Investigation of wind induced wave climate close to the Koohmobarak Area, Gulf of Oman

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Abstract

Wind induced wave is of great importance due to its high energy. In this study wave climate in the Gulf of Oman close to the Koohmobarak area is investigated. Wave climate study is necessary for determination of long-term analysis of wave statistics as well as climate change effects in the study area. First, wave climate is study using both measured and simulated wave data close to the study area. Due to the lack of reliable wave data, long-term simulation, i.e. 35 years simulation, is carried out to find the wave characteristics in the Gulf of Oman. Since, the Gulf of Oman might be affected by swells from the Indian Ocean, large scale wave simulation all over the Indian Ocean is performed using WAVEWATCH III model. Then, medium scale wave simulation with fine mesh is carried out close to the study area and yearly and monthly wave roses are determined.

Keywords: WAVEWATCH III, ERA5, wave modelling, ISWM, Monitoring

1. Introduction

Wind-induced waves are usually considered as the most important waves in the wave spectrum at sea. Wave height and period increase as wind speed, wind duration or fetch length increase. Therefore, the characteristics of generated waves are a function of wind speed, wind duration and effective fetch length, and so on.

Because of the high energy of the wind-induce waves, determination of their characteristics for engineering analysis and design of nearshore and offshore structures is of great importance. In this regard, determination of wave parameters in deep water as well as wave transformation from deep water to shallow water is required. In this study the wave climate in the Koohmobarak area (Figure 1) is investigated. The study area is located at the southern part of the Strait of Hormuz, about 3 km north of Koohmobarak with geographic coordinates of 57.288 E and 25.857 N (Figure 1). The closest port to the study area is the Koohmobarak port. In the present study, long-term wave characteristic in deep water of the study area is investigated. Prior to numerical simulation, different sources of wave data in the study area were investigated to find the general wave climate in the area.

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2. Materials and Methods

2.1. Available wave data

In this study, two sources of data have been investigated in order to study the wave condition in the study area and extract some wave characteristics from the available data sources.

- Wave data from ISWM project
- Wave data from monitoring and modeling studies of Hormozgan Province project
- Measured wave data in monitoring and modeling studies of Hormozgan Province project

Location of available sources of wave data is illustrated in Figure 2.

2.2. Wave data from ISWM project

Long-term wave modeling (11 years) in Iranian Seas has been carried out in ISWM project. To do so, third generation spectral wave model (SW module) of MIKE 21 software for the period of 1992 to 2002 was used. As mentioned before modified ECMWF wind data has been used as the model forcing and the obtained results of wave simulation were evaluated based on the available buoy and satellite data. Figure 3 shows the position of the existing stations from the ISWM project in the vicinity of the study area. Time series of wave data in these four stations were obtained and analyzed.

Figure 4 shows the annual wave rose at different ISWM stations around the study area. Comparison of wave rose at different stations shows that in addition to the west and northwest waves, the study area is also affected by southeast waves. These waves propagate from the Oman Sea to the Strait of Hormuz. It should be noted that due to the presence of a shoreline changes orientation, some of these waves do not reach the study area. Comparison of wave rose at ISWM-15-43 and ISWM-14-43 indicates that southeast waves reached to the study area with less intensity after making changes in the direction of the waves.
Figure 2: Location of different wave data sources close to the study area

Figure 3: Location of ISWM model outputs close to the study area
2.3. Wave data provided by monitoring project simulations

In monitoring and modeling studies of Hormozgan Province project, long-term wave modeling for a period of 27 years (1983 - 2009) was carried out. Wave modeling was performed using the WAVEWATCH III model. Results of wave simulation at a point close to the study area were available (Figure 2). This point corresponds to a water depth of about 90 m. The time series data for this point includes the wave height, period and direction. The highest recorded wave height of the device is about 3.9 m (westerly).

Figure 5 shows the annual wave rose close to the study area (as shown in Figure 2) based on simulated waves in monitoring project. It is seen that the prevailing wave direction is southeasterly, while westerly waves are also important. It is necessary to explain that the selected station directly is exposed to the southeast waves, and therefore, the southeast waves reach this station without changing their intensity and direction. The location of the study area does not seem to be affected by southeast waves.
2.4. Measured wave data provided by monitoring project simulations

For monitoring project, several wave measuring stations were installed in the locations shown in Figure 2. The first device called ADP was installed at longitude 57.049569° and latitude 26.675494° and at a depth of 8 meters in the Sirik region. The device has recorded hourly wave data for three months (from 15/10/2009 to 16/01/2010). The maximum wave height recorded by this device is about 1.5 meter coming from direction 234°. The wave rose derived from this measurement is presented in Figure 6. It is clearly seen that the direction of dominant waves is from the southwest. Also, according to the measured data at this station, about 87 percent of the time, the wave height in the region is less than 0.3 m.

![Figure 6: Wave rose at Sirik based on measurements](image)

The second device which is called Mini was installed at longitude 57.290547° and latitude 25.818181° at a depth of 8 meters in the Koohmobarak region (Figure 2). This device recorded hourly wave data for 46 days (from 2/11/2010 to 18/12/2010). The maximum wave height recorded by this device is about 0.8 m from direction 250°. The measured wave rose of this device is shown in Fig 7. According to this figure, it is clearly seen that the direction of the prevailing waves is similar to the data provided by the ISWM from the west. Also, according to measured data at this station, about 83% of the time, the wave height in the region is less than 0.3 m.

![Figure 7: Wave rose at Koohmobarak based on measurements](image)

The third device, AWAC, is located at longitude 57.753447° and latitude 25.608077° located at a depth of 25 meters in Jask area (Figure 2). This device recorded hourly wave data for about 6 months (from 07/07/2010 to 23/01/2011). The maximum wave height measured at this station was about 1.8 m (southeast). The wave rose derived from this measurement is shown in Figure 8. It is clearly seen that the dominant wave direction in this area is similar to those provided by the ISWM and monitoring projects from the southeast. Also, according to the measured wave data at this station, about 22 percent of the time, the wave height in the region is less than 0.3 meters.

![Figure 8: Wave rose at Jask based on measurements](image)
2.5. Analyzing the available wave data

According to the available data and plotted wave roses, it can be concluded that in deep water the dominant waves are westerly and southeasterly. However, due to the shoreline changes orientation south of the study area, southeastern waves do not appear to be affecting the nearshore area in front of the study area. Due to the importance of long term accurate wave data for design of nearshore and offshore structures, it seems that the available wave data are not reliable enough, especially for extreme value analysis. Therefore, long term wave simulation is necessary. To do so, large scale wave modeling is carried out using WAVEWATCH III model. Then, medium scale wave modeling is carried out using SW module of MIKE 21 software. Prior to the long term (35 years) wave modeling, model calibration and validation are performed using available measured data.

3. Large scale wave simulation

Long-term deep water wave data is required within the study area. According to the location of the study area and based on available wave data, this area can be affected by the waves coming from the Oman Sea/ Arabian Sea, as well as waves generated in the eastern part of the Persian Gulf and the Strait of Hormuz. In fact, the area could be slightly affected by the swell waves of the Indian Ocean. The main objective of the large scale wave modeling is to prepare accurate boundary conditions on two lines for the medium scale wave model which will be presented in the next section. Figure 9 shows the location of the model output for providing the open boundary conditions of the medium scale model. To provide the wave results on the open boundaries, wave simulation for 35 years in the period of 01/01/1984-30/12/2018 is carried out.

Figure 9: Location of large scale model output on two lines for providing the open boundary conditions of the medium scale model

3.1. Computational domain and boundary conditions

One of the common issues in wave modeling is the availability of reliable data as the open boundary condition. In this study, wave modelling is carried out by simulating waves in the Indian Ocean from Indonesia in east to African shores in west, and the Persian Gulf, Gulf of Oman and Bay of Bengal in...
north to Antarctica in south (Figure 10). Although a smaller domain could be considered for modelling, but some possible effects from different parts of the Indian Ocean, like swells, might not be fully reflected in final results. In fact, one of the main reasons for selecting large computational domain including the entire Indian Ocean for wave modeling is attributed to the open boundary condition. This is due to the fact that there was no efficient and reliable data source available for 35 years to use as input for open boundary conditions near the desired location. Thus, considering the large computational domain, there is no need to apply boundary conditions on the open boundaries.

Since only the northern part of Indian Ocean, particularly Persian Gulf, Gulf of Oman and Strait of Hormuz were important in terms of accuracy of results and inserting more effect on the study area, the whole domain was divided into 3 sub-domains with mosaic setup and different spatial resolutions (Figure 10). By approaching to the north of domain (from Rank I to Rank III sub-domains), the spatial resolution of domains were getting finer for achieving more accurate results for the intended area. The computational domain, three sub-domains and spatial resolutions are presented in Figure 10. Sub-domains I, II and III were respectively discretized in structured rectangular grid with resolutions of 0.75⁰, 0.25⁰ and 0.1⁰ in both longitude and latitude directions. Thus, by reducing the computational time, the accuracy of wave modeling in the desired area is not reduced.

3.2. Numerical Model

In order to achieve the deep water long-term wave data (for 35 years) close to the study area, large-scale wave modeling is carried out using WAVEWATCH III® of version 5.16 (WW3DG, 2016). This is a full spectral third-generation wave model developed at National Centers for Environmental Prediction (NCEP/NOAA) that solves the balance equation for the wave action density spectrum (DN/Dt=S/σ, D/Dt is the total derivative, N is the wave action density spectrum, S is the net source and sink terms and σ represents the relative frequency in either Cartesian or spherical coordinate system). In the conservative form several physical processes are considered in source terms (S) including wind-wave interaction, quadratic nonlinear wave-wave interaction and whitecapping dissipation as the governing processes.
in deep water as well as several shallow water processes, such as bottom friction, surf-breaking (i.e., depth-induced breaking) and scattering due to wave-bottom interactions.

Nonlinear wave–wave interaction is responsible for the energy transfer from frequencies close to the peak frequency to both low and high frequencies, which is important during wave development and distinguishes the third generation models from earlier generations. Wind-wave interaction and whitecapping dissipation represent separate physical processes; however, they are somehow interrelated due to the fact that the balance of these two source terms governs the integral growth characteristics of the wave model (Tolman, 2014). In WWIII model, several source term packages are available to calculate $\text{Sin}$ and $\text{Sds}$ including WAM cycle 3 (Komen et al., 1984), Tolman and Chalikov’s (1996), WAM cycle 4 (Gunther et al., 1992) and Ardhuin et al.’s (2010) which can be employed in model by activation of ST1, ST2, ST3 and ST4 switches, respectively.

The spectral space was discretized over 30 logarithmically spaced frequencies ranging from 0.04 to 0.635 Hz and 24 directions with 15° resolution using Discrete Interaction Approximation (DIA) method (Hasselmann et al., 1985) which includes the nonlinear wave-wave interaction. In addition, source term packages of WAM Cycle 4 with BJA parameterization was used for calculating wind-wave interaction and whitecapping dissipation.

3.3. Bathymetry and wind data

Numerical wave models require extensive input data, such as bathymetric and time series of wind field datasets. In this study, the 1-arc minute ETOPO1 bathymetry data (Amante and Eakins, 2009) was used as the bathymetric data (Figure 11). It should be noted that gridgenv3.0 grid generating program, which comes as an auxiliary piece of code for WWIII, was employed for creating modelling prerequisite bathymetry, land mask and two-way obstruction files.

Wind field data is the most important forcing data for wave modelling. According to studies performed in the previous section, ERA5 wind speed with spatial and temporal resolution of $0.25^\circ \times 0.25^\circ$ and 3-hour is used for wave modeling.

Figure 11: Bathymetry data for the whole computational domain (1 arc-minute)
3.4. Model outputs

As mentioned before, large scale modelling is carried out to provide the boundary conditions for medium scale model. Therefore, time series of wave height, period, direction and directional standard deviation on two lines illustrated in Figure 9 were extracted from the WAVEWATCH III model. Figure 12 shows the time series of simulated significant wave height at STL2 point as shown in Figure 9.

![Figure 12: Ten year time series of simulated significant wave height STL2 point as shown in Figure 9](image)

4. Medium scale wave modelling

After 35-year modeling of the waves by the WAVEWATCH III model and calculating wave characteristics on the lines shown in Figure 9, another long-term modeling is done to determine the long-term wave parameters in deep water within the study area. This modelling is called medium scale wave modeling which is described in this section.

4.1. Numerical model

MIKE 21 SW includes a new generation spectral wind-wave model based on unstructured meshes. The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas. Fully spectral formulation of MIKE 21 SW is used for wave modeling. The fully spectral formulation is based on the wave action conservation equation, as described in e.g. Komen et al. (1994) and Young (1999), where the directional-frequency wave action spectrum is the dependent variable. The basic conservation equations are formulated in either Cartesian co-ordinates for small-scale applications or polar spherical co-ordinates for large-scale applications.

The discretization of the governing equation in geographical and spectral space is performed using cell-centered finite volume method. In the geographical domain, an unstructured mesh technique is used. The time integration is performed using a fractional step approach where a multi-sequence explicit method is applied for the propagation of wave action. MIKE 21 SW is used for the assessment of wave climates in offshore and coastal areas. A major application area is the design of offshore, coastal and port structures where accurate assessment of wave loads is of utmost importance to the safe and economic design of these structures.

MIKE 21 SW is particularly applicable for simultaneous wave prediction and analysis on regional scale and local scale. This module handle the several phenomena including shoaling, refraction, bottom dissipation, wave breaking, wind-wave generation, frequency spreading directional spreading, wave-wave interaction and wave-current interaction.

The dynamics of the gravity waves are described by the transport equation for wave action density. In horizontal Cartesian co-ordinates, the conservation
equation for wave action can be written as:

$$\frac{\partial N}{\partial t} + \nabla.(\bar{v} N) = \frac{S}{\sigma}$$

Where $N(\vec{x}, \sigma, \theta, t)$ is the action density, $t$ is the time, $\vec{x} = (x, y)$ is the Cartesian co-ordinates, $\bar{v} = (c_x, c_y, c_\sigma, c_\theta)$ is the propagation velocity of a wave group in the four-dimensional phase space and $S$ is the source term for the energy balance equation. $\nabla$ is the four-dimensional differential operator. The energy source term, $S$, represents the superposition of source functions describing various physical phenomena

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{surf}$$

Where $S_{in}$ represents the generation of energy by wind, $S_{nl}$ is the wave energy transfer due non-linear wave-wave interaction, $S_{ds}$ is the dissipation of wave energy due to whitecapping, $S_{bot}$ is the dissipation due to bottom friction and $S_{surf}$ is the dissipation of wave energy due to depth-induced breaking.

4.2. Model setup

Making the mesh and bathymetry file is the first step in model setup. Applied bathymetry data includes data of National Cartographic Center, ETOPO1 data and recent local hydrographic data within the study area (scale is 1:1000). The generated mesh and bathymetry file as well as the open boundaries for medium scale wave model are shown in Figure 14. It is seen that in order to achieve accurate results within the study area, finer mesh is used close to the study area. In fact the mesh size varies from about 20 km in the distant area to less than 500 meters in the study area. It should be noted that in this model the water level is assumed as the MSL water level. This is due to the fact that the model results are used in relatively deep water where the water level variations due to the tide and storm surge are not affected the simulated wave parameters.

As can be seen in Figure 13, there are open boundaries on the left and right sides of the computational domain. Open boundary condition including wave height, period, direction and directional standard deviation, derived from large scale wave model, i.e. WAVEWATCH III results, are implemented on the open boundaries.

4.3. Model calibration

The results of the model are calibrated with the measured data at three stations mentioned in the previous section, which include Kooomobarak Mini, Jask AW and Sirik ADP. It should be noted that in all simulations, ERA5 wind speed was used as the model forcing. Several parameters that could affect the simulated wind-induced wave simulation results were investigated in the MIKE21 SW wave model. These parameters include the computational mesh size, number of spectral frequency and direction, accuracy of the computational method, wave breaking coefficients, bottom friction and whitecapping coefficients. In the calibration step, abovementioned parameters are tuned to provide more accurate results.

According to the several numerical tests, number of direction and frequency were set to 25 and 16, respectively for the spectral discretization. Also, numerical tests showed that decreasing the computational mesh size is somewhat effective in improving the modeling results, but further reduction of mesh size only increase the computational cost with no improvements of modeling results. Finally, the mesh size was chosen optimally so that spatial discretization does not affect the model results. Results indicated that the main calibration parameters are the whitecapping and bottom friction coefficients. Therefore, several simulations have been carried out to find the best coefficients as presented in Table 1.
Figure 13: Computational domain, applied mesh and location of open boundaries in medium scale wave model

Table 1: Default and calibrated MIKE 21 SW model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default values</th>
<th>Calibrated values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nikuradse Roughness (kn)</td>
<td>0.04</td>
<td>0.002</td>
</tr>
<tr>
<td>Whitecapping (Cdis)</td>
<td>4.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
5. Results and discussion

5.1. Model validation

5.1.1. Model validation at Sirik (ADP device)

As mentioned in the previous sections, the ADP device recorded wave data hourly at a depth of 8 meters for three months in Sirik region. Figure 14 shows the comparison of ADP-measured wave rose and numerically simulated one in Sirik. As seen, it is clear that the numerical model has generally predicted the wave direction in the region well. It seems that the predicted waves are rotated about 22.5 degrees in comparison with the measured values. In addition, the percentage of calm condition of the sea in the region (the wave heights less than 0.3 m) is about 86% according to the measured results, while based on the numerical model, it is about 69%. This means that the results of the numerical model are slightly high for predicting low waves, which will lead to a conservative design.

Figure 15 shows the comparison of the measured wave height and direction and the numerically simulated ones. It is clearly seen that the numerical model has a good performance in prediction of waves with height of more than 0.3 m. However, the numerical model over-predicted the waves with the height of less than 0.3 m. It should be noted that these waves with height of less than 0.3 m are not important for the extreme value analysis and design of structures, therefore it can be concluded that the model performance for the prediction of wave characteristics is acceptable for the Sirik region.
5.1.2. Evaluation of the model results in Koohmobarak (MINI device)

As mentioned before, a wave measurement device was placed at the depths of 8 m in Koohmobarak area for 46 days to record the time series of wave characteristics every hour. Figure 16 shows the comparison of the measured and simulated wave roses in Koohmobarak. Based on this figure, it is clear that the numerical model has generally well predicted the wave direction in the region. In addition, according to the measured results, the percentage of calm condition in the region is about 83%, while the numerical model predicted this value about 88%. Therefore, the overall performance of the model is acceptable in the prediction of the wave height and direction.

In order to more investigate the modeled wave parameters, Figure 17 shows the comparison of the measured and modeled wave height and direction in Koohmobarak area. It can be seen that the numerical model is capable of modelling the relatively extreme conditions with more intense waves. However, unlike the Sirik station, the numerical model slightly under-predicted the waves with the height of less than 0.3 m. As mentioned before, these waves are not important for the design of structures in this study and therefore, similar to Sirik region the model performance for the prediction of wave characteristics is seems acceptable for the Koohmobarak region.

Figure 16: The comparison of the measured wave roses using MINI device and the simulated one in Koohmobarak

Figure 17: The comparison of the measured and simulated wave height and direction in Koohmobarak region
5.1.3. Evaluation of the model results in Jask (AWAK device)

As mentioned before, a wave measurement device was placed at location with depth of 25 m in Jask area for 6 months to record the time series of wave characteristics every hour. Figure 18 shows the comparison of AWAC-measured wave rose and numerically simulated one in Jask. As seen, it is clear that the numerical model has generally predicted the dominant wave direction in the region well. In addition, the percentage of calm condition of the sea in the region (the wave heights less than 0.3 m) is about 20% according to the measured results, while based on the numerical model, it is about 3%. This means that the numerical model slightly overestimates the wave heights for relatively calm conditions (the wave heights less than 0.3 m). In addition, Figure 19 shows the comparison of the height and direction of the measured waves by this device and the numerically modeled ones. It can be seen that the numerical model has been able to predict the waves well in the region in these six months. Storm peaks (except one case) were also well simulated. It seems that the model has a good performance in the prediction of wave characteristics in Jask area similar to those observed in the other locations, i.e. Sirik and Koohmobarak.

Figure 18: The comparison of the measured wave roses using MINI device and the simulated one in Jask region

Figure 19: The comparison of the measured and simulated wave height and direction in Jask region
5.1.4. Quantitative validation of the medium scale wave model

To further investigate the performance of MIKE21 SW module employing ERA5 wind field, error indices including BIAS, SI, and R indices were calculated for cases with observed wave height greater than 0.5 m (Kazeminezhad et al. 2005; Kazeminezhad and Siadatmousavi 2017) and presented in Table 2. It is seen that in all of the stations, the value of R is more than 0.7, which shows the good correlation between the measured and modeled significant wave height. In addition, the BIAS value is also close to zero, and this indicates that the average difference between the measured and modeled wave heights is negligible. On the other hand, the scatter of data for all the stations is less than 30%, which is an acceptable error range in the prediction of the wave heights.

![Figure 20: Location of selected points in the study area for analysis of the wave](image)

Table 2: Error indicators for HS simulation from MIKE21 SW using ERA5 wind source at different stations

<table>
<thead>
<tr>
<th>Station</th>
<th>SI</th>
<th>R</th>
<th>BIAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sirik</td>
<td>0.24</td>
<td>0.75</td>
<td>-0.01</td>
</tr>
<tr>
<td>Koohmobarak</td>
<td>0.30</td>
<td>0.78</td>
<td>-0.07</td>
</tr>
<tr>
<td>Jask</td>
<td>0.30</td>
<td>0.77</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

6. Wave analysis based on modeled results

The calibrated medium scaled wave model introduced in the previous section was used for long term simulation of wave pattern in the study area. Wave simulation has been performed for 35 years from 1984 to 2018. To analyze the wave condition in the study area, four stations were selected as illustrated in Figure 21. These stations are selected at depths of 60, 40, 20 and 10 meters, respectively. The exact locations of these points are given in Table 3.

Figure 21- Figure 24 show the wave rose plots for these points based on the 35 years model results, for P1, P2, P3 and P4 stations, respectively. Based on the obtained results, it is clear that in P1 station with 60 m depth, the dominant wave is mainly from the south-east (from 135 to 180 degrees). These waves reach the study area from the Oman Sea and include about 63% of the waves that reach the study area. The maximum significant wave height from this side at P1 station is about 3.0 m. In addition, in some cases the area is affected by waves with the height more than 2.7 m and frequency of 0.03% from the west and south-west (from 225 to 315 degrees). The maximum significant wave height from this side at P1 station is about 3.7 m.
The analysis of wave rose Figure 22 shows that the waves propagated from the Oman Sea at P2 station are oriented about 22.5 degrees southward (in comparison to P1 station), therefore the dominant direction of the waves at this station is from 155.5 up to 202.5 degrees. One of the reasons for this phenomenon can be the presence of a headland on the coastline of the Koohmobarak. The highest wave that reaches this station is about 2.4 m. It should be noted that the 2.4 m wave at this station is corresponded to a 3 m wave at the P1 station. Therefore, it can be concluded that the energy of incoming waves from the Oman Sea decrease at P2 station due to the large scale wave refraction. At this station, the western and southwest wave heights (from 225 to 315 degrees) are the same as P1 station. The maximum wave height in this direction at P2 station is about 3.6 m. To more investigate the large scale wave transformation close to the study area, wave field for two cases are presented in Figure 25 and Figure 26. Figure 25 shows the status of incoming waves from the south-west to the study area. It is clearly seen that for southwesterly waves, the study area is relatively located in the shadow area of the headland and these waves reach the study area after wave transformation. On the other hand, incoming waves from southwest reach to the study area with no serious change in their height and direction as illustrated in Figure 26.

Table 3: Location of the selected stations for analysis of the wave in the study area

<table>
<thead>
<tr>
<th>Point</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>25.84306</td>
<td>57.22389</td>
</tr>
<tr>
<td>P2</td>
<td>25.84925</td>
<td>57.24585</td>
</tr>
<tr>
<td>P3</td>
<td>25.85376</td>
<td>57.26151</td>
</tr>
<tr>
<td>P4</td>
<td>25.85677</td>
<td>57.27003</td>
</tr>
</tbody>
</table>
Figure 23 shows that the incoming waves from the Oman Sea to the P3 point with the 20 m depth are again exposed to a rotation of 22.5 degrees (clockwise). Among the incoming waves from the Oman Sea, the maximum significant wave height at this station is about 1.8 m from the south. The highest wave height at this station is about 3.4 m and comes from 256 degrees.

Figure 24 also shows that the wave characteristic at P4 with 10 m depth is approximately the same as those at 20 m depth. The maximum wave height in this point is about 3.2 m from 250 degrees.

Figure 23: The 35-year wave rose plot based on the simulation results in P3

Figure 24: The 35-year wave rose plot based on the simulation results in P4

Figure 25: The propagation of south-eastern waves near the study area
In order to study the wave climate in different months, monthly wave roses are plotted in Figure 27 based on 35-year simulated wave data at P1 station. As can be seen, the highest and lowest percentage of calm condition in the study area are in July (about 7%) and November (about 53%), respectively. In addition, Figure 27 shows that the highest waves occurred in the winter, and in particular February. On the other hand, the lowest wave height occurred in autumn and October. A closer examination of the wave roses shows that in the summer, most of the incoming waves to the P1 station are from the Oman Sea. Nevertheless, these waves always exist in all seasons, and their percentage is low in autumn, especially in November it is less than other months. Figure 28 also shows the maximum simulated significant wave height at P1 station for different months. It is seen that the maximum significant wave height (3.7 m) has been occurred in February.

7. Conclusions

- In deep water area, the dominant wave is mainly from the south-east (from 135 to 180 degrees). These waves reach the study area from the Oman Sea and include about 63% of the waves that reach the study area.
- The energy of incoming waves from the Gulf of Oman decrease in shallower water due to the large scale wave refraction and presence of a headland on the coastline of the Koombark.
- For southwesterly waves, the study area is relatively located in the shadow area of the headland and these waves reach the study area after wave transformation. On the other hand, incoming waves from southwest reach to the study area with no serious change in their height.
Figure 27: The monthly wave roses at P1 station based on 35 years wave simulation

Figure 28: The maximum simulated significant wave height in different months at P1
• The highest and lowest percentage of calm condition in the study area occur in July (about 7%) and November (about 53%), respectively.

• The highest waves occurred in the winter, and in particular February. The lowest wave height occurred in autumn and October.

• In summer, most of the incoming waves to the P1 station are from the Oman Sea. These waves always exist in all seasons, and their percentage is low in the autumn, especially in November it is less than other months.

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