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Level ice forces on hydraulic structures during ice season

Силовое воздействие льда на гидротехнические сооружения на протяжении ледового сезона

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Ключевые слова: ледовая нагрузка; ледовые сценарии; дрейфующий лед; исходные ледовые параметры; численная модель льда

Abstract. The current study investigated the variability of the main parameters of drifting level ice during ice season and how this variability affects the ice load. The study was carried out on the example of hydraulic protective structures of the floating nuclear thermal power plant in the city of Pevek. Numerical modeling was performed to determine the ice load reduction factor for the case when the vertical wall is formed by the consolidated ice fragments on an inclined structure. Statistical information on the main ice parameters was gathered and provided in the article. Ice loading calculations were conducted by several calculation methods. Based on the results of the study, general conclusions were made on the specifics of ice loading alternation during ice season and conclusions regarding design ice loading on hydraulic structures in the port of Pevek.

Аннотация. В работе исследуется изменчивость основных параметров ровного ледового покрова в течение ледового сезона и то, как эта изменчивость влияет на ледовую нагрузку. Исследование проводится на примере проекта гидротехнических сооружений плавучей атомной теплоэлектростанции в городе Певек. Проводится численное моделирование для определения коэффициента снижения ледовой нагрузки на вертикальную стенку в случае, когда она образована путем смерзания ледовых обломков на наклонной конструкции. Представляется статистическая информация об основных исходных ледовых параметрах. Расчеты ведутся по нескольким расчетным методикам. По результатам исследования сделаны как общие выводы о воздействии ровного дрейфующего льда на гидротехнические сооружения, так и частные применительно к гидротехническим сооружениям ПАТЭС г. Певек.

1. Introduction

In Arctic conditions ice loadings often exceed the total impact from all other environmental forces. Therefore correctness of ice impact estimation has the direct influence on safety, material consumption and the economical attractiveness of any Arctic project.

In 2006 Timco and Croasdale conducted a study of how much might be the difference in ice loading calculations made by ice specialists from various countries and organizations [1]. Despite the conclusion that over the years the ice loading calculations has got better convergence, the calculated values still can differ by several times. The discrepancies in calculations, first of all, take place due to lack of unified methodology of ice loading calculations and differences in design provisions of National Standards of different countries.

The object of current investigation was the issue of accurate estimation of ice loading from drifting level ice on hydrotechnical structures. The work was concentrated on study of variability of drifting level ice parameters and ice loadings on hydrotechnical structures during ice season in order to point out how maximum design ice loading should be assigned. The ice loading calculations were done by different methodologies in order to compare the convergence of results. The study was carried out on example of protective hydraulic structures of floating nuclear thermal power plant in the city of Pevek, Chukotka Autonomous District of Russia.

The same issues have been addressed before. Previously, the specialists from the Canadian Arctic Center did the research on the level ice parameters variability in Canadian waters [2] and showed that the maximum ice strength characteristics do not usually coincide with the maximum ice thickness. This study raised a reasonable question how to determine the correct values for ice parameters to get the correct maximum ice loading? None of the standards gives the clear answer on that. Besides, there are no recommendations of how long should be the statistical data of ice parameters, necessary to get the design values.

Regarding comparison of ice calculation methods by different standards many studies have been done, including [3–5]. The main conclusion was that calculation approaches differ as well as the design ice loading values. Besides, each ice loading calculation method has its advantages and disadvantages. The recommendation was to calculate ice loadings by several methods to reduce the probability of calculation mistakes. Some works pointed out shortcomings of Russian design standard [6], the others indicated the limitations of ISO 19906 design provisions [7]. But none of the works did the clear recommendations about optimal ice loading calculation methodology.

Therefore, development and improvement of ice loading calculation methodology stays to be relevant nowdays and requires further investigations.

The main target of the study was to point out how ice parameters and theoretical ice loadings change throughout the ice season; to show how important it is to have a long-term data on the first break-up of landfast ice and the beginning of ice drift. One of the main points was also to provide the formula which could be useful for ice loading calculations and which could combine advantages of different design approaches.

To achieve the goals of the current work, the following tasks were done:

– ice impact scenarios on the Pevek hydraulic structures were determined ;

– ice loading calculating methods were defined;

– the main ice parameters were collected based on long-term meteorological data;

– a numerical modeling was performed to clarify the ice force reduction factor for the case when ice acts on the vertical wall, formed by frozen ice on the surface of the inclined structure;

– calculations were carried out, discussed and conclusions were presented afterwards.

The floating nuclear thermal power plant "Akademik Lomonosov" in the city of Pevek of the Chukotka Autonomous District, which is to be put into operation in 2019, will become the northernmost nuclear power station in the world. The floating power unit is protected from extreme external influences (sea waves and ice impacts) by hydraulic structures in the form of gravity based L-type mole, provided with a special berth for the positioning and detachment of the floating unit (Figure 1). The length of the berth is 210 meters. The structure of the outer wall of the mole has an inclined profile with an angle of inclination of 45 °.

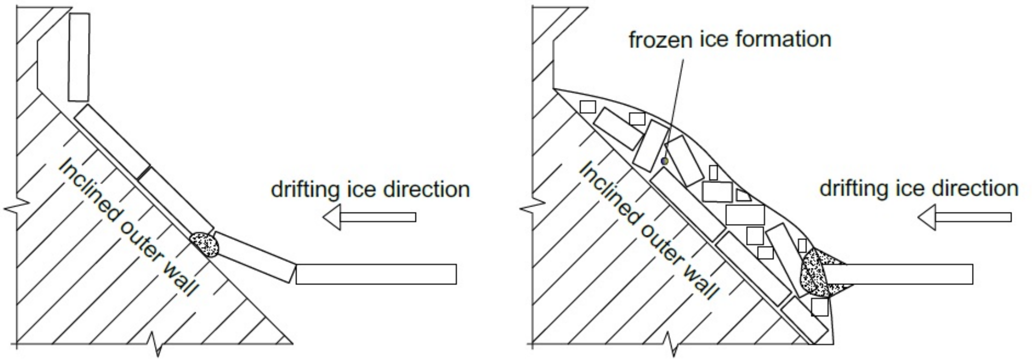
Figure 1. Floating nuclear thermal power station in Pevek city of the Chukotka Autonomous Region of Russia

2. Methods

Analytical solutions and numerical modelling in ANSYS was used in order to investigate how ice parameters and drifting ice loadings vary throughout the ice season. Ice parameters were calculated by long-term data series, available on public meteorological web-sources.

The protective hydraulic structures of the floating power station Pevek has an inclined front edge. Therefore, as shown in Figure 2, two scenarios of level ice impact on the structure were considered:

1. when the drifting level ice interacts with an inclined wall and breaks up by bending;
2. when the broken ice pieces get frozen on an inclined wall and therefore makes the drifting level ice act on a structure as on a vertical wall.



a) b)

Figure 2. Scenarios of level ice impacts on an inclined wall of the mole: a) when ice breaks up by bending; b) when level ice interacts with vertical wall made of frozen ice on an inclined wall

Ice load calculation on an inclined wall

According to Russian Standard SP 38.13330.2012 [8] horizontal force from drifting level ice on an inclined wall is calculated by the formula, MN:

$$F = k_\beta k_\Delta R_f bhtg(\beta + arctgf) + m_h[1 + A_1(f - 0.1) + A_2(f - 0.1)^2]b \quad (1)$$

where k_β, k_Δ, m_h, A_1, A_2, – coefficients, represented in the standard [8]; f – friction coefficient; R_f – bending strength, MPa; b – width of a structure, m; h – design thickness of ice, m.

Ice load calculation on a vertical wall

According to SP 38.13330.2012 the force from drifting level ice on a vertical wall of a wide structure is calculated by the formula, MN:

$$F_{c,w} = 2.2 \cdot 10^{-3} Vh\sqrt{Ak_V R_C \rho} \quad (2)$$

At the same time the ice load, calculated by (2), should not exceed the value by the formula:

$$F_{b,w} = k_V k R_C bh \quad (3)$$

where V – ice drift speed, m/s; A – ice floe square area, m²; k, k_V – coefficients from SP 38.13330.2012; R_C – compression strength, MPa; ρ – ice density, kg/m³;

For comparison the ice load can be calculated by the formula from the international standard ISO 19906 [9]:

$$F = p_{eff} bh \quad (4)$$

$$p_{eff} = C_R \left(\frac{h}{h_1}\right)^n \left(\frac{b}{h}\right)^m \quad (5)$$

where C_R=2.8MPa; n=-0.3; m=-0.16.

It is well-known that formula (3) from SP 38.13330.2012 in some cases may give an underestimated values of ice load due to not quite correct account of the scale effect of ice loading [4]. When deriving formula (3), there was no extensive field data of ice forces on extended structures. At the same time formula (4) from ISO 19906 in case of absence of multiyear ice will give somewhat overestimated values. In [10] a modified formula was presented, which, on one hand, takes into account the dependence of ice pressure on the ice thickness h and the ratio b/h, on the other hand allows to take into account the variability of ice strength during ice season, thereby compensating for the shortcomings of formulas (3), (4). K.N. Shkhinek in one of his works [4] also mentioned the necessity of considering these two provisions. The formula is as follows:

$$F = k_V \left(\frac{b}{h}\right)^m \left(\frac{h}{h_1}\right)^n \tilde{A} R_C bh \quad (6)$$

where m, n – empirical coefficients; $\tilde{A}$ – strength correlation coefficient (to be defined experimentally or based on available field data of large-scale ice force measurements).

At the structure-ice contact area (bh) up to 30m² - n=-0.76, m =-0.38; when contact area is more than 30m² - n =-0.34, m =-0.17. The coefficient $\tilde{A}$ in the study was taken to be $\tilde{A}$ = 1.25. At a given value, the load according to formula (6) gives design ice forces comparable with the field data of measured ice loadings on extended structures presented in [11–13].

When the vertical wall is made of frozen ice blocks on an inclined wall, a reducing factor $k_{\beta i}$ should be applied to formulas (3), (4), (6):

$$F_h = k_{\beta i} F \quad (7)$$

In SP 38.13330.2012 coefficient $k_{\beta i}$ is presented only for the case of frozen ice blocks on a conical structure. Thus, in order to get the value of this factor for the case of inclined extended structures, numerical simulation was carried out in ANSYS Explicit Dynamics. A numerical 3D model was used, for which the following assumptions were made:

1) ice was considered as a solid body;

2) the brittle destruction of ice was considered at relatively high rates of its deformation. It was also assumed that before the brittle fracture began, ice behaved elastically under load. To describe the behavior of ice under load, the Mohr-Coulomb model was used. Table 1 presents the characteristics of the numerical ice model.

3) brittle fracture in dynamics was taken into account by removing individual finite elements (in ANSYS the method is called Element Erosion Technique). As a criterion for destruction, the limit principal normal deformations of ice were assumed.

4) the hydrostatic and hydrodynamic effects of water were not taken into account.

Table 1. Parameters of the numerical ice model

Density, kg/m3	900
Elastic modulus, MPa	6000
Poisson coefficient	0.3
Internal friction angle, ˚C	30
Cohesion coefficient, MPa	1.0
the limit principal normal deformations of ice	0.001

3. Results and Discussion

According to AANII studies [14], temperature anomalies have a natural 60-year fluctuation period (Figure 3). Obviously, temperature anomalies directly effect changes of ice parameters. Therefore, it can be assumed that ice parameters maximum values will also have up-and-down cycles comparable with temperature anomalies fluctuations.

It is obvious that statistical series should be as long as possible. But desirable minimal period should be taken 50-60 years. In the absence of long statistical series of ice parameters (thickness, direction and drift velocities), they can be restored by numerical reanalysis based on hydrometeorological data (for example, as it was done in [15]).

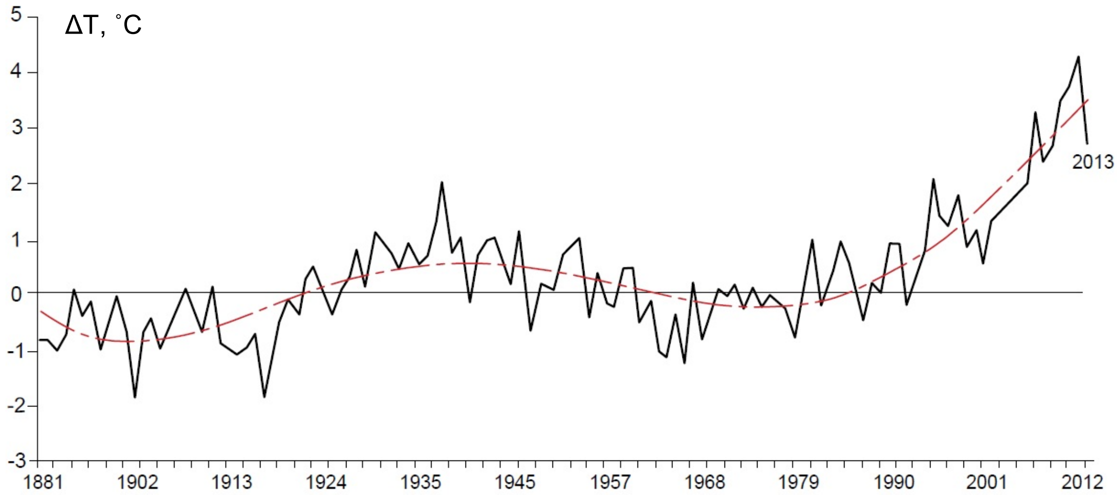


Figure 3. Graph of temperature anomalies in the North Region 70–85 n.l. (1891–2013)

Therefore, taking into account the recommended 50–60 years length of statistical data, the design level ice parameters were determined for the port of Pevek in order to get the accurate values of ice loading from drifting level ice. The results of expedition Pevek-2011 from April 30 to May 18, 2011 [16], were also taken into account.

Dates of stable ice cover settling and the first failure of landfast ice

Table 2 presents the dates of the main sea ice phases, associated with the stable ice cover settling and the first landfast ice failure in the area of Pevek station.

Table 2. The main sea ice phases (Pevek station, 1941–2010)

	Stable ice cover settling	First landfast ice failure	Q-ty of days with ice
Average	18.10	12.06	294
Earliest	30.09	24.05	251
Latest	14.11	08.07	365
R.m.s. deviation	8	9	32

Water and air temperature

Water and air temperature statistical data is presented in tables 3, 4, collected during 1977–2016 on Pevek meteorological station and presented in [17].

Table 3. Water temperature data from Pevek meteorological station, C˚

Month	Q-ty surveys	Minimum	Average	Maximum
January	431	-1.6	-1.4	0.9
February	283	-1.6	-1.5	-1.2
March	306	-1.6	-1.4	-1.1
April	350	-1.6	-1.3	1.0
May	1215	-1.6	-0.7	6.1
June	3250	-1.2	2.8	12.3

Table 4. Statistical air temperature data from Pevek meteorological station, C˚

Month	Q-ty surveys	Minimum	Average	Maximum
January	1110	-41.6	-25.0	1.7
February	1007	-49.6	-27.1	0.4
March	1111	-39.8	-26.1	-1.6
April	1080	-35.4	-17.3	3.3
May	1111	-27.3	-3.9	13.1
June	1076	-7.5	4.4	19.9

Ice salinity

A long series of statistical salinity data for ice is not available. During the Pevek-2011 expedition the measured salinity of the ice was at the range from 0.24 ‰ to 4.45 ‰ with an average value of 3.00 ‰. Increased salinity was observed, as a rule, in the middle layers of the ice cover (70–90 cm), which is typical for fibrous sea ice during the spring warm-up period.

Ice thickness

Table 5 shows the average and extreme monthly (from January to May) values of ice thickness and its standard deviation for the last 70 years – from winter 1941/1942 to 2010/2011, taken from [18].

Table 5. Statistical sea ice thickness data from Pevek station, cm

Month	January	February	March	April	May
Average	98	119	137	151	141
Maximum	137	159	175	186	193
Minimum	68	83	94	101	79
R.m.s. deviation	14	16	17	19	29

The design ice thickness (with 1 % annual probability of exceedance) for the port of Pevek was determined by the normal probability distribution function of random variables (Gaussian distribution):

$$h_{100} = h_{av} + 2.58 \cdot \sigma_h \quad (8)$$

where h_{100} – the design ice thickness with 1 % annual probability of exceedance (with a 100 year return period), m; h_{av} – the average value of ice thickness, m; σ_h - standard deviation, m.

For each month of the ice season (January-May), the design ice thickness was determined. The results are shown in Table 6.

Table 6. Values of design ice thickness throughout the ice season h_{100}, cm

Month	January	February	March	April	May
h_{100}, cm	134	160	181	200	215

Thickness of snow cover

Precipitation quantity in the area of Pevek is small. The maximum height of snow cover varies from 10 to 100 cm and changes considerably from year to year. The average maximum height of the snow cover for long-term observations is 52 cm.

During the Pevek-2011 field expedition in April-May 2011, the ice was found to be just slightly snow-covered: the thickness of the snow cover varied from zero to 14 cm. After the snowstorm on May 18, the thickness of the snow cover increased to 18 cm.

Drifting ice floes sizes

Statistical data on the sizes of drifting ice floes in the Pevek Strait is not available. But taking into account the relatively small width of the strait (5 km at the entrance to the strait from the north, 3.5 km in the vicinity of the Pevek port), the theoretical dimensions of the drifting ice can not exceed 3 km in diameter. The more likely maximum ice floe size is 1–2 km or less.

Dynamic ice characteristics: speed and direction of drifting ice

According to numerous studies, maximum ice loads on structures take place at an ice deformation rate $\varepsilon = 10^{-3} s^{-1}$. This rate of deformation corresponds to an average ice drift velocity of 0.01–0.1 m/s.

Long-term statistical data on the velocity and drifting direction of ice in the port of Pevek is not available. Nevertheless, the dynamics of ice, modeled in the THREETOX program [19] for 2011, showed the possibility of ice speed up to 0.25 m/s. As for the direction of ice drift, there are evidences that an intensive ice drift towards the shore occurs every 5–10 years.

Design ice compression and bending strength

Taking into account statistical hydrometeorological data, the compressive and bending strength was found monthly from January to May in accordance with provisions of the national standard SP 38.13330.2012. The results are shown in Table 7.

Table 7. Calculated ice compressive and bending strength for the port of Pevek

Month	T_a, C˚	T_w, C˚	h_{100}, cm	S,‰	h_s, cm	T_i, C˚	R_C, MPa	R_f, MPa
January	-25.0	-1.4	134	3	20	-8.3	2.28	0.26
February	-27.1	-1.5	160	3	25	-8.8	2.40	0.27
March	-26.1	-1.4	181	3	30	-9.7	2.57	0.27
April	-17.3	-1.3	200	3	25	-7.7	2.05	0.24
May	-3.9	-0.7	215	3	10	-2.9	0.96	0.17

where T_a – average monthly air temperature; T_w – temperature of water; h_{100} – design ice thickness; S – salinity of ice; h_s – snow cover thickness; T_i-temperature of the upper edge of ice (calculated based on temperature of air and thickness of snow); R_C – compression strength; R_f – bending strength.

When determining the design temperature of the upper edge of ice, the problem of heat transfer through a two-layer wall (ice-snow) was solved. The thermal conductivity of the ice was taken as 2.25 W/m*deg; thermal conductivity of snow with a density of 150–200 kg/m^3 (January-February) – 0.15 W/m*deg; thermal conductivity of snow with a density of 200-300 kg/m^3 (March-April) – 0.20 W/m*deg; thermal conductivity of snow with a density of 300–350 kg/m^3 (May) – 0.30 W/m*deg; coefficient of heat-emission on the border of snow-air – 10 W/m^2*deg.

The calculated values of strength, in general, are in the range of values that are usually obtained in laboratory and field tests, namely R_C=1-5 MPa, R_f=0.1-1.0 MPa [20–23].

Figure 4 shows the joint graph for the change of design ice thickness and average ice strength during the ice season from January to May, typical for the area of the port of Pevek. It can be seen that during the landfast ice failure and the beginning of ice drift, which is statistically observed at the end of May to the middle of June, the ice strength is 20–40% of the maximum ice strength during the ice season. In April, apparently, the ice thickness and strength curves intersect, and the drifting ice (if the drift is possible at the time) could impose the biggest impact on the structure.

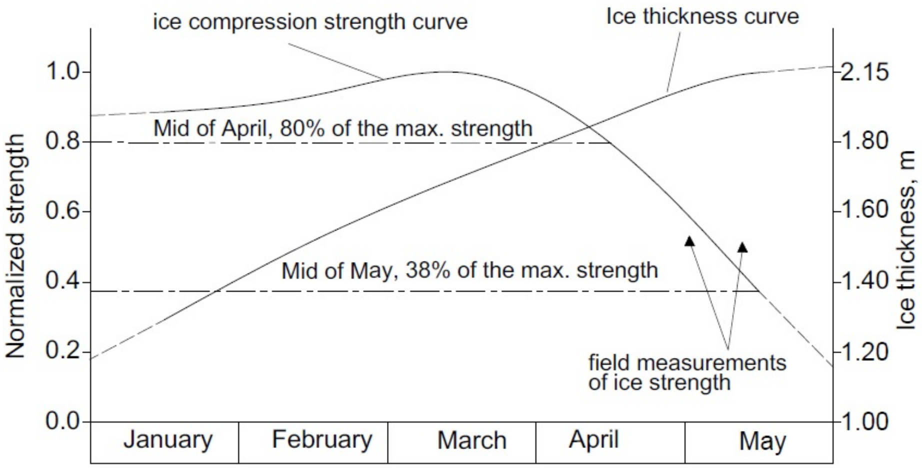


Figure 4. The joint graph of the ice thickness and compression strength alternation during ice season for the port of Pevek

These observations, in general, match the results of a study conducted by specialists from the Canadian Arctic Center in one of the Canadian Arctic waters [2]. Among the main conclusions was the fact that the strength of ice during the cold months (January-March) was relatively stable. In spring, with the increase of solar radiation and air temperature, the strength of ice began to decrease noticeably. In mid-May it accounted for about 70 % of winter ice strength, in early June – 50 %, before the active breaking of landfast ice strength was no more than 10 % [24, 25].

In SP 38.13330.2012 factor $k_{\beta i}$ takes into account the reduction of design load on a vertical wall when it is formed by frozen ice on the surface of an inclined structure. In the Standard it's presented only for a conical support structure. Its' value for the slope angle β=45˚ is equal to $k_{\beta i}$=0.6.

In order to evaluate the reduction factor in the case of an extended wall of the mole, which also has a slope of 45°, numerical modeling was carried out. For this purpose, four scenarios were simulated, graphically presented in Figure 5.

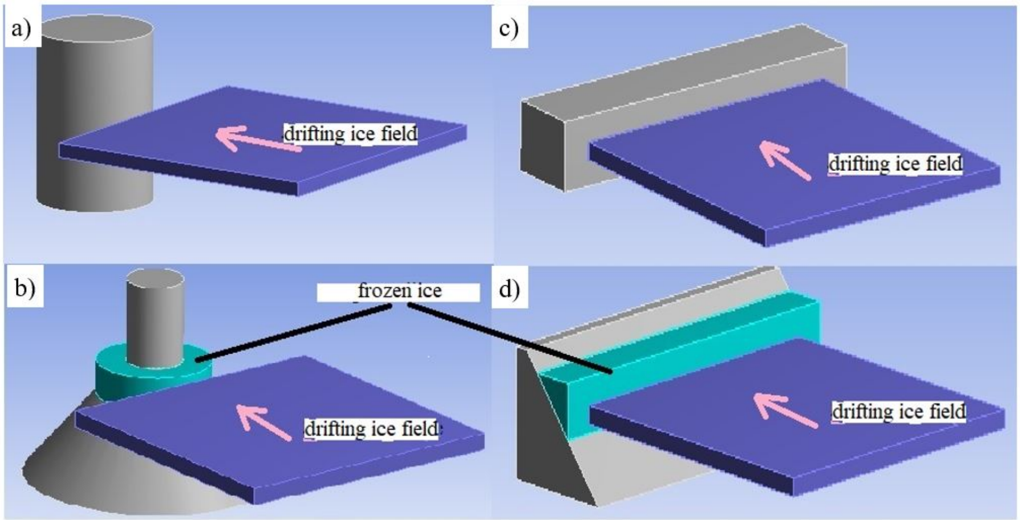


Figure 5. Scenarios of drifting ice impact on: a) cylindrical support; b) conical support with a frozen ice on it; c) vertical wall; d) inclined wall with a frozen ice on it

The results of the simulation draw the following conclusions:

1. Ice loading on a conical support with a frozen ice on it reached only 52 % of the same load on a cylindrical vertical support (assuming that the strength of the frozen ice was comparable to the strength of the ice field). This conclusion confirms the value presented in the national standard, namely $k_{\beta i}$=0.6. As it can be seen in Figure 6, during the initial contact of the drifting ice floe with the frozen ice on a conical support, local destruction of the frozen ice takes place, which leads to its further complete failure. This fact leads to a significant reduction of ice force comparing to ice impact on vertical support.

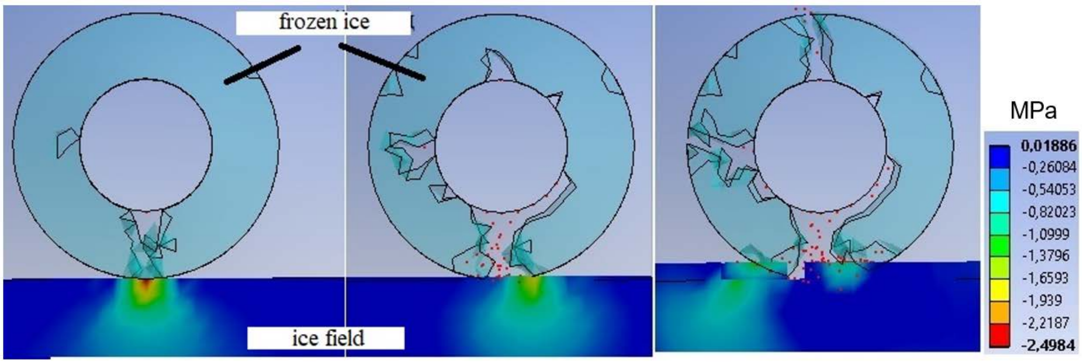


Figure 6. Failure process of the frozen ice on a conical support and principal normal stress concentrations in the drifting ice floe

2. Comparing scenarios C and D (Figure 5), assuming high strength of the frozen ice on an inclined wall (comparable to the strength of an ice field), numerical simulation did not show as much difference in the total ice load on the structure as for scenarios A and B, due to absence of local destruction effect shown in Figure 6. Taking into account the unevenness and inhomogeneity of the ice, frozen on the inclined wall, the load reduction factor for the case of ice action on an extended structure can be taken equal to $k_{\beta p}$=0.8 (based on the results of the numerical simulation).

Taking into account the data for the main ice parameters and the results of numerical modeling, table 8 presents the calculated ice loadings from the level drifting ice on the outer wall of the 210-meter-long berth of Pevek floating nuclear thermal power station. The calculation was limited to the month of May, since according to statistics, the earliest ice break occurs in May. In June and July, the thickness of the ice will only decrease, as will its strength.

Table 8. Calculated ice loadings from drifting level ice on the 210-meter-long berth of Pevek floating nuclear thermal power station, MN

Ice loading	January	February	March	April	**May** (statistically proved ice drift)
Ice loading on an inclined wall in case of absence any frozen ice on it. Calculation according to provisions from SP 38.13330.2012 and formula (1)	74.6	77.3	78.9	78.7	**75.5**
Ice loading on a vertical wall, formed by ice blocks consolidation on an inclined structure					
According to formula (2) (from SP 38.13330.2012)	105.6	129.3	151.4	149.4	**109.9**
According to formula (3)* (from SP 38.13330.2012)	205.3	258.1	312.6	275.5	**138.7**
According to formula (6)*, (from [7])	246.0	294.0	329.8	308.3	**153.3**
According to provisions of international standard ISO 19906 and formula (4)*	257.2	299.5	333.1	362.9	**386.2**

* - accounting ice load reduction factor $k_{\beta p}$=0.8.

4. Conclusions

1. The ice load on an inclined wall from the drifting level ice is relatively stable throughout the ice season. The growth of ice thickness is proportional to the drop in its flexural strength. A noticeable reduction in ice load is expected only when the temperature of the air and water rises above 0 °C, when both thickness and strength start to decrease simultaneously.

2. The ice load on a vertical wall varies throughout the winter. For the climatic conditions of the Pevek port, theoretically, the maximum ice load could be expected in March-April (which follows from the data in Table 8). But, statistically the ice does not move until May, when the load is about half of its maximum value during the winter. This confirms the validity of the provision that *the maximum ice load from drifting ice should be determined for the month of the first ice break, taken on the basis of long-term observations or by statistical reanalysis of ice conditions based on meteorological data (recommended for at least 50–60 years)*. Otherwise, the overestimation of the ice load can be more than 2 times.

3. The formula (4) from ISO 19906 can be used to determine the maximum ice load only for the winter months. For warm ice, the ISO 19906 will give significantly overestimated results.

4. When calculating ice forces according to formula (3) (from SP 38.13330.2012), some underestimation of ice loading on extended structures is possible. The field full-scale measurements and the formula (6), deduced on their basis, gave values on 10 % higher (for the berth 210m long). Formula (6) may be useful for calculation of ice loadings from drifting level ice as it combines advantages of two methodologies, by ISO 19906 and by SP 38.13330.2012.

5. The study also gave conclusions specific to ice loadings from level drifting ice on the hydrotechnical structures of the floating nuclear thermal power station of Pevek. Due to the fact that the area of the Pevek port is closed from the vast drifting ice fields by the islands Big and Small Routan, the landfast ice is fairly stable until the end of May. Therefore the most probable maximum ice load from drifting level ice is expected in May to be 109.9 MN or 0.52 MN/m (in the absence of ice crushing). To ensure the high level of reliability of hydrotechnical structures, the design load from drifting ice can be taken for the case of ice crushing (compression failure), which is 153.3 MN or 0.72 MN/m.

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