Climatic changes in the calculated levels of port hydraulic structures for the Indiga Port area

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Abstract. The development of the mineral resource base of the Arctic region of the Russian Federation has become possible, among other things, due to the increase in the duration of the navigation period and the improvement of navigation conditions due to climatic changes. The development of oil and gas reserves in this region creates the need to provide marine transport infrastructure, and, consequently, the development of existing and construction of new port hydraulic structures.

The author of the article reviewed the data of satellite observations of the sea level anomaly in the area of the construction of the Indiga port in the southeastern part of the Barents Sea from October 1992 to September 2022. It is shown that there is a stable positive trend towards sea level increasing over a period of 30 years, which indicates that a number of data series used in constructing probability curves according to regulatory methods are nonstationary. The lack of consideration of climatic changes in the level regime leads to incorrect results of calculations of water levels of a given probability according to current regulatory methods, therefore, the article deals with an example of considering the data of climatic modeling of the level regime of the Indiga port area for the life cycle of port hydraulic structures. Dividing the service life of the structure into stages, which consider the change in the marks of the structure or its absence, depending on the actually observed increase in the level of the water area, will ensure the reliability and safety of operation throughout the life cycle. The reserves laid down during the design and the creation of long-term reconstruction plans will make it possible to carry out work on raising the berth marks for berthing structures and the marks of the upper structure of protecting structures with the least expenditure of material resources and time.

Keywords: Climate change, port hydraulic structures, sea level change, climate modeling, fencing structures, berthing structures, sea level probability curve

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1 Introduction

Changes in the global climate system are an integral part of the life of the Earth's population and their active research in the previous decades allowed us to confirm with sufficient certainty the fact of the presence of climate changes and, in addition to the natural influence on the climate associated with a wide number of factors, the most global of which is the solar luminosity, to identify significant anthropogenic influence [1] caused by the economic activity of mankind [2].

Changes in the global climate system are manifested as follows: reduction of the area of sea ice, degradation of continental glaciers, increase in surface air temperature, increase in ocean heat content, sea level rise, degradation of frozen soils, etc. In this regard, the governments of the countries are forced to adapt and change the vector of development considering the climate changes [3].

Regional features of climate change have a significant impact on specific countries and the values of climatically significant characteristics in the region. The heterogeneity of the distribution of isofields of changes in surface temperature on the planet has a pronounced shift towards a bigger absolute temperature change in polar regions [4]. Due to the fact that the Russian Federation is located in the northern hemisphere and has significant territories located beyond the Arctic circle, it is the Arctic region of the country that is most affected.

The richness of the continental Arctic shelf of the Russian Federation in oil and gas, as well as the presence of significant deposits of other mineral resources in the coastal regions makes it attractive for development in terms of the availability of resources [5]. At the same time, hard climatic conditions and the lack of necessary technologies often lead to the economic inexpediency of industrial development even in such a region rich in raw materials.

However, climatic changes and scientific and technical forecast allowed the development of this region to begin, examples of large implemented or planned projects can be Arctic LNG 1, 2, 3 and Ob LNG in the Yamalo-Nenets Autonomous Okrug, the construction of the Northern Latitudinal Passage providing a railway connection to the port of Sabetta, the construction of a "Center for the construction of large-tonnage offshore structures" and "Marine transshipment complex of liquefied natural gas" in the Murmansk area, design of the Indiga port in the Czech Bay area.

In the XXI century, the increase in the scale of international trade has become unprecedented, while most of all cargo transportation is carried out with the help of the sea transport fleet. The development of existing trade routes and the creation of new ones is very important for the economies of coastal countries. In particular, the Russian Federation, due to its geographical location, has direct access to the Pacific and Arctic Oceans.

The transportation of minerals by sea, the largest share of which are hydrocarbons, is carried out both to the countries of Europe and to the Asia-Pacific region, in connection with which a significant number of sea transport facilities have been created and actively operated. A major trade route is the Northern Sea Route, which allows cargo to be transported by sea from the Atlantic to the Pacific Ocean through the Arctic Ocean.

On the territory of the Russian Federation, activities are carried out in 61 seaports [6], including 39 ports in the waters of the Arctic and Pacific Oceans, that is, more than half of all ports of the Russian Federation. As noted earlier, climate change is most pronounced in the polar regions, which include the Arctic zone of the Russian Federation. Active climatic changes in this region lead to a reduction in the area of ice, which favorably affects the conditions of navigation in the region and allows you to increase the duration of the navigation period.

The increase in the duration of the navigation period from several months (in the twentieth century) to almost year-round navigation (currently with proper icebreaking
during winter periods), led to adaptation to climate changes in the economic development policy of the Arctic zone of the Russian Federation, with the help of investments in the development of the Northern Sea Route [7, 8].

The development of the Northern Sea Route, that is, an increase in the turnover of international and coastal traffic, is associated with the need to develop the existing port infrastructure and build a new one [9]. The most significant, from the point of view of port hydraulic engineering, are fencing and mooring structures, which are often one structure combining these functions – the so-called berths – mole.

When designing port hydraulic structures, it is necessary to consider the impact of the hydrosphere on structures, which is expressed in considering the hydrostatic load from the water surface with no waves, dynamic wave load from wind waves, ice load from the effects of ice fields, etc.

One of the most indisputable and obvious manifestations of climate change is an increase in the average level of the World Ocean, which is recorded everywhere [10, 11]. The purpose of this work is to analyze the standards for determining the calculated levels of the water area for the design of port hydraulic structures in the Russian Federation [12, 13] and to develop scientifically based proposals for adapting the existing approach in engineering practice to the conditions of observed and forecast climatic changes.

2 Methods

This paper uses data from numerical model calculations of the climate system, namely sea level forecast data from the 6th IPCC Assessment Report [14]. The IPCC, as a part of the UN, is recognized by the international community engaged in the theoretical and practical assessment of climate change, as well as the development of global and regional forecasts of climate change based on the project of mutual comparison of Combined Models (CMIP).

Also, to assess the trends of climate changes in the level regime in the considered region, NASA data were used [15], which presents long-term time series of observations of sea level using altimetric satellites of the TOPEX/Posidion, Jason-1, Jason-2 and Jason-3 missions. Satellite observations made it possible to consider the dynamics of the sea level anomaly in the Indiga Port region in the period from October 1992 to September 2022.

The study of the probability curves of the level regime was carried out according to the current regulatory methodology, which is used for coastal protection structures in the Russian Federation, as well as considering the instructions of the State Hydrological Institute (St. Petersburg). For the construction of sea level probability curves, the Pearson distribution of type III was considered using the binomial distribution according to the Foster – Rybkin tables and the gamma distribution. The requirements given in the regulatory documentation for the design of hydraulic structures, berthing hydraulic structures and marine protective structures of the slope profile were also considered.

3 Results

For berthing and fencing structures, the level regime of the water area is critically important. During construction and operation, the lowest and highest syzygial water levels are significant, which directly affect the determination of the berth mark at the pier and the top of the crown wall for fencing structures.

In accordance with the requirements of regulatory documentation [16], the main port hydraulic structures are divided into three categories of importance, for each of which the calculated levels of the water area of a given probability are assigned, at the highest calculated levels, loads and impacts on hydraulic structures are determined. Probability -
the value that will be exceeded with a given probability is defined as the ratio of the number of cases in the interval to the total number of cases under consideration. For port hydraulic structures of the I category of importance, i.e. the most technically complex and key structures are determined by the level of probability of 1%, for II and III categories of importance – 5%.

Under the conditions of current and forecast climate changes, one of the significant variables is the global average sea level, which has a positive upward trend with a statistically significant acceleration. In this regard, there is some contradiction between the actually observed changes in the level regime and the regulatory methodology.

In accordance with the current regulatory methodology, in order to determine the level regime of the water area of a given probability, it is necessary to calculate and plot the probability curve. The probability curves are constructed based on data from long-term (at least 40 years) observations of sea level in the considered region, representing the probability distribution of establishing a given sea level using the Pearson type III distribution [12, 13].

However, in the current regulatory methodology, a method for determining hydrological parameters is used, which is based on the assumption of the stationarity of a number of observations that have predetermined limits for changing the values of the parameter in question, despite the interannual variability. In this regard, consideration of the conditional static case completely excludes the use of the existing methodology for non-stationary conditions of the problem.

The climatic changes in the average level of the World Ocean observed in recent decades and the regional expressions of this process allow us to conclude that there is a steady positive trend towards sea level rise, which is ubiquitous for the considered Arctic region. Thus, the actual observed data refute the hypothesis about the possibility of applying a methodology for determining hydrological characteristics based on the condition of stationarity of the series of observations, which is subject to the opinion of hydrologists [17].

In this paper, a point in the Barents Sea considered in the immediate vicinity of the projected port of Indiga with coordinates 68° N and 47° E. Figure 1 shows the data of satellite altimetry of the water surface in the period from October 1992 to September 2022 for the considered point [15], for which there is a positive trend towards sea level change (in subsequent analysis, the minimum value in the considered period was taken as zero). The distribution curve of the mean sea level is shown in Figure 2, and the level with a probability of 1% is 587.37 mm (adopted according to the Foster-Rybkin table). Sea level rise does not occur linearly in time and has acceleration [18], but even assuming a linear change in sea level in accordance with the trend obtained since 1992, sea level increasing will be 504 mm.
Fig. 1. Satellite observations of sea level anomaly at the point (68° N; 47° E)

The sea level probability curve based on satellite observations of the sea level anomaly at the point (68° N; 47° E) will be used in the design when determining loads and impacts on hydraulic structures. However, as it was shown in Figure 1, a steady positive long-term trend towards sea level rise is observed for the considered area, therefore, solving the problem of determining the calculated sea level of a given probability in conditions of stationary data series is incorrect and will lead to erroneous results that will lose their relevance by the time the construction of the hydraulic structure is completed.

As a result of consideration of this task, based on the assumption of the reliability of the climate modeling data given in the IPCC Assessment Report 6 for 50% percentile for each of the considered scenarios – Shared Socio-Economic Pathways (SSPs) [19, 20], and on the assumption of the immutability of wind and wave surge parameters, the following sea level rise values were obtained for the considered area at various climate change scenarios [14]:

- SSP1-1.9 (Very Low future Greenhouse Gas Emissions): 748 mm;
- SSP2-4.5 (Intermediate future Greenhouse Gas Emissions): 919 mm;
- SSP3-7.0 (High future Greenhouse Gas Emissions): 1062 mm;
These values significantly exceed the range of a considered values used in the method of construction according to the Foster – Rybkin table, which implies probability from 0.01 to 99.9 and clearly demonstrate the nonlinearity of the trend of sea level change.

4 Discussion

The values obtained on the basis of a long-term series of observations for the level of 1% probability cannot be reliably applied for practical purposes, since even with a linear change in sea level, the growth will exceed the difference between the levels of probability of 1% and 99% according to the probability curve constructed at the time of design, not to mention SSP scenarios that even for the most optimistic the scenarios imply an increase in sea level by 748 mm.

How could the projected climatic changes in sea level be considered when designing port hydraulic structures? If we consider the sea level probability curve based on the assumption of the same nature of the Cs asymmetry coefficient, then when determining the probability level of even the most optimistic scenario SSP1-1.9, using the $H_{1\%202120}$ probability curve constructed on the basis of long-term data, equal to the sum of $H_{1\%2020}$ and $\Delta H_{CH}$, the level is 1335.37 mm.

The resulting sea level value will have a repeatability equal to 1% under the assumptions made, however, using the design probability curve, we get that the repeatability of this level will be $5.8 \times 10^{-10}$, which is only 2.64 times less than the age of the Earth. The example shown above demonstrates the incorrectness of using data from long-term observations of sea level, in the presence of a positive upward trend, based on the condition of their stationarity.

The use of numerical climate modeling data makes it possible to construct probability curves of levels for periods equal to the fixed period of capital repairs of the structure throughout the entire life cycle. The breakdown of the life cycle of the structure into stages, for each of which the maximum design level is determined considering climatic changes, will allow you not to be in conditions of excessively inflated marks of the structure in the first years of operation and at the same time meet the requirements of reliability and safety of the structure.

Thus, the introduction of requirements for raising the marks of the upper part of the structure in connection with the projected increase in sea level at the design stage will slightly increase capital costs during design and construction, but the introduced reserve will reduce the cost of funds and time for the necessary work to raise the level of the berth and the upper structure of protective structures in the future.

The question remains open as to which of the scenarios of sea level rise should be considered as the baseline when assessing the projected sea level rise. According to the author, since, according to climate forecasts, the graph of sea level rise looks nonlinear, that is, in the early stages (the first few decades), the difference in absolute values between the scenarios is not so significant, then structures can be designed using aggressive scenarios SSP5-8.5.

During the next planned overhaul, it would be advisable to organize scientific support in order to compare the rates of sea level rise used in the design and observed at that time, in order to adapt to the actual scenario of climate change in the considered area. Using the assumptions mentioned earlier, a graph of the security curve for the SSP5-8.5 scenario was constructed, in which the sea level change from 2020 to 2120 is equal to 1195 mm, see Figure 3. With such a construction of the probability curve, it will naturally include values corresponding to less aggressive scenarios.
Fig. 3. The sea level probability curve based on satellite observations of the sea level anomaly at the point (68° N; 47° E) adjusted for sea level rise according to SSP5-8.5

A number of authors claim that even the most aggressive SSP5-8.5 scenario, when considering 50% of the quantile, does not provide reliable modeling of the process of sea level rise and in reality, it may turn out to be large. However, consideration of aggressive scenarios at 95% quantile at the initial stages of the construction life cycle can lead to unjustified overestimation of the cost of construction and economic inefficiency.

5 Conclusions

The considered data of satellite observations show the presence of a positive steady trend towards an increase in the level of sea for the studied area near the port of Indiga. This result is a local expression of the global process of sea level rise, mainly associated with changes in the thermal content of sea waters and the contribution of melting glaciers.

The methodology used in the Russian Federation for determining the calculated levels of the port's water area for calculating the parameters of loads and impacts on hydraulic structures is based on the stationarity of a number of observations used to construct probability curves. In the presence of a constant rise in sea level, the use of this technique will lead to unreliable values of the calculated sea level already at the completion of the construction of the structure.

In order to ensure the conditions of reliability and safety during the operation of port hydraulic structures, it is necessary to consider the forecast climatic changes in accordance with the level of responsibility and the duration of the life cycle of the structure when designing. Incorrect determination of the calculated sea level for protective and mooring structures can lead to the occurrence of unrecorded loads during the design phase of operation, arising both from a water area with no waves and in the conditions of a calculated storm.

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