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Loads on hydraulic engineering and berthing structures of the coastal zone of the Neva Bay

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Abstract. The object of the research is the hydraulic structures in the Neva Bay, including ports, dams, and navigation facilities, which are subjected to natural loads such as ice, wave, wind, and water level fluctuations. The study focuses on analyzing the impact of these forces on the stability and safety of these structures. The research is of high relevance due to the increasing challenges posed by climate change, which alters hydrological and ice conditions, and the growing human activity in the region that places additional pressure on the bay's ecosystem and infrastructure. The analysis of natural loads is crucial for the design of resilient structures that can withstand extreme weather events and maintain safe operations in the Neva Bay. The goal of the research is to assess the natural loads on hydraulic structures in the Neva Bay, providing reliable calculation methods for their impact. The tasks include analyzing the ice regime, wave and wind loads, and utilizing modern modeling techniques to develop optimal design solutions for these facilities. The results demonstrate that ice and wave loads significantly affect the safety of hydraulic structures in the Neva Bay, and appropriate measures, such as protective piers and icebreaker assistance, can mitigate these impacts. The research provides valuable data for the design of durable and resilient infrastructure in the region, accounting for the specific natural conditions of the Neva Bay.

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1. Introduction

The object of study is the hydraulic structures located within the Neva Bay. These include various infrastructure elements such as dams, culverts, shipping locks, berthing facilities, and other navigation and port structures. The research focuses on analyzing the natural loads these structures experience, particularly from waves, ice, wind, and water level fluctuations. Additionally, it examines the hydrological, climatic, and ice effects in the bay, evaluating their impact on the stability and safety of these engineering facilities.

The Neva Bay is the eastern part of the Gulf of Finland of the Baltic Sea, located near Saint Petersburg and the Leningrad Region, where the Neva River flows into the Gulf of Finland, and extends from the mouth of the Neva to the line connecting the cities of Sestroretsk and Lomonosov [1]. The Neva Bay is of great hydrographic, ecological and socio-economic importance for the region [2-4]. The Neva Bay is distinguished by its relatively shallow nature, with depths not exceeding an average of 6-8 meters, which is due to the presence of significant bottom sediments brought by the Neva River [5-6]. These sediments include sand, silt and organic matter, forming unique ecosystems of the coastal zone [7-8]. The hydrological regime of the Neva Bay is subject to significant fluctuations in water level caused by both river runoff and sea tides, as well as periodic surges of water during strong westerly winds, which can lead to flooding in Saint Petersburg [9-10]. From an ecological point of view, the Neva Bay is a significant natural zone, which includes a variety of biotopes and is a habitat for many species of aquatic flora and fauna [5, 11-13]. At the same time, the bay ecosystem experiences significant anthropogenic pressure as a result of human activity, including urbanization, industrial production and shipping [14-16]. This leads to pollution of water resources, eutrophication and changes in the natural processes of self-purification of the reservoir.

The Neva Bay is an important transport hub, where many hydraulic structures are concentrated, which ensure shipping, industrial production, passenger transportation and protection of the territory from unfavorable hydrological conditions. An important element of the protection of the Neva Bay and adjacent territories from floods was the construction of the Complex of protective structures of St. Petersburg from floods, which is dams, culverts and shipping locks. This complex not only protects the city, but also allows regulating the water exchange between the Neva Bay and the rest of the Gulf of Finland [17]. The Big Port of St. Petersburg is a large port of Russia in the waters of the Neva Bay, including several cargo terminals. Various cargo terminals are concentrated here. The sea passenger port of St. Petersburg ("Marine Facade") specializes in receiving passenger ships, including cruise liners and ferries [18-19]. The berthing facilities are equipped for the comfortable reception of large passenger ships and provide access for tourists to the city center. The Neva Bay is home to large shipbuilding companies, such as the Admiralty Shipyards, which have their own berthing facilities for launching ships, repairing them, and maintaining them. Along the coast, there are yacht clubs equipped with marinas for small vessels, making the water area attractive for sailing and walking. Dredging operations are regularly carried out to prevent coastal erosion and maintain the necessary depth for shipping.

Hydraulic structures and berthing facilities in the Neva Bay are subject to various natural loads, including hydrological, climatic, and ice effects [20].

In the Neva Bay, waves are formed under the influence of the wind blowing from the west from the Gulf of Finland. The average wave height in the bay is about 0.5–1.5 meters, but in severe storm conditions it can reach 2.5–3 meters. Wave loads affect berthing structures, especially during autumn and winter storms, causing erosion of the coastline and affecting the structural elements of hydraulic structures [21-22].

The Neva Bay is subject to a seasonal ice regime, when an ice cover forms in winter. Typically, the ice reaches a thickness of 30–50 cm, although it can be thicker in severe winters. Ice loads include ice pressure on hydraulic structures, dams, piers, and bridge supports [23-24].

Hydrostatic loads in the Neva Bay are associated with changes in the water level, which are caused by both the Neva river runoff and sea surges. The water level can rise by 2–3 meters in the case of strong westerly winds.

This research topic is highly relevant due to several critical factors that intersect ecological, engineering, and socio-economic concerns in the Neva Bay region. With the ongoing impacts of climate change, the frequency and intensity of extreme weather events, such as storms, surges, and ice cover variations, are expected to increase. Given the critical role of hydraulic structures—such as dams, locks, and piers—in protecting Saint Petersburg and the surrounding region from flooding and facilitating maritime transport, ensuring their safety and functionality is of paramount importance. The research directly addresses the risks posed by wave and ice loads, which can undermine the stability of these structures, potentially leading to catastrophic failures with significant economic and environmental consequences.

The goal of this research is to analyze the natural loads acting on hydraulic structures in the Neva Bay, with a focus on ice, wave, wind, and water level fluctuations, to ensure the safe design, operation, and durability of engineering facilities such as ports, dams, and navigation structures in the region. Some tasks of the research include:

Analyze the impact of natural loads on hydraulic structures in the Neva Bay, specifically addressing ice, wave, wind, and water level variations.

Develop calculation methods for determining the values of various impacts (ice, wave, wind, and water level changes) that affect the stability of structures in the Neva Bay.

Investigate the ice regime of the Neva Bay, including its formation, thickness, and effects on hydraulic structures, with a particular focus on ice hummocking and mid-winter ice conditions.

Calculate ice loads using the relevant formulas considering key factors such as ice movement speed, thickness, and compressive strength.

Assess wind loads in the Neva Bay region, especially the effects of prevailing west and west-northwest winds on hydraulic structures.

Examine wave heights and wave loads in the Cabotage Harbor, and propose measures, such as protective piers, to mitigate wave impacts and ensure the safe operation of hydraulic structures.

Apply modern methodologies, including numerical modeling, to more accurately assess natural loads and optimize design solutions for hydraulic structures based on the specific conditions of the Neva Bay.

Methods and approaches to determining loads on hydraulic structures include both traditional engineering methods and modeling and monitoring technologies [25]. In recent years, there has been significant progress in the field of numerical modeling, the use of remote sensing data, and the application of intelligent systems for load assessment. The use of software packages for numerical modeling allows calculating wave loads and currents in a reservoir, taking into account the bottom topography, wind speed, and other factors [26]. Ice regime models take into account the formation and movement of ice, ice pressure on structures and possible collisions with icebergs. In Arctic conditions, it is possible to use models that take into account multi-year ice and its drift. Satellites and drones provide data on ice conditions, wave height, water level and other parameters. This data can be quickly processed to assess loads in real time. Analysis of natural loads on hydraulic structures is an important aspect of engineering design and operation aimed at ensuring the safety, durability and cost-effectiveness of these facilities. Without an accurate analysis of loads, there is a risk of structural failure, which can lead to emergency situations and environmental disasters. Load assessment allows you to design structures taking into account expected extreme conditions, reducing the likelihood of failure. One of the tasks of the analysis is to assess the intensity and frequency of various natural loads. For example, it is important to know the average and maximum wave height, ice thickness, the likelihood of extreme events (storms, water surges). In the current conditions of climate change, it is important to consider how natural loads may change in the future (for example, rising sea levels, more frequent storms or melting ice). This helps to adapt designs to changing conditions.

2. Methods

The ice cover of the Neva Bay is usually smooth [23, 27]. The upper layer of ice is cloudy white, opaque; it consists of frozen wet snow. The lower layers of ice are lead-gray and quite transparent. Sometimes at the beginning of winter, before the ice reaches a thickness of 15-20 cm, its movements and hummocking are observed. This occurs mainly during westerly winds, which are accompanied by a rise in water level. As the level rises, the ice cover breaks away from the banks, and through cracks appear in it. The wind completes the destruction. It happens that a solid ice cover turns into a bizarre mosaic of slabs of various shapes and sizes. Each slab lives its own life. At the junction of two slabs, either hummocks or leads are formed. Crawling onto the shore, the ice floes seem to plow it; and then low sand banks appear.

In mid-winter, the ice cover of the bay, the thickness of which is 30-60 cm, at an air temperature of -5 °C has the following strength characteristics: bending strength - 8.5 kg/cm^2, one-sided compression strength - 16.0 kg/cm^2 (1.6 MPa). The ice thicknesses are presented in the Table 1.

Table 1 - Maximum ice thickness (cm) during winter [23, 28].

Water body, area	Characteristics of winter		
	Soft	Normal	Harsh
Coastal areas of the Neva Bay	30 — 40	50 — 70	80 — 100
Central regions of the Neva Bay	20 — 30	30 — 40	60 — 80

According to the Ministry of Emergency Situations and Roshydromet [28], the thickness of the ice in the Kronstadt area usually does not exceed 60 cm. It is worth considering that the fairway along which the design object is located, as well as the port infrastructure, are regularly cleared using icebreakers, as shown in the figure 1.

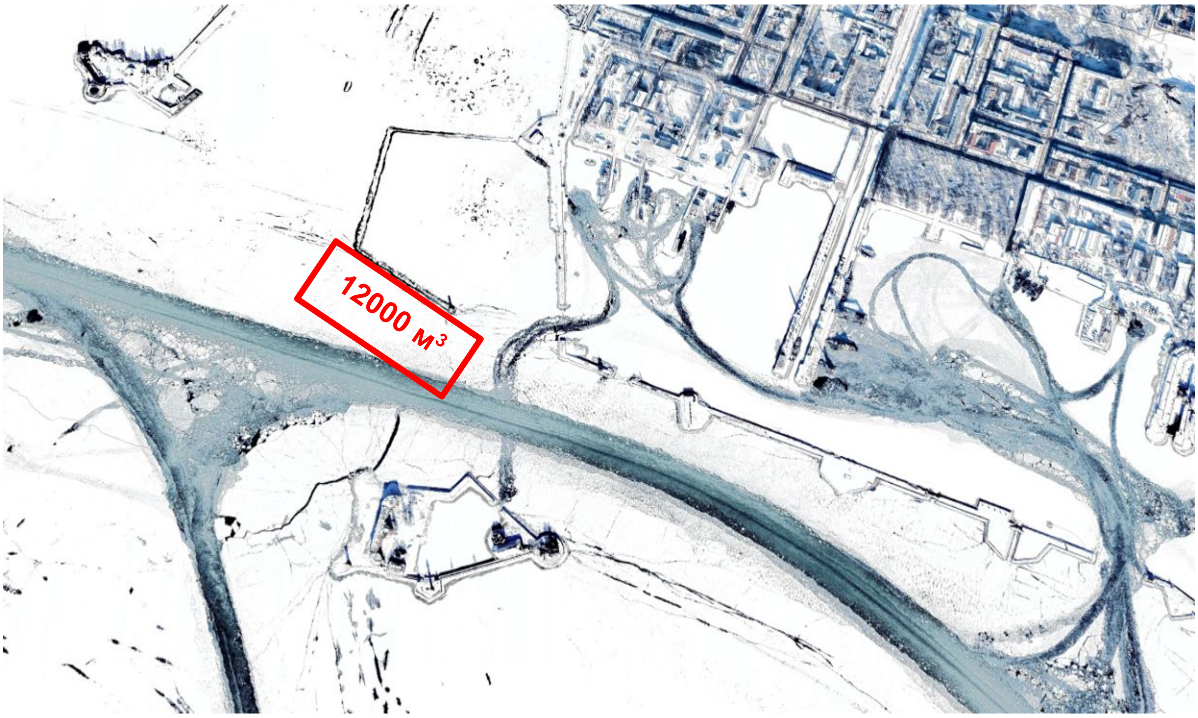

Figure 1. Breaking ice using icebreakers.

The maximum load on the outer southern pier of the Coastal Harbour from fields of level ice on an extended structure is determined by formula (1) in accordance with Russian State Standard SP 38.13330.2018:

$$F_{c,w} = 2.2 \cdot 10^{-3} \cdot V \cdot h_d \cdot \sqrt{A \cdot k_v \cdot R_c \cdot \rho} \approx 4.2MN \quad (1)$$

where V — the speed of movement of the ice field, m/s, is taken as 0.6 m/s;

h_d — the guaranteed thickness of level ice, m, is taken as 1 m;

A — the maximum area of an ice field (or the total area of several ice fields exerting pressure on each other), m^2, is taken as 12000 m^2;

k_v — coefficient, 0.5 is taken;

ρ — water density;

R_c — The one-way compression strength is taken as 1.6 MPa;

There are no loads on internal structures from flat ice fields. It is worth noting that the instructions for assessing ice loads according to SP 38.13330 differ for different versions of the documents. In the work [29] using the example of ice load on a pile foundation, it was shown that in some cases the load according to the new method becomes greater, while in others it is possible to reduce the load for the 2018 version.

The loads on structures from a continuous ice cover during its thermal expansion are determined by formula (2) in accordance with SP 38.13330.2018 per 1 meter of the structure:

$$q = h_d \cdot k_L \cdot p = 80 \, {}^{kN}\!/_{m} \quad (2)$$

where h_d — the guaranteed thickness of level ice, m, is taken as 1 m;

k_L — coefficient of loss of stability of ice cover, 0.8 is taken;

p — pressure due to elastic and plastic deformation, kPa, 100 is taken.

The latest version of Russian State Standard SP 38.13330 (2018 version) introduced a large fork in the calculations of salt and fresh ice. Figure 2 shows a surface illustrating the behavior of the calculated force from ice action when varying the initial data. Some studies [27], indicate that the result of calculations with a salinity of more than 3‰ should be additionally checked. In the Gulf of Finland, the salinity of the water is not high, which is due to the large influx of fresh water from the rivers, especially from the Neva (2/3 of the total flow). The salt water of the Baltic mixes with fresh water, but has a higher density and is located at depth, and fresh water spreads over the surface. Therefore, the further west and deeper the water sample is taken, the saltier it will be. Thus, the result according to SP 38.13330.2018 can be accepted as for relatively fresh ice near the mouth of the rivers.

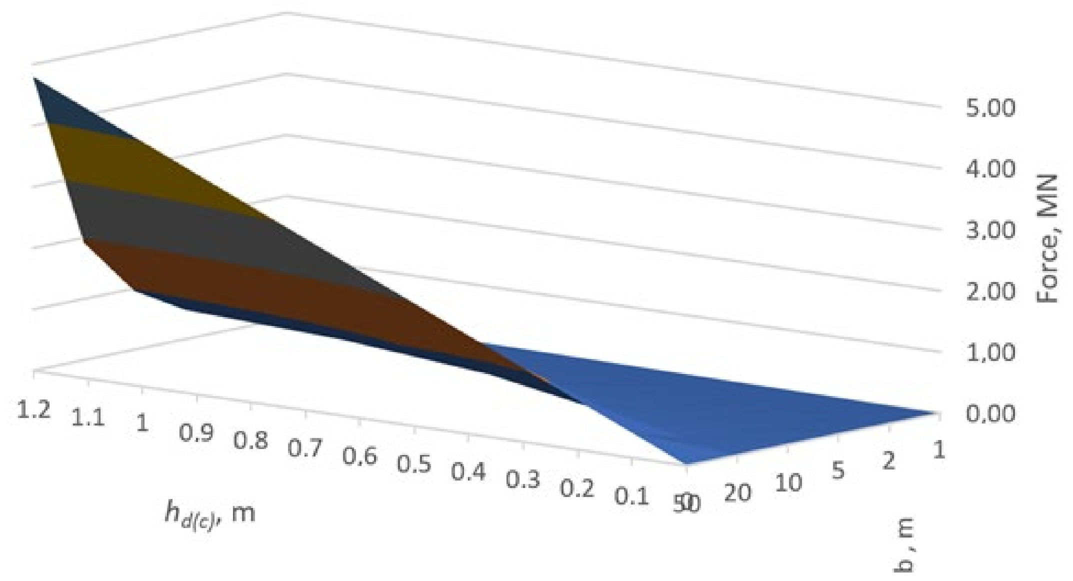

Figure 2. Behavior of the calculated ice force on a structure with varying width and thickness [20].

The vertical load (per 1 m of length along the front of the structure) from the ice cover frozen to the structure when the water level changes is determined by formula (3) in accordance with SP 38.13330.2018:

$$f_d = 2.24 \cdot 10^{-3} \cdot \rho \cdot g \cdot h_0 \cdot h_d \cdot \left(\frac{v^2}{g \cdot h_d{}^3} \right)^{1/12} = 20\, kN/m \tag{3}$$

where h_0 — change in UV, m, we take 0.5 m;

h_d — the guaranteed thickness of level ice, m, is taken as 1 m;

v — kinematic viscosity of water at 0 °C, $v = 1,793 \cdot 10^{-6} m^2/s$.

Ice load modeling using numerical methods is recommended in some works [20], to move to the next step of technological development, however, when implementing projects in the current legal field, significant efforts are required to justify the use of the results of a numerical calculation that is not standardized.

According to in-kind observations of meteorological stations located in the area of the navigation passage S1 KZ, the prevailing wind direction is W, WNW (240 - 290 degrees). The maximum wind speed is 29 m/s, the average value of the maximum wind gusts is 12.6 m/s.

For the worst mooring option, in the south direction or north direction, the load value is calculated using formula (4) in accordance with SP 38.13330.2018:

$$Q_w = 460 kN \tag{4}$$

where A_n – lateral above-water projection, m^2, is taken as 100 for a yacht with dimensions of 20*5, 1000 for a yacht with dimensions 100*10

V_n – transverse component of wind, m/s, we take 25 m/s

ξ – the coefficient depending on the largest horizontal dimension is taken as 1.

For a vessel 100 m long, $Q_w = 460kN$, the longitudinal component is insignificant.

3. Results and Discussion

The analysis showed that: the estimated wave load height is 1.1 meters for a half-wave in the fairway area. The loads on structures from a solid ice cover with its thermal expansion are 80 kN/m. The loads on structures from an ice cover frozen to a structure with a change in water level are 20 kN/m. Wind loads for the worst-case location of a vessel with an above-water part length of 20 m, a height of 5 m and a wind speed of 25 m/s are 46 kN/m, for a vessel 100 m long and 10 m high – 460 kN/m. The maximum load on the outer southern pier of the Coastal harbor from flat ice fields is 4.2 MN. Verification dynamic calculations of wave loads and wave heights were carried out for two options. The calculations are shown in the figures 3, 4, 5, 6. The recommended maximum wave height according to clause 6.1.8 of Russian State Standard GOST R 58736—2019 is 0.3 meters. Figures 29 and 30 show 2 different scales: from -0.7 to +0.7 meters and, for clarity, a scale from -0.15 to 0.15 meters is shown.

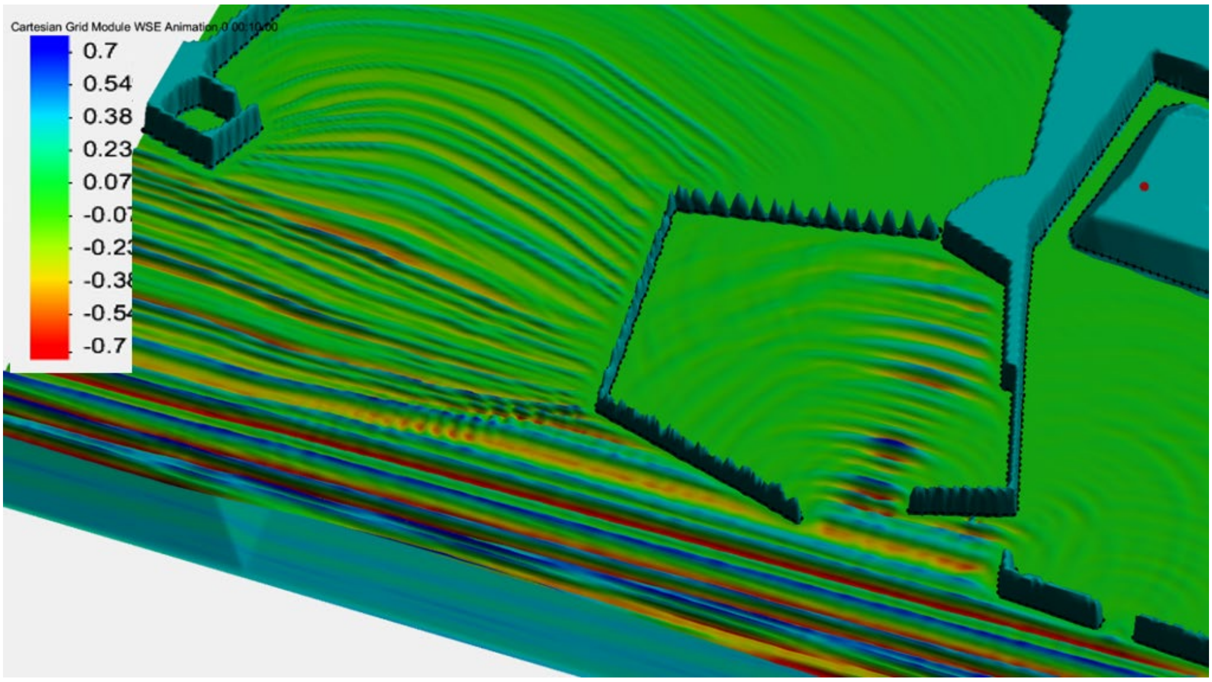

Figure 3. Result of wave height calculation in Kabotazhnaya and Kupecheskaya harbors (option 1), example 1.

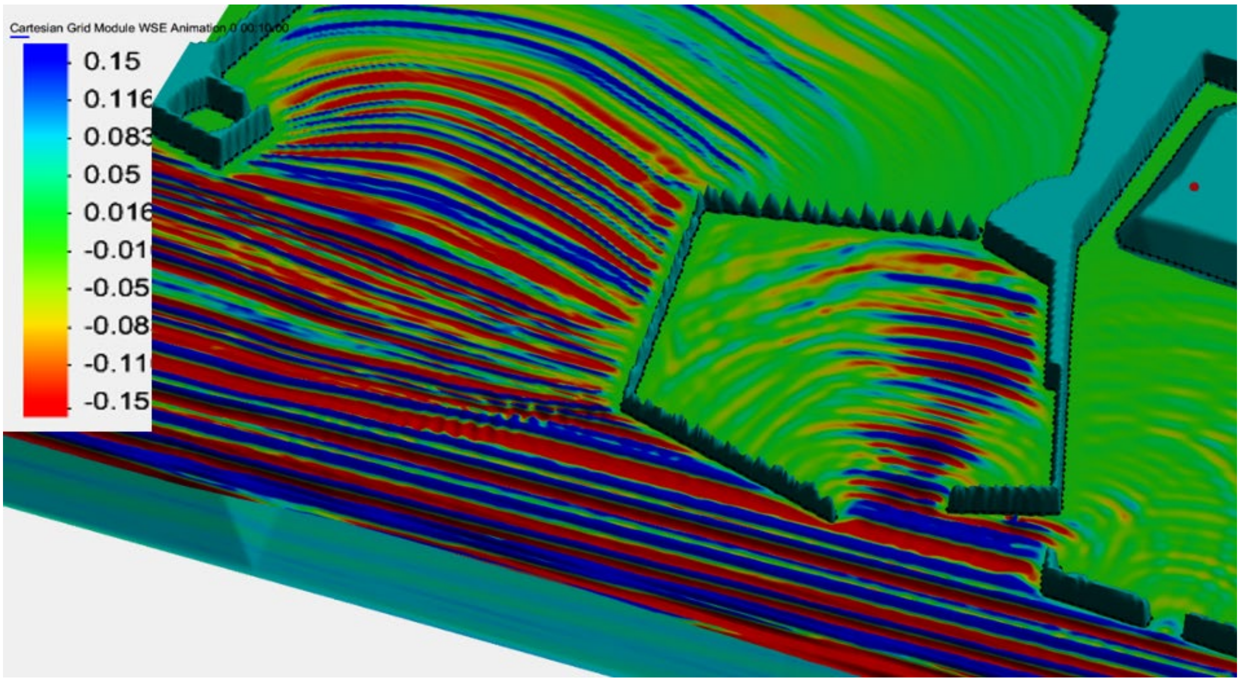

Figure 4. Result of wave height calculation in Kabotazhnaya and Kupecheskaya harbors (option 1), example 2.

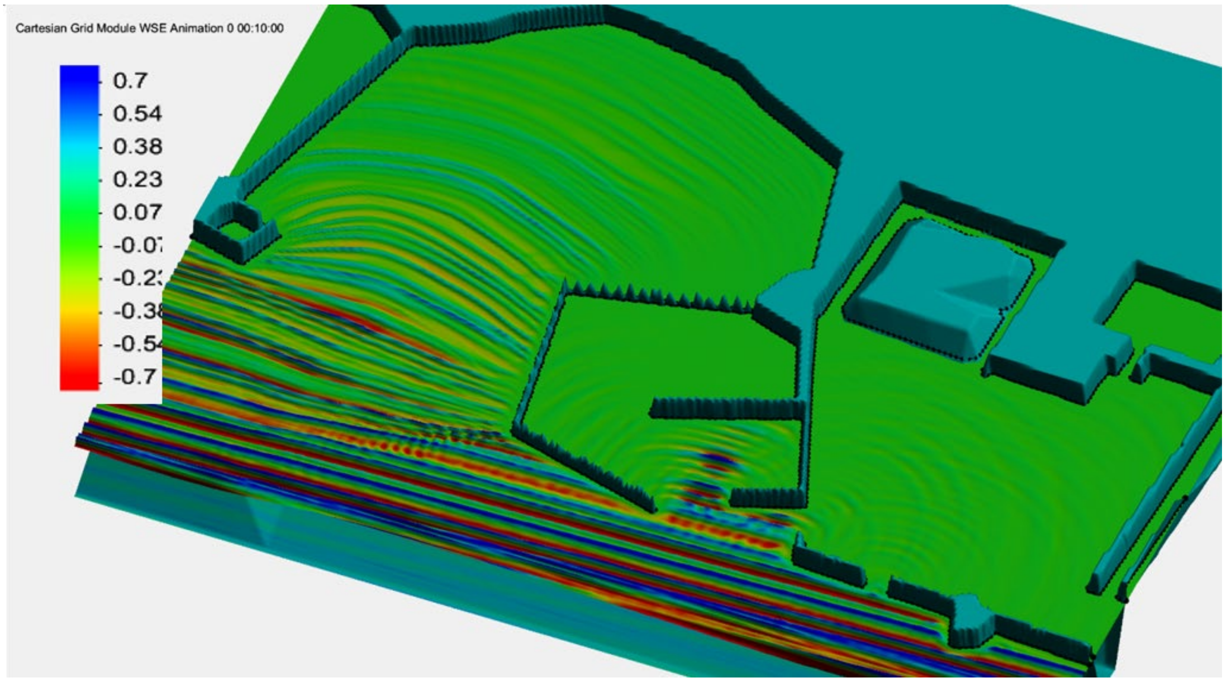

Figure 5. Result of wave height calculation in Kabotazhnaya and Kupecheskaya Aharbors (option 2), example 3.

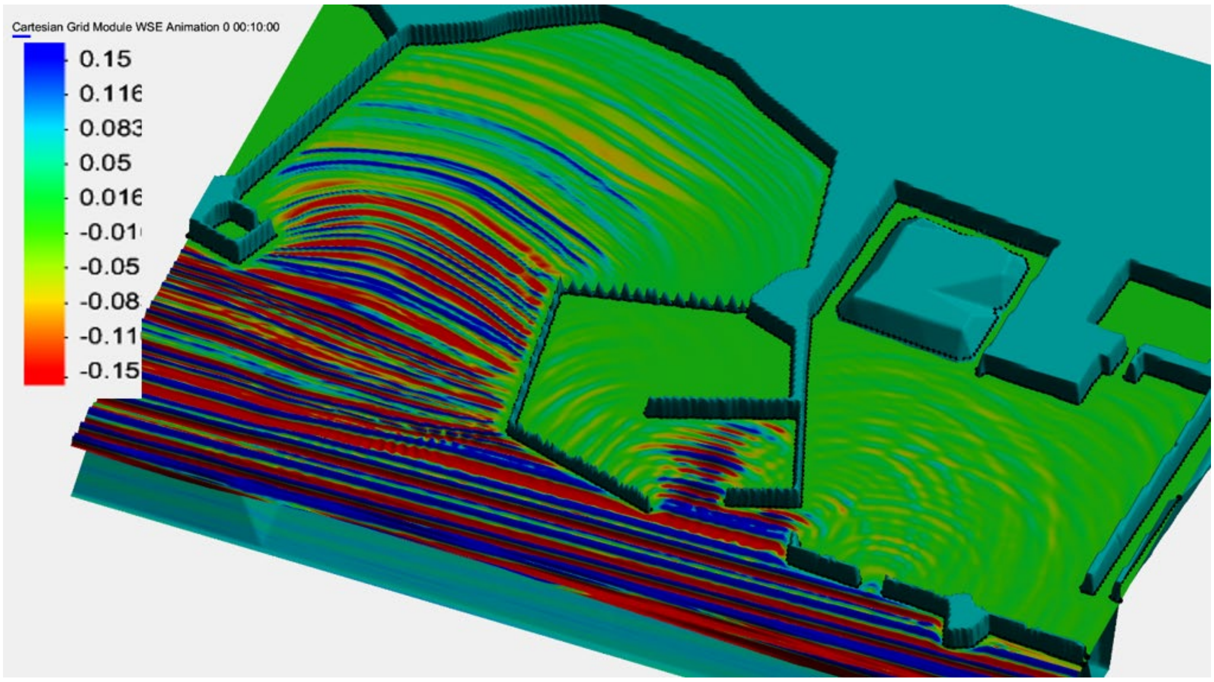

Figure 6. Result of wave height calculation in Kabotazhnaya and Kupecheskaya harbors (option 2), example 4.

Figures 7, 8 have wave height in meters (ETA) and the wave load in kN/m are determined for a design period of 600 seconds. Table 2 shows the maximum values of the wave height and the force of its impact at each design point.

Figures 7, 8 show graphs of wave height and loads at the design points. The maximum values of wave height and force at a given time at the design points are shown in Table 2 for two design cases.

Table 2. Maximum values of wave height and force at the calculated points at the moment of time.

No. of calculated point	Option	Maximum wave height. h (m)	Maximum force from wave. F (kN/m)	Time. s
1	1	1.6	580	340
	2	1.6	580	340
2	1	0.13	137	370
	2	0.14	141	380
3	1	0.14	224	360
	2	0.16	227	360
4	1	0.4	370	360
	2	0.4	380	360
5	1	0.18	96	380
	2	0.07	92	380
6	1	0.6	410	355
	2	0.002	34.1	370
7	1	0.19	91	380
	2	0.025	82	400
8	1	0.6	380	400
	2	0.005	22.5	460

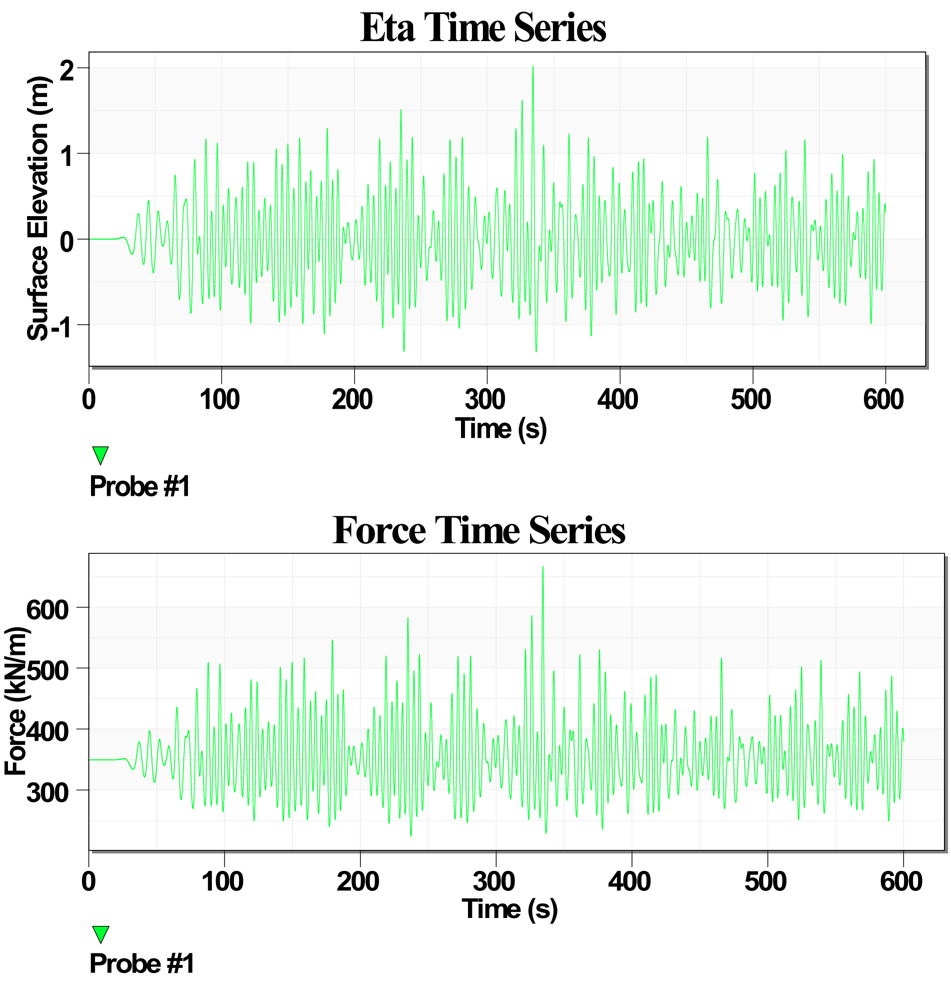

Figure 7. Design point 1, option 1, h (m) F (kN/m).

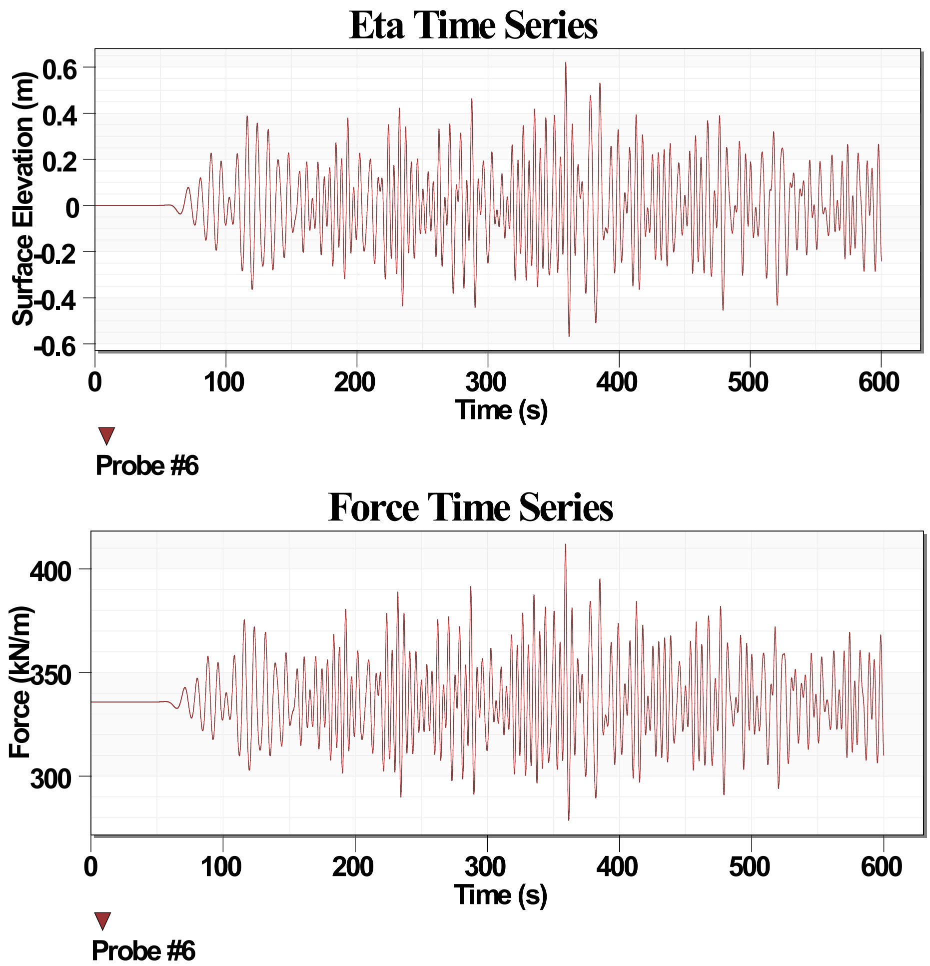

Figure 8. Design point 2, option 1, h (m) F (kN/m).

Based on the results of calculating the wave height at design points 1 and 2, in the first design option (without a protective pier with a 250 m long berth wall) the maximum wave height is observed at the entrance to the harbor (design point 1) is 1.6 meters. The wave height at design point 2 is 0.6 meters, which exceeds the maximum wave height recommended by the manufacturer for the selected pontoons, which is 0.5 meters, as well as the recommended wave height of 0.3 meters according to clause 6.1.8 of Russian State Standard GOST R 58736—2019. In this regard, the optimal design option is option No. 2, with a protective pier with a 250 m long berth wall.

To analyze the results a comparison with another works were performed. The study by Ryabchuk [1] focuses on the anthropogenic and natural influences on Neva Bay, addressing the bay's role as a technogenic lagoon. Similar to the conclusions of the current research, it highlights the significance of hydrodynamic factors, such as ice and wave conditions, which impact the hydraulic structures. The research acknowledges the importance of natural forces like ice and wave activity, aligning with the emphasis on these factors in the current study. Kozinets and colleagues [2] focus on anthropogenic impacts, particularly on the bottom morphology of the Neva Bay. While the current study is more concerned with the design and calculation of loads on hydraulic structures, it also touches on similar aspects related to the environmental changes in the bay, such as the influence of water level fluctuations and ice conditions. Both studies stress the need for tailored engineering solutions based on the bay's dynamic conditions. Prishchepenko [5] discuss the long-term impacts of human activity on the region’s ecosystem and geological environment. The current research shares an understanding of how natural forces, such as wind and ice, interact with human-made structures, influencing their design and longevity. Both studies reflect the importance of regional factors like ice cover and wind direction in shaping engineering solutions. Sharapov [20] made an emphasis on the development and application of calculation methods for ice loads, including parameters such as ice thickness, movement speed, and compressive strength. The current study aligns with the approaches outlined by Sharapov particularly in using SP 38.13330.2018 for ice load estimations. Väli [26] suggest that accurate hydrodynamic models are necessary for understanding and mitigating the risks posed by changing water conditions, which are crucial for designing resilient infrastructure. Golubkov [11] study the ecological impacts of environmental changes in the Neva Estuary, while the current research focuses more on engineering solutions for hydraulic structures. Both works acknowledge the importance of monitoring regional environmental conditions, such as water turbidity and primary production, which can influence structural stability indirectly by affecting water properties.

The research findings align closely with the conclusions in the references, particularly with respect to the significance of ice, wave, and wind loads in the design and operation of hydraulic structures in the Neva Bay. The reviewed studies corroborate the need for specialized calculations, regional modeling, and tailored engineering solutions to address the unique challenges posed by these environmental forces.

4. Conclusion

1. The analysis of loads on hydraulic structures in the Neva Bay is crucial for the design and operation of engineering facilities, such as ports, dams, and navigation structures.
2. Special attention must be given to ice and wave loads, as well as the influence of wind and changes in water levels, since these factors significantly impact the stability of structures. The study addressed various types of impacts typical for the Neva Bay's conditions and provided calculation methods for determining the values of these impacts.
3. The ice regime in the Neva Bay is characterized by a relatively smooth ice cover, largely due to the low salinity of water caused by the influx of freshwater from the Neva River. Ice hummocking, which can occur at the beginning of winter, is linked to ice movement caused by westerly winds and rising water levels. In mid-winter, the ice thickness ranges from 30-60 cm. According to the Ministry of Emergency Situations and Roshydromet, the ice thickness in the Kronstadt area does not exceed 60 cm, confirming regional characteristics of the ice regime.
4. Calculations of ice loads show they can be determined using the formula from SP 38.13330.2018, considering factors such as ice movement speed, thickness, and compressive strength. Structures within protective facilities are not subject to significant ice loads, as icebreaker assistance enables the timely removal of ice from shipping routes and port waters.
5. Wind loads also significantly impact structures in the Neva Bay, with the prevailing wind direction being west and west-northwest.
6. The analysis of wave heights and wave loads in the Cabotage Harbor suggests the need for measures to reduce wave activity to ensure safe operation of hydraulic structures. Protective piers could help mitigate wave impact.
7. Load analysis and calculations aid in selecting optimal design solutions that ensure the safety and durability of hydraulic structures. The application of modern methods, such as numerical modeling, allows for a more precise assessment of loads and the design of hydraulic structures tailored to regional conditions. As a result of the study, the loads on structures in the Neva Bay were calculated.

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