Experimental and Numerical Study on the Hydrodynamic Performance of Suspended Curved Breakwaters

Eksperimentalna i numerička analiza hidrodinamičkih svojstava visećih zakrivljenih valobrana

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Abstract

The purpose of breakwaters is to protect the ports, beaches, or beach facilities from strong waves and storms, as they help establish calm inside the port and thus achieve safety for ships and ease of operation. This paper presents an experimental and numerical study of unconventional alternatives to the vertical breakwater in order to evaluate the hydrodynamic performance of the proposed models. Two proposed cases for a semi-submerged breakwater were selected in the form of a half-pipe section with an inside diameter of 20 cm and a thickness of 1 cm. Case (a) was of the concave type of semicircular breakwater, while case (b) was of the convex type. Numerical modeling FLOW 3D was used to construct numerous scenarios for numerical simulation of the proposed breakwaters. The obtained results indicates that, when comparing the wave transmission coefficient (K_t) and its reflection coefficient (K_r) with the relative water depth (*h/L*), the transmission coefficient decreased with the relative height of the wave, while the reflection coefficient was completely reversed. In case (a), K_t was less than in case (b) at a range of 10% to 15%, while K_r in case (a) was bigger than in case (b) at a range of 5% to 10%. When the wave hit the breakwater, it was reflected back as its energy is dissipated in less water depth and its speed decreases as it approaches the port. The velocity of the wave decreases as it approaches the bottom, which means that the wave is affected by the depth of the water, i.e. the lower the water depth, the lower the wave velocity. Case (a) was more efficient and effective in wave dissipation, current velocity, and bed stability than case (b), so it is recommended to use case (a) due to its efficiency in protecting coastal areas and generating electricity.

KEY WORDS

convex and concave breakwaters design
coastal wave zones
deep water regular waves
hydrodynamic analysis
numerical model
wave energy dissipation

Sažetak

Svrha valobrana je zaštita luka, plaža ili plažnih objekata od jakih valova i oluja. Pomažu održati mirnu površinu mora unutar luke i time postići sigurnost za brodove i jednostavnost upravljanja. U ovom radu predstavljeno je eksperimentalno i numeričko istraživanje nekonvencionalnih alternativa vertikalnom valobranu kako bi se ocijenila hidrodinamička izvedba predloženih modela. Odabrana su dva slučaja za polupotopljeni polucijevni valobran unutarnjeg promjera 20 cm i debljine 1 cm. Slučaj (a) bio je konkavnog tipa polukružnog valobrana, dok je slučaj (b) bio konveksnog tipa. Numeričko modeliranje softverom FLOW 3D korišteno je za izradu brojnih scenarija za numeričku simulaciju predloženih valobrana. Dobiveni rezultati pokazuju da, kada se usporede koeficijent transmisije vala (K_t) i njegov koeficijent refleksije (K_r) s relativnom dubinom vode (h/L), koeficijent transmisije opada s relativnom visinom vala, dok je koeficijent refleksije potpuno obrnut. U slučaju (a), K_t je bio manji nego u slučaju (b) u rasponu od 10 % do 15 %, dok je K_r u slučaju (a) bio veći nego u slučaju (b) u rasponu od 5 % do 10 %. Kada je val udario u valobran, reflektirao se natrag jer se njegova energija raspršuje na manjoj dubini vode, a njegova brzina opada kako se približava luci. Brzina vala se smanjuje kako se val približava dnu, što znači da na val utječe dubina vode, tj. što je dubina vode niža, to je brzina vala manja. Slučaj (a) bio je djelotvorniji i učinkovitiji u disipaciji valova, brzini struje i stabilnosti dna u odnosu na slučaj (b), pa se preporučuje korištenje slučaja (a) zbog njegove učinkovitosti u zaštiti obalnih područja i proizvodnji električne energije.

KLJUČNE RIJEČI

dizajn konveksnih i konkavnih valobrana
zone obalnih valova
pravilni valovi u dubokim vodama
hidrodinamička analiza
numerički model
disipacija energije valova

1. INTRODUCTION / *Uvod*

The coastal zone is one of the most important and vital parts of any country. The coastal areas and ports have significant economic impacts because they contribute to a variety of areas, including promoting foreign trade, developing and revitalizing coastal tourism, establishing urban neighbor hoods and stability, as well as providing new job opportunities with high returns for young people and constructing fishing ports that increase fish abundance [1, 2]. Natural phenomena such as waves, winds, tides, and currents near the shore, on the other hand, have an

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impact on the beaches and the stability of the coastal zone [3]. The breakwater provides a place in the calm sea where ships can safely berth, and a temporary protection during construction and oil and mineral exploration. When the waves hit the breakwater, they lose a lot of energy [4, 5]. Traditional breakwaters (rubble mounds, vertical caissons, and gravity walls) are commonly utilised to offer a sheltered, calm sea area for vessels to dock and unload [6, 7, 8]. With deeper water, some types need to be wider, which thus results in the need for more building materials [9, 10, 11]. In addition, such breakwaters obstruct littoral drift, resulting in significant erosion or accretion. They stifle water circulation, causing water quality to deteriorate and the ecosystem to become unbalanced. Moreover, traditional structures necessitate trained personnel and specific foundation requirements during construction. All of this adds up to an unaffordable construction expense [12, 13, 14, 15]. Water waves are permitted in leisure ports as long as the waves do not cause harm to tourists. It allows some of the waves to get through the intended barrier, thus providing a beautiful view of the beach [16, 17, 18]. Many studies have previously been conducted to propose new breakwater configurations, improve their performance, and investigate their hydrodynamic characteristics in reducing impact waves. The development of various geometric configurations has received a lot of attention. Various numerical model studies were also used to try to understand the physical behavior of breakwaters in motion [19, 20]. Many researchers have studied breakwaters. For example, Mani (1991) [21] investigated the performance of various types of floating breakwaters in the laboratory. At the Indian Institute of Technology's ocean engineering center, hydraulic model experiments were conducted in a 2.0 m wide, 30 m long, and 1.5 m high wave flume. The variation of transmission and reflection coefficients as a function of relative depth, relative width, wave steepness, and gap to diameter ratio was shown in dimensionless graphs by the author. Sundar and Subbarao (2002) [22] conducted an experimental study on the quarter frontal face pile aided barrier. Dynamic pressures were measured. Different gap ratios were linked to transmission, reflection, and energy loss coefficients. To test the validity of the suggested two theoretical models, Koraim (2005) [23] experimentally investigated the performance of a caisson backed on a large spaced pile system and pile breakwaters consisting of one row of circular and square piles. A caisson supported on a tightly spaced pile system, as well as pile breakwaters made up of two rows of circular and square piles positioned in straight and staggered locations, were also investigated. Rageh and Koraim (2010) [24] evaluated an experimental scenario, the performance of barriers caissons supported by two or three columns of piles. The caisson construction and the supporting pile system were tested. A breakwater of this type helps dissipate wave energy from 10% to 30%. Lokesha et al. (2019) [25] investigated the hydrodynamic behaviour of a trapezoidal barrier with permeabilities of 0% and 11%. It was noticed that the perforated reef had greater wave dissipation than the non-perforated reef. Thus, the goal of this study was to recommend and investigate the hydrodynamic characteristics of an innovative economic barrier that could be tested experimentally and numerically.

1.1. Problem Statement

Curved types of breakwaters are commonly used for the following reasons:

- One of the most common solutions in deep waters.
- Used in the low-soil bearing capacity coastal areas.
- Low-medium wave energys effectively implemented.
- Constant refreshing of the coastal region's water masses enabled, which reduces pollution, thus making these types of breakwaters superior to those that act as barrier walls.
- Occupy a tiny area so that the seafloor organisms are not harmed.

1.2. Research Objectives

Research objectives are:

- Propose appropriate breakwater types for defending beaches and recreational harbours, taking into consideration both efficiency and cost.
- Investigate the efficiency of the proposed type of breakwater experimentally and numerically under the different prevailing environmental conditions.
- Utilize the dissipated energy from sea waves as an alternative source of electrical power generation.

2. MATERIALS AND METHODS / *Materijali i metode*

2.1. Wave Flume / *Valni kanal*

The hydraulics laboratory at Zagazig University, Faculty of Engineering was used to conduct several experiments. The experiment was conducted in an open channel to investigate the interaction between regular waves and half pipes, semi-submersible breakwater systems. The flume's length, width, and height were 12 m, 2.00 m, and 1.20 m, respectively, while the water depth (*d*) was 0.40 m, as shown in Photo 1. Two recording position sites (P_2 and P_1) in front of the breakwater model at distances of 0.25*L* and 0.5*L*, respectively, where *L* is the wave length, were chosen to measure the incident and reflected wave heights .One recording site (P_3) was chosen behind the breakwater model at a distance of 2.00 m to measure the transmitted wave heights, as shown in Figure 1. The open channel walls were composed of reinforced concrete. The effect of the channel walls on the generation and dissipation of waves was neglected, and an inclined wall with a 3:1 slope was placed at the end of the channel to absorb and reflect the waves naturally without random interference. Regular waves of various frequencies are generated by the wave generator. The proposed model was placed at the flume's center. One half pipe was fixed in a vertical position, representing two different cases (a & b). Case (a) was of the concave type of semicircular breakwater, while case (b) was of the convex type, as shown in Figure 2. The used half-pipe was made of plastic, with a diameter of 0.20 m and a thickness of 0.01 m. The scale ratio between the full scale and the model scale prototype of the analysed curved breakwater was 1:10.

2.2. Wave Generator / *Generator valova*

The wave generator was of the flap variety. It was put in at the flume's upstream end. It was made up of a steel gate with hinges, supported by the flume bed, and included two steel rods attached to two 0.36 m diameter steel flywheels. A 5.00 HP motor with a variable speed of 1400 rpm is connected with the system. To create waves in periods between 0.60 and 4 seconds, a gearbox was used to lower the number of rotations to a range between 15 and 90 rpm. The general view of the wave generator is presented in Photo 2.

Photo 1 Wave flume overall view
Fotografija 1. Prikaz valnog kanala

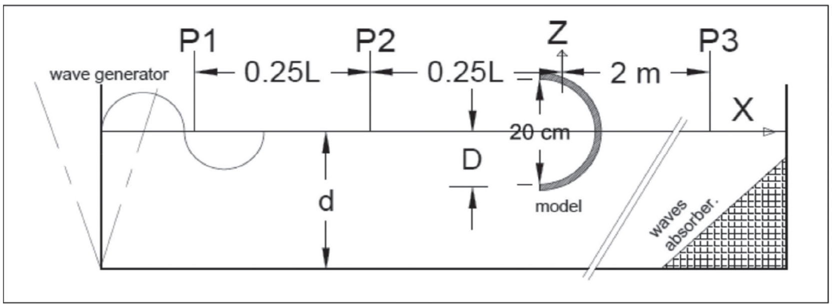

Figure 1 Definition sketch for the model of breakwater in the wave flume
Slika 1. Definicijska skica za model valobrana u valnom kanalu

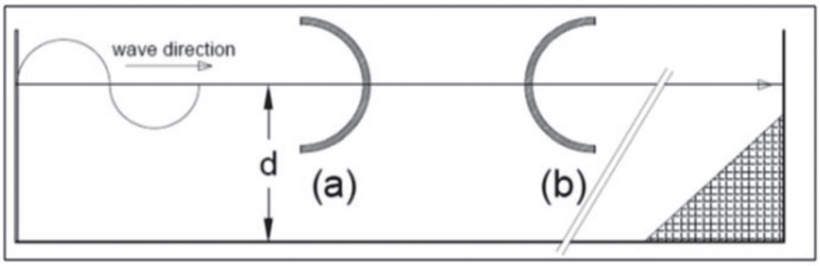

Figure 2 Definition sketch for two different cases (a & b) in the wave flume
Slika 2. Definicijska skica za dva slučaja (a & b) u valnom kanalu

Photo 2 General view of the wave generator
Fotografija 2. Prikaz generatora valova

Table 1 The experimental parameters for the chosen model

Tablica 1. Parametri za eksperimentalna ispitivanja odabranog modela

Parameter	The range of water surface level	Dimensions	Units
Water Depth (*d*)	0.40	(L)	(m)
Wave periods (*T*)	1.2 to 2	(T)	(sec.)
Wave Length (*L*)	2.05 to 4.1	(L)	(m)
Wave incident (H_i)	2.07 to 3.65	(L)	(cm)
Relative draught (*D/d*)	0.25	Dimensionless	-
Relative water depth (*d/L*)	0.1 to 0.24	Dimensionless	-

2.3. Waves / *Valovi*

Five different regular wave periods (*T*) (1.2 sec, 1.4 sec, 1.5 sec, 1.8 sec, and 2 sec) were used to create a set of run conditions, with the finish time of each run based on the wavelength (*L*), which varies depending on the wave period. The most important features of the regular wave are: wave height; wave length; wave time; wave travel direction; wave travel speed, and wave gradient. The wave breaks when the wave steepness (*h/L*) equals 0.14. Therefore, an inclined wall was placed at the end of the channel to absorb the waves. The bottom did not affect the waves in deep water, but it affected them in the case of intermediate or shallow water. Table 1 shows the experimental parameters for the chosen model.

2.4. Governing Coefficients / *Koeficijenti*

The three parameters of this study that determine the hydrodynamic performance of the proposed breakwaters are discussed. The first is the reflection coefficient (K_r), which shows how much energy was reflected from the barrier; the second is the transmission coefficient (K_t), which shows how much energy is transmitted after the breakwater; and the third is the energy dissipation coefficient, which shows how much energy is dissipated.

2.5. FLOW 3D Model / *FLOW 3D model*

The suggested breakwater was numerically simulated using FLOW-3D. FLOW-3D is a popular Computational Fluid Dynamics (CFD) program. In terms of coastal and maritime engineering, the suggested program includes a rule that allows for a variety of applications. To calculate the three-dimensional Reynolds averaged Navier Stokes (RANS) formulas were used and this program's coding is based on the finite volume theory. The hydrodynamic boundary conditions, no slip and in the direction of the unit vector normal, are presently at the boundaries of the object hydrodynamically analysed in the imposed fluid flow field (viscosity and vortices are present; therefore the RANS equation system is applied and solved). The validity of the above-mentioned numerical models in predicting breakwater efficiency is also verified by comparing their results with the present experimental results along with other experimental and theoretical results obtained from other studies [26, 27, 28]. The comparison was made to the present experimental results under the same conditions as the wave case in terms of its frequency and time to reach the end of the channel, which was 12 seconds, and this case was for an emerging wave without a breakwater. The wave surface profile shows a nearly complete correspondence between the results of the numerical and physical model. This means that the numerical model can represent the wave in its entirety, as shown in Figure 3. There was an increasing phase shift of the wave surface profile between the experimentally and numerically obtained results as time progressed. This can be explained by the fact that the waves reflected at the end of the channel affect the waves generated, and that the time of arrival of the waves to the end of the channel laboratory differs from the time of arrival numerically, in addition to the laboratory conditions, so differences were observed in the wave surface between the numerical model and the laboratory with the progression of time.

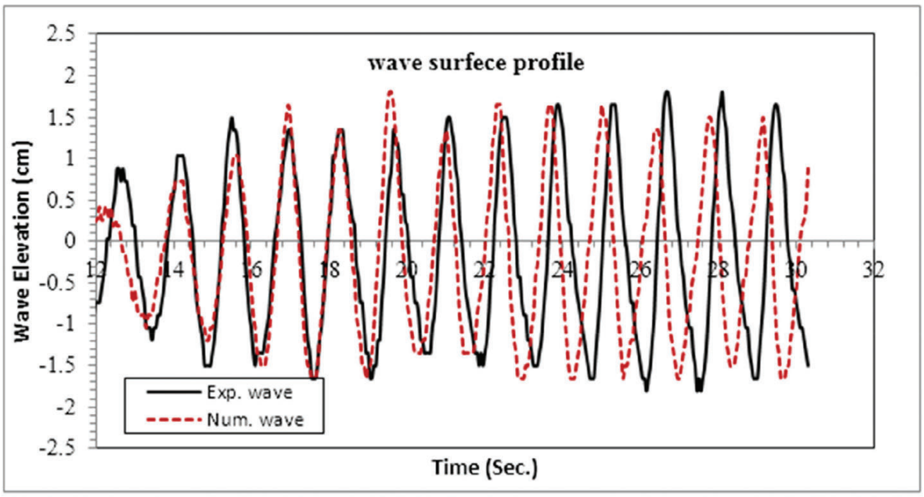

Figure 3 Comparison between the experimental and numerical models in surface wave at wave period (*T*) = 1.4 sec and wave incident (H_i) = 2.8 cm

Slika 3. Usporedba eksperimentalnog i numeričkog modela u površinskom valu pri valnom periodu (T) = 1,4 s i visini upadnog vala (Hi) = 2,8 cm

2.6. Numerical Modeling / *Numeričko modeliranje*

A commercial CFD software package based on volume of fluid (VOF) labeled FLOW 3D was actually used for the numerical analysis of the scale curved breaker model. To achieve a convenient balance between accuracy and time, two distinct grids with different cell sizes were used [29]. Low frequency waves have mesh cells of 1 cm diameter in each direction, while high frequency waves have mesh cells with a diameter of 0.5 cm in each direction, as the greater the number of mesh cells, the higher the accuracy of the results [30]. To avoid any recoveries, whether from the open channel end or the wave paddle, it is critical to examine the time frame for monitoring the wave height according to the wavelength. Calculating the height of reflected and emitted waves in the event spectrum is critical. As a result, by utilizing the wave profiles produced from the reflection factor (k_r) it is estimated that [31]:

$$K_r = H_r / H_i \qquad (1)$$

Where: H_r is reflected wave height and H_i is incident wave height. The transmission factor (K_t) was determined from the wave transmission profile using the following equation:

$$K_t = H_t / H_i \qquad (2)$$

The energy dissipation coefficient (K_d) can be calculated using the preceding formulae and the following equation [31]:

$$K_d = 1 - K_r^2 - K_t^2 \qquad (3)$$

3. RESULTS AND DISCUSSION / *Rezultati i rasprava*

The hydrodynamic efficiency of the two forms of breakwater was investigated experimentally and numerically in this paper. The relationship between the experimental and numerical transmission coefficient (K_t) and the relative wave length (*d/L*) was illustrated in Figure 4.

Waves are divided into three zones according to the values of *d/L*, a) deep water waves at $d/L < 0.5$, b) transition water waves at d/L = (0.04–0.5) and c) shallow water waves at $d/L > 0.04$. In this study, *d/L* was 0.1 to 0.24 in the transition water wave zone. Figure 4 emphasized that with the increase in the relative water depth (*d/L*), the transmission coefficient (K_t) decreases. This can be explained by observing the motions of water molecules. The acceleration and velocity of the water particles rise as *d/L* increases. The water particle velocity and acceleration suddenly change as a wave crosses the breakwater model, and the turbulence that results from this abrupt shift in particle motion causes the wave energy to dissipate

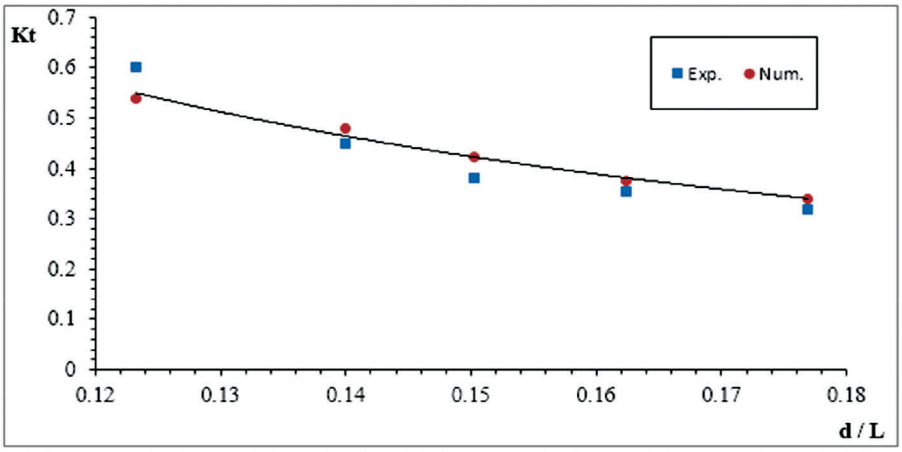

Figure 4 Comparison between transmission coefficient and relative length experimentally and numerically
Slika 4. Usporedba koeficijenta prijenosa i relativne duljine eksperimentalno i numerički

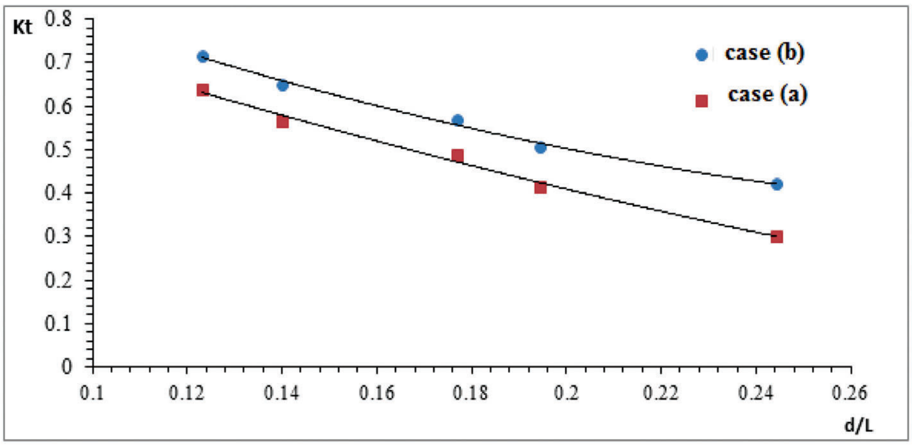

Figure 5 Comparison of transmission coefficient (K_t) against relative water depth (*d/L*) for two cases of breakwaters
Slika 5. Usporedba koeficijenta prijenosa (K_t) u odnosu na relativnu dubinu vode (d/L) za dva valobrana

(Rao et al., 2003) [32]. The results showed that by comparing the experimental and numerical results of the proposed breakwaters in this study under the same conditions, a very good agreement between the experimental and numerical results for the studied transmission coefficient (K_t) of the analysed wave breakwater design has been achieved, and the difference between the results was within 3%. The numerical model was capable of representing the basic features of the proposed barrier and is reliable in similar situations. Figure 5 shows the comparison of the proposed breakwaters (a&b) for transmission coefficient (K_t) against relative water depth (*d/L*) by using numerical models.

The results showed that as the (*d/L*) increased, the (K_t) decreased. It was noted that the transmission coefficient (K_t) in case (a) was less than the transmission coefficient (K_t) in case (b) at a range of 10% to 15% due to the difference in the position of the barrier and the surface area of the barrier facing the wave. Figure 6 shows the comparison of the reflection coefficient from the convex and concave types of the incident regular wave system breakwater design.

The results showed that when the (*d/L*) increased, also the (K_r) increases. The reflection coefficient (K_r) in case (a) was larger than in case (b) at a range of 5% to 10%. The comparison between the first and the second case shows that in the first case the energy dissipation was higher than in the second. Figure 7 shows the comparison of two different drafts in case (a) for transmission coefficient (K_t) against relative water depth (*d/L*) by using numerical models.

Figure 7 illustrates that when the barrier draft (*D*) increased, the wave transmission coefficient decreased, resulting in an increase in the ratio (*d/L*) of 10 to 20% for *D/d* = 0.25 and 0.50. The area through which the water flows lessens as *D/d* rises and the transmitted wave energy falls. The circular section of the half pipe was suspended on evenly spaced vertical piles. By using the numerical model, the wave velocity can be estimated in front of and behind the barrier. The distribution and direction of vortices can be seen in the numerical model. Figure 8 shows vortex distribution and velocity of waves by Flow-3d.

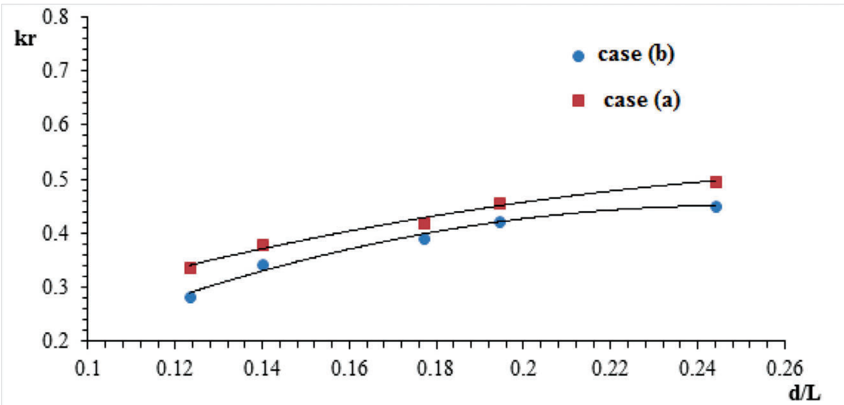

Figure 6 Comparison between two different cases (a&b) for reflection coefficient (K_r) against relative wave length (*d/L*) by using numerical models

Slika 6. Usporedba dva slučaja (a&b) za koeficijent refleksije (K_r) u odnosu na relativnu valnu duljinu (d/L) korištenjem numeričkih modela

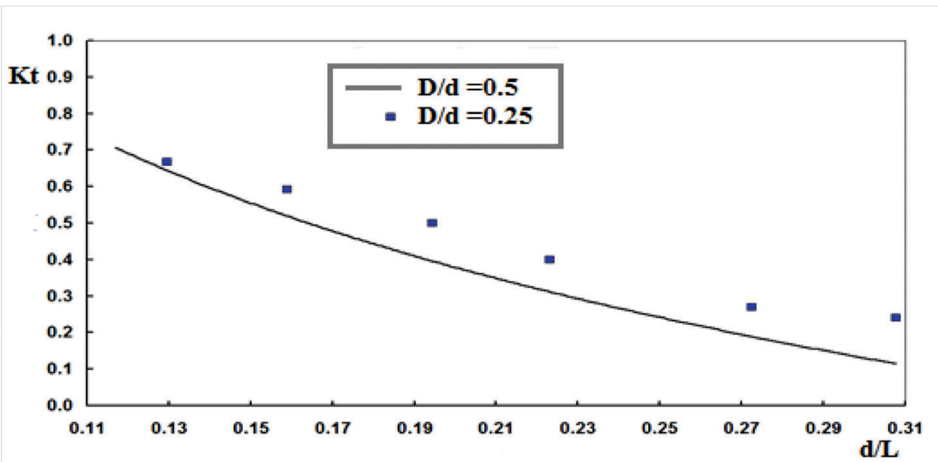

Figure 7 Comparison between two different drafts in case (a) for transmission coefficient (K_t) against relative water depth (*d/L*) by using numerical models

Slika 7. Usporedba dva gaza u slučaju (a) za koeficijent prijenosa (K_t) u odnosu na relativnu dubinu vode (d/L) korištenjem numeričkih modela

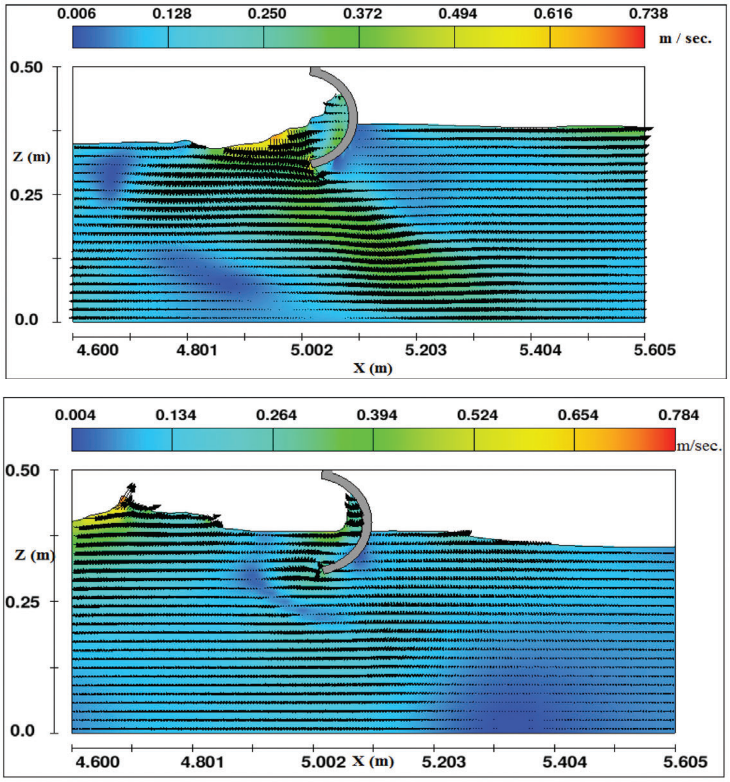

Figure 8 Vortex distribution and velocity of waves by (flow-3d)

Slika 8. Distribucija vrtloga i brzina valova po (flow-3d)

The distribution of velocities in front and behind the breakwater was not studied in the entire channel, but at the coordinates shown in Figure 8, so the x-axis shows only part of it. Figures 8 show that the velocities in front of the barrier are large while the velocities behind it were small. It was noted that the waves are scattered at the edge of the barrier, which helped to disperse the energy of the waves. Figure 9 shows the comparison between the velocities of waves at three different probes of the front at breakwater (a) $z = 20$ cm, (b) $z = 28$ cm, and (c) $z = 38$ cm.

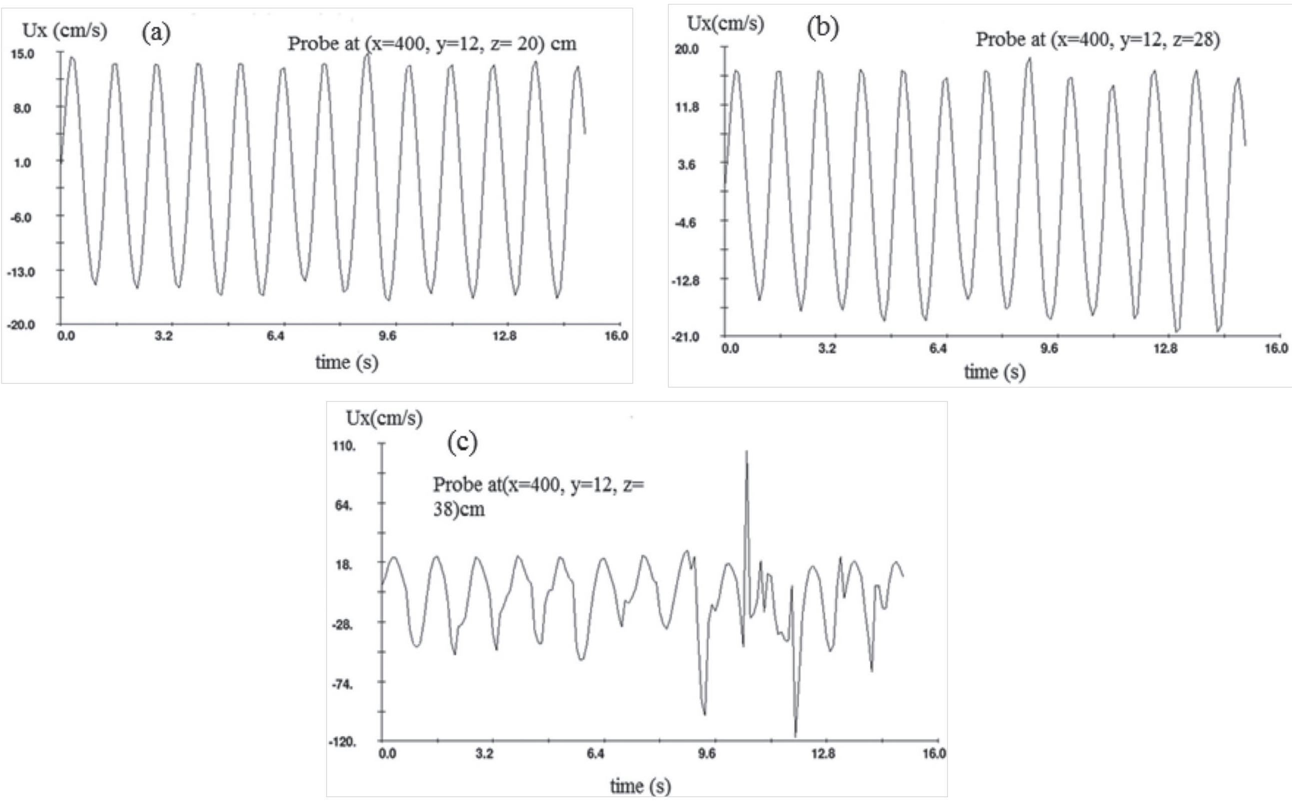

Figure 9 Comparison between the velocities of waves at three different probes on the front part of the breakwater (a) $z = 20$ cm, (b) $z = 28$ cm, and (c) $z = 38$ cm

Slika 9. Usporedba brzina valova na tri različite sonde na prednjem dijelu valobrana (a) z = 20 cm, (b) z = 28 cm i (c) z = 38 cm

The wave velocity was studied over time at a constant point at $x = 400$ cm, $y = 12$ cm for three different depths at $z = 20$cm, 28cm, 38cm, the beginning of the coordinates in the positive direction at the entrance of the channel in the direction of the wave. Figure 9 shows that the velocities in the direction of the x axis changed with the depth change in the direction of axis *z*. Also, the velocity of the waves near the surface of the water was as high as possible.

4. CONCLUSION / *Zaključak*

From the previous analysis of the obtained results, the following conclusions are drawn:

- Both wave barriers proposed in the study were laboratory and numerically tested, and the numerical results were in agreement with the laboratory by a large 95%.
- Hollow semi-submersible wave barriers are economical and easy to implement, especially at recreational beaches.
- The study showed that the efficiency of the hydrodynamic performance of the proposed breakwater case (a) was better than case (b).
- Using the dissipated energy from sea waves as an alternative, clean and renewable source to generate electricity is highly recommended.
- The tested model of innovative wave barriers reduces the transmission of waves within harbors.
- The proposed numerical model may be used to predict the pile breakwater efficiency.
- The numerical model is used to determine the velocity field, pressure, and velocity vectors around the wave barrier.
- The proposed breakwater reduces the velocity of the waves behind it and also disperses the waves through it.
- In front of the breakwater and at the crest of the wave, the hydrodynamic pressure is extremely high.
- The numerical model is capable of recreating the majority of the key characteristics of experimental data and theoretical results.

List of symbols / *Popis simbola*

D = breakwater draft.
d = water depth.
D/d = Relative draught.
d/L = Relative water depth.
H_t = height of the wave that was transmitted.
H_r = reflected wave height.
H_i = height of the incident wave.
h = depth of the bath.
h/L = the wave steepness.
K_d = energy dissipation coefficient.
K_r = factor of reflection.
K_t = factor of transmitting.
L = length of wave.
P_1, P_2 = two recording positions in front of the breakwater.
P_3 = recording position in behind the breakwater.
T = wave period.
t = time.
x, y, z = axis in three dimensions.

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