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INTERACTION OF SEA GRAVITY WAVES WITH PORT PROTECTION STRUCTURES IN NUMERICAL MODELS

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Abstract. The paper is dedicated to numerical modeling of interaction of sea wind waves with port protective structures. A classification of existing numerical wave models is presented depending on their accuracy and demands on computing power. The main studied effect of the interaction of waves with port protective structures is diffraction of waves in protected water area. In this paper is studied a test case with conservative wave diffraction – two converging breakwaters on a flat bottom with varying of entrance width and approaching waves period. The test case was physically modeled in a wave basin, as well as numerically modeled using the Boussinesq wave model implemented in the MIKE 21 software. As part of setting up the numerical model, the most correct way to model protective structures on the numerical model is proposed and justified – with rejection of wall enclosing sponge layers from entrance section side and with gradual decrease of sponge coefficients towards entrance section. Satisfactory agreement was obtained with a spread of values 10-15% as a result of results comparing of numerical and physical modeling. This made it possible to conclude that the proposed method for protective structures modeling allows to correctly calculate diffraction of waves in protected water area, and the wave model used can be considered verified by results of physical experiments.

Keywords: numerical modeling, wind waves, sea waves, gravity waves, diffraction, breakwaters, sea port, MIKE 21

ЧИСЛЕННАЯ РЕАЛИЗАЦИЯ ВЗАИМОДЕЙСТВИЯ ГРАВИТАЦИОННЫХ ВОЛН С ОГРАДИТЕЛЬНЫМИ СООРУЖЕНИЯМИ МОРСКОГО ПОРТА

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Аннотация. Работа посвящена методу численного моделирования взаимодействия морских ветровых волн с оградительными сооружениями морского порта. Представлена классификация существующих численных волновых моделей в зависимости от их точности и требованиям к вычислительной мощности компьютера. В статье основным исследуемым эффектом взаимодействия волн с гидротехническими сооружениями порта является дифракция волн на защищаемой акватории. Для ее консервативного исследования в работе используется тестовая задача – два сходящихся оградительных сооружения на плоском дне с варьированием шириной входного створа и периодом подходящих волн. Тестовая задача физически смоделирована в волновом бассейне, а также численно с помощью волновой модели Буссинеска, реализованной в ПК MIKE 21. В рамках настройки численной модели предложен и обоснован наиболее корректный способ воспроизведения оградительных сооружений на численной модели – с отказом от ограждающей поглощающие слои стенки со стороны входного створа и постепенным уменьшением коэффициентов поглощения к входному створу. В результате сравнения результатов численного и физического моделирования получено удовлетворительное совпадение с разбросом значений 10-15%. Это позволило сделать вывод о том, что предложенный способ реализации оградительных сооружений позволяет корректно рассчитать дифракцию волн на защищаемой акватории, а используемую волновую модель считать верифицированной результатами физических экспериментов.

Ключевые слова: численное моделирование, ветровые волны, морские волны, гравитационные волны, дифракция, оградительные сооружения, морской порт, MIKE 21

INTRODUCTION

A large-scale work on the reconstruction and construction of maritime transport infrastructure is going in Russia. According to the development program of the Ministry of Transport of Russia, the total capacity of seaports should increase by 25% [1,2] in 2035. One of the important tasks that arises in the implementation of a seaport project is forecasting the development of wind waves in a water area. The height marks of port's hydraulic structures, the possibility and safety of ship processing and servicing, as well as the stability of individual elements of hydraulic structures or, less often, the supporting structures, depend on the parameters of wind waves. Overestimation of the parameters of wind waves can lead to unjustified construction costs. Underestimation causes difficulties in the operation of port for its intended purpose [3].

To protect against storm wind waves, protective structures are installed along port water area perimeter. In gaps between these structures, navigation routes are laid for ships. At the same time, protective structures often become the most expensive objects of seaport due to the need to install them at great depths. Therefore, a top priority is to finding the optimal balance between the length of protective structures and the allowable downtime in the work of port due to excessive wind waves in the water area when performing a feasibility study of the project [4]. Wind waves arise at great depths under action of wind. They propagate to hydraulic structures, near which waves experience transformation processes such as diffraction behind the gap between protective structures, reflection from structures, refraction with decreasing depths in the water area. The final wave regime in port water area is the interference of coming, diffracted and reflected waves, which is schematically presented in Figure 1.

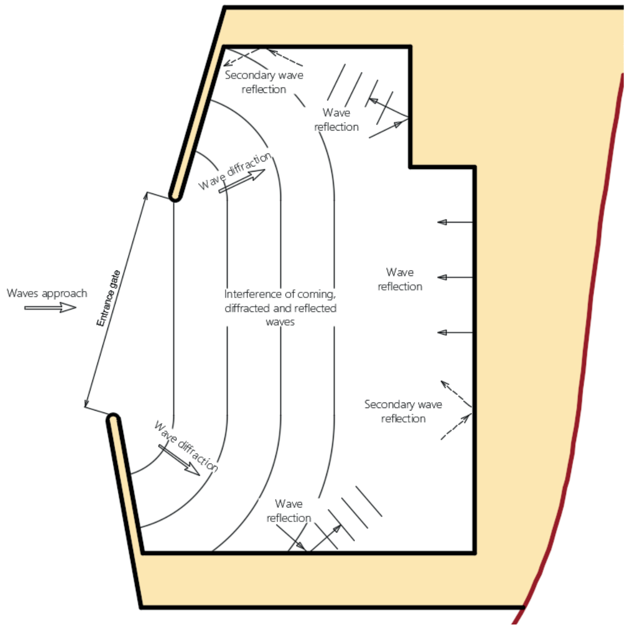

Figure 1. Transformation of wind waves and formation of a wave regime in the water area of seaport

The main process of wave transformation studied in this paper is diffraction. The diffraction means the phenomenon of wave rounding around obstacles, which occurs behind a gap between protective structures and is accompanied by a change in wave heights both up and down. The first methods for calculating diffraction in the water area of seaport were based on the linear theory of waves using the Young principles (energy transfer along the wave front) and Huygens-Fresnel principles (determining the shape of wave fronts). In the Russian scientific literature, the main attention was paid to the method for wave amplitude diffusion. This method was proposed by Malyuzhinets [5] for sea waves on the basis of studies on the diffraction of electromagnetic waves by Leontovich and Fock [6–8]. Further, it was developed by Zagryadskaya [9,10], Krylov et al [11]. In the works of Penny and Price [12], similar transformations were obtained based on the Sommerfeld method for calculating the diffraction of electromagnetic waves [13]. In the middle of the 20th century, the main attention was paid to the energy method for calculating diffraction, which was developed by Karaushev [14], Galenin [15], Krylov et al. [11], Zavyalov [16] and etc. This method subsequently became the basis of the normative calculation method. Besides, some problems of wave field diffraction allowed to solve the problem using methods based on the mild-slope equations [17, 18].

Currently, to determine the protection of port water area from wind waves, either simplified calculation methods presented in regulatory documents are used. Traditional physical modeling in specially equipped wave pools [19,20], or numerical modeling [21–23] are applied as well. Modern numerical wave models allow predicting the parameters of wind regime in port water area in various configurations and for various wave formation conditions with sufficient efficiency. The main disadvantages of numerical models are the limited applicability of some ones and the need to verify the model for each individual object due to the large number of calibration settings. Thus, although numerical methods are attractive to researchers due to their capabilities and relatively low labor costs, they require accuracy in application and at least partial verification of the results.

Today, there are a large number of numerical wave models designed to simulate the propagation of sea waves in certain conditions. There are some approaches to the systematization of wave models which are presented mainly by foreign authors [24,25]. However, the classifications presented in these papers contain gaps in the nomenclature of existing numerical models. And they can hardly be called final. This paper proposes a classification of existing numerical wave models. The classification is based on their accuracy and resource intensity.

In this study, the main attention is paid to one of the aspects of numerical modeling of the wind waves development in port water area. It is the reproduction of protective structures on a numerical model. The motivation for the study was the spread of the results of calculating wave diffraction in protected water area of port, depending on the method of implementing the head of a protective structure in a computational finite element mesh. Such nuances of numerical simulation strongly affect on the results of diffraction calculation, on the basis of which conclusions are drawn about the protection of port water area and, accordingly, decisions are made about the need for additional costs for the development of the port's protective structures. This makes such studies relevant.

MATERIALS AND METHODS

Classification of numerical waves models

Currently, various numerical wave models are available to simulate the propagation of wind waves both in extensive water areas of the oceans and seas, and in small local water areas of seaports. All of them have their advantages and disadvantages, as well as some restrictions. In the paper, several generalized classes of the most common wave models have been considered.

Spectral wave models based on the law of conservation of wave action solve the wave energy balance equations in the spectral representation and describe the transfer of wave energy in time and space. This class of models is the least demanding on the computing power. Therefore, that is often used to simulate the development of wind waves in vast water areas. Spectral models account all the features of wave generation, their propagation and dissipation. However, this do not consider the phases of individual waves, which makes them inapplicable for accurate calculation, for example, diffraction or reflection of waves near hydraulic structures. Recently, spectral wave models began to include an approximate method for calculating wave diffraction, based on the mild-slope equation obtained at first in the paper [26]. Nevertheless, the use of spectral models has become established in modeling the development of waves in extensive water areas in order to determine the parameters of waves on the way to port. After that, these results are used as boundary conditions for more accurate models, in which the wave regime is modeled already in port water area.

Wave models based on mild-slope equations are often used directly to simulate the penetration of waves into protected water areas. The use of mild-slope equations, supplemented by the principles of linear wave theory, allows considering of this class of models as quite economical in terms of computing power requirements. The disadvantage of these models is the regular approximation of the simulated waves. As well as those do not allow simulation of the nonlinear waves or the nonlinear interactions between them.

Wave models based on Boussinesq equation are distinguished, first of all, by a more accurate approximation of the distribution of orbital velocities over depth, as well as the possibility of calculating nonlinear effects of wave formation on the free surface of water (for example, wave breaking). The equations, on which this class of models is based, allow to use the frequency and angular distribution of waves by introducing a higher-order dispersion term into the equations. In addition, the Boussinesq equations are also obtained in terms of velocity near the free surface, near the bottom, and at an arbitrary depth [27]. Due to this, models based on the Boussinesq equations are considered as the most flexible for simulation of various specific port areas. Thus, they have become most widespread in recent years.

Non-hydrostatic wave models account non-hydrostatic pressure when simulate sea waves. That allows to accurately simulate the distribution of current velocities and orbital velocities in depth. The basic equations of the model are written in three-dimensional form. That is, the vertical coordinate becomes part of the solution, and is not approximated by some conditions, as in models based on the mild-slope equations or the Boussinesq equations. A significant disadvantage of this class of models is the impossibility of simulating wave breaking. In addition, non-hydrostatic models already have significantly higher requirements for computer processing power, which also limits their application.

Free-surface wave models based on the Navier-Stokes equations are the most expensive in terms of resource consumption. However, they allow accurate modeling of nonlinear wave processes, including wave breaking. Today, this class of models remains practically inapplicable in engineering practice even for the smallest port water areas. These models assume the use of Reynolds-averaged Navier-Stokes equations using turbulent flow models to implement the convergence of the Navier-Stokes equations. Theoretically, the Navier-Stokes equations can also be solved explicitly, considering the turbulence of the flow, but this is still several orders of magnitude more computationally expensive due to the very small spatial and temporal discretization that must be used in this case.

In this paper, the classification of the above and some other classes of wave models according to the criteria "accuracy / required computing resources" was proposed. Figure 2 presents this classification.

The accuracy of the results obtained, which acts as the y-axis, is a debatable parameter in this case. It is based primarily on the number of wave formation and development factors accounted by the model. It should also be noted that some types of models (especially models based on the Boussinesq equations) include a fairly diverse subset of models. The differences between which can also be significant. Thus, the location of models on the chart corresponds to a certain average representation of the types of models relative to other types.

In this paper, a study on the penetration of sea wind waves into the protected water area of port has been performed. The numerical simulation presented in the paper is performed using a numerical wave model based on Boussinesq type equations and implemented in the software MIKE 21, in the module "Boussinesq Waves (BW)". Basic information about that is given in [28].

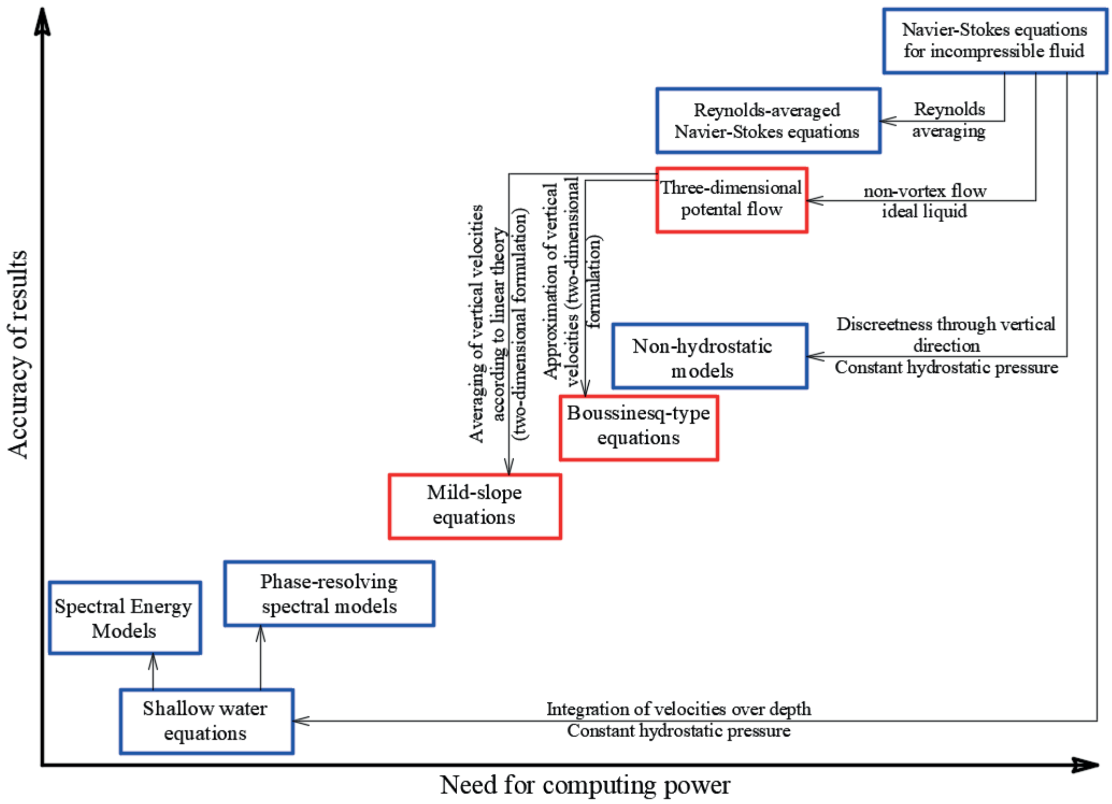

Figure 2. Classification of numerical wave models (models that consider only potential flow are highlighted in red)

Diffraction coefficient

To describe the diffraction pattern in port water area, a wave diffraction coefficient, k_d, which is a dimensionless parameter that characterizes the ratio of the heights of diffracted and approaching waves, is used:

$$k_d = \frac{h_d}{h}, \quad (1)$$

where h_d is the height of the diffracted waves; h is the height of the waves coming to seaport.

Formulation of the test problem

Studies of the diffraction of gravity waves in protected water area were carried out in a specially designed conditional port area, where wave diffraction is of decisive importance, and other effects of wave transformation can be neglected. The conditional port consists of two converging protective structures located on a flat bottom with a depth of 10 m. In total, two widths of the entrance section of 130 and 195 m are considered in the work. As well as five periods of waves coming in the water area are as follows 4.25; 5.65; 7.10; 8.50; and 9.90 s. Thus, within the framework of the study, 10 formulations of the wave diffraction problem were considered. A schematic representation of the test area is shown in Figure 3.

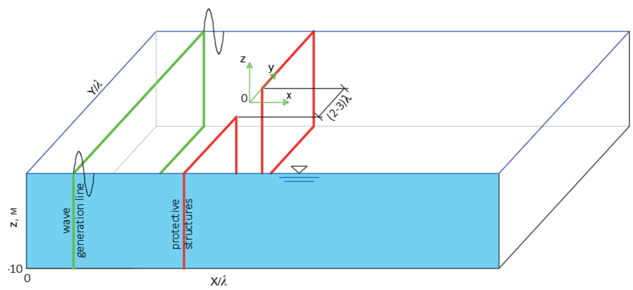

Figure 3. Schematic representation of the test area for wave diffraction studies

Numerical model settings

The first step in setting up a numerical wave model is traditionally the choice of the spatial and time step of the model. The spatial resolution (or linear dimensions of finite elements) and the time step are chosen in accordance with the so-called Courant number, which means a dimensionless quantity that determines the order of numerical convergence (or sensitivity) of the model. The "physical" meaning of the Courant number is that it determines the number of finite elements that the wave passes in one-time step, and the expression for it is written as follows:

$$Cr = c\frac{\Delta t}{\Delta x}, \qquad (2)$$

where $c = \sqrt{gd}$ is the wave propagation speed;
Δt is the time step;
Δx is the size of the finite element.
Satisfactory convergence of the numerical solution is achieved at Cr<1. Based on this condition and taking into account the initial waves, the mesh size was adopted of 2 m, and the time step was 0.14 s. The total simulation time in all models is assumed to be 30 min or 12860 steps. The maximum value of the Courant number was 0.69.
Another feature of numerical simulation is the assignment of boundary conditions on the contour of the model, as well as on some internal elements. For the numerical absorption of energy and wave height in the MIKE 21 BW model, the so-called "sponge" (or absorbing) layers (Sponge layers) proposed in [29] are implemented in the MIKE 21 BW model. They can be installed, for example, along the absorbing elements of the model (beaches) or along the boundaries of the model in order to prevent waves that go beyond the model from returning to the computational domain. Absorbing layers are selected cells of the computational mesh of finite elements, in which the conditions for the sponge coefficient are set, varying from 1 (no absorption) to 10 (maximum absorption). In this case, the numerical implementation of absorption is such that as the wave moves deeper into the absorbing layers, the sponge coefficients should gradually increase exponentially.

The main setting of the numerical model, which became the motivation for this study, was the choice of a method for implementing protective structures on the numerical model. The fact is that the recommendations given by the developers of the software used give dubious results. We mean the head of the protective structure, which was previously recommended to be reproduced, as shown in Figure 4.

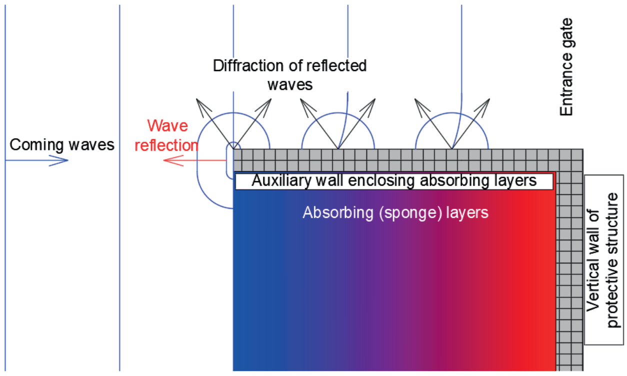

Figure 4. Scheme of the interaction of coming waves with an auxiliary wall enclosing absorbing layers

This option provides for the installation of a certain number of absorbing layers before the construction, which adsorb the energy of coming waves to prevent the development of secondary waves in the water area in front of the construction and in the entrance gate. From the side of the entrance gate, the absorbing layers are covered by a vertical wall, similar to the wall of the protective structure itself. Thus, a kind of channel is formed on the model in the entrance gate, bounded on two sides by walls. This way of implementing protective structures is proposed for use by the developers of the DHI MIKE 21 BW software package. However, it encounters several objections in terms of the correspondence of such a model to real conditions, which is discussed in more detail by the results of a test run of a series of experiments below.
As an alternative to the recommended option, the paper considered three additional options for the implementation of protective structures, shown in Figure 5. Here, option a) is

recommended. The second option (option b)) provides for the implementation of absorbing layers in front of the structure similar to option a), but without the construction of a wall perpendicular to the wall of the protective structure. The third option (option c)) was proposed rather to confirm the fundamental solution on the obligatory arrangement of absorbing layers in front of the structure and is a model of protective structures as close as possible to real conditions. The last option (option d)), as well as option b), provides for the rejection of the wall enclosing the sponge layers from the side of the entrance section, but with a different idea for the implementation of the absorbing layers themselves. It is proposed to gradually reduce the sponge coefficient as it approaches the head of the protective structure. Thus, it allows to avoid the interaction of waves passing through the alignment with layers of "rough" absorption of wave energy, as in the second variant.

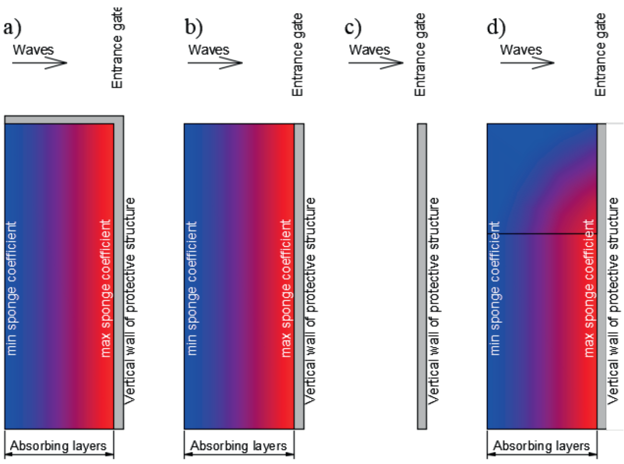

Figure 5. Schemes for the implementation of protective structures and absorbing layers in a numerical experiment

RESULTS

To validate the numerical simulation results, the wave regime was tested in the experimental water areas for all four expected options. Simulation results in the form of isofields of dimensionless diffraction coefficients are presented in Figure 6. The comparison of the results indicates a significant loss of diffraction coefficients and their dependence on a good specification of degree observations. The first considered variant with the formation of a certain entrance channel at the out-of-the-way section gives dubious results. High diffraction coefficients are found near the walls that protect the sponge layers from the inlet section, and a beating is detected in the inlet section itself. The physical meaning of that remains unclear. Most likely, this is the occurrence of behavior under the wave when it hits the auxiliary wall. The wave first diffracts on a single cell of the auxiliary tissue, and then develops, simultaneously being reflected from them and propagating towards the entrance target. Besides, a bending of the wave train is observed on the model of the nearby auxiliary wall in the direction of slowing down the motion of the wave fronts of the walls. Figure 4 presents the exemplary scheme of this mechanism.

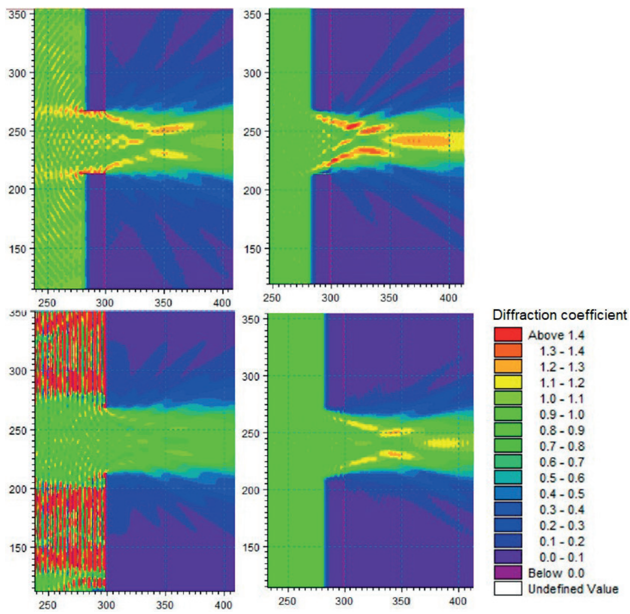

Figure 6. Isofields of diffraction coefficients obtained for different schemes for the implementation of protective structures in the numerical model (top left - option a); top right - b); bottom left - c); bottom right - d))

The above factors of interaction of waves with structures in option a) are the cause of the

appearance of a beat in the entrance section and can be considered a reason for abandoning such a scheme for the execution of protective structures.
Calculations according to option c) showed the instability of the model, which did not allow to complete the calculation correctly. At the same time, the obtained results on the distribution of diffraction coefficients in the enclosed water area are close to the accepted assumptions. Despite the high similarity of such a model with the real scheme of experiments, it is difficult to implement such a scheme with stable finding of solutions at each time step in practice.
The results of simulation for options b) and d) showed qualitatively similar results of the distribution of diffraction coefficients in the enclosed water area. The same positions of the extrema of the diffraction coefficients that propagate from the heads of the protective structures to the axis of the entrance section, and the field of large diffraction coefficients at some distance from the entrance section strictly in zone of light. In this case, the maximum diffraction coefficients observed in option b) are about 1.4; in option d) are about 1.2. That is, the quantitative difference in the results is more noticeable. The results obtained on the model in option b) are obviously subject to the influence of secondary waves reflected from layers with "coarse" sponge coefficients, which are considered as a structure with partial absorption / reflection of energy. Thus, at the contact surface of waves with cells with large sponge coefficients, which here, in contrast to option a), are not covered by an auxiliary wall, an interaction mechanism is observed similar to that considered in option a) and shown in Figure 4. In option d), this mechanism also takes place. However, its effect and, consequently, the degree of development of the secondary wave, is significantly less due to the contact of the transmitted waves with the cells with the lowest sponge coefficients. It should also be noted that the results obtained according to variant d) are similar to the results obtained according to variant c), where there are no sponge layers in front of the structures at all.
Thus, the modeling of protective structures presented in Figure 6 (d)), can be recommended as the best in terms of a compromise between the correctness of the results obtained and the stability of the numerical solution.
To verify the results that were obtained by numerical simulation with the accepted option of reproducing protective structures on a numerical model, the same test problem was performed in a wave basin. Physical experiments were carried out at the Research Center "Sea Coast" in Sochi on a scale of 1:50 for 10 statements of the test problem.
Figure 7 shows a diagram of a physical experiment, as well as a photograph taken during the experiments.
The experimental data were obtained for all formulations of the test problem at 16 control points. The diffraction coefficients at the points were obtained by the ratio of the recorded wave height at the point to the wave height at control point No. 1 (the closest point to the wave generator).
Comparison of the simulation results and experimental data is provided in figure 7. The line closest to the protective structures is conventionally called "line1", the farthest - "line2". A visual comparison of the results is shown in Figure 8.
Thus, a satisfactory qualitative agreement between the results of numerical and physical modeling is visually noted, with some reservations. First, lower diffraction coefficients are observed everywhere in the zone of light compared to those that were obtained by calculation. On average, the error in the zone of light between experiments and calculations was 18% for all experiments. Secondly, the excess of the "experimental" diffraction coefficients over the "calculated" ones is noted in the zones of the wave shadow. Here the average error was about 10%. According to the comparison, the coincidence of the diffraction coefficients at points located on the boundary of the wave shadow is also noted. On average, for all considered cases, the diffraction coefficients along the wave shadow boundary take values from 0.5 to 0.7.

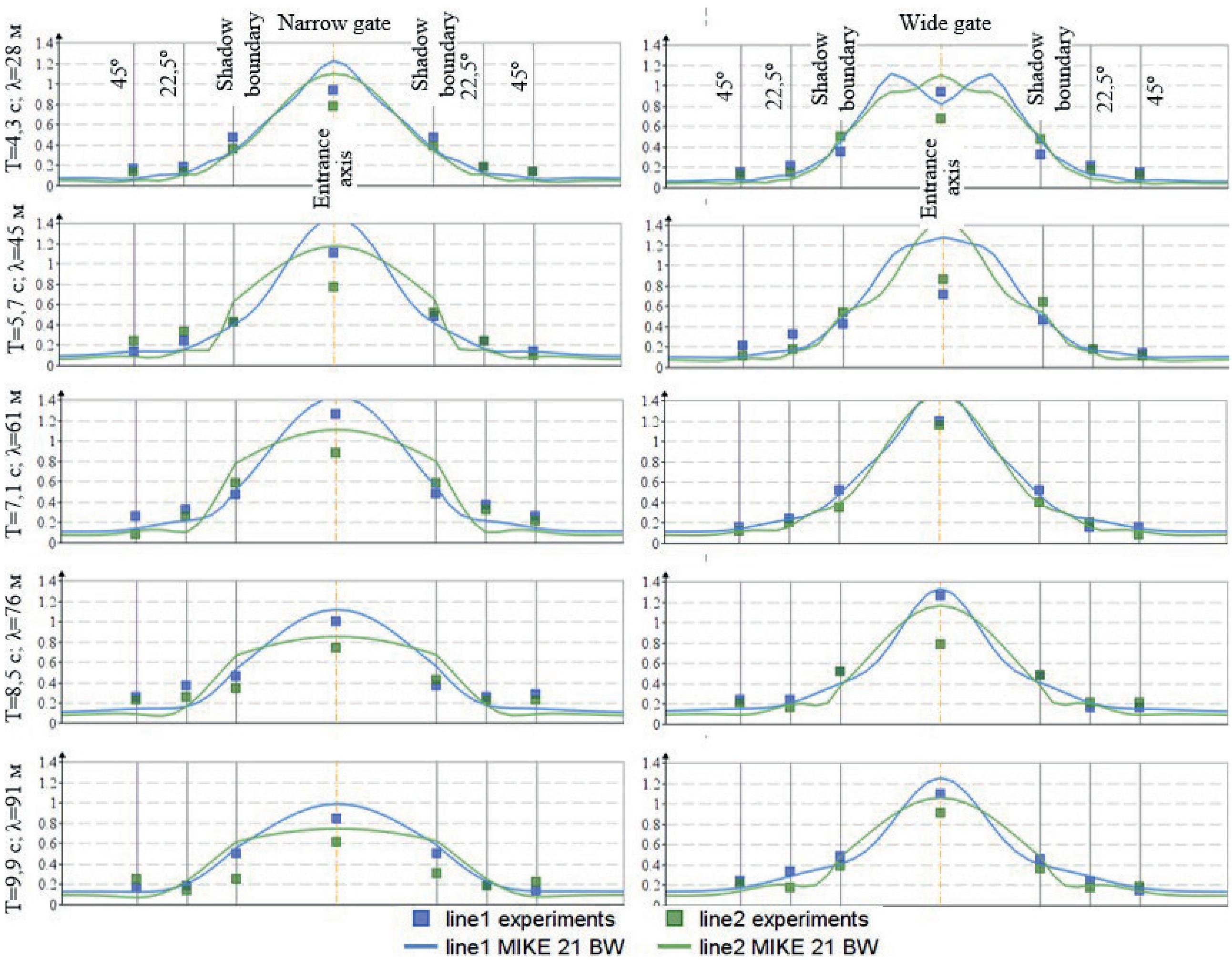

Figure 8. Comparison of the simulation results and the experimental data for all statements of the test problem

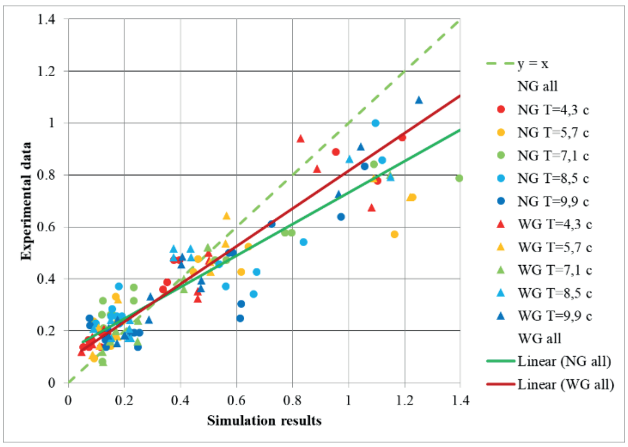

Figure 9. Lines of regression relationship between the diffraction coefficients obtained by physical and numerical modeling (NS - narrow section; WS - wide section)

Regression analysis was performed for quantitative comparison of the obtained results. The results presented above were subjected to statistical processing separately for the narrow gate (NG) and wide gate (WG). As a result of which the regression lines between the "experimental" and "calculated" diffraction coefficients were obtained, shown in Figure 9.

In the zone of deep wave shadow, the diffraction coefficients obtained on the physical model exceed those obtained by simulation. This, first of all, is evidenced by the position of the lower point of the lines of regression relationships, which for all models is above the reference line y=x. Apparently, there was a weak secondary wave in the physical basin due to wave reflection from the model boundaries. Analyzing the results obtained, the height of the waves formed by the secondary wave was limited to a few millimeters, which gave a significant error at points where the height of the original waves was small (in the zone of deep wave shadow). But it gave a negligible error at points where the height of the original model waves was of the order of centimeters. On the contrary, there is an excess of the diffraction coefficients obtained on the numerical model over those obtained on the physical one at points close to unity of the diffraction coefficients (mainly in the light zone).

The table below presents the results of calculating a set of basic statistical parameters that are commonly used to evaluate the predictive capabilities of wave models, based on the results of comparing the calculated and measured diffraction coefficients.

Table. The main statistical indicators characterizing the degree of coincidence of the results

gate	Regression Equation Coefficients		R	R^2	MSD
	a	b			
narrow	0,606	0,126	0,93	0,86	0,21
wide	0,727	0,089	0,95	0,89	0,16

Thus, the numerical model gives an average error of 10–15% in comparison with the results of physical experiments. Taking into account that the main contribution to the fluctuations of statistical indicators is made by control points in a deep wave shadow, where the influence of the secondary waves is significant, that developed on the physical model. The obtained coincidence of the data allows to recognize the numerical wave model with the chosen method of implementing protective structures applicable for such studies.

CONCLUSION

The analysis presented in the paper allows to build an original classification of numerical wave models depending on their accuracy and the requirements for computer processing power. The proposed classification combines both the most common spectral wave models and modern models that implement the Navier-Stokes equations with a free surface. The resulting classification is presented graphically in Figure 2.

The experiments presented in the paper allows to choose and justify the most correct way to model the seaport protective structures on a numerical model to simulate the diffraction of sea waves in port water area. The proposed option provides for the rejection of the auxiliary wall enclosing the sponge layers from the side of the entrance section, with a gradual decrease in the sponge coefficient towards the head of the protective structure. For substantiation, physical experiments were carried out. The diffraction of waves was studied conservatively for different parameters of the width of the entrance gate and the period of the approaching waves. Comparison of the simulation results and experimental data led to the conclusion that the method proposed in the paper for the modeling of protective structures on the numerical model is justified.

In addition, the obtained satisfactory agreement of the results allows to consider the numerical wave model used in the work, based on the Boussinesq equations and implemented in the MIKE 21 software package, verified by the data of physical experiments. It should be highlighted that both numerical wave models and physical experiments are not ideal in terms of the results obtained, and an error exists in each method. For a physical experiment, the error is primarily due to the accuracy of the measuring equipment and the development of secondary waves in the basin. When performing numerical simulations, the error most strongly depends on the spatial resolution of the finite element mesh. Nevertheless, the diffraction problem considered in the paper, the results for which were obtained by such different methods and coincide with satisfactory accuracy, allows to state with confidence that the numerical model used with the proposed settings is applicable for modeling waves in water areas where the effects of wave diffraction are strong.

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