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NUMERICAL MODELING OF WAVE-ICE INTERACTION WITH A SINGLE SUPPORT

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Abstract: The change in the joint wave-ice load acting on a freestanding hydraulic structure under conditions of ice freezing to the support is considered. The existing scientific works on this problem were analyzed and the appropriate research method was chosen. The topic of the article is relevant in the light of active development of the Arctic part of Russia and construction of new hydraulic structures, which require more accurate methods of determining ice and wave loads. The novelty of the work lies in the analysis of the joint impact of the wave and ice floe on the structure. Numerical modeling in LS-DYNA program and analytical methods presented in normative documents were used for the study. Verification of the model by loads was performed by comparing numerical data with the results of analytical calculation. Changes in the horizontal forces of wave and ice floe pressure on the structure, as well as the wave impact on the ice floe were obtained. Dependences of changes in these forces and their ratios on the ice floe length were plotted. In the course of analyzing the results it was determined that the ice floe pressure force on the structure changes most significantly. The cyclic character of changes in the wave and ice forces was also revealed. Presumably, this is due to the dynamic nature of ice breakup and the effect of "ice floe surfacing-submergence". In further research, it is recommended to apply the developed model for different scenarios involving other types of ice and types of structures. The results of the paper can be used to develop more accurate methods for analytical calculation of the impact of waves and ice on structures.

Keywords: Mathematical models, ice, waves, numerical modeling, ice loads, wave loads, LS-DYNA

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ВЗАИМОДЕЙСТВИЯ ВОЛН И ЛЬДА С ОДИНОЧНОЙ ОПОРОЙ

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Аннотация: Рассмотрено изменение совместной волно-ледовой нагрузки, действующей на отдельно стоящее гидротехническое сооружение в условиях примерзания льда к опоре. Был проведен анализ существующих научных работ по данной проблеме и выбран соответствующий метод исследования. Тема статьи актуальна в свете активного освоения арктической части России и строительства новых гидротехнических сооружений, требующих более точные методы определения ледовых и волновых нагрузок для обеспечения безопасности строительства. Новизна работы заключается в анализе совместного воздействия волны и льдины на сооружение. Для проведения исследования использовались численное моделирование в программе LS-DYNA и аналитические методы, представленные в нормативных документах. Верификация модели по нагрузкам была выполнена путем сравнения численных данных с результатами аналитического расчета. Получены изменения горизонтальных сил давления волны и льдины на сооружение, а также воздействия волны на льдину. Построены графики зависимостей изменений этих сил и их соотношений от длины льдины. В ходе анализа результатов определено, что наиболее значительно изменяется сила давления льдины на сооружение. Также был выявлен циклический характер изменения волновой и ледовой сил. Предположительно, это связано с динамическим характером разрушения льда и эффектом "всплытие-погружение льдины". В дальнейших исследованиях рекомендуется применять разработанную модель для различных сценариев, включающих другие типы льда и виды конструкций. Результаты статьи могут быть использованы для разработки более точных методик аналитического расчета воздействия волн и льда на сооружения.

Ключевые слова: математические модели, лед, волны, численное моделирование, ледовые нагрузки, волновые нагрузки, совместные нагрузки, LS-DYNA

INTRODUCTION

To date, the joint impact of waves and ice on structures remains poorly studied. The approach adopted in the regulatory documents is to separately determine the wave and ice loads on a structure using a combination factor. This method does not take into account hydraulic effects arising from the impact of waves on the ice floe, such as ice floe surfacing and submergence, as well as redistribution of ice debris in the water. In addition, the nature of changes in ice and wave loads on the structure depending on the ice field length, wavelength and other characteristics is unknown.

The purpose of this paper is to investigate the wave-ice effect on a freestanding support and then analyze the dependencies of each of the loads on the wavelength of the wave and ice field. The objective of the paper is to study the changes in the load on the structure caused by the factors of ice freezing with the support and the impact of a single surface wave.

To solve this problem, a numerical model was developed in the LS-DYNA program. The structure in the model is designed as a vertical support of square cross-section, but any other shape of the cross-section of the structure can be used. The wave impacts the ice floe, causing it to collide with the structure, which leads to an increase in the kinetic energy of the ice floe motion and intense changes in the load on the ice floe and the support. The horizontal forces of wave and ice floe impact on the structure were measured in the model. The research methods include analysis of numerical simulation results and comparison with the results of calculations performed by analytical methods.

Numerical modeling studies of wave-ice interaction use models in which each ice floe is treated as a separate fundamental degree of freedom. According to the data from the paper Kantarzhi I. G., 2023 [1], this type of models allows to take into account many different physical and mechanical phenomena and provides high predictive accuracy of calculations.

Numerical calculations in this work are performed through the use of LS-DYNA program, which is actively used to analyze the impact of ice load on structures in other studies. The main purpose of such works is the correct selection of physical and mechanical properties of ice, as well as modeling of plausible processes of crack formation with subsequent failure. The Cohesive Element Method (CEM), which allows creating additional layers with unique properties between the volumetric finite elements of the ice floe, is particularly widespread.

In the study of Gurtner A., 2009 [2], the impact of an ice floe on a rigid lighthouse and its foundation was analyzed in order to determine the nature of stress redistribution in the structure. The model was built correctly, but with significant simplifications: ice thickness and velocity were not taken into account, and the hydraulic effects of water were completely ignored (the ice floe moved on a rigid smooth surface). These limitations were corrected in a subsequent study by Gurtner A., 2010 [3].

In a study by Daiyan H., 2011 [4], the variation of ice load on an inclined structure is considered as a function of the friction coefficient between the ice floe and the structure, as well as the inclination angle of the structure. The Arbitrary Lagrangian-Eulerian (ALE) method is used for modeling the aquatic environment, which is also used in this paper.

In the paper by Pang S. D., 2015 [5], the effect of mesh size and finite element shape on the magnitude of ice load applied to a cylindrical structure is studied. It is found that the use of CEM method gives ice load results that are directly proportional to the mesh size. The use of octahedral hexahedrons facilitates mesh construction but limits crack propagation along orthogonal trajectories, which makes the use of tetrahedral meshes preferable.

In Herrnring H., 2019 [6], the accuracy of a CEM model for simulating ice splitting under tension is analyzed. It is found that larger elements of the generated mesh due to their non-uniform distributed volume reduce the peak normal stresses, which may be the reason for requiring higher tensile forces when modeling coarse mesh ice.

In a study by Zhan K., 2020 [7], the dependence of ice loading on the inclination angle of the structure and ice thickness is studied. It is found that the CEM method reliably models the load changes due to the formation of ice debris. According to the calculation results, the increase in the inclination angle led to a decrease in the vertical load, which can be explained by a reduction in the formation of new debris. The results of the work were confirmed by comparison with experimental data.

Recommendations on the application of the CEM method are presented in Herrnring H., 2018 [8], where the advantages and disadvantages of this method for modeling the interaction of ice with structures are considered. Among the advantages, the preservation of the full volume of the ice floe in the defragmented state and the ability to model arbitrary crack propagation trajectories are noted. Major disadvantages include mass loss during ice breakup and high computational resource requirements.

For the latter two reasons, the CEM method was not applied to ice modeling in this work.

Among the studies dealing with numerical modeling of ice-structure interaction that do not use the coupling element method are the following works.

In the study by Mintu S., 2018 [9], an ice floe interaction model with a cone structure is developed using Smoothed Particle Hydrodynamics (SPH) and Computational Fluid Dynamics (CFD) technique. This has achieved high accuracy of results, but the SPH method, like the CEM method, requires significant computational resources.

In a study by Jeon S., 2020 [10], numerical modeling of the interaction of flat ice with structures was performed using the Drucker-Prager plasticity model and erosion model, which contributed to modeling the rapid loss of the ice floe's bearing capacity characteristic of brittle ice failure.

In the work of Jang H. S., 2024 [11], a collapsible foam model with damping and stretching constraints, as well as the already mentioned Drucker-Prager model that takes into account various yield criteria including dynamic strain rate, were used to model the impact of an ice floe on marine structures. The results showed that the yield criterion in the Drucker-Prager model within the elastic-plastic framework most adequately reflects the realism of ice impact loads.

There are very few studies devoted to direct numerical modeling of simultaneous wave and ice impact on structures.

One of them is the work of Behnen J., 2021 [12], which presents a model of wave, ice and structure interaction created in the LS-DYNA program. It compares different water modeling methods such as CFD, ALE and SPH in terms of computational time, but no analysis of the direct changes in the ice load acting on the structure.

Most of the works on the subject are devoted to experimental study of the problem.

The paper by D. J. McGovern (2014) investigates the impact of an ice floe on a structure under the influence of different waves. With irregular waves, impacts can occur at any time, whereas with regular waves, impacts can occur at crests. As the wavelength decreases, the probability of impact increases.

The work of S. Mintu (2021) studies the impact of waves on a hexagonal support at different ice concentrations and wavelengths. It is found that analytical methods accurately determine the average ice loads, but the prediction of impulsive loads remains unpredictable.

A study by A. Tsarau (2017) evaluates ice loads on a cylindrical structure when regular waves pass through an ice field. The aim is to determine the changes in the vertical displacement of the ice, the hydrodynamic force of the wave and the impact force of the ice floe. In all cases, an increase in ice load with increasing wave height was observed.

METHODS

The Mohr-Coulomb model is used to model the ice frozen to the structure. The physical-mechanical and geometric characteristics of the ice floe are taken as follows: density ρ_i = 900 kg/m^3, Young's modulus E = 5,2 GPa, shear modulus G = 2 GPa, Poisson's ratio ν = 0.3, angle of internal friction φ = 30°, cohesion c = 0.5 MPa, shear strength R_s = 0.85 MPa, compressive strength R_c = 1.82 MPa, tensile strength R_e = 0.57 MPa, thickness h_d = 0.4 m, width B = 5 m, length L varies from 1 to 10 m.

The CONSTRAINED_TIED_NODES_FAILURE keyword is used to model the breakage of ice into debris, which allows breaking the connection between nodes of a common solid element when a certain value of plastic volumetric strain is reached, which was assumed to be 0.35% according to [16].

The edge nodes of the ice floe are constrained to move towards the y-axis.

MAT_VACUUM, which is a virtual vacuum modeling material, is used to model air.

For water modeling, ALE method and MAT_NULL material are used, the characteristics of which are presented in Table 1.

Table 1. Properties of water. Source: [17].

Quantity	Unit of measurement	Value
Density ρ_w	kg/m^3	1000.00
Dynamic viscosity μ_d	Pa*s	0.001

The state of water is described by the Gruneisen equation [18] (1):

$$p = \frac{\rho_0 C^2 \mu\left[1+\left(1-\frac{\gamma_0}{2}\right)\mu-\frac{a}{2}\mu^2\right]}{\left[1-(S_1-1)\mu-S_2\frac{\mu^2}{\mu+1}-S_3\frac{\mu^3}{(\mu+1)^2}\right]^2}+(\gamma_0+a\mu)E, \quad (1)$$

where p – water pressure, ρ_0 – initial density of water, C = 1500 m/s – speed of sound in water. S_1 = 1.75, S_2 = 0, S_3 = 0 – shock adiabatic slope coefficients, γ_0 = 0.28 – Gruneisen coefficient characterizing the thermal pressure from the vibrating atoms, a = 0 – coefficient characterizing the slope of the graph of dependence of the Gruneisen coefficient on the volume, $\mu = \rho/\rho_0 - 1$, ρ – current water density, E – internal energy per unit volume of water. Values are taken according to [19].

To create a wave, the model uses a rigid body of triangular shape [20] (Fig. 1), where the short side a_b is taken to be equal to the wave height h ($a_b = h$) and the long side b_b is taken to be half the wavelength λ ($b_b = 0.5\lambda$). The body moves in a cycle, sinking into the water and then rising, thus creating waves, according to law (2):

$$f(t)=0.5h\sin(2\pi t/T), \quad (2)$$

where t is time, T is wave period.

The water depth d was modeled so that the ratio d/λ was kept constant. The calculations are performed at two wavelengths equal to 16 m and 32 m, so the depth was assumed to be 3 m and 6 m, respectively.

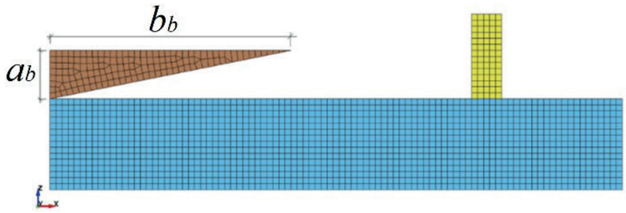

Figure 1. Wave modeling. Source: Compiled by the authors

The boundary conditions for the model are reproduced by the CONSTRAINED_GLOBAL keyword, which defines a global plane of boundary conditions-restrictions around the model.

The dimensions of the structure are a = 1; b = 1 m, and the height is 5.8 m. The base nodes are motion and rotation constrained.

The contact between the ice floe and the structure is reproduced by the CONTACT_AUTOMATIC_SURFACE_TO_SURFACE keyword. The coefficient of static friction is 0.2. The coefficient of dynamic friction is 0.1 [19].

The contact of ice floe debris with each other is reproduced by the CONTACT_AUTOMATIC_SINGLE_SURFACE keyword. The coefficient of static friction is 0.1. The coefficient of dynamic friction is 0.05 [19].

The gravitational force in the model is accounted for by the LOAD_BODY_Z keyword.

The model is shown in Fig. 2.

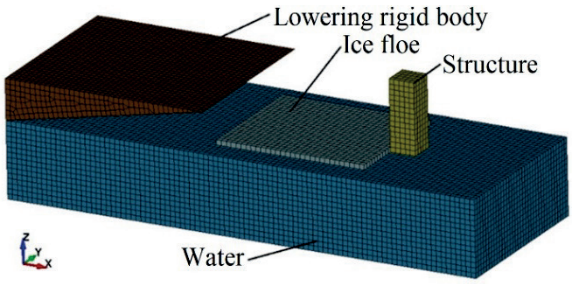

Figure 2. *A model of wave, ice and structure interaction. Source: Compiled by the authors*

Verification of the model by ice load.
The model described above is used, but without the rigid body – wave-producer (Fig. 3). The velocity vector $V = 1$ m/s is applied to the back side of the ice floe. The graph of the time dependence of the horizontal force on the ice floe is shown in Fig. 4.
The results obtained from the model are compared with the analytical calculation according to SP 38.13330.2018. The formula for determining the horizontal force of ice impact on a vertical structure $F_{c,w}$ is presented below (3):

$$F_{c,w} = 2.2*10^{-3} V h_d \sqrt{A k_V \rho_w R_c} = \\ = 2.2*10^{-3}*1*0.4*\sqrt{3*1*1000*1.82} = \\ = 0.065 \text{ MN} = 65.02 \text{ kN} \quad (3)$$

where $A = 3b^2 = 3*1^2 = 3$ m^2 – the maximum area of the ice field affecting the structure; k_V – ice deformation velocity coefficient – it is taken equal to 1.0, because not the first ice movement is taken into account, but the entire ice floe movement.

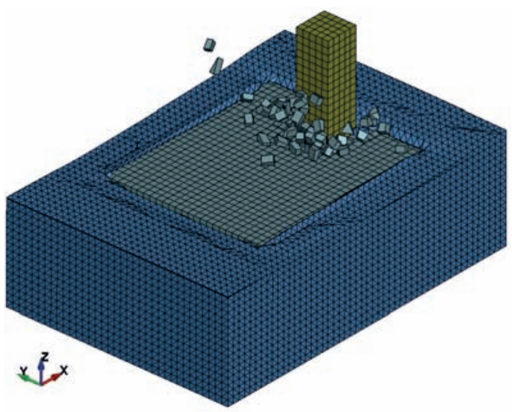

Figure 3. *Model of ice floe-structure interaction. Source: Compiled by the authors*

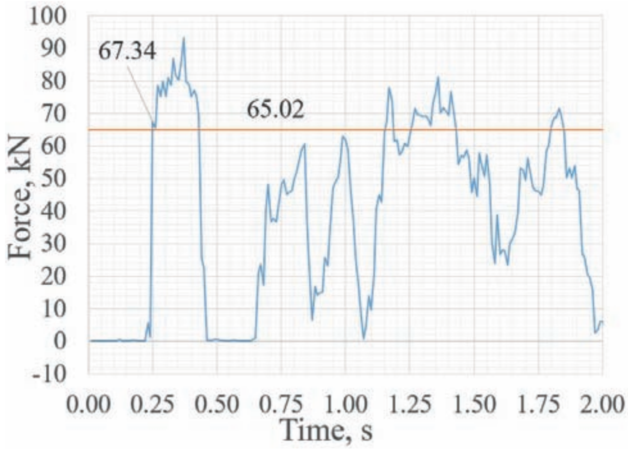

Figure 4. *Graph of change in the horizontal component of the ice floe impact force on the structure. Blue line – results obtained from the model. Orange line – calculation according to SP 38.13330.2018. Source: Compiled by the authors*

The first ice breaking against the structure occurred at a reaction force equal to 67.34 kN, which is approximately equal to the ice force obtained analytically – 65.02 kN. Subsequently, due to the formation of ice debris, the loads either increase (debris gets stuck between the ice floe and the structure) or decrease (debris goes to the bottom or piles up on the ice floe).
The nature of the loading is cyclic, which can lead to dynamic effects.
Verification of the model by wave loading.
The model described in the first section is used, but without the ice floe. Verification is performed for waves of height $h = 1.6$ m with lengths $\lambda = 16$ m (Fig. 5, *a*) and $\lambda = 32$ m (Fig. 5, *b*). The plots of the changes in the wave force on the structure are presented in Fig. 6. and Fig. 7.
The model results are compared with the analytical calculation according to SNiP 2.06.04-82. The maximum force of the wave impact on the structure Q_{max} is determined by formula (4):

$$Q_{max} = Q_{i,max}\delta_i + Q_{v,max}\delta_v, \quad (4)$$

where $Q_{i,max}$ is the inertial component of the wave force on the structure (5):

$$Q_{i,max} = 0.25\rho w g \pi b^2 h k_v \alpha_i \beta_i, \quad (5)$$

where $Q_{v,max}$ is the velocity component of the wave force on the structure (6):

$$Q_{v,max} = 0.083\rho wgbh^2k_v^2\alpha_v\beta_v, \qquad (6)$$

δ_i and δ_v – coefficients of combination of inertial and velocity components of the wave impact force on the structure, depending on the distance between the top of the wave and the center of the structure x, m: for λ = 16 m x = 1.6 m, corresponding to the calculation time t = 1.5 s (Fig. 8, *a*); for λ = 32 m x = 4.1 m, corresponding to the calculation time t = 1.4 s (Fig. 8, *b*), is taken; k_v – coefficient depending on the relative size of the structure; α_i and α_v – inertial and velocity coefficients of depth; β_i and β_v – inertial and velocity coefficients of the obstacle shape.
The calculations are presented in Table 2.

Table 2. Calculation of the wave force on a freestanding structure according to SNiP 2.06.04-82. Source: Compiled by the authors

λ, m	16	32
d, m	3	6
k_v	1	1
α_i	0.9	0.875
α_v	2.1	1.5
β_i	1.6	1.6
β_v	1.6	1.6
$Q_{i,max}$, kN	17.74	17.25
$Q_{v,max}$, kN	7.03	5.02
δ_i	1	0.9
δ_v	0.6	0.4
Q_{max}, kN	21.96	17.53

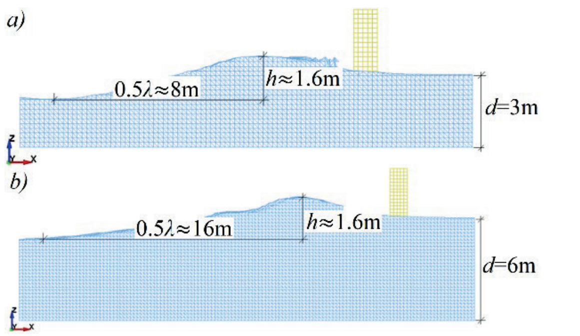

Figure 5. Wave-structure interaction model: a – at λ = 16 m, b – at λ = 32 m. Source: Compiled by the authors

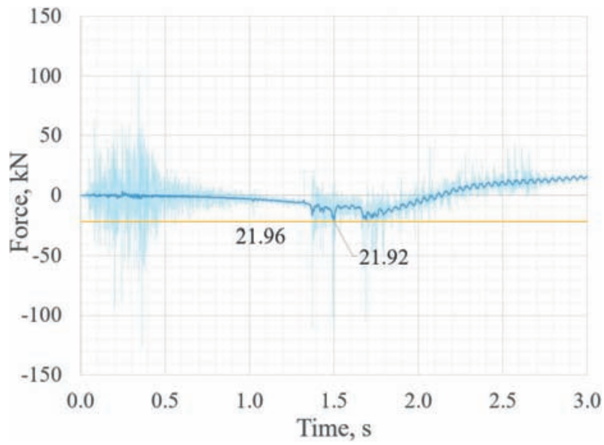

Figure 6. Graph of the change in horizontal wave force on the structure at λ = 16 m. Cyan line – results obtained from the model for the structure. Blue line – smoothed results from the model. Orange line – calculation according to SNiP 2.06.04-82. Source: Compiled by the authors

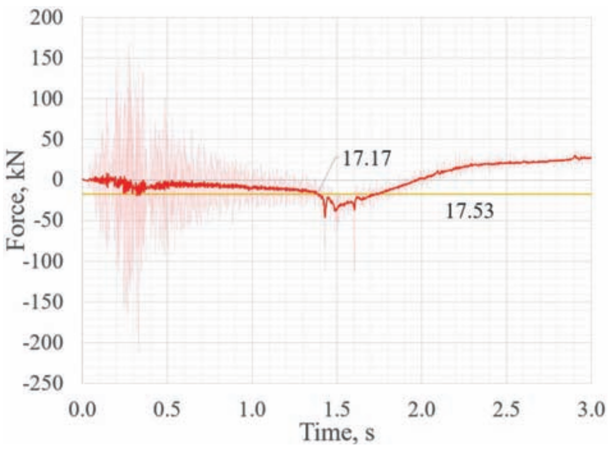

Figure 7. Graph of change of horizontal wave force on the structure at λ = 32 m. Pink line – results obtained from the model. Red line – smoothed results from the model. Orange line – calculation according to SNiP 2.06.04-82. Source: Compiled by the authors.

In both cases, the numerical (21.92 kN and 17.17 kN) and analytical (21.96 kN and 17.53 kN, respectively) methods give almost completely convergent results.

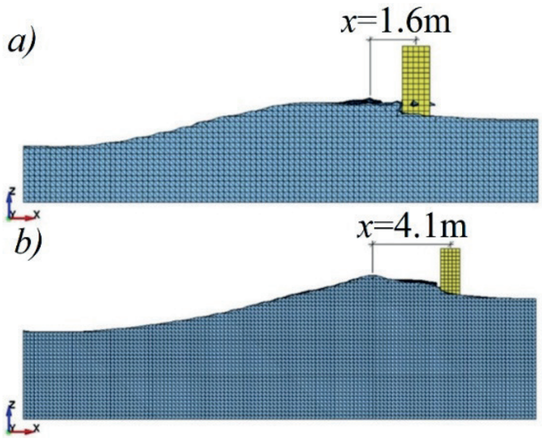

Figure 8. Coordinates of the wave top: a – at time t = 1.5 s for λ = 16 m, b – at time t = 1.4 s for λ = 32 m. Source: Compiled by the authors

RESULTS AND DISCUSSION

The model described at the beginning of the paper is used. Eleven calculations were performed for wavelengths $\lambda = 16$ m and $\lambda = 32$ m, respectively, with ice floe length L ranging from 0 to 10 m each. The wave pressure force per running meter of ice floe F_{wi}, the ice floe pressure force on the structure F_{is}, the wave pressure force on the structure F_{ws}, and the total horizontal force on the structure F_s were measured. For each load, the average values were taken at the moment of the most active interaction with the structure. The values of force ratios $F_{wi}^{\lambda=16m}/F_{wi}^{\lambda=32m}$ and $F_s^{\lambda=16m}/F_s^{\lambda=32m}$ are presented in Table 3.

Table 3. Dependence of the ratios $F_{wi}^{\lambda=16m}/F_{wi}^{\lambda=32m}$ and $F_s^{\lambda=16m}/F_s^{\lambda=32m}$ on the ice floe length. Source: Compiled by the authors

L, m	$F_{wi}^{\lambda=16m}/F_{wi}^{\lambda=32m}$	$F_s^{\lambda=16m}/F_s^{\lambda=32m}$
0	1	1
1	0.59	0.45
2	0.47	0.60
3	0.90	0.76
4	0.81	0.56
5	0.79	0.49
6	0.74	0.62
7	0.72	0.81
8	0.65	0.57
9	0.63	0.46
10	0.46	0.42

Graphs of changes in horizontal forces F_{wi}, F_{is} and F_{ws} are shown in Fig. 9.

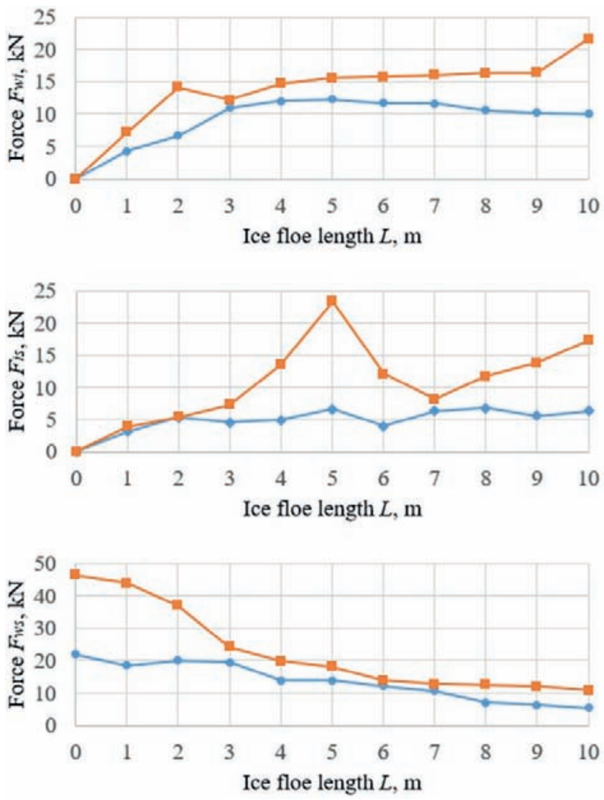

Figure 9. Dependence of forces F_{wi}, F_{is} and F_{ws} on L at λ = 16 m (blue line) and λ = 32 m (orange line). Source: Compiled by the authors

As Fig. 9 shows, the pattern of variation of the wave force on running meter of ice floe F_{wi} and structure F_{ws}, starting from $L = 3$ m becomes almost linear. While the force F_{is} exhibits cycles, and the peak values of the cycles are larger the longer the wavelength of the wave.

Graphs of changes in the F_{is}/F_{ws} and F_{wi}/F_{ws} ratios are shown in Fig. 10.

Figure 10 shows the cyclic dependence for the F_{wi}/F_{ws} and F_{is}/F_{ws} ratios on L. And, while the variation of F_{is}/F_{ws} remains linear enough to approximate this relationship by a linear function of the form $f(L) = aL + b$ (red dashed line in Fig. 10), F_{wi}/F_{ws} varies significantly, allowing the function to be averaged as follows (7):

$$f(L) = kL + g|sin(aL+b)| + c, \quad (4)$$

where k, g, a, b and c are some values depending on the wavelength and height of the wave, ice thickness and strength, and other parameters. For the blue dashed line in Fig. 10, this function has the form: $f(L) = 0.117L - 0.2|\sin(L - 2)|$ when $L \geq 2$ m. And for orange – $f(L) = 0.1L - 0.79|\sin(0.6L)| + 0.79$ at $L \geq 3$ m. It should be noted that in order to use dependences of the type (7) for practical calculations, it is necessary to relate the cyclic nature of loads to the physics of the interaction process between the wave, ice floe and structure.

The plots of the change in F_s are shown in Fig. 11. Fig. 11 also shows the cyclic character of the decrease of the total horizontal force on the structure with the growth of the ice floe length.

The plots of changes in the ratios $F_{wi}^{\lambda=16\text{m}}/F_{wi}^{\lambda=32\text{m}}$ and $F_s^{\lambda=16\text{m}}/F_s^{\lambda=32\text{m}}$ are shown in Fig. 12.

Fig. 12 shows that the ratio of loads $F_{wi}^{\lambda=16\text{m}}/F_{wi}^{\lambda=32\text{m}}$ for $L \geq 3$m changes rather linearly – by 0.04 per 1 m of ice floe length.

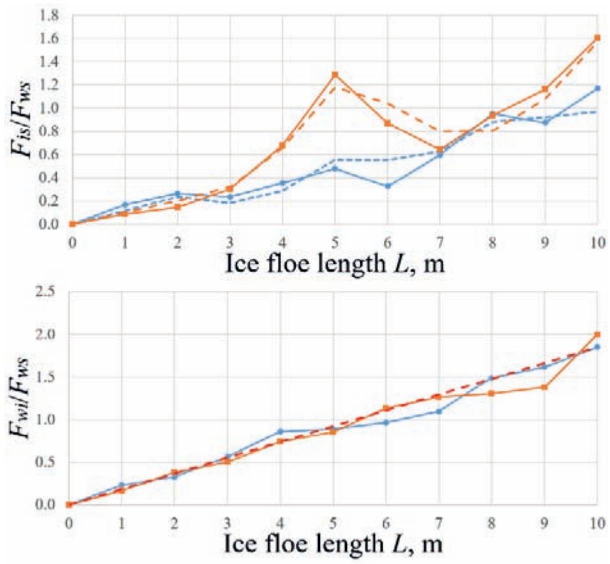

Figure 10. Dependence of F_{is}/F_{ws} and F_{wi}/F_{ws} ratios on L at λ = 16 m (blue line) and λ = 32 m (orange line). Blue dashed line – smoothed F_{is}/F_{ws} function at λ = 16 m; orange dashed line – smoothed F_{is}/F_{ws} function at λ = 32 m; red dashed line – linearization of F_{wi}/F_{ws} function. Source: Compiled by the authors

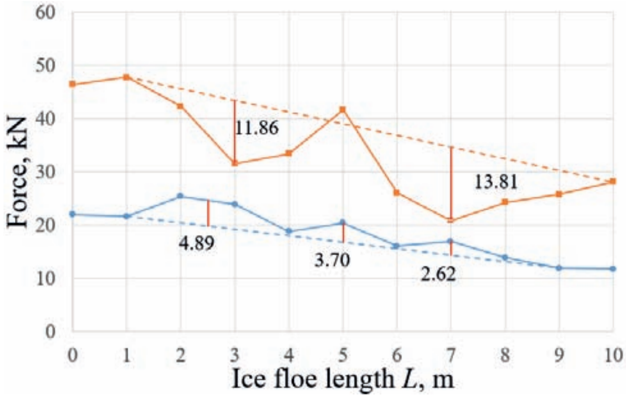

Figure 11. Dependence of force F_s on L at λ = 16 m (blue line) and λ = 32 m (orange line). Source: Compiled by the authors

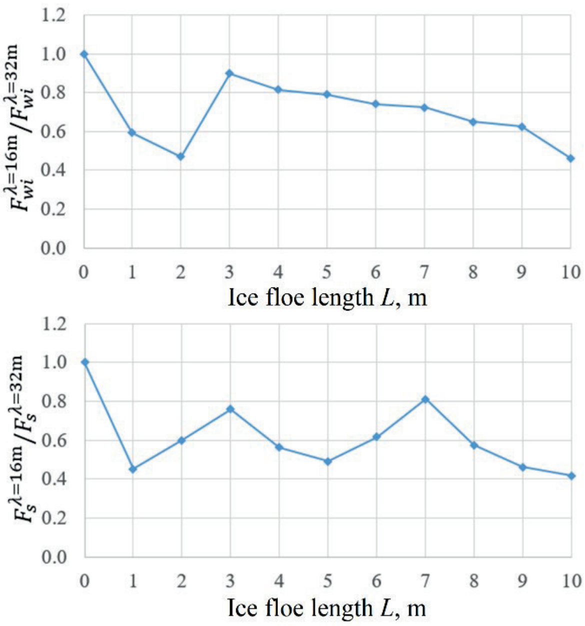

Figure 12. Dependence of $F_{wi}^{\lambda=16m}/F_{wi}^{\lambda=32m}$ and $F_s^{\lambda=16m}/F_s^{\lambda=32m}$ on L. Source: Compiled by the authors

The dependence of $F_s^{\lambda=16\text{m}}/F_s^{\lambda=32\text{m}}$ also changes cyclically, where the coefficient of the force ratio F_s changes from 0.4 to 0.8 with further decrease. It can also be noted that the ice force will change over time, and not only because of further wave action and ice breakup. During the interaction with the wave, the ice floe first rises (Fig. 13, *a*) and then falls (Fig. 13, *b*), causing a change in the horizontal component of the force. As the length of the ice floe increases, the load peaks decrease and almost reach zero, but as the wavelength increases, the forces continue to increase due to the stronger influences of the ice floe surfacing-submergence effect, decreasing to zero only when *L* reaches 10m.

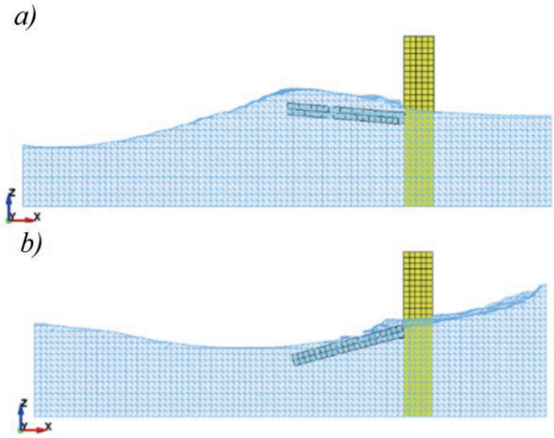

Figure 13. Changing the position of the ice floe: a – surfacing, b – sinking. Source: Compiled by the authors

CONCLUSION

A study analyzing the change in the total wave-ice load on a free-standing vertical support in the case of ice freezing with the structure has been carried out, with the development and verification of a numerical model in the LS-DYNA program. The following conclusions can be drawn from the results of the work:

1. The dependence between the forces of wave and ice impact on the structure at different wavelengths with keeping constant the ratio of water depth to wavelength d/λ has been established. It turned out that the pressure force from the ice floe changes most noticeably, and not only the peak values of the loads differ, but also the character of their distribution depending on the ice floe length.
2. The cyclic nature of the dependence of wave pressure forces on ice and ice pressure on the structure on the ice floe length was determined. When developing the normative method of calculation for wave loads acting on streamlined barriers, these dependencies can be used.
3. The character of the change of the wave pressure force on ice and the total force acting on the structure depending on the length of the wave and ice floe is revealed. The variation of the wave pressure force with a sufficiently long ice field was found to be linear, whereas the total force acting on the structure also varied cyclically. This information may be useful in determining the general law of variation of wave-ice load on structures.
4. In further research, it is advisable to continue using the developed numerical model to analyze the changes in loads depending on the thickness and physical and mechanical properties of ice. Similar calculations should also be carried out for structures of other shapes and designs. In the end, combining the methods of normative documents and the results of the numerical model, it is possible to develop more accurate methods for calculating the wave-ice impact on hydraulic structures.

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