EXTREME DESIGN STORMS FOR FLOATING NUCLEAR POWER PLANT PROJECTS

Izmail Kantarzhi
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Dept. of Hydraulics and Hydraulic Structures
of National Research Moscow State Civil Engineering University, RUSSIA
kantardgi@yandex.ru

Abstract

The overflow of waves over the crest of the protective structures of the port of refuge of a floating nuclear power plant creates a threat of accident risks. The design of hydraulic structures of floating nuclear power plants requires the determination of design storms with a frequency of up to 1 time in 10000 years: overflows, force loads, etc. This is an unconventional task for marine hydraulic engineering. The methodology and results are shown in relation to the design of the PEVEK floating nuclear power plant (FNPP) port in the Chaun Bay of the East Siberian Sea. To calculate the probability of waves of rare recurrence up to 1 time in 10000 years, the method of annual maxima applied to storms for the thirty-year period 1991–2021 is used, the distribution of peak values in which is approximated using GEV (in the form of a Weibull distribution). Maps of possible large wind waves of recurrence once every 5, 10, 25, 50, 100, 1000, 10000 years on the approach to the port were obtained. To calculate the characteristics of waves in the East Siberian and Chukchi Seas, up to the deep-water boundary of the FNPP water area, the SWAN model was used, the wind fields for the calculation of which are based on the data of the NCEP/NCAR reanalysis of wind fields in the period from 1991 to 2021. To construct extreme wave fields of various recurrence, the maximum values of wave heights for each year were selected at 993 points of the nodes of the rectangular grid with a cell size of 22 m for the FNPP water area. Thus, a numerical model of wave generation and transformation has been developed based on the adaptation of the SWAN model on an unstructured grid covering the East Siberian Sea design area. The mesh cells thicken towards the FNPP water area, decreasing in this region to a characteristic size, about 2.5 m. To calculate extreme wind-wave fields over a 30-year period, 37 storm scenarios were selected. Those periods of extreme winds from July to September were selected, in which the average wind speed in the area of the Chaunskaya Bay exceeded 10 m/s. Wave fields were obtained for all these storms in the FNPP region, the statistical processing of which made it possible to obtain wave fields of significant (13% in the storm system) waves with a frequency of 5, 10, 25, 50, 100, 1000 and 10000 years. At about 300 m from the shore, the height of significant waves of this frequency will vary in the range from 1.3 m to 3.4 m. Wave heights of 50%, 5%, 1%, 0.1% of the probability in the storm system in the same area were calculated. For waves of 1% probability with recurrence once in a hundred years, the height of the waves reaches 3.1 m, once in 1000 years - 4 m, once in 10000 years - 4.5 m.

Keywords: storm, nuclear power plant, overflow, accident risks

I. Introduction

The site for the construction of onshore and hydraulic structures for the operation of the floating nuclear power plant based on the floating power unit of project 20870, is located one kilometer northeast of Pevek.

In the available materials of hydrometeorological surveys, it is noted that in the water area of the port of Pevek, in the area of the berths, with the winds of the north-eastern quarter, the maximum wave height can be 1.8 m.

The purpose of the research is to ensure the selection of a rational layout and designs of hydraulic structures designed for a floating nuclear power plant in Pevek, Chukotka region.

Figure 1: *Overview map of the East Siberian Sea and the Chukchi Sea with the location of the city of Pevek*

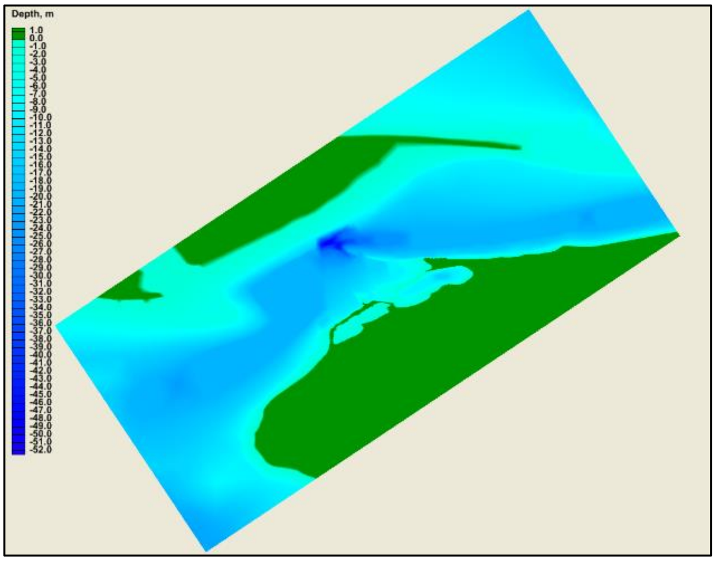

Figure 2: *Distribution of depths in the Pevek Strait, constructed from a digital map supplemented by digitization of the depth map*

In accordance with the work plan, the research includes the following works:

1. Analysis, evaluation and generalization of source materials, including:
   - fund materials and observational data obtained as a result of engineering surveys;
   - factors that cause hydrodynamic and thermohaline processes;
   - typification of ice conditions of the Chaunskaya Bay.
2. Analysis of options for the layout of hydraulic structures with recommendations for choosing the final option for the location of the station.
3. Assessments of lithodynamic processes in the area of the station location to justify dredging operations.
4. Mathematical modelling of lithodynamic processes in the area of the station location to substantiate dredging operations.

5. Modeling of wave, current and ice fields (including under conditions of a combination of unfavorable hydrodynamic factors of rare recurrence - waves, currents, fluctuations in sea level and ice) to determine the layout of hydraulic structures that provide minimum loads from waves, currents and ice, namely:

- mathematical modelling and calculation of wave and wind fields in the water area, including the places of potential location of the hydroelectric station (calculations should be carried out using modern methods for the provision of loads once in 10000 years, taking into account the change in sea level according to global estimates due to climate change, as well as tidal and surge currents);
- mathematical modelling in 2D format and calculation of current fields in the water area, including the locations of the potential location of the station gas station (calculations should be carried out using modern methods for the provision of loads once in 10000 years, taking into account the change in sea level according to global estimates due to climate change, as well as tidal and surge currents);
- Mathematical modelling and calculation of the dynamics of ice fields in the water area under storm conditions, for the areas of potential location of the gas station. The calculation should be carried out taking into account the typification of possible ice impacts on hydraulic structures in the Chaunskaya Bay, including loads from a moving hummocky ice field, in particular an "ice storm", from a continuous ice field when it expands, loads from ice jammers.

Next, we will consider the method adopted in this work for determining extreme design waves with a probability of up to 1 time in 10000 years.

II. Methods

The following methods and models were used for numerical modeling of waves in the studied water area. COASTOX-MORHO is a software system designed to solve two-dimensional equations of wave propagation, current formation, sediment transport, bottom and shore erosion based on high-performance numerical algorithms. COASTOX uses finite volume methods on unstructured grids, parallelization algorithms for calculations on multiprocessor and/or multi-core systems. The system can be used for calculations on personal computers and multiprocessor clusters, additional modules of the system allow you to calculate the transfer of pollutants (toxic elements and radionuclides) in rivers and the coastal zone of the sea.

In the last decades, the spectral model of the Technical University of Delft (Denmark) SWAN [1], distributed in open code, has become a generally accepted tool in the world practice of coastal engineering for calculating the transformation of wind waves from deep water to the coastal zone.

The HWAVE-S model [2] is a semi-spectral version of the HWAVE monochromatic model. Models of this class are based on the assumption that irregular wind waves are represented as a linear superposition of an infinite number of harmonic waves propagating independently of each other. Such models also include the REF/DIF-S [3] and ARTEMIS models [4]. HWAVE-S allows you to simulate the refraction-diffraction transformation of the wind wave spectrum near structures.

In the implementation of projects for scientific and technical support of engineering projects, both the above models and open-source models are used - the WRF meteorological model, the VERY oceanographic model, the Wave Watch spectral model of the formation and transformation of wind wave fields.

According to the existing technology of mathematical modeling, in the tasks of marine hydraulic engineering and hydraulics (design of hydraulic structures of ports and shore protection structures), the following main stages are distinguished:

1. Calculation of climatic characteristics of wind waves at specified points on the approach to the object under study (port, coastal area) on the basis of spectral models of wind waves from wind fields over the sea for a long-term (30 - 50 years) period (using meteorological element fields from the reanalysis of NCEP\NCAR or ERA-40 meteorological fields, with their possible downscaling (dynamic interpolation) using numerical weather forecast models.

2. Calculation of the wave regime of a coastal zone or enclosed sea area based on mild slope equations (in elliptical, parabolic or hyperbolic approximation) or nonlinear dispersion equations of the Boussinesque type.

3. Calculation of coastal currents generated by the combined influence of wind, waves and sea tides, taking into account the possible reverse influence of currents on the transformation of waves.

4. Calculation of sediment transport in the coastal zone and reformation of the bottom and banks.

In modern practice, three methods of statistical analysis of extreme values of oceanographic (hydrometeorological) parameters are used, based on approaches developed in the modern theory of statistics of extreme values [5-9]. These approaches are considered using the example of extreme wind wave statistics, taking into account that the same approaches are applicable to statistics of extreme values of current velocities and other hydrometeorological characteristics.

III. Results

I. Technologies for Mathematical Modeling of Wind Wave Fields in the Water Area of the FNPP Location

To calculate the characteristics of waves in the East Siberian and Chukchi Seas, up to the deep-water boundary of the FNPP water area, the following will be used: the SWAN model, for the calculation of which wind fields are used, the data of the NCEP/NCAR reanalysis of wind fields in the period from 1991 to 2021 are used, with the involvement of data refined from satellite observations and wave measurements in the region for adjustments.

NCEP/NCAR reanalysis is a project of the National Centers for Environmental Prediction (NCEP) of the US Hydrometeorological Service (NOAA) and the US National Center for Atmospheric Research (NCAR) to restore meteorological element fields over the past 40 years around the globe, using instrumental observations and modeling results [10], http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis.html, http://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml).

As the main source of meteorological data after 1999, the final analysis (http://dss.ucar.edu/datasets/ds083.2/) meteorological fields were used, which were used to initialize global weather forecast models of the US National Center for Environmental Forecasting (NCEP). These fields are calculated by the Global Data Assimilation System (GDAS, http://www.emc.ncep.noaa.gov/gmb/gdas/).

An important circumstance in favor of the choice of these data was their relatively high resolution (1 degree compared to the resolution of 2.5 degrees of the NCEP and ERA-40 reanalysis data) and the fact that, in addition to standard observations, these data assimilate a variety of satellite measurements, including propulsion wind measurements made using the SSM/I microwave radiometer [11], as well as other measurements. produced from NOAA satellites (using AMSU, HIRS instruments) and GOES geostationary satellites. These data were not used in the calculations of the NCEP R2 and R1 re-analyses, so it is preferable to use the data of the final analysis. Data from the final analysis have been available since 1998. For earlier periods (from 1990), NCEP reanalysis data 2 [12] were used, which cover the entire required period.

In addition, downscaling (dynamic interpolation) of wind data from NCEP reanalysis for several of the strongest storms for the FNPP region was carried out by the WRF meteorological regional model, with a grid resolution of up to 1*1 km to assess the significance of such downscaling for the accuracy of calculating wave characteristics on the approach to the FNPP water area. In the event that downscaling shows a significant effect of grid thickening on the calculation accuracy for wind speed, such calculations will be performed for all selected storms for the calculation period.

The results of the SWAN model calculations will be used as boundary conditions for the HWAVE–S model, a half-spectral model that, based on the equations of gentle slopes, allows you to successfully describe the diffraction effects and the effects of wave reflection from the protective structures, which is especially important for the area adjacent to the FNPP barrier breakwaters.

Taking into account the ROT methodology, at least 30 of the strongest storms will be selected over the specified 20-year period and the distribution of peak values in the resulting sample is approximated using GEV and GPD distributions. At the same time, as an estimated value of wave height for each control point near structures, the highest of the probability values of 1 time in 10000 years, calculated by these two methods, will be recommended. In addition, similar calculations will be made for the 21st century maximum possible storm scenarios, taking into account adjustments for changes in sea level and wind speed, in line with existing studies of climate global change.

Such a methodology is adopted on the basis that the requirements for the design characteristics of extreme wave parameters once every 10000 years do not mean that it is necessary to consider not the period of 10000 years of continuous operation of the floating nuclear power plant, but only the risks of the implementation of such an extreme phenomenon as storm waves of probability once every 10000 years during the 21st century, which justifies the use of climate change scenarios in the 21st century to calculate such availability.

II. Computational Grids of the Wind Wave Model in the Water Area of the FNPP Location

Wind field calculations were carried out on an unstructured grid covering the East Siberian Sea from 150° to 178° E. longitude and to the north to 80° S. latitude (Fig. 3). The number of computational mesh nodes is 94143, the number of elements is 185910. The linear size of the elements in the FNPP water area is about 2.5 m.

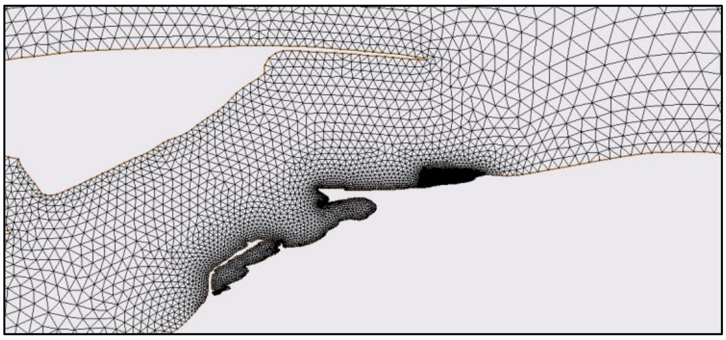

Figure 3: *A fragment of the grid for calculating wind waves in Pevek area.*

To construct extreme wave fields of various recurrence, the maximum values of wave heights for each year were selected at 993 points of the nodes of the rectangular grid with a cell size of 22 m for the FNPP water area. For each point of the grid, Weibull distribution parameters were obtained, from which the values of the heights of waves of rare repeatability were calculated. Maps of possible large wind waves of recurrence once in 10000 years are given in Fig. 4 (the map is built in the metric coordinate system). The dots show the location of the proposed wave protection moles of the floating nuclear power plant.

For greater clarity of the values of the heights of waves of rare recurrence, the values at the cross-section points (Fig. 5) located at a distance of about 300 m from the shoreline on the isobath were interpolated from the above fields.

Graphs of the heights of significant (13% certainty) waves along this section for waves of different recurrence (YRP - years return period) are presented in Fig. 6.

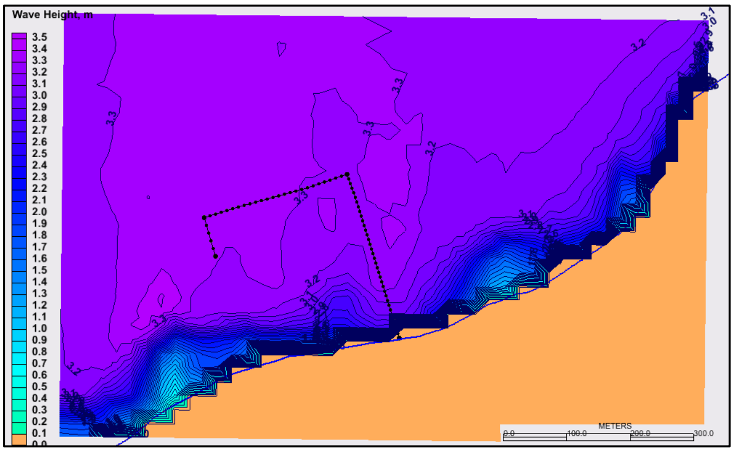

Figure 4: *Heights of significant waves, possible once in 10000 years*

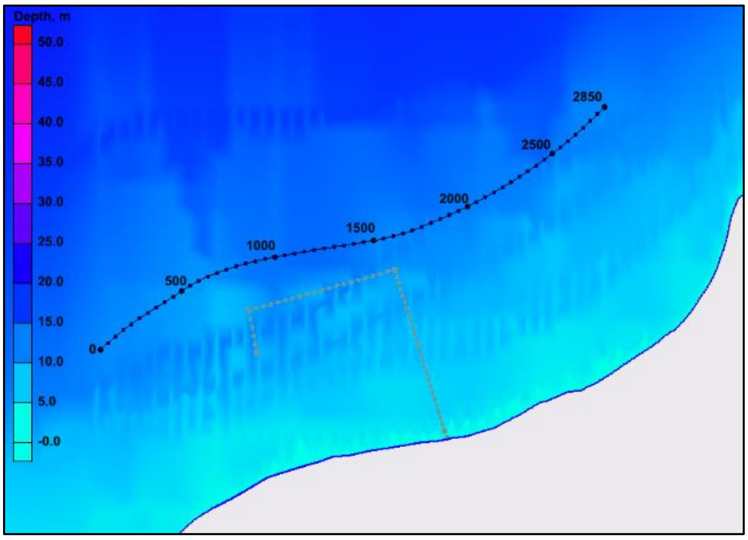

Figure 5: *Line of issuing points, 300 m from the shoreline*

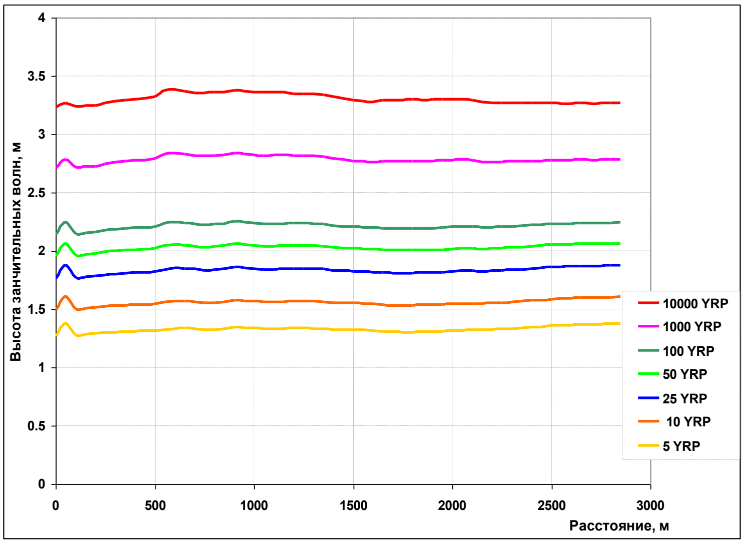

Figure 6: *Heights of significant waves of rare repeatability along a cross-section*

Wave heights of 50%, 5%, 1%, 0.1% of probability (availability in the storm system) were calculated according to Glukhovsky's formula [13] for waves of rare recurrence:

$$\frac{h}{\overline{h}} = \left[-\frac{4}{\pi}(1 + 0{,}4h^*)\ln F_h \right]^{\frac{1-h^*}{2}} \tag{1}$$

where h is the height of the waves of a given position, $h^* = \overline{h}/D$, F_h is the security of the wave height (fractions of one), D is the actual depth of the place (m).

The average wave height ($\overline{h}$) was calculated iteratively using formula (1) from the height of significant or 13% of the waves.

IV. Discussion

To calculate the availability of waves of rare recurrence up to 1 time in 10000 years, the POT method was used, applied to storms for the twenty-year period 2000 - 2021, the distribution of peak values in which is approximated by GEV and GPD distributions with the selection of the highest values from those calculated by these two methods. The generally accepted methodology for calculating oceanographic parameters in the context of climate change is based on the use of projections - scenarios of global meteorological processes in the 21st century, recommended by the UN International Commission on Climate Change (IPCC), followed by the calculation of global oceanological models of sea level change. The results of such calculations regarding the global change in wind fields and sea level were used to adjust the calculations of wave heights, current velocities and erosion intensity in the FNPP area.

For all types of modeling, initial data files were prepared, including bathymetry of the site with grids thickening to the construction site. This made it possible to simulate the fields of external factors in the design area on grids with dimensions up to 2.50 m in the plan. In addition, the necessary hydrometeorological information was collected as initial information for modeling. Survey materials, information from international hydrometeorological databases available on the Internet, as well as direct requests to Roshydromet organizations were used as sources of information. Thus, the models used are "tuned" for the conditions of the FNPP design site and can be used in the future.

Modeling was carried out for specific conditions, the modeling results were compared with the available observational data and measurements of the relevant parameters: current velocity, ice thickness. Comparisons show that the models can be successfully used to determine the design characteristics of the external load on the plant's hydraulic structures.

Wind field analysis in the region, conducted using the wind field from 2000 to 2021 from NCEP/NCAR Reanalysis-2. It should be noted that the atmospheric pressure obtained from the results of Reanalysis-2 at the installation point of the weather station, at the FNPP onshore site, in July-August 2021, is in good agreement with the measurement data. The dynamics of the change in wind speed at this point corresponds to the measured one, with a slight excess of the speed in the peaks of the storm wind from Reanalysis-2 over the measurement data in the specified period.

A numerical model of wave generation and transformation has been developed based on the adaptation of the SWAN model on an unstructured grid covering the East Siberian Sea from 150° to 178° E. longitude and to the north to 80° S. Latitude. The grid cells condense to the FNPP water area, decreasing in this region to a characteristic size: about 2.5 m. 37 storm scenarios were selected to calculate extreme wind-wave fields for the 30-year period from 1991 to 2021. Those periods of extreme winds from July to September were selected, in which the average wind speed in the area of the Chaun Bay exceeded 10 m/s. Wave fields were obtained for all these storms in the FNPP region, the statistical processing of which made it possible to obtain wave fields of significant (13% in the storm system) waves with a frequency of 5, 10, 25, 50, 100, 1000 and 10000 years. At a distance of about 300 m from the shore, the height of significant waves of this frequency will vary in the range from 1.3 m to 3.4 m. Wave heights of 50%, 5%, 1%, 0.1% of the probability in the storm system in the same area were calculated. For waves of 1% probability with a recurrence of once in a hundred years, the height of the waves reaches 3.1 m, once in 1000 years - 4 m, once in 10000 years - 4.5 m. At the same time, at the 10 m isobath in the FNPP water area, the maximum height of significant (13%) waves did not exceed 2 m over the analyzed 30-year period.

The periods of waves with recurrence from 5 to 100 years, with the probability in the storm system from 50% to 0.1% in the water area of the floating nuclear power plant, vary in the range of 4.4 - 6.5 seconds, and for waves with a recurrence of once every 10000 years, the periods reach 7.8 seconds. It should be noted that the simulation results for waves with a recurrence of once in a hundred years do not contradict the data given in the Terms of Reference for Design Surveys, according to which "on the approach to the port of Pevek" 1% of the wave has a height in the range of 3 m - 5 m and a period of 6.9 seconds.

The wave height fields in the design area are quite heterogeneous, it is advisable to take this fact into account when choosing the location of the berth. The height of waves in a storm with a recurrence of 1 time in 10000 years with a probability of 1% is about 5 m.

To calculate the load from waves on the hydraulic structures of the station, it is recommended to take at the approach to the structure, at a water depth of 10 m, the height of waves in a regime storm with a recurrence of once every 10000 years, a probability in the storm system of 1% - 4.6 m, a probability of 0.1% - 5.4 m, an average wave period of 6.91 s, the direction of the waves - N-SW. If necessary, the period of waves of 1% probability – 7.81 s, and the period of waves of 0.1% – 7.94 s, with a recurrence of 1 time in 10,000 years, can be used for calculations.

Similar wave modes are recommended to be adopted in physical modeling of the stability of hydraulic structures to the wave load.

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