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ESTABLISHING PATTERNS OF CHANGE IN THE COEFFICIENTS OF REFLECTION, TRANSMISSION, AND DISSIPATION OF WAVE ENERGY DEPENDING ON PARAMETERS OF A PERMEABLE VERTICAL WALL

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The object of research is permeable vertical walls (breakwaters) with different degrees of permeability.

This paper reports the results of experimental research into the interaction of gravity waves with models of permeable vertical walls (breakwaters), which were formed from cylindrical piles of circular cross-section.

With the help of visual and instrumental studies, the features of interaction of surface gravity waves with permeable vertical walls of different permeability have been identified. The degree of wave transformation by these walls was also determined in the form of reflection, transmission, and dissipation coefficients of wave energy.

It was established that with a decrease in the permeability of the vertical wall and an increase in the steepness of the initial wave and a decrease in its period, the height of the reflected wave increased. The pattern of the transmitted wave height had the opposite trend.

It was determined that the wave reflection coefficient increased with a decrease in the permeability of the vertical wall and the steepness of the initial wave. The wave transmission coefficient had the opposite trend, namely, it increased with increasing wall permeability and with decreasing steepness of the initial wave. The gravity wave energy dissipation coefficient decreased with increasing vertical wall permeability, but for waves with a significant steepness $h_i/\lambda>0.038$, a decrease in the wave energy dissipation coefficient was observed for walls with low permeability and the appearance of extreme values of this coefficient.

Thus, features in the interaction of surface gravity waves with permeable vertical walls (breakwaters) of different permeability have been researched and the degree of wave transformation by these walls has been determined, which could make it possible to effectively design and operate permeable vertical walls as coastal protection structures

Keywords: gravity wave, permeable vertical wall, breakwater, reflection, wave transmission, wave energy dissipation

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1. Introduction

The rise in the level of the World Ocean and the increase in the number and intensity of storms, typhoons, and tsunamis require the improvement of coastal defense construction both quantitatively and qualitatively. Coastal defense structures in the form of dikes, dams, and breakwaters protect coastal infrastructure, shorelines, recreation areas, beaches, moorings, etc., which is extremely important for countries with access to the seacoast. Therefore, significant attention is paid to the design and construction of coastal protection structures, and in particular to breakwaters in the form of vertical walls, both in scientific and practical terms.

Traditional breakwaters or vertical walls that extend from the surface of the water to the seabed in the coastal zone have a number of disadvantages in terms of their economy and environmental safety. The location of such structures, which have a sufficiently large length along the coastline, leads to significant erosion of the soil in front of the structures. This occurs due to the action of wave motion, especially under stormy conditions. It also leads to a significant increase in the length of the migration path of marine animals between the open sea and the coastal zone or places of reproduction and feeding. In addition, the large length of closed coastal protection structures worsens the exchange of water masses between the seaward part of breakwaters, walls, dams, and their coastal water areas. This causes significant pollution of the water surface in the protected zone and an increase in bottom sediments in this zone. Therefore, much attention is paid to the development and design of permeable coastal defense structures, which have pile structures of different permeability in the bottom parts. Such structures have relatively small financial and material costs, improve environment in the locations of these structures, reduce bottom erosion and bottom soil erosion processes, and large-scale circulation currents around permeable structures.

The characteristics of wave reflection from mooring structures affect the navigation of ships, the life of the ship, the stability of the mooring structure, and the overall functioning of the protective barrier. The characteristics of wave penetration and dissipation are among the main ones during the design, construction, and operation of coastal protection structures and other hydrotechnical structures.

Penetrating breakwaters and vertical and inclined walls are widely used in harbors, ports, and marinas to create calm zones from wave loads. Therefore, the study of wave propagation through porous walls or screens is of considerable scientific interest to specialists in applied mathematics and mechanics, as well as hydraulic engineers. During the interaction of the wave field with the permeable structure, reflection, penetration, and dissipation of waves occur [1]. Reflected waves are formed in front of the front surfaces of breakwaters, and penetrating waves move through the gaps of the permeable wall and form behind it [2]. The main source of wave dissipation [3] is detachment regions on streamlined piles [4], the formation of jet and eddy currents [5], and the generation of trailing eddy currents [6]. Establishing patterns of changes in the coefficients of reflection, penetration, and dissipation of gravity waves depending on the parameters of the permeable vertical wall has further practical application during the design and operation of permeable vertical walls.

Therefore, given the above, it is advisable to conduct experimental studies on the development of methods and procedures for determining the characteristics of the interaction of gravity waves with models of coastal defense structures in the form of permeable vertical walls of different permeability. This will make it possible to establish the patterns of changes in the coefficients of reflection, penetration, and dissipation of waves depending on the parameters of the permeable wall. This is an urgent task and meets the requirements of modern coastal defense construction.

2. Literature review and problem statement

There are various research approaches to study the effect of wall porosity on the characteristics of breakwaters and their interaction with the surrounding wave field, including computational equations, analytical methods, numerical modeling, and physical or experimental model testing. A lot of analytical, numerical, and experimental works have been performed, which are reported in the review paper [7], which are aimed at the development of economically and environmentally effective permeable coastal protection facilities and structures using modern methods and models of numerical and physical modeling. Starting with work [8], the first tests were conducted to determine the characteristics of the interaction of the wave field with the permeable structures of coastal protection structures partially buried in deep water conditions [9]. Later, for example, works [2, 10] expanded the understanding of this interaction, defined the main structural and hydrodynamic parameters that affect the efficiency of using permeable breakwaters and vertical walls. In particular, in [10], studies of the effect of a permeable vertical wall in front of a caisson breakwater on the reflection of a gravity wave were carried out. However, in [7–10] not enough attention was paid to determining the influence on the coefficients of reflection, penetration, and energy dissipation of various structural elements of a permeable wall, namely, the shape and location of piles or supports and a wider range of wall permeability (from 10 % to 60 %).

Before a new permeable or perforated wave enters the stage of physical model testing, it is necessary to conduct thorough parametric studies and investigate the physical mechanism to verify its realism and ensure the success of experimental model testing. Among non-physical modeling approaches, analytical and numerical methods based on potential flow theory are often used because they are more efficient than those that consider flow viscosity. In addition, the conditions of inviscid, incompressible fluid and inertial flow are assumed [11]. Potential flow models assist in understanding the underlying mechanisms that determine the performance of porous breakwaters or vertical or inclined walls. The results provide satisfactory estimates of important hydrodynamic parameters, as noted in [7].

Numerical modeling of the interaction of waves with permeable vertical or inclined walls or breakwaters was carried out using the methods of computer hydrodynamics [12]. The mathematical models built are based, as a rule, on the linear theory of waves and their interaction with obstacles. These include the methods of decomposition by eigenfunctions [13], quasi-linear methods that take into account the nonlinear characteristics of local areas of the permeable wall [14]. It should be noted that the method of decomposition by eigenfunctions is the most widely used analytical approach. According to this method, it is assumed to divide the entire fluid region into several subregions, to construct analytical equations of the velocity potential, which partially satisfy the boundary conditions. Then the unknown parameters are solved by matching the solution on the boundaries of the subdomains. Analytical models using the method of eigenfunctions are reported in [1, 15] to estimate the reflection and penetration of monochromatic waves by slotted single-row and double-row breakwaters. In work [13], the peculiarities of wave scattering by an array of thin, porous walls in the ocean with a variable topography of the bottom were considered using numerical modeling methods using the theory of linear waves. Since the existing mathematical models [16, 17] use significant simplifications, an important component is their experimental verification [18, 19]. Thus, vertical and inclined walls with horizontally located slits were investigated in [16]. However, the influence of the formation of vortex structures, which originate during the formation of a coupled flow, was not determined, and the porosity of the structure was insignificant (from 10 % to 30 %). In [17], a vertical wall with horizontal slits was also considered, and the wall did not reach the bottom of the wave channel. Therefore, in [18], research was conducted with a group of vertical piles and the characteristics of the horseshoe-shaped vortex structures generated at the junction of the piles with the bottom of the channel were determined. But the studies were carried out for stationary flow and the peculiarities of the formation of vortex structures around piles, and their influence on soil erosion and erosion is observed for wave motion only when there are currents between the piles during the interaction with the piles of crests and troughs of waves. In work [19], wave loads on a continuous dam were determined and the permeability of the structure was not investigated, and accordingly, wave transformation coefficients were not obtained.

In [20–22], experimental studies were carried out to determine the features of the wave field transformation. For example, in [20], studies were performed with perforated vertical and inclined plates of low permeability (up to 20 %). It was determined that the greatest absorption of wave energy occurred for 10 % permeability of a plate with holes inclined at an angle of 15 degrees. In works [21, 22], experiments were conducted with single-row perforated pile structures with penetration up to 30 %. It was determined that the greatest wave transformation was observed for a permeability of 24 % [22], and perforation in the form of holes on bearing pile structures was optimal for a permeability of 12.4 % [21]. In these works, as well as in [16], studies were carried out for small permeability of the walls, which is insufficient for the practical use of permeable walls from the point of view of the formation of eddy and jet currents between the piles and the corresponding changes in the coefficients of reflection, penetration, and dissipation of wave energy.

In [23–25], experimental studies were carried out on the determination of soil erosion near a group of supports under the conditions of wave and channel currents, as well as the determination of the sources of formation of erosion. For example, in [23] research was carried out to study the mechanisms of erosion generation near a group of piles under the action of regular waves. Erosion was formed by the oscillating current through the gaps between the supports, which was generated by the wave field, and the depth and shape of the erosion depended on the intensity of the wave movement, the permeability of the vertical wall, and the dimensions of the supports themselves. In work [24], the peculiarities of the formation of soil erosion in the tandem configuration of the supports, which were flowed around by the current at a constant speed under shallow water conditions, were experimentally investigated. In [25], the peculiarities of the generation of scours and the sources of the formation of scours under the conditions of group flow around piles were studied. The sources of soil erosion, which are jet and eddy currents between the piles, were established, and the zones of formation and evolution of horseshoe-shaped vortex structures and trailing vortices were shown. The geometric, kinematic, and dynamic characteristics of unsteady and non-homogeneous flow in the gaps between permeable fire structures are presented. Works [24, 25] determine the peculiarities of the formation of eddy and jet flows in multi-pile structures from the point of view of hydrodynamics, but they do not consider the reciprocating movement of the liquid between the piles during wave loading.

In [26, 27] the results of measurement of velocity and pressure pulsation fields inside recesses on the streamlined surface and near them are reported. In [26], the peculiarities of the generation of coherent vortex structures inside a spherical hole were investigated and the parameters of the field of wall pressure pulsations, the sources of which are eddy and jet currents generated by the hole, were determined. In [27], the velocity and pressure fields generated by the hole generator of vortices were studied. The spectral and correlation dependences of velocity and pressure pulsations were obtained, and the spatial-temporal characteristics of the wall velocity and pressure field were determined, as well as the vortex structure of the boundary layer of the plate with a hole. It was established [28] that the dynamic pressure of wave motion on a permeable vertical obstacle gradually decreased from the front part of the obstacle to its stern part. It was determined that the ability of perforated plates to absorb waves depended on the characteristics of the wave field, optimal porosity and slope of the structure, and the dynamic pressure coefficient decreased with increasing relative water depth. Works [26, 27] were carried out for a stationary flow and determine the peculiarities of the formation of the eddy current in depressions and behind obstacles on the streamlined surface and do not take into account the influence of wave motion on hydrodynamic parameters and wave transformation coefficients. In [28], the influence of the features of the design of the permeable vertical wall on the transformation coefficients of the vortex motion was not investigated.

In work [29] it was established that the most probable period of occurrence of a breakthrough wave is the time of a spring flood or heavy rain. At this time, water pressure structures are subjected to significant loads, which lead to the destruction of their individual elements or the entire structure. However, the study did not consider the reflection coefficient depending on the penetration of the wall. In [30], to reduce erosion in the area of bridge crossings, it is proposed to regulate the riverbed by creating a channelized riverbed. The results of the calculations showed that erosion in the span of the road bridge has decreased and does not exceed 1.5 m. However, the paper did not conduct research on the influence of the permeability of the bridge supports on the coefficient of deflection of the wave crest.

Taking into account the above research results and critical remarks about the findings and unexplored features of the formation of eddy and jet currents between piles or supports of permeable vertical walls and the influence of the degree of their permeability on the features of wave transformation, there is a need to conduct additional scientific research. At the same time, it is necessary to determine the features of the interaction of surface gravity waves with permeable vertical walls and their transformation in a broader sense of the degree of permeability of the wall because this is required by the economic and environmental feasibility of using such walls. It is also necessary to determine their influence on bottom currents and deformation of the bottom surface in the locations of permeable vertical walls.

3. The aim and objectives of the study

The purpose of our work is to determine patterns in the interaction of surface gravity waves with permeable vertical walls (breakwaters) of different permeability and to determine the degree of transformation of waves by these walls, which will allow effective design and operation of permeable vertical walls.

To achieve the specified goal, the following tasks must be completed:

– to conduct experimental research on the transformation of wave motion through the interaction of waves with models of permeable vertical walls of different permeability;

– to establish regularities of changes in the heights of the reflected and transmitted waves from the permeability of the wall at different steepness and the initial period of the wave crest;

– to determine the coefficients of reflection, penetration, and dissipation of gravity wave energy through a permeable vertical wall.

4. Research materials and methodology

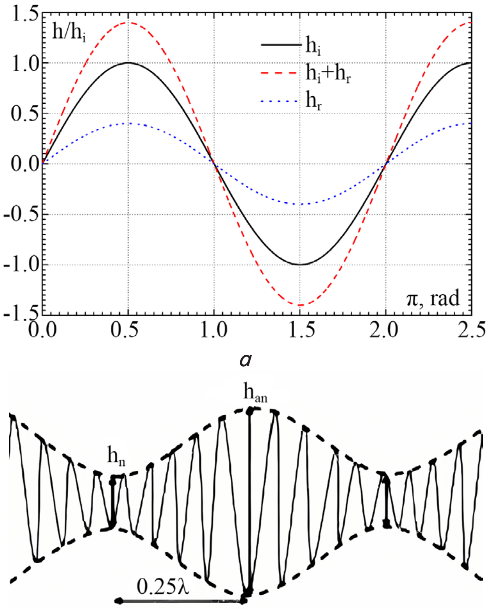
4. 1. Theoretical aspects of evaluating the parameters of reflected and transmitted waves when interacting with permeable vertical walls

The object of research is permeable vertical walls (breakwaters) with different degrees of penetration. The hypothesis put forward assumes that during the interaction of gravity waves with permeable walls, the transformation of waves in the form of a wave reflected and transmitted through a vertical wall occurs, wave energy is dissipated, eddy and jet reciprocating currents are formed between the piles and scouring and washing deformations of the scouring soil occur near permeable vertical walls.

The work was carried out under laboratory conditions on models of permeable vertical walls with different permeability from 10 % to 60 % and for different parameters of gravity waves generated by shield wave generators.

The effectiveness of breakwaters or vertical walls, which are used as coastal protection structures, is determined by the characteristics of the formation of reflected and penetrating waves. Also, the ability to absorb or dissipate wave energy by a breakwater. The efficiency of such structures is determined by the coefficients of wave reflection (C_R), wave penetration (C_T), and wave energy dissipation (C_E). The determination of these coefficients in research was carried out by measuring wave heights in front of and behind a penetrating breakwater.

The height of the reflected wave was determined in two ways. The first method is to determine the height of the reflected wave by measuring the height of the standing wave with a wave height sensor, which was located along the axis of the wave channel in front of the breakwater at a distance of more than one length of the initial wave. It should be noted that the height of the initial wave was measured in test studies of the operation of the wave generator in the absence of a vertical wall inside the wave channel and wave absorption. The height of the reflected wave was determined by subtracting the height of the initial wave from the height of the standing wave, as schematically shown in Fig. 1, *a*. This representation is possible when the standing wave is a superposition of the initial and reflected waves, which have the same period and transfer speed (velocities are in opposite directions).



a

b

Fig. 1. Methods for determining wave heights: *a* – single-point; *b* – two-point

As a result, the speed of movement of the standing wave in the longitudinal direction is zero and the standing wave makes only vertical oscillations. For this method of determining the height of a reflected wave, the wave reflection coefficient was determined as:

$$C_R = \frac{h_R}{h_i}. \tag{1}$$

The second method is to determine the height of the reflected wave using two wave height sensors, one of which was a wavelength (λ) away from the breakwater and the other 1.25λ away from the breakwater. The first sensor measured the height of the wave (h_{an}) in the swelling of the standing wave, which was formed as a result of the interference of the initial wave and the reflected wave. The second sensor measured the wave height (h_n) at the node of the standing wave (Fig. 1, *b*).

The height of the initial wave was determined as:

$$h_i = \frac{h_{an} + h_n}{2}, \tag{2}$$

and the height of the reflected wave was defined as:

$$h_R = \frac{h_{an} - h_n}{2}. \tag{3}$$

Hence, the wave reflectance was defined as:

$$C_R = \frac{h_R}{h_i} = \frac{h_{an} - h_n}{h_{an} + h_n}. \tag{4}$$

The penetrating wave height (h_T) was measured by a wave height sensor at a distance of 0.5λ along the longitudinal axis of the wave channel behind the permeable vertical wall. As a result, the wave transmission coefficient through the vertical wall was calculated as:

$$C_T = \frac{h_T}{h_i}. \tag{5}$$

The values of wave reflection and transmission coefficients, as well as the ratio between them, are greatly influenced by physical processes that occur during the interaction of waves with permeable coastal defense structures. When a breakwater is installed in the marine environment, significant changes in the wave field occur [9]. Interference, diffraction, and transformation of waves are observed, reflected, standing and penetrating waves appear, collapse of waves occurs. Orbital velocities of wave motion undergo changes, turbulence increases, especially for breakwaters with negligible permeability. In front of the breakwater and supporting piles, horseshoe-shaped and wake vortices are generated, as well as jet currents between the piles. This leads to an increase in friction between the wavy surface and the moving fluid, as well as the dispersion or dissipation of wave energy.

The law of conservation of energy of the initial gravity wave interacting with a permeable vertical wall follows the equation:

$$E_i = E_R + E_T + E_D, \tag{6}$$

where E_i is the energy of the initial wave ($E_i = \rho g h_i^2 / 8$); E_R is the energy of the reflected wave ($E_R = \rho g h_R^2 / 8$); E_T is the energy of the wave ($E_T = \rho g h_T^2 / 8$); transmitted through the waveguide; E_D is the energy of the wave dissipation. Substituting the values of E_R, E_T and E_D into equation (6), and also dividing the components of this equation by E_i, we get:

$$1 = \left(h_R / h_i\right)^2 + \left(h_T / h_i\right)^2 + E_D / E_i, \tag{7}$$

or

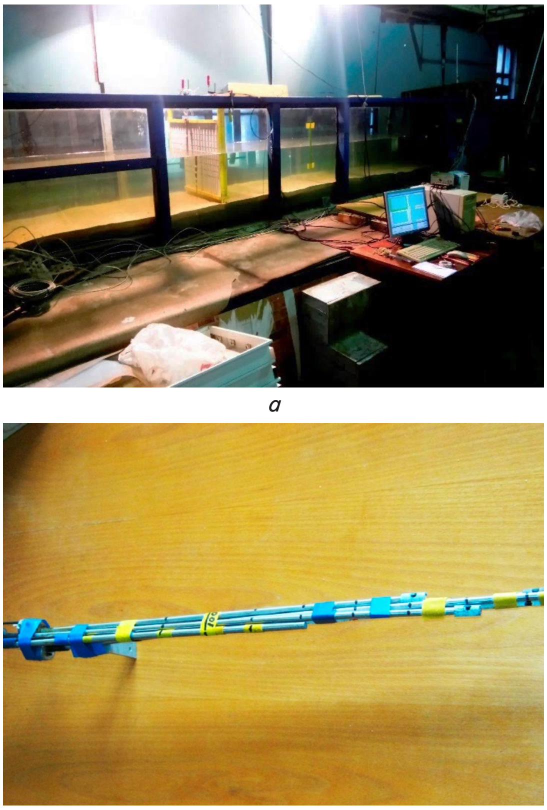
$$C_E = 1 - \left(C_R^2 + C_T^2\right). \tag{8}$$

The above dependences and formulations for determining the coefficients of reflection, transmission, and dissipation of wave energy were used during calculations and analysis of experimental data.

4. 2. Methodology of experimental studies on the effect of a permeable vertical wall on the movement of gravity waves

Experimental work on determining the influence of a permeable vertical wall on the movement of gravity waves was performed under laboratory conditions in a wave channel. The open-type wave channel was 50 m long, 1 m wide, and 1 m deep. The channel was equipped with a shield-type wave generator and an oblique breakwater. The side walls of the wave channel were made of thick-walled glass for conducting visual studies and video-photography. At a distance of about 40 m from the wave generator, a measuring area was equipped, where models of the structures under study, data collection, and registration systems, coordinate devices, and means of mounting sensors and video surveillance were located. The bottom of the wave channel at the location of the permeable vertical wall model was filled with sifted quartz sand to a height of 0.2 m, and the water level above the sand surface was H=0.4 m (Fig. 2, *a*).

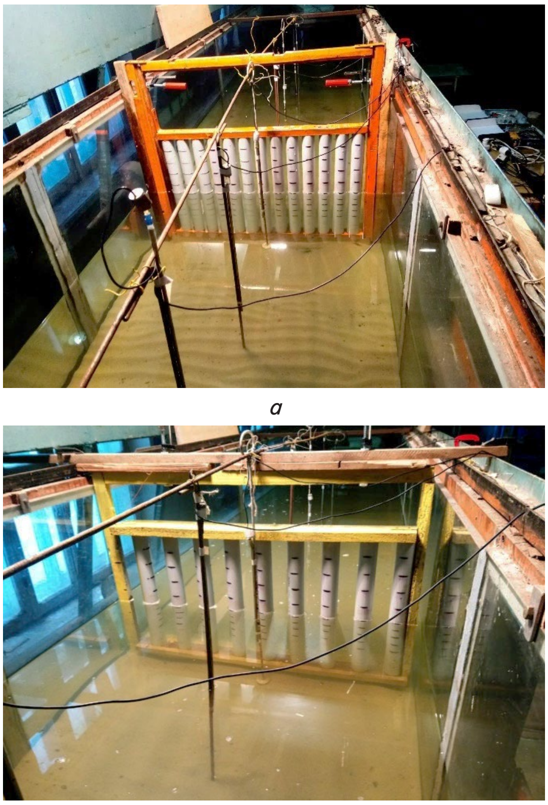
In the experiments, a vertical wall of different penetration was used, which is made of cylinders with a circular cross-section with a diameter of d=0.05 m. An example of the location of permeable vertical walls in a wave channel is shown in Fig. 3. Thus, Fig. 3, *a* shows a model of a permeable vertical wall with a permeability of 20 %, and Fig. 3, *b* shows a wall with a permeability of 50 %.



a

b

Fig. 2. Experimental setup: *a* – experimental bench; *b* – a group of wave height sensors



a

b

Fig. 3. Models of the permeable vertical wall inside the wave channel: *a* – permeability 20 %; *b* – permeability 50 %

The length of the permeable vertical wall was 1 m, and the wall was installed perpendicular to the longitudinal axis of the channel. Thus, the vertical wall covered the width of the wave channel, and the wave motion passed through the gaps of the permeable wall into the aft part of the channel. As a result of the interaction of gravity waves with a vertical wall, the height of the waves in front of the wall was higher than behind it. The difference between these wave heights depended on the degree of penetration of the vertical wall, which was recorded by wave height sensors and video surveillance and analysis of the results of visual studies. Fig. 3 shows individual wave height sensors located both in front of and behind the vertical wall.

Gravitational wave heights were measured by specially designed piezoresistive wave height sensors, which are shown in Fig. 2, *b*. The structure of these sensors was designed on the basis of highly sensitive dynamic and static pressure sensors using a thin-walled quartz membrane, on which micro electronic elements were applied [26], which recorded the deflection of the membrane under the action of a pressure drop [27]. These sensors were mounted on a thin-walled stainless steel tube, and the other end of this tube was submerged below the surface of the water for a fixed distance. Thus, Fig. 2, *b* shows a group of wave height sensors that were immersed to different depths from the water surface and recorded as static pressure corresponding to the sensor's immersion depth. The dynamic pressure formed under the action of the wave motion at the fixed depth of the location of each sensor was also recorded. Thus, a group of wave height sensors or individual such sensors were placed vertically in the wave channel and recorded wave heights both along the depth of the channel and along its longitudinal axis in front of the vertical wall and behind it. The sensitivity of such sensors was 2.0 Pa or 0.2 mm of water column.

Wave height sensors were located along the longitudinal axis of the wave channel both in front of the permeable vertical wall model and behind it. In addition, the sensors were located at the minimum possible distances in front of the frontal and aft surfaces of the vertical wall. The sensors were fixed both individually at the research site and as a group at different depths, as shown in Fig. 2, *b*, near the surface of the wall for recording the wave pressure on the surface of the vertical wall. The locations of the sensors varied depending on the problem being solved in one or another of the researched areas, as well as the parameters of the wave motion. In total, 8 to 12 wave height sensors worked simultaneously in the experiments. That made it possible to study the peculiarities of the interaction of the wave field with the model of the permeable wavelet in sufficiently wide limits of the spatial field both along the length of the channel and along its depth.

The electrical signals generated by the wave height and wave pressure sensors were fed to electrical signal amplifiers, filtered, and fed to a 16-channel analog-to-digital converter and then to a computer system for processing and analyzing experimental data.

Processing and analysis of the results of experimental studies were carried out using standard and specially developed algorithms and programs using the apparatus of probability theory and mathematical statistics.

In addition to instrumental measurements of the parameters of the wave field, visual studies were carried out using various dyes, inks, and contrasting colored water-soluble coatings, which were washed away by water under the influence of wave motion. Images were recorded using a digital video camera, processed, and analyzed using a custom-built graphics computer station. This station made it possible to speed up and slow down the video material, as well as to do a frame-by-frame data analysis with its fixation on the computer.

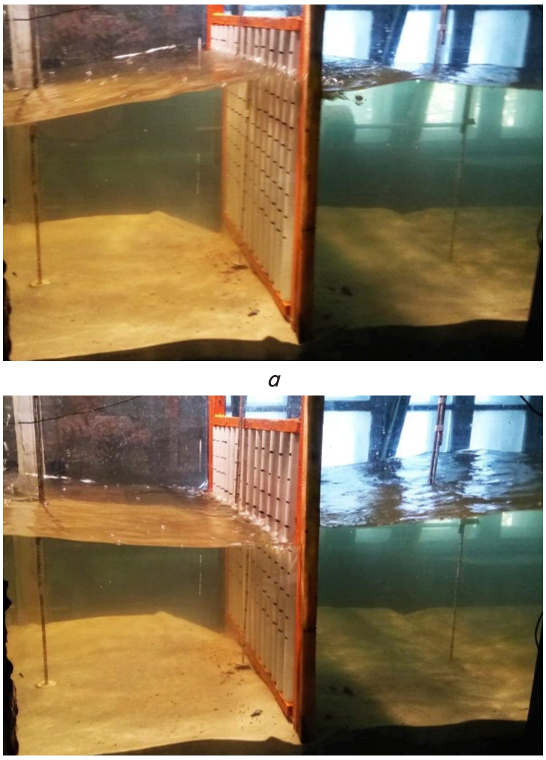
Thus, experimental studies of the interaction of gravity waves with models of permeable vertical walls (breakwaters) with cylindrical piles of circular cross section of different permeability were carried out under different parameters. Flow depth $H=0.05$ m; height of the initial gravity wave generated by the wave generator $h_i=(0.04–0.24)$ m. Gravity wave period $T=(0.8–3.3)$ s; wavelength $\lambda=(1.2–17.4)$ m; frequency of wave motion $f=(0.3–1.2)$ Hz; and wave number $k=(0.4–5.3)$ 1/m. The permeability of the vertical wall model is $\Delta=(0–60)$ %; the diameter of the cylindrical pile is $d=0.05$ m.

5. Results of investigating the peculiarities of interaction of wave motion with permeable vertical walls

5. 1. Results of visual studies on wave motion transformation

According to the program and methodology of experimental research, visual observations and registration of features of interaction of wave motion with permeable vertical walls were carried out in parallel with instrumental measurements of wave field parameters. Measurements were performed both in front of the permeable vertical wall and behind it using a group of wave height sensors.

The results of visual studies with the help of video-photographic equipment made it possible to evaluate the transformation of the wave field due to the interaction of waves with models of permeable vertical walls of different permeability. Examples of moments of approach of the crest and sole of gravity waves for vertical wall permeability of 20 % and 50 % are shown in Fig. 4, 5.

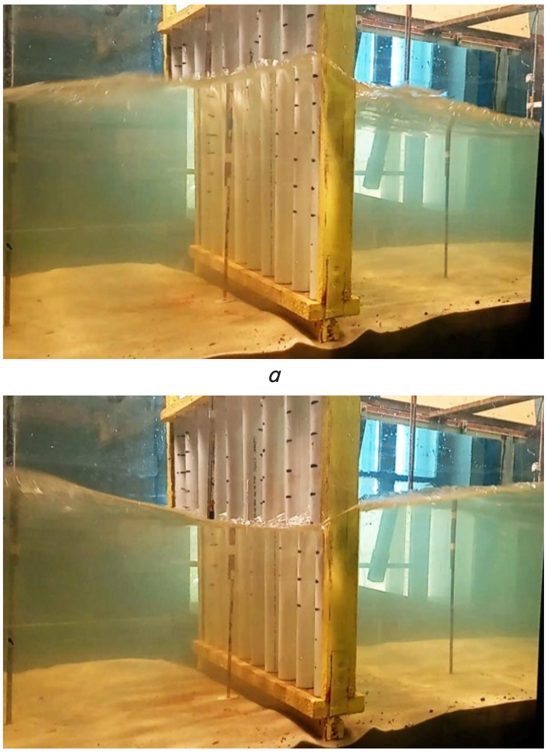

a

b

Fig. 4. The moment a gravity wave approaches a model of a permeable vertical wall with a permeability of 20 %: *a* – wave crest; *b* – soles of the wave

Thus, the wave height in front of a vertical wall with a permeability of 20 % is almost 4–5 times higher than behind it. During the approach of the crest of the wave to the wall (Fig. 4, *a*), a fairly intense flow of water through the gaps in the wall to its aft side was observed. When the bottom of the gravity wave approached the wall (Fig. 4, *b*), the flow was observed in the opposite direction from the aft part of the permeable vertical wall to its frontal part. As the height of the initial wave increased, the speed of water movement through the gaps in the wall increased.

Fig. 5 shows the moments of the crest and trough of a gravity wave through a model of a permeable vertical wall with a permeability of 50 %.



a

b

Fig. 5. The moment a gravity wave approaches a model of a permeable vertical wall with a permeability of 50 %: *a* – crest of a wave; *b* – soles of the wave

The results of visual studies showed that the difference in wave heights in front of the permeable wall and behind it significantly decreased compared to the variant of studies with a 20 % permeability wall. Such wide gaps between the cylinders caused a decrease in the fluid flow rate between the frontal and aft parts of the permeable vertical wall. It should be noted that the maximum velocities occurred during the approach of the wave crest and its sole to the surface of the porous wall, but the directions of their movement were opposite.

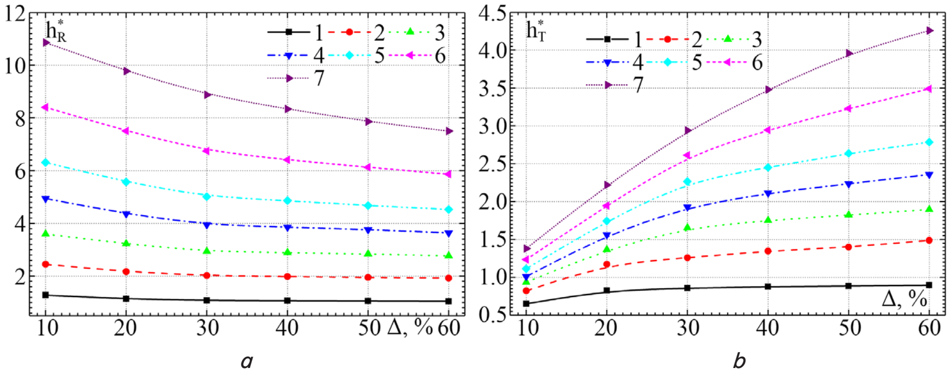
5. 2. Results of instrumental research on wave transformation

We have obtained results of the measured wave heights and the calculated results of the values of the coefficients of reflection, passage and dissipation of gravity waves depending on the permeability of the vertical wall and parameters of wave motion. They showed the features and degree of influence of a permeable vertical wall on the wave field generated in the wave channel.

Fig. 6 shows the values of the measured heights of the reflected (h_R/H) and transmitted (h_T/H) waves, which are normalized to the depth of the wave channel (H), in front and behind a permeable vertical wall with circular cross-section piles from the permeability of the wall $\Delta=b/(d+b)$, where b is the width of the gap between the cylinders with a diameter d, for different steepness of the initial wave (h_i/λ), where λ is the length of the initial wave.

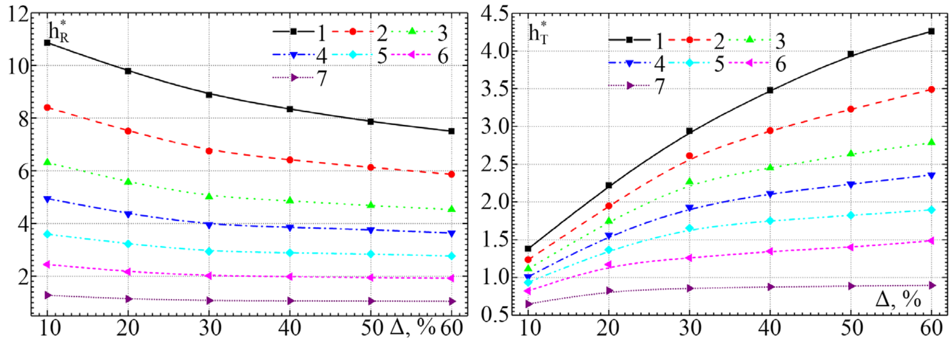
The results of our study showed that with a decrease in the permeability of the vertical wall and an increase in the steepness of the initial wave, the height of the reflected wave increased (Fig. 6, *a*). As the permeability of the vertical wall decreased, the height of the penetrating wave also decreased, as shown in Fig. 6, *b*, but increased with increasing steepness of the initial wave. At the same time, the rate of decrease in the height of the reflected wave and increase in the transmitted wave is significantly higher with an increase in the width of the gap for low permeability of the wall than in conditions of high permeability of the wall.

Fig. 7 shows the values of the measured heights of the reflected and transmitted waves. They are normalized to the depth of the wave channel (H), in front and behind the permeable vertical wall with piles of circular cross-section from the permeability of the wall for different periods of the initial wave. The normalized wave heights are given depending on the normalized period of the initial wave TU_φ/d, where T is the period of the initial wave, U_φ is the phase velocity of the wave motion, and d is the diameter of the cylindrical pile. It should be noted that the phase speed of the wave motion was calculated from the dependence $U_\varphi=\lambda/T$.



a *b*

Fig. 6. Dependences of wave heights on wall permeability for different steepness of the initial wave: *a* – reflected; *b* – permeable: curve 1 – $h_i/\lambda=0.002$, curve 2 – $h_i/\lambda=0.006$, curve 3 – $h_i/\lambda=0.020$, curve 4 – $h_i/\lambda=0.038$, curve 5 – $h_i/\lambda=0.065$, curve 6 – $h_i/\lambda=0.116$ and curve 7 – $h_i/\lambda=0.204$



a *b*

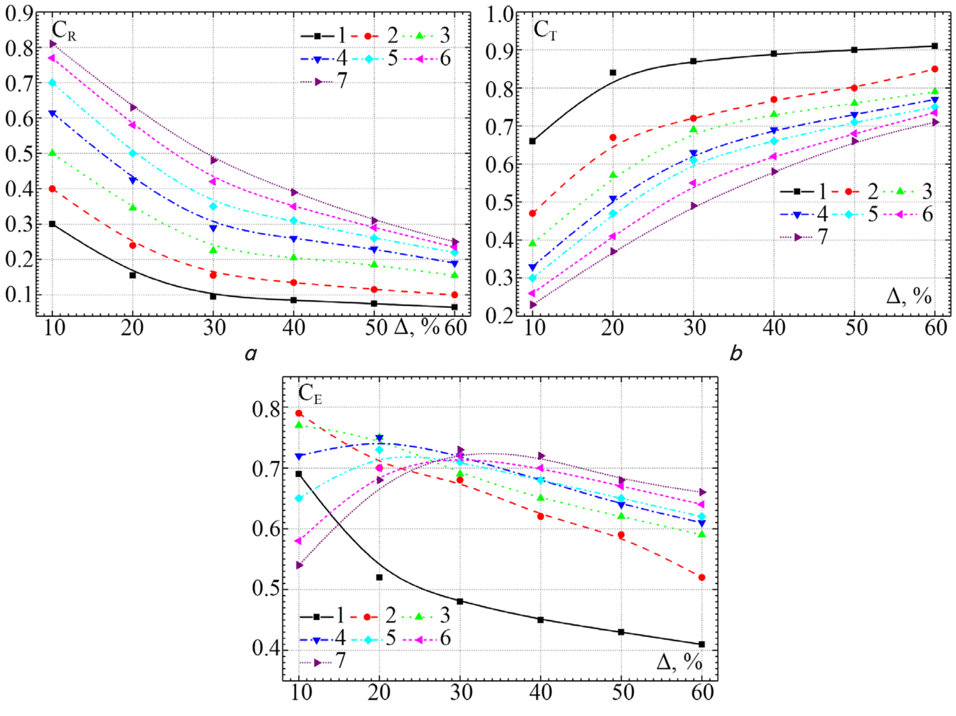
Fig. 7. Dependences of wave heights in front of and behind the vertical wall on the permeability of the wall for different periods of the wave: *a* – reflected; *b* – permeable: curve 1 – TU_φ/d=23.6; curve 2 – TU_φ/d=32.8; curve 3 – TU_φ/d=45.8; curve 4 – TU_φ/d=63.8; curve 5 – TU_φ/d=94.5; curve 6 – TU_φ/d=154.3 and curve 7 – TU_φ/d=347.1

The results of our measurements showed that the height of the reflected wave decreased as the permeability of the vertical wall increased and the wave period increased, which is shown in Fig. 7, *a*. The height of the penetrating wave increased under conditions of greater permeability of the vertical wall and with a decrease in the period of the initial wave (Fig. 7, *b*).

5. 3. Dependences of changes in the coefficients of reflection, penetration, and dissipation of gravity wave energy by a permeable vertical wall

Fig. 8 shows the dependences of the coefficient of reflection (C_R), penetration (C_T) and energy dissipation (C_E) of a gravity wave by a permeable vertical wall with piles of circular cross-section on the permeability of the wall for different steepness of the initial wave (h_i/λ). C_R coefficients were calculated from dependences (1) or (4), C_T coefficients were calculated from (5), and C_E coefficients were determined from dependence (8).

According to the research results shown in Fig. 8, *a*, the wave reflection coefficient increased with a decrease in the permeability of the vertical wall and an increase in the steepness of the initial wave. The wave penetration coefficient had the opposite trend (Fig. 8, *b*), namely, it increased with increasing wall permeability and with decreasing steepness of the initial wave. The gravity wave energy dissipation coefficient decreased with increasing vertical wall permeability. But for waves with a significant steepness of the initial wave h_i/λ>0.038, a decrease in the wave energy dissipation coefficient for walls with low permeability and the appearance of extreme values of the C_E coefficient were observed. At the same time, the maxima of the wave energy dissipation coefficient were recorded under conditions of increased permeability of the vertical wall and increased steepness of the initial wave (Fig. 8, *c*).



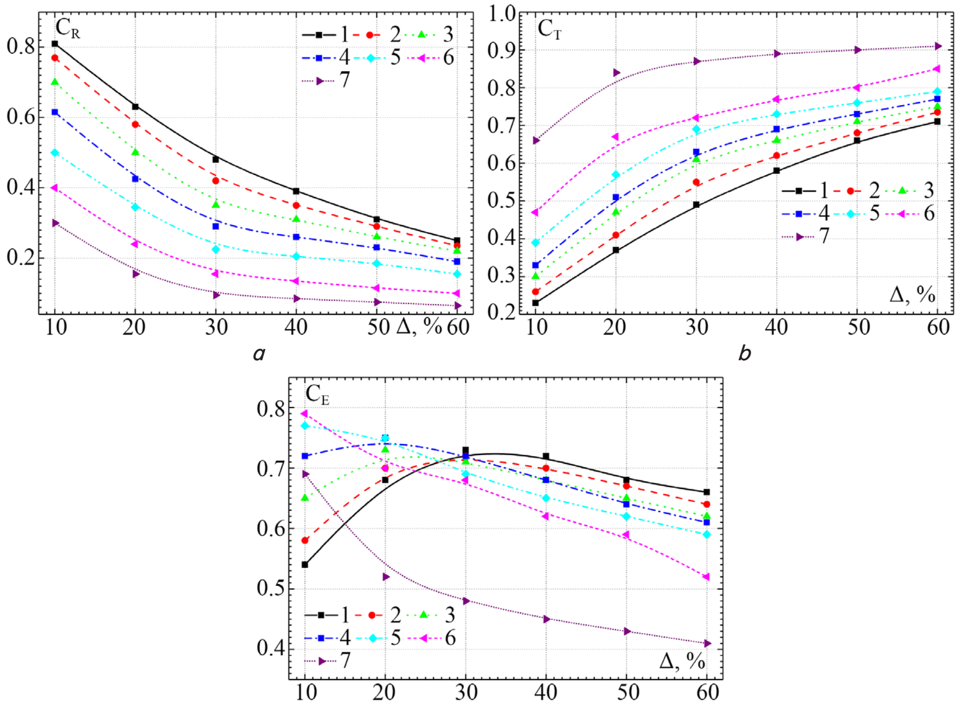
a *b*

c

Fig. 8. Dependences of the change in coefficients of the gravity wave through a permeable vertical wall on the permeability of the wall for different steepness of the initial wave: *a* – reflection; *b* – penetration; *c* – energy dissipation: curve 1 h_i/λ=0.002; curve 2 – h_i/λ=0.006; curve 3 – h_i/λ=0.020; curve 4 – h_i/λ=0.038; curve 5 – h_i/λ=0.065; curve 6 – h_i/λ=0.116 and curve 7 – h_i/λ=0.204

Fig. 9 shows the results of measuring the coefficients of reflection, penetration, and dissipation of gravity wave energy by a permeable vertical wall with piles of circular cross-section from the permeability of the wall for different normalized periods of the initial wave (TU_φ/d).

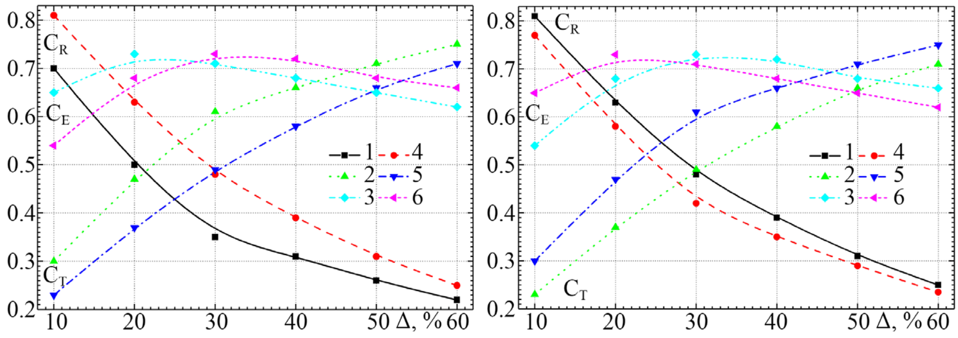
The results of our study showed that with a decrease in the permeability of the vertical wall and the normalized period of the gravity wave, the wave reflection coefficients by the permeable wall increased (Fig. 9, *a*), and the wave penetration coefficients, on the contrary, decreased (Fig. 9, *b*). The gravity wave energy dissipation coefficients had maximum values for small wave periods (Fig. 9, *c*), and the maxima (C_E) were observed at higher wall permeability for shorter wave periods.Fig. 10 shows the results of investigating the coefficients of reflection, penetration, and dissipation of waves near a permeable vertical wall from the permeability of the wall. The results were obtained for the parameters of the steepness of the initial wave and the normalized wave period, in which the extremes of the wave energy dissipation coefficients were observed in Fig. 8, 9, *c*. Thus, in Fig. 10, *a*, curve 1 corresponded to the C_R wave reflection coefficient for $h_i/H=0.065$, curve 2 – C_T for $h_i/H=0.065$, curve 3 – C_E for $h_i/H=0.065$, curve 4 – C_R for $h_i/H=0.204$, curve 2 – C_T for $h_i/H=0.204$, curve 3 – C_E for $h_i/H=0.204$. In Fig. 10*b*, curve 1 corresponded to C_R for $TU_\varphi/d=23.6$, curve 2 – C_T for $TU_\varphi/d=23.6$, curve 3 – C_E for $TU_\varphi/d=23.6$, curve 4 – C_R for $TU_\varphi/d=45.8$, curve 2 – C_T for $TU_\varphi/d=45.8$, curve 3 – C_E for $TU_\varphi/d=45.8$.



a *b*

c

Fig. 9. Dependences of the change in coefficients of the gravity wave through a permeable vertical wall on the permeability of the wall for different periods of the initial wave: *a* — reflection; *b* — penetration; *c* — energy dissipation: curve 1 — $TU_\varphi/d=23.6$; curve 2 — $TU_\varphi/d=32.8$; curve 3 — $TU_\varphi/d=45.8$; curve 4 — $TU_\varphi/d=63.8$; curve 5 — $TU_\varphi/d=94.5$; curve 6 — $TU_\varphi/d=154.3$ and curve 7 — $TU_\varphi/d=347.1$



a *b*

Fig. 10. Dependences of changes in the coefficients of reflected, transmitted, and dissipation of waves near a permeable vertical wall on the permeability of the wall: *a* — for different steepness of the initial wave; *b* — for different normalized wave period: curve 1 — C_R for $h_i/H=0.065$, curve 2 — C_T for $h_i/H=0.065$, curve 3 — C_E for $h_i/H=0.065$, curve 4 — C_R for $h_i/H=0.204$, curve 2 — C_T for $h_i/H=0.204$, curve 3 — C_E for $h_i/H=0.204$. In Fig. 10, *b* curve 1 corresponds to C_R for $TU_\varphi/d=23.6$, curve 2 — C_T for $TU_\varphi/d=23.6$, curve 3 — C_E for $TU_\varphi/d=23.6$, curve 4 — C_R for $TU_\varphi/d=45.8$, curve 2 — C_T for $TU_\varphi/d=45.8$, curve 3 — C_E for $TU_\varphi/d=45.8$

It should be noted that the maxima of the gravitational wave energy dissipation coefficients were observed under those conditions when the values of the wave reflection and wave penetration coefficients had the same values or almost the same values (Fig. 10).

6. Discussion of results related to wave transformation through permeable vertical walls

In contrast to the results of research on the transformation of the wave field with walls with a permeability of 10–30 %, which were obtained in works [16, 20–24], in the presented studies, the range of changes in the permeability of the vertical wall is increased to 60 %. In [20–24], only the features of wave transformation are studied. And in this study, the influence of permeable vertical walls with piles that reached the sandy soil on the wave transformation coefficients for various parameters of gravity waves was determined.

In contrast to works [1, 4–6, 18], the peculiarities of the interaction of waves with permeable walls and wave loads on the structure were established using modern methods of experimental research.

The results of visual and instrumental studies, which were performed under laboratory conditions on models of permeable vertical walls, were obtained. They made it possible to establish the peculiarities of the interaction of surface gravity waves with permeable vertical walls of different permeability and to determine the degree of transformation of waves by these walls.

Visual studies using video and photo equipment showed that as the steepness of gravity waves increased and the permeability of the vertical wall decreased, the height of the reflected wave in front of the permeable wall increased and the height of the penetrating wave behind the wall decreased. This is due to an increase in hydraulic resistance by walls of lower permeability. Thus, in Fig. 4, the height of the reflected wave is much higher than that in Fig. 5, and the heights of the penetrating wave, on the contrary, are smaller. In addition, the flow of liquid through the gaps between the piles in the case of wall permeability of 20 % (Fig. 4) is more intense than in the case of permeability (Fig. 5). The maxima of the flow rate were observed during the approach of the crest or sole of the gravity wave to the surface of the permeable vertical wall. However, the direction of fluid movement through the slits was opposite under the conditions of the approach of the crest and the sole of the wave.

It was established that the presence of a penetrating breakwater significantly changes the wave field. Interference, diffraction, and transformation of waves were observed, reflected, standing, and penetrating waves appeared, and wave collapse occurred.

Orbital velocities of wave motion have undergone changes, turbulence has increased, especially for breakwaters with negligible permeability. In front of the breakwater and supporting piles, horseshoe-shaped and trailing eddies, as well as jet currents between the piles, formed. This resulted in increased friction between the wavy surface and the moving fluid, as well as the dissipation or dissipation of wave energy.

It was established that with a decrease in the permeability of the vertical wall and an increase in the steepness of the initial wave, the height of the reflected wave increased (Fig. 6). So, for example, for a penetration of 10 %, an increase in the initial wave steepness (h_i/λ) from 0.002 to 0.204 led to an 11-fold increase in the reflected wave, and for an initial wave steepness $h_i/\lambda=0.204$, a decrease in wall permeability from 60 % to 10 % caused an increase in the height of the reflected wave by almost 2 times (Fig. 6, *a*). As the permeability of the vertical wall decreased, the height of the penetrating wave also decreased, but increased with the steepness of the initial wave, as shown in Fig. 6, *b*. As the results of the study showed, the height of the penetrating wave increased under conditions of lower permeability of the vertical wall and with a decrease in the period of the initial wave (Fig. 7, *a*), which is due to an increase in hydraulic resistance and the coefficient of friction. The height of the penetrating wave, on the contrary, increased under the conditions of increasing the permeability of the vertical wall and decreasing the wave period, which is shown in Fig. 7, *b*.

It was determined that the wave reflection coefficient increased with a decrease in the permeability of the vertical wall and an increase in the steepness of the initial wave (Fig. 8, *a*). The wave penetration coefficient had the opposite trend (Fig. 8, *b*), namely, it increased with increasing wall permeability and with decreasing steepness of the initial wave. The gravity wave energy dissipation coefficient (Fig. 8, *c*) decreased with an increase in the permeability of the vertical wall. However, for waves with significant curvature $h_i/H>0.038$ a decrease in the wave energy dissipation coefficient for walls with low permeability and the appearance of extreme values of the C_E coefficient were observed. At the same time, the maxima of the wave energy dissipation coefficient were recorded under the conditions of increased permeability of the vertical wall and increased steepness of the initial wave. The maximum value of the gravity wave energy dissipation coefficient $C_E=0.74$ occurred for the permeability of the vertical wall of 20 % and the steepness of the initial wave $h_i/\lambda=0.038$ (Fig. 8, *c*).

As the period of gravity waves and the permeability of the vertical wall increased, the wave reflection coefficients decreased, which is illustrated in Fig. 9, *a*. The coefficients of wave penetration, on the contrary, increased, and the rate of increase of this coefficient took place under conditions of low permeability of the wall (Fig. 9, *b*). The energy dissipation coefficients had extreme values for the largest of the studied periods of gravity waves and decreased in the region of low and high permeability of the vertical wall (Fig. 9, *c*). But in these areas, the lowest values of wave energy dissipation coefficients were observed under conditions of long wave periods for high wall permeability and short wave periods for low vertical wall permeability.

It was established that the maxima of the energy dissipation coefficients of gravitational waves were observed under those conditions when the values of the wave reflection and wave penetration coefficients had the same values or almost the same values.

Solving problems in the study of wave transformation (reflection, penetration, and dissipation of wave energy), establishing the characteristics of the interaction of waves with permeable walls is of practical importance, as it will allow the successful design and operation of permeable vertical wave walls.

The results of wave transformation (reflection, penetration, and dissipation of wave energy) obtained in the work have limitations when the permeability of vertical walls is from 10 % to 60 %. The steepness of the initial wave h_i/λ is from 0.006 to 0.204 and the normalized wave period TU_φ/d is from 23 to 347. And also under shallow sea conditions, which is due to the technical and design characteristics of the wave channel. The results should be taken into account when trying to apply in practice the design and operation of permeable vertical walls in compliance with the requirements of the criteria of similarity between model and real conditions of work.

It should be noted that in order to more effectively use the results of model studies in the practical application of such breakwaters, it is necessary to conduct work in an extended range of variable research parameters. Also, the continuation of research in this direction will be the determination of wave load and the transformation of wave energy by permeable vertical walls.

7. Conclusions

1. As a result of our experimental studies, it was established that the difference in wave heights in front of a permeable wall with a permeability of 50 % and behind it significantly decreased compared to the variant of research with a wall with a permeability of 20 %. Such wide gaps between the cylinders caused a decrease in the fluid flow rate between the frontal and aft parts of the permeable vertical wall. It should be noted that the maximum velocities occurred during the approach of the wave crest and its sole to the surface of the porous wall, but the directions of their movement were opposite.

2. The results of the study showed that with a decrease in the permeability of the vertical wall and an increase in the steepness of the initial wave, the height of the reflected wave increased. As the permeability of the vertical wall decreased, the height of the penetrating wave also decreased, but increased with the steepness of the initial wave. At the same time, the rate of decrease in the height of the reflected wave and increase in the transmitted wave is significantly higher with a decrease in the width of the gap for low permeability of the wall than under conditions of high permeability of the wall.

3. It was found that as the permeability of the vertical wall and the normalized period of gravity waves decreased, the coefficients of wave reflection by the permeable wall increased, and the coefficients of wave penetration, on the contrary, decreased. The gravitational wave energy dissipation coefficients had maximum values up to (0.72–0.75) for small wave periods ($TU_\varphi/d<45$). The maxima of the gravity wave energy dissipation coefficients were observed under those conditions when the values of the wave reflection and wave penetration coefficients had the same values or almost the same values.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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