Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XIII, 2024
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

MODERN PROTECTION SOLUTIONS AGAINST COASTAL EROSION

Iulian IANCU, Alexandru DIMACHE, Oana-Stefania BUCUR, Daniel CORNEA

Technical University of Civil Engineering of Bucharest,
122-124 Lacul Tei Blvd, Bucharest, Romania

Corresponding author email: alexandru.dimache@utcb.ro

Abstract

Romania is one of the countries that experience the coastal erosion phenomenon, a natural process found along shorelines worldwide, caused by the action of waves and currents that entrain sediments. In the context of climate change, a significant intensification of coastal erosion has been observed in our country, especially due to increased wave heights resulting from severe storms. Reducing wave energy using traditional coastal protection structures is not always effective, besides being factually inefficient, it is also extremely costly, both in terms of investment and maintenance. In recent years, modern technologies for wave energy dissipation have been developed, such as the use of floaters, submerged air cushions, and even the use of sound waves to attenuate the force of waves. The paper presents a solution to reduce wave energy using submerged mats, with direct benefits on reducing the erosive power of waves and ensuring coastal protection. The goal is to optimize the solution of submerged mats, ensuring maximum efficiency at minimum cost by adjusting the structural characteristics of the mat (length, thickness, elasticity, permeability) to the characteristics of the waves.

***Key words**: coastal erosion, submerged mats, wave energy.*

INTRODUCTION

Coastal erosion is a natural process that occurs in coastal areas, mainly caused by the action of waves and currents, which leads to the entrainment of sediments into the sea or ocean. In the context of the increasingly pronounced effects of climate change, as well as human activities, the phenomenon of beach erosion has intensified in recent decades, especially due to the increase in wave height and the severity of weather events. The effect of coastal protection structures and the turbulence that occurs as waves break in the surf zone add an additional layer of complexity to the phenomenon of coastal erosion. As a result of this phenomenon, beaches loose sediment through longshore transport, due to longitudinal marine currents, but also through offshore transport due to wave action (Coveianu, 2016).
The Romanian coastal area is facing this problem, especially in the southern part where there is a developed tourist area and where it has been found that up to tens of centimeters of beach disappear annually. The economic effects of this phenomenon are extremely serious, ranging from the reduction of the tourist potential of the beaches to the undermining of the stability of important buildings that are at risk of collapsing. (Tatu et al., 2015). The phenomenon of beach erosion was previously counteracted by the alluvial input from the Danube, which has now been drastically reduced with the construction of the Iron Gates I and II hydroelectric power plants. In this situation, it is necessary to protect the beaches by limiting the erosive power of the waves, correlated with the beach widening projects that are currently being implemented on the Romanian coast.
The mechanism of beach erosion by waves is well known: waves that reach the shore continuously "bite" from the beach sand, and it has been scientifically established that in the withdrawal phase (descending phase) of the wave, a greater amount of sand is drawn into the sea compared to the amount of sand pushed by the wave towards the beach in the ascending phase (Tatu et al., 2015).
The mechanism of wave propagation that reaches the shore is a complicated one, the wave motion without mass transport transforming into one with mass transport, with breaking and with the last phase, the run-up, that is with ascension on the slope of the shore (Holthuijsen, 2007). However, the erosive action of waves depends

on their energy in the vicinity of the shore, energy that must be reduced as much as possible. The main methods of protecting coastal areas against the erosion process can be grouped into two main categories: coastal protection structures and beach nourishment works. There are several types of coastal protection structures: dikes (breakwaters), groynes, seawalls, spurs and sills. The reduction of wave energy using classic coastal protection structures has proven to be ineffective over time. This is mainly because the current structure of the dikes does not substantially reduce the water velocity or the velocity of the currents, respectively the oscillatory motion due to wave action (Tatu et al., 2016). Beach nourishment, on the other hand, in the absence of other protective measures, would only slow down the erosion phenomenon.

In recent years, modern technologies have been developed, such as the use of air wave attenuators, submerged mattresses, wave energy conversion into mechanical energy, vegetation and even the use of sound waves to attenuate the force of waves (Dalrymple et al., 1990; Yu et al, 2021).

Air-Filled Wave Attenuators (AFWA) are in fact floating air-filled breakwaters used to absorb wave energy. These types of breakwaters are popular because they have a lower environmental impact than traditional breakwaters, which can disrupt marine ecosystems (Pereira et al., 2022). Air-Filled Wave Attenuators are made of flexible waterproof materials, the main body consisting of a floating module in the form of a rectangular prism filled with air. This is ballasted with sandbags placed all around. The volume of air acts as a hydraulic shock absorber, absorbing the energy of the waves. Wave attenuators are very efficient, capable of attenuating up to 95% of the incoming wave height and do not affect marine ecosystems like traditional breakwaters.

Submerged mattresses are structures that use a flexible porous membrane filled with water to dissipate wave energy (Koley et al., 2022; Collins et al., 2021). The principle of wave energy dissipation by submerged mattresses is based on two mechanisms: the deformation of the mattress as the waves passes over the mattress membrane, and the formation of turbulence and vortices as the water passes through the porous membrane. Submerged mattresses represent a promising and innovative approach to coastal protection, offering a balance between cost and wave attenuation performance.

Vegetation, such as seagrass, can attenuate and dissipate wave energy, acting as a natural barrier (Ikha et al., 2022). Vegetation can have a stabilizing effect on sediment transport, keeping them in shallow water areas, leading to energy dissipation. Wave energy attenuation by vegetation is the process by which waves are reduced in height and energy as they pass over or through vegetation. The amount of wave energy attenuated by vegetation depends on a number of factors, including the type of vegetation, its density, the water depth and the wave characteristics (Bradley et al., 2009).

An emerging alternative to traditional wave energy attenuation methods is the use of sound waves. This technology is still under development, but it has the potential to be more efficient and less costly than traditional methods. There are several ways in which sound waves can be used to attenuate wave energy. One method is to use a system of speakers to generate underwater sound, which propagates and interacts with the waves, reducing their energy. Another method is to use a system of air bubbles to create an underwater sound field that dissipates wave energy.

In the context of modern coastal protection solutions against the phenomenon of erosion, and for wave energy dissipation, the article aims to study the effectiveness of submerged breakwaters for reducing energy, and implicitly wave amplitude, with a direct beneficial effect on the erosive power of waves. The paper proposes a mathematical model to determine the mechanical energy consumed from the energy of a wave with certain characteristics, which passes over a submerged mattress made of a homogeneous material, deforming it.

The use of submerged mattresses has clear advantages over the classic breakwaters used today. The most important of these are the much lower investment costs, practically zero maintenance costs (being submerged, they do not deteriorate the marine landscape and do not affect surface activities such as navigation, in general, and marine sports, in particular), and they fix the sand on the seabed, preventing its entrainment by longitudinal currents.

MATERIALS AND METHODS

To develop a mathematical model for the energy dissipated from wave energy by a submerged mattress, the determining parameters of the waves were first determined. These parameters will be used to evaluate the efficiency of the mattress both on the mathematical model developed and on the physical model that will be developed later for the calibration and validation of the mathematical model.
The submerged mattress will be made of a homogeneous permeable material, filled with water, and waterproofed with an elastic membrane on all sides.

The determination of the wave characteristics was conducted in the wave channel (Figure 1), within the Hydraulics Laboratory of the Technical University of Civil Engineering Bucharest (UTCB). The wave channel has a length of 16 m and a width of 1 m, the maximum water depth being 0.9 m. The channel, which has a fixed slope, is equipped at one end with a wave generator and at the opposite end with an attenuator designed to dissipate wave energy and prevent the occurrence of the reflection phenomenon, which would alter the characteristics of the incident waves.
The wave generating system consists of a flat, movable flap that is hinged at the bottom of the channel and is set in motion at the top by a crank-slider system (Figure 2).

Figure 1. Wave Channel - Hydraulics Laboratory, UTCB

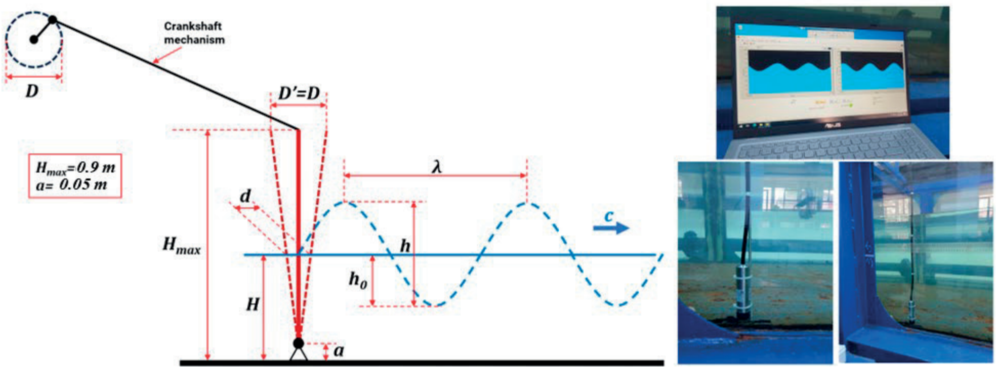

Figure 2. Schematic of the wave generation system and level transducers

The determination of the wave characteristics was conducted considering a water depth H = 0.5 m. The determining parameters of the measured waves were the wave height h, the period T and the wavelength λ. To determine the amplitude of the waves, two level sensors placed at 4 m from each other were used. The wavelength, respectively the wave period, was measured between two successive crests of the waves. The results of the measurements are presented in Table 1.

Table 1. Measured waves characteristics

Wave height h (m)	Wavelength λ (m)	Period T (s)	Celerity c (m/s)
0.14	1.65	1.06	1.56
0.13	1.23	0.90	1.37
0.12	1.10	0.83	1.33
0.10	0.94	0.74	1.27
0.09	0.72	0.66	1.09

Based on the measurements, the propagation speed (celerity) of the waves was calculated. The physical model of the wave energy mitigation device - the submerged mattress - that will be tested later in the wave channel will have the following dimensions: length $L_s = 4$ m, width $b = 1$ m and height $h_s = 0.1$ m. The permeability characteristics and elasticity of the submerged mattress will be established at the time of making its physical model. Based on the measured characteristics of the waves and the proposed characteristics of the submerged mattress, the following mathematical model was developed.

MATHEMATICAL MODEL

A submerged mattress with the following dimensions is considered: L_s – mattress length, b – mattress width and h_s – mattress height (thickness), made of a homogeneous material with permeability coefficient k. The mattress is waterproofed on all sides and filled with water.
A wave passes over the submerged mattress with the following characteristics: wave height h (the vertical distance between the crest and the base of the wave), the oscillation period T (the time between two successive maxima or minima), respectively the wavelength λ.
The wavelength λ is the distance travelled by the wave, when it travels (propagates) with speed c (the celerity or speed of propagation of the wave), during a period T. Therefore, $\lambda = c \cdot T$ and is equal to the distance between two adjacent crests.

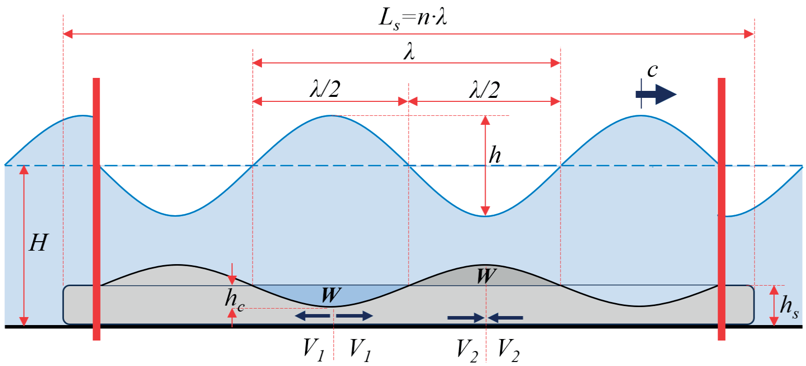

Figure 3. Mathematical model for wave energy attenuation using a submerged mattress of homogeneous material

Function of the height of the wave, respectively of the elasticity of the mattress, at the moment in Figure 3, it will compress over a distance λ/2, respectively it will decompress over the same length λ/2, on a section of the mattress having the length Ls/n, where n is the number of sections of the mattress of length equal to the wavelength λ. The maximum value of the height compression, respectively of the mattress decompression, is hc. With cc was noted the compression coefficient of the mattress cc=hc/hs.

At other moments in time, the deformation of the mattress will have a different shape (Figure 4) but, overall, the compressed or decompressed volumes remain the same.
To evaluate the energy consumed from the wave energy to compress the mattress, a calculation scheme is used that is based on the evaluation of the average speed of water flow in the mattress, at the time of its compression and decompression under the action of the wave, using Darcy's calculation formula of the flow velocity in a permeable medium.

Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XIII, 2024
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

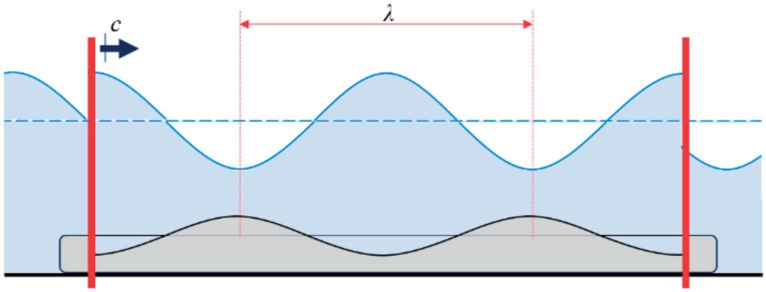

Figure 4. Deformation of the submerged mattress

To estimate the average flow speed in the mattress, the water flow speed in the mattress will be evaluated first to the maximum, V_{1max} in the area where the mattress compresses to the maximum, respectively V_{2max} in the area where the mattress decompresses.
The volume with which the mattress is compressed, respectively decompressed, along the length $\lambda/2$ is W:

$$W = \frac{2}{3} \cdot \frac{\lambda}{2} \cdot h_c \cdot b = \frac{\lambda \cdot h_c \cdot b}{3}$$

Then, the maximum water flow velocity in the mattress in the compressed area is:

$$V_{1max} = \frac{1}{2} \cdot \frac{W}{h_c \cdot b} \cdot \frac{1}{\Delta t} = \frac{1}{2} \cdot \frac{\lambda \cdot h_c \cdot b}{3 \cdot h_c \cdot b} \cdot \frac{1}{\Delta t} = \frac{\lambda}{6 \cdot \Delta t}$$

where Δt is the time interval in which the wave travels a distance Δs, and the mattress is compressed, respectively decompressed by the moving volume W. To obtain the average speed of water flow in the compressed area of the mattress, it will be averaged between 0 and V_{1max}.

$$V_1 = \frac{0 + V_{1max}}{2} = \frac{\lambda}{12 \cdot \Delta t}$$

In the area where the mattress decompresses the speed is:

$$V_{2max} = \frac{1}{2} \cdot \frac{W}{(h_s + h_c) \cdot b} \cdot \frac{1}{\Delta t}$$

$$V_{2max} = \frac{1}{2} \cdot \frac{\lambda \cdot h_c \cdot b}{3 \cdot \left(\frac{1}{c_c} \cdot h_c + h_c \right) \cdot b} \cdot \frac{1}{\Delta t}$$

$$V_{2max} = \frac{\lambda \cdot c_c}{6 \cdot (c_c + 1) \cdot \Delta t}$$

and the average speed of water flow in the area where the mattress decompresses is:

$$V_2 = \frac{0 + V_{2max}}{2} = \frac{\lambda \cdot c_c}{12 \cdot (c_c + 1) \cdot \Delta t}$$

The average water flow rate in the mattress is:

$$V_m = \frac{V_1 + V_2}{2} = \frac{1}{2} \cdot \left(\frac{\lambda}{12 \cdot \Delta t} + \frac{\lambda \cdot c_c}{12 \cdot (c_c + 1) \cdot \Delta t} \right)$$

$$V_m = \frac{1}{24} \cdot \frac{\lambda}{\Delta t} \cdot \left(1 + \frac{c_c}{c_c + 1} \right) = \frac{1}{24} \cdot \frac{\lambda}{\Delta t} \cdot \left(\frac{2 \cdot c_c + 1}{c_c + 1} \right)$$

The average water flow rate in the mattress is reduced in relation to those presented previously:

- the material from which the mattress is made is not perfectly elastic and does not deform as soon as it is subjected to the pressure force of the wave;
- the flow of water in the mattress (through the permeable medium) is "braked" by the inertia of the liquid mass. Darcy's law used is for a permanent, stabilized flow regime; in fact, in reality, the flow has a strong non-permanent flow regime;
- the mattress has a finite length, being closed at both ends, where the flow is blocked.

As a result, in the calculation of the average hydraulic gradient, from Darcy's law, to determine the head loss, the attenuation coefficient of the water flow speed c_{at} was introduced.

$$I_m = \frac{c_{at} \cdot V_m}{k} = \frac{\frac{1}{24} \cdot \frac{\lambda}{\Delta t} \cdot \left(\frac{2 \cdot c_c + 1}{c_c + 1} \right)}{k}$$

$$I_m = \frac{c_{at}}{24 \cdot k} \cdot \frac{\lambda}{\Delta t} \cdot \left(\frac{2 \cdot c_c + 1}{c_c + 1} \right)$$

The head loss Δh_r over a length Δl will be:

$$\Delta h_r = I_m \cdot \Delta l$$

The head loss on a part of mattress length $\lambda = \frac{L_s}{n}$ will be:

$$h_r = \frac{c_{at}}{24 \cdot k} \cdot \frac{\lambda}{\Delta t} \cdot \left(\frac{2 \cdot c_c + 1}{c_c + 1} \right) \cdot \lambda$$

The head loss on a mattress length equal to λ, for a wave of period T (during a period T the wave travels the length λ) is:

$$h_r = \frac{c_{at}}{24 \cdot k} \cdot \frac{\lambda^2}{T} \cdot \left(\frac{2 \cdot c_c + 1}{c_c + 1} \right)$$

To evaluate the energy loss from head loss, the motion in the mattress is equated to a unilinear flow with velocity:

$$V_{echiv} = \frac{W}{b \cdot h_s \cdot T} = \frac{\frac{\lambda \cdot h_c \cdot b}{3} \cdot c_c}{b \cdot h_c \cdot T} = \frac{1}{3} \cdot \frac{c_c \cdot \lambda}{T}$$

The mass carried by the water in the interval T is:

$$m = Q_m \cdot T = \rho \cdot b \cdot h_s \cdot V_{echiv} \cdot T$$

$$m = \rho \cdot b \cdot \frac{h_c}{c_c} \cdot \frac{1}{3} \cdot \frac{c_c \cdot \lambda}{T} \cdot T = \frac{1}{3} \cdot \rho \cdot b \cdot h_c \cdot \lambda$$

The energy consumed (dissipated) by the mattress from the wave energy is:

$$E_r = h_r \cdot m \cdot g$$

$$E_r = \frac{c_{at}}{72} \cdot \frac{\lambda^3}{k \cdot T} \cdot \left(\frac{2 \cdot c_c + 1}{c_c + 1} \right) \cdot \rho \cdot g \cdot b \cdot h_c$$

The wave mechanical energy corresponding to unit length of wave crest with wavelength λ is (Luca & Luca, 2002):

$$E = \frac{\rho \cdot g \cdot h^2 \cdot \lambda}{8}$$

The mechanical energy of the wave across the entire width of the mattress is:

$$E_v = E \cdot b = \frac{\rho \cdot g \cdot h^2 \cdot b \cdot \lambda}{8}$$

To determine the height h_f of the wave at the exit from the mattress, from the initial energy of the wave E_v we subtract the energy dissipated by the mattress E_r and then from the resulting final energy E_f we get the height of the wave h_f.

$$E_f = E_v - E_r$$

$$E_f = \frac{\rho \cdot g \cdot h_f^2 \cdot b \cdot \lambda}{8}$$

$$h_f = \sqrt{\frac{8 \cdot E_f}{\rho \cdot g \cdot b \cdot \lambda}}$$

RESULTS AND DISCUSSIONS

The mathematical model created for the calculation of the energy dissipated by the mattress from the wave energy, was applied to the characteristic values of the waves measured in the wave channel, considering a mattress having the length equal to the wavelength of the wave, the unit width (b = 1 m) and height h_s = 0.1 m. The coefficient of permeability of the material from which the mattress is made was considered k = 1 m/s. The attenuation coefficient of the water flow velocities in the mattress was considered to be c_{at} = 0.30. This coefficient depends on the elasticity of the material from which the mattress is made and the material that waterproofs the mattress. It was considered that the mattress is compressed by half of its height, the compression coefficient of the mattress being c_c = 0.5.

For a wave of known characteristics (h, λ, T), he variation in wave height, between the entry and exit of a mattress with the characteristics ($L_s = \lambda$, h_s, b, k), depends on two parameters: the ratio between the attenuation coefficient and the permeability coefficient, c_{at}/k, respectively on the compression coefficient c_c. The compression coefficient is specific to the mattress, depending on its elasticity and permeability coefficient. The only unknown coefficient is the attenuation coefficient of the speeds c_{at}. To determine it, an inverse calculation can be made considering that the wave height is reduced by 10% by the mattress, to be able to determine the order of magnitude of the coefficient. Thus, doing the calculation for the wave characteristics in Table 1, it is obtained that the attenuation coefficient of the speeds varies between 0.21 and 0.27.

Considering the attenuation coefficient as having the value $c_{at} = 0.3$, the obtained results (Table 2) indicate an attenuation of the wave energy on average by approximately 24%, and of the wave height by approximately 13%.

The efficiency of the submerged mattress in reducing wave energy, respectively the parameters that condition the efficiency will have to be determined experimentally on a physical model. These parameters are the permeability coefficient of the mattress material and the compression coefficient that will have to be measured, respectively the attenuation coefficient of the water flow speed in the submerged mattress that will have to be determined experimentally.

Considering the characteristics of the wave with the height h = 0.12 m and changing only the compression coefficient of the mattress between 0.05 and 0.6, in Figure 5 is presented the variation of the height of the wave at the exit from the mattress and of the energy dissipated by it, according to this coefficient.

The mathematical model made provides the anticipated results, but without a calibration and validation of it on a physical model it will not be able to be used for a constructive optimization of submerged mattresses made of homogeneous materials and filled with water.

Table 2. Application of the mathematical model to calculate the energy dissipated by the mattress and the wave height at the exit from the mattress

Wave characteristics	**Height h_s (m)**	**0.14**	**0.13**	**0.12**	**0.10**	**0.09**
	Wavelength λ (m)	1.65	1.23	1.10	0.94	0.72
	Period T (s)	1.06	0.90	0.83	0.74	0.66
Features of the submerged mattress	Length L_s (m)	1.65	1.23	1.10	0.94	0.72
	Width b (m)	1.00	1.00	1.00	1.00	1.00
	Height h_s (m)	0.10	0.10	0.10	0.10	0.10
	Permeability coefficient k (m/s)	1.00	1.00	1.00	1.00	1.00
	Attenuation coefficient of the water flow speed c_{at}	0.30	0.30	0.30	0.30	0.30
	Compression coefficient c_c (-)	**0.50**	**0.50**	**0.50**	**0.50**	**0.50**
	Compressed/uncompressed height h_c (m)	0.05	0.05	0.05	0.05	0.05
Energy consumed (dissipated) by the mattress E_r (j)		11.55	5.63	4.37	3.06	1.54
The energy of the wave upon entering the mattress E (j)		39.66	25.49	19.42	11.53	7.15
The energy of the wave at the exit from the mattress E_f (j)		28.11	19.86	15.05	8.47	5.61
The height of the wave at the exit from the mattress h_f (m)		**0.118**	**0.115**	**0.106**	**0.086**	**0.080**

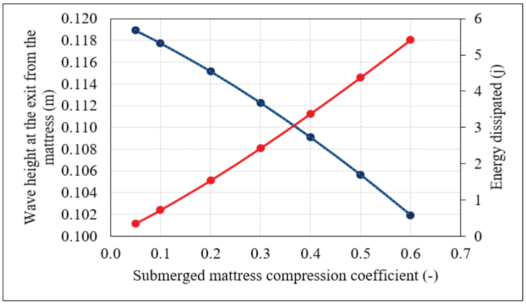

Figure 5. The variation of the wave height at the exit from the submerged mattress and the dissipated energy, as a function of the compression coefficient of the submerged mattress

On the physical model of the submerged mattress, it will be possible to study several constructive variants of the mattress (length, thickness, elasticity, permeability) to obtain a maximum yield at a minimum cost. Various physical modelling scenarios will be developed,

Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

modifying the determining parameters of the waves, to evaluate the efficiency of the mattress, depending on its constructive characteristics.

CONCLUSIONS

The reduction of wave energy using innovative solutions can lead to reliable results if these solutions are well based and studied on scale physical models and/or through numerical simulation.

The article proposes a mathematical model for the optimization of a submerged mattress, made of a homogeneous material, waterproofed and filled with water, for the mitigation of waves in the coastal area and protection against beach erosion. The mathematical model made must be calibrated and validated on a physical model in the wave channel.

From the application of the mathematical model, an important decreasing of the mechanical energy, respectively of the height of a wave of known characteristics is observed, which lead to the demonstration of the concept regarding the functionalities and characteristics of the submerged mattress solutions in laboratory conditions, respectively to the validation and demonstration of the functionality of the solution under relevant operating conditions.

The final goal of this research regarding the effectiveness of submerged mattresses, is to calibrate and validate the mathematical model on a scaled physical model, tested in a wave channel.

Various constructive and location variants of the submerged mattress will be studied, aiming, through optimization, a maximum efficiency with minimum cost, by correcting the constructive characteristics of the mattress (length, thickness, elasticity, permeability) to various wave characteristics (amplitude, period, wavelength).

To the extent that the results of measurements on the physical model will prove their effectiveness in mitigating waves and protecting against beach erosion, the impact of the project can be an important one in terms of coastal protection solutions, socio-economic and environmental implications.

ACKNOWLEDGEMENTS

This work is supported by a National Research Grants of the Technical University of Civil Engineering Bucharest, project number UTCB-09/2023.

REFERENCES

Bradley, K. & Houser, C. (2009). Relative velocity of seagrass blades: Implications for wave attenuation in low-energy environments, *Journal of Geophysical Research*, *114*.

Collins, I., Hossain, M., Dettmer, W., Masters, I. (2021). Flexible membrane structures for wave energy harvesting: A review of the developments, materials, and computational modelling approaches, *Renewable and Sustainable Energy Reviews*, *151*.

Coveianu, A.L. (2016). *Marine Hydraulics Research*, Bucharest, RO: PhD Thesis.

Dalrymple, R.A., Martin, M.W., (1990). Wave attenuation by air-filled flexible membranes, *Journal of Waterway*, *Port, Coastal, and Ocean Engineering*, *116*(1), 36-52.

Holthuijsen, H.L. (2007). *Waves in Oceanic and Coastal Waters*, Delft University of Technology and UNESCO – IHE, Cambridge University Press.

Koley, S., Vijay, K.G., Nishad, C.S., Sundaravadivelu, R. (2022). Performance of a submerged flexible membrane and a breakwater in the presence of a seawall, *Applied Ocean Research*, *124*.

Ikha, M., Andadari, G.R., Reeve, D. (2022). An integrated study of wave attenuation by vegetation, *Wave Motion*, *110*.

Luca, O., Luca B.A. (2002). *Construction Hydraulics*, Timisoara, RO: Orizonturi Universitare.

Pereira, E.J., Teh, H.M., Ma, Z. (2022). Hydrodynamic Performance of Air-Filled Wave Attenuator for Wave Control: Experimental Study, *J. Shanghai Jiao Tong Univ. (Sci.)*, *27*(3), 316-325.

Tatu, G., Dimache, A.N., Iancu, I., Coveianu, A.L., Ciugulea, O. (2015). A new vision on the marine dikes' structure, *Ecology, Economics, Education and Legislation, II*, 27-34.

Tatu, G., Dimache, A.N., Iancu, I., Mateescu, R., Mârzali, I. (2016). Studies on continuous and oscillating currents through breakwaters, *Ecology, Economics, Education and Legislation Conference Proceedings, I,* 629-636.

Yu, Y., Zhang, X., Yan, X., Wu, G. (2021). Numerical study on wave attenuation by a flexible air cushion breakwater, *Applied Ocean Research*, *108*.