Journal of Coastal Research	SI 50	322 - 328	ICS2007 (Proceedings)	Australia	ISSN 0749.0208

Extreme Waves in the Arabian Gulf

S. Neelamani, K. Al-Salem and K. Rakha

Coastal and Air Pollution Department
Environment and Urban Development Division
Kuwait Institute for Scientific Research
P.O. Box : 24885
13109 Safat, KUWAIT.
nsubram@kisr.edu.kw

ABSTRACT

NEELAMANI, S.; AL-SALEM, K. and RAKHA, K., 2007. Extreme waves in the Arabian Gulf. Journal of Coastal Research, SI 50 (Proceedings of the 9th International Coastal Symposium), 322 – 328. Gold Coast, Australia, ISSN 0749.0208

The extreme significant wave heights were predicted for return periods of 12, 25, 50, 100 and 200 years for 38 different locations in the territorial and offshore locations of various countries in the Arabian Gulf (Kuwait, Saudi Arabia, Bahrain, Qatar, UAE and Iran). The input wave data for the work was obtained by hindcasting of waves, using a WAM model. Wave data was hindcasted for a total period of 12 years, starting from 1st Jan, 1993 to 31st Dec, 2004. The peak over threshold method, with 1.0 m as threshold value was used for selecting the data for the extreme wave analysis. In general, Weibull distribution is found to fit the data well compared to the Gumbel distribution for all these locations. It is found that the significant wave heights for 100 year return period varies from 3.0 to 4.5 for water depths of 9 to 16 m, whereas in the offshore sites it is found to vary from 5.0 to 7.0 m, where the water depth varies from 30 to 60 m. A large number of coastal projects are in progress in the Arabian Gulf and many new projects are being planned in this region for the future. The results presented in this paper will be useful for optimal design of the ocean structures in the Arabian Gulf region.

ADDITIONAL INDEX WORDS: *Gumbel and Weibull distribution, significant wave height, mean wave period, hindcasted wave data*

INTRODUCTION

Establishing the extreme wave heights for different return periods for different types of marine structures is very essential for their safe and economic design. A lack of this information will result either in an unsafe or an over designed (and hence uneconomical) structure. For example the weight of armour unit of a breakwater depends on the design significant wave height to the power of 3. Hence, selection of 2 m or 3 m significant wave height results in an armour unit weight ratio of 8:27. Hence, it is essential to correctly predict the design wave heights for different return periods. In the Arabian Gulf waters, as on today, most of the coastal structures appear to be over designed, since there is no systematic work carried out as on date on extreme wave heights for different return periods.

The Arabian Gulf, a marginal sea in a typical arid zone, is an arm of the Indian Ocean. It lies between the latitude of 24° -30° N. The gulf covers an area of 226,000 km^2. It is 990 km long and its width ranges from 56 to 338 km. It has a total volume of 7000 to 8400 km^3 of seawater (EL-GINDY and HEGAZI (1996)). The entire basin lies upon the continental shelf. The average water depth of the Arabian Gulf is about 35.0 m. However, water depth of more than 107 m is available in some places in the south-eastern part of the Arabian Gulf. The Gulf's water depth increases in the south east direction. It is connected to the Gulf of Oman and the Arabian Sea through the Strait of Hormuz, which is 56 km wide with an average water depth of 107 m and allows water exchange between the Arabian Gulf and Arabian Sea. Further details of the Oceanographic Atlas of Arabian Gulf can be obtained from AL-YAMANI *et al* (2004). In the Arabian Gulf, in general the dominant wind direction is north-westerly (ELSHORBAGY *et al.* (2006). Arabian Gulf is one of the very active marine areas on the earth. Most of the oil produced in the Gulf countries is transported through the Arabian Gulf waters. It is also a strategically important area. Most of the countries around the Arabian Gulf rely on the seawater for desalination and for cooling purposes in power plants. A large number of coastal and offshore project activities are in progress/being planned in the Arabian Gulf waters; Viz manmade coastal developmental projects such as palm and world shaped water fronts in Dubai, Durrat Al-Bahrain - a jewellery shaped water front development in Bahrain and similar projects in Qatar, ultra modern ports in Kuwait, a number of submarine pipeline and offshore oil and gas platforms, projects for development of tourism industries etc. Design of all these varieties of marine structures requires estimates of wave height for different return periods. An attempt is made in the present paper to report the extreme waves in the Arabian Gulf waters for different return periods. CAIRES and STERL (2005) have estimated the 100 year return value for significant wave height from the ERA-40 data for the whole oceans of the earth. The wind data used in this study is obtained from grid of 1.5° x 1.5°. Unfortunately this coarse grid cannot provide much information for the countries surrounding the Arabian Gulf, since the width of the Arabian Gulf itself is of the order of 1.5° only. Hence we have purchased wind data for finer grid size of 0 5° x 0 5° and the wind speeds are linearly interpolated for grid size of 0.1° x 0.1° for running the WAM model for hindcasting the significant wave height and for further extreme analysis of waves.

LITERATURE REVIEW

There are a large number of works done by many scientists around the world on extreme value prediction of winds and waves. GUMBEL (1958) was the first who had developed a statistical method for predicting the extreme values of natural random events like wind speed. Recorded annual maximum wind speed for as many years as possible, was the input for this method. Gumbel's extreme value distribution is widely used by the wind engineering community around the world, since the method is simple and robust. Information related to the collection of data samples for extreme value analysis can be found from NOLTE (1973), CARDONE *et al* (1976), PETRAUSKAS and AAGAARD (1971) and JAHNS and WHEELER (1973). Details regarding the plotting formula used for the extreme wave predictions are available in PETRAUSKAS and AAGAARD (1971). The procedure to extreme wave height predictions are explained in SARPKAYA and ISAACSON (1981) and in KAMPHUIS (2000).

Extreme value analysis for waves is discussed in detail in MATHIESEN *et al*. (1994), GODA *et al*. (1993) and GODA (1992). COLES (2001) has provided the statistical details of extreme value prediction based on the annual maximum data points and Peak Over Threshold (POT) method. Additional information on POT and its application is provided in FERREIRA and GUEDES SOARES (1998) and LEADBETTER (1991). All these literatures provide the information and knowledge for carrying out a detailed extreme value analysis and are used for the present work.

INPUT DATA GENERATION

For the present work, the wave data was hindcasted using WAM model for a total period of 12 years, starting from 1st Jan, 1993 to 31st December, 2004. The output from the WAM model is the significant wave height and the mean wave period for every one hour. The data was hindcasted for the whole Arabian Gulf waters with a grid size of 0.1° x 0.1°. The model was validated using measured data as provided in AL-SALEM et al. (2005). The extreme wave analysis is carried out for a total of 38 different

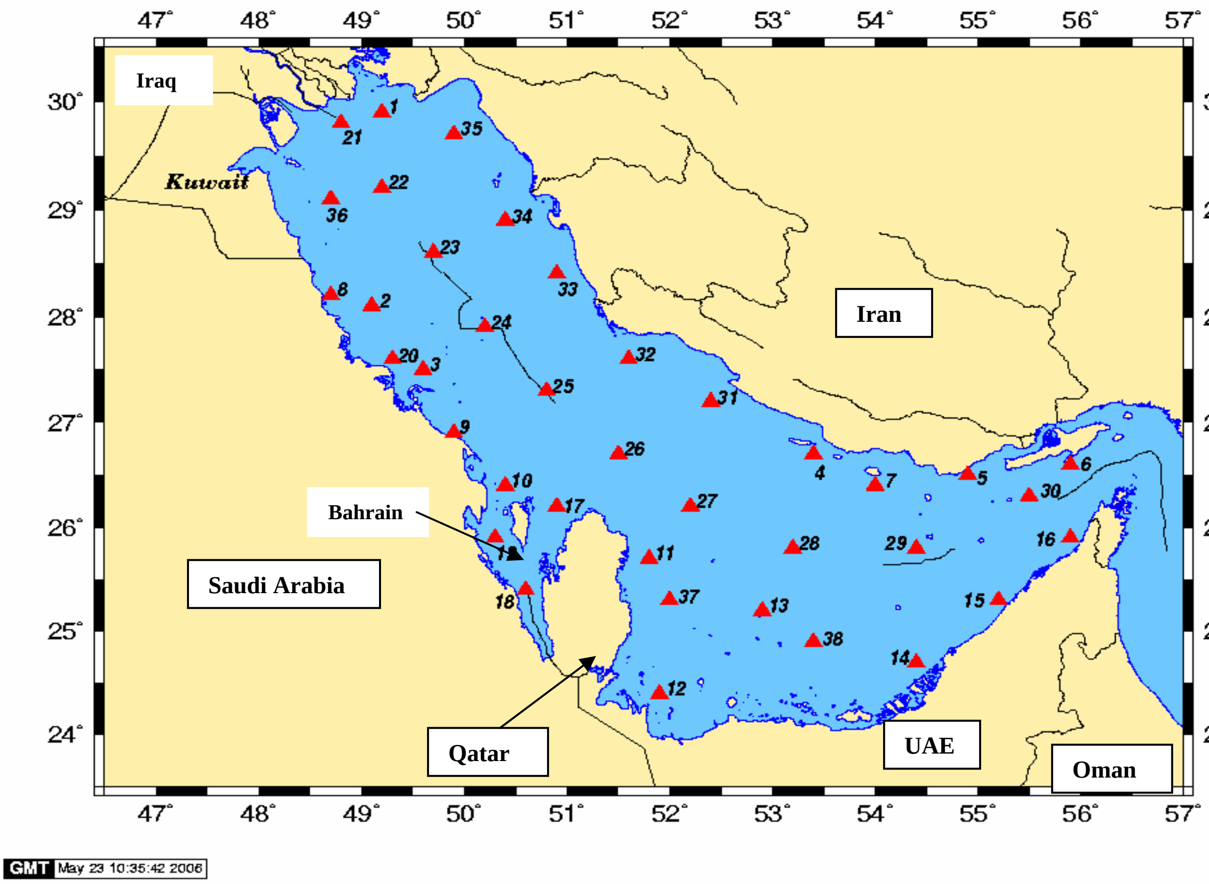

Figure 1. Locations in the Arabian Gulf waters

locations in the Arabian Gulf as shown in Fig.1. Each location has a total of 105,192 data points. The longitude, latitude and water depth of each location are given in Table 1.

Table 1: Longitude, Latitude and local water depth at 38 different locations in the Arabian Gulf waters

Location	Longitude (°E)	Latitude (°N)	Water depth (m)	Remarks/Nearest Country
1	49.2	29.9	15	Iran
2	49.1	28.1	15	Saudi Arabia
3	49.6	27.5	15	Saudi Arabia
4	53.4	26.7	61	Iran
5	54.9	26.5	11	Iran
6	55.9	26.6	31	Iran
7	54.0	26.4	55	Iran
8	48.7	28.2	9	Saudi Arabia
9	49.9	26.9	16	Saudi Arabia
10	50.8	26.4	12	Bahrain
11	51.8	25.7	19	Qatar
12	51.9	24.4	10	UAE
13	52.9	25.2	16	UAE
14	54.4	24.7	10	UAE
15	55.2	25.3	16	UAE
16	55.9	25.9	20	UAE
17	50.9	26.2	9	North west of Qatar
18	50.6	25.4	17	South west of Qatar
19	50.3	25.9	20	between Saudi Arabia and Bahrain
20	49.3	27.6	9	Saudi Arabia
21	48.8	29.8	10	between Kuwait-Iran
22	49.2	29.2	33	between Saudi Arabia-Iran
23	49.7	28.6	45	between Saudi Arabia-Iran
24	50.2	27.9	48	between Saudi Arabia-Iran
25	50.8	27.3	62	In between Bahrain-Iran
26	51.5	26.7	39	In between Qatar-Iran
27	52.2	26.2	44	In between Qatar-Iran
28	53.2	25.8	54	In between UAE-Iran
29	54.4	25.8	59	In between UAE-Iran
30	55.5	26.3	57	In between UAE-Iran
31	52.4	27.2	79	Iran
32	51.6	27.6	22	Iran
33	50.9	28.4	42	Iran
34	50.4	28.9	44	Iran
35	49.9	29.7	24	Iran
36	48.7	29.1	19	Kuwait
37	52.0	25.3	15	East of Qatar
38	53.4	24.9	20	UAE

The maximum and average significant wave heights for these 38 locations based on the 12 year hindcasted data are provided in Fig.2. The highest maximum significant wave height is hindcasted

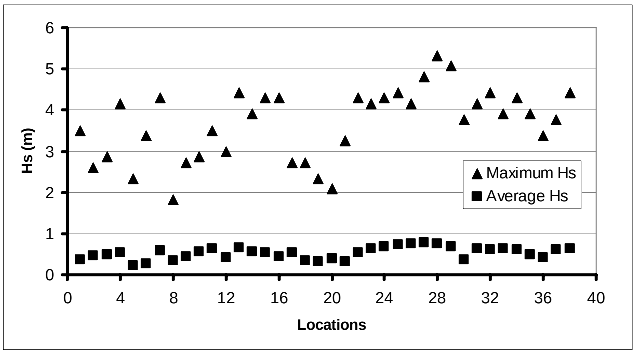

Figure 2. Maximum and average value of the hindcasted significant wave height for Arabian Gulf waters based on the hindcasted waves from 1.1.1993 to 31.12.2004.

At location 28 (Hs = 5.33 m) and the lowest maximum significant wave height is hindcasted at location 8 (Hs = 1.82 m). Similarly the maximum average wave height for 12 year has occurred at location 27 with Hs = 0.77 m and the minimum average wave height has occurred at location 5 with Hs = 0.21 m.

METHODOLOGY

The Gumbel and Weibull distribution are used for the extreme value prediction. The input data point selection is done carefully. The statistics of long term prediction of wave requires that the individual data points used in the statistical analysis be statistically independent. Hence, any hourly wave height depends very much on the wave height of the previous hours and hence the theoretical condition of statistical independence is not met. In order to produce independent data points, only storms should be considered. The commonly used method to separate wave heights into storms is called Peak Over Threshold (POT) analysis (COLES (2001)). A threshold wave height of 1.0 m is selected for the present analysis. The No. of storm events/year with threshold wave height of 1.0 m for different locations is provided in Fig.3.

It is seen that there are 9 locations which have more than 80 No. of storm events/year (with threshold significant wave height of 1.0 m). It is also seen that there are 14 locations which have 60 to 80 storm events/year. There are 6 locations amongst the selected 38 locations with less than 40 storm events/year. This important information is vital for marine operations around these locations. The data points used in the POT analysis are the peaks occurring during each storm with threshold wave height of 1.0 m. The total number of data points used for the extreme wave analysis is hence 12 times the No. of storm events/year.

The data points for each location are arranged in the descending order. The probability of exceedance, Q is calculated using the formula

$$Q = (i-c_1)/(N+c_2) \qquad (1)$$

where
i : Rank
N : Total number of data points
c_1=0.44 and c_2 = 0.12 for Gumbel distribution and
c_1=0.20+ (0.27/α) and c_2 = 0.20 + (0.23/α) for Weibull distribution,
where α is the shape parameter. The value of α is varied from 0.8 to 1.3 with an increment of 0.05 and the value of α, which gives

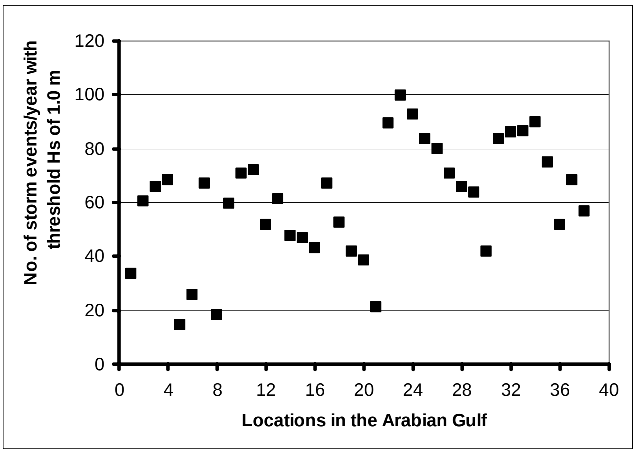

Figure 3. No. of storm events/year with threshold significant wave height of 1.0 m in the Arabian Gulf waters

best fit for the data set is selected. The detailed description of Gumbel and Weibull distribution can be found from many sources (For example, see KAMPHUIS (2000)).

Prediction of the Wave Height for the Selected Return Period

The return period, T_R and the probability of exceedance are linked by the following expression

$$Q = 1 / (l\, T_R) \quad (2)$$

where 'l' is the number of event/year. For the present problem, we know the total number of storm events exceeding threshold value of H_s = 1.0 m for each selected location. Since the data is for a total duration of 12 years, the value of 'l' can be calculated immediately (Refer Fig.3). Now according to Gumbel distribution, the expected significant wave height, H_{TR} for a selected return period can be estimated as follows:

$$H_{TR} = g - b\ \text{In}[\text{In}(1/P)] \quad (3)$$

$$\text{i.e. } H_{TR} = g - b\ \text{In}[\text{In}\{(lT_R)/(lT_R-1)\}] \quad (4)$$

Similarly for Weibull distribution, the formula is

$$H_{TR} = g + b\ [\text{In}(1/Q)]^{1/\alpha} \quad (5)$$

$$\text{i.e. } H_{TR} = g + b\ [\text{In}(lT_R)]^{1/\alpha}] \quad (6)$$

Now it is possible to obtain the extreme wave height for any selected return period.

RESULTS AND DISCUSSION

Significant wave heights for different return periods

The following are the steps used for the long-term prediction of waves in the Arabian Gulf:-

a. The significant wave height data set for each location based on POT value of 1.0 m is obtained from hindcasting technique.
b. The wave heights obtained at each location are arranged in descending order.
c. The plotting formula, as discussed in eqn.1 is used to reduce the wave height data to a set of points describing the probability of exceedance of wave height, Q.
d. The wave height is then plotted against the reduced variate of Gumbel distribution (-In [In (1/P)]) and Weibull distribution ([In (1/Q)] $^{1/\alpha}$).

A straight line is fitted by using least square techniques through the points to represent a trend. The slope and intercept is obtained. From this, the parameters of the probability distribution are obtained. Eqn. 4 and 6 are used for predicting wave heights for chosen return period (12, 25, 50, 100 and 200 years etc.) for Gumbel and Weibull distribution respectively.

A typical Gumbel distribution plot for location 23 is provided in Fig.4. The equation of the best line fit and the correlation coefficient are provided. For the same location, the Weibull distribution plot is given in Fig.5 and the equation for the best line fit and the value of correlation coefficient is also given. Similar plots are prepared for all the 38 locations. It is found from this analysis that Weibull distribution is better than Gumbel distribution for all the 38 locations.

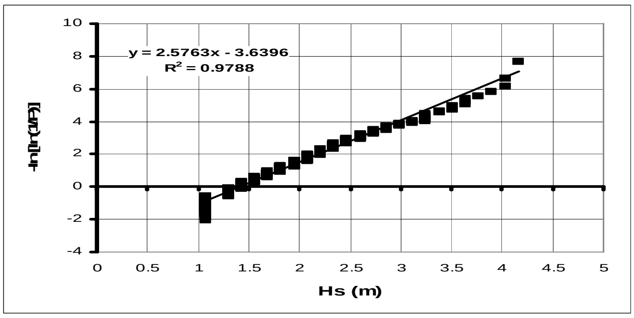

Figure 4. Gumbel distribution plot for Location 23

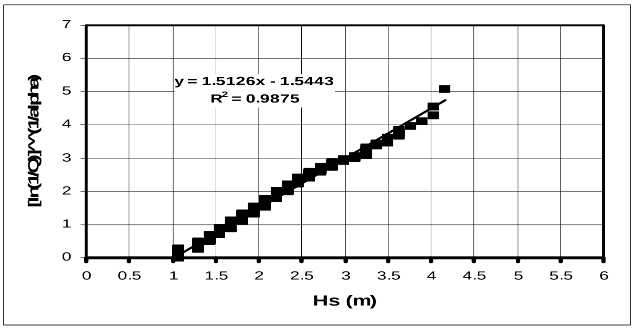

Figure 5. Weibull distribution plot for Location 23

The location parameter, scale parameter, shape parameter and the coefficient of regression obtained for all the 38 locations based on the Weibull distribution are given in Fig.6, 7 , 8 and 9. These parameters can be used in eqn. 6 to get wave heights corresponding to any required return period. It is seen that the Location parameter varies from 0.904 to 1.044, scale parameter from 0.24 to 1.126. The shape parameter for the best line fit is also varies from 0.95 to 1.3. The coefficient of regression for the best line fit for most of the locations is closer to 1.0 and is better than the corresponding Gumbel distribution fits for different locations. Hence, it is recommended to use Weibull distribution for extreme wave height prediction in the Arabian Gulf waters.

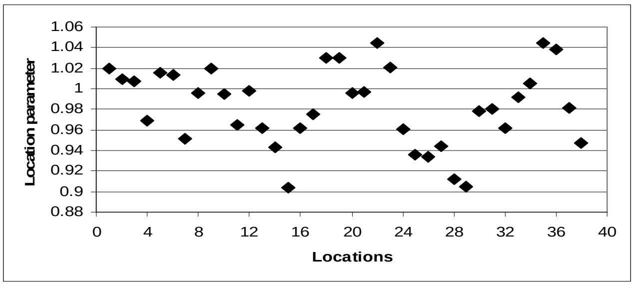

Figure 6. Location parameter based on Weibull distribution for 38 locations in the Arabian Gulf

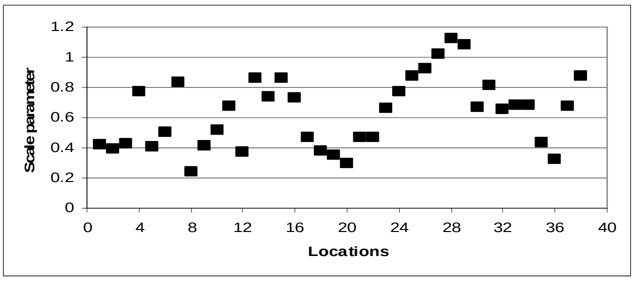

Figure 7. Scale parameter based on Weibull distribution for 38 locations in the Arabian Gulf

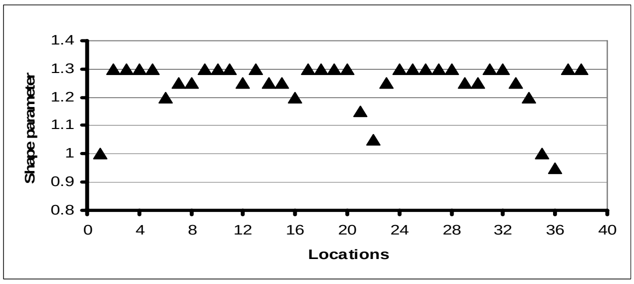

Figure 8. Shape parameter based on Weibull distribution for 38 locations in the Arabian Gulf

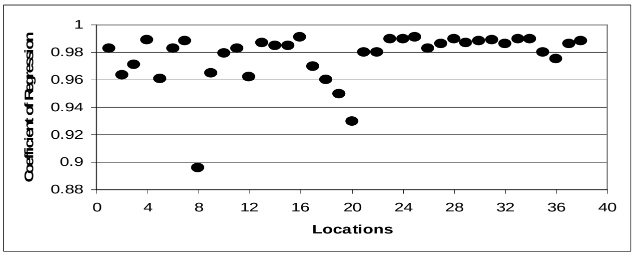

Figure 9. Coefficient of Regression for the best line fit for Weibull distribution for 38 locations in the Arabian Gulf

The predicted wave heights for the different locations based on Weibull distribution for return periods of 12 years, 25 years, 50 years, 100 years and 200 years are provided in Fig.10. Also a plot showing the predicted extreme significant wave height for 100 year return period in the Arabian Gulf at different locations is given in Fig. 11 for quick reference. In general, the extreme waves on the territorial waters of Kuwait, Saudi Arabia, Bahrain, Qatar and UAE are smaller compared to the Iran's territorial waters and in the Arabian Gulf midway between the longitudinal boundaries of both the sides. If we consider the whole Arabian Gulf then the predicted 100 year significant wave varies from 2.2 m (in the Saudi Arabian territorial waters) to 7.0 m (midway between UAE and Iran). Even on the longitudinal direction of the Arabian Gulf along its midway, the 100 year return period ways are of the order of 5 m in the Northern part of the Gulf and is about 6.0 to 7.0 m in the southern part of the Gulf. This could be due to the higher water depths and longer fetch length available for the southern part of the Gulf for the North West winds. Design of any marine structures in these locations need to consider these points for safe and economic designs. The territorial waters off UAE coast, where large number of artificial coastal development projects are going on, the 100 year return period significant waves are of the order of 5.0 to 5.5 m.

Joint probability of mean wave periods and significant wave heights

Wave height and wave periods are independent parameters. However, it can be seen in general that as wave height increases, it is likely that wave period also increases. On the other hand, the probability of occurrence of high waves and long periods are more pronounced than the probability of occurrence of high waves and short periods. Joint probability of wave height and wave period is used for predicting the wave period for a wave height of any desired return periods (KAMPHUIS (2000)). The joint distribution is simplified by relating wave period to wave height via the combinations of greatest frequency. The significant wave height and mean wave period is related by the following equation:

$$T_{mean} = C_3 \, (H_s)^{C4} \qquad (7)$$

The value of C_3 and C_4 is obtained for all the 38 locations in the Arabian Gulf waters and is given in Fig.12 and 13 respectively.

It is recommended to use the respective C_3 and C_4 values for the chosen locations for the estimation of T_{mean}. The average value of C_3 and C_4 is 4.398 and 0.2648 respectively and may be used for finding out the approximate value of the mean wave period for the Arabian Gulf waters for the selected significant wave heights corresponding to a desired return period of the event.

CONCLUSIONS

Gumbel and Weibull extreme value distributions are used in order to obtain significant wave heights at 38 different marine locations in the Arabian Gulf waters. Data obtained based on WAM model for 12 years are used. Peak over threshold of 1.0 m is used for synthesising the raw data. Based on Joint probability analysis, polynomial type predictive equations for the mean wave period from the significant wave heights of intended return periods were obtained. The following are the conclusions obtained out of this investigation.

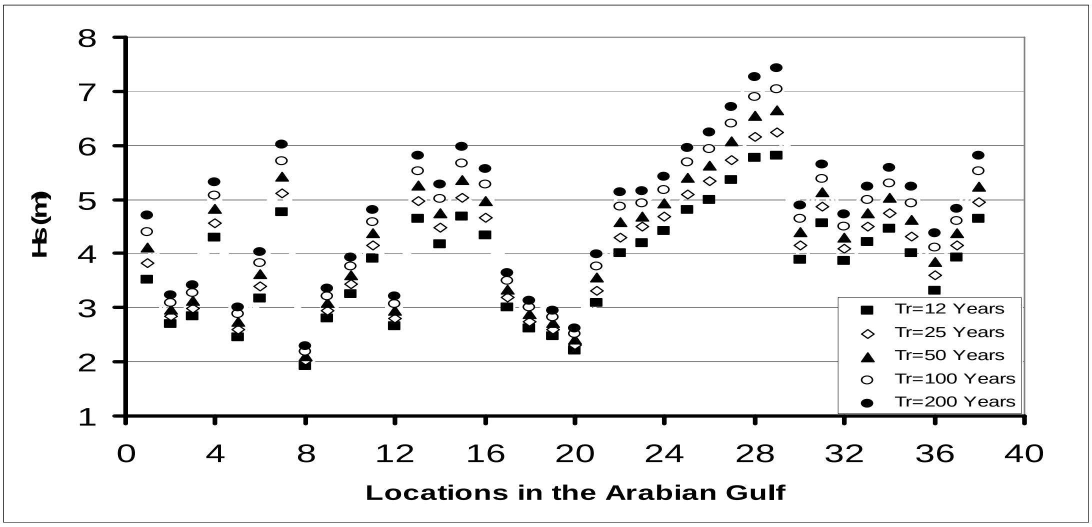

Figure 10. Predicted extreme significant wave heights in the Arabian Gulf waters for different return periods based on Weibull distribution

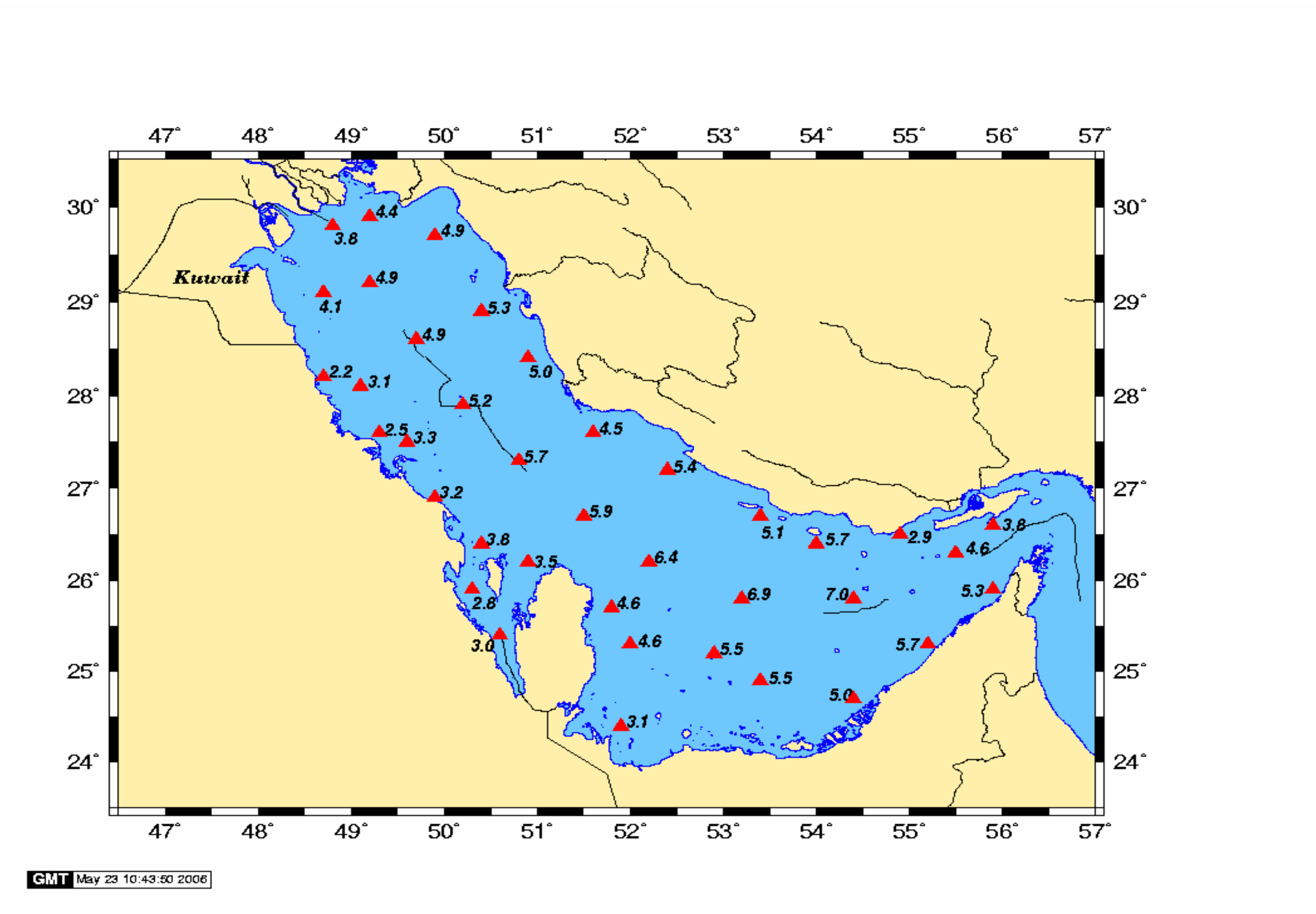

Figure 11. Predicted extreme significant wave heights for 100 year return periods in the Arabian Gulf waters for different return periods based on Weibull distribution

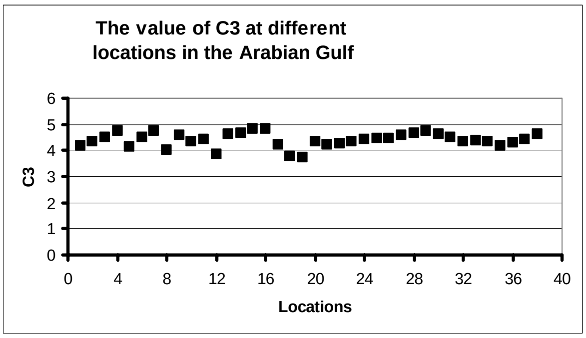

Fig.12 The value of C_3 for different locations in the Arabian Gulf waters

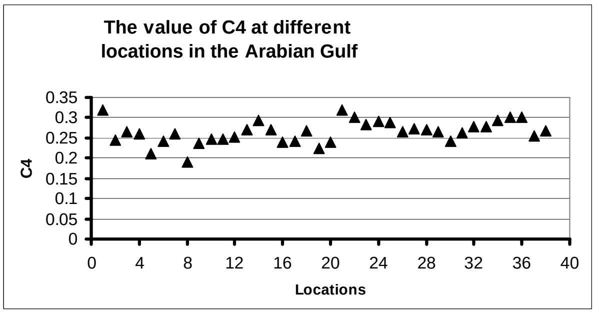

Fig.13 The value of C_4 for different locations in the Arabian Gulf waters

1. The Weibull distribution is very suitable for extreme wave height prediction in the Arabian Gulf waters.
2. Though the Arabian Gulf covers an area of about 226,000 square km, the extreme significant wave height vary from 2.2 m to 7.0 m for 100 year return period, among these 38 locations. This spatial variation of the wave height must be considered for design of marine structure in these locations.
3. In general the value of extreme significant wave heights are smaller in the territorial waters of Kuwait, Saudi Arabia, Bahrain, Qatar compared to the territorial waters of UAE and Iran.
4. The maximum value of the 100 year return period significant wave height is 7.0 m and it is expected to occur in deeper waters in between UAE and Iran (Around location 28).
5. $T_{mean} = 4.398\ (H_s)^{0.2648}$ can be used for predicting the mean wave period for any predicted significant wave height which pertains to any return period of the event in the Arabian Gulf.
6. A large number of coastal and offshore projects are in progress and many new projects are planned for the near future in the Arabian Gulf waters. The results of the present study will be highly useful for optimal design of different types of ocean structures in the Arabian Gulf.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Kuwait Foundation for Advancement of Science for partially sponsoring the project. We express our thanks for Kuwait Institute for Scientific Research, Kuwait for providing all the infrastructure facilities to carry out this work.

REFERENCES

AL-SALEM, K., RAKHA, K.A., SULISZ, W., and AL-NASSAR W., 2005. Verification of a WAM Model for the Arabian Gulf. *Arabian Coast 2005 Conf*., Dubai, 27-29 Nov., 2005.

AL-YAMANI, F.Y., BISHOP, J., RAMADHAN, E., AL-HUSAINI, M., and AL-GHADBAN, A., 2004. *Oceanographic Atlas of Kuwait's Waters.* Kuwait Institute for Scientific Research, Kuwait. 203 p.

CAIRES, S., and STERL, A., 2005. 100-Year return value estimates for Ocean wind speed and significant wave height from the ERA-40 data. *Journal of Climate*. Vol. 18, pp.1032-1048.

CARDONE, V.J., PIERSON, W.J., and WARD, E.G., 1976. Hindcasting the directional spectra of hurricane generated waves. *Journal of Petrol. Tech*., Vol. 28, pp.385-394.

COLES, S., 2001. *An introduction to Statistical modelling of extreme values*. Springer-Verlag, 208 p.

ELSHORBAGY, W., AZAM, M.H., and TAGUCHI, K., 2006. Hydrodynamic Characterisation and Modelling of the Arabian Gulf. *Journal of Waterway, Port, Coastal and Ocean Engineering*, ASCE, Vol.132, No.1, pp.47-56.

EL-GINDY, A., and HEGAZI, M., 1996. *Atlas on Hydrographic conditions in the Arabian Gulf and the upper layer of the Gulf of Oman*, University of Qatar, 170p.

FERREIRA, J.A., and GUEDES SOARES, C., 1998. An application of the peaks over threshold method to predict extremes of significant wave height. *J. Offshore Mech. Arct. Eng*., Vol.120, pp.165-176.

GODA, Y., 1992. Uncertainty of design parameters from viewpoint of extreme statistics. *Journal of Offshore Mechanics and Arctic Engineering.*, ASME, Vol.114, pp.76-82.

GODA, Y., HAWKES, P., MANSARD, E., MARTIN, M.J., MATHIESEN, E., PELTIER, E., THOMPSON, E., and VAN VLEDDER, G., 1993. Intercomparison of extremal wave analysis methods using numerically simulated data. *Proc. 2nd Int. Symp. On Ocean Wave Measurement and Analysis*, ASCE, New Orleans, pp.963-977.

GUMBEL, E.J., 1958. *Statistics of Extremes*. Columbia University Press, New York.

JAHNS, H.O. and WHEELER, J.D., 1973. Long-term wave probabilities based on hindcasting of severe storms. *Journal of Petrol. Tech.*, Vol.25, pp.473-486.

KAMPHUIS, J.W., 2000. *Introduction to Coastal Engineering and Management.* Advanced series on ocean engineering-Vol.16, World Scientific, Singapore Chapter.4. Long term wave analysis. pp.81-102.

LEADBETTER, M.R., 1991. On a basis for "peak over threshold" modelling. Stat. *Prob. Lett*., Vol.12, pp.357-362.

MATHIESEN, M., HAWKES, P., MARTIN, M.J., THOMPSON, E., GODA, Y., MANSARD, E., PELTIER, E., and VAN VLEDDER, G., 1994. Recommended practice for Extreme wave analysis. *J. Hydraulic Research.*, IAHR, Vol. 32, pp.803-814.

NOLTE, K.G., 1973. Statistical methods for determining extreme sea states. *Proc. 2nd International Conference on Port and Ocean Engineering Under Arctic Conditions*, Univ. of Iceland, pp. 705-742.

PELTRAUSKAS, C. and AAGAARD, P., 1971. Extrapolation of historical storm data for estimating design wave height. *Journal of Soc. Petrol. Eng*., Vol.11, pp.23-37.

SARPKAYA, T., and ISAACSON, M. DE ST. Q., 1981. *Mechanics of Wave Forces on Offshore Structures*. Van Nostrand Reinhold Company, New York, USA.