Analysis Method of Wave Resource Characteristics in Field Test of Wave Energy Converters

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Abstract. In the field test of wave energy converters, analyzing the characteristics of wave resources in the sea area of the tested wave energy converter, is the basis of evaluating the power characteristics of the wave energy converter scientifically and accurately. On the basis of analyzing the analysis methods of wave resource characteristics at home and abroad, the joint distribution analysis method of significant wave height and mean wave period is studied in this paper, and the characteristics of wave resources of the tested sea area are analyzed by using the field measurement data. The results show that the joint distribution map can represent the distribution of wave parameters in the tested sea area from the aspects of significant wave height and mean wave period concurrently. With the analysis method of combining the rose diagram of wave parameters, histogram of wave parameters, and joint distribution map of significant wave height and mean wave period concurrently. The research results provide references for the field test and the design of optimal working conditions of the wave energy converter.

Keywords. Wave energy, wave energy converter, field test, wave resources

1. Introduction

In the winter of 2021, the energy crisis plaguing Europe was raging, with the rising prices of natural gas and electricity and the significant increase of the cost of energy consumption for the residents [1]. The global energy market came under attack due to factors including especially the COVID-19 pandemic and the prices of fossil fuels including coal, oil and natural gas saw a big rise [2]. Besides, the use and consumption of fossil fuels would lead to enormous amounts of greenhouse gas emissions such as carbon dioxide, and speed up the melting of Antarctic and Arctic glaciers, thus provoking a series of environmental problems like sea-level rise [3]. Therefore, the development and utilization of green, safe, renewable and pollution-free wave energy resources has become a universal consensus of the international community [4].

In recent years, China, Europe and America have made achievements in the R&D field of wave energy converters. Many of wave energy converters have carried out demonstration applications of real sea state and grid-connected power generation [5]. In the test site of wave energy converters, field test and evaluation has been conducted
on power characteristics, power quality characteristics, maintainability and reliability of the wave energy converters, which is a very important means of promoting the improvement of power generation technology of wave energy converters and furthering the breakthrough and progress of key technologies [6]. Therefore, many countries have engaged in the construction of wave energy converters test sites. The European Marine Energy Centre (EMEC), which is located in Orkney, Scotland, is an internationally renowned and early established testing and certification center for marine energy converters. Since its establishment in 2003, a number of wave energy converters have been tested in EMEC, which has greatly promoted the formation and development of the local industry of wave energy converters [7]. Moreover, test sites of wave energy converters like BIMEP in Spain and Galway Bay in Ireland have tested the wave energy converters, advancing the improvement of the local wave energy power generation technology [8, 9]. China has invested a lot of money in the construction of the test site of wave energy converter [10]. At present, the Ministry of Natural Resources, in accordance with the layout “North-Southeast, shallow and deep sea”, has systematically promoted the construction of the national integrated marine test site system and planned 4 national integrated marine test sites—Weihai Shandong, Zhoushan Zhejiang, Zhuhai Guangdong and “deep sea”. The national integrated marine test site in Zhuhai, Guangdong Province can provide testing services for the full-scale wave energy converters and other relevant marine instruments and equipment.

For the time being, many experts and scholars have analyzed and evaluated the wave energy resources in China, mostly by establishing models of relevant key areas and verifying the model with the field measurement data and drawing the distribution map of the wave energy flux resource in the concerned area based on the wave energy flow evaluation formula of the US Electric Power Research Institute (EPRI) [11-14]. This work has manifested the spatial distribution of coastal wave energy resources in China at a macro level, providing references for the sea area of wave energy demonstration power stations [15]. China has now identified the tested sea area for full-scale wave energy converters and relevant scholars have studied the hydrodynamic influence between berths and temporal distribution of wave parameters in such sea area [16, 17], but there are few studies on the joint distribution of wave parameters. Therefore, this paper first studies the analysis method of the wave parameter joint distribution and analyzes the characteristics of the wave energy flux resource in this sea area with the field measurement data so as to provide references for the field test and the design of the optimal working conditions of wave energy converters in China.

2. Analysis Method

In the R&D and design of wave energy converters, the optimal working conditions of wave power generation devices should be designed in the range where the distribution of the significant wave height and mean wave period in the tested sea area of wave energy converters are densely concentrated. Therefore, it is necessary to pay attention to the analysis method of the wave height and wave period joint distribution to provide references for the field test and the design of the optimal working conditions of wave energy converters.

After obtaining the wave height and wave period data of the tested sea area, two data sets, \( H_t \) and \( T_t \), can be formed,
where $H_n$ is the $n$th wave height obtained (unit: m) and $T_n$ is the $n$th wave period (unit: s).

In equations (1) and (2), $H_n$ and $T_n$ are one-to-one correspondents, namely,

$$ (H_n, T_n) \in \{(H_1, T_1), (H_2, T_2), \ldots, (H_n, T_n)\} $$(3)

When processing the field test data, first, the one-to-one correspondent $(H_i, T_i)$ data are divided into $j$ groups according to the wave height and the fixed interval $\Delta H$ (generally, the value is 0.2 m) of wave height,

$$ j = \left\lfloor \frac{H_{\text{max}} - H_{\text{min}}}{\Delta H} \right\rfloor $$

where $H_{\text{max}}$ is the max value of wave height data (unit: m) and $H_{\text{min}}$ is the min value of wave height data (unit: m).

The $(H_i, T_i)$ data in ascending order according to the $H_i$ are divided into $j$ groups according to the $\Delta H$. Then the number of the intervals divided (the $j$ groups) is represented by $k$, whose domain is the integer between 1 and $j$, namely,

$$ k \in \{1, 2, 3 \ldots j\} $$

Then $(H_k, T_k)$ is the $k$th data set of the $j$ groups, and the interval of $H_k$ can be expressed as:

$$ H_{\text{min}}^k \in (H_{\text{min}}^k + (k - 1)\Delta H, H_{\text{min}}^k + k\Delta H) $$

Equation (6) is a left-open and right-closed interval, which solves the attribution of the interval segmentation point. But the min value $H_{\text{min}}^k$ of the significant wave height should be specified in the first interval.

In the same way, the $k$th $(H_{\text{min}}^l, T_i)$ data set divided according to wave height is divided into $l$ groups according to the wave period and the fixed interval $\Delta T$ (generally, the value is 0.5 s) of the wave period.

$$ l = \left\lfloor \frac{T_{\text{max}} - T_{\text{min}}}{\Delta T} \right\rfloor $$

where, $T_{\text{max}}$ is the max value of the wave period data in $(H_{\text{min}}^l, T_i)$ data set (unit: s); $T_{\text{min}}$ is the min value of the wave period data in $(H_{\text{min}}^l, T_i)$ data set (unit: s).

The $(H_{\text{min}}^l, T_i)$ data set in ascending order according to $T_i$ is divided into $l$ groups according to the $\Delta T$. Then the number of the intervals divided (the $l$ groups) is represented by $m$, whose domain is the integer between 1 and $l$, namely,
Then \((H_{ik}, T_{im})\) is the \(m\)th data set of the \(l\) groups, and the interval of \(T_{im}\) can be expressed as:

\[
T_{im} \in \left[ T_{\min} + (m-1)\Delta T, T_{\min} + m\Delta T \right]
\]

Like equation (6), the equation (9) is also a left-open and right closed interval and the min value \(T_{\min}\) of the wave period in the \(k\)th \((H_{ik}, T_{i})\) data set should also be specified in the first interval.

The number of intervals divided according to equations (6) and (9) for the wave height and wave period is:

\[
c = j \cdot l
\]

Then the distribution frequency of the data set \((H_{ik}, T_{im})\) that can be statistically divided in each interval in the entire data set \((H_{i}, T_{i})\) is \(f_{km}\) and the relationship is:

\[
\sum_{km} f_{km} = 1
\]

where \(f_{km}\) is the joint distribution probability of wave height and wave period in a sea area.

3. Field Application

3.1. Application Time and Sea Area

From May to June 2021, in the Dawanshan sea area, Zhuhai, Guangdong Province, the wave elements in the tested area of the wave energy converters were measured. The tested area is about 2 km east-west and 1.5 km north-south, the water depth is about 28 m.

3.2. Wave Measuring Equipment and Methods

The wave parameters were measured by a Directional Waverider MKIII buoy with a diameter of 0.7 m and were transmitted to the data receiver in real time. During the field measurement, the equipment clock was calibrated against Beijing Standard Time. At half-hours and hours, a group of wave parameters including wave height, wave period and wave direction would be stored. The relevant technical parameters are shown in Table 1.
Table 1. Technical parameters of Directional Waverider.

<table>
<thead>
<tr>
<th>Measured parameters</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave height</td>
<td>0-20 m</td>
<td>0.5% reading value</td>
</tr>
<tr>
<td>Wave period</td>
<td>1.6-30 s</td>
<td></td>
</tr>
<tr>
<td>Wave direction</td>
<td>0-360°</td>
<td>±0.5°</td>
</tr>
</tbody>
</table>

4. Results and Analysis

During the field contrast tests, 1,500 groups of wave parameters were obtained. After deleting abnormal data caused by abnormal data transmission, unstable deployment and recovery, only 1,400 groups of data were used for the feature analysis of wave energy flux resources. The characteristics of wave resources in the tested sea area can be reflected in a comprehensive and objective way with the analysis method of combining the wave rose of significant wave height, wave rose of mean wave period, histogram of significant wave height, histogram of mean wave period and joint distribution map.

4.1. Wave Rose of Tested Sea Area

The waves in the real ocean environment can be considered as a sum of sine waves of different directions, phases, frequencies and amplitudes. The significant wave height, mean period and wave direction in the tested area are varied. Therefore, these parameters acquired by the wave measuring equipment are the statistical value within the measurement period. The spectral peak direction, characterizing the maximum wave energy spectrum density, is a wave parameter much concerned in the field test of wave energy converters. Besides, the wave rose diagram can vividly capture the distribution changes of wave parameters such as wave height at an observation point from different directions during several years or one year, season and month. Hence, the rose diagrams of significant wave height and mean wave period of wave energy converters in the tested sea area at the spectral peak direction are drawn and shown in Figures 1 and 2.
Figure 2. Wave rose of average wave period.

Figure 1 indicates that during the field measurement, the significant wave height in the tested sea area is mostly distributed between 0.8-1.0 m. Figure 2 indicates that during the field measurement, the mean wave period in the tested sea area is mostly distributed between 3.5-4 s. Figures 1 and 2 indicate that during the field measurement, most of the waves are located between south and southwest, especially the number of waves on south-southwest accounting for 55% of the total. The distribution of the wave direction is significantly influence by the southwes trade wind direction of Dawanshan sea area in this season [18].

4.2. Histogram of Significant Wave Height

Statistical analysis is made on the distribution of significant wave height using the measured data and the distribution histogram of significant wave height is as shown in Figure 3.
Figure 3 indicates that during the field measurement, the significant wave height data of wave energy converters in the tested sea area are distributed between 0.4-1.7m, with the majority between 0.5-1.3m. Besides, the data between 0.8-0.9 m are the most, accounting for 26.1% of the total. Figure 3 characterizes the distribution of significant wave height in more detail compared to Figure 1.

4.3. Histogram of Mean Wave Period

Statistical analysis is made on the distribution of mean wave period and the distribution histogram of mean wave period is as shown in Figure 4.

Figure 4. Distribution histogram of mean wave period.

Figure 4 indicates that during the field measurement, the mean wave period data in the tested area of wave energy converters are distributed between 2.8-5.6 s, with the majority between 3.2-4.4 s. Besides, the data between 3.6-3.8 s are the most, accounting for 20.0% of the total. Likewise, figure 4 characterizes the distribution of mean wave period in more detail compared to Figure 2.

4.4 Joint Distribution

4.4.1. Data of Joint Distribution

Figures 3 and 4 represent the statistical analysis of the significant wave height and mean wave period respectively. But in the field test and the design of optimal working conditions of wave energy converters, the joint distribution of the significant wave height and mean wave period in the tested sea area should be considered. Therefore, with the calculation and analysis method of the wave height and wave period joint distribution presented in this paper, during the period of field measurement, the joint distribution probability data of wave height and wave period of wave generation devices in the tested sea area of the divided interval are shown in Table 2.
Table 2. Joint distribution data of significant wave height and mean wave period.

<table>
<thead>
<tr>
<th>Significant wave height/m</th>
<th>0.4-0.6</th>
<th>0.6-0.8</th>
<th>0.8-1.0</th>
<th>1.0-1.2</th>
<th>1.2-1.4</th>
<th>1.4-1.6</th>
<th>1.6-1.8</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5-3</td>
<td>0.477%</td>
<td>0.614%</td>
<td>0.205%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>1.296%</td>
</tr>
<tr>
<td>3-3.5</td>
<td>1.569%</td>
<td>10.573%</td>
<td>8.799%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>20.941%</td>
</tr>
<tr>
<td>3.5-4</td>
<td>1.364%</td>
<td>11.187%</td>
<td>21.282%</td>
<td>7.299%</td>
<td>1.160%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>42.292%</td>
</tr>
<tr>
<td>4-4.5</td>
<td>1.432%</td>
<td>4.911%</td>
<td>4.843%</td>
<td>6.003%</td>
<td>4.570%</td>
<td>0.477%</td>
<td>0.205%</td>
<td>22.442%</td>
</tr>
<tr>
<td>4.5-5</td>
<td>0.955%</td>
<td>2.387%</td>
<td>3.070%</td>
<td>1.705%</td>
<td>0.136%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>8.254%</td>
</tr>
<tr>
<td>5-5.5</td>
<td>1.023%</td>
<td>2.865%</td>
<td>0.819%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>4.707%</td>
</tr>
<tr>
<td>5.5-6</td>
<td>0.000%</td>
<td>0.000%</td>
<td>0.688%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>0.000%</td>
<td>0.068%</td>
</tr>
<tr>
<td>Total</td>
<td>6.821%</td>
<td>32.538%</td>
<td>39.086%</td>
<td>15.007%</td>
<td>5.866%</td>
<td>0.477%</td>
<td>0.205%</td>
<td>100.000%</td>
</tr>
</tbody>
</table>

4.4.2. Map of Joint Distribution

To visually characterize the distribution of the data in Table 2, the joint distribution map of significant wave height and mean wave period is drawn using the data in Table 2 as shown in Figure 5.

Figure 5 indicates that during the field measurement, when the significant wave height of wave energy converters in the tested sea area in the joint distribution map is near 1.0 m, mean wave period 4.0 s, the data distribution probability of significant wave height and mean wave period is large, around 21.3%. The joint distribution data of significant wave height and mean wave period are located between 0.8-1.2 m and 3.5-4.5 s respectively. Figure 5 characterizes the joint distribution of significant wave height and mean wave period more intuitively.

5. Conclusion

Aimed at the analysis method of characteristics of wave resources in the field test of wave power generation devices, the analysis method of joint distribution on significant wave height and mean wave period, and the characteristics of wave resources of wave energy converters in the tested sea area are analyzed using the field measurement data.
The results show that during the field measurement, the distribution probability of the significant wave height in the interval of 0.8-0.9 m and the distribution probability of mean wave period in the interval of 3.6-3.8 s are 26.1% and 20.0% respectively for the tested area of the wave energy converters. The peak of the joint distribution probability of significant wave height and mean wave period occurs near the significant wave height of 1.0 m and the mean wave period of 4.0 s, with a value of 21.3%. The research results are of great reference significance for the design of optimal working conditions of wave power generation devices and the analysis of the distribution characteristics of wave energy flux resources in the tested sea area of the wave energy converters. In addition, with the progress of the field test and demonstration application of wave energy converters, the analysis method of the characteristics of wave energy resources will be bound to have a promising future.

References