters (2 m). Relative load dependence on the diameter of the structure is understandable, as a ratio of the additional ice (ice collar) size to the diameter of the structure is decreasing with increase of the structure diameter.

Small variation exists for different thermo-transfer abilities of the constructions (thickness of the steel wall). Wall thicknesses 2-6 cm were used in the calculations (presented in the Fig.15 by different dots). Load on the freezed structure to the load when structure cuts through the level ice ratio decreases with FDD increase.

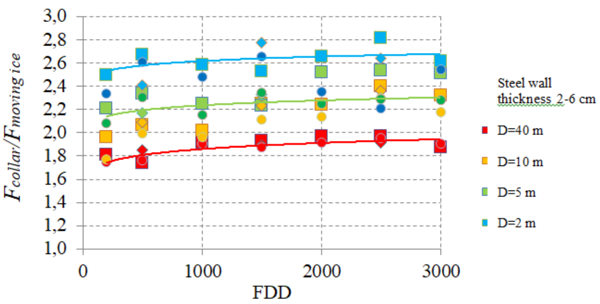

Figure 15. Relative load on the freezed in the ice structure $\frac{F_{collar}}{F_{moving\ ice}}$ depending on the FDD for the different diameters of the structure (2 - 40 m)

The above mentioned results were obtained by choosing the diameter of the structure and following calculation of the parameters depending on the FDD. Level ice thickness depends on the FDD. Result depending on the level ice thickness presumably useful for certain purposes. The relative load on the freezed in the ice structure $\frac{F_{collar}}{F_{moving\ ice}}$ depending on the ratio of structure diameter to level ice thickness D/h_{ice} is presented in the Fig.16.

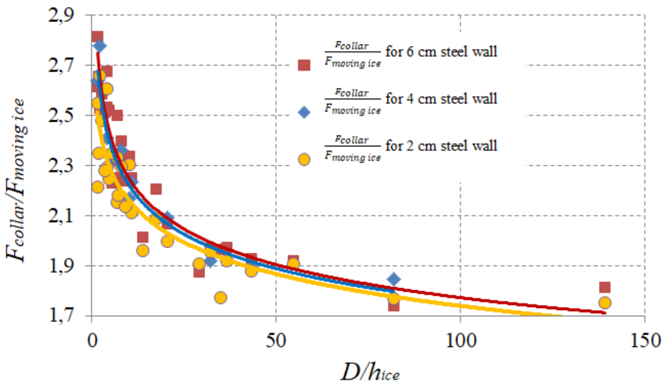

Figure 16. Relative ice load on the freezed in the ice structure F_collar/F_(moving ice) depending on the D/h_ice for the different thicknesses of steel wall of the structure (2, 4, 6 cm)

The obtained dependencies are the result of the application of the described method for combination of 2D solutions in vertical and horizontal planes. Models which consider ice material as a multiple disks with prescribed interaction laws have advantages for the consideration of the ice break process. However, stochastic approach for the disks model is required. Above presented graphs are dependent on the basic parameters as FDD and structure diameter and therefore they are easy to use for engineering needs. Results can be used for quality improving of ice load estimation.

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