Hybrid modeling of wave processes in the scientific justification of hydraulic solutions

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Abstract. To determine the wave or ice load on offshore hydraulic structures, calculation methods and modern mathematical models are used, as well as field observations and laboratory studies. Each of these methods has advantages and disadvantages. Sharing existing methods provides an approach called “hybrid or composite modeling.” Hybrid modeling provides the most reliable approach for designing safe facilities. However, the interaction of the individual components of hybrid modeling requires further research. This article is devoted to the study of the problems that arise when verifying the results of numerical modeling of wind waves using field and laboratory model measurements. The experience of studying the projects of the port-shore protection complex in Imeretinka, Sochi, the LNG terminal in the Ob Bay and the port in the East Bay of the Sea of Japan is used.

1. Introduction
Currently, marine hydraulic engineering in the world and in Russia is an area of active development. The main external loads on offshore hydraulic structures are determined by surface waves and ice fields, the correct determination of the characteristics of which largely determines the safety of the designed structures. Both computational methods and modern mathematical models are involved, as well as field observations and laboratory studies.

In this case, a rather complex interaction of calculation, numerical and experimental methods arises, requiring special study. The interaction of methods is called a hybrid or, more recently, a composite approach.

For a long time, the author has been leading a group that is engaged in pre-design studies of wave processes to ensure the design and construction of port, shelf and shore protection structures of various projects. In these studies, the problems of the interaction of methods with each other within hybrid modeling arose. Some of these problems and related results are discussed in this article.

2. Hybrid modeling of wave processes
The main regulatory document providing the determination of the design parameters of waves and ice are the construction rules of SP 38.13330.2012 “Loads and impacts on hydraulic structures (wave, ice and from ships)”, introduced in 2013. In accordance with them, engineering materials are used hydrometeorological surveys, long-term field observations of hydrometeorological processes in the design area.

In this case, observations of the characteristics of ice fields are used directly for ice, and observations of the fields (speed and direction) of the wind are used for waves. Recommended methods for calculating the elements of waves in deep water from the wind fields, as well as waves at
the structure. Since the calculation method was supposed to be applicable for the whole variety of natural conditions of the shelf and coastal zone of the seas, some averaged approaches were proposed. And although these methods are supplemented by some empirical corrections, they remain averaged and allow unpredictable errors when applied to the specific conditions of the design area. It is assumed that the errors in the determination of the design parameters of waves and ice will be compensated by the engineering reserves adopted during the design.

However, this approach is poorly applicable for the most critical facilities. Therefore, as can be assumed, these circumstances led to the inclusion in SP 38.13330.2012 of the following requirement: “Loads from waves and ice on hydraulic structures of class I, as well as the calculated wave elements in open and enclosed waters, must be clarified based on field observations and laboratory studies”. That is, the elements of waves obtained by calculation must be compared with field observations in the construction area and adjusted according to the results of such a comparison. This norm applies to the most responsible hydraulic structures of class I.

The method for determining the design characteristics of waves in a joint venture is the equivalent wave method [1]. In accordance with the distribution function of wind speed in a given wave-hazardous direction (storm mode), a design storm corresponding to the class of construction is determined. This estimated storm is assumed to be equivalent to the storm regime for the construction area.

However, the estimated storm parameters cannot be directly compared with the data of field measurements of waves in the area of the construction site, even if such data are available. Since the measurement data refer to specific time and hydrometeorological conditions, and the calculated storm is virtual, equivalent in terms of determining the load on the designed structure of a long-term sequence of storms.

Another approach to determining the design parameters of waves on the approach to the construction uses reanalysis to restore the hydrometeorological conditions for the construction area for a sufficiently long previous period (several decades) and determine the characteristics of severe storms for this period [2, 3].

To determine the operational characteristics of waves in the open sea on the approach to the projected object, the data of the analysis of wind fields for the last 30-50 years are used, on the basis of which periods of the most severe storms in the region under consideration are distinguished, the wave characteristics for which are calculated on the basis of the SWAN numerical model. This approach, which has become generally accepted in modern foreign and Russian studies [4–7], allows one to obtain wave characteristics directly in the study area, where there are no permanent stations for observing waves.

When re-analyzing hydrometeorological conditions, the characteristics of specific storms are established, which can be compared with the data of direct measurements of waves in the region and, thus, fulfill the above requirement of the joint venture to refine the calculated characteristics of waves by comparison with the data of field measurements.

The resulting sequence of storms can be used to construct the distribution functions of heights and wave periods. In addition, if the estimated storm with a security of once every hundred years (for Class I facilities) is determined on the basis of data from long-term observations of the wind, then storms close to the calculated characteristics can be distinguished from the sequence of storms obtained by reanalysis.

As an example of the application of the method of reanalysis of hydrometeorological conditions to determine the calculated wave parameters, the data on the coast protection project in Imeretinka (Black Sea, Sochi) are given below.

The wave regime of the coast of the Imereti Lowland is modeled from long-term data of the wind field over the Black Sea, with subsequent calculation of wave transformation in the coastal zone based on equations of approximation of gentle slopes. Such an approach made it possible to calculate the wave parameters of the largest storms of recent decades directly in the coastal zone of the Olympic
complex and to evaluate the impact of the designed shore protection structures on changes in wave characteristics in the coastal zone.

To determine the operational characteristics of waves in the open sea on the approach to the Imereti coast, we used data from the analysis of wind fields over the Black Sea in 1980–2010, based on which periods of the most severe storms in the region under consideration were identified, for which the wave characteristics were calculated based on the SWAN model [7]. This approach allows one to obtain wave characteristics directly in the study area, in which there are no permanent stations for observing waves.

To calculate the characteristics of the waves on the deep water border of the Imereti coast, we analyzed the NCEP / NCAR reanalysis data of the wind fields from 1980 to 2010 using data adjusted for satellite observations and wave measurements in the region for corrections.

After 1999, the NCEP “final analysis” meteorological fields were used as the main source of meteorological data [8], in which the meteorological fields were additionally adjusted due to satellite remote observation data.

For calculations by the SWAN wave model in the specified 30-year period, periods of strong winds were selected, from the South to the North-West, with wind speeds of 12 m/s and more, which can lead to high storm waves on the coast near the city of Sochi. Wind was estimated for the entire eastern part of the Black Sea (east of Kerch). In total, in the period 1979–2010, 67 severe storms were revealed by the specified criterion.

The wave field calculations were carried out by the spectral model of SWAN on three regular rectangular grids in spherical coordinates (latitude-longitude). The first grid includes the entire Black Sea region. The square mesh size of the first grid is 1.5 minutes. The second grid is nested in the first and includes the coastal zone of Sochi. The mesh size of this grid is 9 s. The third grid, nested in the second, covers the area of Imereti Bay from the mouth of the river. Mzymta to the river. Psou, and the cell size of this grid is also 10 times smaller than the cell size of the previous (second) grid and is 0.9 s. Bathymetry for computational grids was interpolated at grid nodes according to GEBCO topographic data publicly available on the Internet on a thirty-second grid, and for the coastal part of Imereti Bay, depths measured by an echo sounder were used as part of the development of the shore protection project.

The calculations were carried out by the SWAN spectral model in three stages – on each of the three nested grids with sequential data transmission at the boundary points between them.

Based on the results of calculations of the characteristics of the identified 63 strongest storms in the period 1980–2010, their statistical characteristics were analyzed using the WMO method [6]. To assess the frequency of storm waves in the mode, empirical integral probability distribution functions of wave heights (IFDW) are plotted at the seashore border of the coastal shelf zone in the region of the eastern tip of the port. The transition from IFDW to the values of security P is carried out according to the formula $P = 1 – IFDW$, and, accordingly, the frequency of the storm $n$ (the number of years the value of this parameter can be exceeded) $n = 1 / P$. The repeatability of wave periods was similarly determined.

The 15 strongest storms in the indicated period were received, ranked by the height of a significant wave, and Table 1 shows the calculated frequency of wave heights and periods in the storm system.

| Repeatability every n years | IFDW  | $H, m$ | $T, s$ | Storm Dates                              |
|-----------------------------|-------|--------|--------|------------------------------------------|
| 1                           | 0     | 3.1    | 5.7    |                                          |
| 5                           | 0.8   | 5.5    | 7.5    |                                          |
| 10                          | 0.9   | 5.8    | 8.0    | 1995-01-01, 1998-02-17, 1999-12-29, 2006-03-03, 2007-11-11 |
| 25                          | 0.96  | 6.5    | 8.4    | 1989-12-07, 1987-01-03, 1987-01-27       |
| 50                          | 0.98  | 7.0    | 9.5    | 1993-01-25                               |

As follows from the presented results, the fifteen most severe storms in the region have a security of 2–20 %. The average direction of the approach of the waves to the coastline along these 15 storms...
is 222 degrees. Moreover, the average direction of approach of the waves of the four strongest storms is 216 degrees with deviations of only 1–2 degrees in this group. Thus, we can conclude that the highest waves approaching the sea border of the Imereti coast, taking into account its exposure, are mainly frontal.

Testing the results of calculations based on field observations is possible only with the use of measurement results in other areas. Directly in the coastal zone of Imeretinka, such measurements were not carried out.

The eastern section of the shore of Imereti Bay from the river. Mzymta to metro Konstantinovsky has an extremely complex relief of the underwater slope due to the presence of underwater canyons (Fig. 1). Canyon the New comes close to the shore, its edge is expressed in relief from depths of 7–8 m. The canyon bed is relatively straightforward. The front of the canyon has a width of about 400 m. According to repeated surveys, the edge of the canyon Novy moves towards the coast with an average speed of 1.0 m/year.

The waves above the underwater canyons can be focused, significantly increasing in height. At the same time, high and steep waves pass along the canyon channel to the shore, producing disastrous effects on structures and beaches. Thus, according to unconfirmed data from BBC News Europe, January 30, 2013, a record high wave with a height of 100 feet (about 30 m) was observed on the coast of Portugal. This wave was observed over the Nazare Canyon. At the same place in November 2011, a record wave of 78 feet (24 m) in height was recorded in the Guinness Book of Records. The effect of focusing waves over canyons is not described by the method of calculating wave refraction based on geometric optics.

Wave fields for the coastal zone of the Imereti Lowland were modeled by the SWAN model on unstructured meshes. The choice of unstructured grids for calculating coastal wave fields was made because of the need for a more detailed resolution of the numerical grid (about 6 m) in the coastline area, which made it possible to more accurately take into account the influence of complex bathymetry of the region and to avoid interpolation errors in further calculations of hydrodynamic models.

Storm scenarios were calculated for 5 years from 1983 to 1987, as well as 3 large storms – December 1989, January 1993 (maximum for a 30-year period) and November 2007. At the sea boundary of the computational grid, wave spectra obtained from calculations on grid No. 2 of Sochi. The calculated wave characteristics at the outer boundary of the detailed computational grid of the coastal zone were used to calculate wave fields in the coastal zone with a detailed description of the HWAVE refractive-diffraction model, which is based on the monochromatic or spectral version on the hyperbolic approximation of the gentle slope equation [9–15]. Figure 2 shows the wave field off the coast of the Imereti Lowland, calculated respectively by the spectral version of the HWAVE model during periods of maximum storm in December 2009.

![Figure 1. Bathymetric plan of the underwater coastal slope for the eastern section of the coastal zone of Imeretinka (with canyons)](image-url)
Figure 2. Field of significant wave heights near the Imereti coast during the storm maximum period 12.2009 calculated by the HWAVE_S model (incident wave H = 3.03 m, T = 9.22 s).

The calculation results indicate a more pronounced zone focusing and divergence in the wave field than follow from similar calculations SWAN model due to rugged terrain of the coastal area of Imeretinskaya lowland.

In order to further verify the calculated wave characteristics for the coast of the Imereti Lowland, in the shallow basin of the laboratory of MGSU Research Laboratory Of Offshore Oil And Gas Industrial Facilities, physical modeling of the waves was performed in the selected hazardous areas of the shore protection dam design (Fig. 3). Simulation scale 1: 25.

The wave heights during the experiments were measured at several points along the coastal profile. The measurement results were compared with mathematical modeling of wave transformation.

The transformation of waves on slopes for modeling model studies was simulated using a nonlinear numerical model based on the Boussinesq-Zheleznyak-Pelinovsky (Serre) equations with special additives [10]. An example of calculating the transformation of waves on a model coastal slope is shown in Fig. 4. Statistical processing of measurement and calculation data was carried out, and a regression dependence of the measured and calculated wave heights was constructed. Correlation coefficient of measured and calculated wave heights: R = 0.985, which indicates a very good agreement between the results of physical and numerical modeling.

Figure 3. A model of a section of the shore of the Imereti Lowland under the influence of waves in the MGSU basin.

Figure 4. An example of mathematical modeling of wave transformation on the coastal slope of a physical model.
3. Verification of the results of numerical simulation

Another important task of hybrid modeling technology is to verify the results of numerical simulations by comparing them with field and laboratory measurements. This issue is considered on the example of modeling the wave regime and lithodynamic processes for the design of port hydraulic structures of the Terminal for liquefied natural gas and stable gas condensate "Utrenny", seaport of Sabetta.

The location of the designed Terminal is the eastern coast of the Ob Bay, south of Cape Halcyneisal, between the mouths of the Haltsanayakh and Nyadayngcho rivers. Figure 5 shows the red layout of the Layout option of the Remote terminal, orange – the boundaries of the simulation area (Projection UTM43, EPSG: 32643).

Modeling was carried out for 3 layout options of the Terminal, characterized by the presence and configuration of the protective structures, as well as the number of berths and the size of the approach channel.

The simulation technology used includes the following steps.

At the initial stage of the work, the calculations were carried out using the SWAN model, version 40.85, then the calculation was based on the later version of SWAN 41. 10AB. Since the beginning of the century, the SWAN model has been used as a tool for calculating coastal wave fields (for example, [7]). The model is based on the equation of the balance of the density of the wave action (or the balance of energy conservation, in the absence of flows) with sources and sinks. The model describes the generation, propagation, refraction, diffraction, reflection and passage of waves through flooded obstacles.

![Figure 5. Map of the Ob Bay with the layout scheme of the Terminal](image.png)

The ARTEMIS model [16, 17] is based on an extended version of the equation for the gentle slopes of the UPS [10], which, along with the originally incorporated capabilities for calculating the transformation of waves in the coastal zone, taking into account refractive and diffraction processes, adds the ability to calculate the influence of dissipation, due to bottom friction and destruction of waves in the coastal zone. In the ARTEMIS code, the equations of gentle slopes are solved numerically by the finite element method using a parallel computing algorithm.

Three time scenarios were calculated for verification – August and September 2012, September 17, 2015 – October 18, 2015, and July 10, 2016 – July 27, 2016. For the first period, the calculated heights and directions of the waves were compared with those measured near the Sabetta and Nord points (Fig. 6-a). For the second and third periods, a comparison was made with measurements of two wave-measuring buoys in the area of the Terminal (Fig. 6-b)

The results of comparing the measured and calculated wave heights show relatively high values of the correlation coefficient of these values in the range 0.87–0.90 and low values of standard deviations (SD) – 0.21–0.25 for Sabetta and Nord stations.
The results of comparing the measured and calculated periods of significant waves give the values of the correlation coefficients for these values of 0.67–0.73 and the values of standard deviations (VSD), about 0.8 sec. Moreover, the calculation results somewhat overestimate the wave periods, the characteristic period of high waves, about 5 seconds.

To verify the ARTEMIS wave model, a numerical simulation of wave fields was performed for the conditions of physical modeling of the port in the East Bay of the Sea of Japan. Physical modeling of wave propagation in the port water area was carried out in the wave pool of the “GS” Research Laboratory for sections in the area of the East and West breakwaters. A schematic representation of the plan of the port model in the wave basin is shown in Fig. 7.

The results of comparing the measured and calculated values of the wave heights shows a high value of the correlation coefficient of the data (0.94). However, in this case, the values of the waves obtained by numerical simulation were averaged in a circle with a radius of about a quarter of the wavelength centered at the control point. This allowed to reduce the effect of partially standing waves forming in the port water area as a result of multiple reflection [9].

As part of the development of a mathematical model of waves for the three options for arranging port facilities and presetting the model, a 3-directional wave was selected with a frequency of 1 time per 100 years, 1 % coverage, the parameters of which were obtained from the initial statistical processing of a 30-year period of extreme waves. Azimuth of wave 270 °, wave period 7.03 s, wave height 3.57 m.

To obtain wave distributions of varying repeatability and security in the water area of the Terminal, the SWAN spectral model calculates the parameters of extreme wind waves over a 30-year period, on the approach to the Terminal facilities.
To calculate the wave mode in the water area of the Terminal, the ARTEMIS wave model was chosen [16]. It describes the reflection of waves and allows you to enter different reflection coefficients at the border areas of the computational domain corresponding to port structures of various types.

4. Conclusion
When designing modern offshore hydraulic structures to determine the main external wave load, it is necessary to apply the technology of hybrid modeling. The technology includes the use of numerical wave modeling for the design area, as well as verification of calculation results using data from field observations and experimental laboratory studies. This approach allows us to ensure reliable determination of the characteristics of loads and impacts at the level of modern scientific research and is used in modern specialized scientific centers [18–22]. Details of hybrid modeling technology require further research.

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