UDC 532.517 **DOI: 10.20998/2222-0631.2025.01(8).04**

V. A. VOSKOBOINICK, A. M. ONYSHCHENKO, O. A. VOSKOBOINYK, A. V. VOSKOBIINYK, D. V. TRUDENKO

INTERACTION OF SURFACE GRAVITY WAVES WITH PERFORATED SCREEN

The paper examines the interaction of surface gravity waves with cylindrical marine structures within the framework of a finite depth fluid model. The problem is considered in a potential formulation. The impact of a perforated screen as a protective element around a cylindrical structure on reducing force loads on it and changing the deflection of the free surface of the water was investigated. The dependence of wave diffraction on screen perforation and its position relative to the cylinder was established. Wave diffraction research methods and their application to solving problems are discussed. Analytical solutions were built and calculations were made on this basis, which allow investigating the influence of the geometric proportions of the structure on the lateral force, in order to establish the minimum and maximum wave loads. The dependence of the total scattering power and the scattering diagram on the physical and geometric parameters of the model was established. It is shown that the perforated screen has the properties of a wave absorber, that is, it can be used as a protective element.

Key words: surface gravity wave, cylindrical marine structure, perforated screen, analytical solution, diffraction theory.

В. А. ВОСКОБІЙНИК, А. М. ОНИЩЕНКО, О. А. ВОСКОБОЙНИК, А. В. ВОСКОБІЙНИК, Д. В. ТРУДЕНКО

ВЗАЄМОДІЯ ПОВЕРХНЕВИХ ГРАВІТАЦІЙНИХ ХВИЛЬ З ПЕРФОРОВАНИМ ЕКРАНОМ

У статті розглядається взаємодія поверхневих гравітаційних хвиль з циліндричними морськими структурами в рамках моделі рідини скінченної глибини. Проблема розглядається в потенційній постановці. Досліджено вплив перфорованого екрана як захисного елемента навколо циліндричної конструкції на зменшення силових навантажень на неї та зміну прогину вільної поверхні води. Встановлено залежність дифракції хвилі від перфорації екрана та його положення відносно циліндра. Обговорюються методи дослідження дифракції хвиль та їх застосування до розв'язування задач. На їх основі побудовано аналітичні рішення та проведено розрахунки, які дозволяють дослідити вплив геометричних пропорцій конструкції на поперечну силу, щоб встановити мінімальне та максимальне хвильове навантаження. Встановлено залежність повної потужності розсіювання та діаграми розсіювання від фізико-геометричних параметрів моделі. Показано, що перфорований екран має властивості поглинача хвиль, тобто його можна використовувати як захисний елемент.

Ключові слова: поверхнева гравітаційна хвиля, циліндрична морська структура, перфорований екран, аналітичне рішення, теорія дифракції.

Introduction. Various types and forms of coastal protective and wave-absorbing structures are widely used during the construction of coastal hydrotechnical structures to improve the environmental protection and ecological conditions of the coastal infrastructure. These structures protect the beaches from scour, and the shores from soil erosion. They absorb and reduce wave heights and their load on coastal hydrotechnical structures, improve shipping conditions and the operation of port and wharf facilities [1 – 5].

In many scientific centers, laboratories and design organizations, considerable efforts are focused on determining the optimal shapes, sizes, structural elements and locations of wave energy absorbers. For this, dams, breakwaters, single- and multi-layer porous plates, screens, pile structures and other permeable marine facilities are used [6 – 9].

In this research, the problem of the interaction of surface gravity waves with vertical cylindrical obstacles of large transverse dimensions is considered. In reality, marine structures are subjected to various loads: buoyancy forces, gravity, wind forces, thermal internal forces, some functional loads, flow forces. However, in mathematical modeling it should be taken into account that the most significant dynamic effect is caused by the interaction of waves with structures [10]. Mathematical methods of investigating wave diffraction problems are discussed in monograph [11].

Exact solutions of the problem of diffraction of surface gravity waves on a circular column, located on a cylindrical base of variable and constant depth, were obtained and analyzed in paper [12] within the framework of the theory of shallow water. A correction for a liquid of finite depth is made with calculating the lateral force and the moment of forces. Research [13] shows the correspondence between the theoretical calculations of loads on a circular cylinder according to [14] and the data obtained experimentally.

The interaction of monochromatic waves with a horizontal porous elastic membrane placed horizontally in water was investigated in the paper [15] within the framework of the two-dimensional theory of hydroelasticity. Due to the fact that the wave number in the region above the membrane is complex, energy dissipation occurs. On the basis of the considered model, the coefficients of transmission, reflection and dissipation of waves were calculated. The theoretical model and numerical calculations were confirmed by a number of conducted experiments, which showed a close correspondence between theory and practice.

The linear potential theory of wave diffraction on a vertical circular cylinder with a perforated horizontal annular plane in a liquid of finite depth was considered in research [16]. The mechanism of reducing the loads on the cylinder with the help of a porous ring plate compared to an impermeable ring was investigated.

The work [17] is devoted to the study of the perforation parameter of a thin permeable wall. Using an experimental physical model, the horizontal force component, wave transmission and reflection coefficients were calculated. Recommendations for using the formula for finding resistance coefficients and inertial effect have been introduced. A complete estimate of the porosity parameter was presented.

In work [18] was considered the theory of a porous wave generator. An analysis of small-amplitude surface gravity waves in a liquid of finite depth, generated by horizontal oscillation from a porous vertical plate, was carried out. The influence of parameters of the wave effect and porosity effect on the wave surface and hydrodynamic pressure was discussed in detail.

The design optimization of the multilayer porous wave absorber in research [19] was achieved using a controlled artificial neural network (ANM) and an analytical model, confirmed by CFD and experiments. The analytical model was established using a matched eigenfunction expansion method (MEEM) by applying a boundary condition with a quadratic relationship between the pressure drop and the velocity of fluid movement at the porous screens. Input key features of the multi-layer porous wave absorber were selected through the parametric study along with the reflection coefficient as a target feature.

The interaction of regular waves with a concentric system consisting of an inner solid and an outer perforated cylinder was experimentally studied in research [20]. The effect of perforation on wave loads on the inner cylinder was determined y varying the value of the screen permeability coefficient.

In the work [21] theoretically investigated the interaction of waves with a system of permeable circular cylinders protruding above the water. The side of each of them was permeable and thin. It is shown that the perforation of the structures leads to a significant change, namely the reduction of the hydrodynamic loads acting on the cylinders, as well as the rolling of the waves.

The interaction of short-crest waves with a system of two concentric cylinders, the inner one of which is impenetrable, and the outer one is perforated, is theoretically considered in the article [22]. The effects of force loads, deflection of the free surface and diffraction from the wave number, design parameters and porosity of the outer cylinder were analyzed.

Setting of the task. In a linear formulation within the framework of a fluid model of finite depth, using the Darcy equation for a perforated screen, the problem of wave diffraction is formulated.

Fluid in the task is considered ideal, incompressible, and its motion is irrotational. The liquid occupies areas

$$\Omega_0 = \{r, \theta, z \mid r \ge l_0;\ 0 \le \theta < 2\pi;\ -H_0 \le z \le 0\},$$

$$\Omega_1 = \{r, \theta, z \mid a \le r < l_0;\ 0 \le \theta < 2\pi;\ -H_0 \le z \le 0\}$$

in accordance with the diagram in Fig. 1.

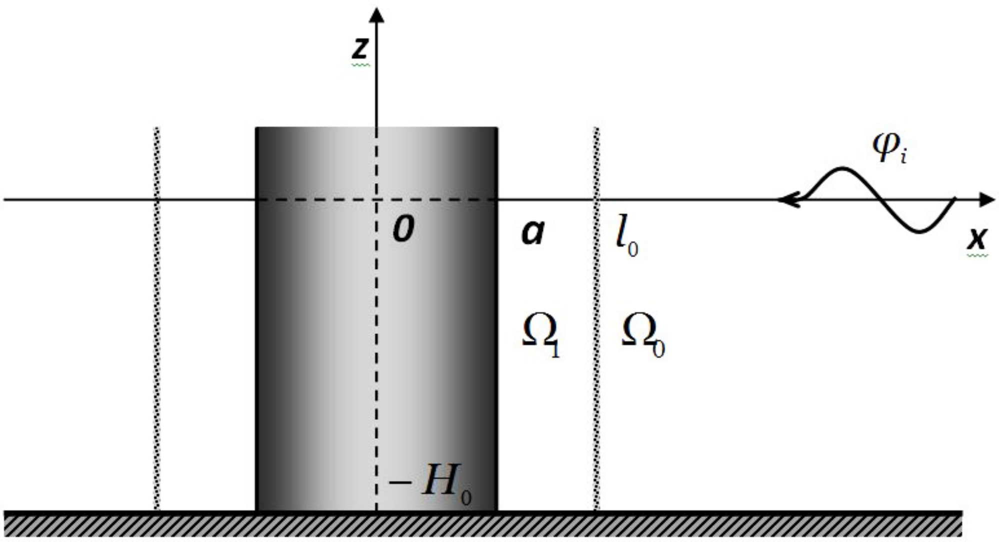


Fig. 1 – Geometry of the task.

Let us introduce velocity potentials $\vec{v} = \vec{\nabla}\Phi$ in each considered region of the problem under consideration in accordance with the above assumptions.

Let a perforated absolutely thin hollow cylinder of radius l_0 surround a rigid cylindrical body of radius a. Both cylinders are installed on an impenetrable bottom and a plane sinusoidal wave with velocity potential is streamed to them.

$$\Phi_i = \frac{iAg}{\omega}\frac{chk_0\left(z+H_0\right)}{chk_0H_0}e^{i\left(k_0 r\cos\theta+\omega t\right)},$$

where k_0 is the wave number, A is the amplitude of the incident wave, ω is the cyclic frequency. Due to the stationarity of the process, the multiplier $e^{i\omega t}$ is dropped in the future: $\Phi_j = \phi_j\left(r, \theta, z\right)e^{i\omega t}$, $j = 0, 1$.

The unknown functions of the velocity potentials must satisfy the Laplace equation (1) in each of the regions under consideration. The boundary conditions at the bottom and on the free surface of the water are expressed by dependencies (2) and (3), respectively. The boundary condition of impermeability on the cylinder is expressed by dependence (5). The conjugation condition when passing through a perforated screen corresponds to (4) and expresses the equality of velocities and Darcy's filtration law. It is believed that the permeable cylinder is made of material with very small pores. This allows us to make the assumption that the normal component of the velocity through the perforated screen is linearly proportional to the variable pressure on both sides of it (correctly at low Reynolds numbers).

The task in the internal Ω_1 and external Ω_0 areas has the form:

$$\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}+\frac{1}{\gamma^2}\frac{\partial^2}{\partial z^2}\right)\phi_j=0\,,\quad \gamma=\frac{H_0}{a}\,,\quad j=0,1\,. \tag{1}$$

$$\frac{\partial \phi_j}{\partial z}=0 \quad \text{at} \quad z=-H_0\,, \tag{2}$$

$$\frac{\partial \phi_j}{\partial z}-\omega^2\gamma^2\phi_j=0 \quad \text{at} \quad z=0\,, \tag{3}$$

$$\frac{\partial \phi_0}{\partial r}=\frac{\partial \phi_1}{\partial r}=ik_0G_0(\phi_0-\phi_1)\,,\quad G_0=\frac{b\omega}{\mu k_0} \quad \text{at} \quad r=l_0\,, \tag{4}$$

$$\frac{\partial \phi_1}{\partial r}=0 \quad \text{at} \quad r=a\,, \tag{5}$$

where G_0 is Chwang parameter, perforation coefficient.

The Sommerfeld condition of wave attenuation at infinity must also be fulfilled

$$\lim_{r\to\infty}\sqrt{r}\left(\frac{\partial \phi_s}{\partial r}+ik_0\phi_s\right)=0\,,\quad \lim_{r\to\infty}\phi_s=0\,.$$

The statement of the problem is given in dimensionless values, which are entered as follows:

$$r^*=\frac{r}{a}\,,\quad k_0{}^*=k_0\cdot a\,,\quad \omega^*=\frac{\omega a}{\sqrt{gH_0}}\,,\quad t^*=\frac{t\sqrt{gH_0}}{a}\,,\quad \phi_j{}^*=\frac{\phi_j}{a\sqrt{gH_0}}\,,\quad z^*=\frac{z}{H_0}\,. \tag{6}$$

The values of H_0 and a are saved as trace parameters. The drop-down field will be written as follows

$$\phi_i=\frac{iA}{\omega}\frac{ch\gamma k_0\left(z+H_0\right)}{ch\gamma k_0H_0}e^{ik_0r\cos\theta}\,. \tag{7}$$

The potential in the outer region is the sum of the potentials of the incident and scattered fields: $\phi_0=\phi_i+\phi_s$.

Solving of the problem. Solutions in regions are sought by the method of separation of variables and have the form:

$$\phi_0=\sum_{m=0}^{\infty}\cos m\theta\left[\varepsilon_m i^{m+1}\frac{A}{\omega}\frac{ch\gamma k_0\left(z+H_0\right)}{ch\gamma k_0H_0}J_m\left(k_0r\right)+\sum_{n=0}^{\infty}A_{mn}\frac{\cos\gamma\mu_n\left(z+H_0\right)}{\cos\gamma\mu_nH_0}H_m^{(2)}\left(i\mu_nr\right)\right],$$

$$\phi_1=\sum_{m=0}^{\infty}\cos m\theta\sum_{n=0}^{\infty}\frac{\cos\gamma\mu_n\left(z+H_0\right)}{\cos\gamma\mu_nH_0}\left[B_{mn}J_m\left(i\mu_nr\right)+C_{mn}N_m\left(i\mu_nr\right)\right],$$

where $J_m(x)$, $N_m(x)$, $H_m^{(2)}(x)$ are cylindrical Bessel, Neumann, and Hankel functions of the second order, respectively.

The dispersion relation is sought from the conditions on the free surface and has the form:

$$1-c\gamma k_0H_0th\gamma k_0H_0=0\,,\quad c=\frac{1}{\gamma^2\omega^2H_0}\,,\quad \omega^2=\frac{k_0}{\gamma}th\gamma k_0H_0\,,$$

$$1+c\gamma\mu_nH_0tg\gamma\mu_nH_0=0\,.$$

where μ_n are the real positive roots of the last equation at $n>0$, $\mu_0=-ik_0$.

The ratio between the roots is as follows:

$$\frac{\mu_n}{\mu_l}=\frac{tg\gamma\mu_lH_0}{tg\gamma\mu_nH_0}\,.$$

Substituting the solutions into the conjugation conditions and the boundary condition leads to an infinite system of equations.

$$\varepsilon_m i^{m+1} k_0 \frac{A}{\omega} \frac{ch\gamma k_0 \left(z+H_0\right)}{ch\gamma k_0 H_0} J'_m\left(k_0 l_0\right) + \sum_{n=0}^{\infty} i\mu_n A_{mn} \frac{\cos\gamma\mu_n\left(z+H_0\right)}{\cos\gamma\mu_n H_0} H'^{(2)}_m\left(i\mu_n l_0\right) =$$

$$= \sum_{n=0}^{\infty} i\mu_n \frac{\cos\gamma\mu_n\left(z+H_0\right)}{\cos\gamma\mu_n H_0}\left[B_{mn} J'_m\left(i\mu_n l_0\right) + C_{mn} N'_m\left(i\mu_n l_0\right)\right],$$

$$\sum_{n=0}^{\infty} i\mu_n \frac{\cos\gamma\mu_n\left(z+H_0\right)}{\cos\gamma\mu_n H_0}\left[B_{mn} J'_m\left(i\mu_n l_0\right) + C_{mn} N'_m\left(i\mu_n l_0\right)\right] =$$

$$= ik_0 G_0 \left\{\varepsilon_m i^{m+1} \frac{A}{\omega} \frac{ch\gamma k_0\left(z+H_0\right)}{ch\gamma k_0 H_0} J_m\left(k_0 l_0\right) + \sum_{n=0}^{\infty} A_{mn} \frac{\cos\gamma\mu_n\left(z+H_0\right)}{\cos\gamma\mu_n H_0} H^{(2)}_m\left(i\mu_n l_0\right) - \right.$$

$$\left. - \sum_{n=0}^{\infty} \frac{\cos\gamma\mu_n\left(z+H_0\right)}{\cos\gamma\mu_n H_0}\left[B_{mn} J_m\left(i\mu_n l_0\right) + C_{mn} N_m\left(i\mu_n l_0\right)\right]\right\},$$

$$\sum_{n=0}^{\infty} i\mu_n \frac{\cos\gamma\mu_n\left(z+H_0\right)}{\cos\gamma\mu_n H_0}\left[B_{mn} J'_m\left(i\mu_n a\right) + C_{mn} N'_m\left(i\mu_n a\right)\right] = 0 .$$

The operation of finding unknown coefficients can be simplified by using the orthogonality of the functions $\cos\gamma\mu_l\left(z+H_0\right)$ and $\cos\gamma\mu_n\left(z+H_0\right)$ on the interval $\left(-H_0;0\right)$, due to which we will obtain new dependencies, from which it follows that $A_{mn} = B_{mn} = C_{mn} = 0$ at $n > 0$. Thus, the solutions of the problem have the form:

$$\phi_0 = \frac{ch\gamma k_0\left(z+H_0\right)}{ch\gamma k_0 H_0} \sum_{m=0}^{\infty}\left[\varepsilon_m i^{m+1} \frac{A}{\omega} J_m\left(k_0 r\right) + A_{m0} H^{(2)}_m\left(k_0 r\right)\right]\cos m\theta , \tag{8}$$

$$\phi_1 = \frac{ch\gamma k_0\left(z+H_0\right)}{ch\gamma k_0 H_0} \sum_{m=0}^{\infty}\left[B_{m0} J_m\left(k_0 r\right) + C_{m0} N_m\left(k_0 r\right)\right]\cos m\theta , \tag{9}$$

where the unknown coefficients are:

$$A_{m0} = -\frac{A}{\omega}\varepsilon_m i^{m+1} \frac{J'_m\left(k_0 l_0\right)\Delta 1 + iG_0 J_m\left(k_0 l_0\right)\Delta 2}{H'^{(2)}_m\left(k_0 l_0\right)\Delta 1 + iG_0 H^{(2)}_m\left(k_0 l_0\right)\Delta 2} , \tag{10}$$

$$B_{m0} = \frac{A}{\omega} G_0 \varepsilon_m i^{m+2} N'_m\left(k_0 a\right) \frac{J_m\left(k_0 l_0\right) H'^{(2)}_m\left(k_0 l_0\right) - J'_m\left(k_0 l_0\right) H^{(2)}_m\left(k_0 l_0\right)}{H'^{(2)}_m\left(k_0 l_0\right)\Delta 1 + iG_0 H^{(2)}_m\left(k_0 l_0\right)\Delta 2} , \tag{11}$$

$$C_{m0} = -\frac{A}{\omega} G_0 \varepsilon_m i^{m+2} J'_m\left(k_0 a\right) \frac{J_m\left(k_0 l_0\right) H'^{(2)}_m\left(k_0 l_0\right) - J'_m\left(k_0 l_0\right) H^{(2)}_m\left(k_0 l_0\right)}{H'^{(2)}_m\left(k_0 l_0\right)\Delta 1 + iG_0 H^{(2)}_m\left(k_0 l_0\right)\Delta 2} , \tag{12}$$

$$\Delta 1 = N'_m\left(k_0 a\right)\left[J'_m\left(k_0 l_0\right) + iG_0 J_m\left(k_0 l_0\right)\right] - J'_m\left(k_0 a\right)\left[N'_m\left(k_0 l_0\right) + iG_0 N_m\left(k_0 l_0\right)\right],$$

$$\Delta 2 = J'_m\left(k_0 a\right) N'_m\left(k_0 l_0\right) - J'_m\left(k_0 l_0\right) N'_m\left(k_0 a\right).$$

Numerical calculations. The important for the applied nature is the theoretical study of loads on structures created by a wave field on the basis of the considered task. The question of how far from the column to install protective screens in order to minimize the force effect of the wave field becomes especially acute. The behavior of the field itself, both near the cylinder and in the far zone, should also be of interest. It should be taken into account that diffraction phenomena are strongly manifested on complex obstacles. In this case the field emitted from some elements of the structure affects the diffraction of waves on other parts of it. This relationship leads to a very complex picture of the wave process.

The deviation of the free surface relative to the undisturbed state η, the value of the maximum horizontal component of the force F on the cylinder, the total scattered power (the energy flow of the scattered field) Q, as well as the scattering diagram (the energy flow depending on the angle) Q_θ in the far zone are determined from the formulas:

$$\eta = -\frac{1}{g}\frac{\partial \Phi}{\partial t}; \quad \vec{F} = \iint_s P\vec{n}ds \lim_{x\to\infty} , \quad Q = \frac{dE}{dt} = -\iint_S \rho \frac{\partial \Phi}{\partial t}\cdot\frac{\partial \Phi}{\partial \vec{n}} ds , \tag{13}$$

where $\vec{n}$ is the radius vector of the unit normal to the surface, $\frac{\partial}{\partial \vec{n}}$ is derivative along the normal to the surface. In this problem, the considered surface is the side surface of an imaginary cylinder, the elementary surface of which is $ds = rdzd\theta$ (r is fixed), the pressure is determined from the linearized Bernoulli equation: $P = -\rho\frac{\partial \Phi_j}{\partial t}$.

Dimensionless quantities are entered as follows:

$$\eta^* = \frac{\eta}{A},\ F^* = \frac{F}{\rho g a A H_0},\ ds^* = \frac{ds}{H_0 a},\ P^* = \frac{P}{\rho g H_0},\ Q^* = \frac{Q}{\rho g H_0 \sqrt{g H_0} A^2}\ . \tag{14}$$

Due to the symmetry of the wave field pattern relative to the OX axis, and taking into account the values of the velocity potentials in the regions under consideration, we obtain the following formulas for the quantities under consideration in a dimensionless form:

$$\eta = \tilde{\eta} e^{i\omega t},\ \tilde{\eta} = -\frac{1}{A} i\omega \phi_j,\quad j = 0, 1, \tag{15}$$

$$F_x = \tilde{F}_x e^{i\omega t},\ \tilde{F}_x = -\frac{1}{A}\omega i a \int_0^{2\pi} \int_{-H_0}^{0} \phi_1 \cos\theta dz d\theta,$$

$$\tilde{F}_x = -\frac{ia\omega\pi}{\gamma k_0 A} th\gamma k_0 H_0 \left[B_{10} J_1(k_0 a) + C_{10} N_1(k_0 a) \right]. \tag{16}$$

The total scattered power in the far zone, taking into account the asymptotic expansions of the Hankel function of the second order and its derivative, takes the form:

$$\tilde{Q} = C_g \tilde{Q}^{\circ} e^{-2ik_0 r},$$

where $C_g = \frac{1}{2}\sqrt{\frac{th\gamma k_0 H_0}{\gamma k_0}}\left(1 + \frac{2\gamma k_0 H_0}{sh 2\gamma k_0 H_0}\right)$ - group velocity.

$$\tilde{Q}^{\circ} = \frac{2i}{\gamma k_0} \sum_{m=0}^{\infty} (-1)^m \tau_m a_m^2\ . \tag{17}$$

The scattering diagram in the far zone is calculated by the formula:

$$\tilde{Q}_\theta = -\frac{1}{\gamma A^2} \int_{-H_0}^{0} i\omega \varphi_0 \frac{\partial \varphi_0}{\partial r} r dz,\quad \tilde{Q}_\theta = C_g e^{-2ik_0 r} \tilde{Q}_\theta^{\circ},$$

where

$$\tilde{Q}_\theta^{\circ} = \frac{2i}{\pi k_0 \gamma} \sum_{m=0}^{\infty} a_m e^{i\frac{m\pi}{2}} \cos m\theta \sum_{n=0}^{\infty} a_n e^{i\frac{n\pi}{2}} \cos n\theta\ . \tag{18}$$

Analysis of results. On the basis of analytical and numerical calculations of the problem, it was established that the presence of a perforated screen affects the behavior of the wave process and the interaction of waves with the structure.

The deflection of the free water surface was calculated in the direction of wave propagation (Fig. 2). Dotted lines indicate the deviation of the free surface in the absence of a screen. Moreover, its value in the presence of a perforated screen decreases in the inner region and has a significant decrease behind the structure.

Thus, it is possible to talk about the selection of the distance between the cylinder and the screen, when waves of a certain length will be captured by the structure, which will lead to their attenuation in a certain direction during their further propagation.

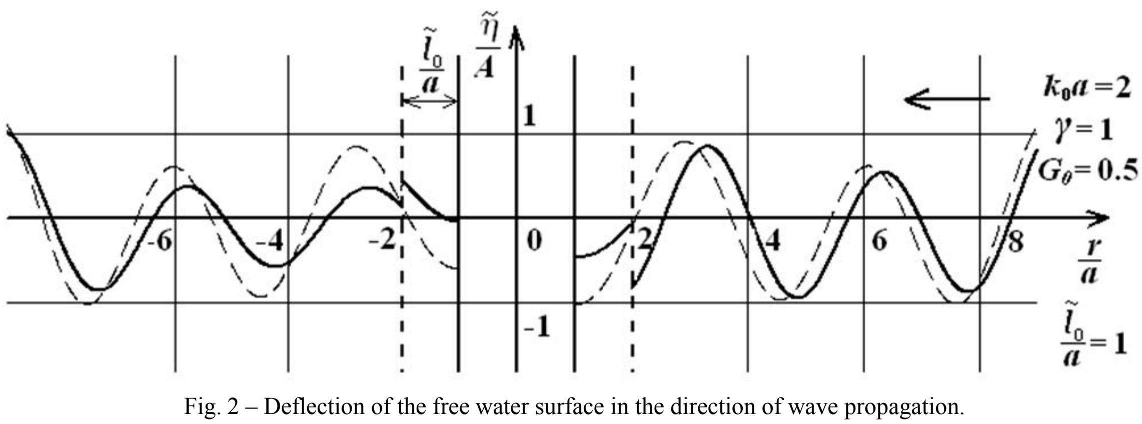
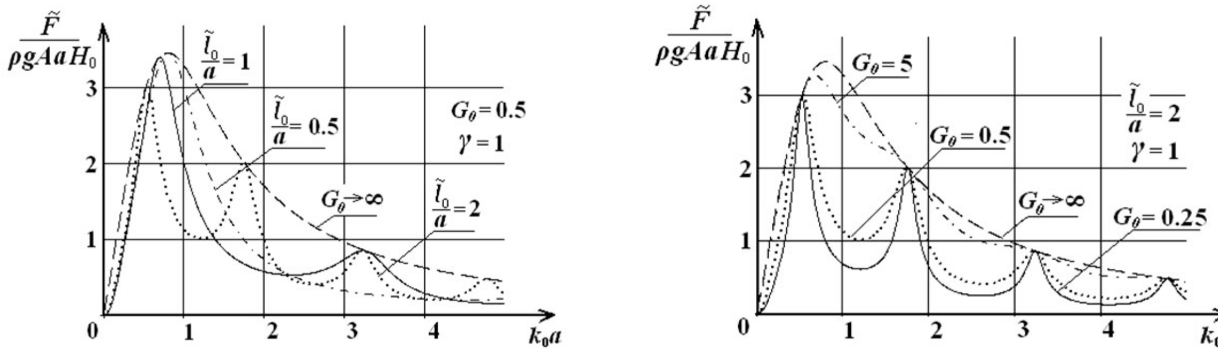


Fig. 2 – Deflection of the free water surface in the direction of wave propagation.

The analysis of the maximum value of the horizontal component of the force on the "column-screen" structure shows the following. The load curve on a single column is the upper contour curve of the horizontal component of the force that acts on the column when there is a screen (Fig. 3). With an increase in the perforation coefficient, the force load graphs follow an enveloping pattern (Fig. 3, *b*) and have an extreme character.

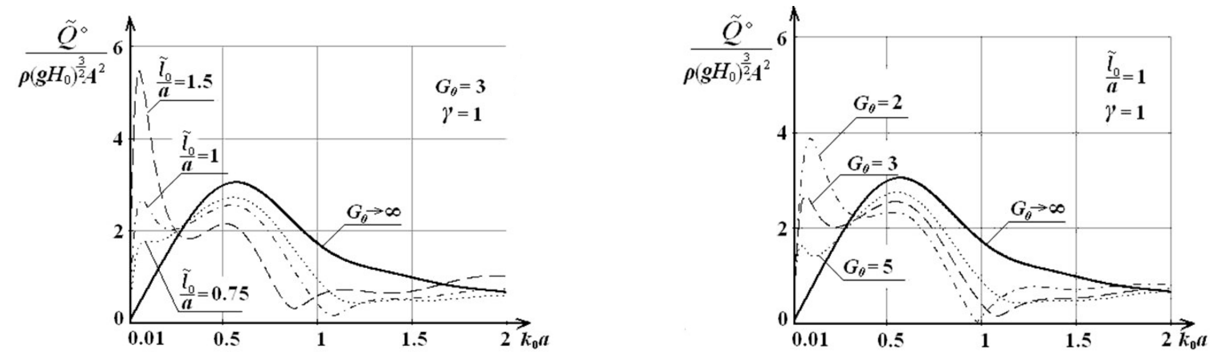


a *b*

Fig. 3 – The maximum value of the horizontal component of the force, which acts on the column.

The number of such extremes per segment value of the wave number has a direct dependence on $\tilde{l}_0$ and does not depend on G_0. As the distance $\tilde{l}_0$ increases, the density of extrema increases. At $\tilde{l}_0 \to 0$ the first extremum follows to the maximum value of the loads on a single column, and the rest follows to infinity (Fig. 3, *a*). The sharp peaks of power loads are the greater when the coefficient is the smaller (Fig. 3, *b*).

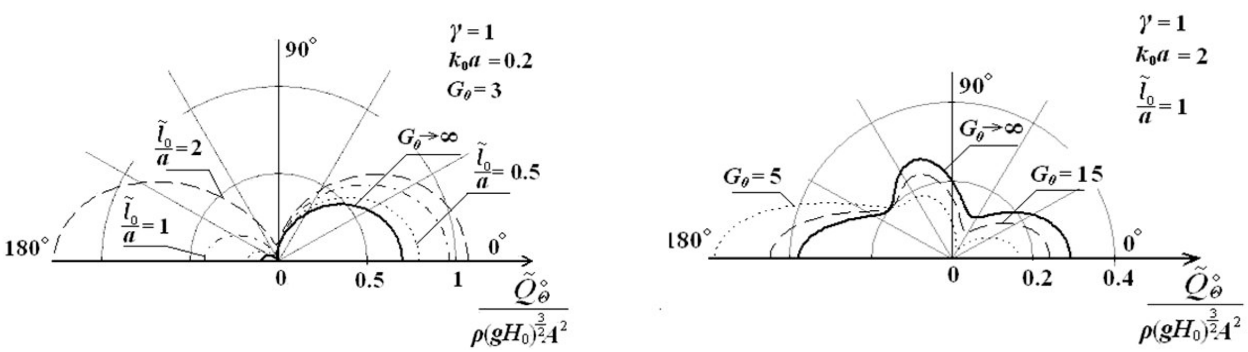
The dependence of the maximum value of the total scattered power in the far zone from the wave number is shown in Fig. 4. Maxima are varied from the distance from the screen to the cylinder (Fig. 4, *a*) and the Chwang parameter (Fig. 4, *b*). As can be seen from the graphs, peaks appear at small wave numbers, which are explained by the geometric complexity of the structure. Moreover, they are increased with increasing distance (Fig. 4, *a*) and decreasing perforation (Fig. 4, *b*). With a further increase in the wave number, the total scattered power decreases in comparison with the unit cylinder, to which the thick solid line corresponds here and in the following.



a *b*

Fig. 4 – Dependence on the wave number of the maximum value full scattered power in the far zone.

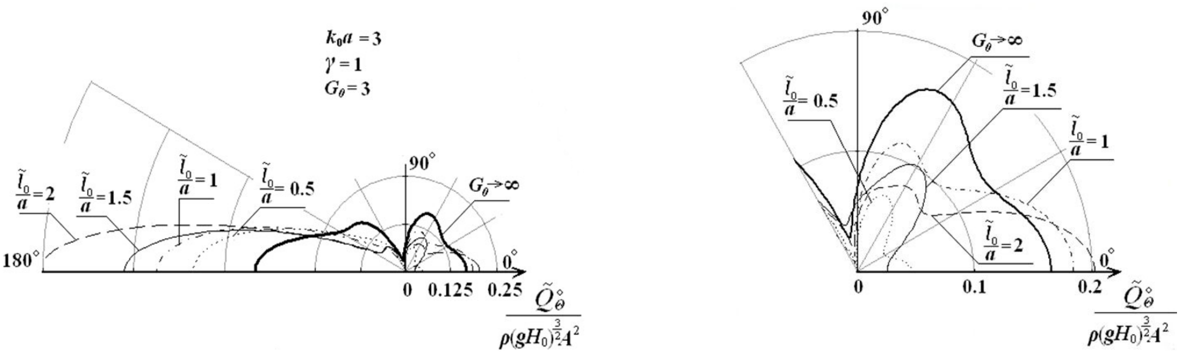
At small wave numbers (Fig. 5, *a*), the presence of a perforated screen increases the scattering diagram both in the rear zone and in the front zone of the wave, and it also increases with increasing distance. As the wave number is increased, the scattering diagram lengthens in the direction of wave propagation. The number of petals is increased (Fig. 6, *a*). The scattering diagram also is lengthened due to the reduction of perforation (Fig. 5, *b*).



a *b*

Fig. 5 – Scatter diagram in the far zone during variation distances from the screen to the cylinder (a) and the Chwang parameter (b).

Calculations show that with some parameters of the system, it is possible to observe the strengthening or weakening of the wave process in the front zone. Thus, at constant values, the energy flow decreases if the screen is located at a distance that is a multiple of half the radius of the cylinder, and increases when the distance is a multiple of the radius (Fig. 6, *b*).

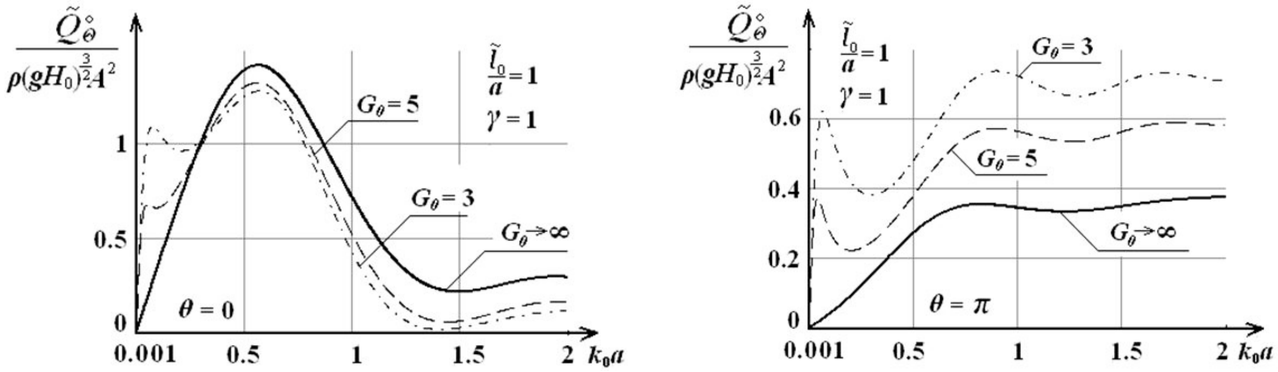


a *b*

Fig. 6 – Scatter diagram in the far zone when the distance from the screen to the cylinder changes.

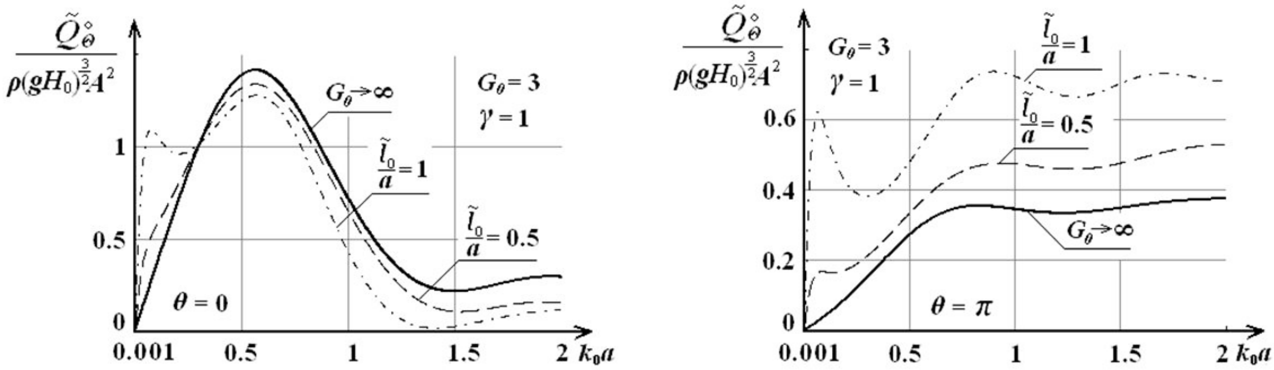
Forward $\theta = 0$ (a) and reverse $\theta = \pi$ (b) scattering are constructed in Fig. 7 and Fig. 8. As can be seen from the graphs, the presence of a perforated screen increases the stream of energy in the direction of wave propagation at all k_0. The reverse scattering has such a property for long waves. Its value decreases in comparison with a single cylinder.

Research of the behavior of forward and reverse scattering from the position of the screen relative to the cylinder are presented in Fig. 9 for values of wave numbers $k_0a = 1$ (a) and $k_0a = 3$ (b). As can be seen from the graphs, with an increase in the distance $\tilde{l}_0$ from 0 to 3 radii, forward scattering increases in both cases in comparison with a single cylinder, and also increases with an increase of perforation. Perforation has the opposite effect on reverse scattering and reduces its value in almost all positions of the screen (Fig. 9, *b*).



a *b*

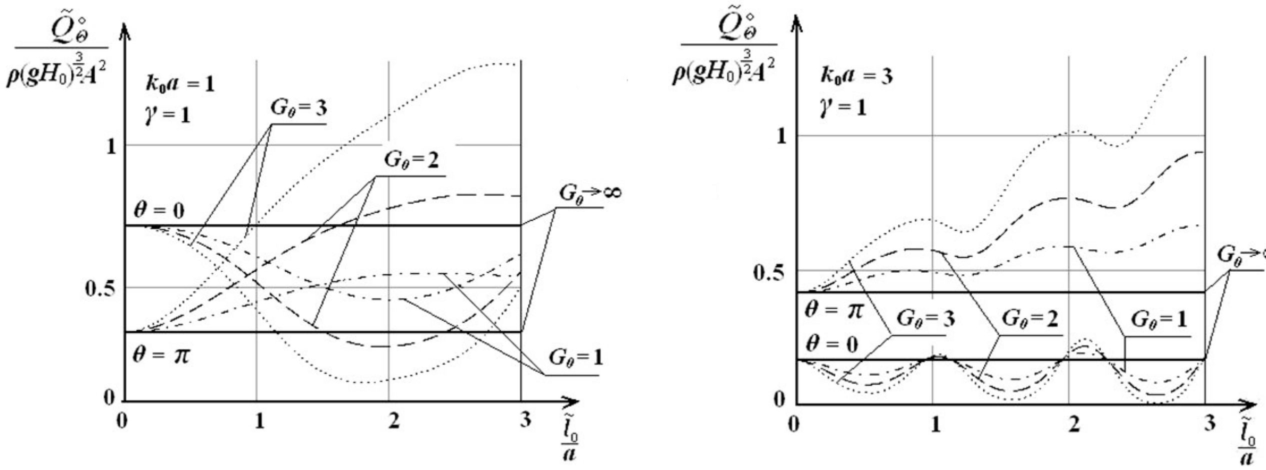
Fig. 7 – Dependence of forward and reverse scattering on the wave number with variation of the perforation coefficient.



a *b*

Fig. 8 – Dependence of forward and reverse scattering on the wave number depending on the position of the screen relative to the cylinder.

An analysis of the diffraction of surface gravity waves on a cylindrical structure surrounded by a perforated screen was carried out. The analysis of the total dissipated power, scattering diagrams, forward and reverse scattering was carried out. It is shown that the perforated screen has the properties of a wave absorber, that is, it can be used as a protective element.



a *b*

Fig. 9 – Dependence of forward and reverse scattering on the distance between the screen and the cylinder with variation of the perforation coefficient.

Conclusions. The problem of the theory of diffraction of surface gravity waves on a vertical column, which is surrounded by a cylindrical perforated screen, is solved. Analytical solutions were built and calculations were made on this basis, which allow investigating the influence of the geometric proportions of the structure on the lateral force, in order to establish the minimum and maximum wave loads. The analysis of the total dissipated power, scattering diagrams, forward and reverse scattering was carried out. The dependence of the total scattering power and the scattering diagram on the physical and geometric parameters of the model was established. It is shown that the perforated screen has the properties of a wave absorber, that is, it can be used as a protective element.

Bibliography

1. *Koley S.*, *Panduranga K.* Energy balance relations for flow through thick porous structures // Int. J. Comp. Meth. Exp. Meas. – 2021. – Vol. 9. – no. 1. – P. 28 – 37. DOI: 10.2495/CMEM-V9-N1-28-37.
2. *Voskoboinick A.*, *Voskoboinick V.*, *Turick V.*, *Voskoboinyk O.*, *Cherny D.*, *Tereshchenko L.* Interaction of group of bridge piers on scour / in: Hu Z., Petoukhov S., Dychka I., He M. (Eds.). Advances in Computer Science for Engineering and Education III. ICCSEEA 2020. // Advances in Intelligent Systems and Computing, Springer, Cham. – 2021. – Vol. 1247. – P. 3 – 17. DOI: 10.1007/978-3-030-55506-1_1.
3. *Voskoboinick V. A.*, *Gorban I. M.*, *Voskoboinick A. A.*, *Tereshchenko L. N.*, *Voskoboinick A. V.* Junction flow around cylinder group on flat plate / in: Sadovnichiy V. A., Zgurovsky M. Z. (Eds.), Contemporary Approaches and Methods in Fundamental Mathematics and Mechanics. // Understanding Complex Systems. Springer, Cham. – 2021. – P. 35 – 50. DOI: 10.1007/978-3-030-50302-4_3.
4. *Diaz-Carrasco P.*, *Molines J.*, *Gomez-Martin M. E.*, *Medina J. R.* Neural Network calibration method for VARANS models to simulate wave-coastal structures interaction // Coastal Eng. – 2024. – Vol. 187. – P. 104424–1–13. DOI: 10.1016/j.coastaleng.2023.104443.
5. *Zhai H.*, *Jeng D.-S.* Impacts of wave-induced seabed response on local scour around a pipeline: PORO–FSSI–SCOUR–FOAM // Coastal Eng. – 2024. – Vol. 187. – P. 104424–1–27. DOI: 10.1016/j.coastaleng.2023.104424.
6. *Voskoboinick V.*, *Onyshchenko A.*, *Voskoboinyk O.*, *Makarenkova A.*, *Voskobiinyk A.* Junction flow about cylindrical group on rigid flat surface // Heliyon. – 2022. – P. e12595–1–12. DOI: 10.1016/j.heliyon.2022.e12595.
7. *Vijay K. G.*, *Neelamani S.*, *AlYousif A.* Hydrodynamic analyses of multiple porous plates attached to the front of a vertical composite breakwater // J. Coastal Eng. – 2022. – Vol. 266. – P. 112964–1–19. DOI: 10.1016/j.oceaneng.2022.112964.
8. *Voskoboinick V.*, *Khomitsky V.*, *Voskoboinyk O.*, *Tereshchenko L.*, *Voskoboinick A.* Wave loads on protective dam of the Marine channel of the Danube-Black sea // Hydro-environ. Res. – 2021. – Vol. 35. – no3. – P. 1 – 12. DOI: 10.1016/j.jher.2021.01.003.
9. *Onyshchenko A.*, *Kovalchuk V.*, *Voskoboinick V.*, *Voskobiinyk A.*, *Aksonov S.*, *Trudenko D.*, *Hrevtsov S.* Establishing patterns of change in the coefficients of reflection, transmission and dissipation of wave energy depending on parameters of a permeable vertical wall // Eastern-European J. Enterprise Technologies. – 2024. – Vol. 4/5(130). – P. 46 – 56. DOI: 10.15587/1729-4061-2024.309969.
10. *Brebbia C. A.*, *Walker S.* Dynamic analysis of offshore structures. – London : Newnes-Buterworths, 1979. – 334 p.
11. *Selezov I. T.*, *Krivonos Yu. G.* Mathematical methods in the problems of propagation and diffraction of waves. – Kyiv : Naukova Dumka, 2012. – 242 p.
12. *Selezov I. T.*, *Sydorchuk V. N.*, *Yakovlev V. V.* Transformation of waves in the coastal zone of the shelf. – Kyiv : Naukova Dumka, 1983. – 283 p.
13. *Chakrabarti S. K.*, *Tam W. A.* Interaction of waves with large vertical cylinder // J. Ship Res. – 1975. – Vol. 19, no. 1. – P. 23 – 33. DOI: 10.5957/jsr.1975.19.1.23.
14. *MacCamy M. C.*, *Fuchs R. A.* Wave forces on piles: A diffraction theory // Techn. Memorandum. – 1954. – Vol. 69. – P. 1 – 17.
15. *Cho I. H.*, *Kim M. H.* Interactions of horizontal porous flexible membrane with waves // J. Waterw. Port Coast. Ocean Eng. – 2000. – Vol. 126. – no. 5. – P. 245 – 253. DOI: 10.1061/(ASCE)0733-950X(2000)126:5(245).

16. *Wu J.*, *Chwang A. T.* Wave diffraction by a vertical cylinder with a porous ring plate // J. Eng. Mech. – 2002. – Vol. 128. – no. 2. – P. 164 – 171. DOI: 10.1061/(ASCE)0733-9399(2002)128:2(164).
17. *Li Y.*, *Liu Y.*, *Teng B.* Porous effect parameter of thin permeable plates // Coastal Eng. J. – 2006. – Vol. 48. – no. 4. – P. 309 – 336. DOI: 10.1142/S0578563406001441.
18. *Chwang A. T.* A porous wavemaker theory // J. Fluid Mech. – 1983. – Vol. 132. – P. 395 – 406. DOI: 10.1017/S0022112083001676.
19. *George A.*, *Poguluri S. C.*, *Kim J.*, *Cho I. H.* Design optimization of a multi-layer porous wave absorber using an artificial neural network model // J. Coastal Eng. – 2022. – Vol. 265. – P. 112666–1–16. DOI: 10.1016/j.oceaneng.2022.112666.
20. *Vijayalakshmi K.*, *Neelamani S.*, *Sundaravadivelu R.*, *Murali K.* An experimental study of regular wave loads on a perforated circular cassette and suction pipe configuration // J. Ocean Technol. – 2007. – Vol. 2. – no. 2. – P. 50 – 63.
21. *Williams A. N.*, *Li W.* Wave interaction with a semi-porous cylindrical breakwater mounted on a storage tank // Ocean Eng. – 1998. – Vol. 25. – P. 195 – 219. DOI: 10.1016/S0029-8018(97)00006-1.
22. *Song H.*, *Tao L.* The effect of short-crested wave phase on a concentric porous cylinder system in the wind blowing open sea // Proc. 16th Australasian Fluid Mechanics Conference. – Crown Plaza, Gold Coast, Australia, 2007. – P. 1276 – 1282. http://hdl.handle.net/10072/18044.

References (transliterated)

1. Koley S., Panduranga K. Energy balance relations for flow through thick porous structures. *Int. J. Comp. Meth. Exp. Meas*. 2021, Vol. 9, no. 1, pp. 28–37. DOI: 10.2495/CMEM-V9-N1-28-37.
2. Voskoboinick A., Voskoboinick V., Turick V., Voskoboinyk O., Cherny D., Tereshchenko L. Interaction of group of bridge piers on scour. (in: Hu Z., Petoukhov S., Dychka I., He M. (Eds.). Advances in Computer Science for Engineering and Education III. ICCSEEA 2020.) *Advances in Intelligent Systems and Computing*, *Springer*, *Cham*. – 2021, Vol. 1247, pp. 3–17. DOI: 10.1007/978-3-030-55506-1_1.
3. Voskoboinick V. A., Gorban I. M., Voskoboinick A. A., Tereshchenko L. N., Voskoboinick A. V. Junction flow around cylinder group on flat plate. (in: Sadovnichiy V. A., Zgurovsky M. Z. (Eds.), Contemporary Approaches and Methods in Fundamental Mathematics and Mechanics). *Understanding Complex Systems. Springer, Cham*. 2021, pp. 35–50. DOI: 10.1007/978-3-030-50302-4_3.
4. Diaz-Carrasco P., Molines J., Gomez-Martin M. E., Medina J. R. Neural Network calibration method for VARANS models to simulate wave-coastal structures interaction. *Coastal Eng*. 2024, Vol. 187, P. 104424–1–13. DOI: 10.1016/j.coastaleng.2023.104443.
5. Zhai H., Jeng D.-S. Impacts of wave-induced seabed response on local scour around a pipeline: PORO–FSSI–SCOUR–FOAM. *Coastal Eng*. 2024, Vol. 187, P. 104424–1–27. DOI: 10.1016/j.coastaleng.2023.104424.
6. Voskoboinick V., Onyshchenko A., Voskoboinyk O., Makarenkova A., Voskobiinyk A. Junction flow about cylindrical group on rigid flat surface. *Heliyon*. 2022, P. e12595–1–12. DOI: 10.1016/j.heliyon.2022.e12595.
7. Vijay K. G., Neelamani S., AlYousif A. Hydrodynamic analyses of multiple porous plates attached to the front of a vertical composite breakwater. *J. Coastal Eng*. 2022, Vol. 266, P. 112964–1–19. DOI: 10.1016/j.oceaneng.2022.112964.
8. Voskoboinick V., Khomitsky V., Voskoboinyk O., Tereshchenko L., Voskoboinick A. Wave loads on protective dam of the Marine channel of the Danube-Black sea. *Hydro-environ. Res*. 2021, Vol. 35, no3, pp. 1–12. DOI: 10.1016/j.jher.2021.01.003.
9. Onyshchenko A., Kovalchuk V., Voskoboinick V., Voskobiinyk A., Aksonov S., Trudenko D., Hrevtsov S. Establishing patterns of change in the coefficients of reflection, transmission and dissipation of wave energy depending on parameters of a permeable vertical wall. *Eastern-European J. Enterprise Technologies*. 2024, Vol. 4/5(130), pp. 46–56. DOI: 10.15587/1729-4061-2024.309969.
10. Brebbia C. A., Walker S. *Dynamic analysis of offshore structures*. London, Newnes-Buterworths, 1979. 334 p.
11. Selezov I. T., Krivonos Yu. G. *Mathematical methods in the problems of propagation and diffraction of waves*. Kyiv, Naukova Dumka, 2012. 242 p.
12. Selezov I. T., Sydorchuk V. N., Yakovlev V. V. Transformation of waves in the coastal zone of the shelf. Kyiv, Naukova Dumka, 1983. 283 p.
13. Chakrabarti S. K., Tam W. A. Interaction of waves with large vertical cylinder. *J. Ship Res*. 1975, Vol. 19, no.1, pp. 23–33. DOI: 10.5957/jsr. 1975.19.1.23.
14. MacCamy M. C., Fuchs R. A. Wave forces on piles: A diffraction theory. *Techn. Memorandum*. 1954, Vol. 69, pp. 1–17.
15. Cho I. H., Kim M. H. Interactions of horizontal porous flexible membrane with waves. *J. Waterw. Port Coast. Ocean Eng*. 2000, Vol. 126, no. 5, pp. 245–253. DOI: 10.1061/(ASCE)0733-950X(2000)126:5(245).
16. Wu J., Chwang A. T. Wave diffraction by a vertical cylinder with a porous ring plate. *J. Eng. Mech*. 2002, Vol. 128, no. 2, pp. 164–171. DOI: 10.1061/(ASCE)0733-9399(2002)128:2(164).
17. Li Y., Liu Y., Teng B. Porous effect parameter of thin permeable plates. *Coastal Eng. J*. 2006, Vol. 48, no. 4, pp. 309–336. DOI: 10.1142/ S0578563406001441.
18. Chwang A. T. A porous wavemaker theory. *J. Fluid Mech*. 1983, Vol. 132, pp. 395–406. DOI: 10.1017/S0022112083001676.
19. George A., Poguluri S. C., Kim J., Cho I. H. Design optimization of a multi-layer porous wave absorber using an artificial neural network model. *J. Coastal Eng*. 2022, Vol. 265, P. 112666–1–16. DOI: 10.1016/j.oceaneng.2022.112666.
20. Vijayalakshmi K., Neelamani S., Sundaravadivelu R., Murali K. An experimental study of regular wave loads on a perforated circular cassette and suction pipe configuration. *J. Ocean Technol*. 2007, Vol. 2, no. 2, pp. 50–63.
21. Williams A. N., Li W. Wave interaction with a semi-porous cylindrical breakwater mounted on a storage tank. *Ocean Eng*. 1998, Vol. 25, pp. 195–219. DOI: 10.1016/S0029-8018(97)00006-1.
22. Song H., Tao L. The effect of short-crested wave phase on a concentric porous cylinder system in the wind blowing open sea. *Proc. 16th Australasian Fluid Mechanics Conference*. Crown Plaza, Gold Coast, Australia, 2007. P. 1276–1282. http://hdl.handle.net/10072/18044.

Надійшла (received) 08.03.2025

Відомості про авторів / Information about authors

Воскобійник Володимир Анатолійович – доктор технічних наук, старший науковий співробітник, завідувач відділу гідродинаміки хвильових та руслових потоків, Інститут гідромеханіки НАН України, м. Київ; тел.: (+38044) 371-65-57; ORCID: http://orcid.org/0000-0003-2161-6923; e-mail: vlad.vsk@gmail.com.

Voskoboinick Volodymyr Anatoliyovych – Doctor of Technical Sciences, Associate Professor, Head of the Department of Hydrodynamics of Wave and Channel Flow, Institute of Hydromechanics of the National Academy of Sciences of Ukraine, Kyiv; tel.: (+38044) 371-65-57; ORCID: http://orcid.org/0000-0003-2161-6923; e-mail: vlad.vsk @gmail.com.

Онищенко Артур Миколайович – доктор технічних наук, професор, завідувач кафедри мостів, тунелів та гідротехнічних споруд, Національний транспортний університет, м. Київ; тел.: (+38044) 280-79-78; ORCID: https://orcid.org/0000-0002-1040-4530; e-mail: onyshchenko.a.m.ntu@gmail.com.

Onyshchenko Artur Mykolayovych – Doctor of Technical Sciences, Professor, Head of the Department of Bridges, Tunnels and Hydrotechnical Structures, National Transport University, Kyiv; tel.: (+38044) 280-79-78; ORCID: https://orcid.org/0000-0002-1040-4530; e-mail: onyshchenko.a.m.ntu@gmail.com.

Воскобойник Олександр Анатолійович – кандидат технічних наук, старший науковий співробітник відділу гідродинаміки хвильових та руслових потоків, Інститут гідромеханіки НАН України, м. Київ; тел.: (+38044) 371-65-57; ORCID: http://orcid.org/0000-0001-8114-4433; e-mail: alexandr.vsk@gmail.com.

Voskoboinyk Oleksandr Anatoliyovych – Candidate of Technical Sciences, Senior Research Fellow at the Department of Hydrodynamics of Wave and Channel Flow, Institute of Hydromechanics of the National Academy of Sciences of Ukraine, Kyiv; tel.: (+38044) 371-65-57; ORCID: http://orcid.org/0000-0001-8114-4433; e-mail: alexandr.vsk @gmail. com.

Воскобійник Андрій Володимирович – кандидат технічних наук, старший науковий співробітник, старший науковий співробітник відділу гідробіоніки та керування примежовим шаром, Інститут гідромеханіки НАН України, м. Київ; тел.: (+38044) 371-65-57; ORCID: https://orcid.org/0000-0001-8045-8625; e-mail: andrew.vsk @gmail.com.

Voskobiinyk Andriy Volodymyrovych – Candidate of Technical Sciences, Associate Professor, Senior Research Fellow at the Department of Hydrobionics and Boundary Layer Control, Institute of Hydromechanics of the National Academy of Sciences of Ukraine, Kyiv; tel.: (+38044) 371-65-57; ORCID: https://orcid.org/0000-0001-8045-8625; e-mail: andrew.vsk@gmail.com.

Труденко Денис Володимирович – аспірант кафедри мостів, тунелів та гідротехнічних споруд, Національний транспортний університет, м. Київ; тел.: (+38044) 280-79-78; ORCID: https://orcid.org/0009-0001-3720-1952; e-mail: tdv.83@ukr.net.

Trudenko Denys Volodymyrovych – PhD Student of the Department of Bridges, Tunnels and Hydrotechnical Structures, National Transport University, Kyiv; tel.: (+38044) 280-79-78; ORCID: https://orcid.org/0009-0001-3720-1952; e-mail: tdv.83@ukr.net.