NUMERICAL AND PHYSICAL MODELLING OF THE WAVE EFFECT ON THE PORT AND COASTAL PROTECTION STRUCTURES

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ABSTRACT

Waves parameters in water area of a projected port are normally obtained by the physical and numerical modeling.The physical modeling allows to define the structural details of the port's facilities and provides with the information for an appropriate numerical model selection.The nearshore hydrodynamic fields are produced by the nonlinear interactions of the shoaling waves of different time scales and currents. To simulate the wind wave propagated to the coasts, wave generated nearshore currents, nonlinear-dispersive wave transformation and wave diffraction in interaction with coastaland port structure, sedimenttransport and coastal erosion, the chains of the models should be used. The open source models WaveWatch III and SWAN has been used to simulate wave statistics of the dedicated areas of the studied coastal areas in high resolution to calculate the statistical parameters of the extreme wave approaching coastal zone construction in accordance with coastal engineering standards.

The problems this approach creates are shown in the case study of the projected port in Vostok (East) Bay, Sea of Japan. Experimental study of waves propagation in the port water area were carried out in the wave basin. The port area was reproduced at the scale of 1:50, and the modeling was conducted under the Froude number similarity. Experimental results are provided for the study of the wave propagation in the port model from the effects of the waves of 5% of exceedance.To confirm the results of the laboratory experiments four relevant mathematical models were used, one of them is the ARTEMIS model which is based on gentle slopes equations. Heights of numerically modeled waves in the control points were compared with the waves measured by the sensors-wave gauges. Calculated values at the control point and minimum and maximum values in a circular neighborhood with the radius of 30 m (1/4 of the average wavelength of 120 m) were compared with the results of the experiments.The proposed approach allows to compare the results of physical modeling with the results of numerical modeling and select the appropriate numerical model based on the results of the comparison.

KEWORDS: numerical modelling, coastal engineering, chain of models, portarea waves, experiments and numerical modelling, method of comparison, standing waves

1. INTRODUCTION

Verification of the developed mathematical model with the help of the available data, as well as the data obtained by special measurements, allows to determine the adequacy of the developed model of waves and currents.

The technology of modeling and verification of models of waves and currents is presented. Brief descriptions of SWAN, ARTEMIS and COASTOX models are given.

Further detailed description of the structure of the interactive model of wind waves and currents, information flows between its three calculation modules based on models SWAN, ARTEMIS and COASTOX, types of input information, specified interactive mode.

Projected marine terminal is to be designed for shipping of finished/refined product and for receiving of crude oil. Mooring facilities are located in the Vostok Bay, Sea of Japan. The Vostok Bay is a part of the southeast side of the Peter the Great Bay and intrudes to the land for 7.3 km approximately. The distance between capes is about 5.8 km and the area of the water table is 38 sq. km with the length of the shoreline of about 29 km. The open part of the Vostok Bay faces the south-southwest direction.

The moorings disposition inside of the bay allows for designing the protection structures from the waves approaching only from the south and west. The layout of the breakwater and the moorings is shown in Figure 1.

The projected marine terminal is designed for procuring of a new refinery with the capacity of 30 million tons per year. The refinery is not built yet and the time of the construction is not yet set up.

Laboratory and numerical studies of the waves at the port water area were conducted to verify the effectiveness of the breakwater in providing of acceptable waves parameters at the moorings

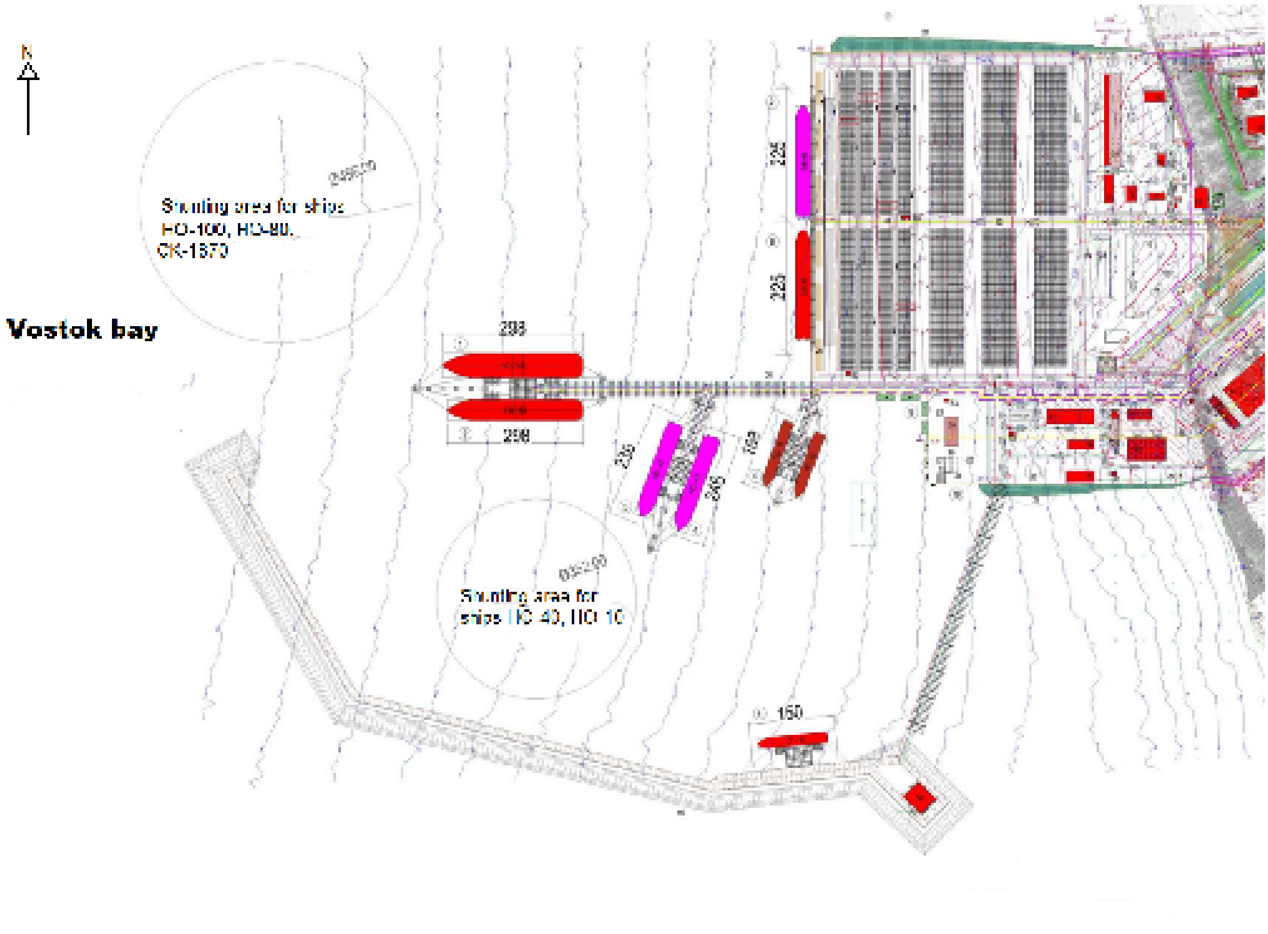

Figure 1. *Marine Terminal Layout. Dimensions are in meters*

2. SIMULATION TECHNOLOGIES OF WAVES AND CURRENTS

The developed interactive model includes as the main modules: the freely distributed model of calculation of wind waves of SWAN, refractive-diffraction model with open source code ARTEMIS, based on the equations of gentle slopes, 2-D model COASTOX_UN of currents calculation based on numerical solution of non-linear equations of shallow water on unstructured triangular grid. Statistical processing of calculation results is carried out in accordance with modern approaches to the statistics of extreme hydrometeorological phenomena.

2.1. SWAN Spectral Model

SWAN model of the Technical University of Delft (Denmark) [1, 2], distributed in open codes, in the last decade has become generally accepted in the world practice in coastal engineering the tool for calculation of transformation of wind waves from zones deep to the coastal zone.

The model is based on the equation of the balance of the density of wave action (or the balance of wave energy in the absence of currents) with sources and drains [1, 2]. The model describes the following wave processes: wind wave generation; propagation of waves in variable depth; change of amplitude of a wave, as a result of changes of depth and current; refraction, due to changes in depth and current; diffraction; blocking and reflection of waves in opposite directional currents; passing waves through flooded obstacles.

The model also considers the processes of wave generation by the wind and their dissipations: dissipation, caused by the collapse on deep water; dissipation caused by the collapse due to the change in depth; dissipation because of bottom friction; wave interaction on deep and shallow water.

At the initial stage of the work, the calculations were performed by SWAN, version 40.85, then the calculation was made on the basis of a later version of SWAN 41. 10AB. The results of calculations were practically not different for both these versions, for calculation points of the analyzed region.

SWAN model since the beginning of the century is increasingly used as a tool for calculating the wave fields of the coastal zone, in the systems of forecasting the wave mode and calculating the characteristics of waves in the engineering objects of the coastal zone (for example, [2-6]). An important step in the application of SWAN model in the Russia was the work, showed good results in comparison with measurements in calculating the regime characteristics of waves in the coastal zones of the Russian seas. SWAN model is used in the Arctic and Antarctic Research Institute as a calculation module for the coastal zone of the Arctic seas, integrated with the model AARI-PD2, as well as, in recent years, in Russian federal service for hydrometeorology and environmental monitoring it was introduced for the prediction of wind disturbance in the Black Sea with detailing in the offshore zones using SWAN.

The model was successfully applied by the MSUCE in many engineering projects of wave hydrodynamics of the coastal zone and tested according to the corresponding data of measurements. As an example of such projects, it is possible to specify: Port Taman, Port Gelendzhik, Port Belokamenka, etc.

The wide use of the SWAN model for the calculation of wave field formation of the coastal zone of the sea caused the choice of this model in comparison with other spectral regional models of wind waves as a tool of calculation wave mode in the Ob lip in the free-of-ice period.

2.2. ARTEMIS Refractive Diffraction Model

An open-source ARTEMIS model is included in the structure of the developed interactive mathematical model of wind waves and currents in the proposed construction for the calculation of wave fields at hydraulic facilities. Model ARTEMIS [7], based on an extended version of the gentle slopes equations [8], in which, along with the original features of the GSE calculation of the wave transformation in the coastal zone, considering the refractive-diffraction processes. It's also added the ability to calculate the impact of dissipation due to friction on the bottom and the destruction of waves in the coastal zone on the wave characteristics. In ARTEMIS code, the equations of gentle slopes are solved numerically by finite element method using parallel computation algorithm. The model is a part of the program complex of calculating the tasks of wave hydrodynamics TELEMAC [9], the version in open codes of which is called TELEMAC-MASCARET [10].

Models based on different versions of the GSE are widely used in engineering tasks of calculating wave characteristics in ports and near offshore hydraulic structures. From many such models we note here only the most frequently used in engineering projects, along with ARTEMIS, the model EMS: Elliptic Mild Slope Wave Module Popular commercial complex of settlement programs of marine hydraulics MIKE-21 [11, 12].

The choice of ARTEMIS as one of the three components of the computational interactive model developed in this project, along with its status as a freely distributed model, is also due to: the successful ARTEMIS testing for a large number of projects for seaports, for example [13-15], and also a set of test calculations, which in comparison with measurement data is presented in model documentation; availability of both the version for regular waves and the spectral version of the model; modern numerical implementation of the model on the unstructured calculation grid, which provides the necessary detail of the wave fields in the calculation areas; effective paralleling algorithm, allowing to significantly reduce the time of calculations when using both multiprocessor and multi-core computer systems; user-friendly interface.

The ARTEMIS model was successfully applied by the MSUCE in many engineering projects of the wave hydrodynamics of the coastal zone of the sea and tested according to the corresponding data of measurements [15]. In the interactive model being developed, the wave characteristics are calculated on the approach by the SWAN model and, then, the mode characteristics of the waves at the entrance to the port are transferred to the more detailed in the coastal zone of the ARTEMIS model grid.

2.3. 2-D Model of Currents Calculation COASTOX

COASTOX [16, 17] using the approximation of shallow water describes the fields of coastal currents generated by the joint influence of wind, gradient currents of the deep sea, tides and wind waves. Numerical solution of the model equations is constructed by the method of finite volumes on unstructured triangular grids. The form of the two-dimensional equations of shallow water includes members describing the effects of bottom friction, wave radiation stresses, horizontal turbulent mixing. Due to the universal structure of equations, they can, except coastal currents, under corresponding boundary conditions and the disconnected module of wave radiation stresses, to describe various wave processes: currents in rivers, transformation of tidal waves, storm surges, tsunami waves. Algorithms of parallelization calculations, on multiprocessor and/or multi-core systems are realized.

The model was used in many engineering tasks to calculate the coastal fields of currents. The conducted comparisons showed its good accuracy and stability of the used computational algorithm, for complex bathymetry and coastal outlines, in comparison with widely used in the world practice programs of numerical solution of shallow water equation on unstructured grids such as Mike-11 of the Danish Institute "DHI" [18], ADCIRC USA [19, 20], CMS-Flow Corps of Engineers of the U.S. Army [21].

The choice of the COASTOX model in the version implemented on unstructured grids is due to the ability of the authors of the model to adapt it effectively to the interactive model being developed, while the model of the modules describing the physical processes and the level of numerical realization (the use of algorithms of parallel calculations on unstructured grids) is not inferior to the most known software complexes of two-dimensional modelling of sea currents noted above.

The results of calculations, obtained, with the help of models SWAN and COASTOX, adapted for the calculation of waves and currents in Ob lip, in comparison with the data of measurements in the region are presented. and results of prediction of wave fields of different repeatability on the structures water area with the help of ARTEMIS model.

3. NUMERICAL AND EXPERIMENTAL STUDY

To study the waves propagation the physical model of the water area of the port was built in the wave basin of the Moscow State National Research University of Civil Engineering (MSCEU). The study program was developed to investigate the distribution of 5% exceedance South and Southwest waves at the port water area and their impact on the eastern and western sides of the breakwater.

The scale of the model of 1:50 was determined based on the water basin size of 27×27 m, actual size of the port water area, distance from the wave generator to the entrance to the port, depth of the basin, prevailing wave direction, and the correspondence of wave processes in nature and in the model as per Froude's similarity criteria.

Four series of experiments were conducted to study South and Southwest waves impact on the eastern and western sides of the breakwater.

At the eastern side of the breakwater, the experiments were conducted for South waves with parameters of $T = 12.3$ s and $h_{5\%} = 5$ m and for Southwest waves with the parameters of $T = 10.4$ s and $h_{5\%} = 5$ m. The modeling parameters were estimated as $T = 1.74$ s, $h_{5\%} = 10$ cm, and $T = 1.5$ s, $h_{5\%} = 10.0$ cm, correspondingly.

At the western side of the breakwater, the experiments were conducted for South waves with parameters of $T = 12.3$ s, $h_{5\%} = 8.5$ m, and for Southwest waves with the parameters of $T = 10.4$ s, $h_{5\%} = 7.2$ m. The modeling parameters were estimated as $T = 1.74$ s, $h_{5\%} = 17$ cm and $T = 1.47$ s, $h_{5\%} = 14.4$ cm, correspondingly.

The description of the study and the results of the physical and numerical experiments related to South waves with the diffraction on the western side of the breakwater is provided below.

The locations of wave sensors and the wave generator in the wave basin is shown in Figure 2.

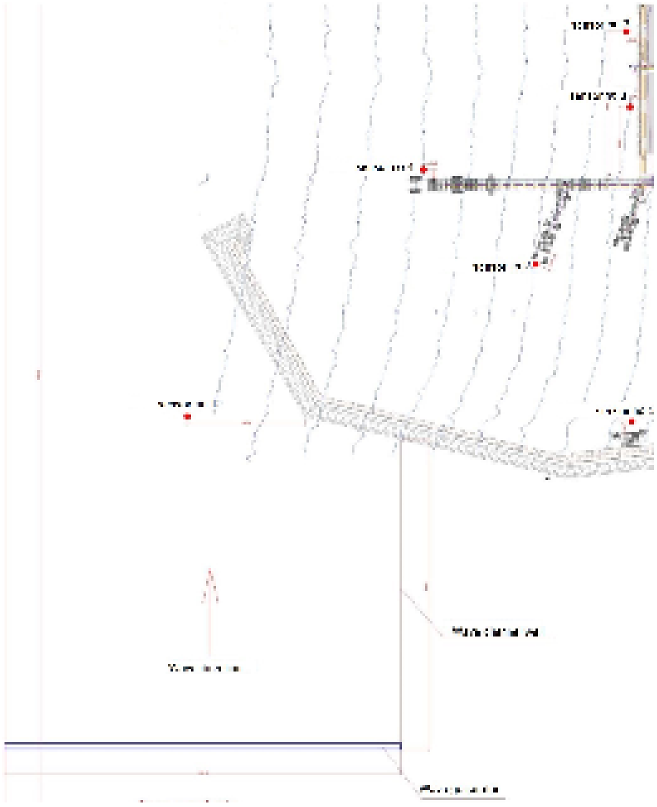

Figure 2. *Marine Terminal Model Layout with the Wave Sensors and Wave Generator Locations. South Waves Impact on the Western Side of the Breakwater Study*

Different numerical model are used for the calculation of shallow waves and waves at the water area of water ports. The spectral model SWAN [1] is worldwide used, and it is an open code.

The model is based on the wave action density balance equation (or conservation of energy under no ambient currents condition) with the source and sink terms. The model can be used in Cartesian or spherical coordinates depending on the scale of applications. Diffraction processes are described approximately and can't provide detailed wave field solution for wave interactions with hydrotechnical structures.

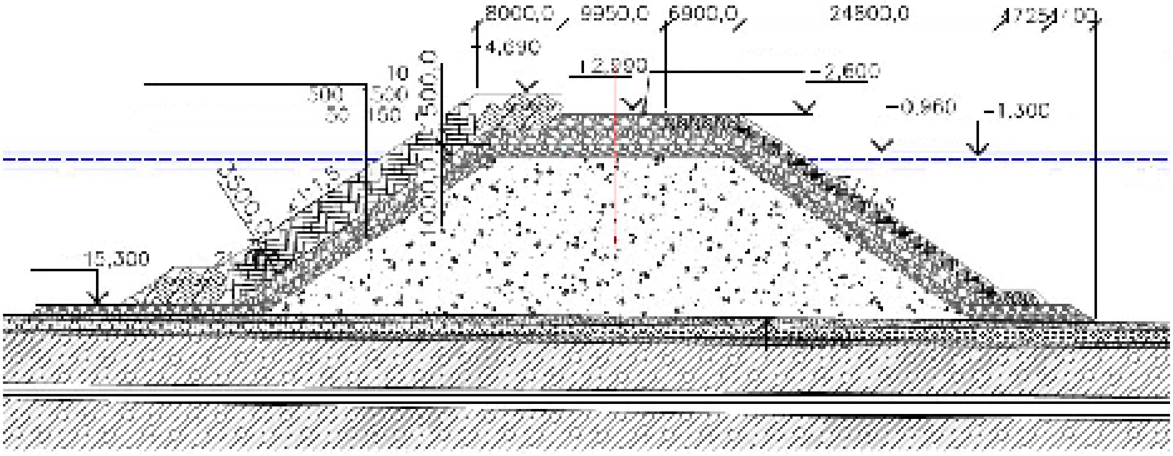

Figure 3. *Cross section of the protected breakwater, slope type. The horizontal sizes are in millimeters, the vertical levels shown in meters, Baltic System*

The results of the physical modeling were compared with the results of the numerical modeling conducted by the using of the ARTEMIS software. Software ARTEMIS is based on the gentle slope hydrodynamic equations [8]. The software solves the waves transformation in coastal zones including the processes of refraction-diffraction, bottom friction energy dissipation and breaking of waves. The finite element numerical method is utilized to solve the elliptic equations. ARTEMIS is successfully used for similar studies [15, 16, 22]. It is an open source software and can be found on the website http://www.opentelemac.org/[9].

The bathymetric map of the Sea of Japan, Peter the Great Bay and Vostok Bay, with the scale of 1:25000 obtained by the echo-sounder survey was digitized and used for the numerical modeling. The port's structures were included into the digitized map.

Waves interaction with the different types of structures were considered by introduction of the reflection coefficients along the structure's boundaries. The reflection coefficient of kr=0.9 was used for the vertical structures and for the side slopes of the wave canal. The reflection coefficient of 0.5 was used for the slopes of the structures protected by armor berm.

Two types of the breakwater were considered. Main type was a wave impermeable structure with a revetment slope. An alternative type was a structure with wave permeable central part that allows some waves to get to the water area of the port.

The revetment slope was designed with three layers of protection: the bottom layer made of stones with weights from 50 to 150 kg was overlayed by the layer made of stones from 500 to 1500 kg, and the top layer was made of shaped concrete units (hexabits) with weight of 10 tones.

To obtain the reflection coefficients the laboratory experiments of incoming and passing waves were conducted in a wave flume and wave's parameters were recorded. The example the setup of a pier with piles and a surge plate (wave deflector to reduce wave overtopping) in the wave flume is presented in Figure 4.

The bathymetry of the calculation domain for the study of the western side of the breakwater and South waves is shown in Figure 4.

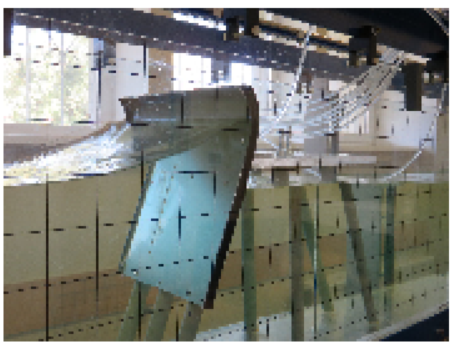

Figure 4. *Experiment Setup for Complex Structures Reflection Coefficients Estimation*

ARTEMIS numerical grids were built in accordance with the numerical modeling requirements. It means that there should be no less than grid's 7 nodes for the wave length. The grids were built for the monochromatic wave with the period of 7 sec and for the number of nodes of 10. The mesh sizes changed from 2 m for shallow water to 8 m for deep water. The size of grids were as following: for the study of the eastern side of the breakwater and South waves the number of nodes were 87959 and the number of elements were 174018; for study of the eastern side of the breakwater and Southwest waves the number of nodes were 88969 and the number of elements were 175945; for the study of the western side of the breakwater and South waves the number of nodes were 81581 and elements were 161487; for study of the western side of the breakwater and Southwest waves the number of nodes were 51317 and the number of elements were 101413.

The bathymetry of the calculation domain for the study of the western side of the breakwater and South waves is shown in Figure 5.

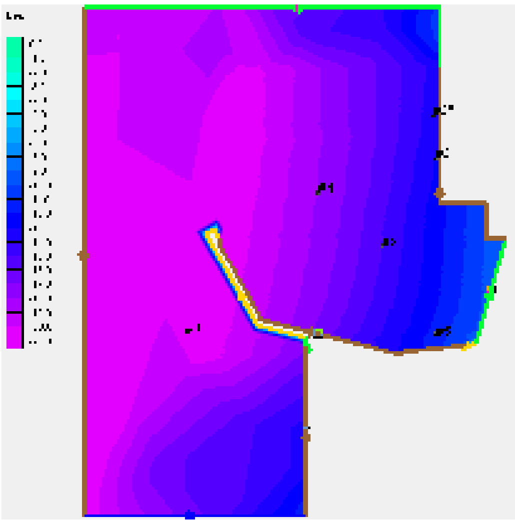

Figure 5. *Modeling Domain of the Study of South Waves Impact on the Western Side of the Breakwater. The wave-generating boundary is drawn blue. The free boundaries are drawn green. The other boundaries are reflecting boundaries with kr = 0.9 (brown), kr = 0.5 (yellow). The control locations 1, 2, 3, 3', 4 and 5 correspond to the locations of the wave sensors in the physical modeling*

The waves parameters generated by the wave generator in physical modeling for the South waves were T = 1.74 s and $h_{5\%}$ = 17.0 cm at the sensor's location 1 (entrance to the port). The corresponding parameters in the numerical modeling were T = 12,3 s, $h_{5\%}$ = 8,5 м, and the values were assigned to the wave generating boundary (Figure 5). The location of the wave-generating boundary in the numerical model corresponds to the location of the wave generator in the physical model.

The results of the numerical modeling of the wave fields are presented on Figures 6 and 7.

4. COMPARISON

General pictures of the wave fields recorded in physical modeling are similar to the obtained in numerical modeling. The numerical modeling exhibits the same diffraction and turn of the wave front at the breakwater head and propagation of the wave further to the diffraction area of the port (Figure 6). The general view of the wave field of the physical model is shown on Figure 8.

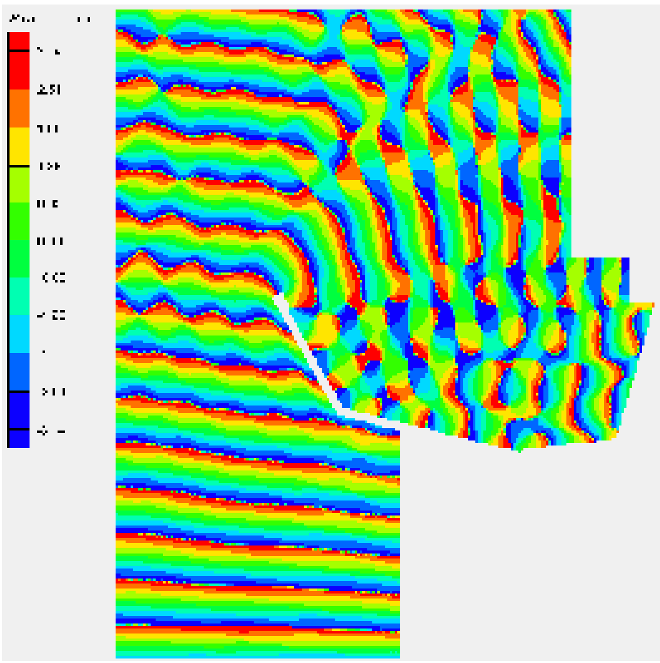

Figure 6. *Calculated Waves Phases for the Physical Model of the Port Water Area for the Study of South Waves Impact on the Western Side of the Breakwater*

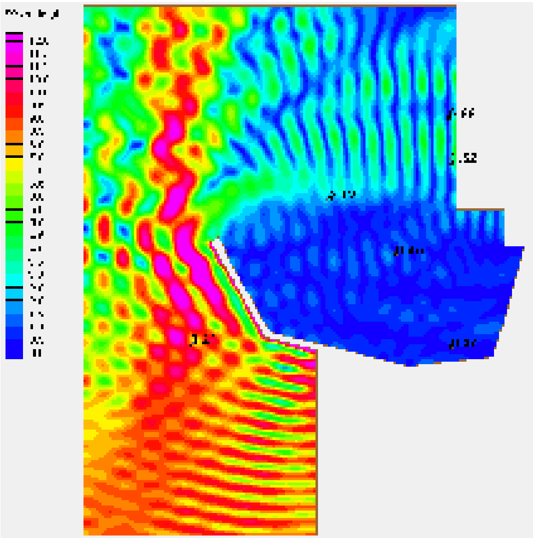

Figure 7. *Calculated Wave Heights for the Physical Model of the Port Water Area for the Study of South Waves Impact on the Western Side of the Breakwater. Wave heights are shown in colors and in numbers at the control locations*

Figure 8. *General View of the Wave Field Generated by South Waves during the Physical Modeling*

The waves heights obtained during the physical modeling and converted to the natural values are summarized in Table 1. The results of the numerical modeling are also presented in Table 1.

Table 1. Wave heights obtained by the ARTEMIS model and recorded during the physical modeling for the study of the South waves impact on the western side of the breakwater. The min and max values of the calculated heights are the calculated values inside of the circle with the radius of 30 m with the center at the sensor location

Control location	Measured wave height, m	Water depth (physical model), m	Calculated wave height, m			Water depth (numerical model), m
			Control point	min	max	
1	8.5	22	8.21	7.00	10.02	20.59
2	1.01	15	0.45	0.02	1.67	14.99
3	0.74	13	2.32	0.21	4.45	13.00
3'	0.94	13.5	0.99	0.23	3.9	13.47
4	1.61	18	2.12	1.28	2.78	18.00
5	0.62	11.5	0.37	0.22	0.69	11.39

Calculated waves heights at the sensor locations 1, 3’ and 4 are similar to the measured, but at the sensor locations 2, 3, and 5 they are somewhat different from the measured. Nevertheless, all obtained results fall to the interval from minimum to maximum calculated values, inside of 30 m radius with the centers at the sensors locations.

The graphical representation of the calculated and measured values is shown in Figure 9.

One of the reasons for the difference between the wave heights, measured and calculated, can be that the wave field for the monochromatic wave is significantly inhomogeneous and shows the changes in series of maximums and minimums. As the results of the many times waves reflections and interferences, the partial standing waves occur at the port water area. Thus, the significant changes in the wave heights at the control location can be observed.

Correspondingly, in spite of the similarity of the wave fields of physical and numerical modeling, the small offset of the minimums and maximums can lead to the significantly different result at the control location. However, within the definite distance from the control locations the calculated heights close to the measured can be found. Therefore, to compare the results, the calculated values within the radius of 30 m or the ¼ of the average wave length of 120 m were considered and shown in Table 1. The results of the measured values reside in the minimum maximum interval for all control locations. The same method of comparison of the calculated and measured results was applied to the other three studies, and the same trend has been observed

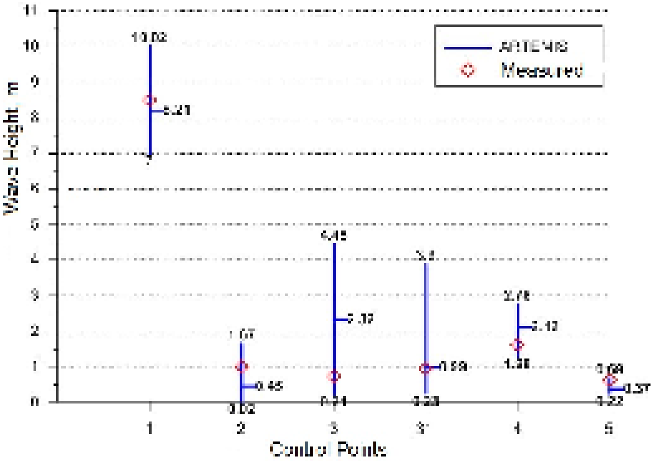

Figure 9. *Wave Heights Measured and Calculated. Study of South Waves Impact on the Western Side of the Breakwater*

5. CONCLUSIONS

The developed mathematical model of waves and currents can be used for the solution of such problems as: determination of the calculated parameters of waves in berthing structures for providing safe conditions of mooring of vessels; determination of the calculated parameters of the waves at the structures for the design of structures (elevation of crests, wave loads, etc.); determination of current fields for prediction of sediment transfer, assessment of the port water area, navigation channels, local washouts at the structures.

When compare the results of the physical and numerical modeling of the wave field at the port water area the phenomenon of the formation of the partial standing waves with different intensities at different locations should be considered. In case of the partial standing waves occurrence, the calculated and measured heights of waves at the corresponding locations can be significantly different. It is recommended to compare the calculated results with the measured results within the radius of the ¼ of the average wave length from the location where waves were measured. The calculated maximum and minimum wave heights within the radius and calculated wave height at the control location should be used for comparison with the measured result at the control location.

The approach of comparison of the results has been used for the study of waves at the water area of the projected oil-tanker port at the Vostok Bay, the Sea of Japan. The approach also allows to determine the use of the numerical model of waves diffraction.

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