COASTAL INFLUENCE OF A PELAMIS WAVE FARM OPERATING IN THE NEARSHORE OF MAMAIA

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ABSTRACT

The objective of the present work is to evaluate the influence of a Pelamis wave farm operating in the vicinity of the Romanian nearshore, more precisely in the Mamaia sector. As a first step, the local wave conditions from the SWAN model were processed in order to identify the evolution of the main wave parameters for a ten-year time interval (between 1999 and 2008). Based on these results, several case studies were considered in order to estimate the influence of the Pelamis wave energy converter systems on the local wave field conditions. The presence of the wave farm in the geographical space was made by activating the obstacle command, which is available in the SWAN model. Generally, it was noticed that the wave conditions are influenced by the local bathymetry and by the incident wave directions, while the presence of the Pelamis system seems to be important for the coastal protection, especially during extreme conditions.

Keywords: Romanian nearshore, SWAN, Pelamis, wave power,
coastal dynamics

1. INTRODUCTION

The coastlines are dynamic environments, which constantly evolve during various time intervals. Generally, most of the changes are noticeable after long time periods (sedimentary processes), while some others are more rapid, being associated with the short, but intense, natural events (as, for example, the storms). Each costal area is shaped by the local processes (erosion and accretion), which are determined by several characteristics, such as: wave conditions, beach configuration and anthropogenic activity. Also, based on the Bruun rule, it was estimated that a future rise of the sea level with 15-30cm (between the years 2040 and 2085) will lead to the disappearance of the beach areas with a maximum width of 30 m, unless they are protected [1].

One of the main factors for the coastal erosion is the wave attack, which cause abrasion and transport of the sediments between the onshore and offshore areas. Also, it is possible that the local sediments would be shifted along the coastline due to the influence of the longshore currents. In those areas, if the lost material is not naturally replenished, it is possible that some beach sectors become more vulnerable to the erosion processes.

During the last decades, the Romanian coastal area registers a continuous degradation of the beach sector, which is caused by the aggressive action of the wave and longshore currents, but also due to reduction of the sediments from Danube [2 -4]. This area is divided in two distinct units (north and south), which present specific coastal processes. The north unit is dominated by the presence of the Danube Delta, which is the second one (as size) in Europe. Generally, the beach sectors from this unit (ex: Saraturile, Letea or Perisor) report heights between several centimeters and 1.7 m (above the sea level), so flooding events are common [5, 6]. In this region the dune formation (sand bars) is seasonal, the entire unit being characterized by fast erosion processes, which lead to the retreat of the shoreline with almost 10 m per year, like in the case of Sulina-Sf. Gheorghe sector [7].

The beach sectors from the southern unit present limited sediment resources and, therefore, they are vulnerable to the storm erosion, especially during the winter time, when large volume of sediments is carried out in the offshore area. In this situation, important land surfaces are lost into the sea, since they are not capable to recover with sediments from Danube, during normal atmospheric condition [8, 9].

One of the most consistent sources of energy from the marine environment is the wave and wind energy [10]. During the last years several type of wave energy converters (WEC) were developed and, this moment, this industry is evolving very fast. In 2008, the first wave farm project, called Agucadoura Wave Farm, was developed, which has an installed capacity of 2.25MW provided by three Pelamis P1 systems [11], so, in the near future, similar projects may develop in the coastal waters in Europe.

In this context, the purpose of the present work it is to identify the influence of a Pelamis wave farm on the local wave conditions from the Romanian coastal area.

2. METHODS AND MATERIALS

In the present work, the SWAN (Simulating Waves Nearshore) modeling system was implemented. This is considered to be a versatile computational tool which computes random, short crested wind-generated waves, in coastal areas [12, 13]. The main philosophy of this model is to solve the spectral energy balance equation, which determines the variation of the wave spectrum in time, spectral and geographical domain:

$$\frac{\partial N}{\partial t} + \nabla\left[\left(\vec{c}_g + \vec{U}\right)N\right] + \frac{\partial}{\partial \sigma}c_\sigma N + \frac{\partial}{\partial \theta}c_\theta N = \frac{S}{\sigma} \qquad (1)$$

where: N is the density spectrum and U is the velocity of the ambient current; $\vec{c}_g$, c_σ and c_θ represent the propagation speeds in the frequency space (σ) and geographical space (θ), respectively; S represents the source and sink terms, which are considered in deep water for various processes, such as: wave interactions and wave generated by wind.

Figure 1 presents some general characteristics of the target area and of the computational domain for Mamaia target area.

As a first step, the wave conditions in the vicinity of the Romanian coastal area were computed in SWAN throughout a numerical simulation (coastal resolution), which uses as an input the wind data provided by the NCEP-CFSR (United States National Centers for Environmental Prediction, Climate Forecast System Reanalysis), which generates the wind field conditions characterized by a spatial resolution of 0.312º x 0.312º and with a time step of 3 hours. The analysis was carried out for a ten-year time interval (between 1999 and 2008), while for the considered target area, the most relevant wave parameter was reported for the point S (29º30'E/44º31'N) located in the vicinity of the target area (presented in Fig. 1a).
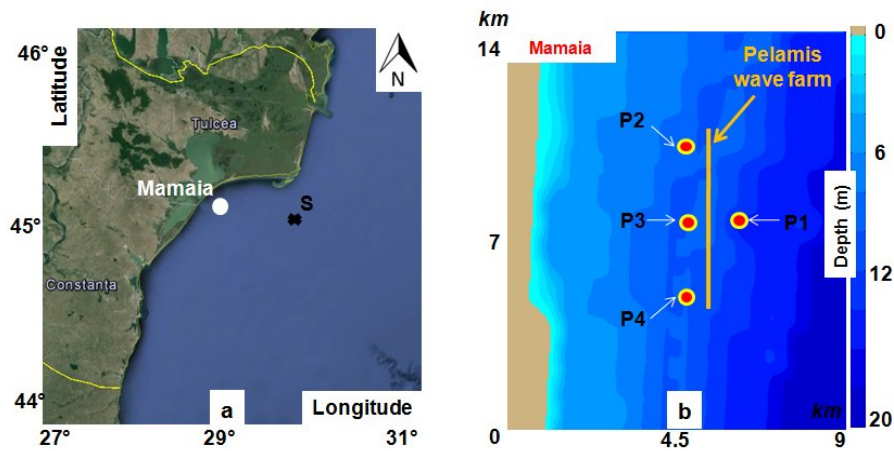

Fig. 1. General characteristics of the computational domain, where: a) overview of the western part of the Black Sea; b) Mamaia target area - the bathymetry is represented in the background, while the location of the Pelamis wave farm is given in foreground

Table 1 presents more details cocerning the processes and physical parameters activated for this simulation (where: Δx and Δy are the resolutions in the geographical space, $\Delta\theta$ is the resolution in the directional space, nf is the number of directions in the spectral space, $n\theta$ is the number of directions in the spectral space, ngx and ngy are the numbers of grid points in x and y direction, np is the total number of grid points).

Table 1. Setup of the SWAN coastal simulations and the activated physical parameters

Model	Coordinates	$\Delta x \times \Delta y$ (m)	$\Delta\theta$ (º)	Mode/scheme	nf	$n\theta$	$ngx \times ngy = np$		
SWAN	Spherical	0.02 × 0.02	10	nonstat/S&L	35	36	141×141=19881		

Input/process	Wave	Wind	Tide	Crt	Gen	Wcap	Quad	Triad	Diff	Bfric	Set up	Br
	X	X	0	0	X	X	X	X	0	X	0	X

The input fields considered in the computational domain are: wave forcing (wave), tide forcing (tide), wind forcing (wind) and currents fields (crt). The

activated physical processes are: generation by wind (gen), whitecapping process (wcap), quadruplet nonlinear interactions (quad), triad nonlinear interactions (triad), diffraction process (dif), bottom friction (bfric), wave-induced setup (setup) and activation of the depth-induced wave breaking (br).

As concerning the implementation of the Pelamis wave farm, this was made in the Mamaia sector, as it may be noticed in Figure 1. The computational domain (Fig. 1b) is defined by a rectangle area with a length of 9 km in x-direction (cross shore) and 14 km in y-direction (long shore), while the background presents the bathymetry of this target area. The foreground presents the location of the Pelamis wave farm, which was made by activating the command obstacle, while the points P1, P2, P3 and P4 are used to identify the influence of the wave farm on the local wave field characteristics. The results obtained from the numerical simulations have been processed throughout the interface for SWAN and Surf Models (ISSM) [14].

3. RESULTS AND DISCUSSION

Figure 2 presents a statistical analysis of the coastal wave conditions, provided by the SWAN simulation, for the time interval January 1999- December 2008.
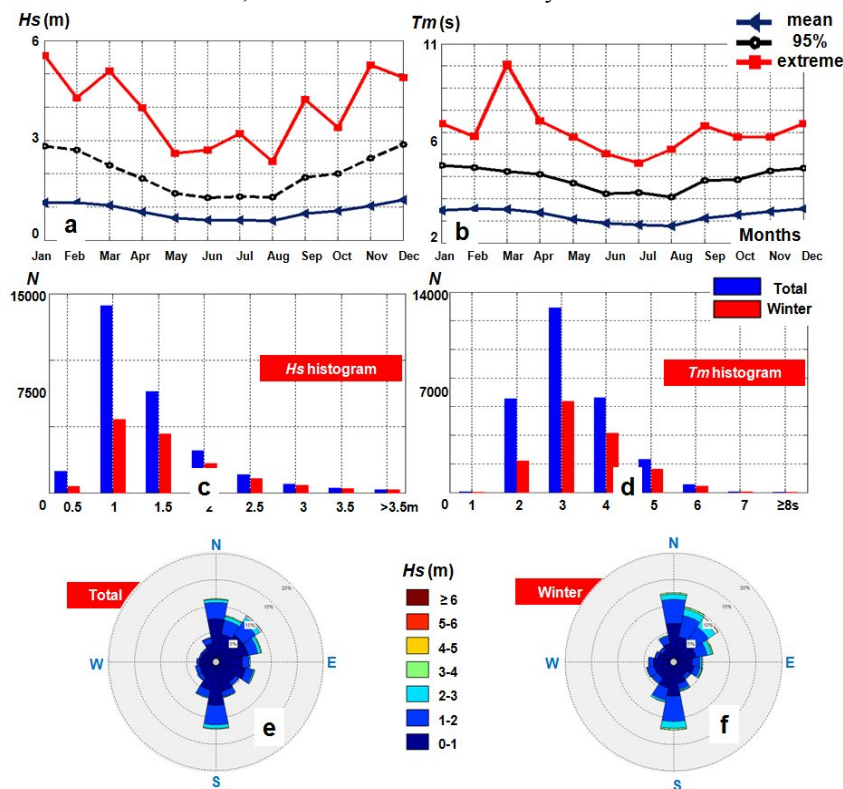

Fig. 2: Wave statistics considering wave parameters from the numerical simulations with the SWAN model, for the time interval January 1999 - December 2008, reported for the point S. Analyses of the parameters Hs (m) and Tm (s) were: a), b) monthly variation of the mean, 95 percentile (95%) and extreme value; c), d) histograms reported for the total and winter time; e), f) wave roses reported for the total and winter time

The results are reported to the point S and illustrate the evolution of the significant parameters wave height (*Hs*) and mean wave period (*Tm*), respectively. As concerning the monthly evolution of the parameter *Hs*, it can be noticed that the mean values are located in the interval 0.57 m-1.3 m, being almost double during the winter time (considered from October to March). In the case of the 95 percentile (denoted as 95%) the differences between the winter time and the rest of the time are more clear, which indicate that this season is more energetic and a significant amount of energy can be obtained during this time. A maximum value of 2.9 m can be observed during January and December, while a minimum of 1.3 m can be expected during June, July and August. In terms of the extreme conditions which are usually associated to the storm events, it may be expected that, during the winter time, the parameter *Hs* to report values in the range of 4.9 m - 5.5 m as compared to a maximum 4.2 m in September and a minimum of 2.4 m in August.

As concerning the monthly evolution of the parameter *Tm* (Fig. 2b), values in the range of 2.8 s - 3.5 s (mean), 4.1 s - 5.5 s (95%) and 6 s -7.4 s (extreme) can be noticed; with the mention that much higher values are being reported during the winter time, while, for the extreme values, an isolated peak can be observed during February.

The frequency distributions of the *Hs* and *Tm* are presented in Figs. 2c and 2d for the total and winter time. For the *Hs*, it can be noticed that most of the values are grouped in the range of 0.5 m -1.5 m for the total time with a peak for the 0.5 m – 1 m interval, while during the winter a similar trend is observed. Regarding the wave period, most of the values are concentrated in the interval 1-4 s with a maximum peak reported for the interval 2 s - 3 s. Figures 2e and 2f present the wave roses for the total and winter time, indicating the north-east and south sector as being more dominant.

Based on the previous results, the following case studies were identified:
- CS1: *Hs*=0.9 m; *Tm*=3.2 s   - average wave conditions;
- CS2: *Hs*=2.3 m; *Tm*=5.3 s   - energetic wave conditions;
- CS3: *Hs*=5.6 m; *Tm*=10.1 s   - extreme situation (storm events).

If we consider the fact that the reference point S is located in the offshore area and the incoming waves will interact with the seabed, it is possible to enter waves coming from several directions, in the Mamaia sector. For the present work, it was considered useful to include the following wave directions: north-east (30°), east (90°) and south-east (150°)

The Pelamis machine is an offshore floating wave energy converter, which can operate in water depths greater than 50 m and can be installed at 2 km – 10 km from the coast. This is a semi-submerged attenuator, which allows the waves to pass down along the machine and to adjust the position of the machine according to the direction of the incoming waves [15].

Figure 3 presents the setup of the Pelamis wave farm in the Mamaia sector and also an overview of this WEC system. In order to give a more realistic overview of the influence of the farm in the geographical space, each system (of the farm) was adjusted to be aligned to the corresponding wave direction. There are 31 Pelamis units (modeled as obstacles), separated by a 150 m space (in x and y direction), and distributed on a two lines configuration. The length of each WEC unit was set to a 190 m value, while the transmission coefficient was set to 0.5, which means that only 50% percent from the incoming waves is transmitted.
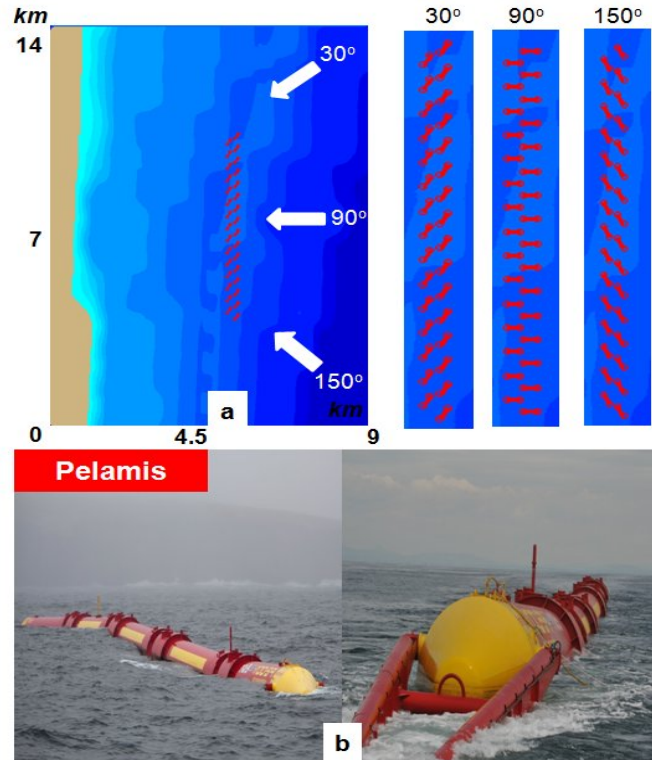
Fig. 3. Characteristics of the Pelamis wave farm: a) configuration of the wave farm according to the incoming waves from north-east (30$^{\mathrm{o}}$), east (90$^{\mathrm{o}}$) and south-east (150$^{\mathrm{o}}$); b) overview of the Pelamis system

Figure 4 illustrates the nearshore transformation of the local wave fields for the case study CS1. Considering the orientation of the Mamaia sector, this target area was rotated with 32$^{\mathrm{o}}$ (counterclockwise) so the considered wave directions (in nautical convention) will appear to be modified by this value.

When there is no wave farm can be noticed that the wave conditions for the interval 0.5-1m are dominant. Close to the shoreline, there is a decrease in magnitude of the wave fields (Hs<0.5 m), which is normal because the dissipative effects of the shallow water areas become more important. The waves coming from east (90$^{\mathrm{o}}$) generate a narrow strip, while, for the north-east waves (30$^{\mathrm{o}}$), this influence seems to be more significant, especially in the lower part of the target area.

In the presence of the Pelamis systems, it seems the wave field from the vicinity of the shoreline extends to the wave farm only in the case of the north-east and south-east waves, while for the wave coming from east the farm presents much lower influence on the local wave condition from the offshore area and a greater influence on the wave characteristics from the proximity of the shoreline. If we consider the north-east waves, the following variations of the parameter Hs are being reported by the reference points: P1 (0.66 m), P2 (0.76 m/0.76 m), P3 (0.66 m/0.64 m) and P4 (0.6 m/0.46); the first value indicates the situation in the absence of the wave farm. Near the shoreline, the local wave heights present values close to 0.46 m, while the presence of the farm can be considered insignificant since it modifies the

initial values with only 0.05 m. For this wave direction, the following variations in the directional space can be mentioned: P1 (37^o6`), P2 ($37^o5$`/37^o9`), P3 ($40^o$/$42^o6$`) and P4 (43^o12`/$34^o2$`). A similar evolution of the wave parameter is observed in the case of the south-east waves.
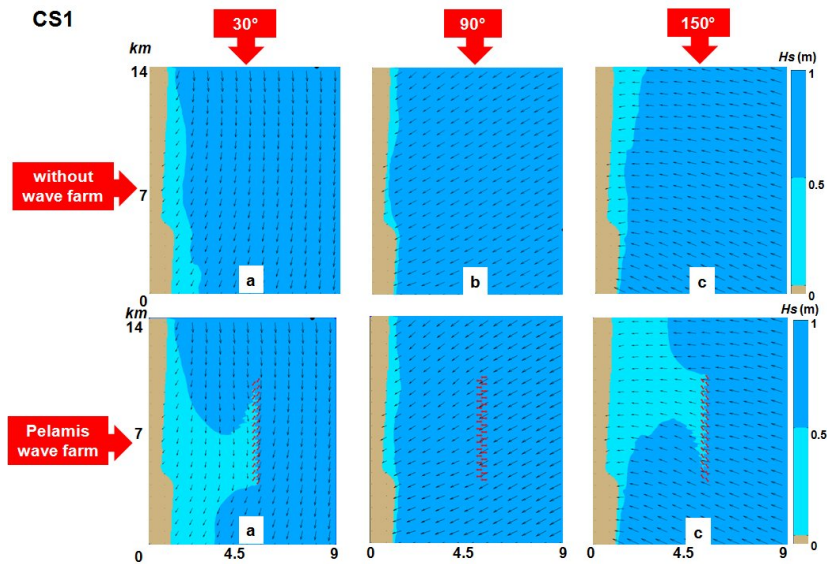
Fig. 4. Evaluation in the geographical space of the influence of the Pelamis wave farm considering the case studies CS1, for: a) waves coming from north-east (30°); b) waves coming from east (90°); c) waves coming from south-east (150°)
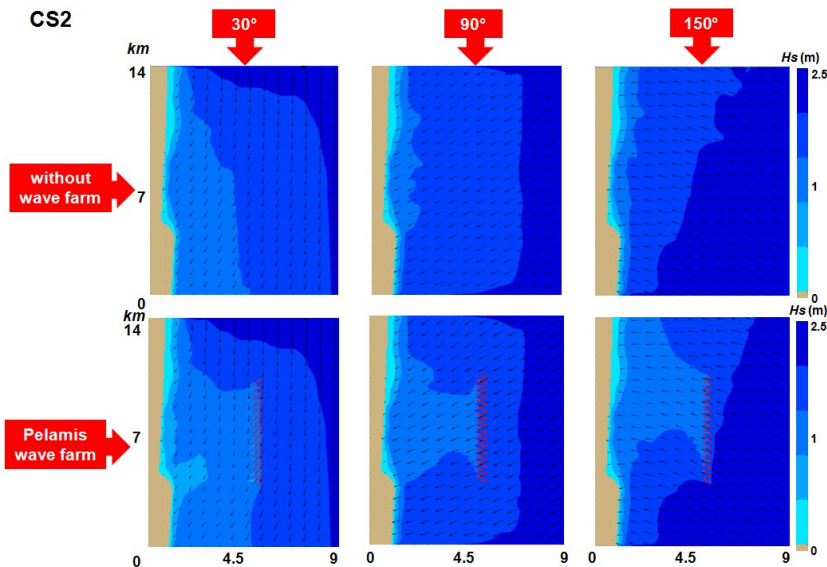
Fig. 5. Evaluation in the geographical space of the influence of the Pelamis wave farm considering the case studies CS2, for: a) waves coming from north-east (30°); b) waves coming from east (90°); c) waves coming from south-east (150°)

Considering a more energetic situation, Figure 5 presents the influence of the WEC farm, for the case study CS2. At this moment, it can be noticed that the local bathymetry significantly influences the transmission pattern of the wave in the geographical space.

In the vicinity of the Pelamis farm (in the central area), the wave coming from north-east can be reduced with a maximum 0.5m value on the contact with the farm, while similar values of 0.6 m and 0.75 m can be reported for the south-east and east waves, respectively. From all the reference points, P4 registers much higher differences in terms of the parameter Hs: 1.54 m/1.10 m – north-east waves, 1.75 m/1.56 m – east waves and 2.03 m/1.86 m – south-east waves. Close to the shoreline the initial wave conditions are located in the range of 1.1 m - 1.2 m (north-east waves), 1.4 m -1.5 m (east waves) and 1.5 m -1.8 m (south-east waves), which can be reduced to 0.9 m -1 m (north-east wave) in the presence of the farm and with no significant variations for the remaining directions.

Also, it is important to be mentioned that the influence of the wave farm seems to be more significant in the case of the south-east waves, while the incoming waves are significantly reduced by the local bathymetry until they reach the Pelamis systems, for the remaining situations.

Figure 6 presents the evolution of the wave fields in the presence of the wave farm for the case study CS3. For this extreme situation, the target area register a mixture of local wave characteristics. Analyzing the central area, on the contact with the wave farm, the incoming waves can be reduced to a value of 2.5 m (from 5 m) until the wave reaches the coastline and break. A value of 1.3 m is registered in the case of the east waves while a value of 2 m can be encounter for the south-east waves.
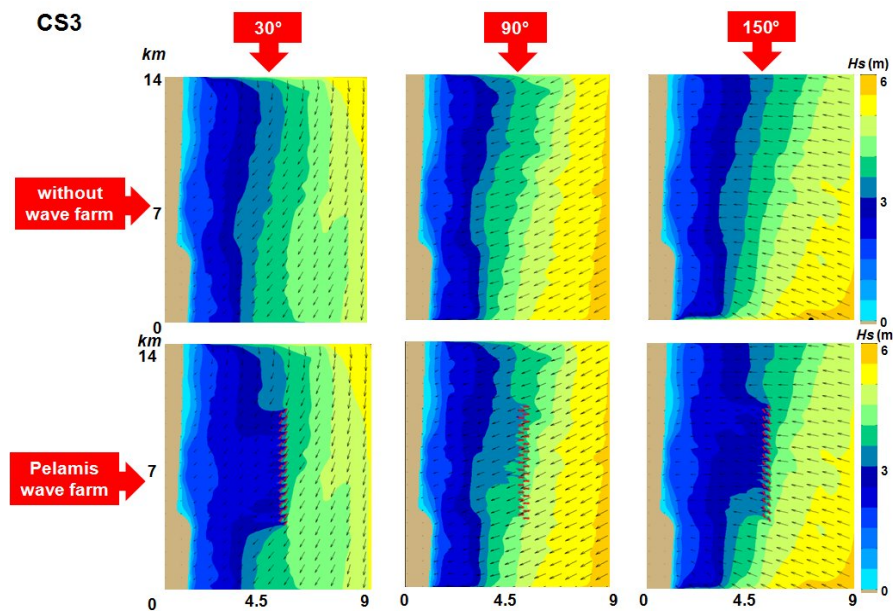

Fig. 6. Evaluation considering in the geographical space of the influence of the Pelamis wave farm, the case studies CS3, for: a) waves coming from north-east (30°); b) waves coming from east (90°); c) waves coming from south-east (150°)

4. CONCLUSIONS

A general evaluation of the influence of a Pelamis wave farm operating in the Mamaia sector was performed in this work based on numerical simulations carried out with the SWAN spectral model. In order to identify the local wave characteristics from this target area for a ten-year time interval (January 1999-December 2008), an initial SWAN simulation was carried out, based on the NCEP-CFSR wind data fields.

Based on these results, several case studies were identified in order to evaluate the influence of the wave farm. Since the corresponding Pelamis systems are modelled as obstacles, it is expected any future variations to be related to the severity and directions of the incoming waves. The wave farm was aligned parallel to the coastline in order to replicate a real scenario, where the local sediment transport will not be affected.

Generally, it can be noticed that the wave farm presents a significant influence in the central part of the target area, between the wave farm and the shoreline, with the mention that the influence of the wave farm is very low (or inexistent) in the shallow water areas. This is due the fact that the dissipative effects become more important. Maybe the most important changes occur in the offshore area, where on the contact with the wave farm, the incoming wave conditions can be significantly reduced (with almost 2.5 m – in the case CS3). Although, after this, a local regeneration of the wave is noticed, the presence of the farm seems suitable for the coastal protection since it will significantly reduce the severity of the wave attacks.

The current results look interesting and they indicate that a future wave energy farm operating in the Romanian nearshore can locally reduce the severity of the incoming waves, which will be an advantage for the coastal protection, during storm conditions.

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