Wave Characteristics in Northeast Coastal Waters of Zhoushan Island Under the Influence of Winter Monsoon

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Abstract. Waves at 12 m water depth in the northeast coastal waters of Zhoushan Island were measured from November 2014 to February 2015, and the characteristics were described. The study showed that the significant wave height varied from 0.08 to 1.35 m with the average of 0.36 m during the winter monsoon period, but the maximum of the maximum wave height is close to the maximum value of some typhoon waves of the same place. The monthly main wave direction varied from ENE to N to NE to ENE. Relatively high correlations exist between some wave parameters and relationships between them were identified. Most of the waves have a bimodal spectrum and the influence of monsoon on waves is intermittent.

1. Introduction
There are many islands around Zhoushan Island, and the underwater terrain is complex, so the wave characteristics of the water area near different Islands are different. The northeast coastal waters of Zhoushan Island locate at the northwest of the east China Sea. In this area, northerly wind prevails in winter, while southerly wind reigns in summer. The main subversive climates for coastal structures are strong gale of the cold wave in winter and spring as well as the typhoon in summer and autumn. Yang et al (2017)¹¹ studied the characteristics of typhoon winds and waves in the northeastern coastal waters of Zhoushan Island. They found that the height and direction of waves caused by typhoon vary greatly from deep water to shallow water, and the spectra are mainly bimodal. But the characteristics of the wave under the influence of the winter monsoon in the region are unclear.

Relevant studies at home and abroad are mainly focused on describing the annual and seasonal variations of wave characteristics in some specific sea areas. Some of studies are paid to correlation relationships among various wave parameters and their variations under the influence of monsoon. Indian specialist Kumar et al (Kumar et al 2011, Kumar et al 2012, Amrutha et al 2015, Amrutha and Kumar 2017)²⁻⁵ focused on wave characteristics off the coast of India by summer monsoon. Yang et al (2013)⁶ showed that most of wave spectra are single peaked in south coastal waters of Jiangsu
province under the influence of winter monsoon, and the main wave direction varied from WNW direction to ESE direction. Zhou et al (2020)[7] studied the wave characteristics in the nearshore waters of Sanmen bay, Zhejiang province. The results show that the dominant wave direction and the strong wave direction are both E due to the topography, and the sea waves are mixed waves consisting of swells and wind-seas.

This study puts emphasis on wave characteristics in northeast coastal waters of Zhoushan Island under the influence of winter monsoon, and the mathematical statistics, regression analysis and spectral analysis will be used in present study. The knowledge on characteristics of waves in Zhoushan Island coastal waters during the winter monsoon is required for design of coastal structures and prediction of waves using wave models.

![Location of wave measurement](image)

**Figure 1. Location of wave measurement (30.101°N, 122.293°E)**

### 2. Wave Data And Methods

#### 2.1. Wave Data and Wave Station

The data of wave surface in this paper were measured by the Acoustic Wave and Current profiler (AWAC) during November 2014 to February 2015, and were recorded every hour for 17 minutes duration at a frequency of 2 Hz. The measuring position locates in the Northeast coastal waters of Zhoushan Island, Zhejiang province, East China Sea (figure 1), where the average water depth is 12 m.

#### 2.2. Data Processing Methods

In this study, The collected time series (2853 records) were subjected to standard error checks for spikes, steepness and constant signals through the Storm processing software of AWAC (Pedersen et al 2002)[8]. Zero-up crossing method is adopted to count wave parameters from the measured wave records. For example: the significant wave height $H_{1/3}$, the mean wave period $T_{mean}$, and the maximum wave height $H_{max}$, etc. In the meantime, Fast Fourier Transform method (FFT) is used to calculate wave energy spectra by using wave surface data, and the obtained coarse spectra are smoothed within the frequency domain with 64 degrees of freedom. The high frequency cut off is 1 Hz with resolution ratio 0.01Hz. Some wave spectral parameters are calculated from the smooth wave spectra. For instance, the zero-order moment $m_0$, the mean wave period $T_{m01}$, the mean wave period $T_{m02}$, the maximum spectral energy $S_{max}$, the spectral width parameter $\varepsilon$, the spectral peak period $T_p$, the correlation coefficient $r$, etc (Holthuijsen 2007)[9]. Finally, regression analysis is applied to analyze variation relationships of various parameters.

### 3. Results and Discussion

#### 3.1. Variation of Wave Parameters

The mean value of the monthly wave parameters does not change obviously, but the maximum value of the wave parameters varies greatly. Among them, The maximum of the maximum wave height $H_{max}$
=2.25 m, appears at 1:00 on January 14th with NE direction, whose corresponding period $T_{\text{max}}$ is 5.0s, is higher than that of other months and close to some of the maximum value of typhoon waves (Yang et al 2017)\cite{1}. The significant wave height variation range from November, 2014 to February, 2015 is 0.08 m–1.35 m, and the mean value is 0.36 m (Table 1). The average value of the mean wave period is 3.2 s and the mean peak period is 5.5 s, which is greater than that of South Coastal Waters of Jiangsu (Yang et al 2014)\cite{10}. The variation range of peak period (1.6 s to 15.7 s) is larger than that of average wave period (1.8 s to 6.3 s). The spectral width ranges from 0.36 to 0.92 with the average spectral width is 0.72, which is also greater than that of South Coastal Waters of Jiangsu (Yang et al 2014)\cite{10}.

Table 1. Range and average value of wave parameters from November 2014 to February 2015.

| Wave Parameters      | November   | December  | January  | February | Total   |
|----------------------|------------|-----------|----------|----------|---------|
| Significant Wave     | 0.10–0.86  | 0.08–1.11 | 0.08–1.35| 0.09–1.03| 0.08–1.35|
| Height, $H_{1/3}$ (m)| 0.37       | 0.38      | 0.37     | 0.34     | 0.36    |
| Maximum Wave         | 0.18–1.57  | 0.12–1.94 | 0.13–2.25| 0.15–1.86| 0.12–2.25|
| Height, $H_{\text{max}}$ (m) | 0.63      | 0.65      | 0.62     | 0.58     | 0.62    |
|Mean Wave period, $T_{\text{mean}}$ (s) | 2.5–6.3 | 1.8–5.5 | 1.9–5.0 | 1.8–5.4 | 1.8–6.3 |
|Peak wave period, $T_p$ (s) | 3.5      | 3.1       | 3.1      | 2.9      | 3.2     |
|Spectral width parameter, $\varepsilon$ | 0.36–0.89 | 0.48–0.92 | 0.48–0.92 | 0.5–0.91 | 0.36–0.92 |
|Maximum spectral energy (m²/Hz) | 0.006–0.51 | 0.003–1.12 | 0.002–1.2 | 0.004–0.77 | 0.002–1.2 |

The waves in January, 2015 are influenced most by the monsoon among these months, whose occurrence probability of $H_{1/3} > 1$m is 1.3%, higher than that of other two months, and the same trend to the occurrence probability of 0.5 m $< H_{1/3} < 1.0$m during December and January period (Table 2). So, the occurrence probability of $H_{1/3} < 0.5$m during December and January is smaller than other two months.

Table 2. The occurrence probability of significant wave height in several levels from November 2014 to February 2015 (unit: %).

| Proportion | November | December | January | February | Total |
|------------|----------|----------|---------|----------|-------|
| 1< $H_{1/3}$<1.5 | 0.0      | 0.5      | 1.3     | 0.3      | 0.6   |
| 0.5 <= $H_{1/3}$<1 | 19.3     | 26.3     | 24.1    | 14.7     | 21.3  |
| 0<$H_{1/3}$<0.5 | 80.4     | 73.1     | 74.6    | 82.1     | 77.4  |

Table 3. Probability distribution of the wave direction of significant wave height from November 2014 to February 2015 (unit: %).

| Wave direction | N | NNE | NE | ENE | E | ESE | SE | SSE | S | SSW | SW | WSW | W | WNW | NW | NNW |
|----------------|---|-----|----|-----|---|-----|----|-----|---|-----|----|-----|---|-----|----|-----|
| November      | 2.9 | 10.4 | 18.9 | 41.3 | 21.3 | 3.5 | 0.6 | 0.0 | 0.1 | 0.1 | 0.0 | 0.1 | 0.3 | 0.0 | 0.0 | 0.3 |
| December      | 23.5 | 16.4 | 17.9 | 18.1 | 5.5 | 2.8 | 1.5 | 0.7 | 0.7 | 0.3 | 0.0 | 0.1 | 0.3 | 0.5 | 1.6 | 10.1 |
| January       | 8.7 | 17.5 | 28.8 | 27.6 | 10.8 | 2.3 | 1.2 | 0.4 | 0.1 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.7 | 1.3 |
| February      | 2.5 | 7.9 | 15.9 | 34.8 | 25.0 | 6.5 | 1.2 | 0.1 | 0.1 | 0.7 | 0.1 | 0.1 | 0.3 | 0.3 | 0.6 | 0.7 |
| Total         | 9.7 | 13.2 | 20.5 | 30.2 | 15.3 | 3.7 | 1.1 | 0.3 | 0.3 | 0.4 | 0.0 | 0.1 | 0.2 | 0.3 | 0.7 | 3.2 |
3.2. Wave height and Wave period

There exists a good correlation between significant wave height $H_{1/3}$ and maximum wave height $H_{max}$ (figure 2), with correlation coefficient 0.99. Theoretically, the value of $H_{max}/H_{1/3}$ is 1.53 (Longuet-Higins 1952)\[11\], and Goda (1974)\[12\] mentions in the design of vertical breakwaters that the ratio is 1.8. The statistics and analyses show that the ratio is 1.71 (range 1.28~3.09), which is higher than the ratio 1.65 of Jiangsu coastal wave under the influence of winter monsoon raised by Yang et al (2014)\[10\]. The significant wave height $H_{1/3}$ achieved by zero up-crossing method is 3.58 m (figure 3), and the theoretical definition of $H_{m0}$ is $4.0 \sqrt{m_0}$ raised by Rayleigh (Longuet-Higins 1952)\[11\]. In the shallow water areas, according to the calculation of Yang et al (2014)\[10\], the ratio is 3.75. In present study, $H_{1/10}/H_{1/3}=1.25$ is lower than 1.275 raised by Rayleigh. By comparison with theoretical value, the ratios of $H_{1/3}/\sqrt{m_0}$ and $H_{1/10}/H_{1/3}$ are lower, and the main reason is the shallow water effects. Besides, there is a high correlation between significant wave height $H_{1/3}$ and maximum energy spectral density ($r=0.96$), and the relation is $S_{max}=0.63H_{1/3}^{2.2}$ (figure 4) by analysis.

Statistical analysis shows that the waves of mean wave period in 2 s~ 4 s and significant wave height in 0.1 m~0.5 m account for the majority (68.3% of total), and the waves of $H_{1/3}$ higher than 1.0 m are around in 3 s~ 5 s, accounting for 0.55% of total. The frequency of 4 s and above waves is 8.2% total, and long wave period does not mean high waves.

There are good correlations among characteristic wave periods, and the correlation coefficients between $T_{1/3}$ and $T_{mean}$, $T_{1/10}$ are all more than 0.9 with the relations of $T_{1/3}=1.3T_{mean}$ (figure 5) and $T_{1/3}=0.9T_{1/10}$ respectively. The correlations between spectral peak period $T_p$ and $T_{mean}$ is also high ($r=0.92$), and the relation by fitting is $T_p=1.74T_{mean}$.

![Figure 2. Variation of $H_{max}$ (m) and $H_{1/3}$ (m).](image)

![Figure 3. Variation of $H_{1/3}$ (m) and $m_0^{1/2}$.](image)

![Figure 4. Variation of maximum energy spectral density $S_{max}$ (m$^2$/Hz) and $H_{1/3}$ (m).](image)

![Figure 5. Variation of $T_{1/3}$ (s) and $T_{mean}$ (s), $r$ in all figures stand for correlation coefficient.](image)
3.3. Wave Spectral Characteristic

Most of wave spectra during the measurement period were double peaked. From November 2014 to February 2015, the waves of a month with more total spectral energy mean stronger influence of monsoon, which is similar to wave characteristic reflected by monthly average significant wave height. Average maximum spectral density in every month also reflects this characteristic. The range of spectral peak frequency is $0.06 \, \text{Hz} \sim 0.63 \, \text{Hz}$ with average $0.18 \, \text{Hz}$ in these months (Table 1).

The calculation method proposed by Portilla et al. (2009)\cite{13} can be used to distinguish the wind and surge components in waves, that is, to determine whether the ratio between the measured spectral peak and the fully developed wind wave PM spectral peak (Pierson and Moskowitz 1964)\cite{14} at the corresponding frequency is greater than 1. If the ratio is greater than 1, it is wind waves, otherwise, it is swell waves. According to the calculation of the wave data in this paper, wind wave accounts for 32.6% and swell wave 67.4%.

The maximum wave process under the influence of the winter monsoon was analyzed. According to the research, most of the waves are unimodal in a period of time when they start to grow, and the maximum spectral peak gradually increases. After the 13th January 2015, most of the waves become bimodal, that is, the waves contain both wind wave and surge wave. The spectral energy of the low-frequency part (about $0.1 \, \text{Hz} \sim 0.15 \, \text{Hz}$) is larger, and the maximum spectral peak gradually decreases (figure 6). A similar pattern can be found in the wave height increase and decrease process from December 15 to 18, 2014, that is, during the period of wave height increase, most spectral peaks were in the form of unimodal pattern, and from 23 o’clock on December 16, most spectral peaks were in the form of bimodal pattern. However, the difference was that the spectral energy in the higher frequency region ($0.2 \, \text{Hz} \sim 0.4 \, \text{Hz}$) was larger (figure 7). Therefore, under the influence of winter monsoon, the water area of this measuring point is affected by both local wind waves and deep water swells. Moreover, the influence of monsoon on waves in this region is intermittent rather than continuous.

![Figure 6. Variation of Spectral Energy Density (m$^2$/Hz) with Frequency (Hz) and Date, from 12th to 16th January 2015.](image)

![Figure 7. Variation of Spectral Energy Density (m$^2$/Hz) with Frequency (Hz) and Date, from 15th to 18th December 2014.](image)

4. Conclusions

(1) The significant wave height caused by winter monsoon varies from 0.08 m to 1.35 m, with an average value of 0.36 m. The occurrence frequency of waves with $H_{1/3}$ higher than 1 m in January is larger than other three months, that is, the waves in January are influenced most by the winter monsoon.

(2) There is a big difference between percentage occurrences of 16 wave directions from November to February. The main wave direction is ENE direction with the highest percentage of 30.2%. The main wave direction varies from ENE in November to N in December to NE in January to ENE in February which shows that the waves are complex in this place.
(3) There are good relations among some characteristic wave heights, which are different from Rayleigh distribution, and there also exist good relations among some characteristic wave periods.

(4) 67.4% of the waves are dominated by swell waves, and most of the waves have a bimodal spectrum, which is composed of wind waves and swell waves. Moreover, the influence of monsoon on waves in this region is intermittent rather than continuous.

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