Coastal protection structures influence on diffraction and reflection of waves simulation based on 3D wave hydrodynamics model

A I Sukhinov¹, A E Chistyakov¹, E A Protzenko² and S V Protzenko¹

¹Don State Technical University, Gagarin square 1, Rostov-on-Don, 344000, Russia
²Taganrog Institute of A.P. Chekhov (branch) RGEU (RINE), Taganrog, Russian Federation

E-mail: rab55555@rambler.ru

Abstract. The work describes research of wave processes in the presence of shore protection and coastal structures using 3D wave hydrodynamics model. The model presented in the article gives realistic description of the physical wave process near the coastline. The influence of coastal protective structures on the diffraction and reflection of waves is investigated on the basis of 3D wave hydrodynamics model.

1. Introduction

The coastal zone is the main human habitat. In the coastal zone, industrial, civil, hydrotechnical construction is underway, tourism, recreation, etc. are developing. This negatively affects the stability of the coastal zone. Human actions aimed at changing the coastal zone in their own interests began to lead everywhere to the disruption of the stability of natural coastal systems. Solving the problem of coastal protection is connected with the general task of preventing unwanted consequences and their actions. This problem is a key point in harmonizing the relationship between the natural environment and humans in the development of the coastal zone and the sea coast.

Recreational beach complexes are the most important city-forming element of seaside resort towns. They can occupy coastal areas ranging from hundreds of meters to several kilometres along the water's edge and large areas in the adjacent coastal part. This includes both the main urban beach complexes with embankments, park areas and developed service infrastructure, as well as relatively small local autonomous beach areas.

The beaches are the most natural and efficient formations. They provide complete and sustained absorption in areas adjacent to onshore beaches. Beaches can only fulfil this function if they have to be dynamically resistant to waves [1-3].

When choosing coastal protection methods, it is important to take into account errors, as well as take into account the positive results achieved in solving the problem of effective coastal protection. The effectiveness of bank protection measures largely depends on adherence to several conceptual principles.

It is necessary to choose an effective method of bank protection if the decision to build a bank protection structure has been made. The bank protection method should keep the coastal area
dynamically stable. A rational solution to this problem requires an integrated approach to the sea coast as a complex natural system.

Intervention in coastal processes in order to protect the coast from destruction implies the obligatory coordination of natural and technical elements in the form of a single optimized system. The design and construction of coastal protective complexes should cover at least lithodynamic systems or cells that have an autonomous mode of development dynamics, and also have their own sediment balance.

Shore protection technologies are technologies that are used to protect shores from destruction. With the help of modern technologies, reliable structures can be erected. Economic, social and political considerations are taken into account to determine the need for coastal protection. When designing coastal protective measures, it is taken into account that the shores of the seas and other bodies of water are important elements of the human environment and their protection should be carried out in compliance with state requirements for assessing the impact on the environment and nature protection. Flood prevention and mitigation measures are determined by the nature of the flood, storm or abrasion.

Coastal erosion occurs in different ways, but most often it is due to floods, storms and abrasion. The intensification of processes (floods, abrasion, etc.) on the coast can lead to large material and social consequences. For such destruction, coastal protection technologies are required, which must be carried out up-to-date and meet the requirements of the economic justification of engineering solutions and the assessment of their impact on the environment [4, 5].

To continue our consideration of coastal protection technologies, it is first necessary to characterize the above-mentioned damage. A flood is an intense flooding of a large area with water above the annual level, one of the natural disasters. Shore abrasion is the destruction and demolition of land by the surf of water bodies (oceans, seas, lakes, reservoirs, etc.). Waves hitting the shore continuously undermine it, resulting in a wide underwater abrasion terrace that breaks the waves.

Abrasion can increase significantly due to rising ocean levels, tectonic subsidence of the bottom, and increased currents at river mouths.

The coastal defenses are in the conditions of the stage-rhythmic development of the coast. Together with the reduction of the wave impact on the coastal slope and the beach strip, they should regulate the movement of sediments in the coastal zone of the sea. Their action is aimed at redistributing alongshore and lateral transport in order to preserve and restore the beach strip as the main element of coastal protection.

The structures of coastal protective structures during prolonged and seasonal fluctuations in sea level should provide protection of the coast from the effects of waves and ice, both when the sea level rises, and in conditions of its decrease.

Protection of sea coasts from destruction is carried out with the help of special structures. They are divided into coastal fortification and coastal protection.

It is known that coastal protective technologies must solve the problems of stabilization and protect the coastal zone and adjacent land area from destruction. Coastal defenses include breakwaters, artificial reefs, walls, damping waves, sloping coastal fortifications, dams, berms. The holding beach has underwater breakwaters, artificial and natural beaches.

2. Statement of 3D wave hydrodynamics problem

3D wave hydrodynamics mathematical model includes [6-8]:

– equations of motion (Navier - Stokes):

\[
\begin{align*}
\frac{\partial u'_i}{\partial t} + u'u'_i + v'u'_y + w'u'_z &= -\frac{1}{\rho} P'_i + \left( \mu u'_i \right)_{xx} + \left( \mu u'_i \right)_{yy} + \left( \nu u'_i \right)_{zz}, \\
\frac{\partial v'_i}{\partial t} + u'_x v'_i + v'_y v'_y + w'_y v'_z &= -\frac{1}{\rho} P'_y + \left( \mu v'_i \right)_{xx} + \left( \mu v'_i \right)_{yy} + \left( \nu v'_i \right)_{zz},
\end{align*}
\]

(1)
\[ w'_x + uw'_y + vw'_x + ww'_y = -\frac{1}{\rho} P'_x + (\mu w'_y)' + (\mu w'_x)' + (vw'_x)' + g; \]

– continuity equation:

\[ \rho'_x + (\rho u)' + (\rho v)' + (\rho w)' = 0, \quad (2) \]

where \( \mathbf{V} = \{u, v, w\} \) is the velocity vector of the water flow of a shallow water body; \( \rho \) is the density of the aquatic environment; \( P \) is the hydrodynamic pressure; \( g \) is the gravitational acceleration; \( \mu, \nu \) are coefficients of turbulent exchange in the horizontal and vertical directions; \( \mathbf{n} \) is the normal vector to the surface describing the boundary of the computational domain.

Figure 1. Computational domain depth map.

Figure 2. Isolines of the depth function of the bottom surface and the coastline.
Add boundary conditions to system (1)-(2):

- the entrance (left border): \( \mathbf{V} = \mathbf{V}_0, \ P'_n = 0, \)
- the bottom border: \( \rho \mu (\mathbf{V}_n)' = -\mathbf{n}, \ V_n = 0, \ P'_n = 0, \)
- the lateral border: \( (\mathbf{V}_n)' = 0, \ V_n = 0, \ P'_n = 0, \)
- the upper border: \( \rho \mu (\mathbf{V}_n)' = -\mathbf{n}, \ w = -\omega - P'_f/\rho g, \ P'_n = 0, \)
- the surface of the structure: \( \rho \mu (\mathbf{V}_n)' = -\mathbf{n}, \ w = 0, \ P'_n = 0, \)

where \( \omega \) is the intensity of evaporation of a liquid, \( \mathbf{V}_n, \mathbf{V}_t \) are the normal and tangential component of the velocity vector, \( \mathbf{\tau} = \{\tau_x, \tau_y, \tau_z\} \) is the vector of tangential stress. Fig. 1 shows the geometry of the water body.

3. The discrete model of hydrodynamics

The computational domain inscribed in a parallelepiped. For the numerical realization of the discrete mathematical model of the hydrodynamic problem posed, a uniform grid is introduced:

\[
\overline{w}_h = \{t^n = n\tau, x_i = ih, y_j = jh, z_k = kh; \ n = 0..N, i = 0..N_x, j = 0..N_y, k = 0..N_z; \\
N,\tau = T, N, h_i = l_x, N, h_j = l_y, N, h_z = l_z \}
\]

where \( \tau \) is the step by the time, \( h_x, h_y, h_z \) are steps in space, \( N_x, N_y, N_z \) are the number of time layers, \( T \) is the upper bound on the time coordinate, \( N_x, N_y, N_z \) are the number of nodes by spatial coordinates, \( l_x, l_y, l_z \) are the boundaries along the parallelepiped in the direction of the axes \( O_x, O_y \) and \( O_z \) accordingly.

The method of correction to pressure was used to solve the hydrodynamic problem. The variant of this method in the case of a variable density will take the form [9-11]:

\[
\begin{align*}
\frac{\overline{u} - u}{\tau} + u\overline{u}_x + v\overline{u}_y + w\overline{u}_z &= \left(\mu\overline{u}'\right)_x + \left(\mu\overline{u}'\right)_y + \left(\mu\overline{u}'\right)_z, \\
\frac{\overline{v} - v}{\tau} + u\overline{v}_x + v\overline{v}_y + w\overline{v}_z &= \left(\mu\overline{v}'\right)_x + \left(\mu\overline{v}'\right)_y + \left(\mu\overline{v}'\right)_z, \\
\frac{\overline{w} - w}{\tau} + u\overline{w}_x + v\overline{w}_y + w\overline{w}_z &= \left(\mu\overline{w}'\right)_x + \left(\mu\overline{w}'\right)_y + \left(\mu\overline{w}'\right)_z + g,
\end{align*}
\]

\[
\begin{align*}
P'_n + P''_n + P'''_n &= \overline{\rho} - \rho + \left(\overline{\rho\overline{u}'}\right)_x + \left(\overline{\rho\overline{v}'}\right)_y + \left(\overline{\rho\overline{w}'}\right)_z, \\
\frac{\overline{u} - \overline{u}}{\tau} &= -\frac{1}{\overline{\rho}} P'_n, \quad \frac{\overline{v} - \overline{v}}{\tau} = -\frac{1}{\overline{\rho}} P'_n, \quad \frac{\overline{w} - \overline{w}}{\tau} = -\frac{1}{\overline{\rho}} P'_n,
\end{align*}
\]

where \( V = \{u, v, w\} \) are the components of the velocity vector, \( \{\overline{u}, \overline{v}, \overline{w}\}, \{\overline{u}, \overline{v}, \overline{w}\} \) are the components of the velocity vector fields on the «new» and intermediate time layers, respectively, \( \overline{u} = (\overline{u} + u)/2 \), \( \overline{\rho} \) and \( \rho \) are the distribution of the density of the aqueous medium on the new and previous time layers, respectively.
Through \( o_{i,j,k} \) marked the volume of fluid (VOF) of the cell \((i,j,k)\) [10]. VOF is determined by the pressure of the liquid column inside this cell. If the average pressure at the nodes that belong to the vertices of the cell in question is greater than the pressure of the liquid column inside the cell, then the cell is considered to be full \( o_{i,j,k} = 1 \). In the general case, VOF can be calculated by the following formula:

\[
o_{i,j,k} = \frac{P_{i,j,k} + P_{i+1,j,k} + P_{i,j+1,k} + P_{i-1,j-1,k}}{4\rho gh_z}.
\]

We introduce the coefficients \( q_0, q_1, q_2, q_3, q_4, q_5, q_6 \), describing VOF of regions located in the vicinity of the cell (control areas). In the case of boundary conditions of the third kind \( n_{c x y t} = \alpha + \beta \), the discrete analogues of the convective \( uc' \) and diffusion \( (\mu c')' \) transfer operators, obtained with the help of the integro-interpolation method, taking into account the VOF, can be written in the following form [12]:

\[
(q_i)\frac{c_{i+1} - c_i}{2h_z} + (q_j)\left(\frac{c_{j+1} - c_j}{2h_z}\right),
\]

\[
(q_i)\left(\frac{c_{i+1} - c_i}{h_z^2}\right) + (q_j)\left(\frac{c_{j+1} - c_j}{h_z^2}\right) - \left(\frac{c_i - c_{i+1}}{h_z}\right) - \left(\frac{c_j - c_{j+1}}{h_z}\right)\left(\frac{\alpha c + \beta}{h_z}\right).
\]

Similarly, approximations for the remaining coordinate directions will be recorded.

4. Coastal protection structures influence on diffraction and reflection of waves

Decreasing the depth towards the coast or shallow water leads to gradual evolution of gravity surface waves characteristics. Waves transform when they begin to feel the bottom.

The nature of the transformation depends on the bottom topography and the configuration of the coastline. If, during the propagation of waves, their crests are not parallel to isobaths, lines of the same depth, then refraction or refraction occurs, that is, wave rays cease to be straight lines, as in deep water, they bend and tend to become normal to the coast, and the fronts or their crests They tend to become parallel [13-15].

The change of ridges occurs due to the fact that sections of the front closer to the coast, at a shallower depth, move at a slower speed than sections at a greater depth. When waves are refracted on an uneven bottom, their amplitude and length change, but the frequencies remain practically constant.

The wave spectrum undergoes significant changes. The bending of wave rays also occurs during diffraction of waves, they go around obstacles. In this case, the bending of the rays is no longer associated with a change in depth.

The phenomenon of diffraction consists in the propagation of wave energy into an area of wave shadow created, for example, by a bank ledge or an artificial structure such as a breakwater.

Waves reaching shallow waters near headlands move more slowly than over depressions within bays. As a result, the wave front bends, and the wave rays converge at headlands and diverge in bays. This leads to the concentration of wave energy at the capes and to its dissipation in the bays.

When a wave approaches the coast, its crest moves faster than the trough, and the orbital velocity of water particles on the crest of the wave may exceed its phase velocity. At the moment when the crest overtakes the bottom, the wave front becomes vertical and the wave breaks down. The formation of waves in the coastal area is called surf [16].

On more gentle slopes of the bottom, the breaking of waves can occur as a sliding breaker, when water flows down its front slope, as along an inclined plane. Surfers use sliding breaks in the surf zone. In the surf zone, a solitary wave consisting of one crest is also possible.
Waves reaching shallow waters near headlands move more slowly than over depressions within bays. As a result, the wave front bends, and the wave rays converge at headlands and diverge in bays. This leads to the concentration of wave energy at the capes and to its dissipation in the bays [17-19].

When a wave approaches the coast, its crest moves faster than the trough, and the orbital velocity of water particles on the crest of the wave may exceed its phase velocity. At the moment when the “crest overtakes the bottom”, the wave front becomes vertical and the wave breaks down. The formation of waves in the coastal area is called surf.

![Figure 3. The phenomenon of diffraction created by an artificial structure.](image)

On more gentle slopes of the bottom, the breaking of waves can occur as a sliding breaker, when water flows down its front slope, as along an inclined plane. Surfers use sliding breaks in the surf zone. In the surf zone, a solitary wave consisting of one crest is also possible.

5. Results of numerical experiments based on wave-hydrodynamic model

The developed software package is used for the numerical implementation of the proposed three-dimensional model of wave hydrodynamics. It builds a forecast of the movement of the water environment in the presence of a technical object, calculates hydrodynamic power loads on structures.

The most intense growth of waves is observed when the ratio of wave speed to wind speed is less than 0.4-0.5. A further increase in this ratio is accompanied by a decrease in wave growth. Therefore, the waves are dangerous not at the moment of the strongest wind, but at its subsequent weakening. Under conditions of developed excitation, the interference of individual waves occurs, that is, the addition of several waves in space, at which at different points an increase or decrease in the amplitude of the generated wave occurs (up to 2% of the total amount or more), which reach maximum development and exceed the average wave height in two or three times.

Let's turn to the figure, which shows waves running on a coastal aground. Waves traveling through deep water propagate in a certain direction, in the place where the wave begins to feel the influence of the bottom, that is, it enters the shallow coastal zone, refracts, that is, changes the direction of propagation.

The bottom geometry, which is a natural gentle slope, makes it possible to assess the effect of wave refraction, that is, the change in the direction of wave propagation in a shallow coastal strip, as a result of which the wave front tends to take a position parallel to the beach, regardless of the angle at which they initially enter the coastal zone. water. Figure 4 a) shows the process by which a plane wave crest unfolds as it rubs against the bottom in shallow water. Where the slope is wide, flat and its depth changes smoothly, the refraction of surface waves occurs perfectly correctly, so that when the waves enter the surf zone, their crests become almost parallel.
Let us describe the process of occurrence of refraction. When the wave reaches a depth of less than half the wavelength, different sections of the front (crest) will move at different speeds. The area closest to the coastline will slow down, and the front line will bend, refract, cutting off the direction of movement, resulting in refractive waves. If the coastline is not straight but jagged, a very complex wavefield occurs. Not only the wave front is bent, but also the wave beam, therefore, a very complex system of refraction and interference is created.

Single breakwaters, as well as crest-ridges, that is, parallel breakwaters at a certain distance from each other, built to protect the coastal zone, cause diffraction and reflection of waves. Figure 4 b), d) show it. Waves can deviate from direct propagation and bend around obstacles in their path and penetrate into the area behind them, this ability to avoid obstacles is called diffraction. Diffraction depends on the ratio of the wavelength to the size of the obstacle. If the wavelength is greater than the size of the obstacle, then the wave bends around it and propagates further, almost without changing its structure and intensity. When a wave strikes a concrete breakwater at an angle to it, secondary waves do not propagate from the points of the wave front that fell on the breakwater, but from the rest. As a result, the wave will continue on its way and recover behind the breakwater [20].

If the wavelength is comparable to the size of the obstacle, then it partially bends around it. Figure 5 shows the process of their appearance. The wave becomes smaller, shadows appear. If the wavelength is less than the size of the obstacle, then it is reflected from it, and shadow is formed behind the obstacle.

The wave field pattern that appears behind an obstacle can be viewed as a combination of proper diffraction and wave interference. The diffracted wave arises locally in a certain vicinity of the shadow boundary behind the edge of the obstacle. Dividing the wave front surface into so-called half-wave zones, that is, areas whose boundaries are removed from the observer at distances that differ from half the wavelength of the wave incident on the obstacle, the secondary waves emanating from neighboring zones oscillate in antiphase and therefore cancel each other out. In this case, the amplitudes of waves excited by sources separated by one Fresnel zone, on the contrary, add up. The result is an interference wave pattern. The angle between the direction towards the observer and the normal to the front of the
incident wave is of great importance; the larger it is, the smaller the amplitude becomes, and hence the intensity.

Wave scattering occurs when part of the wave goes around an obstacle, and part is reflected from it. Diffraction and scattering processes can greatly distort the structure of the wave field near the coast.

\[ a \]

\[ b \]

\[ c \]

\[ d \]

**Figure 5.** The aquatic environment movement velocity vector.

With walls, shock waves with an extremely sharp and steep leading edge can be observed. Figure 4 c) shows that for the wall of the breakwater, along which the shock wave runs, the pressure equal to zero before the arrival of the front then suddenly reaches its maximum value; further pressure change can be seen from the figure: it falls and goes into the region of lower values.

Figure 5 d) shows that with distance from the source, the wave intensity decreases rapidly. This circumstance is explained not only by geometric reasons - an increase in the area of the wave front as the front moves away from the source, but also by the absorption of wave energy.

The figure shows that as a result of the work of the walls, the wave with all its energy is reflected from it and with force rolls back, eroding the coast. The disappearance of beaches leads to more intense erosion of the underwater slope, and this, in turn, accelerates the deformation or collapse of the walls. Erosion and a decrease in the width of the beach are also observed, which means they contribute to the rapid disappearance of beaches.
The development of a three-dimensional model of wave hydrodynamic processes based on field data made it possible to describe the movement of the aquatic environment of a shallow reservoir, taking into account the presence of bank protection structures and the propagation of waves to the coast.

Modern software package adapted for modeling hydrodynamic wave processes, used in a wide range of parameters for calculating the fields of velocities and pressures of the aquatic environment, as well as for assessing the hydrodynamic impact on the coast and shore protection structures in the presence of surface waves.

Conclusion
The paper studies the influence of coastal protection structures on the diffraction and reflection of waves. The process of occurrence of diffraction, refraction and reflection of waves is described on the basis of 3D model of wave hydrodynamic processes. The movement of the aquatic environment is described, taking into account the presence of bank protection structures and the propagation of waves to the coast. The software package is adapted to simulate hydrodynamic wave processes, is used to calculate the fields of velocities and pressures of the aquatic environment and to assess the hydrodynamic impact on the shore and shore protection structures.

6. Acknowledgments
This paper was supported by the Russian Foundation for Basic Research (RFBR) grant No. 19-31-90091.

References
[1] John M H 2019 Coastal-Trapped Waves Encyclopedia of Ocean Sciences (Third Edition) (Academic Press) 598–605
[2] Tang J, Lyu Y, Shen Y, Zhang M, Su M 2017 Numerical study on influences of breakwater layout on coastal waves, wave-induced currents, sediment transport and beach morphological evolution Ocean Engineering 141 375–387
[3] Huang B, Zhu B, Cui S, Duan L, Zhang J, 2018 Experimental and numerical modelling of wave forces on coastal bridge superstructures with box girders Ocean Engineering 149 53–77
[4] Ferrer M et al. 2016 A multi-region coupling scheme for compressible and incompressible flow solvers for 2-phase flow in a numerical wave tank. Computer & Fluids 125 116–129
[5] Martinez-Ferrer P J, Qian L, Ma Z, Causon D M, Mingham C G 2018 Improved numerical wave generation for modelling ocean and coastal engineering problems Ocean Engineering 152 257–272.
[6] Sukhinov A I, Chistyakov A E 2011 Numerical realization of the three-dimensional model of hydrodynamics for shallow water basins on a high-performance system Mathematical Models and Computer Simulations 3 (5) 562–574
[7] Sukhinov A I, Chistyakov A E, Timofeeva E F, Shishenya A V 2013 Mathematical Model of Calculation of Coastal Wave Processes Mathematical Models and Computer Simulations 5(2) 122–129
[8] Sukhinov A I, Chistyakov A E 2019 Coupled 3D wave and 2D bottom deposit transportation models for the prediction of harmful phenomena in coastal zone Proceedings of the 7th International Conference on Marine Structures (Croatia, Dubrovnik) pp 597–603
[9] Alekseenko E, Roux B and etc. 2013 Nonlinear hydrodynamics in a mediterranean lagoon, Nonlinear Processes in Geophysics 20(2) 189–198
[10] Debolskaya E I, Dolgopolova E N 2017 Vertical distribution of a pollutant in river flow: mathematical modeling Water Resources 44(5) 731–737
[11] Nikitina A V, Sukhinov A I, Ugolnitsky G A, Usov A B 2017 Optimal control of sustainable development in the biological rehabilitation of the Azov Sea. Mathematical Models and Computer Simulations 9 (1) 101–107
[12] Sukhinov A I, Chistyakov A E, Levin I I 2016 Solution of the problem of biological rehabilitation
of shallow waters on multiprocessor computer system 1128–1133.

[13] Protsenko S, Sukhinova, T 2017 Mathematical modeling of wave processes and transport of bottom materials in coastal water areas taking into account coastal structures. *MATEC Web of Conferences* 132 04002

[14] Buzalo N, Ermachenko P, Bock T, Bulgakov A, Chistyakov A, Sukhinov A, Zhmenya E, Zakharchenko N 2014. Mathematical modeling of microalgae-mineralization-human structure within the environment regeneration system for the biosphere compatible city. *Procedia Engineering* 85 pp. 84–93.

[15] Sukhinov A I, Khachunts D S, Chistyakov A E 2015 A mathematical model of pollutant propagation in near-ground atmospheric layer of a coastal region and its software implementation *Computational Mathematics and Mathematical Physics* 55 (7) 1216–1231

[16] Chorin A J 1967 A numerical method for solving incompressible viscous flow problems. *J. Comput. Phys.* 2 (1) 12–26

[17] Hirt C W, Nichols B D 1981 Volume of fluid (VOF) method for the dynamics of free boundaries. *Journal of Computational Physics* 39 (1) 201–225

[18] Suhinov A I, Chistyakov A E, Timofeeva E F, Shishenya A V 2013 Mathematical Model of Calculation of Coastal Wave Processes. *Math. Models Comput. Simul.* 5:2 122–129

[19] Sukhinov A I, Chistyakov A E 2012 Adaptive Modified Alternating-Triangular Iterative Method for Solving Grid Equations With Non-Self-Adjoint Operator. *Math. Models Comput. Simul.* 4 (4) 398–409.

[20] Sukhinov A I, Chistyakov A E, Protsenko E A 2014 Mathematical Modeling of Sediment Transport in the Coastal Zone of Shallow Reservoirs. *Mathematical Models and Computer Simulations* 6(4) 351–363