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NUMERICAL SIMULATION OF WAVE DAMPENING BY A STRUCTURE OF THE HYDRO-ENGINEERING FACILITY IN COMPLETE VERTICAL PROFILE

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Abstract. The article decribes the issues of numerical experimental research related to the determination of the magnitude of the waves damping when they overflow through the upper structure of a protective hydraulic structure (PHS) of an incomplete vertical profile. The presented studies were carried out in order to verify the results of physical experimental studies. Physical experimental studies were carried out in the hydrowave laboratory of the Hydrotechnical Construction Department of the Odessa State Academy of Civil Engineering and Architecture. The numerical model of the design of the PHS of an incomplete vertical profile was made similar to the conditions of the full-scale section of the coast of the Odessa Bay. The design of the PHS of an incomplete vertical profile is supposed to be located at a distance L = 200 (m) from the coastline of the protected area. At the location of the designed protective structure, the estimated water depth d = 4.0 (m). Having built the rays of refraction and transformation of waves when the waves approach the designed structure, the calculated wave height will be h = 2.4 (m); average wavelength λ = 24.5 (m); the elevation of the upper structure of the PHS with an incomplete vertical profile relative to the calm water level was taken equal to ΔH = +1.0 (m), the width of the superstructure of the protective structure B = 4.0 (m). As a result of numerical experiments, the height of the damped wave when it overflows through the upper structure of the PHS structure with an incomplete vertical profile onto the protected water area was h_{tr} = 0.6 (m). The results of numerical simulation differ by – 3.3% from the wave height obtained during the physical experiment.

The use of PHS structures of an incomplete vertical profile, in order to protect the water areas of seaports, as well as elements of the coastal infrastructure of sea cities, will increase the investment attractiveness of creating new projects of protective and coastal protection structures, due to a decrease in the elevation of the surface part.

Keywords: numerical modeling, barrier hydraulic structure of incomplete vertical profile, wave damping.

Introduction. In the practice of building fencing and bank protection hydraulic structures, structures of an incomplete vertical profile are used. Protective hydraulic structures (PHS) of an incomplete vertical profile include structures that allow partial overflow of wave crests through their upper structure to the protected water area with a further change in the main wave parameters. However, in the regulatory documents of many countries on the design of hydraulic structures and publications of various researchers, there are no scientifically based practical recommendations that allow determining the magnitude of wave damping by structures of this type.

The obtained results of numerical simulation differ from the wave height obtained during a physical experiment, the results of which were presented in publications [1-3]. An empirical dependence designed to determine the magnitude of wave damping during their overflow through the upper structure of the PHS structures of an incomplete vertical profile was presented in the publication [4].

Numerical modelling is increasingly being used to study complex physical processes that will be observed during the operation of real objects. The use of numerical methods can significantly reduce the time when creating complex models, reduce financial costs when conducting research and performing fine-tuning (calibration) of the investigated structures of the PHS of an incomplete vertical profile.

Improving the design of hydraulic structures, increasing their reliability and reducing costs is directly related to the improvement of engineering calculation methods. In modern times, the VOF (Volume-of-Fluid) method is widely used in hydrodynamic calculations, which uses the volumetric part of the liquid in the middle of the calculated volume of the finite element mesh as a marker option. This approach was proposed in [5] and has several varieties that differ in the way the marker functions are used or the way in which boundary conditions are set at the media interface [6].

The results of the numerical study presented in the article, related to the determination of the magnitude of wave damping during their overflow through the upper structure of the PHS structure of an incomplete vertical profile onto the protected water area, were obtained in order to verify the results of physical experiments and confirm the reliability of the method designed to determine the values of wave damping by PHS structures incomplete vertical profile.

Analysis of recent research. The conducted literature review showed that studies on the issues of wave damping, and designs of PHS of an incomplete vertical profile, were carried out both in the Soviet Union and abroad. However, to date, there are no practical recommendations in the literature that can be used in engineering practice.

Experimental data from laboratory studies with the frontal wave approach were presented in the publication of O.Yu. Birskaya [7]. In order to determine the wave damping coefficients, which was recommended for use, the formula (1):

$$k_{ВГ} = \frac{h-h_0}{h} = \sqrt{\frac{h}{\lambda}} \cdot (0.23\frac{B}{h} + 2.3\frac{\Delta H}{h} + 1.6), \quad (1)$$

where: h – source wave height (m);

h_0 – residual wave height between the breakwater and the shore (m);

λ – source wave length (m);

ΔH – elevation of the top of the structure relative to the calculated water level (m);

B – ridge width (m).

Having analyzed and compared the results of similar experimental studies related to the determination of the magnitude of wave damping during overflow through the upper structure of the incomplete profile PHS structures made of rock placement, published by (Seeling [8]; Allsop [9-11]; Kobayashi [12]); Sorensen [13], Koohestani [14], Cuomo [15], d'Angremond [16] proposed to use the following relation (2):

$$k_t = -0.4\frac{R_s}{H_i} + 0.80 \cdot (\frac{B}{H_i})^{-0.31} \cdot (1-e^{-0.5\zeta}), \quad (2)$$

where: R_s – elevation of the top of the structure relative to the calculated water level (m);

H_i – source wave height (m);

B – ridge width (m);

ζ – coefficient taking into account the influence of the location of the breakwater in relation to the wave profile, determined by the formula (3);

$$\zeta = \frac{\tan\alpha}{\sqrt{H_i / L_0}}, \quad (3)$$

where: α – angle of propagation of the wave beam with respect to the longitudinal axis of the structure.

Having processed numerous experimental data of wave actions on the PHS of an incomplete vertical profile, Briganti and others [17] in 2003 proposed an empirical dependence (4):

$$k_t = -0.35 \cdot \frac{R_s}{H_i} + 0.51 \cdot (\frac{B}{H_i})^{-0.65} \cdot (1-e^{-0.41\zeta}), \quad (4)$$

where: h_s – elevation of the top of the structure relative to the calculated water level (m);

H_i – source wave height (m);

B – ridge width (m).

The aim of the work was to conduct a numerical experimental study in the ANSYS Fluent software package, related to determining the magnitude of the damping of waves when they overflow through the upper structure of the PHS structure of an incomplete vertical profile onto the protected water area. The studies presented in the publication were carried out in order to verify the previously obtained results of physical experiments, and confirm the reliability of the proposed empirical dependence presented in the publication [4].

Research methods. In the practice of building protective hydraulic structures, structures of an incomplete vertical profile are used (Fig. 1), through the upper structure of which it is allowed, overflow of wave crests with a further change in their main wave parameters. These structures, depending on the conditions of use, can be exposed to both standing and breaking waves.

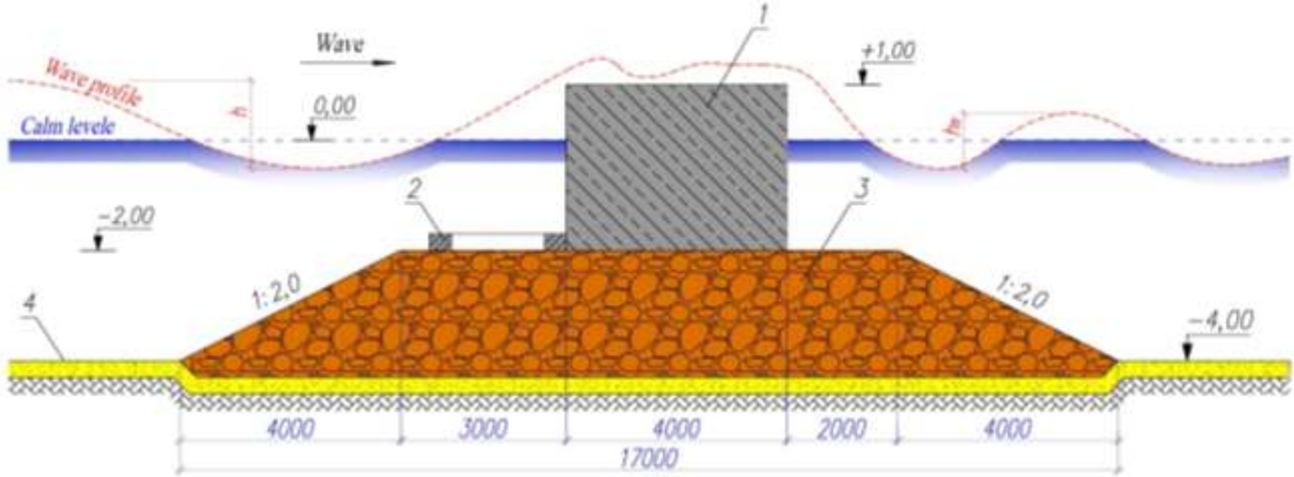


Fig. 1. Cross section of the construction of a breakwater of an incomplete vertical profile:
1 – concrete mass; 2 – pregnant massif (slotted plate); 3 – stone base

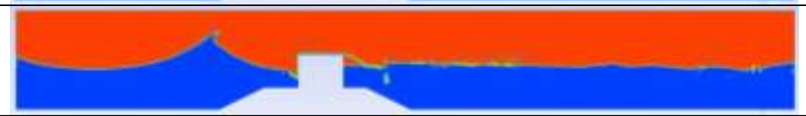
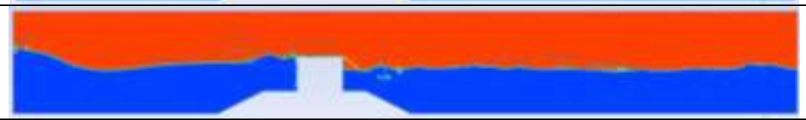
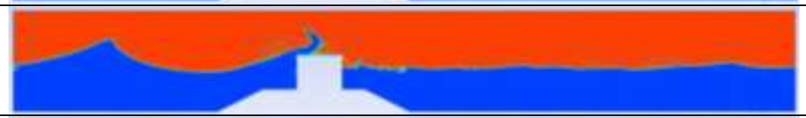
Permissible wave heights expected in protected areas of urban infrastructure are regulated by the parameters of preserving seashores and beach material and preventing flooding of coastal areas due to the impact of storms of rare frequency. In cases of protection from wave impacts of seaport territories, it is recommended to take the permissible wave heights ≤ 1.2 (m). These conditions are established on the basis of the possibility of mooring operations, as well as ensuring, at the moment of contact of ships with the fenders of berthing facilities, the normal component of the speed of approach to the berths.

The project [18] is considered as an example. The design of the PHS of an incomplete vertical profile presented in the article was supposed to be located at a distance L = 200 (m) from the coastline of the protected territory of the Odessa Agricultural Engineering Plant. At the location of the designed protective structure, the water depth d = 4.0 (m). Having built the rays of refraction and transformation of waves when they approach the designed structure, the calculated wave height will be h = 2.4 (m), average wavelength λ = 24.5 (m), the elevation of the upper structure of the PHS of an incomplete vertical profile relative to the calm water level will be ΔH = +1.0 (m), the width of the upper structure of the protective structure B = 4.0 (m). In accordance with the calculations, it was found that in order to avoid flooding the protected area of the plant, the permissible wave height should not exceed h_{tr} < 1.5 (m).

Research results. The authors of the article carried out numerical studies in order to verify the previously obtained results of physical modelling presented in publications [1-3]. The task of the study was to determine the magnitude of the waves damping when they overflow through the upper structure of the PHS structure of an incomplete vertical profile. Numerical simulation was carried out using the ANSYS Fluent software package. When modelling, a numerical model was used, the length of which was 70 meters, and the height was 9.5 meters.

The results obtained during the numerical simulation are presented in Table 1.

Table 1 – Numerical simulation results

№	Wave transformation by design protective hydraulic structure incomplete vertical profile	Time from start of simulation	Suppressed wave height
1		4 second	-
2		5 second	-
3		6 second	-
4		7 second	-
5		8 second	-
6		9 second	0.10 m
7		10 second	0.15 m
8		11 second	0.20 m
9		12 second	0.25 m
10		13 second	0.30 m
11		17 second	0.35 m
12		18 second	0.40 m
13		19 second	0.60 m
14		20 second	0.60 m
15		21 second	0.60 m

In accordance with the obtained results of numerical modeling related to determining the magnitude of wave damping by the PHS design of an incomplete vertical profile, when waves overflow through the upper structure to the protected water area, under the accepted boundary conditions, the damped wave height was h_{tr} = 0.6 m (Fig. 2).

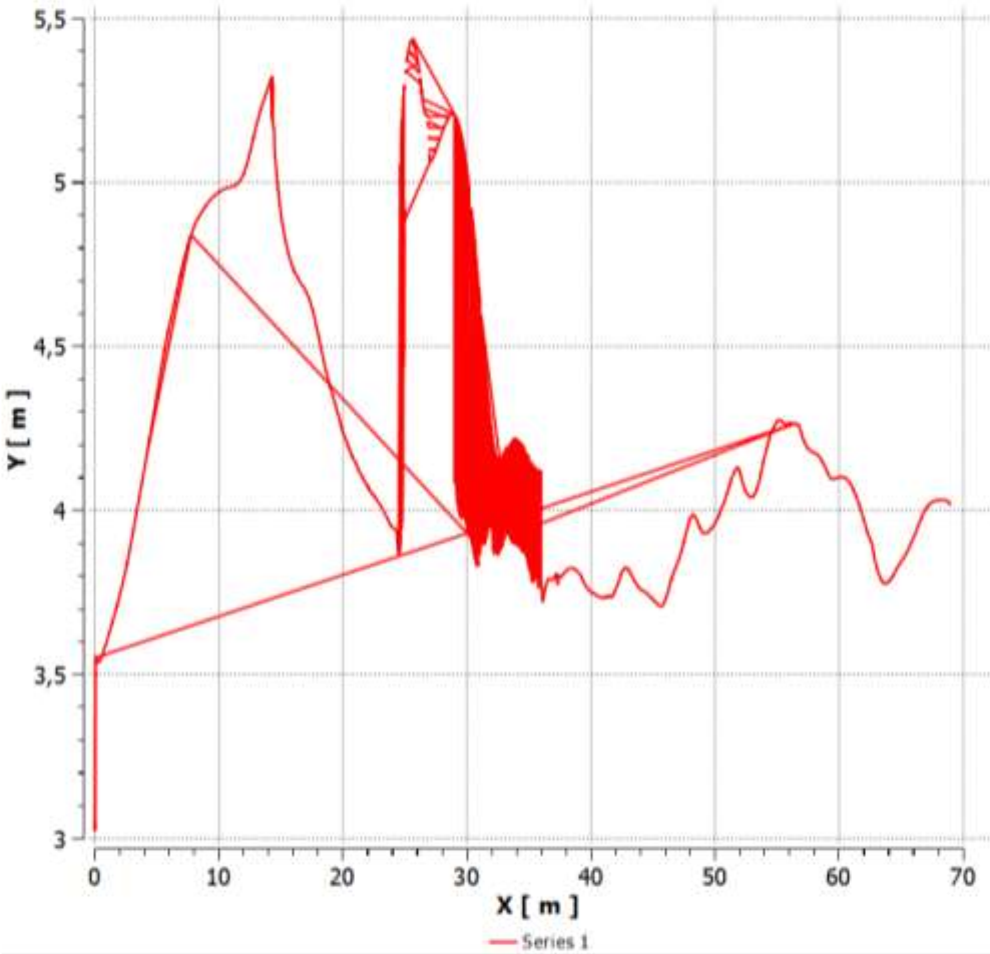


Fig. 2. The level of the free surface of the water during the numerical simulation (21 seconds from the start of the experiment)

In the presented studies, a time interval of up to 21 seconds from the start of the numerical simulation was considered, which made it possible to fully evaluate the wave pattern both in the protected water area itself and in front of the PHS design of an incomplete vertical profile.

The analysis of the vectors and fields of the velocities of movement of water particles in a wave under the influence of an incomplete vertical profile on the PHS structure, in order to establish the magnitude of the waves damping, was carried out on the basis of graphic materials, which were selectively presented in Fig. 3-17. The visualizations show the trajectories of wave movements, which are formed by the velocity vectors of the movement of water particles at the location of the protective structure. Visualizations are reviewed at set time intervals, which were considered in steps of 1 second for a reliable analysis. The accepted duration of the experiment was 21 seconds, which was due to the period and length of the calculated wave, which was used as the boundary condition of the numerical experiment. The criterion for the accepted time interval was the need to stabilize the cyclic recurrence of the movement of the wave profile, which occurred after the passage of at least three cancelled waves to the protected water area.

The results of the numerical simulation at a time equal to 4 seconds from the beginning of the experiment are presented in Fig. 3.

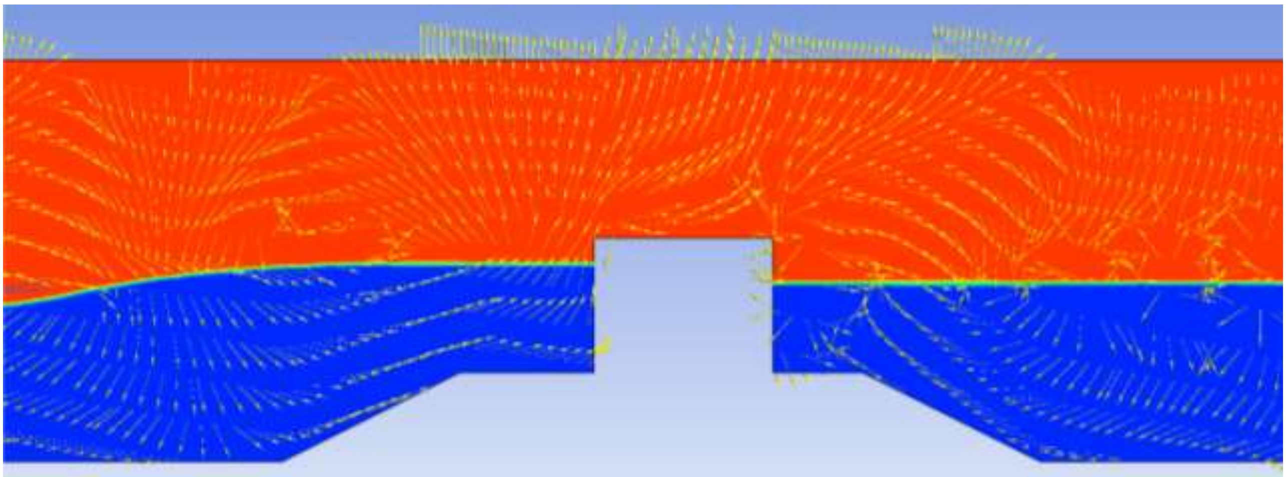


Fig. 3. Vectors of motion of water particles at the moment of time equal to 4 seconds from the beginning of the numerical experiment

In the process of processing the results of the numerical experiment, it was found that the calculated wave, which is formed on the left side of the model (Fig. 3) during its movement, first of all, meets with the influence of the stone base, while partially changing the trajectory of the particles water. With further movement, the transformed wave meets a vertical barrier, and is partially reflected from the upper structure of the PHS structure of an incomplete vertical profile. From this point in time and up to a period equal to 8 seconds (Fig. 7), a standing wave is formed on the left side of the structure, and a calm surface of the water is observed in the protected area. Partial penetration of wave crests into the protected water area begins to appear starting from 10 seconds (Fig. 9) from the start of the numerical experiment, while the formation of a damped wave is observed, which increases with the time of the numerical experiment.

The results of the calculations at the time of 5 seconds from the start of the numerical experiment are shown in Fig. 4.

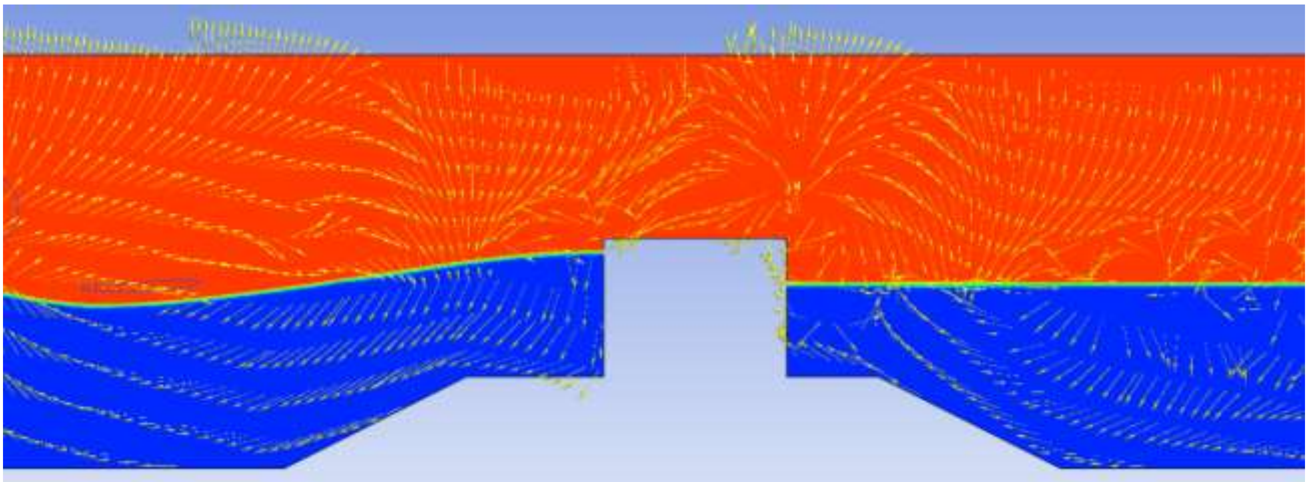


Fig. 4. Vectors of motion of water particles at the moment of time equal to 5 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 6 seconds from the start of the numerical experiment are shown in Fig. 5.

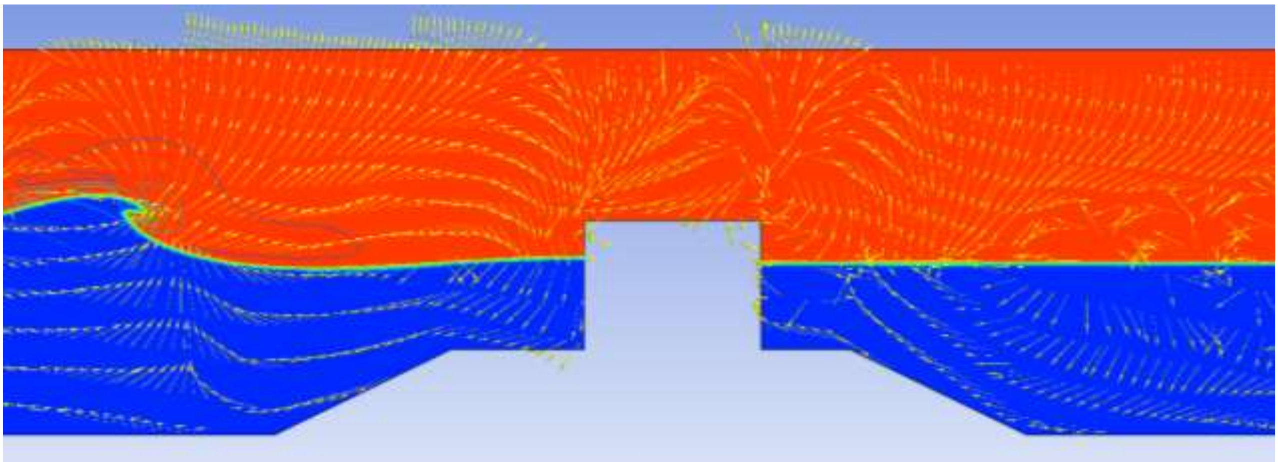


Fig. 5. Vectors of motion of water particles at the moment of time equal to 6 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 7 seconds from the start of the numerical experiment are shown in Fig. 6.

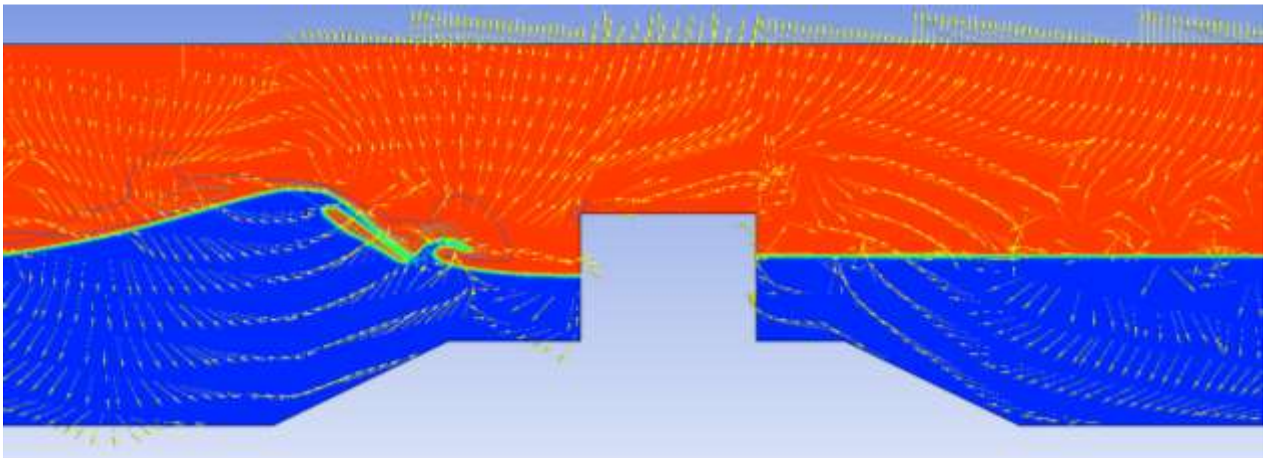


Fig. 6. Vectors of motion of water particles at the moment of time equal to 7 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 8 seconds from the start of the numerical experiment are shown in Fig. 7.

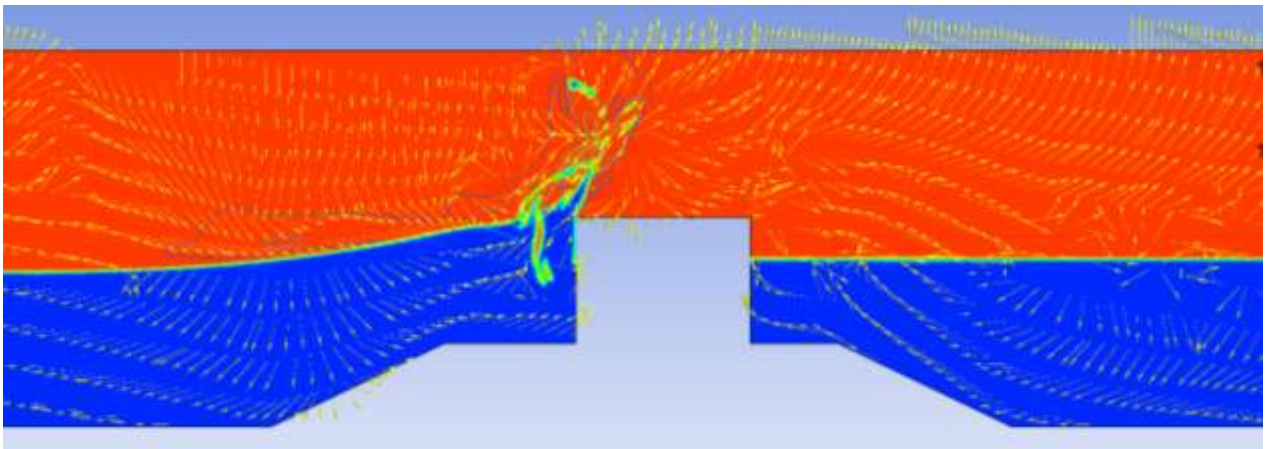


Fig. 7. Vectors of motion of water particles at the moment of time equal to 8 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 9 seconds from the start of the numerical experiment are shown in Fig. 8.

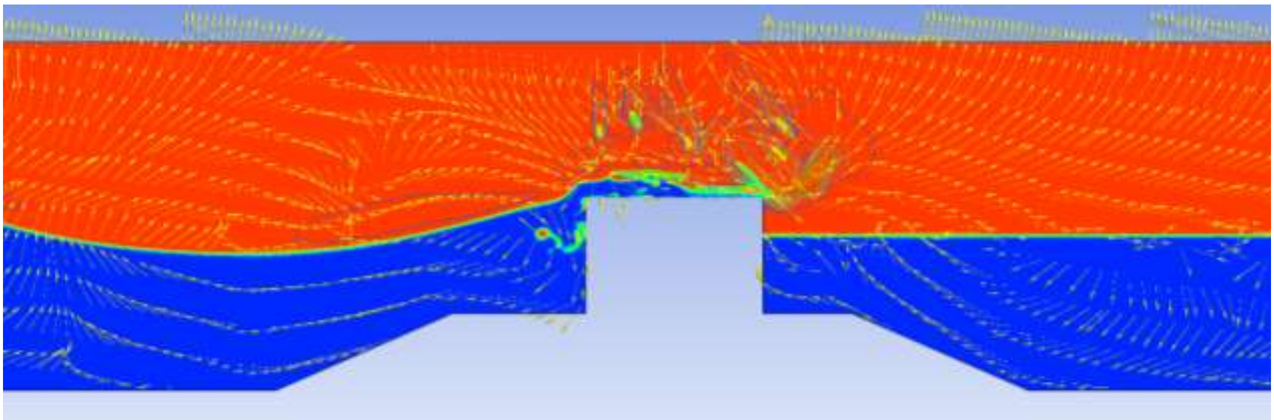


Fig. 8. Vectors of motion of water particles at the moment of time equal to 9 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 10 seconds from the start of the numerical experiment are shown in Fig. 9.

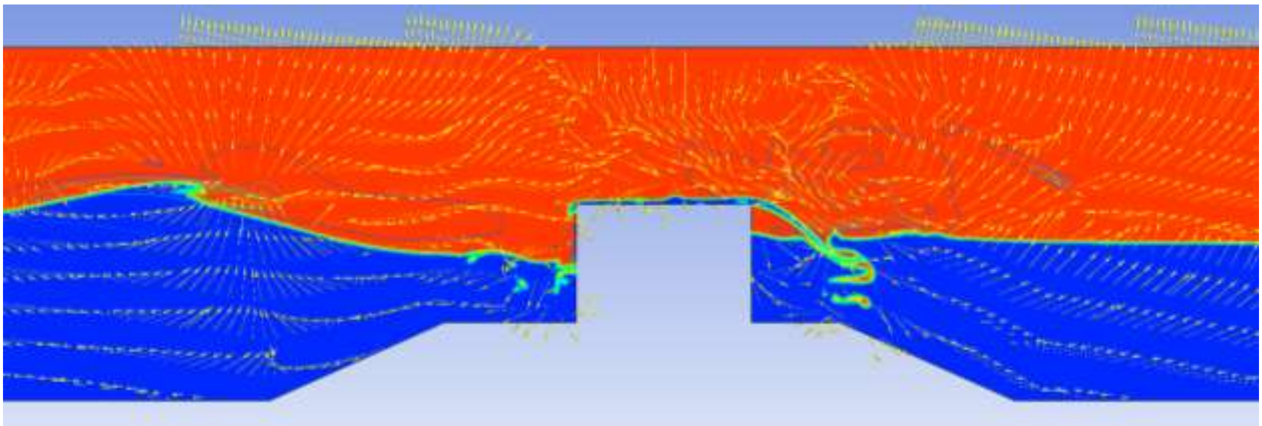


Fig. 9. Vectors of motion of water particles at the moment of time equal to 10 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 11 seconds from the start of the numerical experiment are shown in Fig. 10.

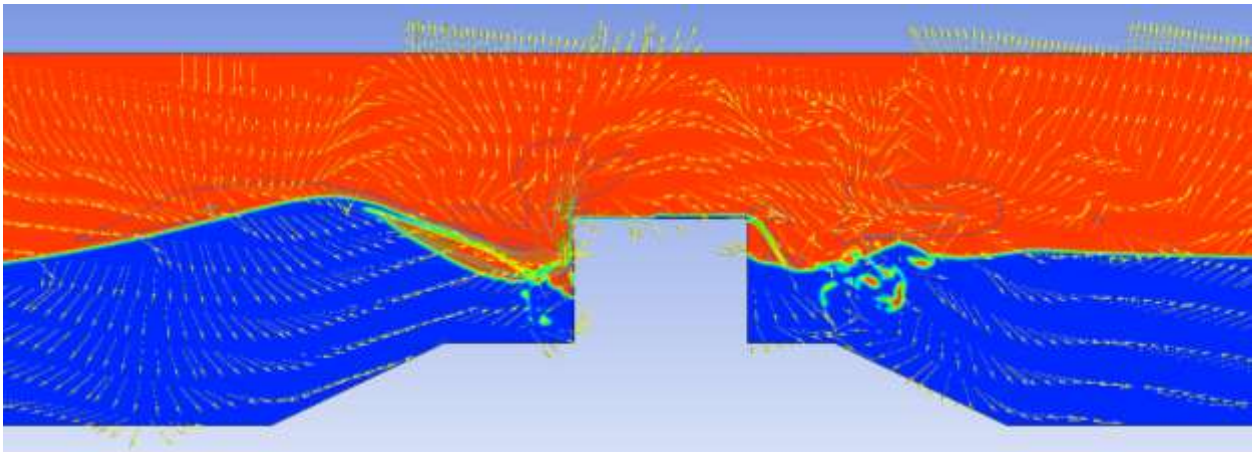


Fig. 10. Vectors of motion of water particles at the moment of time equal to 11 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 12 seconds from the start of the numerical experiment are shown in Fig. 11.

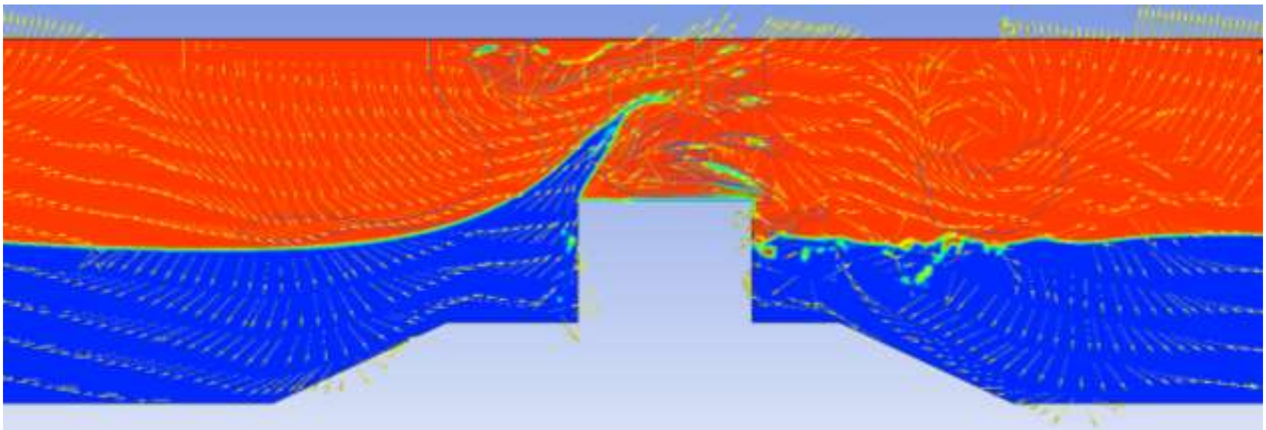


Fig. 11. Vectors of motion of water particles at the moment of time equal to 12 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 13 seconds from the start of the numerical experiment are shown in Fig. 12.

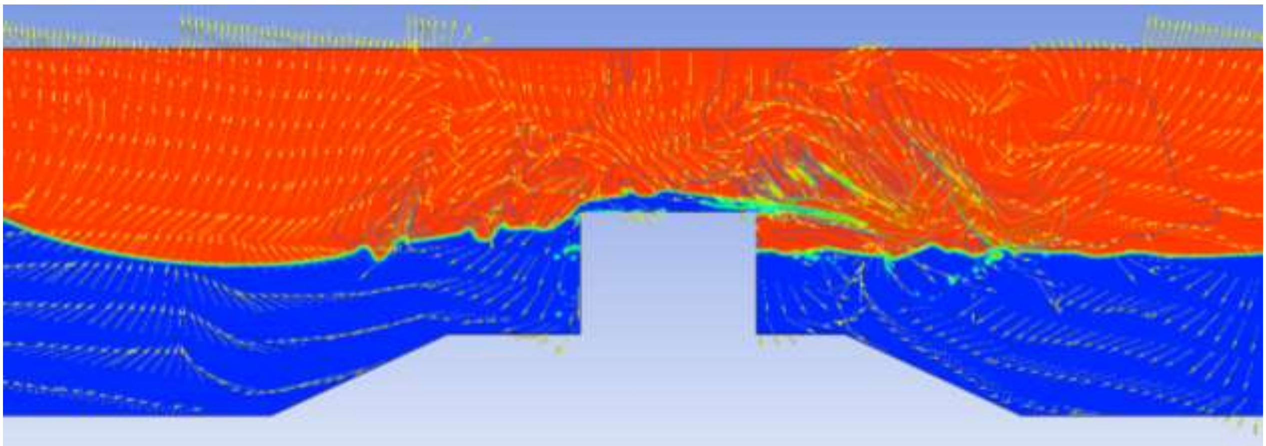


Fig. 12. Vectors of motion of water particles at the moment of time equal to 13 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 17 seconds from the start of the numerical experiment are shown in Fig. 13.

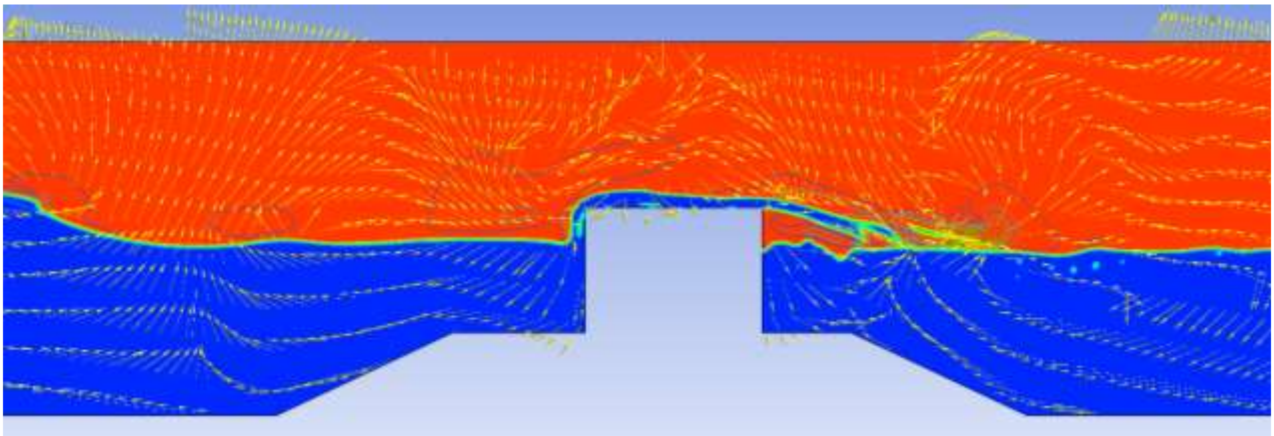


Fig. 13. Vectors of motion of water particles at the moment of time equal to 17 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 18 seconds from the start of the numerical experiment are shown in Fig. 14.

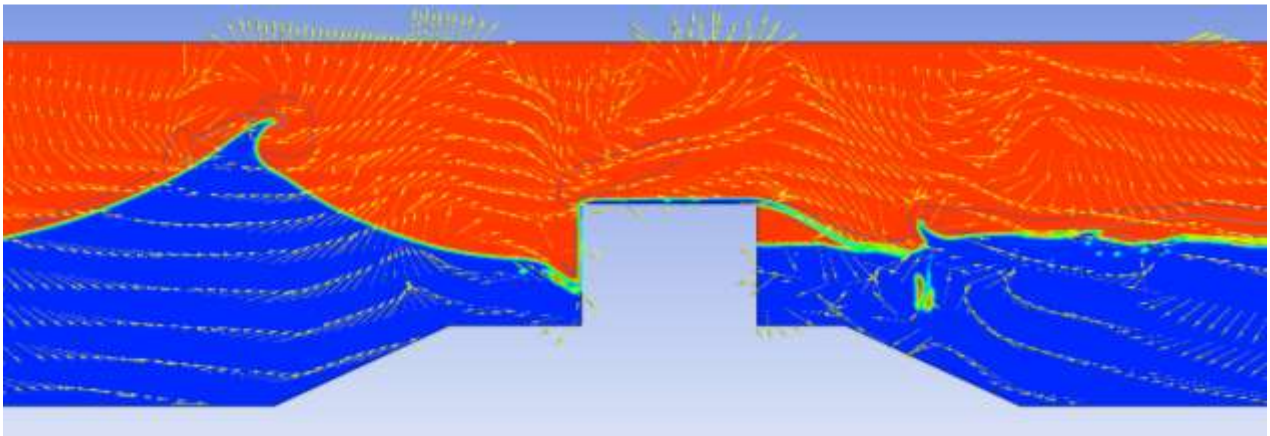


Fig. 14. Vectors of motion of water particles at the moment of time equal to 18 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 19 seconds from the start of the numerical experiment are shown in Fig. 15.

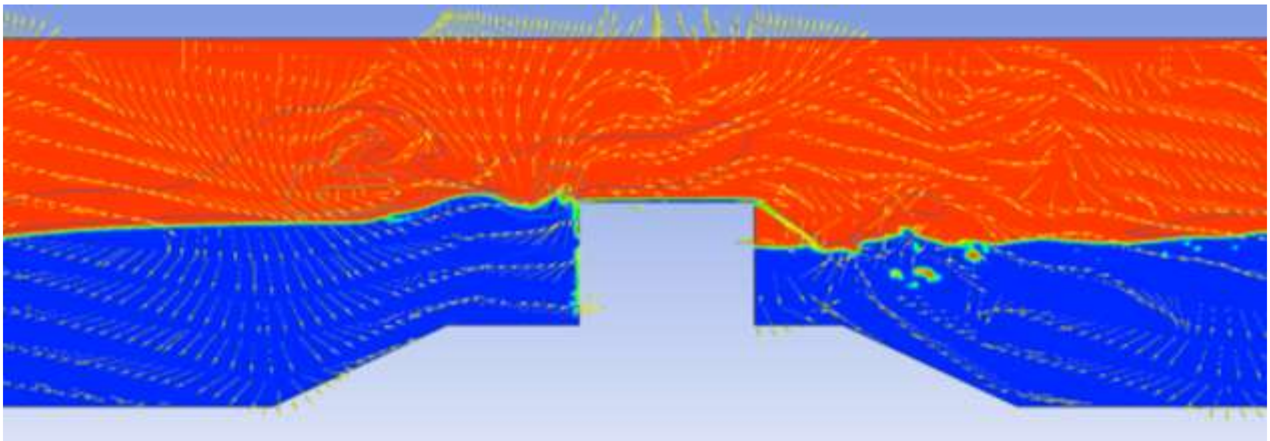


Fig. 15. Vectors of motion of water particles at the moment of time equal to 19 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 20 seconds from the start of the numerical experiment are shown in Fig. 16.

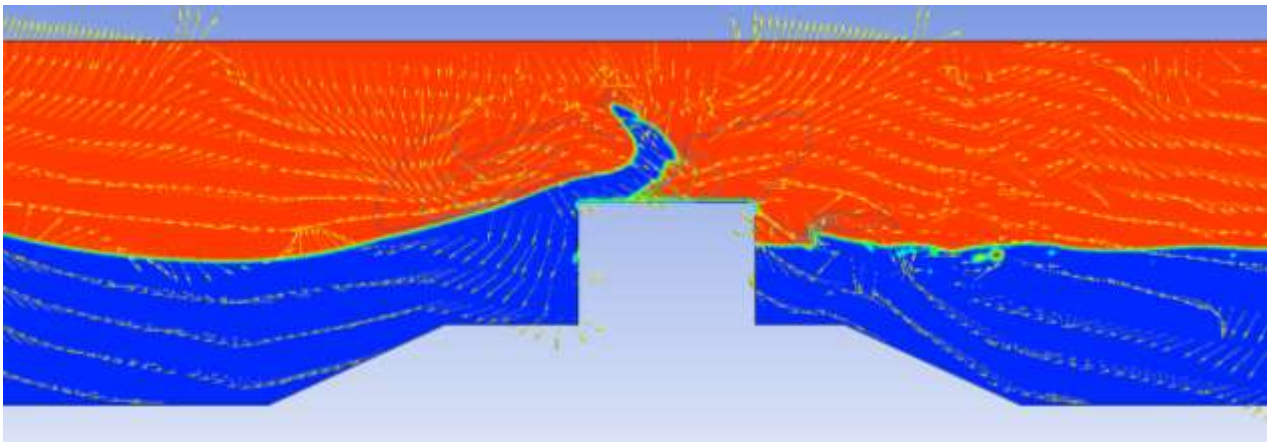


Fig. 16. Vectors of motion of water particles at the moment of time equal to 20 seconds from the beginning of the numerical experiment

The results of the calculations at the time of 21 seconds from the start of the numerical experiment are shown in Fig. 17.

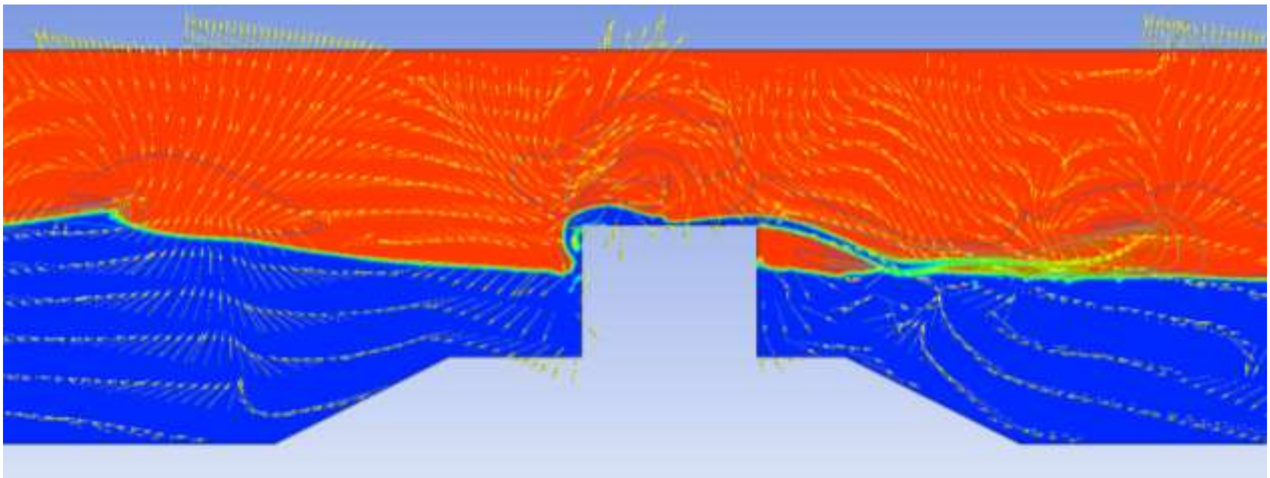


Fig. 17. Vectors of motion of water particles at the moment of time equal to 21 seconds from the beginning of the numerical experiment

In the time interval, starting from 10 seconds from the start of the numerical experiment, the phenomenon of the partial overflow of wave crests through the upper structure of the PHS structure of an incomplete vertical profile onto the protected water area is observed. As a result of the overflow, the formation of transformed waves occurs, which had significantly lower heights.

After that, the process under study is repeated cyclically (Fig. 10-17) until the wave action stops.

Conclusions. The results of the numerical simulation presented in the publication confirm the reliability of physical experimental studies presented in publications [1-3]. With the accepted initial data, the difference in the heights of cancelled waves, which were obtained during the numerical simulation and physical experiment, does not exceed – 3.3%.

An analysis of the results of the trajectories of water particles on the presented visualizations, based on the results of numerical simulation, showed that the PHS of an incomplete vertical profile partially reflect waves from their structure in the direction opposite to the movement of the wavefront, the crests of the waves that have not changed the trajectory of the direction of their movement overflow into the protected water area. Waves reflected from the structure move in the opposite direction, interact with suitable waves and partially damp them (Fig. 12-17). With the accepted initial data, the beginning of the interaction of the incident and reflected waves is observed at a distance equal to half the length of the original wave from the PHS of an incomplete vertical profile, the damping process is extended in time when the waves move to the structure and are repeated cyclically.

The initial wave height during the numerical experiment was taken equal to λ = 24.5 (m), the elevation of the upper structure of the PHS of an incomplete vertical profile relative to the calm water level will be ΔH = +1.0 (m), the width of the upper structure of the protective structure B = 4.0 (m), the obtained value of the quenching coefficient was – 0.75, and the transmission coefficient – 0.25, which suggests that the design of the PHS of an incomplete vertical profile under these initial conditions, the kinetic energy of the waves by – 75%, which corresponds to the results of a physical experiment presented in publications [1-3].

The numerical model presented in the publication made it possible to more thoroughly evaluate the pattern of physical processes observed on both sides of the model of PHS structures with an incomplete vertical profile, designed to protect the water area of seaports, as well as elements of the coastal infrastructure of sea cities. The use of this design will reduce financial costs by 10-15% by lowering the elevation of the surface structure.

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ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ГАСІННЯ ХВИЛЬ КОНСТРУКЦІЄЮ ОГОРОДЖУВАЛЬНОЮ ГІДРОТЕХНІЧНОЮ СПОРУДОЮ НЕПОВНОГО ВЕРТИКАЛЬНОГО ПРОФІЛЮ

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[1]*Одеська державна академія будівництва та архітектури*
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Анотація. Стаття присвячена питанням чисельного експериментального дослідження, пов’язаного з визначенням величини гасіння хвиль при переливі їх через верхню будівлю конструкцій огороджувальних гідротехнічних споруд (ОГТС) неповного вертикального профілю. Представлені дослідження були проведені з метою верифікації отриманих результатів фізичних експериментальних досліджень. Фізичні експериментальні дослідження були проведені у гідрохвильовій лабораторії кафедри «Гідротехнічного будівництва» Одеської державної академії будівництва та архітектури. Чисельна модель конструкції ОГТС неповного вертикального профілю була виконана аналогічною умовам натурного майданчика узбережжя Одеського заливу. Конструкцію ОГТС неповного вертикального профілю, передбачувалося розташувати на відстані L = 200 (м) від берегової лінії території, що захищається. У місці розташування огороджувальної споруди, що проектується, розрахункова глибина води d = 4,0 (м). Побудував лучи рефракції та трансформації хвиль при підході хвиль до споруди, що проектується, розрахункова висота хвиль становитиме h = 2,4 (м); середня довжина хвиль λ = 24,5 (м); піднесення верхньої будови ОГТС неповного вертикального профілю відносно спокійного рівня води було прийнято рівним ΔH = +1,0 (м), ширина верхньої будівлі конструкції огороджувальної споруди B = 4,0 (м). У результаті проведення чисельного експерименту, висота, погашеної хвилі, при переливі її через верхню будівлю конструкції ОГТС неповного вертикального профілю на акваторії, що захищається, становила h_{tr} = 0,6 (м). Отриманні результати чисельного моделювання на 3,3% відрізняються від висоти хвилі отриманій при проведені фізичного експерименту. За результатами проведених експериментальних досліджень була запропонована емпірична залежність, яка може бути використавана у інженерній практиці з метою визначення величини гасіння хвиль, при переливі їх через верхнь будівлю ОГТС неповного вертикального профілю.

Використання конструкцій ОГТС неповного вертикального профілю, з метою захисту акваторій морських портів, а також елементів берегової інфраструктури морських міст, дозволить підвищити інвестиційну привабливість створення нових проєктів огороджувальних і берегозахисних споруд, завдяки зменшенню позначки надводної частини.

Ключові слова: чисельне моделювання, огороджувальна гідротехнічна споруда неповного вертикального профілю, гасіння хвиль.

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