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RUNUP OF A SURFACE SOLITARY WAVE ON A THIN VERTICAL SEMI-SUBMERSED SCREEN

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Abstract. Global climate changes lead to an increase in the number and intensity of extreme events in the seas and oceans (tsunamis, floods, storm surges, etc.). This can have catastrophic consequences involving the destruction of civil infrastructure, the flooding of large areas of recreational land, the loss of life, and can also adversely affect water quality, sediment transport, and habitats for living organisms.

The creation of artificial berms on the seabed and breakwater piers changes significantly the parameters of wave processes, reducing destructive effect of waves in the coastal zone. But the use of traditional coastal protection structures (dams, piers, breakwaters) is not always efficient and economically reasonable. Thin permeable barriers are increasingly being considered as an alternative option in providing economic and ecological protection of coastal areas. The purpose of this research is to substantiate the effectiveness of vertical semi-submerged walls for protection the shores of natural reservoirs from the destructive energy of surface waves. Such a structure is non-permeable near the free surfacer, and is supported by piles at some distance from the bottom, which allows the flow of water and sediments. The physical simulation of the interaction of a nonlinear solitary wave, which is considered as a tsunami model, with a semi-submerged thin vertical barrier is performed in the experimental channel to evaluate the effectiveness of vertical wave barriers against the destructive energy of long waves. It was found that interaction of a solitary wave with an overhanging vertical wall leads to generation both of the reflected wave, due to roll of the incident wave on the structure, and the transmitted wave, which is formed after the liquid mass passes through the gap between the bottom and the wall.

Quantitative characteristics of the interaction of the wave with the obstacle were obtained with the help of capacitive sensors, which were installed along the main axis of the laboratory channel to record the free surface disturbances caused by the propagation of the wave in the channel, its reflection from the wave screen and its transmission downstream. The processing of the received data made it possible to estimate the parameters of a solitary wave, which was formed in the channel by the impact of a heavy body on the water surface, those are the amplitude, length, and velocity of wave propagation. The energy attenuation of a solitary wave is estimated, which is an important characteristic of the channel and makes it possible to obtain more accurate values of reflection and transmission coefficients.

Evaluations of wave reflection and transmission coefficients show that thin partially submerged vertical barriers are sufficiently effective in reducing the energy of nonlinear solitary waves although they do not suppress the waves completely. The depth of the screen-type permeable obstacle immersion relative to the free surface has a significant influence on the reflection/transmission coefficients and its effectiveness, accordingly. It has been established that semi-submerged obstacles can dissipate up to 60% of the incident wave energy.

Keywords: solitary wave, wave screen barrier, submersion, reflection and transmission coefficients.

Introduction. Breakwaters are widely used to provide economical protection of harbors and beaches from surface waves. The study of the interaction of waves with protective structures, as well as the expediency and effectiveness of the means applied to reduce the impact of waves on the shores of natural reservoirs are important aspects of coastal and marine engineering [1].

Recently, breakwaters in the form of thin, rigid vertical barriers, also called a wave screen, have been used or considered. These structures are installed at the entrance to small sea or river harbors to dissipate wave energy and control shoreline erosion. The wave screen consists on cast walls that are connected with the supporting piles at the sides [2]. The upper part of the wall is impermeable and extends above the water level and other part is permeable and consists of closely spaced horizontal slots. This breakwater not only dissipates energy of incident waves but also improves water circulation, facilitates fish passage and minimizes the pollution near shore because it permits the flow exchange between the partially enclosed water body and the open sea. The study of wave interaction with a semi-submerged wave screen is needed to obtain the key information for understanding the hydraulic performance of this structure as a special breakwater. Note, to develop a modern protective structure, coastal engineers have to consider not only its effectiveness against waves, but also care for the environment.

Analysis of recent research and publications. Due to the importance of the problem under consideration, many theoretical and experimental researches have been performed to evaluate the efficiency of vertical barriers against waves. In most of them, only periodic waves were considered, and much less attention was paid to long solitary waves (solitons), although they are very dangerous for coastal areas. The results of the most comprehensive study of the interaction between a solitary wave and a partially submerged vertical barrier are presented in [3]. Transmitted and reflected wave characteristics, as well as velocity fields and wave-induced loads to the structure were obtained experimentally and numerically over a wide range of problem parameters such as water depth, incident wave amplitude and draught of the barrier. Experimental data were used to check a numerical model, based on the Reynolds-averaged Navier-Stokes (RANS) equations and the $(k-\varepsilon)$ turbulence closure model. Calculations were then carried out to obtain additional results, which allowed derive generalized formulae for the maximum run-up height and the maximum wave force. In [4], non-linear and dispersive solitary wave reflection and transmission characteristics after interacting with a partially immersed screen were calculated using the Smoothed Particle Hydrodynamics (SPH) method. Nonlinear waves of different heights when changing the draught of the curtain wall were considered. It was shown that the partially immersed curtain breakwater is effective in dissipating incoming wave energy if its immersion depth is over half of the water depth. In [5], the wave-curtain screen interaction was investigated by the weakly compressible smoothed particle hydrodynamics (WCSPH). It is noted that the submergence depth of wall plays a crucial role on its performance as a breakwater. The conclusion of the study [4] that the relative submergence of the wall by 50% is the most effective for damping wave energy was also confirmed. It was obtained that about 50% of the incident wave can pass the breakwater in this case.

An analytical theory for calculating the hydrodynamic characteristics of a partially submerged porous barrier attacked by a solitary wave is presented in [1]. It is based on the Fourier integral and the procedure of superposition of solutions, which are used to obtain the velocity potentials in the reflection and transmission regions. To evaluate the performance of a partially submerged thin porous wall as a breakwater, the wave run-up, transmission coefficient, and maximum horizontal force under various conditions are presented and discussed. The verification of the analytical solutions was based on a series of experimental measurements where the wave profiles in front of and behind the porous wall were determined.

The purpose of the work. In this paper, we study the prospects for reducing the energy of waves that attack the shores of natural reservoirs with the help of a curtain permeable screen. For this purpose, the laboratory experiments were conducted in which the characteristics of the interaction between a solitary wave and a semi-submerged screen were meagered. The reflection and transmission coefficients are obtained in a wide range of wave amplitudes and draught of the screen. These results make it possible to evaluate the efficiency of the considered device as a breakwater.

Experimental setup. Experiments were conducted in a glass-walled wave tank located at Institute of Hydromechanics of NAS of Ukraine. The wave tank is 16 m long, 0.30 m wide, and 0.70 m deep. In order to generate solitary waves, a heavy body was installed at one end of the channel. The fall of the body to the bottom created a local rise in the water level, which later transformed into a solitary wave. Note that this method of wave generation was first used by Russell (1834) [6]. In the experiments, it was modified by using a special arrangement to cut off the "dispersive train" that develops during the formation of a solitary wave. A model of a protective structure in the form of a semi-submerged curtain screen was mounted in the middle of the wave tank. Logging free surface deformations during the passage of a solitary wave over the screen was made by capacitive gauges, which were posed along the central line of channel. Four sensors, marked as D0…D3, were mounted in front of the curtain screen for recording the parameters of the incident and reflected waves. Sensors D4, D5 were located behind the screen to register the transmitted wave. The system for collection and processing of experimental data made it possible to poll the sensors, convert the received signal into a numerical form with the help of the analog-to-digital converter and quickly analyze the process using a PC. The sensors were calibrated prior to the experiments to obtain a regression relationship between the signals from the sensors and their depth. The average velocity of wave propagation as well as the amplitude, energy and profile of the wave were determined from these data. The picture of the interaction of the wave with the submerged screen was supplemented using a digital video camera. One can find a detailed description of the wave tank and experimental methodology in [7].

Validation of solitary wave generation. Since the generation of solitary waves in the present study followed the "old" method, their profiles were verified by comparing the free surface displacements to be obtained to the theoretical shallow water waveform. Fig. 1 demonstrates the profile of the solitary wave generated during the experiments (markers) and the Korteweg-de Vries wave solution (solid line) [8]:

$$\eta = a \cdot \mathrm{sech}^2\left[\left(\frac{3a}{4H^3}\right)^{1/2}(x - ct)\right],$$

where η is the free surface elevation; x and t are stream wise direction and time; a is the wave amplitude; H is the water depth and c is the wave celerity that can be calculated as $c = \sqrt{g(H + a)}$.

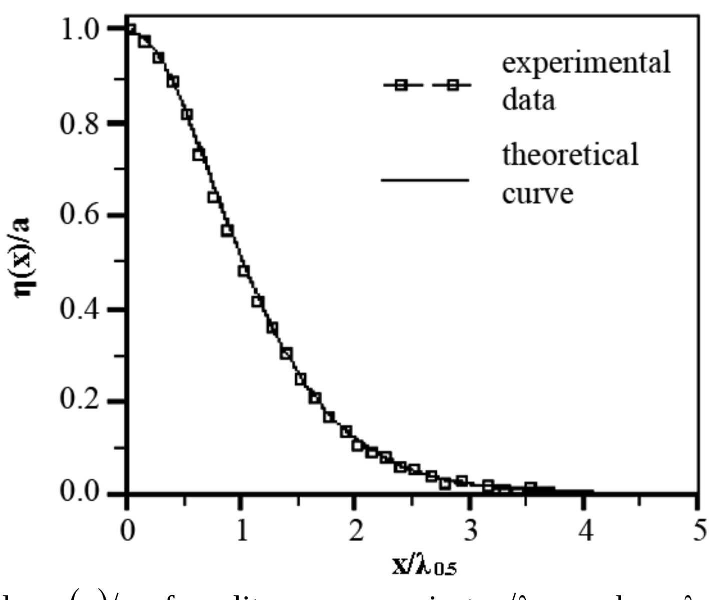

Fig. 1. Relative profiles $\eta(x)/a$ of a solitary wave against $x/\lambda_{0.5}$, where $\lambda_{0.5}$ is the distance from the wave crest to the point corresponding to half the amplitude of the wave [9]

From this comparison, it follows that the waves formed in the experiment are close to typical long waves, which are identified as solitons. A series of tests on the generation of a soliton in the experimental channel showed that the resulting waves are highly repeatable.

The length of such a wave is theoretically infinite; for practical use it can be estimated as the distance containing 95% of the total mass [10], namely:

$$\lambda = 2.12H\Big/\sqrt{a/H}\ .$$

The waves travel over long distances without spending much energy. In a channel of constant depth, their motion is accompanied by only a slight decrease in amplitude, which is a consequence of the dissipation of wave energy due to shear stresses caused by friction of liquid against the walls and bottom of the channel. Fig. 2 depicts the relative profiles of the solitary wave of amplitude $a/H = 0.32$ obtained when travelling the wave in the tank without the curtain screen. An analysis of these data revealed that obtained wave attenuation is close to theoretical estimates from [11].

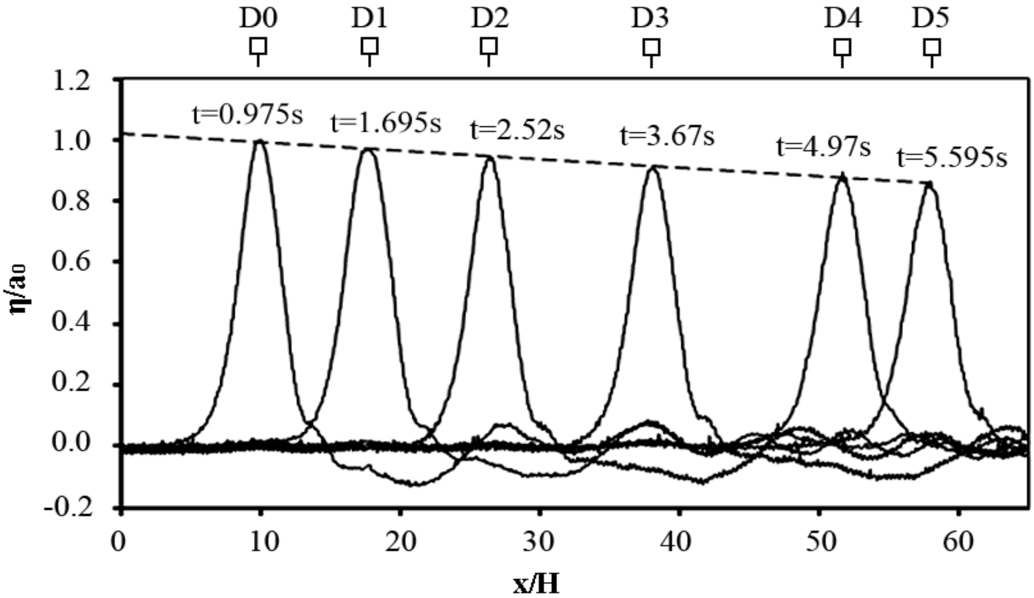

Fig. 2. Evolution of the solitary wave in the laboratory tank with a horizontal bottom

Results and discussion. If the channel is blocked by an obstacle, the solitary wave will undergo significant deformations, the determination of which is the goal of this study. The scheme of the experiment and the coordinate system Oxz are presented in Fig. 3, b. Note that the vertical axis $z = 0$ coincides with the obstacle, which is located between sensors D3 and D4 at distances $\sim 7H$ and $\sim 5H$ from those, respectively. The obstacle has the form of a thin curtain wall (screen) whose upper part rises above the free surface and the lower part does not reach the bottom. So, a slot is present in the channel section through which water can flow. The main geometrical parameter of this structure is the draught z_0 defined as the distance between the undisturbed free surface and the lower edge of the curtain wall (Fig. 3, b). Thus, the parameter z_0 regulates the width of the gap between the channel bottom and the curtain screen. In all the experiments, the protruding section of the screen exceeded the incident wave amplitude to prevent water flow there. The series of the experiments was carried out, in which the heights of transmitted and reflected waves were measured at different values of both the incident wave amplitude and the draught z_0. Technically, the position of the curtain walls relative to the free surface adjusted with the help of a tripod (Fig. 3, a). The water depth in the experimental tank was $H = 13$ cm throughout the experiments. Further, when interpreting the obtained data, all parameters will be referred to the depth H.

The evolution of a solitary wave interacting with a semi-submerged curtain screen is captured on the snapshots presented in Fig. 4. At the top, the initial half of the process is shown, when the wave generated close to the left end of the channel travels to the obstacle. It can be seen that the wave grows as it approaches the screen.

a) b)

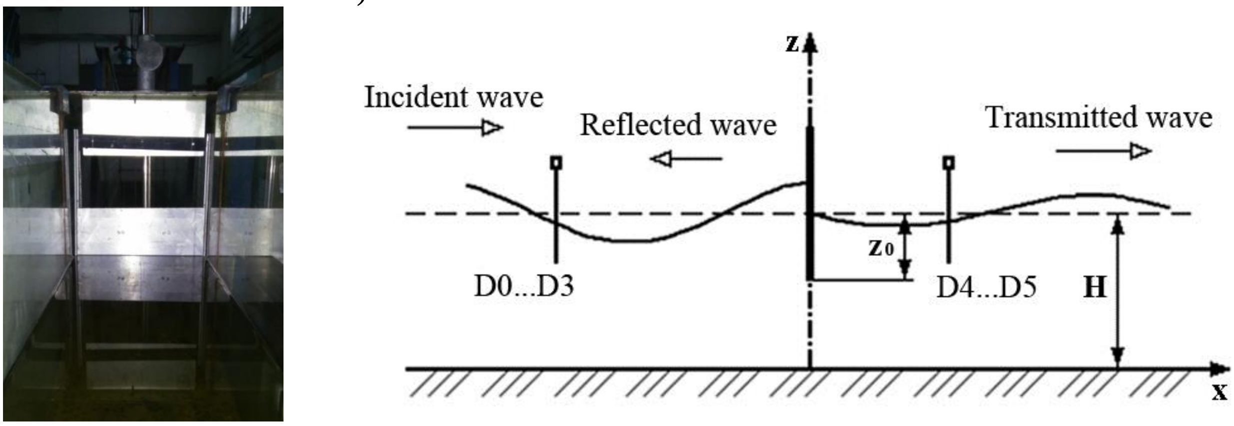

Fig. 3. Scheme of the research:
a – snapshot of the experimental channel with the semi-submerged curtain screen; b – sketch of the interaction between the solitary wave and the semi-submerged screen; the dotted line indicates the level of the free surface at rest; D0–D5 are the capacitive gauges

At the same time as the wave runs the screen, part of the water passes through the gap between the curtain wall and the bottom that causes an increase in the level of the free surface behind the obstacle too. After the runup of the wave reaches its maximum, it rolls down; as a result, a reflected wave is formed that propagates in the opposite direction (to the left end of the channel). The lower part of Fig. 4 demonstrates the final stage of the wave evolution, when the water that has passed between the obstacle and the bottom forms a transmitted soliton, which continues to move forward. It is obvious that the amplitude of the transmitted wave decreases compared to the incident wave owing to energy losses on the reflected wave and turbulent processes initiated by the wave near the obstacle. A series of experiments with different parameters of the problem made it possible to identify the configuration of the protective structure when the incident wave will spend maximal energy to overcome the obstacle.

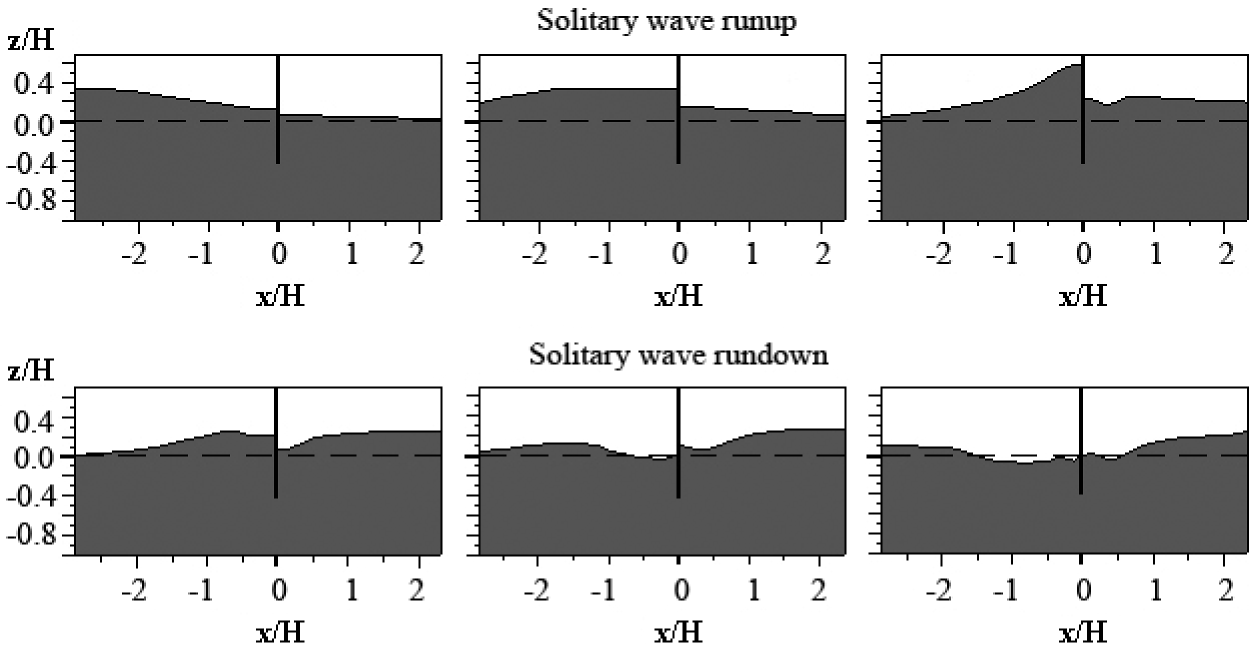

Fig. 4. Snapshots of the longitudinal section of experimental channel demonstrating interaction of a solitary wave with a semi-submerged curtain wall at $z_0 = 5\,\text{cm}$, $H = 13\,\text{cm}$

In Figs. 5, 6 the records of the free surface level obtained by sensors D0–D5 are presented for two configurations of the curtain wall. In the first case, the bottom edge of the wall coincides with the free surface, i.e., $z_0 = 0$, and $z_0 = 5\,cm$ in the second case. The number 1 denotes there the incident wave; 2 – the reflected wave; 3 – the transmitted wave and 4 – the wave reflected from right end of the experimental tank. The free surface disturbances η in these figures are referred to the incident wave amplitude a_0, which is recorded by D0 sensor at the beginning of the experimental tank. The non-dimensional time is introduced as $\bar{t} = t\sqrt{gH}/H = t\sqrt{g/H}$. Note that the given data were obtained at $H = 13\,cm,\ a_0 = 0.32H$.

It is obvious that when interacting a solitary wave with the cross wall lying at the free surface, the bulk of water passes below the obstacle. As a result, the wave is restored almost completely after the obstacle. It is seen in Fig. 5, that the transmitted wave is about 85% of the incident wave. The reflected wave is insignificant; it is recorded by D3 sensor only.

As the draught of the curtain wall increases (Fig. 6), the interaction between the solitary wave and the obstacle intensifies, which is manifested in the rising the energy of the reflected wave. It is now registered by all the sensors located in front of the wall. Data recorded by sensors D4, D5 indicate that the height of the transmitted wave drops significantly compared to the previous case. It is equal here ~75% of the initial value a_0. These results confirm that the depth of wall immersion is a factor that specifies the effectiveness of the curtain wall as a protective structure.

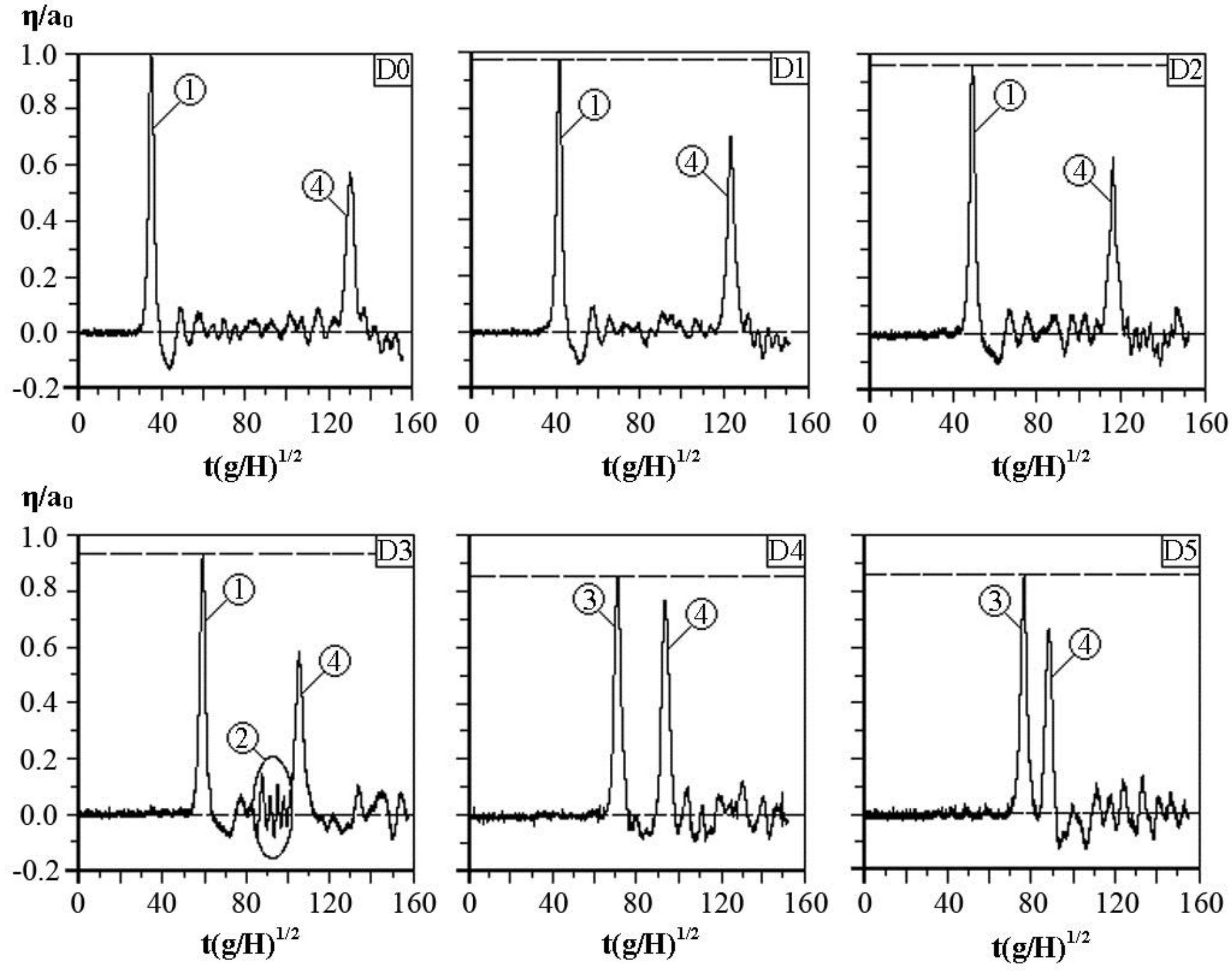

Fig. 5. Free surface disturbances recorded by sensors D0–D5 during the propagation of the solitary wave in the channel with the curtain wall at draught $z_0 = 0$

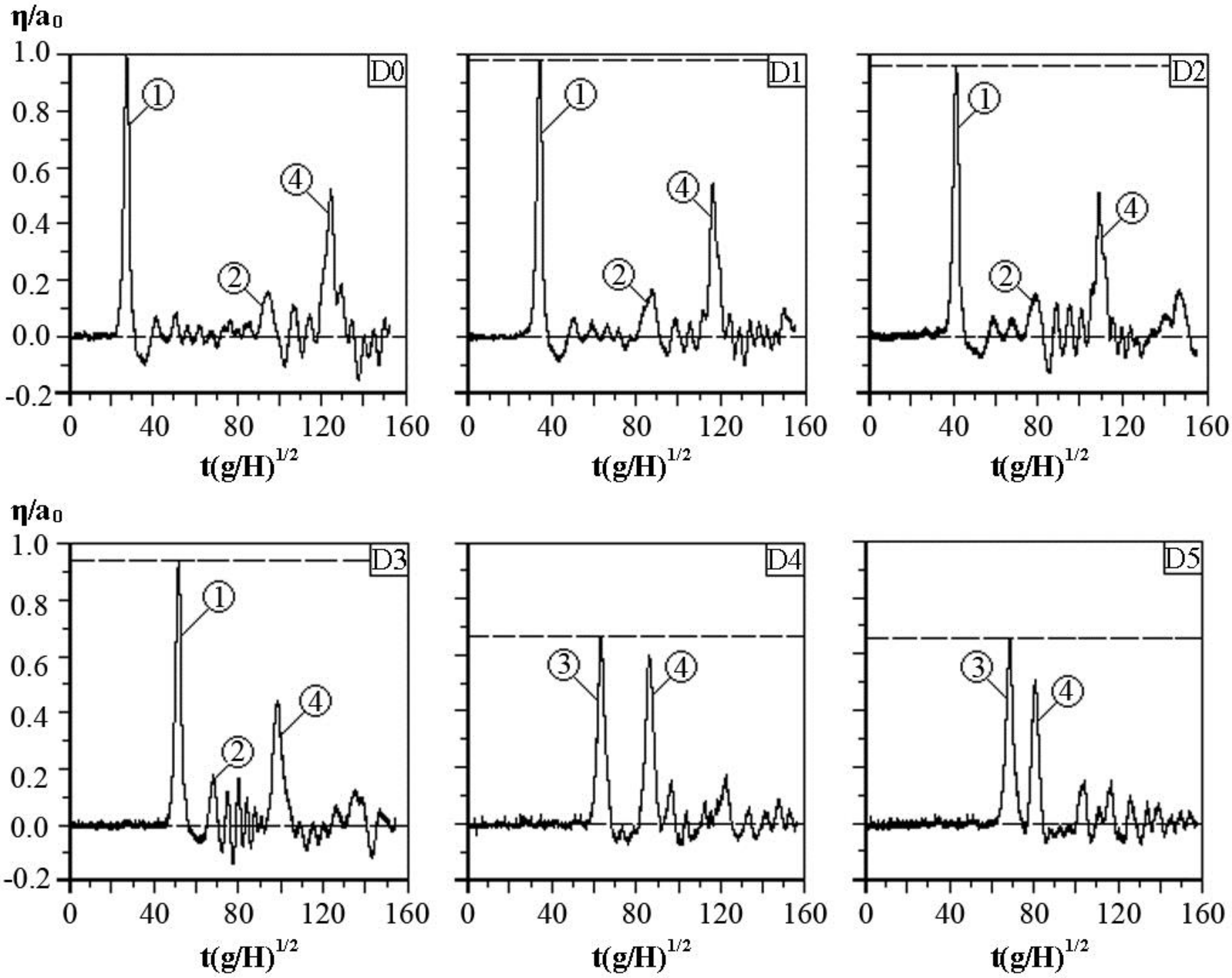

Fig. 6. Free surface disturbances recorded by sensors D0–D5 during the propagation of the solitary wave in the channel with the curtain wall at draught $z_0 = 5\,\text{cm}$

A quantitative criterion used to estimate the effectiveness of a breakwater against surface waves is defined as the ratio of the amplitude of the wave passed through structure to that of the incident wave [12]. It is called the transmission coefficient and is denoted as K_{tr}:

$$K_{tr} = a_{tr}/a_i \,,$$

where a_{tr} is the amplitude of the transmitted wave, a_i is the amplitude of the incident wave.

Similarly, the reflection coefficient K_r is introduced:

$$K_r = a_r/a_i \,,$$

where a_r is the amplitude of the reflected wave.

If a cross wall is installed on the bottom of tank and protrudes above the free surface, the incident wave will be almost completely reflected from this obstacle [12]. In this case, the free surface profiles formed when a solitary wave rolls off the wall are similar to runup of the wave to the obstacle. The decrease in the amplitude of the reflected wave compared to the amplitude of the incident wave recorded in the experiments does not exceed 5%. In this limiting configuration of the breakwater, the transmission coefficient K_{tr} is about zero and the reflection coefficient K_r goes to 1. From the point of view of protection of water areas from waves, such a construction is the most effective, but it does not meet ecological requirements, as it does not allow water exchange and free migration of fishes and other representatives of marine fauna. When the width of gap between the seabed and the lower edge of the curtain wall increases, the effectiveness of the structure against waves will deteriorate, since the transmission coefficient rises and the reflection coefficient, on the contrary, drops. Thus, when using the curtain wall as a breakwater, it is necessary to establish a balance between protective characteristics and environmental requirements.

Fig. 7 illustrates the dependences of the transmission K_{tr} and reflection K_r coefficients on the relative draught of the curtain screen z_0/H calculated based on the data of this investigation. The picture also contains a comparison of the available results with the corresponding data known from [5].

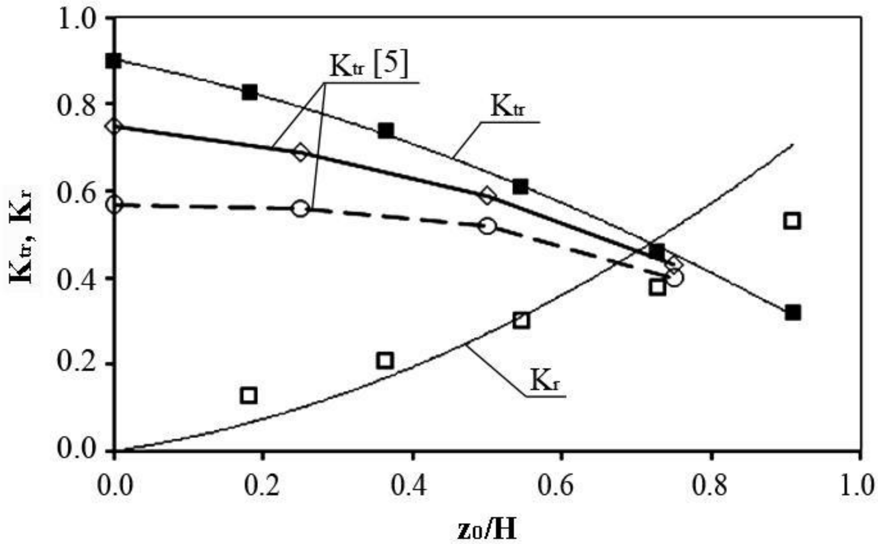

Fig. 7. Transmission K_{tr} and reflection K_r coefficients against the draught to depth ratio z_0/H : curves with markers -■- , -□- correspond to the present investigation, solid thick and dashed lines reflect the results of numerical simulations by SPH and WCSPH methods, respectively [5]

The curves represented in Fig. 7 indicate the good correlation between the transmission and reflection coefficients when a solitary wave propagates in the channel with a cross curtain screen. When the draught of the screen increases, its influence on the process grows which leads to the intensification of the interaction between the wave and the obstacle. The narrower the gap between the bottom and the screen the less water it passes, as a results, the energy of the transmitted wave drops. On the contrary, the energy of the reflected wave increases. It is obtained in the experiments, that the draught to depth ratio z_0/H is decisive in this configuration, at the same time, the water depth in the channel does not a significant effect to the transmission and reflection coefficients. It follows from Fig. 7, that augmentation of the relative draught z_0/H leads to a decrease in the transmission coefficient and an increase in the reflection coefficient. The value of z_0/H at which the coefficients are equal is about 0.7. It is also seen that attenuation of a solitary wave can reach 60-70% when it passes through a semi-submerged curtain screen. This fact points out the high efficiency of such a structure in dissipating the energy of the waves attacking sea shores. It must also be emphasized that a semi-submerged curtain screen will be effective in dissipating the energy of incident waves when its draught exceeds half the water depth.

A comparison of the transmitted coefficient (shaded squares) with the corresponding results of paper [5], which have been numerically calculated with applying the smoothed particle hydrodynamic method (SPH) – solid line in Fig. 7, and the weakly compressible smoothed particle hydrodynamics (WCSPH) – dashed line, demonstrates that the experimental data are slightly overestimated the numerical results. Although the general trend for the dependence of the coefficient K_{tr} on the ratio z_0/H remains. The maximum error was observed at small draughts and it ranges from 15% to 30%. When the draught is large, the error drops to 5-7%.

Conclusions. The results of the experimental research of the interaction between a solitary wave and a semi-submerged curtain screen are presented. It is shown that such a structure can be effective in reducing the energy of waves attacking seashores, although it does not suppress the waves completely. The efficiency of the semi-submerged screen as a breakwater is measured by the transmission coefficient, which is calculated as the ratio of the amplitude of the incident wave to the amplitude of the transmitted wave. The experimental data obtained indicate that the coefficient depends on the ratio of the screen draught to the water depth. If the ratio is less than 0.5, then more than 50% of the energy of the incident wave is carried downstream by the transmitted wave. However, when the draught to depth ratio exceeds 0.5, the semi-submerged screen will be effective in restraining a solitary wave, since the transmission coefficient in this case can drop to 35%. Thus, the target protection when using such structures can be achieved by choosing the draught of the impermeable section of the breakwater.

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НАБІГАННЯ ПОВЕРХНЕВОЇ ПООДИНОКОЇ ХВИЛІ НА ТОНКИЙ ВЕРТИКАЛЬНИЙ НАПІВЗАНУРЕНИЙ ЕКРАН

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Анотація. Глобальні зміни клімату призводять до збільшення кількості й інтенсивності екстремальних явищ в морях і океанах (цунамі, повені, штормові нагони води та ін.). Це може мати катастрофічні наслідки, пов’язані з руйнуваннями цивільної інфраструктури, затопленням великих територій, відведених для рекреаційних цілей, втратою життів, а також може згубно вплинути на якість води, транспортування осаду та середовище існування живих організмів.

Створення штучних берм на морському дні та хвилеруйнівних молів суттєво впливають на параметри хвильових процесів, зменшуючи їх руйнівну дію в прибережній зоні. Але використання традиційних берегозахисних споруд (гребель, молів, хвилеломів) не завжди є доцільним та економічно обґрунтованим. Проникні перешкоди все частіше розглядаються як альтернативний варіант в забезпеченні економічного й екологічного захисту прибережних територій. Метою цієї роботи є обґрунтування ефективності вертикальних напівзанурених стінок для захисту берегів природних водойм від руйнівної енергії поверхневих хвиль. Така споруда є суцільною поблизу поверхні води, а знизу підтримується палями на деякій відстані від дна, що допускає перетікання води та наносів. Виконане фізичне моделювання в експериментальному каналі взаємодії поверхневої поодинокої хвилі, яка розглядається як модель цунамі, з напівзатопленою тонкою вертикальною перешкодою задля оцінки ефективності вертикальних хвильових бар'єрів в зменшенні енергії сильних нелінійних хвиль. В експериментах отримано, що при набіганні солітонної хвилі на навісну вертикальну стінку, відбита хвиля утворюється з накату падаючої хвилі на споруду, а прохідна хвиля формується після проходження маси рідини через зазор між дном і нижньою частиною стінки.

Кількісні характеристики взаємодії хвилі з перешкодою були отримані за допомогою ємнісних датчиків, які були встановлені вздовж головної осі лабораторного каналу і реєстрували збурення вільної поверхні, викликані поширенням хвилі в каналі, її відбиттям від хвильового екрану та проходженням вниз по течії. Обробка отриманих даних дозволила оцінити параметри поодинокої хвилі, що формувалася в каналі ударом важкого тіла об поверхню води – амплітуди, довжини, швидкості поширення. Зроблено оцінку затухання енергії поодинокої хвилі, що є важливою характеристикою каналу і дає змогу отримати більш точні значення по коефіцієнтам відбиття та проходження. Отримані оцінки коефіцієнтів відбиття та проходження хвилі показують, що тонкі частково занурені вертикальні бар’єри хоча й не пригнічують нелінійні солітонні хвилі повністю, але є достатньо ефективними в зменшенні їх інтенсивності. Значний вплив на коефіцієнти проходження/відбиття і, відповідно, ефективність проникної перешкоди екранного типу має глибина її занурення відносно поверхні води. Встановлено, що напівзанурені перешкоди можуть розсіювати до 60% енергії падаючої хвилі.

Ключові слова: поодинока хвиля, хвильовий бар’єр екранного типу, осадка, коефіцієнти відбиття та проходження.

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