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REFLECTION OF WAVES FROM HYDROTECHNICAL STRUCTURES IN DETERMINING THE PORT WATER WAVES

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Abstract: The article considers the influence of taking into account wave reflection and the discrepancy between the results of waves without reflection and with reflection in numerical modeling, compares the results of numerical modeling and the analytical method for determining dangerous directions of waves when servicing ships in the port. The reflectivity of hydraulic structures and the factors on which it depends are considered. Empirical formulas for obtaining the reflection coefficient for the designs of slope structures are presented. An expression for the reflection coefficient is used not only for smooth slopes, but also for permeable ones. The results are compared with the methodology given in normative SP 38.13330.2018. The stepwise behavior of the reflection coefficient is analyzed, depending on the gentleness of the wave and the slope laying.

Keywords: numerical modeling, analytical methods, reflection waves, reflection factor, critical parameter

ОТРАЖЕНИЕ ВОЛН ОТ ГИДРОТЕХНИЧЕСКИХ СООРУЖЕНИЙ ПРИ ОПРЕДЕЛЕНИИ РАСЧЕТНЫХ ВОЛН НА АКВАТОРИИ ПОРТА

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Аннотация: в статье рассматривается влияние учета отражения волн и расхождения результатов между волнами без отражения и с отражением при численном моделировании, сравниваются результаты численного моделирования и аналитического метода для определения опасных направлений волнений при обслуживании судов в порту. Рассматривается отражающая способность гидротехнических сооружений и факторы, от которых она зависит. Представлены эмпирические формулы для получения коэффициента отражения для конструкций откосных сооружений. Используются выражение для коэффициента отражения не только для гладких откосов, но и для проницаемых. Результаты сравниваются с методикой, приведенной в СП 38.13330.2018. Анализируется скачкообразный характер поведения коэффициента отражения, зависящий от пологости волны и заложения откоса.

Ключевые слова: численное моделирование, аналитические методы, отражение волн, коэффициент отражения, критический параметр

INTRODUCTION

An important aspect of port operation is ensuring safe interaction of vessels with berthing facilities [1]. The criteria for this safety are assessed by permissible wave heights, permissible wind speed and, in some cases, permissible current speed. As is known, ports can be protected and unprotected from waves. At the moment, there is one regulatory document designed to determine the permissible wave parameters when servicing vessels for berths that are not sufficiently protected from waves.[1] There are also guidelines and recommendations that combine the ability to determine acceptable wave parameters for servicing ships and determine the port's security.[2,3], while the use of these documents does not exclude their use for unprotected ports. At first glance, in all three presented documents the methodology for determining safe conditions for interaction of vessels with berthing facilities during mooring, parking and cargo operations is quite similar, but upon closer examination, some differences are revealed. Further, it is considered how critical the existing differences in the methods are and how they can affect the final conclusion on the safety of mooring.

As an example, the conditions of the facility, hereinafter referred to as the Terminal (Fig. 1), which is located in the Kola Bay of the Barents Sea, are considered. For comparison, the calculation data obtained as a result of numerical modeling (the SWAN wind wave calculation model [2-3] and the COASTOX-CUR current and water level model) and the results of analytical calculation in accordance with the SP 38.13330 methodology were considered.[4], 2018 edition. Examples of combined modeling are presented in [4-9].

The assessment of safe conditions is carried out for piers No. 1, No. 2 and the port fleet pier; the design vessels with their characteristics are given in Table 1.

According to Figure 1, pier #1 corresponds to control points 5, 6 and 22, pier #2 – 7, 8, 40, 23 and 24 and the harbor fleet pier – 10. Control points 5, 6, 7, 8 and 40 are used to determine wave heights directly at the berth, and control points 22, 23 and 24 are located at a distance from the berth for approximately the width of the vessel. The wave parameters based on the results of the analytical calculation give values only near the object. For numerical modeling, the directions of the calculated storms include 5 rhumbs: N, NE, E, SE and S; for the analytical method, calculated storms of 4 rhumbs were tested: NE, E, SE and S.

Table 1. Parameters of design vessels

Parameter	Name of the vessel			
	SK-6000	SK-11700	Arc 8	Tugboat
Draught in cargo, m	13.5	15.0	14.00	6.0
Draft in ballast, m	8.2	9.0	11.45	
Maximum width, m	40.0	45.61	41.90	13.0
Total length, m	286.45	363.57	289.60	30.0
Displacement, thousand tons	105.81	178.29	124.20	0.645

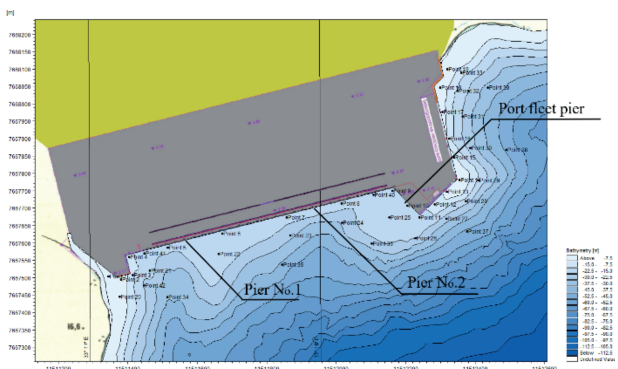


Figure 1. Bathymetry of the Terminal water area with indication of control points for issuing results

Further, based on the results of wave calculations, a table of dangerous wave directions is presented for servicing calculation vessels (for mooring

[1]R 31.3.07-01. Guidelines for calculating loads and impacts from waves, ships and ice on marine hydraulic structures: Supplement and clarification of SNiP 2.06.04 - 82*. Moscow, 2001.

[2]RD 31.33.10-87. Recommended Practice for Accounting for Hydrometeorological Conditions in the Design of Wharves with Insufficient Protection from Wave Action. Moscow, 1987.

[3]RD 31.33.03-88. Recommended Practice for the Determination of Permissible Wind and Wave Conditions for Design of Seaports. Moscow, 1989

[4]SP 38.13330.2018. Loads and impacts on hydraulic structures (wave, ice and from ships): Updated version of SNiP 2.06.04-82*. Moscow, 2018.

operations, parking of a moored vessel and performing cargo operations) at the Terminal.

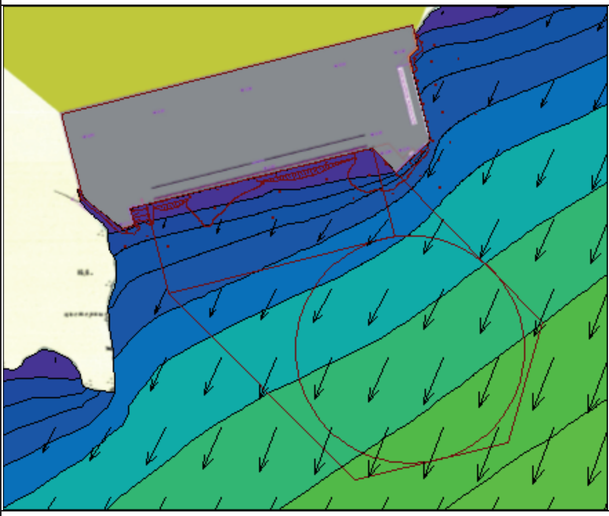
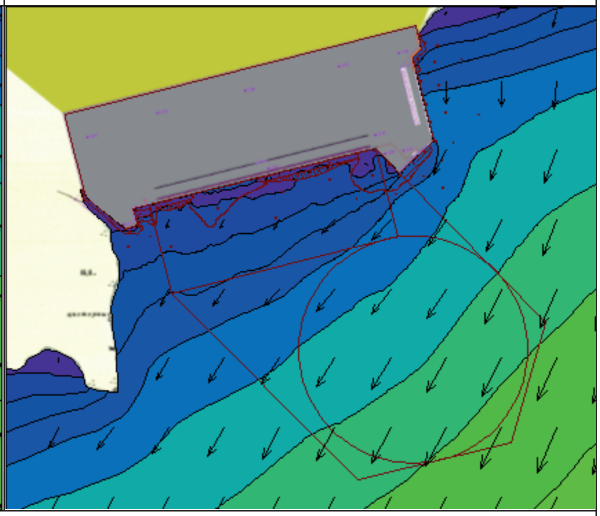
Table 2 shows that there is practically no difference in the results when using different methods for determining safe waves, but taking into account wave reflection plays a significant role. When taking into account reflection, four directions of waves become dangerous, instead of one, S without taking into account reflection. It is also clear that the results diverge for two adjacent berths (along one berth wall). At the same time, approaching the corner of the cordon line (i.e., to the berth of the port fleet) the waves increase significantly, especially taking into account reflection.

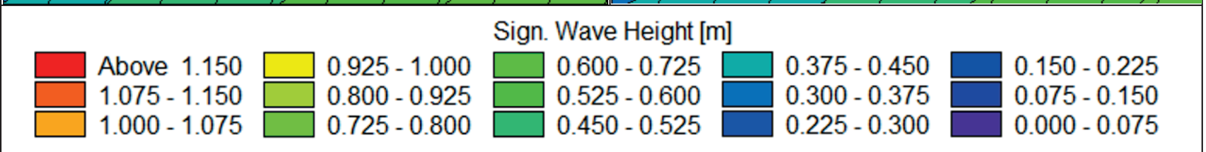
Wave fields for the berthing area and on the approach to it for a storm with a recurrence rate of once per year for all dangerous directions based on the results of numerical modeling are shown in Table 3.

Table 2. Dangerous wave directions for servicing vessels at piers No. 1, No. 2 for design vessels and the port fleet pier for tugboat

	Waves without reflection, numerical modeling			Waves with reflection, numerical modeling			Analytical method	
All design vessels	Pier No. 1	Pier No. 2	Port fleet pier	Pier No. 1	Pier No. 2	Port fleet pier	Pier No. 1, No. 2	Port fleet pier
R 31.3.07-01	S	S	-	NE, E, SE, S	SE, S	S	E, SE, S	S
RD 31.33.10-87	S	S	S	NE, E, SE, S	SE, S	S	E, SE, S	S
RD 31.33.03-88	S	S	-	NE, E, SE, S	SE, S	S	E, SE, S	S

Table 3. Fields of significant wave heights during storms of the N, NE, E, SE and S direction with a probability of once a year with and without reflection

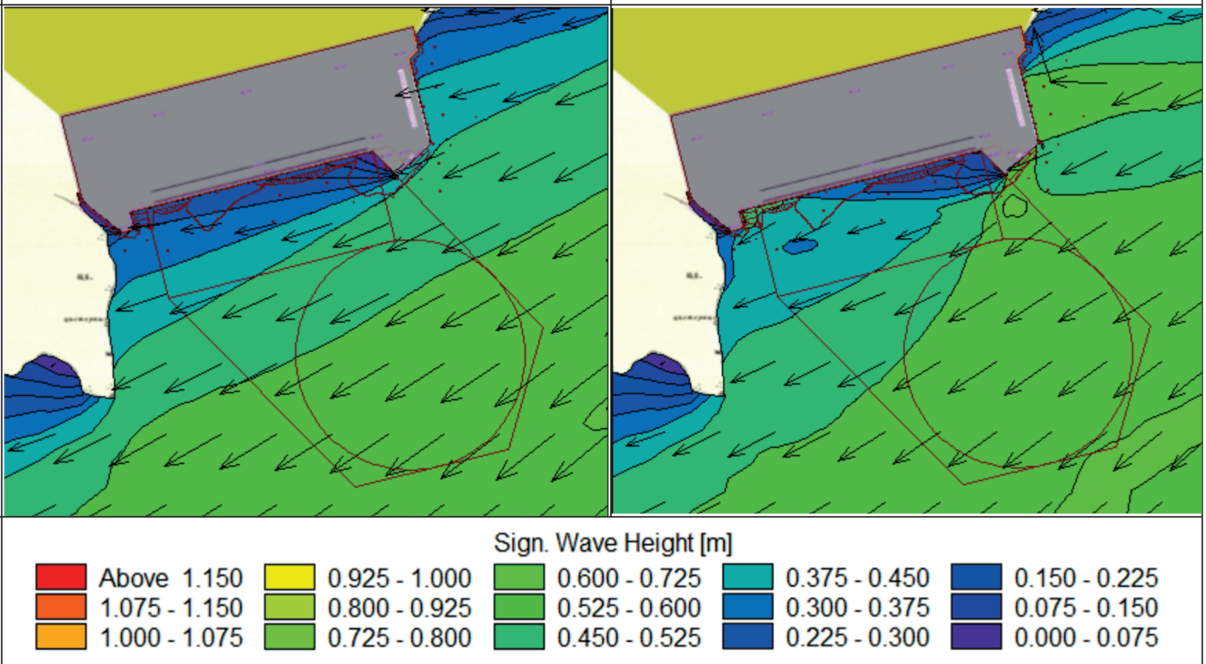
N	no reflection	reflection
Once a year		



Continuation of table 3

Wave parameters	p.5	p.6	p.22	p.7	p.8	p.40	p.23	p.24	p.10
	North direction of wave approach without reflection/ with reflection								
$\bar{\lambda}$, м	0.10/0.10	0.10/0.10	0.70/0.80	0.10/0.10	0.10/0.10	0.10/0.10	0.60/0.60	0.30/0.30	0.10/0.10
$\bar{T}$, c	0.30/0.30	0.30/0.30	0.70/0.80	0.20/0.20	0.30/0.30	0.30/0.30	0.60/0.60	0.40/0.40	0.30/0.30
$\bar{h}$, м	0.01/0.01	0.01/0.01	0.04/0.04	0.01/0.01	0.01/0.01	0.01/0.01	0.04/0.05	0.02/0.03	0.02/0.01
$h_{5\%}$, м	0.02/0.02	0.02/0.02	0.02/0.08	0.02/0.02	0.02/0.02	0.02/0.02	0.02/0.08	0.02/0.05	0.02/0.03

NE	no reflection	reflection
Once a year		

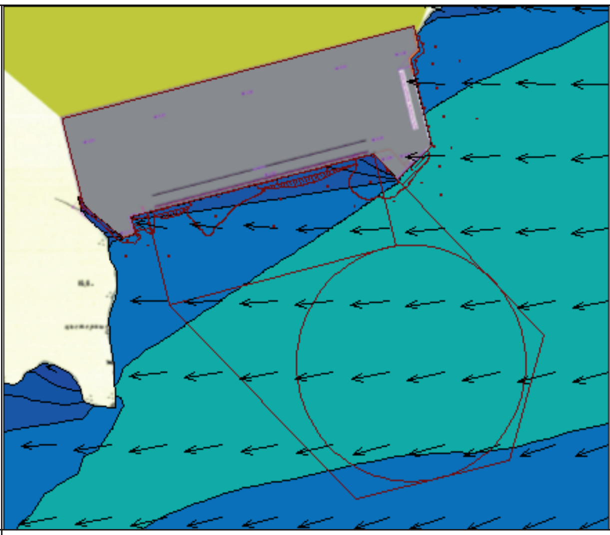


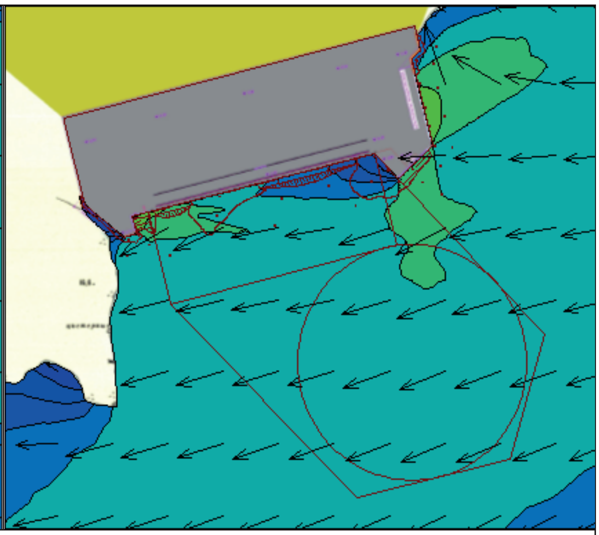
Wave parameters	p.5	p.6	p.22	p.7	p.8	p.40	p.23	p.24	p.10
	North-east direction of wave approach without reflection/ with reflection								
$\bar{\lambda}$, *m*	7.10/11.50	7.00/10.80	6.80/10.70	6.30/10.10	3.90/8.10	1.30/1.30	6.30/10.20	6.00/9.00	0.50/0.50
$\bar{T}$, s	2.10/2.70	2.10/2.60	2.10/2.60	2.00/2.50	1.60/2.30	0.90/0.90	2.00/2.60	2.00/2.40	0.60/0.60
$\bar{h}$, *m*	0.16/0.31	0.16/0.22	0.19/0.27	0.14/0.19	0.10/0.13	0.05/0.06	0.18/0.21	0.17/0.17	0.03/0.03
$h_{5\%}$, *m*	0.29/0.54	0.29/0.40	0.29/0.48	0.29/0.34	0.29/0.24	0.29/0.10	0.29/0.37	0.29/0.30	0.29/0.06

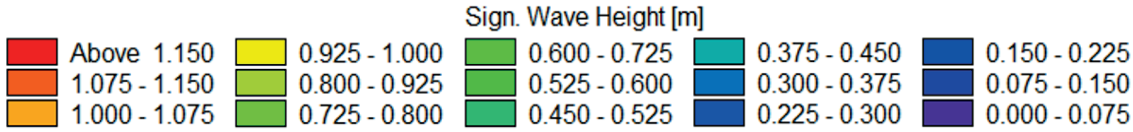
E	no reflection	reflection

Continuation of table 3

Once a year



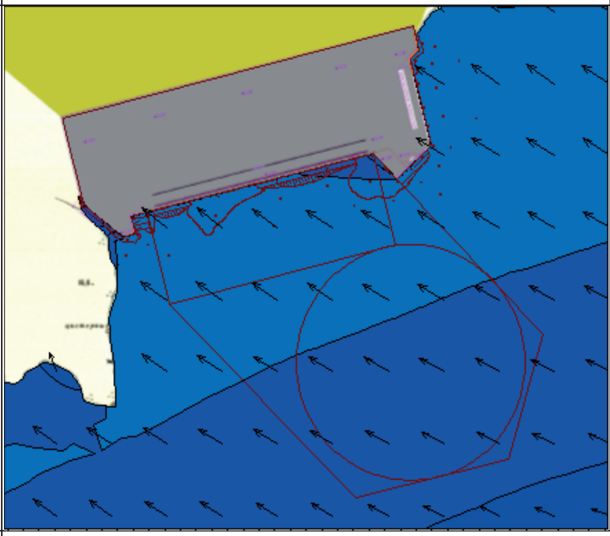


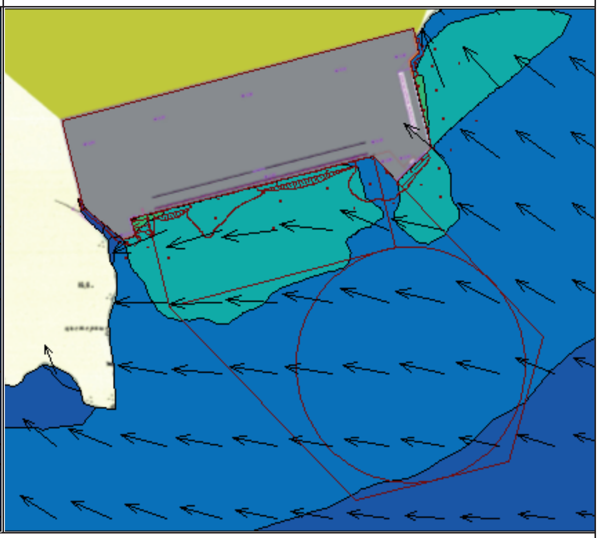


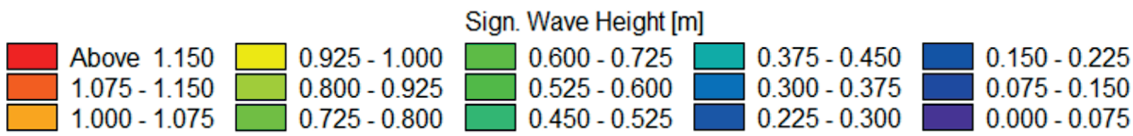
Параметры волн	p.5	p.6	p.22	p.7	p.8	p.40	p.23	p.24	p.10
	East direction of wave approach without reflection/ with reflection								
$\bar{\lambda}$, *m*	6.10/7.50	6.00/6.80	6.10/7.20	5.80/6.40	5.00/5.90	3.80/5.00	6.00/6.80	5.90/6.40	3.50/4.80
$\bar{T}$, s	2.00/2.20	2.00/2.10	2.00/2.00	1.90/2.00	1.80/1.90	1.60/1.80	2.00/2.10	2.00/2.20	1.50/1.80
$\bar{h}$, *m*	0.20/0.33	0.19/0.26	0.21/0.29	0.18/0.24	0.15/0.20	0.11/0.14	0.20/0.25	0.19/0.22	0.08/0.09
$h_{5‰}$, *m*	0.35/0.58	0.35/0.47	0.35/0.52	0.35/0.42	0.35/0.36	0.35/0.26	0.35/0.49	0.35/0.39	0.35/0.16

SE | **no reflection** | **reflection**

Once a year



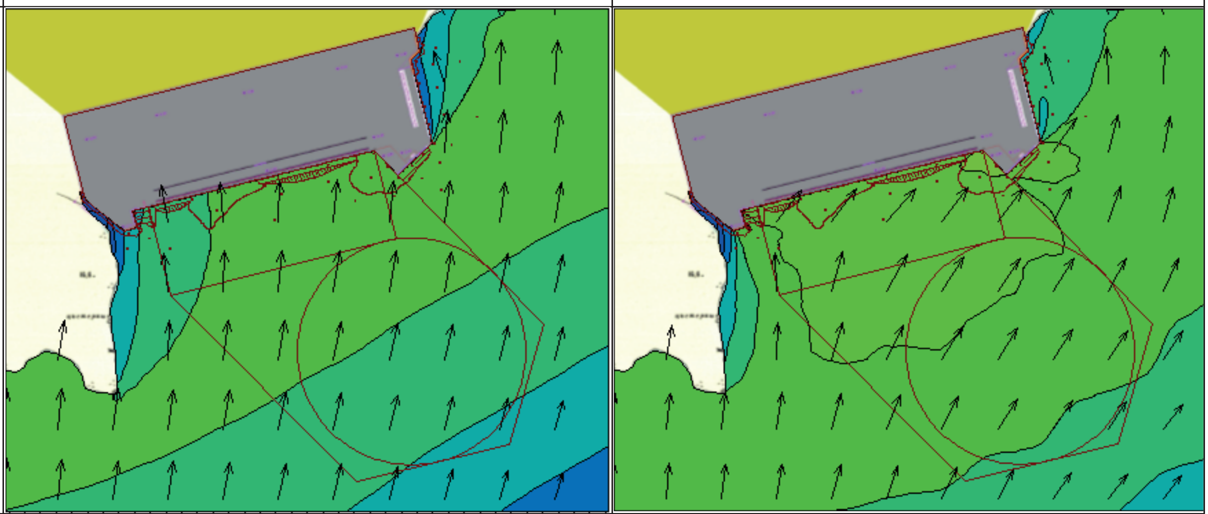




Continuation of table 3

Wave parameters	p.5	p.6	p.22	p.7	p.8	p.40	p.23	p.24	p.10
	South-east direction of wave approach without reflection/ with reflection								
$\bar{\lambda}$, m	5.40/5.80	5.40/5.50	5.50/5.60	5.30/5.30	5.00/5.10	4.50/4.80	5.40/5.40	5.30/5.20	4.40/4.80
$\bar{T}$, s	1.90/1.90	1.90/1.90	1.90/1.90	1.80/1.80	1.80/1.80	1.70/1.70	1.90/1.90	1.80/1.80	1.70/1.80
$\bar{h}$, m	0.21/0.29	0.21/0.27	0.21/0.27	0.21/0.26	0.19/0.25	0.17/0.25	0.21/0.27	0.21/0.26	0.15/0.20
$h_{5‰}$, m	0.37/0.51	0.37/0.47	0.37/0.48	0.37/0.46	0.37/0.45	0.37/0.43	0.37/0.47	0.37/0.46	0.37/0.36

S	no reflection	reflection
Once a year		



Sign. Wave Height [m]

Above 1.150	0.925 - 1.000	0.600 - 0.725	0.375 - 0.450	0.150 - 0.225
1.075 - 1.150	0.800 - 0.925	0.525 - 0.600	0.300 - 0.375	0.075 - 0.150
1.000 - 1.075	0.725 - 0.800	0.450 - 0.525	0.225 - 0.300	0.000 - 0.075

Wave parameters	p.5	p.6	p.22	p.7	p.8	p.40	p.23	p.24	p.10
	South direction of wave approach without reflection/ with reflection								
$\bar{\lambda}$, m	7.60/8.20	7.90/8.50	7.90/8.00	8.20/8.50	8.30/8.40	7.10/8.50	8.20/8.30	8.30/8.50	8.40/9.10
$\bar{T}$, s	2.20/2.30	2.20/2.30	2.20/2.30	2.30/2.30	2.30/2.30	2.10/2.30	2.30/2.30	2.30/2.30	2.30/2.40
$\bar{h}$, m	0.33/0.44	0.35/0.46	0.35/0.42	0.37/0.46	0.37/0.46	0.37/0.48	0.37/0.44	0.37/0.46	0.37/0.51
$h_{5‰}$, m	0.58/0.78	0.58/0.80	0.58/0.74	0.58/0.80	0.58/0.81	0.58/0.84	0.58/0.78	0.58/0.81	0.58/0.90

The largest discrepancy between the wave parameters calculated with reflection and without reflection is obtained for the NE direction, since in this direction the wave front is almost normal to the cordon line and the ship's side, while the port fleet pier is in the wave shadow for both scenarios, as is pier no. 2. And for waves in the N direction, the results with and without reflection are the same practically. For points located at a vessel's width from the berth, for berth no. 1 from the NE to the S direction, the differences in the heights of reflected waves of different strengths from waves without reflection decrease. For berth no. 2 from the NE to the S, the difference in the heights of reflected waves of different strengths from waves without reflection increases.

Thus, wave reflection plays an important role in the resulting wave heights, taking into account the configuration of port facilities relative to the direction of the waves. In turn, this can significantly affect the conclusions about the safe conditions for servicing ships in the port.

When wind waves interact with hydraulic structures, they undergo transformation – mainly diffraction and reflection of waves, often multiple times. At the same time, underwater channels and natural bottom irregularities [10-11], as well as floating objects, which, in turn, act as sources of secondary waves due to their own oscillations [12], can also influence wind waves.

the wave climate in the port water area is formed by the interference of approaching, reflected and secondary generated waves.

The layout of sea ports assumes maximum protection of the inner water area from the impact of large wind waves. However, during a storm, the water area of any port may experience weakened but noticeable waves [13]. In this case, taking into account the reflection of waves from the port's hydraulic structures plays an important role in shaping the wave climate in the port water area. If the degree of reflection is underestimated, the wave load on the structures will be underestimated, and the danger of wave impact on ships sheltering in the port water area during a storm will be underestimated. In addition, incorrect consideration of wave reflection will also affect the unpredictable development of lithodynamic processes in the water area. Washout at berth and protective structures can lead to a loss of local stability of structures, as well as to excessive accumulation of sediments and the accompanying need for extraordinary dredging operations in the shipping waters of the port. If the degree of wave reflection from structures is unreasonably overestimated, there will be an overspending of funds and materials. In any case, incorrect consideration of wave reflection can have negative consequences for both the port's economy and its operational functionality.

METHODS

The reflectivity of hydraulic structures is usually characterized by the reflection coefficient, which is the ratio of the height of the reflected wave to the height of the approaching wave, that is:

$$k_{ref} = \frac{h_{ref}}{h} \quad (1)$$

The reflection coefficient depends on both the type and roughness of the reflecting surface and the parameters of the approaching waves, as well as on the angle between the front of the incoming waves and the axis of the reflecting surface. Determining the exact values of the reflection coefficient for a specific hydraulic structure design for different approach angles and wave parameters can only be done through physical experiments. Therefore, in engineering practice, they resort to a set of empirically obtained reflection coefficients collected in the scientific literature [14-16] and shown here in the figure below.

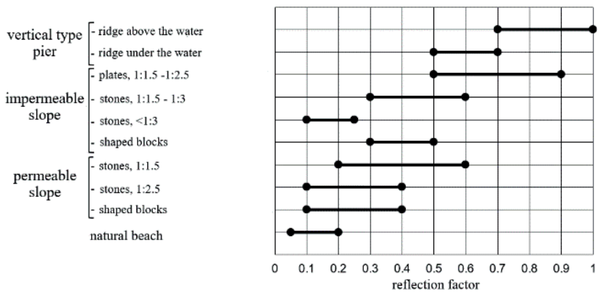


Figure 2. Approximate wave reflection factor of various structures

The choice of reflection coefficient values in the given ranges depends on the steepness of the suitable waves - the longer the waves, the greater the reflection coefficient. The upper limit of the ranges roughly corresponds to long-period swell waves.

In this case, if when calculating the parameters of wind waves in the port water area, the degree of wave reflection from berths with a vertical wall is intuitively clear and with sufficient accuracy and engineering reserve is specified by a reflection coefficient of 0.8-0.9. Then when considering alternative options for the design of a berth wall (for example, with a berth slope), as well as when it is necessary to take into account reflection from slope coastal protection structures, the assignment of a wave reflection coefficient becomes a non-trivial task.

Empirical formulas are known for obtaining the reflection coefficient for some designs of slope structures. They are based on the connection with a critical parameter similar to the wave breaking parameter, which was obtained in [17-18] for a regular monochrome wave and the expression for which is written as follows:

$$\xi = \frac{\tan\alpha}{\sqrt{2\pi h/gT^2}}, \quad (2)$$

where h– wave height; T – wave period; α– slope angle.
The dependence of the reflection coefficient on the critical collapse parameter for a smooth slope (for example, reinforced with slabs), obtained in work [18], is written as follows:

$$k_{ref} = 0.1\xi^2 \quad (3)$$

It was later shown that this expression is valid only for small values of the critical parameter ξ.Therefore, it was further refined in the work [19] for large values of the critical parameter to the following form:

$$k_{ref} = \tanh(0.1\xi^2) \quad (4)$$

and also, in the approximation of irregular waves, with the breaking parameter determined by the significant wave height and the average period over the spectrum:

$$k_{ref} = \frac{a_1 \cdot \xi_m^2}{\xi_m^2 + b_1} \quad (5)$$

The authors of the work [19] first proposed to use the same expression to calculate the reflection coefficient not only for smooth slopes, but also for those with significant porosity. For this purpose, the following values of calibration coefficients were proposed:

Table 4. Values of calibration coefficients for slopes with significant porosity to formula (5)

Slope structure	a_1	b_1
Permeable, stones or shaped blocks	0.75	15
Impermeable, stone or shaped blocks	0.80	10
Plate slope	1.00	4.54

Later, based on newly obtained extensive experimental data on reflection coefficients, it was shown in [20] that this dependence with the proposed coefficients allows obtaining reliable results only for smooth slopes. In the same work, the authors proposed a new formula for smooth and porous slopes with a steepness from 1:1.5 to 1:4.0:

$$k_{ref} = \tanh(A \cdot \xi_m^B), \quad (6)$$

Where A and B are calibration coefficients that take the following values:

Table 5. Values of calibration coefficients for slopes with significant porosity to formula (6)

Slope structures	A	B
Permeable, stones	0.12	0.87
Permeable, shaped blocks (tetrapods, cubes)	0.10	0.87
Impermeable, stones or shaped blocks	0.14	0.90
Plate	0.16	1.43

Then this method of determining reflection coefficients was developed in terms of reflection from smooth slopes of mixed waves (mainly bimodal – wind waves together with swell waves) [21], in terms of using the capabilities of neural networks [22-23], and also received additional confirmation from natural data [24].
As can be seen from the figure below, the use of expression (4) allows us to approximate expression (3) in the region of small values of the critical parameter $\xi<2$, and in the region $\xi>2$ - to get the reflection coefficients that asymptotically tend to 1.0, i.e., total reflection. The graph shows the boundary solutions of expressions (5) and (6) - for a smooth impermeable slope and for a permeable porous slope. This allows us to estimate the minimum and maximum reflection coefficients from slope structures that can be obtained.

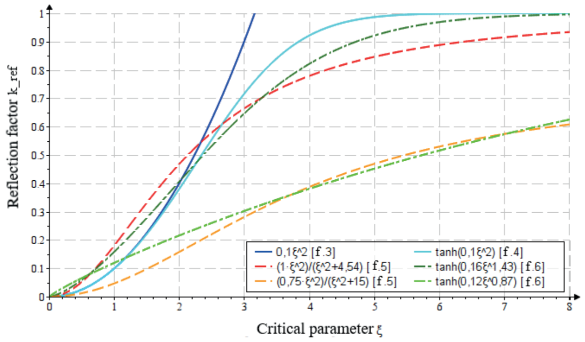


Figure 3. *Dependence of the reflection coefficient on the critical parameter, obtained using expressions (3 – 6) for smooth and porous slopes*

In domestic engineering practice, the method given in SP 38.13330 is used to determine the reflection coefficients of waves from slope structures. The expression for the reflection coefficient according to this method can be written as follows:

$$k_{ref} = k_r k_p k_{ref,i}\sqrt{\cos\theta_r \, e^{-0{,}08r/\lambda}}, \quad (7)$$

where k_r and k_p– coefficients of slope roughness and permeability, taking the following values:

Table 6. *Values of the coefficient of slope roughness and permeability (SP 38.13330.2018 Table D.1)*

Slope structure	Relative roughness, r/h (where *r* is the average size of the material fixing)	k_r	k_p
Concrete (reinforced concrete) plate	-	1	0.9
Gravel-pebble or stone covering, concrete (reinforced concrete) blocks	Less than 0.002	1	0.9
	0.005-0.01	0.95	0.85
	0.02	0.9	0.8
	0.05	0.8	0.7
	0,1	0.75	0.6
	More than 0.2	0.7	0.5

$k_{ref,i}$ – the coefficient depending on the flatness of the wave and the slope is taken from the following table:

Table 7. *Values of the coefficient depending on the wave flatness and slope laying (SP 38.13330.2018 Table A.4)*

Wave flatness, λ/h	Values $k_{ref,i}$ at slopes of the reflective surface *i*		
	1	0.5	0.25
10	0.5	0.02	0,0
15	0.8	0.15	0,0
20	1	0.5	0,0
30	1	0.7	0.05
40	1	0.9	0.18

The analysis of the coefficients proposed by the normative methodology shows that the reflection coefficient is a function of the steepness or flatness of the waves, the slope and the angle between the wave front and the axis of the reflecting structure. If we assume that the waves approach the structure normally, and the wavelength, according to the linear wave theory, is expressed through the period of the waves according to the dispersion relation (without taking into account the water depth):

$$\lambda = \frac{gT^2}{2\pi} \quad (8)$$

then it becomes possible to analytically link the value of the normative reflection coefficients and the critical parameter ξ.

For example, the figure below shows a comparison of the reflection coefficients that can be obtained using expressions (5) and (6), as well as using the normative methodology. As above, the boundary conditions of reflection from the slope are considered: from an impermeable smooth slope and from a permeable extremely porous slope. It should be noted that taking into account the characteristic size of the slope fastening material, r, gives the normative reflection coefficients in the region between the absolutely smooth and extremely porous slope.

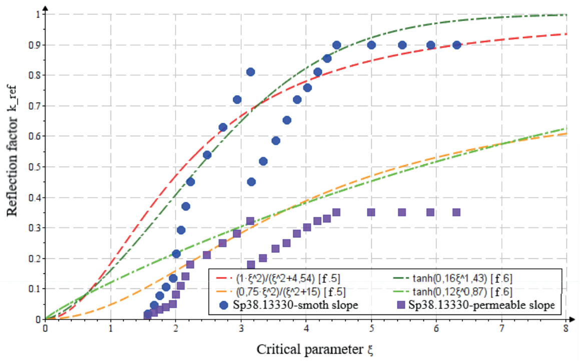


Figure 4. Comparison of reflection coefficients obtained using expressions (5) and (6) and using the normative methodology

According to the obtained results, there is a connection between the reflection coefficients and the critical parameter. A jump in the value of the normative reflection coefficients is noted in the interval $2 < \xi < 3.152$. In this case, the reflection coefficients in the interval $2 < \xi < 2.23$ are characterized by a sharp increase in the growth rate, while the reflection coefficients in the interval $2.23 < \xi < 3.15$ increase with moderate intensity. Note that a jump in the reflection coefficients is observed on both smooth and porous slopes.

RESULTS AND DISCUSSION

An analysis of the behavior of the standard reflection coefficients made it possible to determine that the abrupt nature of the behavior is manifested in the coefficient, which depends on the gentleness of the wave and the slope and is determined according to the table:

Table 8. Values of the reflection coefficient depending on the wave flatness and slope embedment

Wave flatness, λ/h	Values $k_{ref,i}$ at slopes of the reflective surface i		
	1	0.5	0.25
10	0.5	0.02	0,0
15	0.8	0.15	0,0
20	1	0.5	0,0
30	1	0.7	0.05
40	1	0.9	0.18

In this case, the area where the reflection coefficients jump is highlighted in color in Table 8. Bringing the normative coefficients to smooth growth relative to the critical parameter seems to be an important task today, since it allows us to obtain a more reasonable result. The assumption about the smoothness of their behavior relative to the critical parameter is associated with the functions of the dependence of the reflection coefficients on the critical parameter, obtained in the literature cited above and confirmed by extensive experimental data. In this regard, in this paper we propose to consider the updated wave reflection coefficients in the part of Table 8 highlighted by the color scheme. The updated parameters of the reflection coefficient, depending on the wave flatness and slope laying, are given in Table 9.

Table 9. Updated values of the reflection coefficient depending on the wave flatness and slope embedment

Wave flatness, λ/h	Values $k_{ref,i}$ at slopes of the reflective surface i		
	1	0.5	0.25
10	0.5	0.02	0,0
15	0.8	0.15	0,0
20	1	0.25	0,0
30	1	0.40	0.05
40	1	0.55	0.18

The position of the reflection coefficient values in relative dependence on the critical parameter is shown in Figure 5.

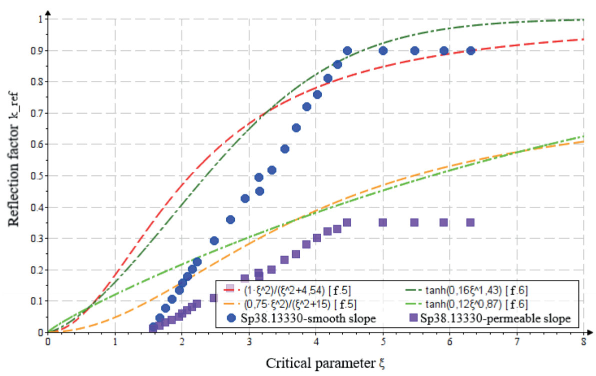


Figure 5. Comparison of reflection coefficients obtained using expressions (5) and (6) and using the normative methodology with adjusted coefficient values $k_{ref,i}$

The obtained distribution of reflection coefficients depending on the critical parameter is more consistent with modern ideas about the interaction of waves with slope hydraulic structures, which is confirmed by the comparison given above.

When analyzing the reflection of wind waves from a structure, it is also necessary to take into account the irregularity of wind waves. Thus, with total reflection, the height of a monochrome wave doubles at all nodes of the standing wave formed. Thus, the height of the waves at a distance from the reflecting structure will be 2h. At the same time, the significant wave height that characterizes irregular waves doubles only at the reflective surface, and in the water area in front of the structure (at a distance greater than one wavelength) it increases by 1.4 times.

This is important to take into account, for example, when calculating the wave protection of berths located opposite wave-reflecting structures.

CONCLUSION

It is shown that taking into account the reflection of waves from the berth under consideration can lead to a significant change in the conclusion about the safety of the conditions for mooring vessels at the berth. This applies both to the methods for determining the conditions of mooring according to normative documents and to the numerical modeling of waves at the berth.

The reflection coefficient from the surfaces of hydraulic structures depends on the steepness or flatness of the approaching waves, the slope, the roughness and permeability of the reflecting structure, and the angle between the wave front and the axis of the reflecting structure. Analysis of the normative methodology SP 38.13330 for determining the reflection coefficient, performed as a function of the reflection coefficient on the critical parameter ξ, showed a jump in values at a certain value of the critical parameter. A method is proposed to eliminate this problem and obtain corrected values of the reflection coefficients.

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