Wave energy along the Romanian Southern Black Sea coast

Viorel-Mihai TANASE¹, Brindusa-Cristina CHIOTOROIU² and Nicolae VATU¹

¹Maritime Hydrographic Directorate, 1 Fulgerului str., Constanta, Romania,
²Constanta Maritime University, 104 Mircea cel Batrin str., Constanta, Romania,

Abstract.
Wave energy is among the resources to provide the most significant contribution to the European energy system in the future. Detailed wave climate analysis is needed for the selection of accurate types of wave energy generation structure and feasibility of wave energy sites. There are current studies on spatial distribution of Black Sea wave energy, that use measured or modeled data. In this study we used measured data (significant wave height and period and wind speed) recorded in 4 locations on the Romanian Southern coast during 5 years (2013-2018) in order to estimate the available wave energy potential.

1. Introduction
The share of energy from renewable sources in gross final consumption of energy continued rising to reach 17% in the European Union in 2016. The Europe 2020 strategy includes a target of reaching 20% of energy in gross final consumption of energy from renewable sources by 2020 [1]. Due to the technological progress, the first ocean energy farms have been created in 2008 [2]. Wave energy is among the resources to provide the most significant contribution to the European energy system. The technological barriers represent the most important challenge that the ocean energy sector needs to address in the short–medium term [1].

In order to design wave farms, the first steps consist of an evaluation of the amount of energy attainable in a specific site: the calculation of theoretical wave energy which represents the physical upper limit of available wave energy at the location for a time period. This calculation is generally followed by the estimation of the technical potential, which represents the amount of energy gatherable with available technology which is less than the theoretical potential considering inefficiencies in wave energy converters and generators and also limiting the area which is available for energy generation [3].

This paper refers to the calculation of significant wave height and period frequencies, energy potential and the power that a meter of crest holds. These parameters were calculated for the Romanian Southern Black Sea coast, for a five-year period.

2. Method and data
Studies on the wave energy potential of the Black Sea have been conducted using different wave prediction models or wave observations [4] [5] [6] [7] [3] [8] [9] [10].

The most important wave resources in the Black Sea are related to winter storms and especially in its south-western part [10]. The offshore locations have greater potential than the nearshore locations [3]. Most of the energy can be obtained from Black Sea waves with significant wave heights less than 3-4 m and with the energy periods of 5 s and 6 s.
The Romanian shelf presents differences between north and south: in the north there is a larger extent of the shelf and smaller depths than in the south part (see Figure 1) [11].

![Figure 1. Location of weather stations on the Romanian Black Sea coast](image)

The study area which is the southern part of the Romanian coast includes the main ports and cities from the coast and can thus benefit not only from the valorization of wave energy, but also from the combined use of wind and solar energy. This would reduce the power variability and would increase the energy power by using the same location, resulting in energy independence [12].

The analysis of the wave energy potential along the Romanian Southern coast was based on visual observations and on the measurements from 4 automated weather stations belonging to the Romanian Navy marine meteorological surveillance network (Midia, Constanta, Tuzla, Mangalia), for the last 5 years (01.06.2013-31.05.2018) [13]. (see Figure 1). The daily mean values were calculated from the observed time series of significant wave heights by averaging all measurements from a particular day with a time resolution of 6 hours. The visual observations on wave height have been made in nearshore areas with low depths (between 8 and 15 m) by experienced meteorologists (most of them by the first author himself). Only the daily mean values of significant wave heights have been used in this paper. In order to complete the database with records on other parameters such as wave period, length and direction, we used measurements made 3 times a day (at 7, 13 and 19 h local time) recorded in 1985, 1986 and 1987 in the annuals oceanographic registers from the National Institute for Marine Research and Development in Constanta [14].
We used the simple linear correlation and considered the significant wave height (H) as an independent variable and the wave period (T) and wave length (λ) as dependent variables (T (s) = f (H); λ (m) = f (H)), see Figure 2.

Therefore, the resulting equations have been used for determination of wave period and length for 2013 to 2018 waves, based on the visual observations on their significant height.

In order to better estimate the wave conditions, the observed waves have been grouped according to their heights and periods. This allowed us to calculate the relative frequency of occurrence of wave height and wave period. The quantification of wave energy was based on the formulas described in 1973 and 1983 [15] [16].

3. Results
The linear wave theory is generally used for the determination of the wave energy and power in coastal engineering and naval architecture. The wave parameters used after simplifying the formulas are the significant wave height (H, units in meters) and period (T, units in seconds).

Relative frequency of occurrence (%) of wave height and period were calculated using specific intervals (see Figure 3). Thereby, the distribution has a positive skewness which indicates that the peak of wave height intervals distribution is 0.1-0.2 m, with a percentage of 36.47%. Waves with heights between 3 to 4.25 m occur less (0.11%), together with the glassy sea (0.11%).

The percentage of significant wave heights between 1.2-2 m is 5.1%, while the percentage of values over 2 m is 1.4% (see Figure 3).

The box plot method shows the monthly variation of the values (see Figure 4).
Figure 4. Multiannual daily mean significant wave height values in Romanian Southern Black Sea coast (01.06.2013-31.05.2018)

The average significant wave height for the entire observed period was 0.444 m based on 7,304 individual recordings.

Table 1. Statistics of Daily Mean Significant Wave Height (01.06.2013-31.05.2018)

| Statistic       | Value | Percentile | Value |
|-----------------|-------|------------|-------|
| Sample Size     | 1826  | Min        | 0     |
| Range           | 4.25  | 5%         | 0.1   |
| Mean            | 0.44475 | 10%       | 0.1   |
| Variance        | 0.19856 | 25% (Q1) | 0.15  |
| Std. Deviation  | 0.4456 | 50% (Median) | 0.3 |
| Coef. of Variation | 1.0019 | 75% (Q3) | 0.55  |
| Std. Error      | 0.01043 | 90%       | 1     |
| Skewness        | 2.5603 | 95%        | 1.32  |
| Excess Kurtosis | 9.0887 | Max       | 4.25  |

Stormy seas are recorded in October and winter months while calm seas in April and summer months (see Figure 4). Table 1 indicates that 50% of values are lower than 0.3 m, and 10% excel 1 m.

The estimation of nearshore wave energy and power requires complex computations due to changes in wave properties because of the effect of wave reaction and shoaling, but also due to specific parameters that need to be calculated for a suitable wave energy converter [17].

In order to calculate the wave energy, we used the following formula:

$$ e = e_C + e_P = 2e_C = 2e_P = \frac{\gamma H^2}{8} $$

(1)

where: $e$ is the total wave energy, $e_C$ is the kinetic energy, $e_P$ is the potential energy, $\gamma$ is the specific gravity of seawater equal to 1012 kgF/m$^3$, and $H$ is the significant wave height.

This formula was already used by other researchers for the study of the Black Sea wave climate [18] [3] [4] [5] [6] [19].

Energy $e$ [J/m$^2$] is in fact a density of wave energy related to surface unit [19].
Figure 5 shows the mean daily variation calculated for the studied period of time of the wave energy. Because of the proportionality of \( e \) with the square wave height, high range values are recorded from a month to another. The highest wave energy values are recorded when stormy sea is observed – in winter months and October. Thence, the highest daily mean value is 236 J/m² in January, and values of about 200 J/m² are recorded in February, October and December. Obviously, in summer months the wave energy is at its lowest values which are about 5 J/m².

The wave power resource, the most important feature in wave energy converters, is calculated using the following simplified formula [15]:

\[
P = H^2 T
\]

where \( P \) is the wave power, \( H \) is the significant wave height, and \( T \) is the wave period.
Figure 6 shows that the highest multiannual mean daily wave power value 31.82 kW/m was recorded on the 26th of February, while the maximum mean value on a specific day was 156.82 kW/m during the blizzard from 26.02.2018, when significant wave heights were about 4-5 m. Similar values were also recorded during another blizzard from 06.01.2017.

Even though in summer days the wave power values are slightly low, the Romanian Southern Black Sea coast wave climate can be characterized by the average daily mean value which is 2.2 kW/m. This value is low when comparing to other areas (e.g. Europe West coast to North Atlantic Ocean has values between 40 and 75 kW/m [20]).

4. Conclusions
Wave energy is among the resources to provide the most significant contribution to the European energy system. One of the main tasks with regards to the wave energy utilization is the preliminary estimation of the available energy potential. The studies conducted in some areas around Europe are based on numerical modeling and in-situ measurements of the wave parameters. For the Black Sea there is a lack of measurements of the wave parameters with some exceptions, and the evaluation of the wave energy potential was based on numerical wave models, while the measurements have been used for model validations [21].

The calculation of the wave energy and wave power presented in this paper is based on observations recorded during 5 years near the Romanian Black Sea coasts. The results show wave potential especially during the cold season, with February being the most productive month and a mean wave power potential (including summer months) of 2.2 kW/m. These estimations are similar to the results obtained by other researchers for the western and southwestern parts of the Black Sea [3] [4] [6] [7] [21]. The western parts are also considered to be more promising in terms of possible wave energy conversion than the eastern parts of the sea [21].

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