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THE USE OF EXTREME WAVE ANALYSIS FOR THE DESIGN OF OFFSHORE STRUCTURES

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Abstract – *The return values of wave data, e.g. 1, 25, 50 and 100 years, are the most important factors in the design of offshore structures. For offshore structures design the maximum wave height (Hmax) is determined for different return values based on long-term measurements or hindcast models. This paper presents the determination of Hmax with different return values for Port Said offshore area located on the northern coast of Egypt based on wave data measurements. The Long-Term analysis is carried out using the Peak-Over-Threshold (POT) method. The results of this study were compared with the results of the hindcast model conducted in the study area to design some offshore platforms located in this area. A comparison demonstrated that the values of Hmax based on the measured data of the study area were more accurate and relaxed than the Hmax values based on the hindcast model. This means that the use of the Hmax (based on the measured data) in the design of offshore platforms will raise the efficiency of existing platforms located in the study area and will also be more economical with new platforms. The results of the present study will be highly useful in improving the performance of offshore platforms located in the offshore area of the northern coast of Egypt.*

Key Words: Significant wave height, Maximum wave height, Peak-Over-Threshold, Extreme wave analysis, Return periods.

1. INTRODUCTION

The extreme wave analysis means how wave parameters can be extrapolate for much longer years than the data used. The return values of wave data (so-called return periods) are generally the dominant factor in the design of many offshore and/or nearshore structures such as fixed offshore platforms, ports, breakwaters, etc.

Offshore structures in deep water are often designed using the maximum wave height (Hmax). In order to determine the maximum wave height, the significant wave height (Hs) should first be determined based on the statistical methods of the wave data set. Then, the expected Hmax can be obtained for different return periods of Hs (e.g. 1-year and 100-years for offshore platforms [1]) using the following equation that follows the Rayleigh distribution [2]:

$$H_{max} = H_s \sqrt{0.5 \ln N} \qquad (1)$$

Where: N is the number of wave cycles (wave train) in the record. It may vary from 1000 to 5000 depending on the interval of record (e.g. 3 hours. 6 hours, 12 hours) and the average of wave period [2] [4].

Many researchers used several statistical methods to estimate the return periods of significant wave height by gathering all available data in a single sample using one of the probability distributions such as Log-Normal distribution, Gumbel distribution and Weibull distribution and then calculating the return periods using the fitted model. These researchers have described these methods in many literatures such as Ochi and Whalen (1980) [4], Smith (1984) [5], Goda (1992) [6], Van Valedder et al. (1994) [7], Coles (2001) [8], de Zea Bermudez & Kotz (2010) [9], Scarrott & MacDonald, (2012) [10], Julio Salcedo-Castro et al. (2018) [11].

Due to the difference in sea-state conditions from site to site, the knowledge of the characteristics of the local wave climate for a specific site is essential for successful estimation of wave return values. The investigation of wave return values will provide significant information for the design of offshore structures located in the study area

In this paper, hourly significant wave heights (Hs) and significant wave periods (Ts) were used to determine the return values of wave data for the study area. This paper is organized as follows: the next section introduces extreme wave analysis method used in this study. Section 3 describes the study area and data description. Section 4 presents the results and discussion. Finally, conclusions are reported in the last section.

2. METHODOLOGY

The theory of statistics requires that the individual data points used in any statistical analysis be statistically independent. Since wave height records depend on each other, they are not compatible to the theory of statistics. Therefore, to convert the recorded wave height data (e.g.

hourly wave height) from dependent values to independent values, we need to select some points as the independent points from the recorded data which is called storms.

The most commonly used method for finding these independent points "storms" is Peak-Over-Threshold analysis (POT). This method determines the minimum wave height, and all measurements above it are considered storms.

Many different distributions such as Log-Normal, Gumbel and Weibull were used to estimate the return periods of significant wave height. However, the Weibull distribution is preferred because it contains extra parameters and therefore it is more likely to produce a good fit to a straight line [2]. This conclusion is also reached by Mathiesen et al. (1994) [12].

2.1 Weibull Distribution

The three parameters Weibull distribution are given by:

$$P = 1 - \exp\left(-\left\{\frac{H-\gamma}{\beta}\right\}^{\alpha}\right) \qquad (2)$$

Where: α, β *and* γ are Weibull distribution parameters and H is the wave height. This equation can also be expressed using the probability of exceedance (Q) to be:

$$Q = \exp\left(-\left\{\frac{H-\gamma}{\beta}\right\}^{\alpha}\right) \qquad (3)$$

It is clear that both equations (2) and (3) give a nonlinear relationship in the form of the Cumulative Distribution Function (CDF) which is difficult to use in wave extrapolation. Since the most robust extrapolation relationship is a straight line, the CDF equations need to be transformed into a straight line to be as follows:

$$Y = AX + B \qquad (4)$$

Where:
Y: the transformed probability axis;
X: the transformed wave height axis;
A: the slope of the straight-line relationship;
B: the intercept of the straight-line relationship.

The coefficients A and B are determined by linear regression analysis. According to the above, the linear transformation of the equation (3) will be based on the logs of both sides:

$$\left(\ln\frac{1}{Q}\right)^{1/\alpha} = \frac{H-\gamma}{\beta} \qquad (5)$$

The parameters of the straight line in equation (4) will be as follows:

$$Y = \left(\ln\frac{1}{Q}\right)^{1/\alpha} = W;\ X = H;\ A = \frac{1}{\beta};\ B = -\frac{\gamma}{\beta} \qquad (6)$$

The two constant A and B can be estimated by using linear regression method, while the third parameter (α) will require some trail and errors. Therefore, the different values of α that control the curvature of the points will be assumed to get the best fit to a straight line (either by eye or by minimizing the residual variance or by maximizing the correlation coefficient A & B) [2].

2.2 Return Period

For Weibull distribution, the extrapolation of the wave height (H_{T_R}) for a specified return period (T_R) greater than the observed data can be calculated based on the following equation:

$$H_{T_R} = \gamma + \beta\,(\ln\{\lambda T_R\})^{1/\alpha} \qquad (7)$$

Where: λ is the number of occurrences for storms over Peak-Over-Threshold (POT) value per the number of years for records.

2.3 Peak-Over-Threshold

The POT method has been used in many applications to identify extreme events (such as wave heights, floods, wind velocities, etc.) to provide a model for independent exceedances over a high threshold. However, this method needs to specify a threshold that is neither too high (to get enough observations) nor too low (not to take into account non-extreme values).

There is no definite correct technique for choosing a sufficient threshold [13]. Many varied approaches of this task have been mentioned in literatures and are often subject to personal judgment. Therefore, Mean Residual Life plot (MRL) will be used in this study to aid picking the optimal threshold value.

The MRL plot is based on the determination of deviation from the mean of the population (i.e. measured data). Since the POT model deals with standard deviation (i.e. residual errors) from the mean data, the MRL plot can be used to determine a true threshold value. The MRL plot will subject to the following formula:

$$\sum_{i=1}^{n_u}(H_{s_i} - u)/n_u\ ;\ H_{s_i} > u \qquad (8)$$

Where: u is the Peak-Over-Threshold value, $n_u$is the total numbers of peaks over the threshold and H_{s_i} is an observation that exceeds the threshold.

The optimum threshold value is at the end of the linear portion (as a straight line) of the MRL plot.

3. STUDY AREA & DATA DESCRIPTION

Port Said is an Egyptian city extending about 30 kilometres along the coast of the Mediterranean Sea, north of the Suez Canal.

In this study, data of significant wave heights (H_s) and significant wave periods (T_s) used based on a 1-hour recording. Data were recorded every 1-hour for a period of 10-minutes (i.e. the 10-minutes record is representative of the 1-hour recording interval).

These data were provided by the Egyptian Navy, Meteorological and Oceanography Division to be used in the study area shown in Figure -1 (in the red dotted circle).

These data were from the beginning of January 2010 to the end of December 2012. The number of readings for these data are 26,280 for H_s and T_s.

Fig -1: The study area location (in red dotted circle) [14]

The analysis of wave data for Port Said region showed that about 85 % of significant wave height are less than or equal 1.60 m with corresponding significant wave period less than or equal 7 second. Furthermore, 55 % of wave's data for this region are dominantly coming from NW direction [15].

Figure -2 shows the wave rose for Port Said region for data used.

4. RESULTS & DISCUSSION

4.1 Optimum Threshold Value

It is recommended to use the Mean Residual Life plot against threshold to determine the optimal threshold value for data used [8]. Then, this optimal threshold value will be used in the extreme wave analysis to determine the significant wave height and significant wave period for different return periods.

The Mean Residual Life can be drawn by representing several values of the point $\left(X = u,\ Y = \sum_{i=1}^{n_u}(H_{s_i} - u)/n_u\right)$ as mentioned in equation (8).

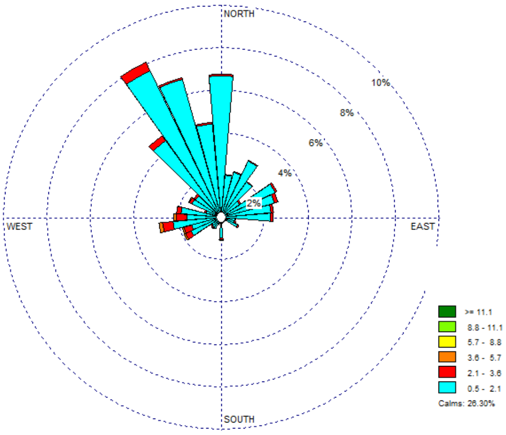

Fig. 2: Port Said wave rose for the data used

Figure -3 shows that the graph looks like a straight line until the threshold value equal to 2.0 m. Therefore, this value is considered as the optimum value of threshold (u).

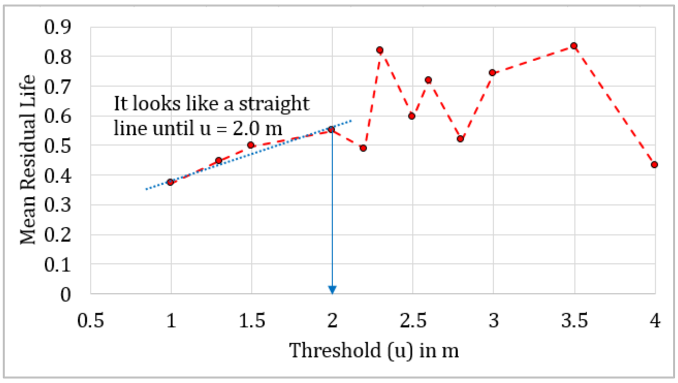

Fig -3: MRL against threshold values (u)

The results showed that 295 wave peaks exceeded the optimum threshold value (u = 2.0 m), which are reasonable to make inferences (i.e. extrapolations) without high variances in the results.

4.2 Extreme Wave Analysis

The joint distribution will be used to describe the relation between the wave heights and wave periods for data used in the study area as shown in Table -1.

This joint distribution can be simplified by determining the relationship between the values of significant wave height (Hs) and the values of significant wave period (Ts) using the following equation:

Table -1: Joint Distribution of Wave Heights and Wave Periods – Port Said

Wave Period (sec)	Significant Wave Height (m)									
	0.25-0.75	0.75-1.25	1.25-1.75	1.75-2.25	2.25-2.75	2.75-3.25	3.25-3.75	3.75-4.25	4.25-4.75	4.75-5.25
0.5- 1.5	0	0	0	0	0	0	0	0	0	0
1.5- 2.5	2639	0	0	0	0	0	0	0	0	0
2.5- 3.5	5626	0	0	0	0	0	0	0	0	0
3.5- 4.5	4734	0	0	0	0	0	0	0	0	0
4.5- 5.5	0	2045	0	0	0	0	0	0	0	0
5.5- 6.5	0	3505	0	0	0	0	0	0	0	0
6.5- 7.5	0	0	1764	0	0	0	0	0	0	0
7.5- 8.5	0	0	0	867	0	0	0	0	0	0
8.5- 9.5	0	0	0	0	284	0	0	0	0	0
9.5-10.5	0	0	0	0	75	131	0	0	0	0
10.5-11.5	0	0	0	0	0	24	0	0	0	0
11.5-12.5	0	0	0	0	0	0	38	12	0	0
12.5-13.5	0	0	0	0	0	0	0	25	0	0
13.5-14.5	0	0	0	0	0	0	0	0	15	16
Calm = 4521										

$$T_s = C_1 H_s^{C2} \quad (9)$$

The analysis of wave data revealed that the coefficients C1 and C2 mentioned in equation (9) are equal to 5.011 and 0.502 respectively (Figure -4).

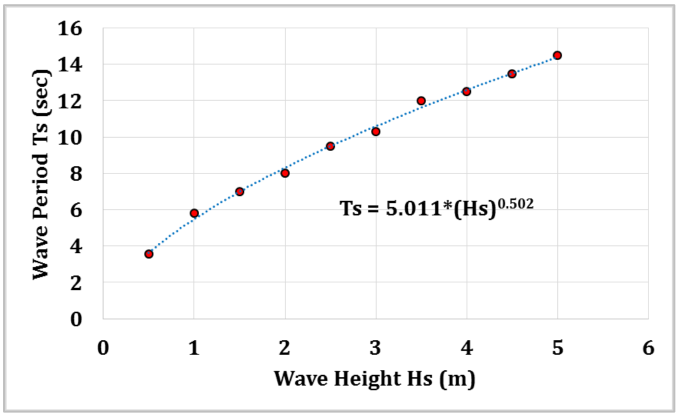

Fig -4: Wave Height-Wave Period relationship

The results showed that the parameters α, β and γ of Weibull distribution shown in equations (2) are equal to 1.05, 0.726 and 1.84 respectively.

Table -2 summarizes the output of the extreme wave analysis for Hs and Ts with different return periods in accordance with equations (7) and (9).

Table -2: Extreme wave analysis outputs with different return periods

Return Period	Wave Criteria	
	Hs (m)	Ts (sec)
1-year	4.90	11.0
10-years	6.40	12.7
100-years	7.90	14.0
10000-years	10.70	16.5

4.3 Maximum Wave Height (Hmax)

The expected values of Hmax related to the Hs values shown in Table -2 can be calculated based on determining the number of waves in the record (N) and the average of wave period ($\overline{T}$) of the peaks [2] [4].

Since the interval of wave records is 1-hour and the average of wave period ($\overline{T}$) equal to 10 sec, the number of waves (N) will be equal to 360 based on the following equation:

$$N = \frac{\text{Interval of wave record (in sec)}}{\text{Average of wave period (in sec)}} \quad (10)$$

According to equation (1) that follows the Rayleigh distribution, the relation between the expected Hmax and the Hs will be as follows:

$$H_{max} = H_s \sqrt{0.5 \ln 360} \qquad (11)$$

Or,

$$H_{max} = 1.71\, H_s \qquad (12)$$

Accordingly, the expected Hmax values using equation (12) and the values of wave periods associated with Hmax values using equation (9) are summarized in Table -3.

Table -3: Hmax and associated Tmax based on field measured data

Return Period	Wave Criteria	
	H_{max} (m)	T_{max} (sec)
1-year	8.30	12.0
10-years	10.90	14.0
100-years	13.50	15.5
10000-years	18.30	18.0

4.4 Existing Wave Criteria

In 2013, an extreme wave analysis was performed using a hindcast model for the study area (i.e. Port Said region) [16]. The design wave criteria were derived from the analysis of 20 years data based on hindcast model.

The number of data used in this study are 29,200 based on 6-hour interval. This data was calibrated and corrected based on the data of one of the old global buoys in the study area, as well as the database of multi-satellite altimeter.

The results of this analysis were used in the structural assessment for the West Akhen platform located on this area (Table -4).

4.5 Comparison between the Results of Field Measured Data and Hindcast Model

By investigating the wave data used in the study area, it was found that the number of data measured for a 3 years period based on 1-hour interval equal to 26280, while the number of data from hindcast model for a 20 years period based on 6-hour interval equal to 29200 (i.e. almost close to each other). This indicates that using measured data for a few years with small intervals (e.g. 1-hour) will give wave criteria more relaxed in their results than the hindcast data for long years with large intervals (e.g. 6-hours).

Table -4: Hmax and associated Tmax based on hindcast model [16]

Return Period	Wave Criteria	
	H_{max} (m)	T_{max} (sec)
1-year	9.50	11.0
10-years	13.2	12.4
100-years	17.00	13.2
10000-years	24.60	15.4

The comparison between the results of wave criteria based on measured data in Table -3 and the results based on hindcast model in Table -4 was made.

Figure -5 shows that the results based on the measured data are less than the results of the hindcast model since they are approximately 80% of their values, which gives an indication of the possibility of improvement in the design results for the offshore structures located in the study area.

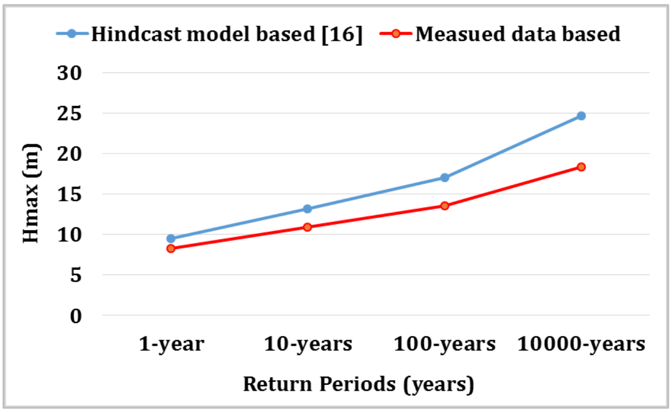

Fig -5: Comparison of wave criteria based on measured data versus hindcast model

5. CONCLUSIONS

This paper focuses on the extreme wave analysis due to its importance in the design of fixed offshore structures. Wave criteria based on measured data for 3 years with 1-hour interval were used to determine the maximum wave height (Hmax) and associated wave period (Tmax) with different return periods. These results were compared with the results from the hindcast model that was carried out in the study area using 20 years data with a 6-hours interval [16]. The conclusions based on this comparison were as follows:

- The results based on measured data (Table -3) are more accurate in their values than those based on hindcast data (Table -4), since they are about 20% less in their values.

- The use of wave data with short interval will improve the results of wave criteria, i.e. 1-hour interval is more accurate than 3-hours or 6-hours intervals.
- This study confirmed that the use of field measured data in calculating wave criteria will be more reliable than other data (e.g. hindcasted data or forecasted data) and thus improve the design of offshore structures as well as increase their ability to withstand additional loads in future.

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