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STUDY OF WAVE ACTION IN THE PORT WATER AREAS PROTECTED BY SINGLE PIERS AND BREAKWATERS

S. I. Pilyaev[1]

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An assessment of the wave conditions in the protected water areas of ports is required when developing a port layout, and especially, when selecting a planned location of the protective structures. The author provides theoretical suggestions as to the calculation of the wave parameters in the protected water area, as well as recommendations concerning the regulatory documents. The results of experimental studies are presented.

Keywords: wave conditions; port water area; protective structures; experimental studies.

Maritime transport is an integral part of the global transport system. Majority of the crude oil, petroleum products, liquefied gas, chemical products, and cargo containers are transported by ships. To ensure normal loading and unloading conditions, as well as safe docking at the port and by the terminals, it is necessary to protect the port water area from waves, which will undoubtedly reduce ship downtime.

Allowable wave conditions in the port water area should not cause heavy wave loads on ships, terminals and coast protection structures. A wave penetrating into the protected area through the port entrance undergoes a number of changes. First of all, such wave is subject to diffraction at the port entrance due to its tendency to turn around and change direction upon passing around an obstacle, which results in a decrease in the specific wave energy, and hence, reduction in wave height within the protected water area ($E \sim h^2$). Besides diffraction, the port wave conditions in the various-depth areas are also affected by wave refraction, which causes waves to turn and loose energy. In addition, there is wave damping, which occurs as a result of energy dissipation due to friction at the water boundary surfaces (near the bottom, at the walls of protective structures, terminals, etc.). Finally, the conditions in the port area are affected quite significantly by the waves reflected from the structures and shores. As a result of interference between the incoming and reflected waves, a complex pattern is created, which is usually referred to as clapotis.

To determine the wave conditions in the port area by considering diffraction, refraction, and reflection of waves, the water area is usually studied by using a mathematical or spatial hydraulic model. Based on the review and analysis of the existing studies conducted in this field, it appears that the proposed theoretical solutions of the diffraction problems, despite the apparent coherence of the presentation, are not yet suitable for practical use because of the insufficient calculation accuracy. The latter is due to the fact that wave diffraction as applied to liquids is more complex compared to light, sound, and electromagnetic media, although many authors use such analogy [1 – 4].

Currently, the main regulatory requirements for calculating wave action in the port water areas enclosed by protective structures are reflected in the applicable standards, such as SP 38.13330.2012 "Loads and impacts on hydraulic structures (from waves, ice, and ships)" representing an updated version of SNiP 2.06.04–82* "Loads and impacts on hydraulic structures (from waves, ice, and ships)" [5].

The above recommendations are used to perform a preliminary assessment of the port water area protection by estimating the wave conditions in the water area protected by a single pier and by a breakwater (Fig. 1).

Calculating wave diffraction in the port water area protected by a single pier. When protecting a port by a single pier (Fig. 1), waves penetrate into the port area by passing around the pier head. Therefore, when determining the wave action intensity in the port water area, a problem of wave diffraction by a single pier should be considered. Many authors [1 – 3] base their solutions of this problem on the T. Young's hypothesis, according to which diffraction is a result of energy transfer along the wavefronts. The propagation of such wavefronts within the water area is determined by the Huygens-Fresnel method. For convenience, the transverse energy transfer was quantitatively expressed as an energy flux (q) or amount of energy passing through the cross-section of an individual wave per unit time. According to

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[1] National Research Moscow State University of Civil Engineering (NRU MGSU), Moscow, Russia; e-mail: monokap@mail.ru

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T. Young, the energy flux is proportional to a wavelength (λ), group velocity (u), and energy gradient ($\partial E/\partial l$) over the wavefront section (∂l), or, in other words:

$$q = -\lambda u \frac{\partial E}{\partial l} = -\lambda u \nabla_l dE. \quad (1)$$

By considering an energy change within a unit volume of the wavefront section, a second-order differential equation was obtained, the solution of which is known from the course of mathematical physics. By applying various boundary conditions, a wave energy distribution within the water area was found and expressed using the diffraction coefficients.

Further theoretical and experimental studies were conducted using a wave tank by V. K. Zavyalov. The results of these studies made it possible to introduce certain corrections and obtain the following expression for calculating the wave diffraction coefficients (k_{dif}) [2]:

$$k_{\text{dif},s} = \frac{1 + 2.3\left(\frac{r}{\lambda}\right)^{1.7}}{1 + 2.3\left(\frac{r}{\lambda}\right)^{1.7} + \left[1.1\left(\frac{r}{\lambda}\right)^{0.67} \tanh^{0.17}\varphi + \frac{r}{\lambda} f(\beta)\right]^{2.5}}, \quad (2)$$

where

$$f(\beta) = \begin{cases} \tan\beta, \text{ for } \beta \le 0; \\ \beta, \text{ for } \beta > 0, \end{cases}$$

β (deg.) is the angle between a wave shadow boundary and a line connecting the pier head and the reference point; r/λ is the relative distance between the pier head and the reference point; φ (deg.) is the angle between a wave shadow boundary and a pier line passing along the inner face of the protective structure.

The obtained analytical expression (with certain corrections) for calculating the diffraction coefficients of waves in the port water area, protected by a single pier, is presented in the regulatory document [5] in the form of nomograms. According to the recommendations provided in [5], the height of diffracted wave (h_{dif}, m) in the protected water area should be determined using the following formula:

$$h_{\text{dif}} = k_{\text{dif}} h_i, \quad (3)$$

where k_{dif} is the wave diffraction coefficient, and h_i is the height of the initial wave of i% occurrence (the projected wave height occurrence within the system, when determining port water area protection, should be assumed equal to 5%).

The projected length is assumed equal to the initial length ($\bar{\lambda}$) at the port water area entrance. For a water area protected by a single pier, the wave diffraction coefficient (d_{dif}) is determined by Eq. (2).

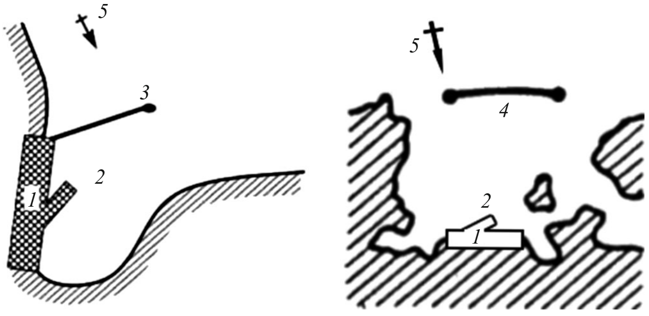

Fig. 1. General view of protective structures: *a*, single pier; *b*, breakwater; *1*, port; *2*, terminal; *3*, *4*, protective structures; *5*, prevailing wind direction.

Calculating wave diffraction in the port water area protected by a breakwater. In this case, waves penetrate into the water area via two entrances. The calculation of the wave parameters within the water area is performed using two energy components coming from different directions. For each of them, the wave height is determined by calculating diffraction around a single pier [5]. The height of diffracted waves ($h_{\text{dif},\,b}$) in the water area, protected by a breakwater, should be determined using Eq. (3). In this case, the wave diffraction coefficient ($k_{\text{dif},\,b}$) in the water area, protected by a breakwater, is calculated using the following formula:

$$k_{\text{dif},b} = \sqrt{k^2_{\text{dif},s1} + k^2_{\text{dif},s2}}, \quad (4)$$

where $k_{\text{dif},\,s1}$ and $k_{\text{dif},\,s2}$ are the diffraction coefficients of waves passing around a single pier determined for the head sections of breakwaters according to Eq. (2).

It should be noted that for a number of years, the NRU MGSU researchers along with the author have been using spatial hydraulic models to conduct wave action studies in the water areas, protected by single piers and breakwaters [6 – 8]. Specific wave action studies were conducted in the water areas of the port of Korsakov, fishing port in the Olga Bay, Podyapol'skii Bay, Mayachnaya Bay (fleet logistics support base), Vostochny Bosphorus Strait near Vladivostok, Seroglazka Bay, Kaspiysk yacht club, etc.

The experimental studies of wave action in the port water area, protected by a single pier and a breakwater, were carried out in the wave tank installed at the NRU MGSU based on a rigid erosion-resistant model. The model was made of cement mortar laid over a profiled sandy base. The profiling of the sandy base of the model was performed using cross-bars installed at a distance of 0.5 to 1.2 m from each other along the entire model, depending on the complexity of the relief. The correctness of cross-bar installation was verified using a leveling instrument. After placing several cross-bars, they were secured and covered with sand. Sand was then leveled, compacted, re-leveled to verify correctness of cross-bar installation, and covered with cement mortar. Wave action in the water area was generated by a movable mechanical pen-

Fig. 2. General view of a model of the port protected by a single pier.

dulum-type wave generator. The height and period of the initial wave was controlled by adjusting the amplitude and frequency of the pendulum. The waves in the water area were measured at strictly fixed points. For this purpose, a coordinate mesh with specific measurements proportional to the actual dimensions was applied to the models. After setting the specified values of height and period of the initial wave at a calm water line, zero lines of all wave meters were recorded. Next, the wave action was initiated, and after 20 movements of the wave generator pendulum (time, required to form an established wave conditions in the water area) the oscilloscope was turned on. The wave action capturing on the oscilloscope tape was continued for 12 to 15 wave periods, followed by recording "zeros" of the wave meters at a calm water line. Next, the wave meters were moved to the next measurement positions and the test was continued following the same sequence. To reduce the effects of random factors and obtain reliable readings of all measured variables, each test was repeated twice. During the tests, all wave meters were checked to ensure proper calibration. Wave simulation was carried out according to the Froude's number [6, 7].

The experimental studies of wave action usually involve waves coming from several directions and having different wave parameters. A general view of the port model with a single-pier protection, based on the layout of the fleet service port in Vladivostok, is shown in Fig. 2.

As a result, a large number of experimental data were obtained. After summarizing and analyzing the results of experimental studies, it should be noted that in the case of a single pier, comparison and analysis of the theoretical and experimental data point to a "satisfactory convergence" of the study results with the discrepancy not exceeding 15 to 20%. In the case of a breakwater, under certain wave conditions the discrepancy exceeded 25 to 30%, which required additional studies.

Based on the experimental data, obtained as a result of studying wave diffraction in the water area protected by a breakwater, the following expression for calculating the diffraction coefficient was tested, which made it possible to improve the convergence between calculated and experimental data by narrowing the discrepancy range down to 8 – 10%:

$$k_{\mathrm{dif},b} = \sqrt{k^2_{\mathrm{dif},s1} \cos\alpha + k^2_{\mathrm{dif},s2} \cos\alpha}, \tag{5}$$

where $k_{\mathrm{dif},\,s1}$ and $k_{\mathrm{dif},\,s2}$ have the same values, and α is the angle between a breakwater line and a line connecting the head sections of the breakwater and the reference point.

After analyzing the causes of possible deviations between the calculated and experimental results, it was found that the existing calculation methods are imperfect due to a

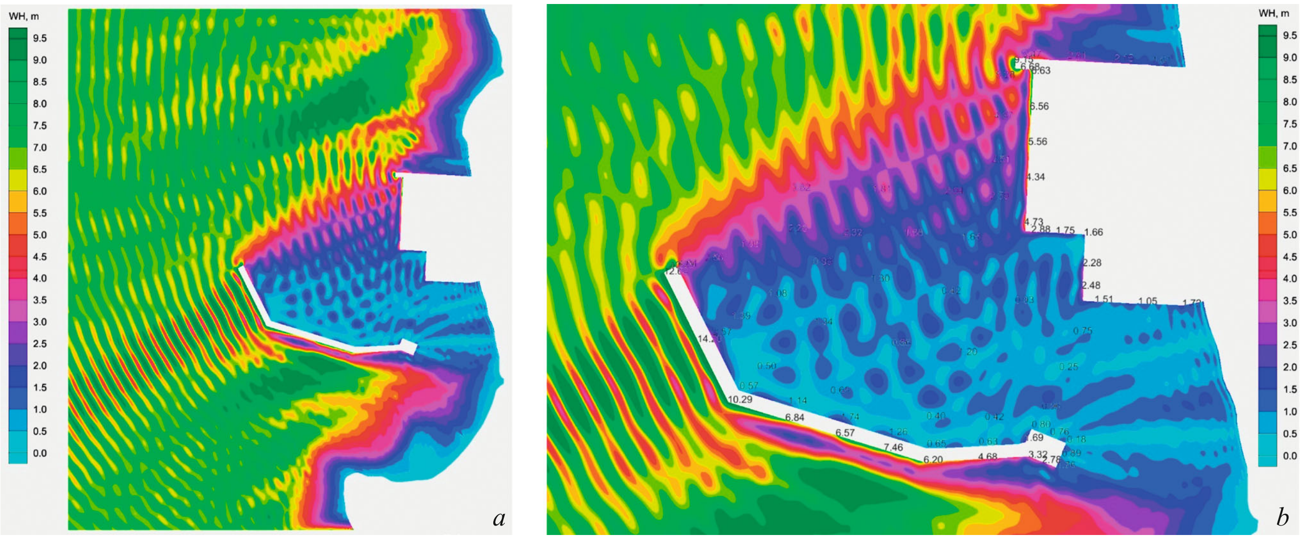

Fig. 3. Wave heights in the port water area, calculated for incident waves (1% occurrence) during SW storm on August 28, 2012. Wave heights are indicated by the field color and values at reference points: *a*, general view of the port water area; *b*, area of terminal structures.

number of built-in assumptions. Therefore, it should be noted that the final decision about a level of protection of the port area against waves must be made after completion of model studies or numerical simulation.

Numerical simulation implies formulating a boundary problem of mathematical physics and developing a numerical solution of this problem. Recently, this method has been actively developed and used to solve problems of determining wave loads and impacts on port hydraulic structures.

In recent years, the NRU MGSU has been using ARTEMIS software package to solve the problems of wave diffraction by protective port structures [9, 10]. This software is an open-access code based on hydrodynamic equations of low-gradient slopes. The advantages of the model include the convenience of changing the boundary conditions along the complex boundaries (by specifying different reflection coefficients), which makes it possible to account for specific design features of the simulated protective structures.

Figure 3 illustrates the wave diffraction calculations in the water area of the future port in the Vostok Bay of the Sea of Japan. The docking area of the port is protected from the south by a breakwater. The results of numerical simulation of the wave field were verified by laboratory physical modeling. The wave parameters in the port water area were obtained, which are required for calculating the protective and docking structures, as well as determining the conditions of safe docking at the terminals.

CONCLUSIONS

1. Based on the numerous studies of wave diffraction in the water areas protected by a single pier, it can be concluded that the comparison of the experimental and theoretical data points to their "satisfactory convergence." When assessing the wave conditions in the port water area, it is advised to use recommendations provided in the existing regulatory documents.

2. To determine the wave parameters in the water area, protected by a breakwater, it is advised to use the provided suggestions and justifications, intended to supplement the recommendations for calculating the port water areas, protected by breakwaters.

3. In case of complex outlines of the port water areas, it is recommended to conduct experimental studies using hydraulic and mathematical models. These studies are crucial when selecting the final layout of the port and location of the protective structures.

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