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Ocean Wave Measurement and Wave Climate Prediction of Peninsular Malaysia

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Abstract: *This paper presents wave measurement and wave climate prediction within Peninsular Malaysia. Rayleigh and Weibull density functions were used to predict wave heights. The total wave energy density was found to be 17.69 MWh/m within an average year, whereas average wave power density varied from 0.15 to 6.49 kW/m. Furthermore, more than 60% of the annual wave energy was caused by wave heights between 0.2 to 1.2 m. Waves with peak periods between 2 and 8 s accounted for more than 70% of the total wave energy. The extreme significant wave heights were predicted, using Gumbel, Weibull and Generalised Pareto distributions, as having return periods of 10 to 200 years for the same locations. The extreme significant wave heights varied from 2.6 to 3.4 m for the aforementioned return periods. The results of the present study will contribute greatly to the design of ocean engineering projects.*

Keywords: Gumbel, Weibull and Generalised Pareto distributions, significant wave height, wave direction, wave period, wave energy density

Abstrak: *Kertas ini membincangkan mengenai pengukuran ombak dan jangkaan musim ombak di Semenanjung Malaysia. Fungsi-fungsi kepadatan Rayleigh dan Weibull digunakan untuk menjangka tinggi ombak. Jumlah kepadatan tenaga ombak secara purata tahunan adalah 17.69 MWh/m, manakala purata kepadatan kuasa ombak berubah daripada 0.15 kepada 6.49 kW/m. Seterusnya, Lebih daripada 60% tenaga ombak tahunan dihasilkan oleh tinggi ombak bererti di antara 0.2 hingga 1.2 m dan ombak dengan tempoh puncak diantara 2 hingga 8 s untuk menjelaskan lebih daripada 70% jumlah tenaga ombak. Tinggi ombak bererti ekstrem untuk tempoh ulangan 10 hingga 200 tahun bagi lokasi yang sama adalah di jangkakan dengan menggunakan taburan Gumbel, Weibull dan Pareto am. Tinggi ombak bererti ekstrem berubah daripada 2.6 kepada 3.4 m untuk tempoh ulangan di atas. Keputusan menunjukkan kajian ini sangat berguna untuk mengoptimumkan rekabentuk bagi projek-projek kejuruteraan lautan.*

Kata Kunci: Taburan Gumbel, Weibull dan Pareto am, tinggi ombak bererti, arah ombak, tempoh ombak, kepadatan tenaga ombak

NOMENCLATURE

H	=	wave height
H_s	=	significant wave height
H_{TR}	=	extreme wave height
N	=	total number of data points/number of samples
P	=	probability of non-exceedence
Q	=	probability of exceedence
T	=	sampling period in years
T_{mean}	=	mean wave period
T_R	=	return period in years
X	=	random variable
Y	=	peaks
A	=	scale parameter
B	=	shape parameter
C	=	location parameter
I	=	rank of data in descending order
k	=	number of exceedances rate per year
u	=	threshold value
λ	=	mean exceedance
θ_m	=	mean wave direction

1. INTRODUCTION

Ocean wave energy has the potential to contribute significant amount of renewable energy to the world's energy demands.[1] The viability of energy wave commercialisation is tremendous as it has been recognised to have the fastest growth rate compared to all other energy sources.[2–4] Environmentally, wave energy conversion appears to be at a relatively early stage. Most environmental impacts occur during the construction and installation phases, but once in operation, wave energy converters (WECs) release no greenhouse gases and are unlikely to affect coastal ecosystems.[5–6] Today, several technologies have been tested on a large scale and in real sea conditions,[7–9] with some nearing commercial stages. For WECs to be competitive, they must be adapted to the local wave climate. The more detailed the knowledge of the wave climate at a particular site, the easier it is for designers of wave energy systems to optimise the technology and make it competitive. Wave energy production is closely related to the wave climate in the intended region.

A wave energy research and development program was established by the International Energy Agency in 1978. The program was led by a consortium of countries, including Ireland, Japan, Norway, Sweden, the United Kingdom and the United States.[10] In the last few decades, various locations have been investigated for their potential to provide wave power for energy conversion.

Previous studies on wave power potential have been undertaken in the UK,[8] Denmark,[11] Belgium,[12] Portugal,[13] Baltic Sea,[14] United States,[15] India,[16] Argentina,[17] Brazil,[18] New Zealand, Ireland, Japan, Chile, Korea, Norway,[19] Australia,[20] China,[21] Spain,[22] Canada[23] and Sweden.[24] Omar and Norazimar[25] reported on preliminary work developing a Malaysian ocean wave database using satellite wave data. Although wave energy potential has been reported for several countries around the world, reliable and year-long wave data are still needed for Malaysia. This study therefore addresses these needs.

The wave climate of the South China Sea by the Peninsular Malaysia is relatively harsh compared to other coasts in Malaysia. From a standpoint of safety and economy, it is important to understand the environmental conditions such as wave height, wind speed and current speed, that would affect the design of ocean-deployed structures, such as seawater intake structures, breakwaters, port and harbour structures, shore protection structures, submarine pipelines, open sea loading and unloading terminals, oil terminals, and offshore platforms. A deficiency in information about the environmental conditions affecting structure design will result in either an unsafe structure or an overly-designed and uneconomical structure. Hence, it is essential to predict the design wave heights for different return periods. Since there has been no systematic extreme wave height predictions completed for the South China Sea near Peninsular Malaysia, this research attempts to address this gap. The present study also describes the specific wave climates in the South China Sea near Peninsular Malaysia.

A number of previous studies have attempted to predict the extreme values for waves and winds. Gumble[26] is the first to develop a statistical method for predicting the extreme values of natural random events like wind speed. His method involves using the recorded annual maximum wind speed for as many years as possible. Gumbel's extreme value distribution is widely used by the wind engineering community around the world because of its simplicity. St. Denis[27] discussed the Gumbel distribution in the context of predicting extreme wave height. Information related to the collection of data samples for analysis can be found in the literature.[28] The procedure for predicting extreme wave heights and consequent analysis has been discussed in detail. Coles[29] has provided the statistical details of extreme value prediction based on annual maximum data points and the peak over threshold (POT) method. Additional information on POT and its application is provided.[30] In the present study, this information is used to carry out a detailed extreme value analysis of the study area.

2. MATERIALS AND METHODS

The study area is contained within the latitudes of 3.5^o N and 6.5^o N and longitudes 102.0^o E and 104.0^o E. The investigation was based on one and two-hour data samples collected at wave measurement points from January 1998 to August 2009. The datasets used for the analysis of wave energy potential were acquired from the Department of Maritime Technology, University Malaysia Terengganu (UMT) and the Malaysian Meteorology Department (MMD), which are available in one and two-hour frequencies (sampling interval). The acoustic wave and current (AWAC) instruments belonging to the UMT were deployed for continued measurement at 20 m water depth 5 km from shore from June 2008 to August 2009.

The instruments were checked and calibrated to ensure the quality of the data collected. Missing and invalid measurements (accounting for approximately 0.8% of the data) were identified within the database and were interpolated using the values of preceding or subsequent hours of the day. To give a better perspective on the representative wave conditions in the coastal area of east Peninsular Malaysia, a medium term analysis based on in situ measurements is presented.

3. MATHEMATICAL MODELLING

3.1 Wave Height

Longuet-Higgins[31] had shown that, based on certain basic assumptions, the probability density function of wave heights can be represented by a typical Rayleigh density function as follows:

$$f(H) = \frac{2H}{a^2}.\exp-\left(\frac{H}{a}\right)^2 \tag{1}$$

where a-scale parameter, H-wave height, $a, H > 0$.

However, the basic assumptions of Longuet-Higgins may not be met in all sea wave states. Hence, we require a model that can accommodate a Rayleigh distribution and fit data under more general conditions. This requirement should be satisfied by the Weibull probability density function[5] (Equation 2).

$$f(H) = \frac{b}{a}\left(\frac{H}{a}\right)^{b-1}.\exp-\left(\frac{H}{a}\right)^b \tag{2}$$

where a-scale parameter, b-shape parameter, a, b, H > 0. The method of maximum likelihood estimate is applied to estimate the Weibull model parameters a and b.

3.2 Extreme Wave Height

The Gumbel, Weibull and Generalised Pareto distributions are generally used for the extreme value prediction.[32] The selection of input data is more important to predict extreme wave conditions. Individual data points used in the analysis of long-term wave predictions must be statistically independent. However, each hourly wave height depends on the wave height of the previous hour, and consequently, the theoretical condition of statistical independence is not met. Therefore, to produce independent data points, only storm events can be considered. The commonly used method to separate wave heights into storms is called Peaks-Over-Threshold (POT) analysis. A threshold wave height of 1.24 m was selected for the present analysis based on IEC 61400-1, Third Edition.[33]

3.3 Gumbel and Weibull Distribution

The Gumbel distribution is given as:

$$P = \exp[-\exp\{-(H-c)/a\}] \tag{3}$$

where P is the probability of non-exceedence (probability of exceedence, $Q = 1 - P$), a the scale parameter and c the location parameter.

The Weibull distribution is a three-parameter distribution and is given as:

$$P = 1 - \exp[-\{(H-c)/a\}^{b}] \tag{4}$$

where b is the shape parameter.

The Q of Gumbel and Weibull distribution can be calculated using the formula

$$Q = (i - d_1)/(N + d_2) \tag{5}$$

where i is the rank of data in descending order, N is the total number of data points, d_1 = 0.44 and d_2 = 0.12 for Gumbel distribution and d_1 = 0.20 + (0.27/b) and d_2 = 0.20 + (0.23/b) for Weibull distribution.[32] The value of b varies from 0.7 to 2.1 with an increment of 0.05. The one which gives best fit for the data set was selected.

3.4 Generalised Pareto distribution

Let X_1, X_2,..., X_n be a series of independent random observations of a random variable X with the distribution function (DF) $F(x)$. To model the upper tail of $F(x)$, consider k exceedances of X over a threshold u, and let Y_1, Y_2,..., Y_k denote the peaks, i.e., $Y_i = (X_I - u)$. Pickands[34] showed that in an asymptotic sense, the conditional distribution of peaks, i.e., $P[(X_i - u)| X_i > u]$, follows the Generalised Pareto Distribution (GPD):

$$G(y) = 1 - \left(1 + \frac{b(y-c)}{a}\right)^{-1/b} \tag{6}$$

where a, b and c denote the scale, shape and location parameters, respectively. Generally, the location parameter is taken as zero. The distribution has an unbounded upper tail, i.e., $0 < y < \infty$ if $b \geq 0$ and bounded as $0 < y < a/b$ if $b < 0$. The exponential DF is a special case of equation 5 when c = 0. It can also be shown that the distribution of maximum peaks, i.e., $W = \max(Y_1, Y_2,..., Y_k)$, follows the generalised extreme value (GEV) distribution with the same shape parameter as that of Y.[35]

A quantile value, H_{TR}, corresponding to a T_R-year return period is calculated from the quantile of peaks corresponding to a return period of λT_R, where λ is the mean exceedance (or crossing) rate per year. If N denotes the number of samples collected over T years and k is the number of exceedances, then $\lambda = k/T$. Thus,

$$H_{TR} = G^{-1}\left(1 - \frac{1}{\lambda T_R}\right) + u \tag{7}$$

where $G^{-1}(\ )$ denotes the Pareto quantile function (QF).

De Haan[36] proposed estimating the GPD scale and shape parameters using the order statistics of exceedances, $\{X_{n-k,n},..., X_{n,n}\}$, where $X_{n-k,n}$ is the smallest data point to exceed a given threshold. Based on an extensive mathematical analysis, the shape parameter b is derived as:

$$b = M_n^1 + 1 - \frac{1}{2}\left(1 - \frac{(M_n^1)^2}{M_n^2}\right)^{-1} \tag{8}$$

In terms of moments of excesses obtained from the log-transformed data:

$$M_n^r = \frac{1}{k}\sum_{i-1}^{k}\left[\ln(X_{n-i+1,n}) - \ln(X_{n-k,n})\right]^r, \quad r = 1 \text{ or } 2. \tag{9}$$

The scale parameter a can be obtained as:

$$a = u\frac{M_n^1}{\rho} \tag{10}$$

where $\rho = 1$ if $c \geq 0$, and $\rho = 1/(1-c)$ if $c < 0$.

Finally, a required quantile value can be estimated as:

$$H_{TR} = -\frac{a}{b}\left[1-(\lambda T_R)^b\right] + u \tag{11}$$

4. RESULTS AND DISCUSSION

4.1 Wave Climates

The wave climate of the South China Sea by the Peninsular Malaysia was analysed for the period 1998 to 2009. The wave height time series data on 7 January 2009 at sample location latitude 5° 35.0' N and longitude 102° 55.5' E is shown in Figure 1.

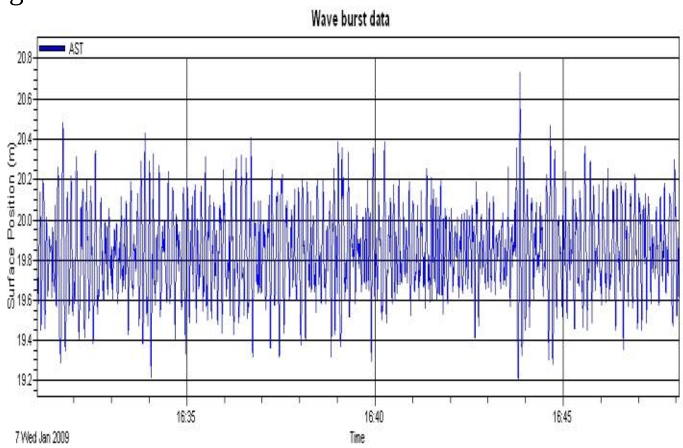

Figure 1: Wave heights time series data on 7 January 2009 at latitude 5° 35.0' N and longitude 102° 55.5' E.

Non-directional spectra reported by the instrument were analysed and are shown in Figure 2 for the same date and location. The result shows, on average, significantly more energy between the 0.1 to 0.3 Hz wave frequencies.

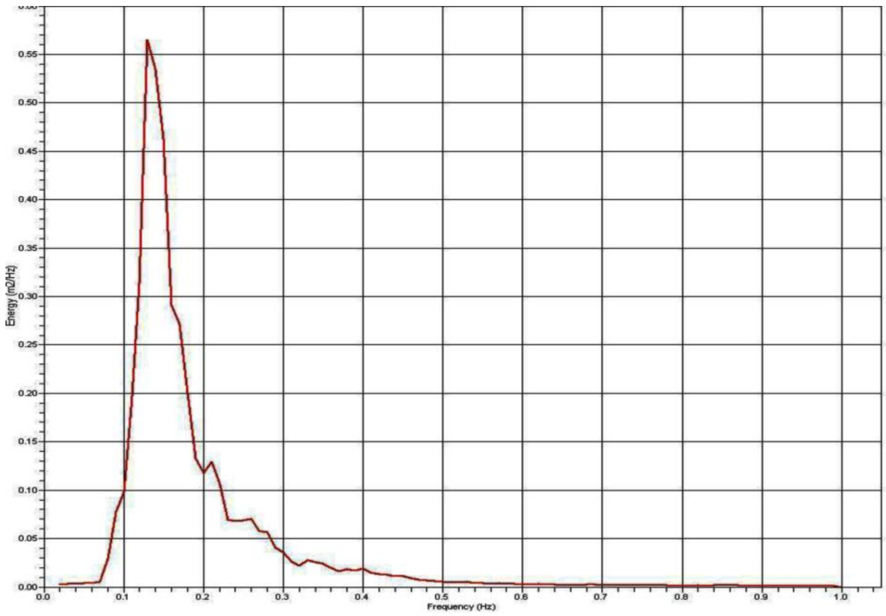

Figure 2: Non-directional energy spectrum reported by AWAC at latitude 5° 35.0’ N and longitude 102° 55.5’ E.

Figure 3 shows directional spectra reported by AWAC measurement systems on 7 January 2009 for the study area. Figure 3 indicates that significantly more energy is contained in north-westerly waves with frequencies of 0.1 to 0.2 Hz.

Wave height and wave periods are independent parameters. However, as wave height increases, it is likely that wave period will also increase. The joint probability of significant wave height and wave mean period is used to predict wave energy potentials. The results for the location of latitude 5° 35.0’ N and longitude 102° 55.5’ E are shown in Table 1.

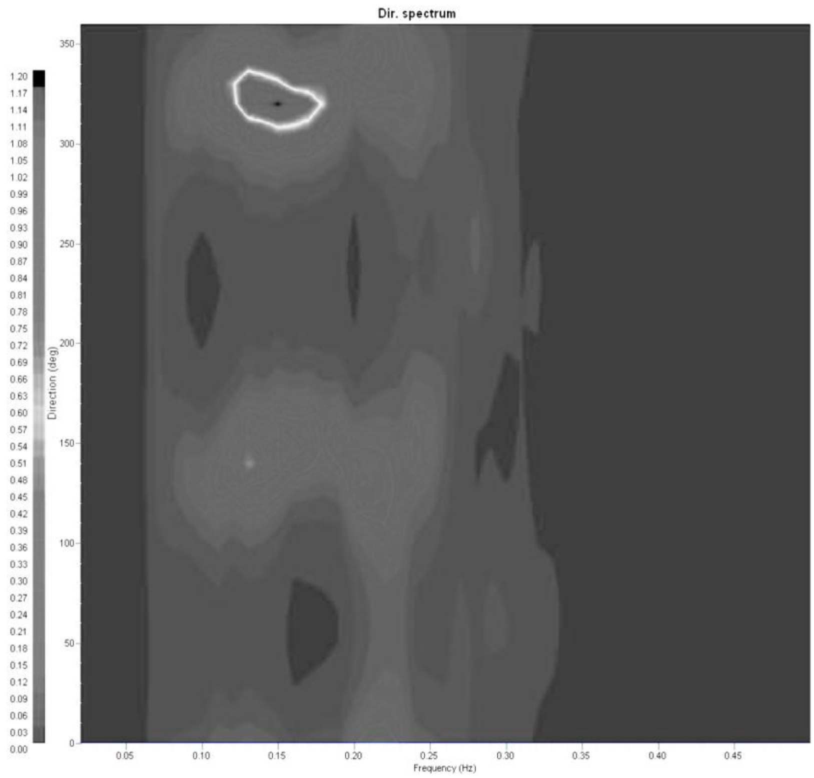

Figure 3: Directional spectra derived by AWAC measurement systems on 7 January 2009; 0, 90, 180 and 270° represent the N, E, S and W, respectively.

Table 1: Joint distribution of significant wave height and mean wave period for the same location (% of total time in an average year).

	Mean time, T_{mean} (s)							
H_s (m)	< = 2	2–4	4–6	6–8	8–10	10–12	12–14	> 14
< = 0.2	0.53	11.01	0.09	0.00	0.00	0.00	0.00	0.00
0.2–0.4	0.37	32.58	1.96	0.00	0.00	0.00	0.00	0.00
0.4–0.6	0.00	10.57	4.70	0.00	0.00	0.00	0.00	0.00
0.6–0.8	0.00	1.76	8.68	0.11	0.00	0.00	0.00	0.00
0.8–1.0	0.00	0.78	7.69	0.18	0.00	0.00	0.00	0.00
1.0–1.2	0.00	0.37	4.52	0.41	0.00	0.00	0.00	0.00
1.2–1.4	0.00	0.00	5.66	0.43	0.00	0.00	0.00	0.00
1.4–1.6	0.00	0.00	3.24	0.23	0.00	0.00	0.00	0.00
1.6–1.8	0.00	0.00	2.63	0.23	0.00	0.00	0.00	0.00
1.8–2.0	0.00	0.00	0.98	0.00	0.00	0.00	0.00	0.00
> 2.0	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00

Furthermore, extreme wave heights vary from 1.13 m to 3.13 m, and monthly mean significant wave height varies from 0.27 m to 1.24 m. In addition, the monthly mean significant wave height is lower in the middle of the year than at the beginning or end of the year.

A similar analysis was carried out combining mean wave direction (θ_m) and significant wave height. Eight sectors were considered for the mean wave direction (N, NE, E, SE, S, SW, W and NW). With the same significant wave height intervals as Table 1, 88 combined intervals of the H_s, θ_m distribution were considered. The sea states from 1998 to 2009 were ascribed to these intervals. The corresponding time percentages computed for the same location are given in Table 2. Waves with a northerly direction account for more than 40% of wave energy, followed by NE, SW and S waves. Additionally, its high wave energy potential was observed during the northeast monsoon season. The directions producing the most wave energy are N and NE, accounting for more than 80% of the total wave energy, which may be used as a reference for this area.

Table 2: Percentage of total time in an average year of sea states in different ranges of θ_m and H_s.

H_s (m)	N	NE	E	SE	S	SW	W	NW	Total (%)
< = 0.2	2.17	2.51	1.21	1.26	1.07	0.94	1.05	1.42	11.62
0.2–0.4	6.71	5.59	4.16	1.85	4.27	5.32	4.47	2.53	34.91
0.4–0.6	5.84	1.83	1.58	0.25	1.21	1.60	1.62	1.35	15.27
0.6–0.8	6.53	0.68	0.32	0.05	1.39	0.71	0.25	0.62	10.55
0.8–1.0	6.99	0.75	0.09	0.00	0.14	0.14	0.21	0.34	8.65
1.0–1.2	3.65	0.94	0.00	0.00	0.05	0.09	0.11	0.46	5.30
1.2–1.4	3.79	1.92	0.14	0.00	0.00	0.00	0.02	0.23	6.10
1.4–1.6	2.17	1.14	0.00	0.00	0.00	0.00	0.00	0.16	3.47
1.6–1.8	1.85	0.98	0.00	0.00	0.00	0.00	0.00	0.02	2.85
1.8–2.0	0.71	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.98
> 2.0	0.16	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.30
Total (%)	40.57	16.76	7.49	3.40	8.13	8.79	7.74	7.12	100.00

For the characterisation and computation of wave energy levels, the wave spectra are assumed to be the same during the sampling interval of two hours. The wave energy in the sea states of each of the combined H_s, T_p intervals in the 1998 to 2009 period was calculated and referred to a one-year period to obtain the value within an average year. The total annual wave energy was obtained as the sum of all intervals. More than 60% of the annual wave energy was provided by mid-height waves, with significant wave heights between 0.2 m and 1.2 m (Table 3). Waves with peak periods between 2 and 8 s accounted for more than 70% of the total wave energy.

Table 3: Percentage of total time in an average year corresponding to sea states with different H_s and P.

	Wave power (kW/m)							
H_s (m)	< = 2.5	2.5–5	5–7.5	7.5–10	10–12. 5	12.5–15	15–17.5	> 17.5
< = 0.2	11.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2–0.4	34.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.4–0.6	15.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6–0.8	10.53	0.02	0.00	0.00	0.00	0.00	0.00	0.00
0.8–1.0	3.72	4.93	0.00	0.00	0.00	0.00	0.00	0.00
1.0–1.2	0.05	4.25	1.00	0.00	0.00	0.00	0.00	0.00
1.2–1.4	0.00	0.68	3.33	2.08	0.00	0.00	0.00	0.00
1.4–1.6	0.00	0.00	0.66	2.01	0.80	0.00	0.00	0.00
1.6–1.8	0.00	0.00	0.00	1.03	0.84	0.75	0.23	0.00
1.8–2.0	0.00	0.00	0.00	0.00	0.14	0.30	0.41	0.14
> 2.0	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.16

The studies reveal that the annual average wave energy is 17.69 MWh/m and the average wave power is 4.04 kW/m. Based on available wave power, the averaged energy values for the South China Sea near Peninsular Malaysia are H_s = 1.22 m and T_p = 5.87 s. Monthly average wave power varies from 0.15 kW/m to 6.49 kW/m. Hence, monthly wave power is not much different in the South China Sea by the Peninsular Malaysia. In addition, the monthly mean wave power is lower in the middle of the year than at the beginning or end of the year.

The intensity of the wave energy fluctuates seasonally, with the highest energy density occurring during the northeast monsoon season when there are more storms and higher winds. Lower energy densities occur during the southwest monsoon season. The wave climate of the South China Sea near Peninsular Malaysia can be divided into three seasons: November to January, February to April and May to October, the last of which represents the calm season for the South China Sea near Peninsular Malaysia.

4.2 Wave Height Prediction

The Rayleigh and Weibull model parameters were computed using equations 1 and 2, respectively, for the long-term and monthly distributions of significant wave heights obtained from the study area. The mean significant wave heights were estimated for each month for the same location by using the Rayleigh and Weibull models. The data are compared with computed mean values. The Rayleigh expression underestimates, and the Weibull expression is more prominent and almost equal to computed values throughout the year (Figure

4). The Weibull scale parameter (0.69) and the shape parameter (1.49) are the average values for the entire year and can be utilised for significant wave height modelling for this study area.

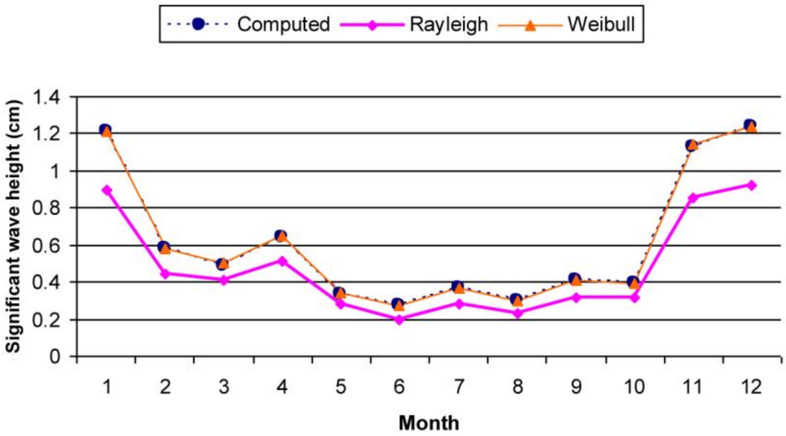

Figure 4: Monthly mean significant wave heights, compared and predicted by Rayleigh and Weibull functions.

4.3 Extreme Wave Prediction

The monthly extreme wave height recorded at the study area in this study period of 12 years is in the range of 1.50 to 3.00 m. These values are in agreement with the wave height (2.62 to 2.88 m) predicted using equations 3, 4 and 11 by the Gumble, Weibull and Generalised Pareto distributions, respectively, for a 10-year return period. The extreme significant wave heights were predicted for the chosen return periods of 10, 25, 50, 100 and 200 years and vary from 2.62 to 3.39 m (Figure 5). Extreme wave heights are an important ocean feature and should be taken into consideration when designing marine structures for the study area.

The coefficient of regression correlation was calculated using MATLAB tool box. The coefficient of regression of the Weibull distribution for the best line fit is better than the corresponding Gumbel distribution fit. The return extreme values which were estimated using the Generalised Pareto distribution are up to 10% higher than the prediction of Weibull distribution. The predicted values of the Weibull and Generalised Pareto distributions are similar. Hence, it is recommended that future research use Weibull and/or Generalised Pareto distributions for extreme wave height prediction in the South China Sea by the Peninsular Malaysia.

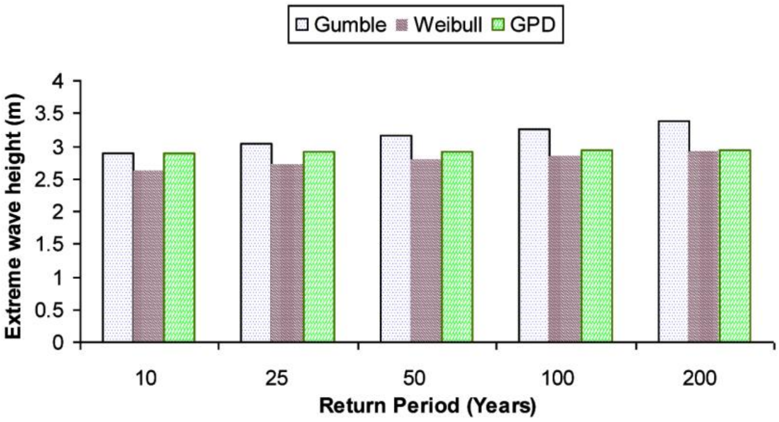

Figure 5: Extreme wave height predicted by Gumble, Weibull and Generalised Pareto distributions.

5. CONCLUSION

The wave climate of the South China Sea near Peninsular Malaysia has been studied. These results are based on 12 years of wave data from a study area contained within latitudes of 3.5° N and 6.5° N and longitudes of 102° E and 104.0° E. The total wave energy over an average year was 17.69 MWh/m, whereas the average monthly wave power varied from 0.15 to 6.49 kW/m. Furthermore, more than 60% of the annual wave energy was provided by significant wave heights between 0.2 to 1.2 m. Waves with peak periods between 2 to 8 s accounted for more than 70% of the total wave energy. Waves with a northerly direction accounted for more than 40% of the total wave energy, and 80% of the total wave energy was represented by waves originating in the N and NE. High wave energy potential was observed during northeast monsoon season. The Rayleigh and Weibull density functions were used to model the wave heights.

The Gumbel, Weibull and Generalised Pareto distributions were used to obtain significant wave heights in the study area. For this study, a threshold wave height of 1.24 m was selected based on previous studies. Statistical 10, 25, 50, 100 and 200 year waves have been estimated to range from 2.62 to 3.39 m. It is recommended that future studies use Weibull and/or Generalised Pareto distribution for extreme wave height prediction in the South China Sea near Peninsular Malaysia.

6. ACKNOWLEDGEMENTS

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