International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2015): 78.96 | Impact Factor (2015): 6.391

Prediction of Wave Parameters off the Nile Delta Coast of Egypt Using Nonlinear Regression Analysis

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Abstract: ***The waves are the most important factor to be considered in the near-shore and offshore activities. Recently, the offshore Nile delta of the Arab republic of Egypt has seen many discoveries in the oil and gas filed, especially in front of Alexandria and Port Said. Therefore, obtaining a formula for predicting wave characteristics based on the measured data of is very important, which will contribute significantly to marine studies and the preliminary engineering design in such mega projects. In this study, the 3 hourly significant wave heights (H_s) and periods (T_s) with corresponding data such as wind speed (u), fetch data (F), sea level pressure (p) and air temperature (C_a) used in analyses based on the hourly observations data. This paper focuses on the prediction of significant wave parameters by using nonlinear regression method based on dimensionless analysis (pi-theorem). Measured offshore waves and meteorological data for Alexandria and Port Said regions, located on the Nile delta coast of Egypt, used in this study. This study aims to find suitable formulas to predict the wave parameters, significant wave height (H_s) and period (T_s), for these regions and evaluating its performance. The results indicated that the formulas gave the satisfactory results that can be used to predict the offshore wave parameters for the Nile delta of Egypt safely.***

Keywords: Nile delta coast, wave parameters, dimensionless analysis, nonlinear regression, near-shore and offshore.

1. Introduction

The waves are the dominant active phenomenon involved in the activities related to the near-shore and offshore zones around the world. A significant amount of wave energy is dissipated at the near-shore region and on beaches. Wave energy forms beaches; sorts bottom sediments on the shore face; transports bottom materials and exerts forces upon coastal structures. So; the knowledge of wave parameters is important for almost near-shore and offshore engineering activities.

For this propose, there are several empirical and numerical methods described in literature, such as; SMB (Bretschneider, 1970), Wilson (Wilson, 1965), JONSWAP (Hasselmann et al., 1973), (Donelan, 1980), Shore Protection Manuel (SPM, 1984), Coastal Engineering Manuel (CEM, 2003), Kinsman (1965), World Meteorological Organization (WMO, 1988) and Goda (2003) [10].

These methods are predicting the appropriate wave parameters, such as; wave height and wave period from fetch length and wind speed. Generally; the empirical methods were developed based on the dimensionless parameters. These simplified methods are particularly preferred for solving of the practical engineering problems, especially during the feasibility study phase for offshore projects to select the project location and determine primary cost estimate and also it can be used in the preliminary design.
The need to study the waves in the deep water area of the Nile Delta of Egypt is the emergence of numerous discoveries of gas in recent years in this area, especially in front of Alexandria and Port Said areas (Figure 1).

Figure 1: Gas fields in offshore Nile Delta, Egypt. (M. Abdel-Aziz Younes, 2015) [11]

In this paper, the 3 hourly significant wave heights (H_s) were predicted from fetch data (F) and meteorological data such as; wind speed (u), sea level pressure (p), and air temperature (C_a) based on hourly observations data by using the nonlinear regression method based on dimensionless analysis.

This paper is organized as follows: the next section introduces method used in this study. Section 3 describes the study area and data description. Section 4 presents measures used to evaluate the accuracy results. Section 5 presents the results of the dimensionless method for each region. Finally, conclusions are reported in the last section.

2. Dimensional Analysis Method

Buckingham's π-theorem (Buckingham, 1914) is fundamental theorem (rule of thumb) of dimensional analysis, since this theorem has been well documented in the literatures (e.g. Fox and McDonald, 1994; Hwang and Houghtalen, 1996; White, 2003) [2].

Procedures for the formation of a complete set of dimensionless products start with a determining the number of dimensionless products can be formed.

If a physical problem involves (n) dimensional variables (q_1, q_2, q_3, ..., q_n). The relationship among the variables may be expressed in functional form such as:-

$$q_1 = f\,(q_2, q_3, ..., q_n) \quad (1)$$

Where: (q_1) is the dependent variable, $(q_2, q_3, ..., q_n)$ are (n-1) independent variables and (f) is an unspecified function (Kemal Günaydın, 2008).

If (m) is the number of fundamental dimensions (M, L and T) required to describe the (n) variables, the Buckingham's π-theorem stated that any such equation can be rearranged into a new equation expressed in terms of dimensionless products, or Pi terms. Such as:-

$$\pi_1 = \emptyset_1(\pi_2, \pi_3, \dots, \pi_{n-m}) \quad (2)$$

The required number of Pi terms is less than the number of original variables by the amount (m). Therefore, if the original variables (n) are independent, then the dimensionless products are equal to (n-m) [12].

3. Study Area and Data

The meteorological and wave data were gathered from deep water zone, open sea area, in the front of Alexandria and Port Said regions located on the coast of the northern Nile delta of Egypt (Figure 2).

The available offshore data for both Alexandria and Port Said regions were from the beginning of January 2010 to the end of December 2012 (for three years). The data have been collected and provided by Egyptian Navy Forces, Meteorological and Oceanographic Division, through the specialized people in this field.

Since the water depth and wave direction does not affect the form of waves in deep water zone, so they are not used in this study. The 3 hourly significant wave heights (H_s) and significant wave periods (T_s) accompanied with wind speed (u), fetch (F), sea level pressure (p), and air temperature (C_a) used in this study based on the available hourly observations data. The values of air temperature (C_a) was divided to the average air temperatures of year (C_{ay}) to be used in the analysis in this study as dimensionless air temperature ratio (C_a/C_{ay}).

3.1 Alexandria data description

Table 1 represents the values of the minimum, maximum and mean of all parameters have been used for Alexandria in this study.

Figure 3 shows the wave rose for Alexandria region from January 2010 to December 2012.

Figure 2: Study area location (Google map)

Table 1: Minimum, Maximum & Mean values for Alexandria datasets

Parameters	*Min. value*	*Max. value*	*Mean value*
U (m/s)	0.0	14.4	5.8
F (m)	0	4410	2812
P (kg/m2)	10012	10286	10129
C_a (°C)	9.6	40.2	22
H_s (m)	0.0	5.6	1.1
T_s (s)	0.0	15.6	5.6

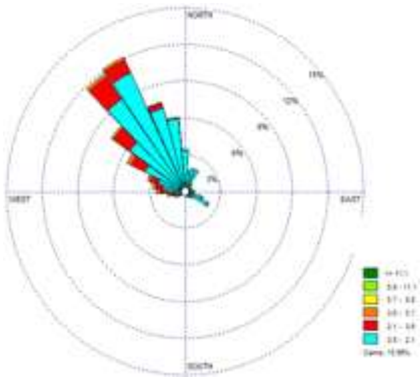

Figure 3: Alexandria wave rose

3.2 Port Said data description

Table 2 represents the values of the minimum, maximum and mean of all parameters have been used for Port Said in this study.

Figure 4 shows the wave rose for Port Said region from January 2010 to December 2012.

Table 2: Minimum, Maximum & Mean values for Port Said datasets

Parameters	Min. value	Max. value	Mean value
U (m/s)	0.0	14.4	5.2
F (m)	0	4590	2581
P (kg/m2)	10192	10508	10346
C_a (°C)	2.4	35.5	22.3
H_s (m)	0.0	5.5	0.86
T_s (s)	0.0	15.7	4.6

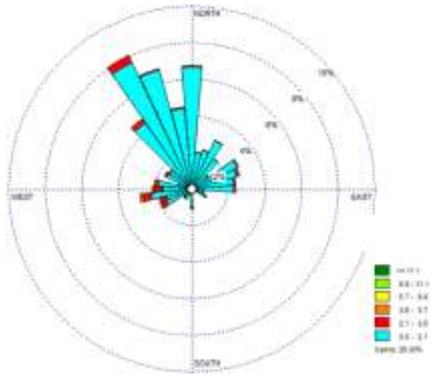

Figure 4: Port Said wave rose

4. Measures of Results Accuracy

Five measures correlation coefficient (R), mean square error (MSE), mean absolute error (MAE) and scatter index (SI) were used in this study to evaluate the accuracy results:

$$R = \frac{\sum_{i=1}^{n} (P_i - \bar{P})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2 \sum_{i=1}^{n} (O_i - \bar{O})^2}} \quad (3)$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n} (P_i - O_i)^2 \quad (4)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |(P_i - O_i)| \quad (5)$$

$$SI = \frac{RMSE}{\bar{O}} \quad (5)$$

$$Bias = (\bar{P} - \bar{O}) \quad (6)$$

In all the above measures, the O_i's represent the observation value, the P_i's represent the predicted value, n is the total number of observations, $\bar{O}$ is the mean of O_i and $\bar{P}$ is the mean of P_i.

5. Results and discussions

In this study, the data for two years (2010 and 2011) were used as a training data to find the prediction formulas for significant wave parameters (H_s) and (T_s). The data for one year (2012) was used as a testing data.

In general, the significant wave height (H_s) and (T_s) are considered the dependent variables, they can be expressed as a function of other independent variables as follows:-

$$H_s = f\left(U, F, \rho_w, g, P, \frac{C_a}{C_{ay}}\right) \quad (7)$$

$$T_s = f\left(U, F, \rho_w, g, P, \frac{C_a}{C_{ay}}\right) \quad (8)$$

The parameters of equations (7) and (8) were expressed in terms of dimensionless parameters by using pi-theorem as follows:-

$$\frac{H_s}{F} = \Phi\left(\frac{P}{U^2\rho_w}, \frac{g\,F}{U^2}, \frac{C_a}{C_{ay}}\right) \quad (9)$$

$$\frac{T_s U}{F} = \Phi\left(\frac{P}{U^2\rho_w}, \frac{g\,F}{U^2}, \frac{C_a}{C_{ay}}\right) \quad (10)$$

Then the dimensionless parameters given in equations (9) and (10) can be written in the following three dimensionless groups (G1, G2 and G3) in order to determine best-fit lines for these dimensionless groups:-

$$G1 = \left(\frac{U^2\rho_w}{P}\right)^{2.5} * \left(\frac{C_a}{C_{ay}}\right) \quad (11)$$

$$G2 = \left(\frac{H_s}{\sqrt{F}}\right) * \sqrt[3]{\left(\frac{U^2}{g\,F}\right)} \quad (12)$$

$$G3 = \left(\frac{T_s U}{F}\right) * \sqrt[3]{\left(\frac{U^2}{g\,F}\right)} \quad (13)$$

Where; G1 is a general group to be used with (H_s) and (T_s), G2 for significant wave height (H_s) and G3 for significant wave period (T_s).

Generally, the form of non-linear regression problem between the two dimensionless groups can be formulated in a power function equation form as illustrated in equations (14) and (15).

So, the formula for significant wave height(H_s):-

$$G_2 = A(G_1)^P \quad (14)$$

And for significant wave period (T_s):-

$$G_3 = A(G_1)^P \quad (15)$$

Where: (A) is the constant equal to $(e^{Intercept})$ for the linear regression output and (P) is the power equal to the slope (m) for the linear regression output.

Different A and P values were obtained for equation of each curve as presented in Sections 5.1 and 5.2.

5.1 Alexandria results

Based on the results from the Alexandria training datasets, the equations (16) and (17) were formulated for H_s and T_s respectively.

$$\frac{H_s}{F^{\left(\frac{5}{6}\right)}} * \sqrt[3]{\frac{U^2}{g}} = 5\times10^{-4}\left[\left(\frac{U^2\rho_w}{P}\right)^{2.5} * \left(\frac{C_a}{C_{ay}}\right)\right]^{0.470} \quad (16)$$

$$\frac{T_s}{F^{\left(\frac{4}{3}\right)}} * \frac{U^{\left(\frac{5}{3}\right)}}{\sqrt[3]{g}} = 3\times10^{-4}\left[\left(\frac{U^2\rho_w}{P}\right)^{2.5} * \left(\frac{C_a}{C_{ay}}\right)\right]^{0.485} \quad (17)$$

The best-fit curve between these dimensionless groups for (H_s) and (T_s) corresponding to equation (16) and (17) are presented in the following figures 5 and 6 respectively. To evaluate the results of predicted H_s and T_s for Alexandria region, the statistical errors between the predicted and observed values were displayed in Table 3 and Table 4 respectively.

Table 3: R, MSE, MAE, SI% and Bias for Alexandria H_s

H_s	R	MSE (m)	MAE (m)	SI%	Bias (m)
Eq. (16)	0.983	0.0736	0.185	21.46	0.167

The results stated in Table -3 revealed that the prediction Eq. (16) gives a very good value in the correlation factor (R) with high correlation value equal to 0.983, which refers to the extent of convergence between the data for the predicted and observed H_s. On the other hand, the lower values for MSE (m), MAE (m), SI% and Bias (m) indicated that the results of the prediction formula of H_s give less error. However, the positive value of bias (0.167 m) indicates that the prediction formula results are slightly overestimated for the values of significant wave height for this region.

Table 4: R, MSE, MAE, SI% and Bias for Alexandria T_s

T_s	R	MSE (sec)	MAE (sec)	SI%	Bias (sec)
Eq. (17)	0.969	2.306	1.139	23.78	1.089

The results stated in Table 4 indicated that the prediction using Eq. (17) gives a good value in the correlation factor (R = 0.969), which refers to the great convergence between the predicted and observed values of (T_s). On the other hand, the low values for MSE, MAE, SI and Bias indicated that the results of the predicted values of (T_s) give less errors. Also, the positive value of bias (1.098 sec) indicates that the results for the prediction formula are slightly overestimated but still within the reasonable limits.

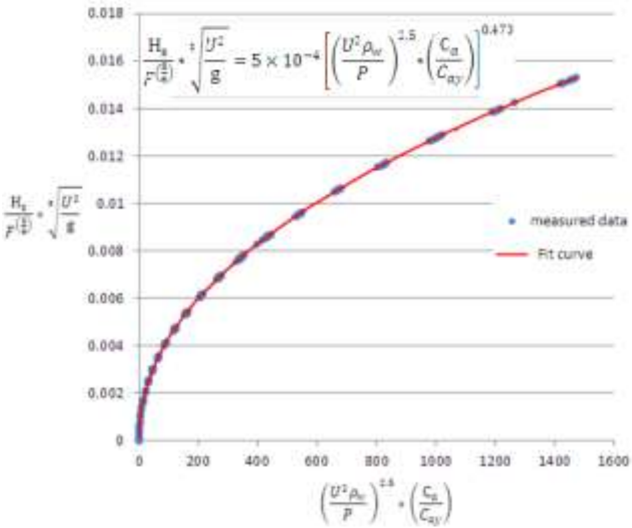

Figure 5: Best-Fit Curve for Alexandria H_s (Eq. 16)

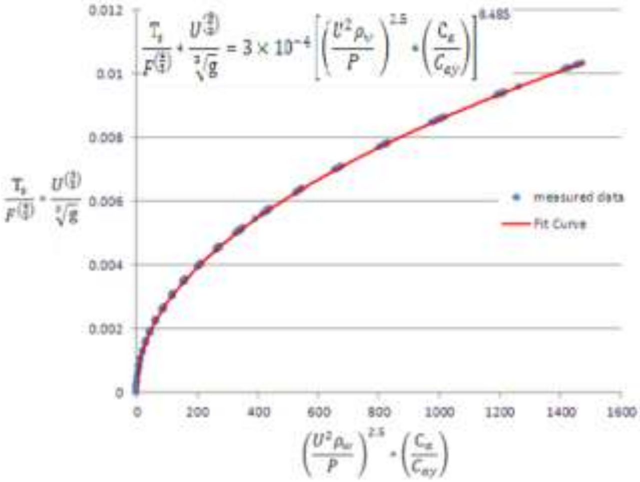

Figure 6: Best-Fit Curve for Alexandria T_s (Eq. 17)

The correlation between observed and predicted for H_s and T_s are shown in figures 7 and 8, respectively.

Figure 7 showed that the correlation between the predicted and observed for H_s gives good results with high accuracy for significant wave height up to 3.0 m, while the significant wave height more than 3.0 m decreasing in accuracy. Although the accuracy of results decrease with increasing significant wave height (for H_s> 3.0 m), they are still within acceptable range as the most of data of H_s for Alexandria region is less than or equal to 3.0 m.

Figure 8 shows that the correlation between the predicted and observed data for T_s seems in good conditions up to 10.0 sec, while the accuracy of results decrease with significant wave period greater than 10.0 sec. Overall, this figure is considered within acceptable range where the most of data of T_s for Alexandria region is equal or less than 10 sec.

Figures 9 and 10 present the observed and predicted values for H_s and T_s, respectively, in form of time series during the testing phase. It is obviously seen from figure 9 that the predicted values of significant wave height are very close to the observed values for $H_s \leq 3.0$ m, while for H_s greater than 3.0 m, the predicted values are slightly higher than the observed values. Finally, the trend of predicted values of H_s is very similar to the trend of observed values of H_s to give satisfactory results.

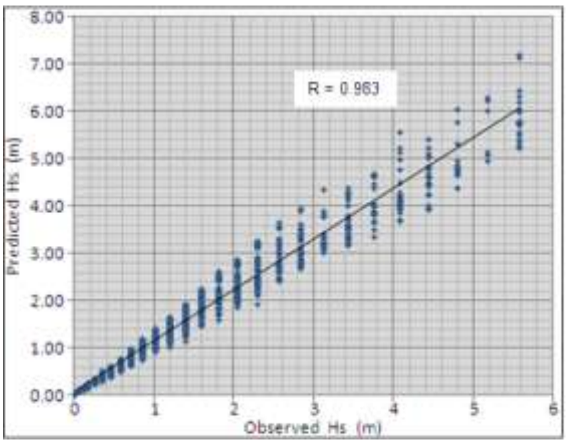

Figure 7: Correlation for Alexandria H_s

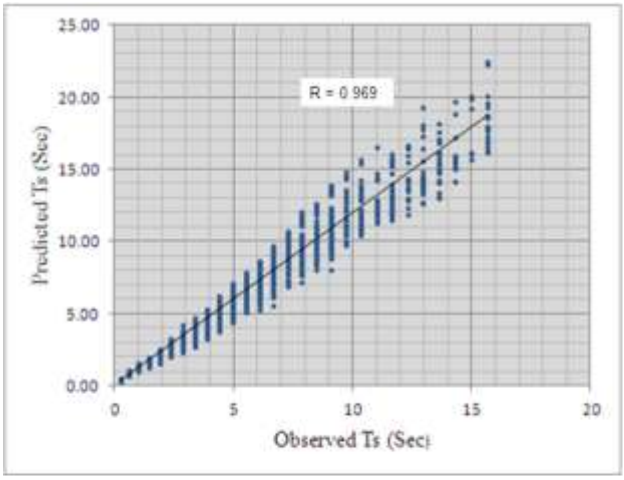

Figure 8: Correlation for Alexandria T_s

Figure 10 illustrates that the predicted values of significant wave period are very close to the observed values for T_s equal to or less than 10.0 seconds. It is noted that the values of T_s greater than 10.0 seconds give predicted values are slightly higher than the observed values. Overall, the predicted values for significant wav period of Alexandria region has trend as same as the trend of the observed values for this region.

5.2 Port Said results

Based on the results from the Port Said training datasets, the equations (18) and (19) were formulated for (H_s) and (T_s) respectively.

The best-fit curve for equation (18) and (19) are presented in the following figures 11 and 12 respectively.

$$\frac{H_s}{F^{\left(\frac{5}{6}\right)}} * \sqrt[3]{\frac{U^2}{g}} = 9 \times 10^{-4} \left[\left(\frac{U^2 \rho_w}{P} \right)^{2.5} * \left(\frac{C_a}{C_{ay}} \right) \right]^{0.430} \quad (18)$$

$$\frac{T_s}{F^{\left(\frac{4}{3}\right)}} * \frac{U^{\left(\frac{5}{3}\right)}}{\sqrt[3]{g}} = 3.5 \times 10^{-4} \left[\left(\frac{U^2 \rho_w}{P} \right)^{2.5} * \left(\frac{C_a}{C_{ay}} \right) \right]^{0.530} \quad (19)$$

To evaluate the results of predicted H_s and T_s for Port Said region, the statistical errors between the predicted and observed values were presented in Table 5 and Table 6 respectively.

Table 5: R, MSE, MAE, SI% and Bias for Port Said H_s

H_s	R	MSE (m)	MAE (m)	SI%	Bias (m)
Eq.(18)	0.969	0.051	0.169	28.47	-0.14

Table-5 shows that the results by the prediction Eq. (18) gives high value in correlation factor (R) equal to 0.969, that refer to the good convergence between the predicted and observed data for H_s while the results for MSE (m), MAE (m), SI% and Bias (m) give fairy low values which are indicated that the prediction by Eq. (18) are given satisfactory results with H_s. Also, the negative value of bias (-0.14 m) indicates that the prediction formula results are slightly underestimated for many values of significant wave height.

Table 6: R, MSE, MAE, SI% and Bias for Port Said T_s

T_s	R	MSE (sec)	MAE (sec)	SI%	Bias (sec)
Eq.(19)	0.928	1.92	1.233	34.26	-0.92

The results in Table 6 indicated that the prediction by Eq. (19) give a reasonable value with the correlation factor (equal to 0.928), that refer to the good convergence between the predicted and observed values of T_s. On the other hand, the low values for the MSE, MAE, SI% and Bias indicated that the results of predicted significant wave period give less error. Also, the negative value of bias (-0.92 sec) indicates that the most of results regarding the prediction Eq. (19) are slightly underestimated.

The correlation between observed and predicted for H_s and T_s are shown in figures 13 and 14, respectively.

Figure 13 showed that the correlation coefficient (R) provides fairly good results. Also, this figure indicates that the correlation between the predicted and observed H_s gives very good results with high accuracy for significant wave height up to 2.5 m, while the significant wave height more than 2.5 m have less accuracy in its results. Although the accuracy of correlation shown in figure 13 decreases as H_s increases, it considers within the acceptable range as the most of data along Port Said region are less than or equal to 2.5 m.

Figure 14 showed that the correlation (R) between the data has a good relationship (≈93%). Also, the correlation between the predicted and observed significant wave period

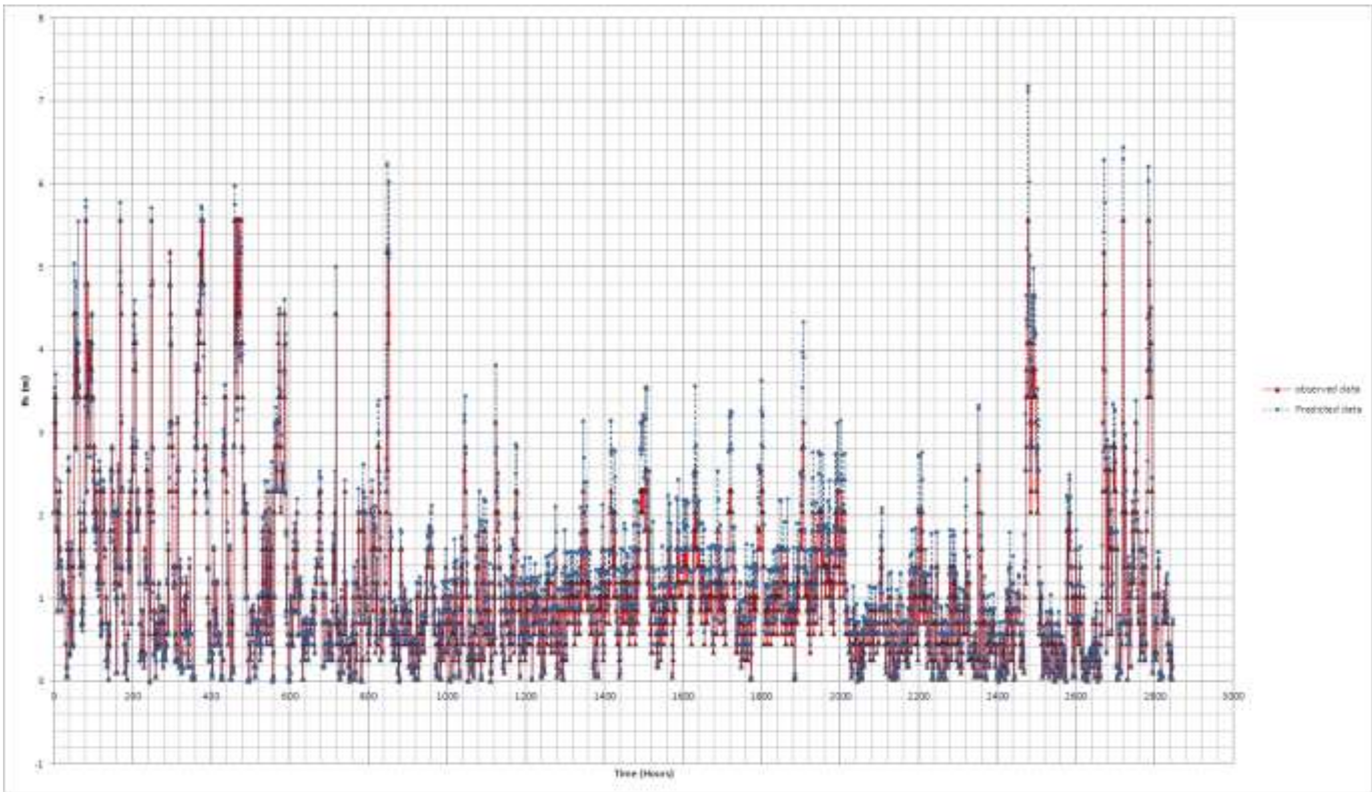

Figure 9: Comparison predicted values by Eq. (16) and observed values for Alexandria H_s

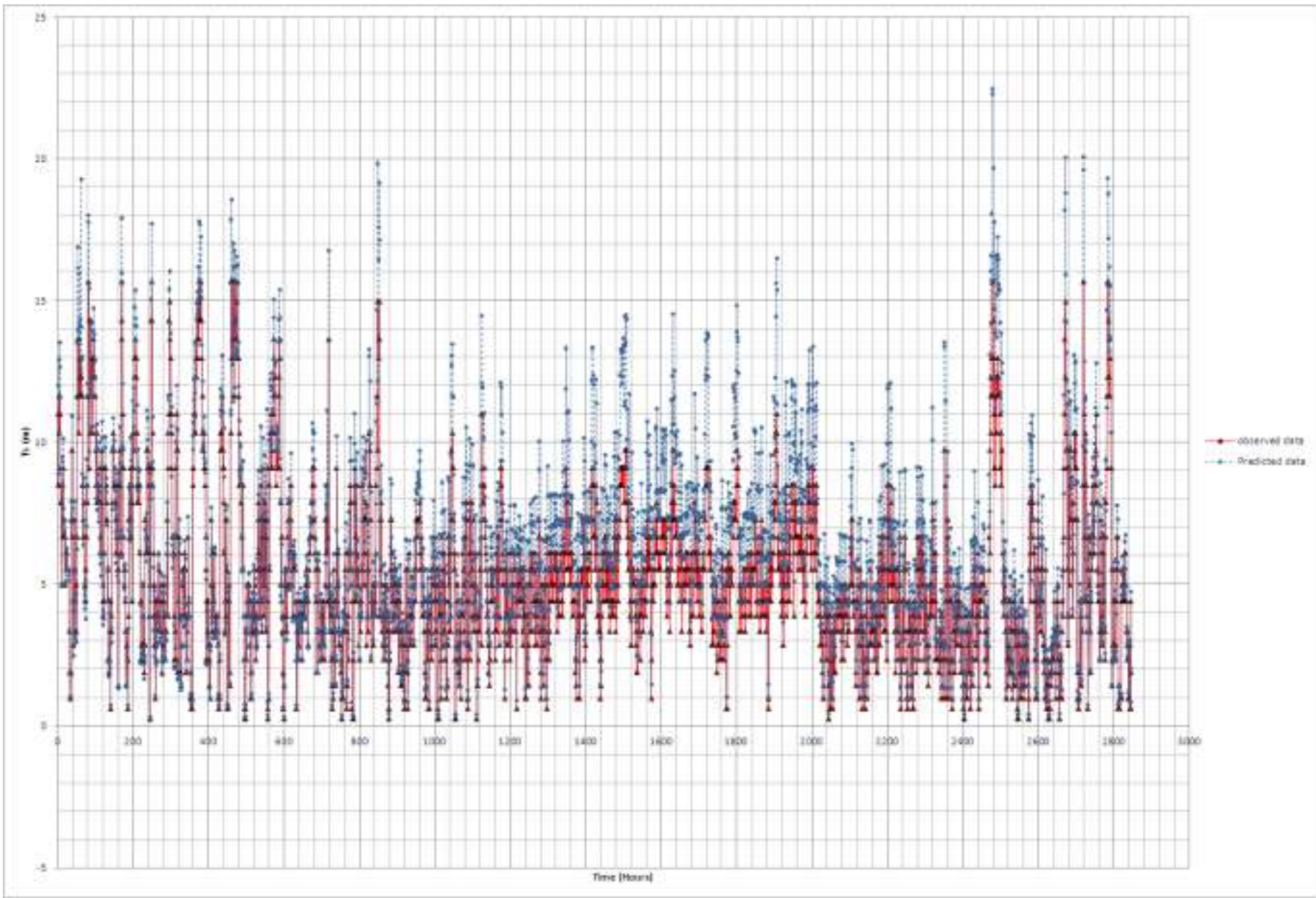

Figure 10: Comparison predicted values by Eq. (17) and observed values for Alexandria T_s

gives good results with T_s up to 8.0 sec, while the accuracy of results decrease with significant wave period greater than 8.0 sec. Overall, this figure is considered within acceptable range where the most of data for Port Said region is equal or less than 8 sec.

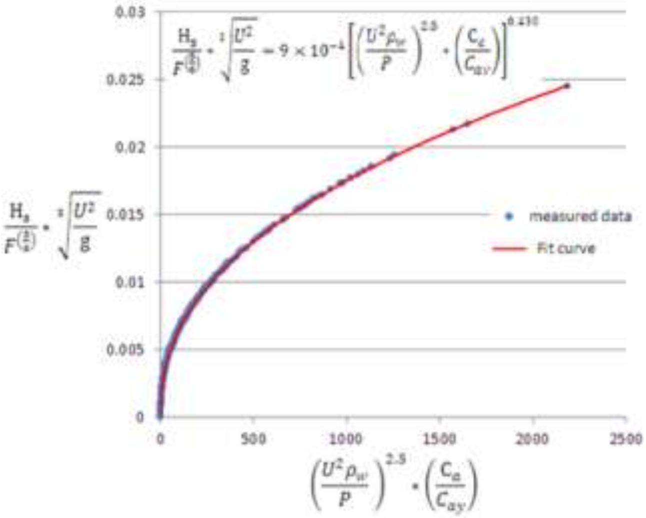

Figure 11: Best-Fit Curve for Port Said H_s (Eq. 18)

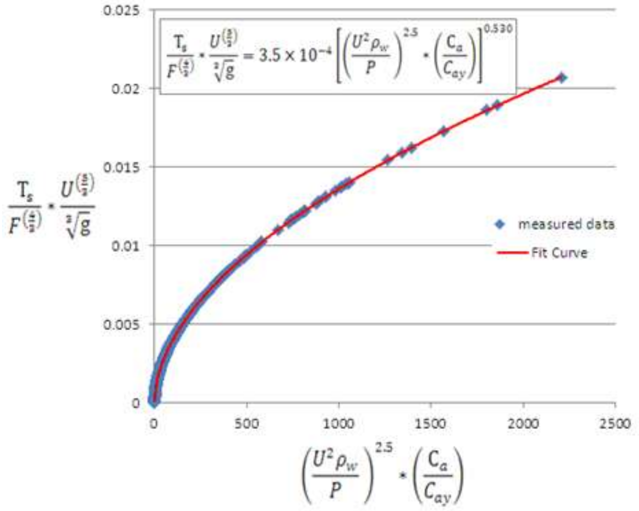

Figure 12: Best-Fit Curve for Port Said T_s (Eq. 19)

Figures 15 and 16 present the observed and predicted values for H_s and T_s, respectively, in form of time series during the testing phase.

It is clear to be seen from figure 15 that the predicted values of significant wave height are fairly close to the observed values for Port Said data. Finally, figure 15 shows that the predicted values of H_s has are very close to the trend of observed values of H_s to give reasonable results.

Figure 16 illustrates that the most of predicted values of significant wave period are fairly close to the observed values. It is obvious, for T_s greater than 8.0 seconds, the predicted values are slightly higher than the observed values (overestimated). Generally, the predicted significant wave period in figure 16 has trend as same as the trend of observed values of T_s in this region.

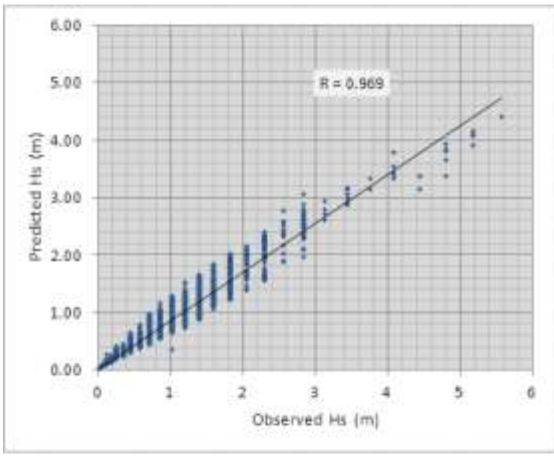

Figure 13: Correlation for Port Said H_s

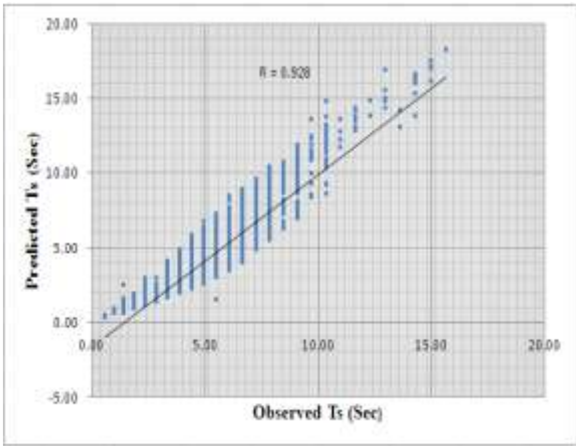

Figure 14: Correlation for Port Said T_s

6. Conclusions

Prediction of wave parameters for the offshore region using nonlinear regression method based on Pi-term theorem is presented in this paper. Three years data from the beginning of January 2010 to the end of December 2012 used in the analysis for both Alexandria and Port Said regions. For each region data, two years were used for the training phase and one year was used for testing phase. The analyses of this study were concluded that:

- The results give a high correlation with H_s (the lowest value is 0.96) and fairly high correlation with T_s (the lowest value is 0.928).
- The results have a minimum statistical errors for H_s and T_s where the MSE, MAE, SI% and bias were reasonable in their values.
- The trend of the predicted values of wave parameters are very similar to the trend of observed values to give satisfactory results.
- The predicting equations used in this study could not gave good results with the high wave ranges ($H_s > 3.0$ m and $T_s > 10$ sec.), but it works well with the small and medium wave height ranges (more than 80% of the Nile Delta wave data does not exceed 3.0 m in significant wave height and 10 sec. in significant wave period.

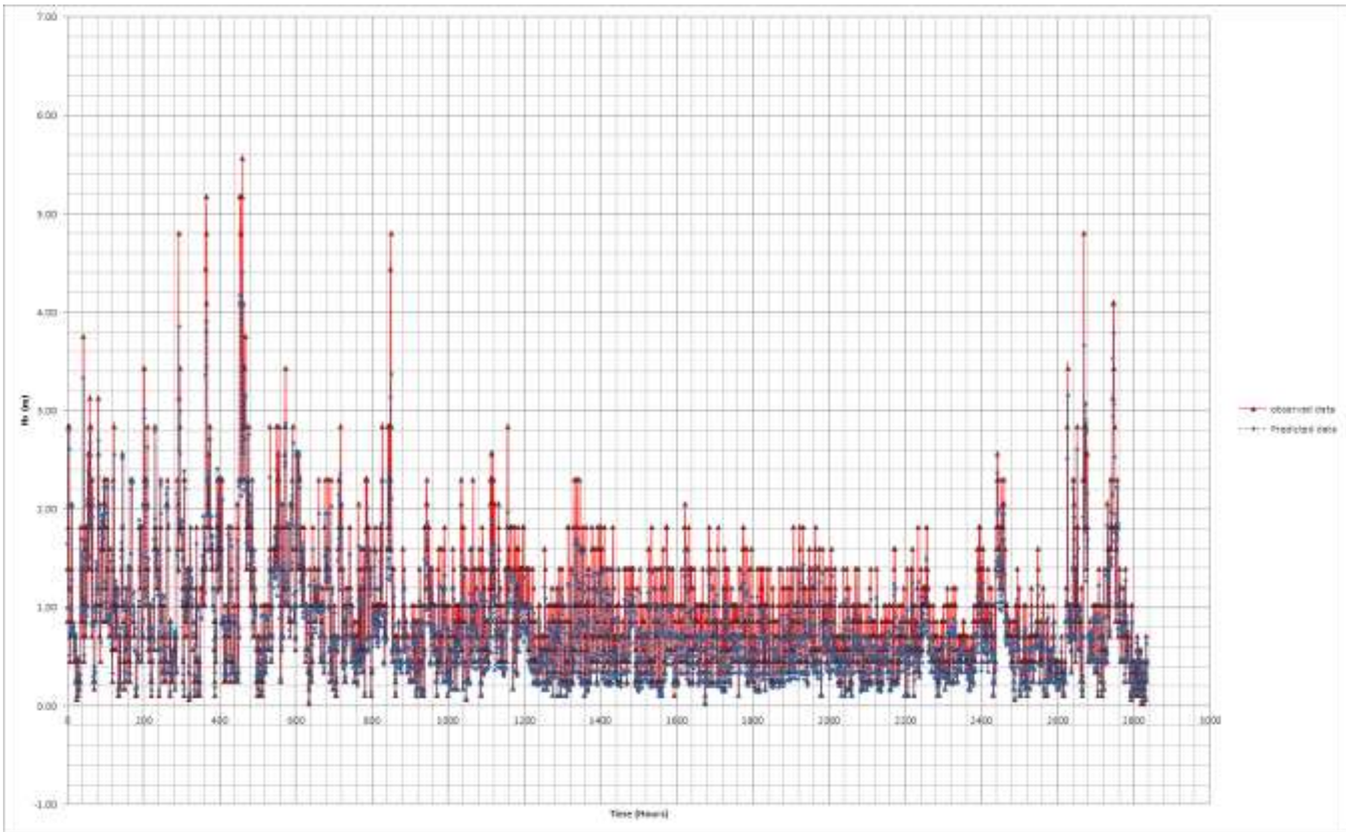

Figure 15: Comparison predicted values by Eq. (18) and observed values for Port Said H_s

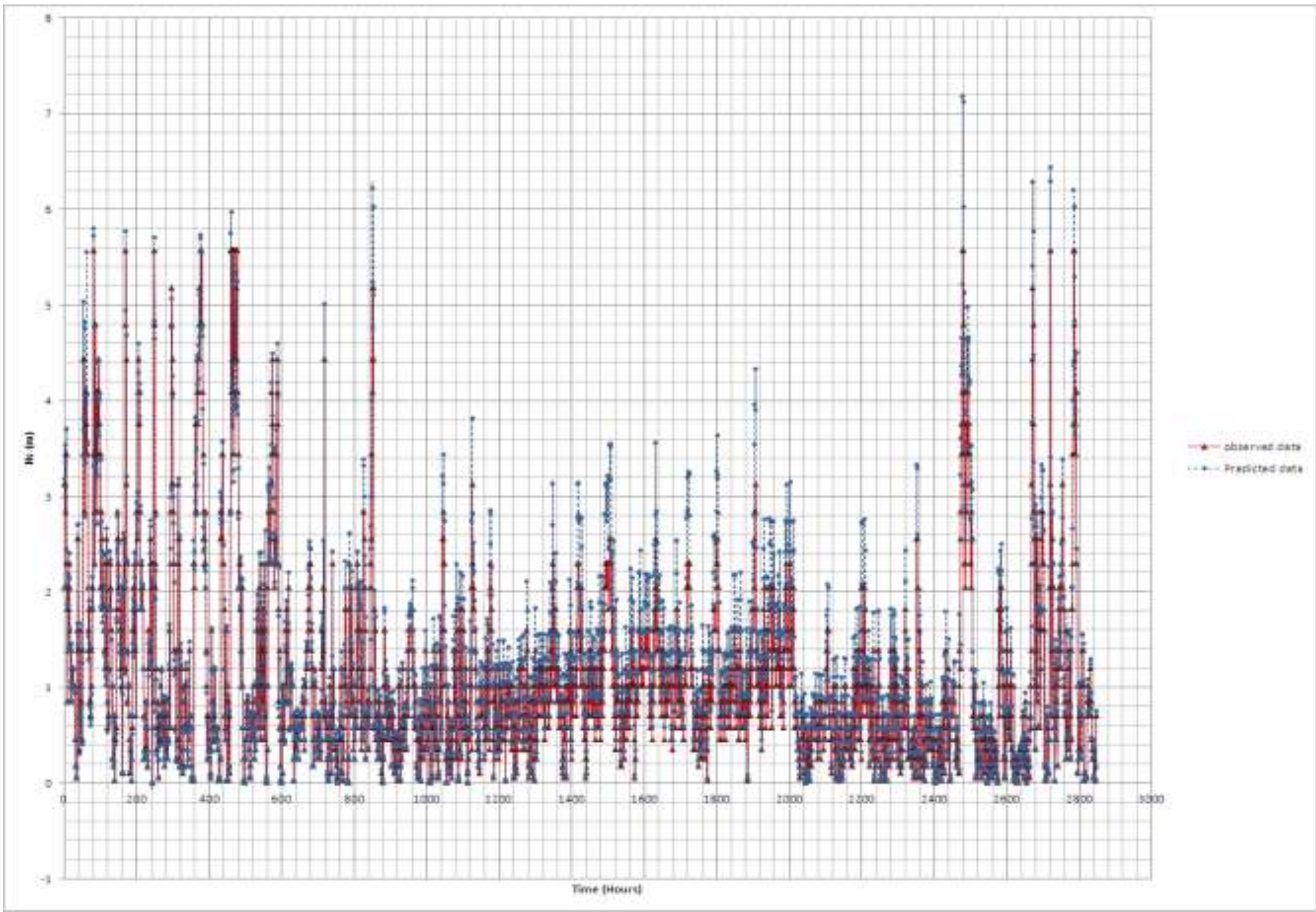

Figure 16: Comparison predicted values by Eq. (19) and observed values for Port Said T_s

Finally, this study showed that the predicting with nonlinear regression method was significantly accurate in their results for the Nile Delta offshore region.

The author hopes that the equations of prediction of wave parameters in this paper encourages serious studies on the topic presented here because of its importance in improving the oil and gas industry in general.

7. Acknowledgement

I would like to express my sincere appreciation to Dr. Moussa S. Elbisy, Dr. Tamer El-Gohary and Dr. Amir M. Mobasher for their sincere help, encouragement and precise advice.

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