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Estimation of Extreme waves in Asaluyeh Using SWAN model

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Abstrct

The design of coastal and offshore structures requires estimation of the significant wave height corresponding to a certain return period, obtained by collecting short-term data. Instrumentally measured, visually observed or numerically simulated wave data can be used for this purpose. In this study a third generation numerical model, i.e. SWAN, was employed for reproducing time series of wave data in Asaluyeh in the Northern coasts of the Persian Gulf. The SWAN model was forced with Dayyer synoptic wind data. The extreme value analysis was conducted based on the measured and hindcasted wave data. The peak over threshold method was used for determination of extreme waves. It was found that although there were some inconsistencies between recorded and simulated data mainly due to the quality of wind source influenced by the orography effects, the differences between design wave heights obtained from measured and simulated data were not significant in any direction. The results of this study also showed that the Weibull distribution is better compared to other distributions for both measured and simulated data in this region. The shape parameter for Weibull distribution was found to be 1.6 for both measured and modeled data. In addition, the effect of threshold value on the extreme wave height was less than 10 percent for all return period.

Keywords: *Persian Gulf, SWAN, third generation, extreme wave height.*

Introduction

Wave characteristics are one of the most important factors in design of coastal and marine structures. The design of coastal and offshore structures requires estimation of significant wave height corresponding to a certain return period. The design wave height is obtained by collecting short-term, .e.g. 3-hourly, data at the given location. Instrumentally measured, visually observed or numerically simulated wave data can be used for this purpose (Goda, 2000). Ocean engineers generally use these data associated with statistical methods to characterize wave climate at a desired probability. Due to the lack of measurements and observations in many regions, and development of numerical wave models, nowadays numerically simulated wave data are widely used as the data bank for extracting design wave characteristics. The quality of wind forcing is the most important factor affects the results of numerical wave models. Therefore, investigation of the effect of wind source on both wave hindcasting and calculation of extreme waves is very important.

A large number of scientists have researched around the extreme value analysis of winds and waves. As an example, Gumbel (1953) was the first who has evolved a statistical method for extracting extreme values of natural events such as winds and waves that have a random essence. Some more details about extreme value analysis can be found in Goda (1992) and Mathiesen et al. (1994). Also Goda (2000) and Kamphuis (2000) have presented the procedure for extreme value analysis of random seas and estimation of the design wave characteristics.

Neelamani et al. (2007) have estimated design wave characteristics for Kuwaiti territorial waters based on 12yr simulated data with WAM model on a $0.1° \times 0.1°$ grid and $0.5° \times 0.5°$ ECMWF wind forcing. They have used POT method to extract storm data and employed Weibull and Gumbel distribution to estimate extreme wave characteristics. According to their findings, the Weibull distribution is better fitted to the storms compared with Gumbel distribution in Kuwaiti territorial waters. Since they validated their results against the measurements in Kuwaiti waters, the validity of their findings along Iranian coasts should be proved. In addition, they have not presented any idea about the effect of modeling results on the extreme value analysis of wave data in the Persian Gulf. Iranian National Center for Oceanography (2005) has used MIKE21 SW forced with ECMWF wind data for wave hindcasting in the Persian Gulf. They have estimated extreme waves in different areas of the Persian Gulf.

The main goal of this study was to investigate using of numerically simulated wave data as a data base for extreme wave analysis in the Persian Gulf. The third generation SWAN model was employed for wave hindcasting in Asaluyeh. Dayyer synoptic wind data were evaluated as the wind input in the SWAN model and their quality was investigated. Extreme value analysis was carried out based on the SWAN modeled wave data. The model results were compared with field measurement both from the viewpoint of wave hindcasting and extreme value analysis. Some remarks on extreme wave estimation in this region such as the superior distribution were also presented.

This paper is organized as follows. Following section describes the study area and the field data. After that the SWAN numerical wave model is briefly introduced. Next section gives the description of results and the final section covers the summary and conclusions.

Study area and the field data

In this study the recorded meteorological and wave data of the Persian Gulf were used. The Persian Gulf is a marginal sea in a typical arid zone and is an arm of the Indian Ocean. It lies between the longitude of *48-57°E* and the latitude of *24–30° N* (Fig. 1). This inland sea is connected to the Gulf of Oman in the east by the Strait of Hormuz. The gulf covers an area of 226000 km^2. It is 990 km long and its width ranges from 56 to 338 km, separating mainly Iran from Saudi Arabia. It has a total volume of 7000–8400 km^3 of seawater. The entire basin lies upon the continental shelf. This Gulf has an average depth of about 35.0 meters and the deepest water depth is about 107 m (Emery, 1956; Purser and Seibold, 1973).

The recorded wave data used in this study were collected by an AWAC buoy which was located in $52^{0}\,30'\,17''\,E$ and $27^{0}\,35'\,39''\,N$. The data were recorded hourly from the first of November, 2002 until 31st October, 2003. Fig. 1 illustrates the location of wave measurement station.

Dayyer synoptic wind data were used as wind input in the SWAN model. This synoptic wind station was located in $51^{0}\,56'\,E$ and $27^{0}\,50'\,N$, which was the nearest station to the wave recording location.

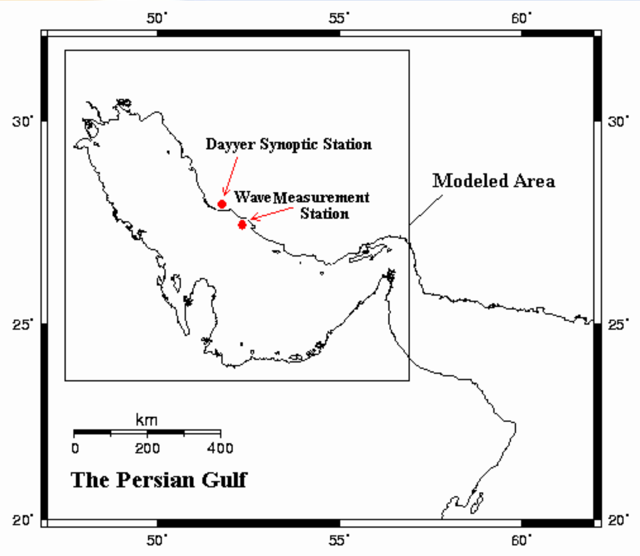

Fig. 1. The location of wave and wind measurement stations and modeled area

SWAN model

The SWAN model (Booij et al., 2004) is a third generation spectral model, designed to obtain realiable estimates of wave parameters in coastal areas, lakes and estuaries. Action density spectrum is considered in the SWAN model rather than energy density spectrum because in the presence of currents, energy density is not conserved. The action density is equal to the energy density divided by the relative frequency:

$$N(\sigma,\theta)=E(\sigma,\theta)/\sigma \qquad (1)$$

Where N is the action density and E is the energy density. The independent variables are the relative frequency σ (as observed in a frame of reference moving with current velocity) and the wave direction θ (the direction normal to the wave crest of each spectral component).

In the SWAN wave model the evolution of the wave spectrum in the position (x,y) and time (t) is described by the spectral action balance equation which for Cartesian coordinates is (Booij et al., 2004):

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial x}C_xN+\frac{\partial}{\partial y}C_yN+\frac{\partial}{\partial \sigma}C_\sigma N+\frac{\partial}{\partial \theta}C_\theta N=\frac{S}{\sigma} \qquad (2)$$

The first term in the left-hand side of this equation represents the local rate of change of action density in time, the second and third terms represent propagation of action in geographical space with propagation velocities C_x and C_y in x and y space, respectively. The fourth term represents shifting of the relative frequency due to variations in depths and currents (with propagation velocity C_σ in σ space). The fifth term represents depth-induced and current-induced refraction and propagation in directional space (with propagation velocity C_θ in θ space).

The term $S=S(\sigma,\theta)$ at the right hand side of the action balance equation is the source term in terms of energy density representing the effects of generation, dissipation and nonlinear wave-wave interactions. This term consists of linear and exponential growth by wind, dissipation due to whitecapping, bottom friction and depth-induced wave breaking and energy transfer due to quadruplet and triad wave-wave interaction.

Results and discussion

In this study SWAN cycle III version 40.41 (Booij et al., 2004) was used for wave hindcasting in Asaluyeh. The model was executed in third generation and nonstationary mode with Cartesian coordinates. Since it has been revealed that using Komen's formulation (Komen et al., 1984) for wind input parameterization lead to more accurate estimation of H_s (Moeini and Etemad-Shahidi, 2007), this expression was used for exponential growths of wind input. Quadruplet wave interaction was activated for nonlinear interaction as well. Dissipation due to whitecapping, bottom friction and depth-induced wave breaking were considered in the simulation.

The geographical domain was discretized into 125×100 cell grid covering the Persian Gulf with 8800×8000 meter resolution in x and y directions, respectively. The spectral space was divided into 25 equal directions in the rose ($\Delta\theta$=360/25=14.40) and 25 logarithmically spaced frequencies, between 0.06 Hz and 1 Hz. This means that the lowest period of simulated wave was 1 second and the highest was about 17 seconds covering typical surface waves in the Persian Gulf. The computational time step was selected as 10 minutes as well.

The model was forced with recorded wind data at Dayyer synoptic station. Forcing of the model was varying in time and constant in domain. Since the SWAN model uses the wind velocity in 10-meter elevation and the measured velocities were in 4-meter elevation, the following equation was used to change the velocities for SWAN input (US Army, 1984):

$$U_{10} = U_Z \left(\frac{10}{z} \right)^{\frac{1}{7}} \qquad (3)$$

The calibration of the model was conducted based on the recorded wave data during November, 2002. The tunable parameter used for calibration was the rate of whitecapping dissipation. Sensitivity analysis showed that other physical parameters such as depth induced wave breaking and bottom friction have no significant effect on the wave characteristics.

Fig. 2 shows qualitative comparison of the hourly time series of modeled H_s against the measurements. Similarly, a two-month recorded wave data during the December, 2002, and January, 2003, was selected to verify the results of calibration process. Fig. 3 gives a comparison between measured and modeled wave height in the verification period. As seen, simulations follow the wave climate trend quite well both in calibration and verification period. But there are a few inconsistencies or delays between measured and modeled data. This could be due to using spatially-constant wind speed and ignoring the wind speed variability on the sea surface. In addition, orography effects on the recorded wind data may result in the existent inconsistencies.

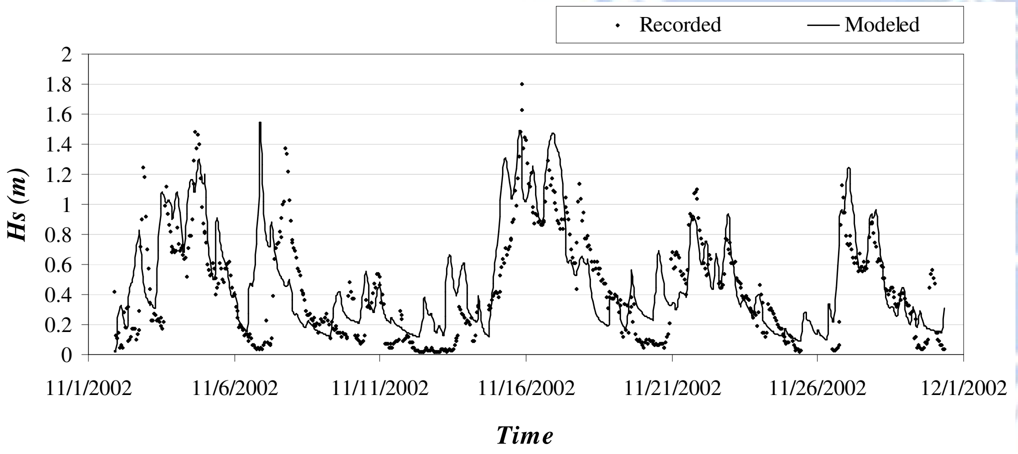

Fig. 2. Comparison of modeled and recorded wave height in the calibration period.

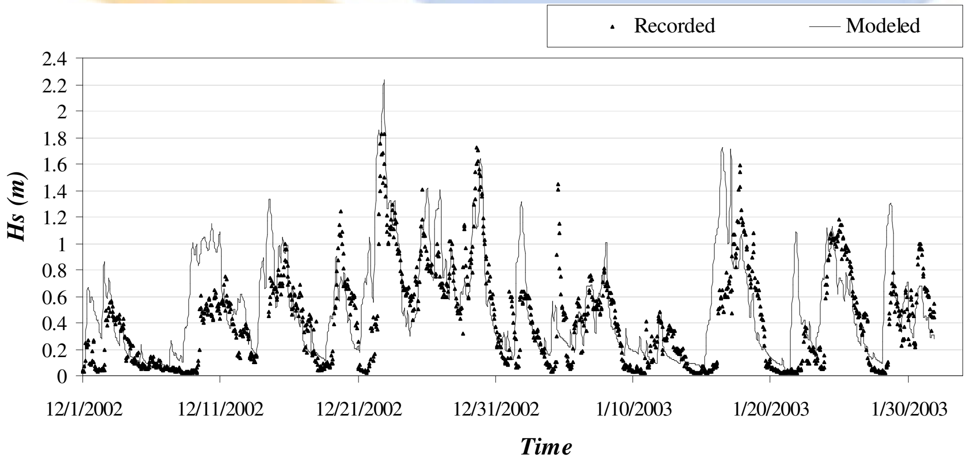

Fig. 3. Comparison of modeled and recorded wave height in the verification period.

After calibration and verification of the SWAN model one year wave hindcasting was implemented corresponding to the measured data.

Extreme value analysis was conducted using modeled and measured wave heights. Peak over threshold method was used for determination of extreme waves. A threshold wave height of 0.5 m was selected for the present analysis. The probability of exceedence was calculated using grouped data. The Normal, Log-Normal, Gumbel and Weibull distributions (Kamphuis, 2000) were used for extreme value prediction. The correlation coefficients between reduced variates of these distributions and significant wave height are presented in table 1 for modeled and measured data.

Table 1. Correlation coefficients for distribution functions

Distribution	**Correlation Coefficient**	
	Measured data	**Modeled data**
Normal	0.9776	0.9809
Log_Normal	0.9856	0.9939
Gumbel	0.9852	0.9959
Weibul	0.9900	0.9963

As seen in table 1, the Weibull distribution is better than other distributions and has the highest correlation coefficient. It should be noticed that the shape parameter for Weibull distribution was found to be 1.6 for both measured and modeled data.

Table 2 shows the extreme wave heights with different return period for both measured and simulated data predicted by the Weibull distribution. The third row of the table 2 is the relative error between extreme wave heights obtained from measured and simulated data computed as:

$$Error = \frac{(H_{simulated} - H_{Measured})}{H_{Measured}} \times 100 \qquad (4)$$

Table 2. The extreme wave heights for different return period with 0.5 m threshold and weibull distribution

Data	**Return period (year)**				
	2	5	10	20	50
Measured	2.13	2.32	2.46	2.59	2.76
Simulated	2.34	2.55	2.76	2.92	3.13
Error (%)	9.94	9.98	12.14	12.66	13.32

As seen in table 2, the errors of prediction of extreme wave heights with simulated data are between 10 to 14 percent for 2-50 year return periods. So it can be concluded that the numerically simulated wave data forced with Dayyer synoptic wind can be used as a suitable database for prediction of design wave height. In addition, according to table 2, the errors increase as the return period increases. This phenomenon shows the increase of confidence intervals for higher return periods.

To investigate the effect of threshold value on the estimation of design wave height a threshold wave height of 1 m was selected and extreme value analysis was implemented again. Table 3 presents the extreme wave heights predicted by the weibull distribution with 1 m threshold.

Table 3. the extreme wave heights predicted by the weibull distribution with 1 m threshold

Data	**Return period (year)**				
	2	5	10	20	50
Measured	2.04	2.20	2.32	2.43	2.57
Simulated	2.31	2.52	2.73	2.90	3.09
Error (%)	13.00	14.35	17.70	19.27	20.02

According to table 2 and 3 the amount of errors increases as the threshold value changes from 0.5 to 1 meter. But the difference between extreme wave heights with threshold value of 0.5 and 1 meter obtained from simulated data is at most about 7 percent for 50 year return period. This value is about 1 percent for the measured data. Therefore, it can be conferred that the level of threshold has a little effect on the extreme wave heights. This finding is in agreement with Kamphuis (2000).

In some cases the directional analysis of extreme wave heights becomes a necessary procedure. Thus, it is useful to investigate the effect of directional analysis on the extreme wave heights. For this purpose the data were divided into 22.5^0 sectors and extreme value analysis was carried out as well. Fig. 4 represents comparison of 5-year directional design wave height obtained from the modeled and measured data. As seen in Fig. 4, the maximum design wave height for modeled data is about 2.70 m for WSW direction. This value is higher than 5-year wave height obtained from the whole data. So it can be concluded that directional extreme value analysis may result in higher values. Note that this sample of directional data is somewhat small and this finding should be investigated by analysis of a wide range of data.

In addition, as seen in Fig. 4, the differences between 5-year design wave heights obtained from measured and simulated wave heights are less than 10 percents for all effective directions. Therefore, it could be concluded that synoptic wind data can be used for estimation of extreme waves with reasonable accuracy in this case.

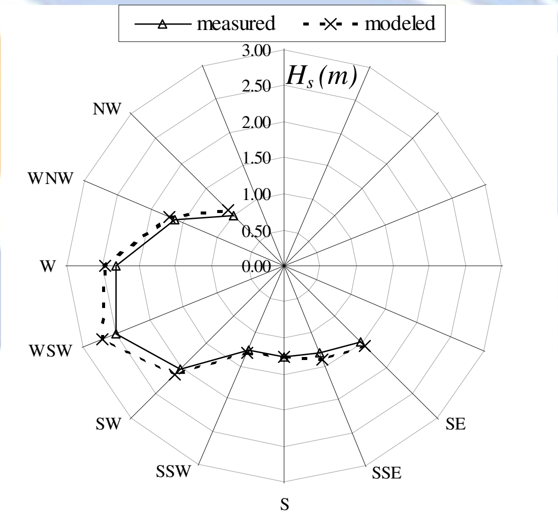

Fig. 4. Comparison of 5-year design wave height obtained from the modeled and measured data

Summary and Conclusion

In this study the SWAN third generation wave model was used for wave simulation in Asaluyeh at the Northern coasts of the Persian Gulf. The SWAN model was forced with Dayyer synoptic wind data. There were some inconsistencies between recorded and simulated data mainly due to the quality of wind source influenced by the orography effects. In addition, using spatially-constant wind speed and ignoring the wind speed variability on the sea surface might affect the results. The extreme value analysis was conducted using peak over threshold method. It was found that the numerically simulated wave data forced with Dayyer synoptic wind can be used as a suitable database for prediction of design wave height. In addition, the Weibull distribution was found to be the best distribution for estimation of extreme waves. The effect of threshold value was not significant on the estimation of design wave heights.

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