Extreme wave heights in the Kuwaiti territorial waters based on 12- and 15-year data

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ABSTRACT

Estimation of extreme waves are essential for the safe and economic design of marine structures. The extreme significant wave heights were predicted for a return period of 100 years for 38 different locations in the territorial waters of Kuwait based on 12 and 15 years of wave data. The input wave data for the work was obtained by hindcasting of waves, using a WAM model. First, the wave data hindcasted for a total period of 12 years were used, and again the work was carried out with 15 years of data. The peak-over-threshold method, with a 1.0 m threshold wave height, was used for estimating the extreme waves. Weibull distribution is used for extreme wave analysis. It is found that the significant wave heights for a 100-year return period varies from 2.0 to 4.5 m. Increasing the input data from 12 to 15 years resulted in an average increase of 8.8% in the predicted 100 year significant wave height and a maximum increase of 20.8%. A large number of marine projects are in progress in the Kuwaiti territorial waters and many new projects are being planned for the future. The results presented in this paper will be useful for optimal design of such marine structures in these waters.

Keywords: Weibull distribution; significant wave height; hindcasted wave data; Kuwaiti territorial Waters.

INTRODUCTION

One of the important requirements for correct prediction of extreme wave heights in the sea is to have reliable long-term raw wave data. The extreme wave heights data for different return periods and for different locations are needed for the safe and economic design of marine structures. A lack of correct extreme wave height information will result either in an unsafe or an over-designed (i.e., uneconomical) structure. For example, the weight of an armor unit of a breakwater depends on the design significant wave height (i.e. the wave height used for the design of marine structures like breakwater) to the power of 3 (Shore Protection Manual, 1984). Hence, selection of 2 m or 3 m significant wave height results in an armor unit weight ratio of 8:27. Therefore, it is
essential to correctly predict the design wave heights for different return periods. The reliability of the predicted extreme wave heights is high if the source data is available for a longer period of time. The extreme wave heights for Kuwaiti territorial waters for different return periods were predicted based on 12 years of data by Neelamani et al. (2007). Additional data for three more years are now added and the work is repeated and the results based on 12 and 15 years of data are presented in this paper.

A marine structure (say a seawater intake system) designed for the design sea state of oceans such as the Gulf of Mexico or Bay of Bengal (the wave climate is severe and cyclone effects are frequent in these seas) need not be adopted for Kuwaiti marine conditions. In the territorial waters of Kuwait, the wave generation is controlled mainly by the limited fetch and shallow water depths, because Kuwait is located in the northwestern part of the Arabian Gulf (Figs.1 and 2), which is a marginal sea in a typical arid zone and is an arm of the Indian Ocean. It lies between latitudes of 28.45 and 30.05 degrees north of the Equator, and longitudes of 46.30 and 48.30 degrees East of Greenwich. In Kuwait, the wind direction is usually northwesterly for 43% of the year, increasing to 63% during summer months and decreasing to 31% during the spring season. Southeasterly winds occur 19% of the year, with maximum occurrence of 27% during spring and minimum of 9% during summer. The southeasterly wind has significant fetch length and hence the dominant waves in the Kuwaiti territorial waters are from the southeast.
Fig. 1. Arabian Gulf and location of Kuwait.
Kuwait has a continental climate, which characterizes all desert geographic regions in general. The total area of the State of Kuwait is 17,818 square kilometers. Territorial waters extend up to 25 to 30 m water depth. There are nine islands in Kuwait: Boubyan Island, Warba Island, Failaka Island, Miskan Island, Umm Al-Namil Island, Awhah Island, Kubbar Island, Qaruh Island and Umm Al-Maradim Island.

The area of Kuwaiti territorial waters is estimated at about 7,611 square km. They can be divided into two areas: the shallow northern area, which is less than five meters deep in most places with a muddy bed, and the relatively deep southern area, which has a bed of sand and silica deposits. Most of Kuwait’s ports are located on the southern shore to take advantage of the deep waters in this area. Kuwait territorial water is one of active navigation routes for the export of crude oil and refined petroleum products, and the import of products from around the world. Though the area of the Kuwaiti territorial waters is not extensive, the wave climates vary significantly from one location to other due to
the significant change in bathymetric conditions. (More details of the Oceanographic Atlas of Kuwait can be obtained from Al-Yamani et al., 2004). Projects such as the development of Boubyan Island and construction of a major port there, Failaka Island for tourism, and development and the construction of marinas on other islands are being planned or are under development. Design of all the marine structures requires estimates of extreme wave heights for different return periods.

An attempt is made to report the extreme waves in Kuwaiti territorial waters for different return periods. Since the selection of a threshold value affects the predicted extreme waves, a detailed analysis is carried out to quantify the effect of threshold value. Caires & Sterl (2005) have estimated the 100-year return value for significant wave height from the ERA-40 data for all the oceans of the earth. The wind data used in their study is obtained from a 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. Therefore, wind data was procured from the European Centre for Medium-Range Weather Forecasts (ECMWF) for a finer grid size of 0.5° x 0.5°, and the wind speeds are linearly interpolated for a grid size of 0.1° x 0.1° for running the WAM model for hindcasting the significant wave heights and for further extreme wave analysis.

LITERATURE REVIEW

There is a large body of work done by scientists around the world on extreme value prediction of winds and waves. Gumbel (1958) is the first who developed a statistical method for predicting the extreme values of natural random events, such as wind speed. Recording annual maximum wind speed for as many years as possible is 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. St. Denis (1969, 1973) has discussed the Gumbel distribution in the context of extreme wave prediction. Information related to the collection of data samples for extreme value analysis can be found in Nolte (1973); Cardone et al. (1976); Petrauskas & Aagaard (1971) and Jahns & Wheeler (1973). Details regarding the plotting formula used for extreme wave predictions are available in Kimball (1960), Gringorton (1963) and Petrauskas & Aagaard (1971). The procedure for extreme wave height predictions are explained in Sarpkaya & Isaason (1981) and in Kamphuis (2000). Extreme value analysis for waves is discussed in detail in Mathieson 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 & Guedes Soares (1998) and Leadbetter (1991). All of the above research provides the information and knowledge for carrying out a detailed extreme value analysis and is used for the present work.

**INPUT DATA GENERATION**

For the present work, the wave data is hindcasted using the WAVE prediction Model (WAM) for a total period of 12 years starting from 1st Jan 1993 to 31st December 2004, and 15 years (1st Jan 1993 to 31st December 2007). The output from the WAM model is the significant wave height and the mean wave period for every one hour. The data is hindcasted for all the Kuwait territorial 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 locations in the Kuwait territorial waters, as shown in Fig.3. Each location has a total of 105,192 data points for the 12-year period, and 131,472 data point for the 15-year period. The longitude, latitude and the water depth of each location are given in Table 1.

![Fig. 3. Water depths in the Kuwait's territorial waters.](image-url)
Table 1. Longitude, latitude and local water depth at 38
different locations in the Kuwaiti territorial waters.

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<tr>
<th>Location</th>
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The maximum significant wave heights for these 38 locations based on the 12-year and 15-year hindcasted data is provided in Fig. 4. Based on the 12-year data, the highest maximum significant wave height is hindcasted at locations 3, 4 and 6 ($H_s = 3.64$ m), and the lowest maximum significant wave height is hindcasted at locations 31 and 32 ($H_s = 1.43$ m). Similarly, the maximum significant wave height hindcasted is based on 15-year data at locations 3, 4 and 6 is 3.64 m (same as that for 12 year wave data), and the lowest maximum significant wave height at locations 31 and 32 is 1.82 m. This because the intensity of storms was higher during the last three years of the 15-year data set when compared to the first 12 year data.

![Fig. 4. Maximum hindcasted significant wave height in Kuwait territorial waters based on 12 and 15 years of data.](image-url)
METHODOLOGY

Weibull distribution is 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 as a result, 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. According to Mathiesan et al. (1994), for Peak Over Threshold methods, the maxima chosen are independent, and there is recommend a time interval of two to four days. For the present work with 38 different locations with threshold value of 1.0 m, the number of storms per year (Fig.5) varies from 5 to 69. Hence the time interval between the events for all these locations varies from 73 days to 5.29 days, which is much greater than 4 days. This criteria is used for selecting a threshold value of 1.0 m. The number of storm events per year with threshold wave height of 1.0 m for different locations based on 12-year and 15-year data is provided in Fig. 5. The number of storms per year based on 15-year data is more than that of the 12-year data collection period. As said above, this is due to the latest 3-year hindcasted data having had more storms than any of the previous years. This will certainly influence extreme wave height prediction. It is seen that the number of storms per year changes significantly when the location is changed.

It is clear that the offshore region in the southern part of Kuwaiti territorial water has more than 40 storms per year with $H_s$ greater than 1.0. The northern part of Kuwaiti territorial waters (around Failaka Island and the eastern side of Boubyan Island) and in shallow waters, the number of storms per year is mostly less than 20; this information is vital for marine operations around these locations.

Details of the Data and Long Term Distribution

The data points used in the POT analysis are the peaks occurring during each storm with a threshold wave height of 1.0 m. In consequence, the total number of data points used for the extreme wave analysis is therefore 12 times the number of storm events per year. The data points for each location are arranged in descending order. The probability of exceedence, $Q$, is calculated using the formula

$$Q = (i - c_1)/(N + c_2),$$

(1)
where ‘i’ is the rank, ‘N’ is the total number of data points, $c_1 = 0.20 + (0.27/\alpha)$ and $c_2 = 0.20 + (0.23/\alpha)$ for the Weibull distribution, where $\alpha$ is the shape parameter. The value of $\alpha$ varies from 0.8 to 1.3 with an increment of 0.05 and the value of $\alpha$, which gives the best fit for the data set selected. The detailed description of Weibull distribution can be found from many sources. (For example, see Kamphuis, 2000.)

![Graph showing the number of storms per year with threshold significant wave height of 1.0 m in Kuwait territorial waters, based on 12 and 15 year data.]

**Fig. 5.** Number of storm events per year with threshold significant wave height of 1.0 m in Kuwait territorial waters, based on 12 and 15 year data.

### Prediction of the wave height for the selected return period

The return period, $T_R$, and the probability of exceedence, are linked by the following expression:

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

where ‘l’ is the number of events per year. For the present problem, the total number of storm events exceeding a threshold value of $H_S = 1.0$ m for each location in Kuwait’s territorial waters is known. Since the data is for a total duration of both 12 years and 15 years, the value of ‘l’ can be calculated immediately (Fig.5). According to the Weibull distribution, the wave height expected for a selected return period $H_{TR}$ can be estimated from the following formula:

$$H_{TR} = \gamma + \beta[\ln(1/Q)]^{1/\alpha}, \quad (3)$$

$$i.e. H_{TR} = \gamma + \beta[\ln(1/T_R)]^{1/\alpha}. \quad (4)$$

where $\beta$ is the Scale parameter and $\gamma$ is the Location parameter.
RESULTS AND DISCUSSION

Following are the steps used for the long-term prediction of waves in Kuwaiti territorial waters for the 12- and 15-year data:

a. The data set for each location is obtained based on a POT value of 1.0 m for all 38 locations for the hindcasted data.

b. The wave heights obtained at each location are arranged in descending order.

c. The plotting formula as discussed in Eq.1 is used to reduce the wave height data to a set of points describing the probability of exceedence of wave height, Q.

d. The wave height is then plotted against the reduced variate of Weibull distribution ([ln (1/Q)]^1/\alpha).

e. 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.

f. Eq. 4 is used for predicting wave heights for a chosen return period (12, 25, 50, 100 years, etc.).

A typical Weibull distribution plot for location 1 is provided in Fig.6. The equation of the best line fit and the correlation coefficient are provided. Similar plots are prepared for all the 38 locations. From the earlier study by Neelamani et al. (2007), it is found that the Weibull distribution is better than the Gumbel distribution for all the 38 locations.

![Weibull distribution plot for location 1.](image)

Fig. 6. Weibull distribution plot for location 1.
The location parameters, $\gamma$, for all the 38 locations based on the Weibull distribution for 12 and 15 year data, are given in Fig.7. It can be seen that the location parameter varies from 0.99 to 1.24 for the 12-year data set, and it varies from 0.98 to 1.04 for the 15-year data set. Varying the data duration from 12 years to 15 years has some influence on this parameter, as depicted in this figure.

![Fig. 7. Location parameter based on Weibull distribution for 38 locations in Kuwaiti territorial waters for 12 and 15 years of data.](image)

The scale parameters, $\beta$, for all the 38 locations based on the Weibull distribution for 12- and 15-year data, are given in Fig.8. The scale parameter varies from 0.11 to 0.47 for the 12-year data set, and varies from 0.18 to 0.47 for the 15-year data set.

![Fig. 8. Scale parameter based on Weibull distribution for 38 locations in Kuwait’s territorial waters for 12- and 15-year data.](image)
The shape parameter, $\alpha$ for all the 38 locations based on the Weibull distribution for 12- and 15-year data are given in Fig. 9. The shape parameter varies from 0.90 to 1.3 for the 12-year data set, and from 0.95 to 1.25 for the 15-year data set.

The coefficient of regression for all 38 locations for the Weibull distribution for 12- and 15-year year data are given in Fig. 10. The coefficient of regression varies from 0.73 to 0.98 for the 12-year data set, and from 0.89 to 0.98 for the 15-year data set. The value of the coefficient of regression provides confidence on using the 12- and 15-year wave data for the prediction of extreme wave heights for 25, 50 and 100 years.

![Graph showing the shape parameter for 12 and 15 years.](image)

**Fig. 9.** Shape parameter based on Weibull distribution for 38 locations in Kuwaiti territorial waters for 12- and 15-year data.

![Graph showing the coefficient of regression for 12 and 15 years.](image)

**Fig. 10.** Coefficient of Regression for the best-fit line for Weibull distribution for 38 locations in the Kuwaiti territorial waters for 12- and 15-year data.
A plot showing the predicted extreme significant wave height for a 100-year return period in the Kuwaiti territorial waters at different locations, based on 12- and 15-year data, is given in Fig. 11.

![Graph showing significant wave height for 100-year return period](image)

**Locations in Kuwaiti Territorial Waters**

Fig. 11. Predicted 100 year significant wave height in the Kuwaiti territorial waters for 12- and 15-year wave data.

Varying the input wave height from 12 to 15 years makes a noticeable influence in predicting the 100-year wave height. In general, the predicted 100-year wave height is higher when 15-year wave-height data is used. The average difference in the predicted 100-year wave height is 0.28 m (8.8%). The maximum difference of 0.6 m (20.8%) is obtained for location 37 (Fig.12). In general, the 100-year return period of significant wave heights in the offshore region of southern Kuwait’s territorial waters is more than 4.0 m. This could be due to the higher water depths in the southern part of Kuwaiti territorial waters. The 100-year significant wave height at the eastern side of Boubyan and around Failaka Island is about 2.0 to 2.5 m only due to limited fetch and shallow water depth conditions. The complete picture of the predicted extreme waves for different locations in Kuwaiti territorial waters can be used for safe and economic design of the projects proposed for the near future, especially for the offshore platform installation for crude oil exploitation.
Fig. 12. Percentage change in 100-year predicted significant wave height in Kuwaiti territorial waters.

CONCLUSION

Extreme wave height analysis is carried out for 38 locations in the Kuwaiti territorial waters by using 12- and 15-year wave data as input. Weibull extreme value distributions are used in order to obtain the extreme significant wave heights for a 100-year return period. Data obtained based on a WAM model for 12 and 15 years are used. POT of 1.0 m is used for synthesizing the raw data. The following are the conclusions obtained out of this investigation.

1 - Changing the input data from 12 to 15 years resulted in a difference in the 100-year significant wave height by a maximum value of 20.8%. The average value is 8.8%.

2 - Though Kuwait’s territorial waters cover an area of about 7,611 square km, the extreme significant wave height varies from 2.0 m to 4.5 m for a 100-year return period in these 38 locations. This spatial variation of the wave height must be considered for the optimal design of marine structures in these locations.

3 - In general, the value of extreme significant wave heights is smaller in the northwestern part of Kuwaiti territorial waters (around Boubyan and Failaka Islands) compared to the offshore waters in the Southern part of Kuwait territorial waters.
4 - The maximum value of the 100-year return period significant wave height is about 4.5 m and it is expected to occur in water depths of about 20 m (around location 3, 4, 5 and 6).

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REFERENCES


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التنبؤ بالارتفاعات القصوى للأمواج في المياه الإقليمية الكويتية المعتمدة على بيانات 12 سنة و15 سنة

سوبرامينيام نيلاماني، كارم رخا، خالد السالم و محمد الخالدي
معهد الكويت للبحوث العلمية – الكويت

خلاصة

تغطي الأمواج ذات الارتفاعات القصوى من العوامل الأساسية للموئل البحري. في هذه الدراسة تم التنبؤ بالارتفاعات القصوى للأمواج العادية لفترة 100 سنة لعدد 38 موقع في المياه الإقليمية الكويتية، وذلك باستخدام بيانات الأمواج التي تم حسابها باستخدام نموذج عددي WAM Model تتم في البداية تحليل هذه البيانات التي تغطي فترة زمنية تصل إلى 12 سنة، وتم إعادة هذا العمل لفترة زمنية أكبر تصل إلى 15 سنة.

وقد استخدم توزيع Weibull لتحليل الأمواج القصوى حيث تم استخدام الأمواج التي يتعدى ارتفاعها عن 0.1 متر لتقدير ارتفاع الأمواج القصوى. ووجد أن ارتفاع الأمواج الممكن حدوثه خلال فترة 100 سنة يتراوح بين 2.00 متر إلى 4.20 متر، وزيادة بيانات الأمواج التي تغطي 12 سنة إلى 15 سنة أدى ذلك إلى زيادة متوسط ارتفاع الأمواج بنسبة 8.8 %، وزيادة ارتفاع الموجات القصوى بنسبة 20.8 %.

وسوف تكون نتائج هذه الدراسة الفائدة في التصميم الأمثل للمشاريع الجارية تثبيتها حالياً أو المخطط تثبيتها في المياه الإقليمية لدولة الكويت.
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مجلة علمية فعالة تقوم بتقديم دراسات علمية في مجالات مختلفة.

رئيسة التحرير
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ترحب المجلة بنشر البحوث والدراسات العلمية المتعلقة بشؤون منطقة الخليج والجزيرة العربية في مختلف علوم البحث والدراسة.

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وتحديث، وفقه، واقتصاد وتربية إسلامية، إلى غير ذلك من تقارير عن
المؤتمرات، ومراجعة كتب شرعية معاصرة، وفتاوي شرعية، وتعليقات
على قضايا علمية.
تنوع الباحثون فيها، فكانوا من أعضاء هيئة التدريس في مختلف
الجامعات والكليات الإسلامية على رقعة العالمين: العربي والإسلامي.
تخضع البحوث المقدمة للمجلة إلى عملية فحص وتحكيم حسب الضوابط
التي تقررت بها المجلة، ويقوم بها كبار العلماء والمختصين في الشريعة
الإسلامية، بهدف الارتقاء بالبحث العلمي الإسلامي الذي يخدم الأمة، ويعمل
على رقعة شانها، تسال المولى عز وجل مزيداً من التقدم والإزدهار.

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