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COASTAL PROTECTIONS PROVIDED BY ENERGY FARMS IN THE ROMANIAN NEARSHORE

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ABSTRACT

The objective of the present work is to give an overview of the coastal protection provided by energy farms that would operate in the Romanian coastal environment of the Black Sea. Based on some previous results, it was possible to identify the wind and wave conditions in the Black Sea area, according to datasets coming from the US National Centers for Environmental Prediction and also by analyzing the satellite measurements provided by the AVISO project. It was first noticed that the western part of the Black Sea seems to present more significant energetic conditions. Usually, the erosion of the coastlines is associated with a higher wave energy level so, as a next step, there were investigated several studie,s which include either wave energy or hybrid wind-wave energy farms for the coastal protection. These are based on the so called "what-if" scenarios and involve an operational WEC (Wave Energy Converter) system, namely the Wave Dragon, and also a wave generator called NEMOS, which is designed to be coupled to an offshore wind farm, while in the last case, it was considered a generic farm defined by various transmission coefficients. Based on these results, it can be concluded that the present work can lead to a better understanding of the variations induced by an energy farm over the wave climate reported in the Romanian nearshore, in this way being possible to choose the optimum solutions for coastal protection applications in terms of the WEC system and the distance of the farm from the coastline.

Keywords: marine energy farms, coastal protection, Black Sea, Romanian nearshore

1. INTRODUCTION

The natural resources contain an impressive amount of energy, which throughout the current state-of-the-art engineering systems can be efficiently converted into electricity. The renewables are quite diverse over the land areas, being obtained from a vast portfolio, which includes solar, wind or geothermal resources. As we approach to the coastal environment, it can be noticed that the natural sources are defined by a much higher power density than the similar ones located on land. This is the case of the sea waves, where the wind acting on the air-water interface gradually releases the energy transmitted by the sun radiation to the flow of the air masses. Usually, the coastal sectors facing the oceans bring attention since they are considered "hot-spots" in terms of wind and wave resources, this being one of the reasons why most of the research is focused on this issue [1-3]. Although in this region the resources are more consistent, the extreme conditions can have a negative impact onto the wind turbines or WEC systems, while a large number of projects concentrated in several regions may significantly reduce the suitable areas for such energy farms. During the recent years, it was noticed a growing interest to study the conditions reported by various enclosed (or semi-enclosed) seas, which seem to reveal coastal sectors with favorable winds and wave conditions. This is the case of the European basins, such as the Mediterranean Sea, which represents one of the first basins where several offshore wind projects are going to be developed, especially on the western side of the sea [4]. Coincidence (or not), going to the east, it can be observed that the western part of the Black Sea also reveals impressive resources in terms of marine conditions, at which it can be added the fact that this region is defined by a shelf environment, where the water depth is much lower as compared to other parts of the sea [5, 6]. From this point of view, some other basins may be included in this category, such as the Caspian Sea, where the northern region is defined by a favorable ratio between the wave/wind energy and the water depth [7].

Since in the western part of the Black Sea some important harbor areas are located, the safety of the marine navigation represents also an important issue, the main concerns being related to the prediction of the extreme conditions. This topic was extensively discussed for the major transportation routes, as well as in the area located at the entrance of the Danube Delta, where interactions between waves and currents can generate rogue waves capable to capsize a ship [7-10]. Another problem related to the extreme wave conditions is reported along the Romanian coastline, where the erosion processes generated by the waves represent a serious threat to the integrity of the beach sectors. This phenomenon is most visible during the winter time, where a short, but intense, storm event can carry out into the sea important volumes of sediments from the beach, which became vulnerable to the erosion process since they will not be capable to naturally regenerate during this interval. Since the aim of a WEC system is to extract the wave energy, there are increasing voices, which consider that a wave farm project will be more suitable for coastal protection than many of the classical solutions applied today [11, 12].

Considering these aspects, the purpose of the present work is to investigate several case studies focused on the coastal protection of the Romanian nearshore throughout energy farms in order to identify a suitable approach for this topic and also some future research directions.

2. WIND AND WAVE CONDITIONS ALONG THE BLACK SEA BASIN

A first analysis is presented in Fig. 1, where the wind and wave conditions from the Black Sea are evaluated. Figure 1a highlights the wind speed reported at 10 m height (*U10*) according to the wind fields coming from the NCEP/CFSR (National Centers for Environmental Prediction/Climate Forecast System Reanalysis - further identified as NCEP), which were processed for a 12-year time interval (1998–2009). Several points located in various coastal sectors of the sea were taken into account, all the points being located in a shallow water area (<50 m) [14]. The results are structured on total time and winter season, the last one being considered the time interval located between October and March (6 months). From the analysis of the total time values, it can be observed that the points from the western part report more consistent values, among them being included the point A1, which is located close to the Romanian nearshore. As it can be observed, this point with a wind speed of 6.2 m/s exceeds most of the points, excepting A2 (Ukraine), which registers a maximum of 6.7 m/s. During the winter season, A1 revealed a value located close to 7.1 m/s, which is close to the conditions reported near A5 (Russia), but below the average values of 7.7 m/s, reported by A2. At this point, it can be mentioned that Romania seems to present important offshore wind resources, as compared to other countries, such as Turkey, which covers an important part of the Black Sea and where, from the four reference points, it can be mentioned a maximum of 4.8 m/s during the winter time. Also, as compared to the Bulgarian sector, Romania seems to have more consistent values, although the two countries are located in the same geographical region.

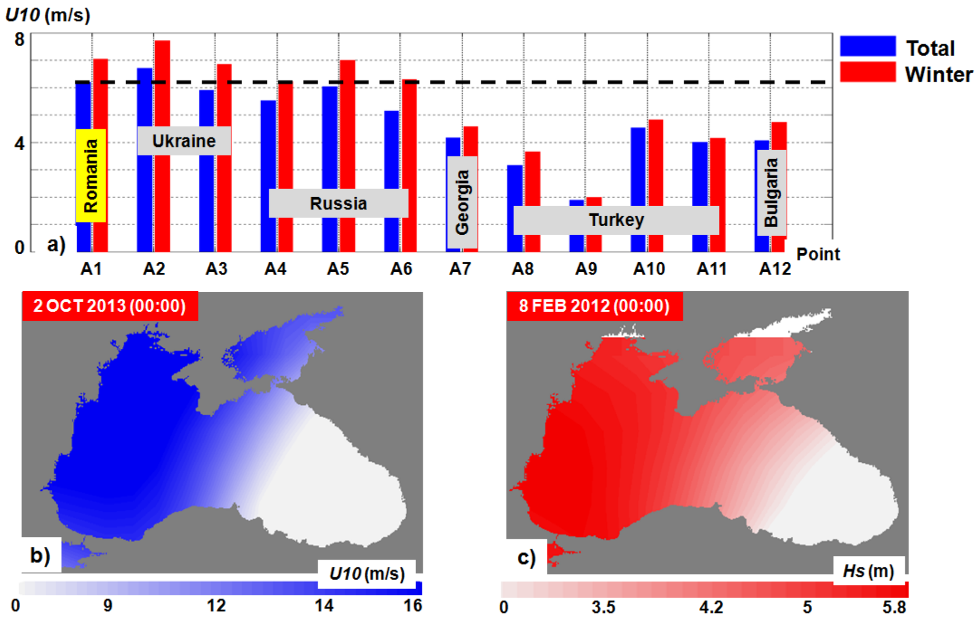

Fig. 1. Environmental conditions reported along the Black Sea area, where the results indicate: a) wind speed (average values) reported along several coastal areas, processed from the NCEP data set; b) spatial distribution of the wind speed reflected by the AVISO satellite measurements for 2.10.2013; c) spatial map of the *Hs* parameter reflected by the AVISO satellite measurements, for 8.02.2012. Results processed from [8, 14].

Going to the satellite measurements, in Figure 1b, there were identified more energetic wind conditions in the western part of the Black Sea. This is based on the information coming from a multi-mission project, which collects various altimeter missions, under the project AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data). For this time frame (2.10. 2013), it can be mentioned a maximum of 16 m/s in the western part of the sea, as compared to the eastern part, where the values gradually decrease below 9 m/s. This situation can be associated to a storm event, which indicates that, even in these conditions, the performances of a wind farm will not be affected since the *cut-out* value of most of the generators are located around 25 m/s (*U80*), although this value is reported for a 80 m height, where the rotor operates.

As concerning the wave conditions, Figure 1c highlights the distribution of the *Hs* parameter, which is related to the significant wave height. This is used to identify the mean wave height of the highest third of the waves. Based on these results, reported for the time frame 8. 02. 2012, it can be observed a maximum value of 5.8 m in the western part of the sea, from which a gradually decrease to the center of the sea is observed. This situation can be associated with an important storm event, which covers the entire sea, with the mention that the real wave heights could be significantly higher since, in this case, we take into account averaged *Hs* values. Taking into account that the Black Sea is an enclosed sea, these events are limited, which may represent an advantage for a wave energy project since the systems will operate during a longer period of time. Also, if we analyze the power matrix of various WEC generators, it can be observed that the *cut-out* values of some systems are much higher than the ones reported in Fig. 1c, as in the case of the Pelamis device, which it is set to a *Hs* value of 8 m.

3. COASTAL PROTECTION BY MARINE FARMS

In order to replicate the virtual impact of a wave farm, various methods are considered, as it can be noticed from Fig. 2. All the considered studies were simulated throughout the SWAN (Simulating WAves Nearshore) spectral model, while the results were processed by using the ISSM interface (Interface for SWAN and Surf Models).

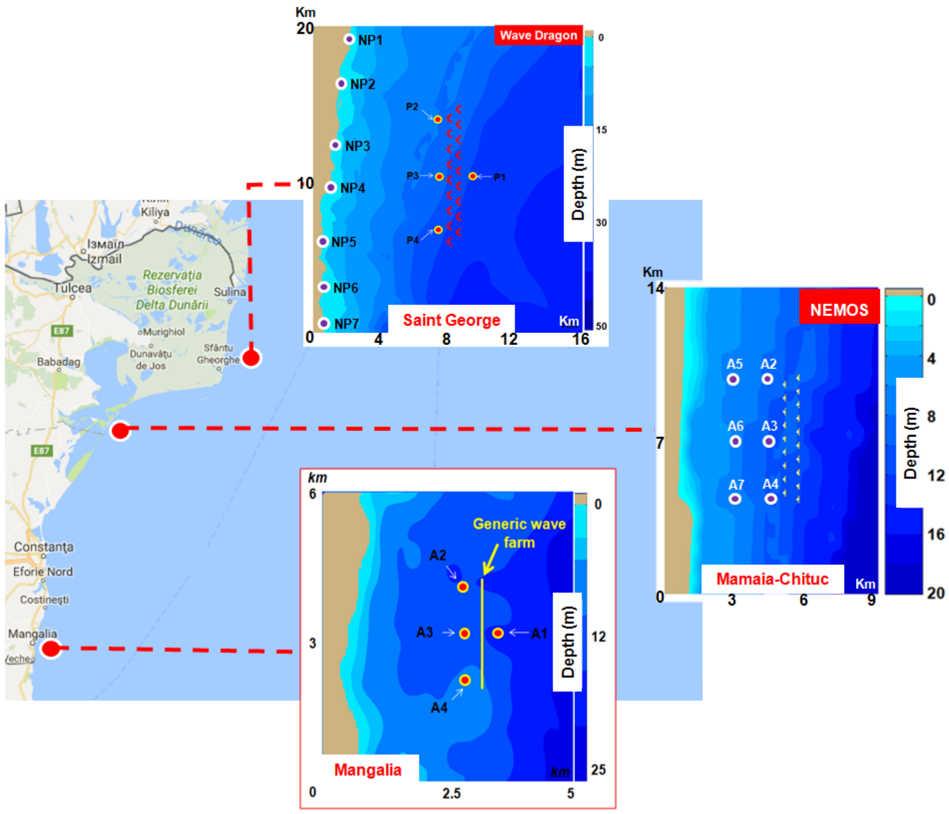

Fig. 2. Overview of the Romanian coastal area and the considered SWAN computational domains, where: a) Saint-George sector → Wave Dragon farm; b) Mamaia-Chituc sector → NEMOS farm; c) Mangalia sector → generic wave farm. Information processed from [15-17].

The first case study is focused on the Saint George area, which is located in the northern part of the Romanian coastline. In this area, it was considered a wave farm, which includes a number of 46 Wave Dragon systems deployed on a two line configuration. The distance between the lines was set to 190 m between each system and it was considered a gap of 25 m, while the length of a single WEC is close to 300 m. It is important to mention that the transmission coefficient of a single WEC was set-up to 0.68, which indicates that only 68% of the waves will be transmitted by the wave farm located at approximately 8 km from the shoreline. In this case, it will be evaluated the influence on the nearshore waves, which will be identified throughout the NP points (NP1-NP7), defined in the vicinity of the shoreline.

Going to the south, close to the sector Mamaia-Chituc, it was considered another scenario, which involves the presence of a hybrid wind-wave farm composed of several wind turbines and NEMOS systems [19]. It is estimated that on a single wind tower will be coupled multiple WEC systems so, for this study, there were considered 19 groups of wind-wave systems, each one being defined by a single wind turbine tower and five NEMOS devices. For this study, the transmission coefficient was set to 0.5, while the spatial configuration of the farm is defined by a two-line layout. The bathymetry of the target area is presented in the background, from which it can be observed a maximum depth of 20 m, while the entire area is defined by a surface of 126 km^2. On the south extremity of the Romanian border, close to Mangalia sector, it was defined in another case study, which involves a generic wave farm defined as an obstacle line, for which various values of the transmission coefficients were associated. The first one was denoted with T1 and corresponds to the scenario where there is no wave farm, the second one (T3) is related to a 0.5 coefficient, while the last one (T5) is similar to an ideal wave farm, where all the waves are absorbed (no wave transmission).

In Table 1, there are analyzed the variations of the wave heights (*Hs* values) reported by the NP points from the area Saint-George. Based on the analysis of the local waves, some relevant case studies were taken into account, namely: a) CS1 → *H*s=0.94 m; *Tm*=3.5 s (average conditions); b) CS2 → *Hs*=2.5 m; *Tm*=5.3 s (energetic conditions); c) CS3 → *Hs*=6.3 m; *Tm*=9.2 s (extreme conditions). In terms of the wave direction, there were simulated the situations when the waves occur from northeast (NE), east (E) and southeast (SE), respectively. In a general analysis, it can be observed that most of the values are positive, which means that the presence of the WEC systems reduces the wave heights, while the negative values are quite insignificant.

Table 1. Differences reported in terms of the *Hs* (in m) values between the no farm scenario and the Wave Dragon farm [15]

Case study	NP1	NP2	NP3	NP4	NP5	NP6	NP7
Direction - NE							
CS1	0	0.003	0.024	0.04	0.059	0.044	0.029
CS2	0	0.006	0.067	0.118	0.166	0.051	0.083
CS3	0	0.008	0.065	0.102	0.066	0.001	-0.005
Direction - E							
CS1	0.014	0.04	0.067	0.068	0.049	0.023	0.01
CS2	0.03	0.127	0.188	0.196	0.135	-0.007	0.017
CS3	-0.009	-0.007	0.032	0.035	0.024	0.001	0.001
Direction - SE							
CS1	0.04	0.057	0.043	0.027	0.006	-0.001	0
CS2	0.12	0.185	0.127	0.083	0.018	0	0
CS3	0.007	0.044	0.045	0.027	0.003	-0.001	0

Besides the wave heights, another important parameter is the direction from which the waves are entering into the target area so Table 2 presents such an evaluation. The results are indicated in terms of the differences reported between a no farm scenario and the WEC farm. It can be noticed that the negative values occur more frequently and they reveal more consistent values regardless of the direction from which the waves are coming.

The results reported for the Mamaia-Chituc sector are presented in Table 3, considering the values reported by the reference points A2-A7, defined in the vicinity of the NEMOS hybrid farm.

Table 2. Differences reported in terms of the direction (in degrees) values between no farm scenario and the Wave Dragon farm [15]

Case study	NP1	NP2	NP3	NP4	NP5	NP6	NP7
Direction - NE							
CS1	-0.051	0.48	3.466	4.771	3.908	-0.064	-1.743
CS2	-0.047	0.368	2.797	4.006	2.538	-0.439	-1.693
CS3	-0.002	0.59	2.768	3.343	1.609	-1.165	-1.398
Direction - E							
CS1	2.468	5.074	2.378	-1.296	-5.297	-3.417	-1.766
CS2	1.782	3.637	0.898	-2.404	-4.57	-3.215	-1.449
CS3	1.816	3.134	2.028	0.357	-0.838	-0.279	-0.082
Direction - SE							
CS1	2.424	-2.176	-5.399	-4.104	-1.185	0.053	0.022
CS2	2.939	-0.859	-4.361	-3.591	-0.995	0.078	0.034
CS3	2.466	-1.432	-2.984	-2.873	-0.519	0.064	0.015

Table 3. Variations of the wave parameters in the presence of the NEMOS farm, reported in the Mamaia-Chituc area [16]

Parameters ↓	**Points →**	A2	A3	A4	A5	A6	A7
CS1.1 (*Hs*=2 m, *Tm*=5 s, *Dir*=62°)							
Hs (m)		0.05	0.3	0.31	0.03	0.18	0.22
Emax (m^2/Hz/deg)		0	0.18	0.39	-0.01	0.19	0.45
Dir (^{o})		3.35	10.29	3.14	2.87	8.49	1.85
Lwave (m)		-0.01	2.21	3.15	0.05	1.55	2.54
CS1.2 (*Hs*=2 m, *Tm*=5 s, *Dir*=182°)							
Hs (m)		0.44	0.39	0.01	0.31	0.2	0.03
Emax (m^2/Hz/deg)		0.74	0.48	0	0.43	0.19	0
Dir (^{o})		-4.03	-9.27	-2.19	-4.28	-7.29	-1.51
Lwave (m)		1.96	1.72	0.14	1.7	1.23	0.1
CS2.1 (*Hs*=4 m, *Tm*=8 s, *Dir*=62°)							
Hs (m)		0.12	0.79	0.78	0.05	0.26	0.5
Emax (m^2/Hz/deg)		-0.03	3.89	5.48	-0.12	3.43	4.76
Dir (^{o})		3.56	5.53	-1	1.86	6.76	-1.59
Lwave (m)		0.24	3.52	14.25	0.57	4.32	5.94
CS2.2 (*Hs*=4 m, *Tm*=8 s, *Dir*=122°)							
Hs (m)		0.51	1.02	0.48	0.23	0.3	0.11
Emax (m^2/Hz/deg)		1.15	6.53	1.09	2.2	5.68	0.46
Dir (^{o})		9.2	-0.13	-7.94	8.78	4.1	-1.59
Lwave (m)		1.57	4.89	2.47	1.49	3.89	2.06

For this study, several scenarios (denoted with CS) were taken into account in order to replicate the most common wave pattern, which may be encountered in this target area. Several wave parameters were taken into account, such as: significant wave heigt (*Hs*), wave energy (*Emax*), direction of the waves (*Dir*) or wavelength (*Lwave*). From these, it can be mentioned that the reference points indicate only negative values for the *Dir* parameter, when it was considered the case study CS1.2.

Based on these elements, it was possible to identify the influence of the hybrid farm in the spectral space for the scenario CS2.2, which is presented in Fig. 3 for all the considered reference points. The results are indicated in terms of a 2D JONSWAP spectrum, from which it can be noticed that the spectral shapes are changing (in direction and frequency) according to the spatial distribution of the reference points and to the direction from which the waves are coming.

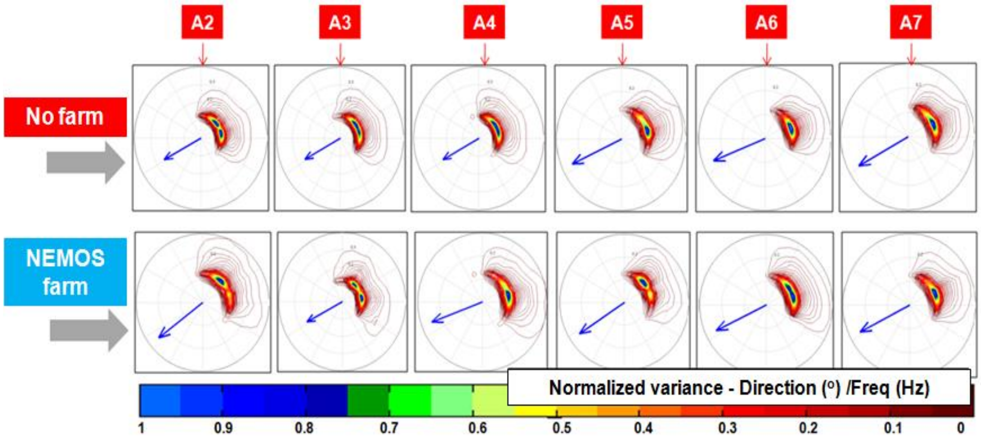

Fig. 3. Evaluation in the spectral space of the influence of the NEMSO hybrid farm considering the reference points A2-A7, for the case study CS2.2 [16]

Figures 4 and 5 presents the influence of the generic farm on the wave conditions reported in the vicinity of the Mangalia sector. The results are focused on the case study CS1, which is related to normal conditions, as compared to CS3, where an extreme storm scenario was simulated. As expected, the magnitude of the shielding effect induced by the farm is related to the value of the transmission coefficient and to the direction of the waves, more important variations being reported for the situation CS3.

4. DISCUSSIONS

As it was noticed from the previous results, three different case studies were presented. Since the presence of the WEC systems was included in the SWAN simulations as obstacles, it is normally to expect some impact onto the local wave fields according to the values assigned for the transmission coefficients. In terms of the wave farm configuration, when the type of the WEC system, which will be developed in a specific area, is known, it is possible to identify in details the influence of the farm. The main advantage is given by the fact that, on a local scale, there can be identified the wave variations, which occur between the generators and the WEC lines, which can be useful for the spatial optimization of the farm in order to capture more energy and to extract more electricity. On a large scale, the influence of such configuration seems to be similar to the one reported by a generic farm, the only differences occurring only when the transmission coefficients are changed.

For the wave fields located in the vicinity of the WEC farm, between the farm and the shoreline, it can be expected an attenuation of the wave heights with almost 50%, after which the wave fields are starting to slowly regenerate until they reach the surf area. Even so, this is important since the energy of the waves will be significantly reduced and the impact on the local beach will be less aggressive. The reference points from the Saint George area also reveal changes in terms of the wave direction, which means that the presence of the farm can shift the erosion/accretion processes in some other coastal sectors, but with a much lower intensity since the wave heights will be reduced.

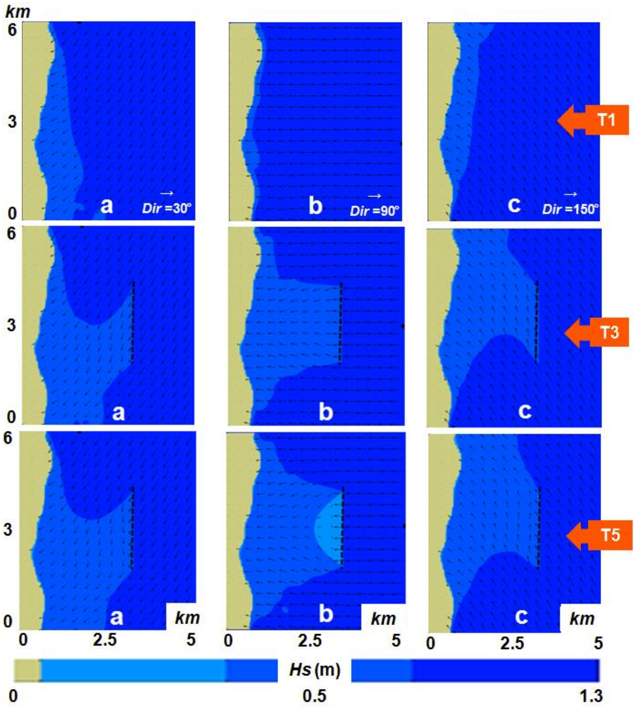

Fig. 4. Influence of the generic farm in the geographical space indicated for the Mangalia sector, in terms of the transmission coefficient T1, T2 and T3. The results are reported for the wave directions: a) northeast (30^o); b) east (90^o) and southeast (150^o); while the case study is related to CS1 (*Hs*=1.3 m; *Tm*=4.6 s) [17].

Although the western part of the Black Sea seems to present more consistent wave resources, at this moment, there is no plan to develop an energy farm project. Therefore, maybe a viable approach for the Romanian nearshore will be to elaborate various scenarios, which involve some commercial WEC systems grouped in a wave farm and defined by a specific transmission coefficient (mentioned by the manufacturer), these results being subsequently applied to a generic farm. In this way, it can be associated a generic farm to a specific WEC system, which will lead to a better understanding of the best solution that could be applied for the coastal protection. Since in the presented case studies, the wave farm was aligned parallel to the shoreline (at various distances), it will be interesting, for the coastal protection and also for the efficiency of the farm, to replicate various spatial configurations in order to identify custom solution for a coastal sector with a particular shoreline orientation and wave characteristics.

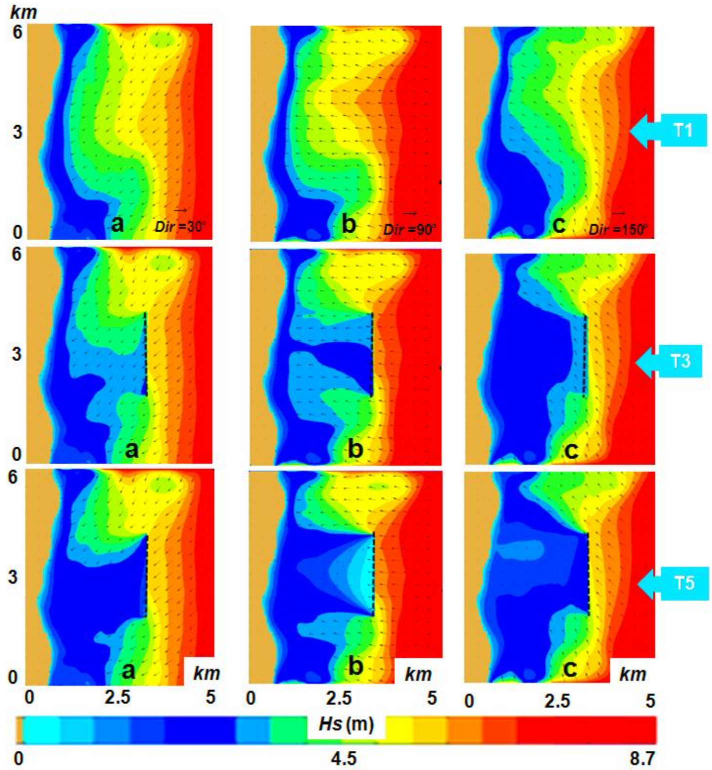

Fig. 5. Influence of the generic farm in the geographical space indicated for the Mangalia sector, in terms of the transmission coefficient T1, T2 and T3. The results are reported for the wave directions: a) northeast (30^o); b) east (90^o) and southeast (150^o); while the case study is related to CS3 (*Hs*=8.7 m; *Tm*=9.4 s) [17].

5. CONCLUSIONS

In this paper, several solutions were proposed for the coastal protection of the Romanian nearshore by considering marine energy farms. The target areas taken into account are representative for this region, being defined along the Danube Delta, the central part of the Romanian nearshore and the southern extremity close to Bulgaria.

From the analysis of the wind and wave conditions, it was possible to highlight the wind and wave energy potential defining the Romanian nearshore areas, bringing into attention, at the same time, the threats that may exist for the maritime transport or for the erosion of the coastal sectors. The results related to the WEC farms, as resulted from the simulations carried out with the SWAN phase averaged spectral model, highlighted the efficiency of the wave farm, which is directly related to the intensity of the incoming waves and to the wave direction. These results can be used to identify the distribution of the currents in the surf area, in this way being possible to evaluate the present and future evolution of the sedimentation rate along various coastal levels.

It can be concluded that this type of research represents a step forward for a better understanding of the solutions that can be applied to protect the Romanian coastal area from erosion, being in line with the latest researches, which consider this approach as a viable alternative to the classical solutions.

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