The Analysis of the Black Sea Waves Features in order to Capitalize their Hydropower Potential

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Abstract: *This paper presents the waves characteristics near the Romanian coastline of the Black Sea, based on a large set of data from National Institute of Meteorology and Hydrology. The main wave's characteristics are: wave height, wavelength, period, wave celerity, Strouhal's number to study the similarity. Analyze is made in order to estimate the waves hydropower potential. From the polynomial integration of the wave's height results this variation during a year. The average height of waves near the Romanian coastline of the Black Sea is about 2.5-3 m in cold seasons and about 1.5-2 m in warm seasons. This paper estimates the hydropower wave's potential for a plant with 5 meters mounted at three different deeps – 10 m, 20 m and 30 m. For waves with average height of about 2 m, it can obtain 58-65 KW. Catching the wave energy near the shoreline is useful to reduce Romanian shoreline erosion*.

Keywords: *wave features, hydropower potential, marine current, shoreline*

1. Introduction

The Black Sea is located at 40°- 46° North Latitude and 27°- 41° East Longitude and has a surface of 423488 km^2. The Romanian coast, at the west side of the Black Sea, is about 245 km long, including the Danube delta. The Black Sea's climate characteristics are influenced by the North Atlantic Oscillation (NAO) and El Nino-Southern Oscillation (ENSO), which from a cyclone over the Black Sea basin [1]. For this reason, the Black Sea level is higher on winters than it is on summers [2].
Marine Black Sea currents generate traveling waves. There are two major ring streamline in horizontal circulation, rotating counterclockwise, having a velocity from 0.08-0.18 m /s (Fig.1). In the Black Sea, the vertical circulation is very slow, "it takes hundreds of years for the waters at the surface to be replaced by near-bottom waters from the deep-sea depression" [3]. "Daily tidal oscillations in the Black Sea do not exceed several centimeters. Severe storms accompanied by waves up to 8-10 m high occur often in winter season. The water temperatures at the surface of the Black Sea extends from –1.2ºC in winter to +31ºC in summer with mean annual level varying from 12ºC in the northwest to 16ºC in the southeast of the basin. Below 500 m the waters have a constant temperature of about 9ºC" [3].
This paper analyses the characteristics of the waves on the Black Sea Coast, regarding their height, wavelength, wave period and velocity, in order to capitalize their hydropower potential.
There are significant fluctuations in the water depth at the Romanian coast – from 1.5-2 m in the northern part of the coast (Mamaia, Constanta), to 150 m offshore and from 2 m in the southern coast area (Mangalia) to 50 m offshore. Current wave - shore interactions cause an erosion rate of 2.4 m per year in Mamaia and 1.5 m per year in Mangalia. Capitalization of wave energy by catching and converting them into energy could reduce this erosion.

Wave geometry is characterised by:

λ - wavelength (m);
h - wave height (m);
T - wave period (s);
L_i – shore width (m);
H - static water level (m);

Sh – Strouhal number
c – wave velocity / celerity (m/s)

The erosion rate is linked with Strouhal's number - representing the ratio between the height of a wave and the wavelength. This Strouhal's number – specified to the Black Sea is between 0.2÷0.05.

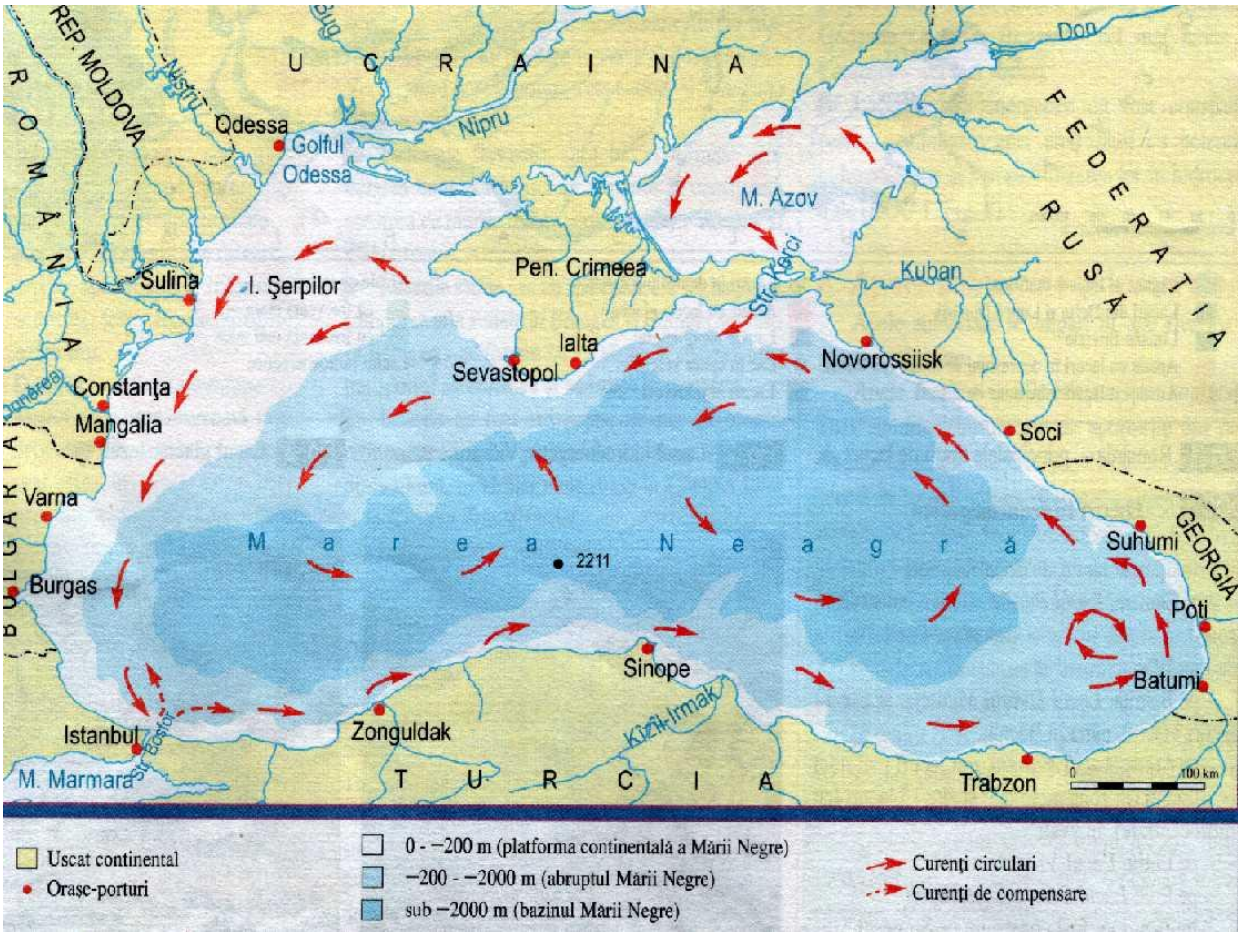


Fig. 1. Black Sea marine currents

Waves' features are important to analyse their hydropower potential, as it is presented in the following paragraphs.

2. Waves features near the Romanian coastline of the Black Sea

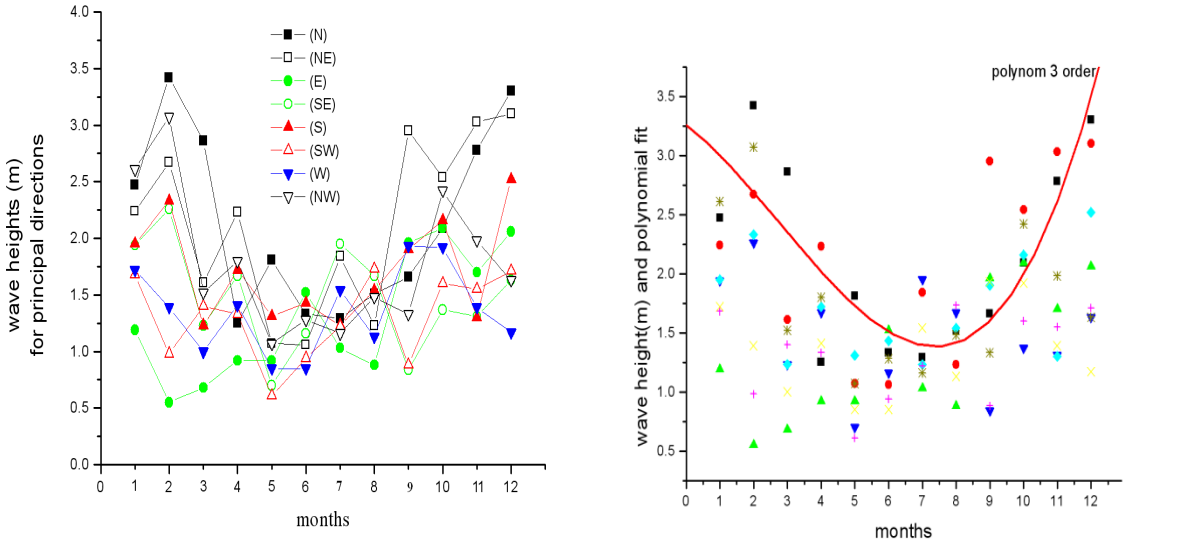
Several Research Institutes in Romania (National Institute of Meteorology and Hydrology, Aquaproiect, The Research and Power Engineering Institute etc.) have conducted measurements to determine wave characteristics on the Black Sea Coast (heights, wavelengths, displacement period and velocity, celerity) in Constanta, Mamaia, Sulina. Some results of their measurements are presented in the graphs below. In this paper, fig. 2 (a), (b) and fig. 3 show the wave height, taking into account the wavelength $h(\lambda)$. In fig. 4, it can identify the time period $T(\lambda)$, while fig. 5 shows the wave celerity $c(\lambda)$ for the three deeps of 10 m, 20 m and 30 m. The graphs were drafted for the Constanta shore. In Sulina, the wave periods and the wavelengths were lower [4], compared to the ones recorded in Constanta.

As you can see in fig. 1, the highest waves were measured on the N, NE and NW directions, in correlation with the directions of sea currents.

In table 1 one can see the heights recorded on each month of the year and on the main directions. In fig. 2.a) and b) also can be seen the variation of wave heights on each month of the year and the polynomial integration of these values.

TABLE 1: Wave height (m) for principal directions

Month	N	NE	E	SE	S	SW	W	NW
1	2.47	2.24	1.19	1.94	1.95	1.68	1.72	2.61
2	3.42	2.67	0.55	2.26	2.33	0.98	1.39	3.07
3	2.86	1.61	0.68	1.23	1.23	1.4	1	1.52
4	1.25	2.23	0.92	1.67	1.72	1.33	1.41	1.8
5	1.81	1.07	0.92	0.7	1.31	0.61	0.85	1.07
6	1.33	1.06	1.52	1.16	1.43	0.94	0.85	1.28
7	1.29	1.84	1.03	1.95	1.23	1.22	1.54	1.16
8	1.51	1.23	0.88	1.67	1.54	1.73	1.13	1.48
9	1.66	2.95	1.96	0.84	1.9	0.88	1.93	1.33
10	2.09	2.54	2.09	1.37	2.16	1.6	1.92	2.42
11	2.78	3.03	1.7	1.31	1.3	1.55	1.39	1.98
12	3.3	3.1	2.06	1.63	2.52	1.71	1.17	1.63



a) b)

Fig. 2. Wave heights recorded on each month of the year and on the main directions (a); polynomial integration (b)

Thus it can be seen that the average height of waves near the Romanian coastline of the Black Sea is 2.5-3 m in cold seasons and 1.5-2 m in warm seasons.

TABLE 2: Waves height, waves length, period and celerity at the water surface for three deeps of 10m, 20m and 30m

h(m)	λ10(m)	λ20(m)	λ30(m)	T(s)	c10(m/s)	c20(m/s)	c30(m/s)
0.5	14.04	14.05	14.05	3	4.68	4.68	4.68
1	24.69	24.97	24.98	4	6.17	6.24	6.24
2	45.24	50.12	50.67	5.7	7.93	8.79	8.88
3	65.55	79.08	83.71	7.4	8.85	10.68	11.31
4	81.23	101.16	110.92	8.7	9.33	11.62	12.74
5	99.49	126.12	142.13	10.2	9.75	12.36	13.93
6	113.76	144.43	164.71	11.3	10.06	12.78	14.57
7	130.84	165.94	190.97	12.6	10.38	13.17	15.15
8	147.39	185.99	215.03	13.8	10.68	13.47	15.58
9	164.53	206.25	239	15	10.96	13.75	15.93
10	182.27	226.78	262.97	16.2	11.06	14	16.23

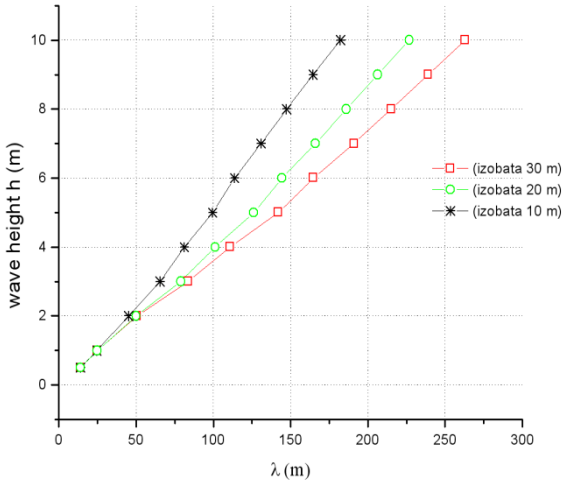


Fig. 3. Wave height depending on the wavelength

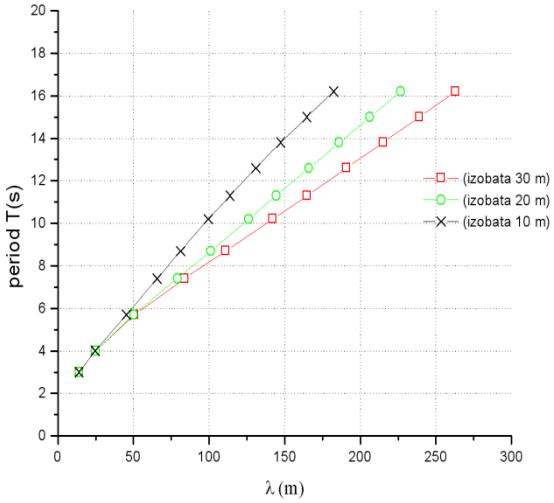


Fig. 4. Wave period depending on the wavelength

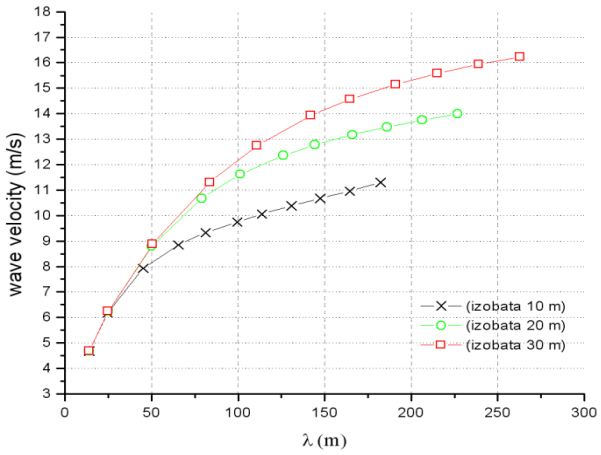


Fig. 5. Wave velocity depending on the wavelength

3. Wave's hydropower potential

Studies regarding the capitalization of hydropower potential of the waves near Romanian Black Sea shore ware made also by other authors [5-9].
Wave celerity is in relationship with the wavelength like in relation (1). Strouhal's number represents the ratio between the height of a wave and the wavelength, like in relation (2).
To capitalize the waves potential near the Romanian coastline of the Black Sea are used relations (3) and (4), assuming the efficiency of the system of 30% [5-6].

$$c = \frac{\lambda}{T} \tag{1}$$

$$Sh = \frac{h}{\lambda} \tag{2}$$

$$P_w = \frac{\gamma h^2}{8}\frac{\lambda}{T}L_i \quad (W) \tag{3}$$

$$P_c = \eta \cdot P_w \tag{4}$$

It can be seen in Table 3 and also in Fig. 6 the power that could be extracted from the wave energy by the systems fitted to each of the three deeps.

TABLE 3: Power of waves and power cached from waves according to the wavelength of the three deeps

h (m)	λ10 (μ)	λ200 (μ)	λ300 (μ)	T (s)	Pw 10 (kW)	Pc 10 (kW)	Pw 20 (kW)	Pc 20 (kW)	Pw 30 (kW)	Pc 30 (kW)
0.5	14.04	14.05	14.05	3	1.43	0.43	1.44	0.43	1.44	0.43
1	24.69	24.97	24.98	4	7.57	2.27	7.65	2.30	7.66	2.30
2	45.24	50.12	50.67	5.7	38.93	11.68	43.13	12.94	43.60	13.08
3	65.55	79.08	83.71	7.4	97.76	29.33	117.94	35.38	124.84	37.45
4	81.23	101.16	110.92	8.7	183.19	54.96	228.13	68.44	250.14	75.04
5	99.49	126.12	142.13	10.2	299.02	89.71	379.06	113.72	427.17	128.15
6	113.76	144.43	164.71	11.3	444.42	133.33	564.24	169.27	643.46	193.04
7	130.84	165.94	190.97	12.6	623.94	187.18	791.33	237.40	910.69	273.21
8	147.39	185.99	215.03	13.8	838.20	251.46	1057.72	317.32	1222.87	366.86
9	164.53	206.25	239	15	1089.48	326.84	1365.74	409.72	1582.60	474.78
10	182.27	226.78	262.97	16.2	1379.68	413.90	1716.60	514.98	1990.54	597.16

For example, catching the wave energy with hydro-pneumatic modules based on air piston, in hypothesis of wave height h = 1 m, with a wavelength of λ = 50 m and a wave period T = 6 s, we can obtain a raw power of 51 kW and a collection power of 15 kW, in the event of a η = 30 % collection efficiency rate, per each five meters of installation width L_i = 5 m [5-8].

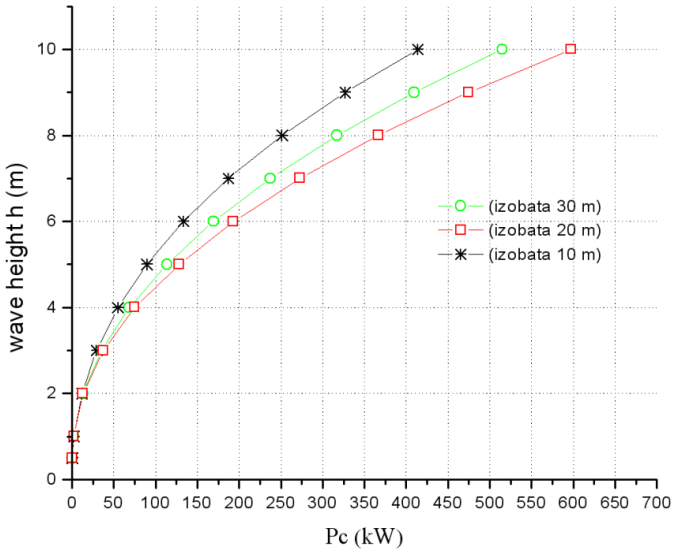


Fig. 6. Estimation of cached Power from wave's energy with hydro-pneumatic modules

For waves of about 2 m, as shown in Fig. 6 can be obtained 58-65 KW in any of the three mounting options. As waves are higher, the power is higher. For h = 8 m, can be obtained 250-370 kW. The plant mounted at 30 m deep provides more power.

4. Conclusions

This paper presents waves features near the Romanian coastline of the Black Sea, based on a large set of data from National Institute of Meteorology and Hydrology and Aquaproiect.
The average height of waves near the Romanian coastline of the Black Sea is 2.5-3 m in cold seasons and 1.5-2 m in warm seasons. Wave's velocity, wavelengths and periods depend on deeps. Strouhal's number – specified to the Black Sea is between 0.2÷0.05.
For waves with average height of about 2 m, it is estimated that can be obtained 58-65 KW for each 5 meter of wave's catching plant, in any of the three mounting options. As waves are higher, the power is higher. The plant mounted at 30 m deep provides more power. Catching the wave energy near coastline is useful also to reduce Romanian shoreline erosion.

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