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Providing a new approach for estimation of wave set-up in Iran coasts

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Abstract

One of the most important natural hazards on the sea shores is increasing the sea level caused by storms and waves. Not paying attention to these risks in the coastal area will lead to loss of capital and damage to human societies. Since, surface water levels are considered as the main border for determining the coastal area, it is important to determine the set-up value due to the wave and wind. Therefore, in this study, in order to evaluate and estimate the wave set-up, using the statistical data of the coast of Iran, the empirical relations presented in this field were compared with the actual values of the occurrence, and using the artificial neural network (ANN) for more precise forecasting of the wave set-up. The results indicate that the estimated method shows about 40% less error than the available formulas.

Keywords: Storm surge; Wave set-up; Coasts of Iran; ISWM.

Introduction

Natural hazards at sea are causing financial and life losses in the coastal zone. Since today, it is important to discuss energy conservation and the use of renewable marine resources (Bargi, *et al.,* 2016), recognizing, and reducing these hazards is necessary to minimize the damage to coastal structures and energy generators at sea (Dezvareh, *et al.,* 2016). One of these risks is the sea level rise caused by the storm and wave. The large changes in water levels in the coastal area are due to phenomena such as tidal surge, storm surges, wind setup, and wave setup that are the effective factors in determining the sea level. As shown in Figure 1, the Gonu storm in Chabahar is a sample of this phenomenon, which caused extensive damage in Oman Sea shore.

Wave-induced sea level rise suggests that the wave setup is a large function of the waves and local conditions and should be modeled separately. There are, of course, simple and empirical relationships for estimating the amount

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Figure 1. Storm surge in the coast of Oman Sea, Chabahar

of water surge caused by the wave (Bowen *et al.,* 1968). This phenomenon was first observed after the storm of 1938 on the northern coast of North America, later discovered by Savage (1957), Fairchild (1958) and Saville (1961). The observation of wave set-up is not simple, but Longuet-Higgins (1983) used the method to measure this phenomenon in a laboratory environment. In the follow up, Nielsen (1988) saw the field study of this phenomenon.

The conclusion of past research is presented in the form of applied relationships in the Coastal Engineering Manual (Engineers, 2002). Since these relations have been simplified, in order to investigate the accuracy of these relationships and to more accurately predict this phenomenon, the present study uses Iranian sea wave modeling (ISWM, 2008), recorded data on the coasts of Iran, and artificial neural network (ANN).

2. Method and materials

2.1. Governing Equations of Wave Set-up

Radiation stress is the momentum flux caused by the ocean waves. In the direction of the propagation of waves, there is a greater momentum flow that is due to the pure pressure of the compressive stress created over a period by the difference of water level in the crown wave relative to the wave height (Dezvareh *et al*., 2012). Radiation stress is caused by the limited wave height. The limited range wave theory can be used to estimate radiation stresses well, and describes phenomena such as wave set-down and set-up (Longuet-Higgins, 1983). In accordance with Equation (1), the depth of water in the stormy conditions is equal to the sum of the still water level and the wave set-up.

$$d = h + \bar{\eta} \qquad (1)$$

In Equation (1), h is the still water level (S.W.L) and $\bar{\eta}$ is the mean water surface elevation relative to the still water level. In general, additional changes to the water level, such as wind, wave, and tides, should also be taken into account at the depth of d.

The wave set-up actually balances the gradient of directional radiation stresses that are perpendicular to the coast. For example, the pressure gradient balances the average gradient of the water with the momentum gradient (Dean and Walton, 2010).

$$\frac{d\bar{\eta}}{dx} = -\frac{1}{\rho g d}\frac{dS_{xx}}{dx} \qquad (2)$$

which, S_{xx} is the perpendicular component of directional radiation stress. As shown in Figure 2, these radiation stresses lead wave set-down and set-up near the coast.

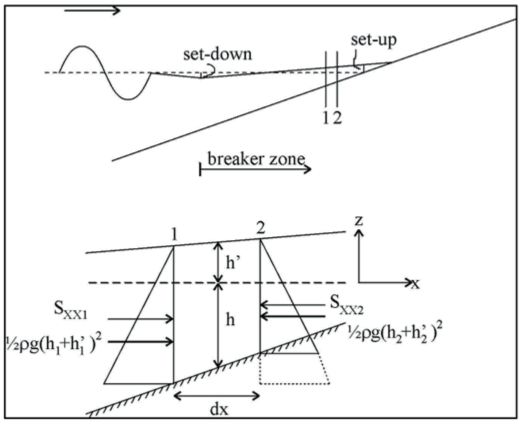

Figure 2. The Effect of radiation stresses on wave set-up and set-down (Van de Graaff, 2009)

The wave set-down in the opposite direction to the sea in the breaking zone is obtained by integrating Equation (2) as follows:

$$\bar{\eta} = -\frac{1}{8}\frac{H^2 k}{\sinh 2kd} \quad (3)$$

The above result is obtained by considering the three assumptions: a) linear wave theory, b) the radiation waves are perpendicular to the coastline and c) the wave set-down in deep water equal to zero ($\bar{\eta}_0 = 0$). The greatest decrease in the water level, or the wave set-down, occurs near the breaking point of waves. As shown in Figure 2, in the wave breaking zone $\bar{\eta}$ increases in the distance between the breaking point and the coastline. Given the linear theory, the water level gradient is calculated according to Equation (4).

$$\frac{d\bar{\eta}}{dx} = -\frac{3}{16}\frac{1}{h+\bar{\eta}}\frac{d(H^2)}{dx} \quad (4)$$

The value of $\bar{\eta}$ depends on the amount of wave degradation in the breaking zone. Assuming that the saturation wave is breaking for a smooth sea bed, the Equation (4) will be simplified as follows:

$$\frac{d\bar{\eta}}{dx} = \frac{1}{1+\frac{8}{3\gamma_b}}\tan\beta \quad (5)$$

which, β is the slope of the sea bed in the coastal area and γ_b is the ratio of the wave height to the depth of water at the breaking point. Combining the Equations (3) and (5), the amount of wave set-up at the still water level of coastline is set as follows:

$$\bar{\eta}_s = \bar{\eta}_b + \left[\frac{1}{1+\frac{8}{3\gamma_b^2}}\right] h_b \quad (6)$$

In the above relation, the first sentence is the amount of wave set-down at the breaking point and the second sentence is the wave set-up in the breaking zone. It is worth noting that for large breaking waves, when the depth of the breaking d_b increases, the wave set-up also enhances. Equation (6) calculates the wave set-up in terms of increasing the still water level on the coastline. In order to calculate the maximum wave set-up and the increased level of the coastline, the intersection point of the wave set-up point and the coastline should be found.

$$\Delta X = \frac{\bar{\eta}_s}{\tan\beta - \frac{d\bar{\eta}}{dx}} \quad (7)$$

$$\bar{\eta}_{max} = \bar{\eta}_s + \frac{d\bar{\eta}}{dx} \quad (8)$$

In Equation (7), ΔX is the displacement toward the coast, and in Equation (8), $\bar{\eta}_{max}$ is the maximum wave set-up. The wave set-up and the spatial variation of wave set-up can be calculated using Equations (3) and (4) for irregular (non-uniform) coastal profiles.

a)

b)

c)

Figure 3. Location of stations a) Caspian Sea, b) Persian Gulf, c) Oman Sea

2.2. Data

In order to estimate the initial wave set-up, the first step is the preparation of basic information including coastal slope, depth of water, wave height, wave period and wave direction, as well as the depth of the wave breaking have been performed. In this regard, the hydrodynamic conditions and depths of the Caspian Sea stations (73 stations), the Persian Gulf (124 stations) and the Oman Sea (53 stations) are considered in accordance with the ISWM report (ISWM, 2008). Figure 3 show the location of stations. This information includes the depth of the deep water wave (H_0), the wave period (T), breaking depth (db) and the slope of seabed (tan β), with regard to the relationships noted in the previous section. Information about some of these stations is given in Table 1 to Table 3. In the Tables 1 to 3, H_S, is the significant wave height based on the annual average over the 12-year period of the ISWM project. Also, in the ISWM report, the proposed relationship between wave height-wave period is elaborated and the following general formula is the basis for calculation and the coefficient *a,* is calculated at each point.

$$T = a * H_s^{0.5} \tag{9}$$

The coefficient *a,* is 3.17 for the Caspian Sea, 3.15 for the Persian Gulf and the Strait of Hormuz, and 3.45 for the northern part of the Oman Sea. Therefore, the Equation (9) and these coefficients are the basis for calculating the period of wave in the tables.

Table 1. Data of some stations of the Caspian Sea

ID	Longitude	Latitude	Slope section	Slope	Hs (m)	Tp (s)	db (m)
1	49.125	38.125	G13	0.014	0.67	4.68	1.05
14	50.125	37.625	G44	0.012	0.73	4.79	1.27
22	50.75	37.125	M10	0.01	0.74	4.96	1.29
28	51.5	36.75	M46	0.018	0.76	4.98	1.19
67	53.75	37.25	M118	0.003	0.53	4.52	0.87

Table 2. Data of some stations of the Persian Gulf

ID	Longitude	Latitude	Slope section	Slope	Hs (m)	Tp (s)	db (m)
4	48.875	29.875	KH4	0.0003	0.40	1.99	0.67
18	50.25	29.5	B7	0.0022	0.46	2.13	0.77
34	54.375	26.5	H44	0.0082	0.48	4.09	0.85
49	55.75	26.625	H85	0.0018	0.41	3.95	0.64
77	57.25	25.5	H144	0.0019	0.52	7.09	1.13

Table 3. Data of some stations of the Oman Sea

ID	Longitude	Latitude	Slope section	Slope	Hs (m)	Tp (s)	db (m)
6	57.75	25.5	H161	0.0019	0.55	7.34	1.00
21	58.75	25.25	H198	0.0007	0.705	8.29	1.01
38	60.25	25.125	SB44	0.0025	0.925	9.43	2.01
48	61.375	24.875	SB96	0.0103	1.06	9.55	2.27
53	61.625	25	SB104	0.0013	0.81	9.80	1.59

Table 4. Real and calculated wave set-up in some stations of the Caspian Sea

ID	Real Wave Setup (cm)	Calculated Wave Setup (cm)
1	8.33	11.81
14	10.91	14.29
22	10.91	14.51
28	10.13	13.39
67	9.00	9.79

Table 5. Real and calculated wave set-up in some stations of the Persian Gulf

ID	Real Wave Setup (cm)	Calculated Wave Setup (cm)
4	5.29	7.54
18	7.20	8.66
34	6.41	9.56
49	4.61	7.20
77	3.26	12.71

Table 6. Real and calculated wave set-up in some stations of the Oman Sea

ID	Real Wave Setup (cm)	Calculated Wave Setup (cm)
6	13.44	11.25
21	13.11	11.36
38	25.14	22.56
48	26.21	25.54
53	26.61	17.83

According to the database (ISWM, 2008), and based on the Equations (3) to (8), the values of wave set-up are determined in the Tables 4 to 6. Also, the actual values observed at the stations considered during the monitoring project by the buoy, are presented in the sidebar of the calculated values.

In the next section, estimation of the wave set-up is based on the ANN model and its results are compared with the results obtained from the empirical and simplified equations.

2.3. ANN Model

Scientists observed biological systems and natural systems and provided descriptions for these systems, and then these mathematical descriptions were converted into a series of computational blocks, in which the blocks were created in the form of neural networks, genetic algorithms, particle swarm algorithms, and so on which is called computational intelligence. The most important feature of these algorithms is the inspiration of nature, since nature has chosen almost the best possible way, given its time (Haykin, 1994). For the first time, Flood and Kartam (1994) argued that artificial engineering networks were used in civil engineering. In their paper, they used the popular form of the progressive neurology under the supervision. In this article, for the first time, a graphical interpretation of the neural network was introduced. In fact, the purpose of this paper was to ensure the development of this technology in civil engineering.

In this paper, the modeling and approximation of the functions of the neural networks will be used to estimate the wave set-up of the coasts of Iran based on the input data presented in the previous section. Also the statistical parameters are presented which indicate the accuracy of the matching of the two series of data. These parameters include Bias, RMSE, CC, CV and STEYX.

Bias is equal to mean error that is the mean of all differences between the estimated values and the true values.

$$Bias = \frac{\sum_{i=1}^{n}[(x_c)_i-(x_r)_i]}{n} \quad (10)$$

Root Mean Square Errors (RMSE) is calculated using squared differences; it tends to be dominated by outlying estimates far away from the true value (Walther *et al*., 2005).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}[(x_c)_i-(x_r)_i]^2}{n}} \quad (11)$$

Correlation Coefficient (CC) is a numerical measure of some type of correlation, meaning a statistical relationship between two variables. The variables may be two columns of a given data set of observations, often called a sample, or two components of a multivariate random variable with a known distribution.

$$CC = \frac{\sum_{i=1}^{n}[(x_c)_i-(\bar{x}_c)_i][(x_r)_i-(\bar{x}_r)_i]}{\sqrt{\sum_{i=1}^{n}[(x_c)_i-(\bar{x}_c)_i]^2\sum_{i=1}^{n}[(x_r)_i-(\bar{x}_r)_i]^2}} \quad (12)$$

In equations 10, 11 and 12, n is the number of data pairs, x_c and x_r are the calculated data and the real data, respectively (Haghroosta and Ismail, 2015).

Coefficient of variation (CV) is a standardized measure of dispersion of a probability distribution or frequency distribution.

$$CV = \frac{\sigma}{\bar{x}} \quad (13)$$

where, σ is the standard deviation and $\bar{x}$ is the average of data.

STEYX returns the standard error of the predicted y-value for each x in the regression. According the equation 14 the standard error is a measure of the amount of error in the prediction of y for an individual x. (Boddy and Smith, 2009).

$$STEYX = \sqrt{\left[\frac{1}{n(n-2)}\right]\left[n\sum y^2-(\sum y)^2-\frac{[n\sum xy-(\sum x)(\sum y)]^2}{n\sum x^2-(\sum x)^2}\right]} \quad (14)$$

3. Results

3.1. Estimation of wave ratio by the ANN model

In order to train the neural network, 250 data have been used. This information is about the stations in the Caspian Sea, the Persian Gulf, and the Oman Sea, and the specifications of some of these stations were included in the previous section.

Because inputs are not of the same type, all input and output data are normalized to better assess the performance of the neural network. Also, with the effort and error to get the best answer, finally the number of hidden layers is 3, each of which contains 10 neurons and the number of output layers is 1.

In the case of ANN model, the system could teach neurons well after about 5 repetitions. This system has greatly reduced validation and experimentation with the goal of reducing the RMSE in educational data. Studying the ANN, the comparison of target values and output of the neural network is performed as follows. In the following diagrams (Figure 4), the correlation between normalized real values of wave set-up and the normalized values obtained from the neural network are plotted for training, validation, test, and total data.

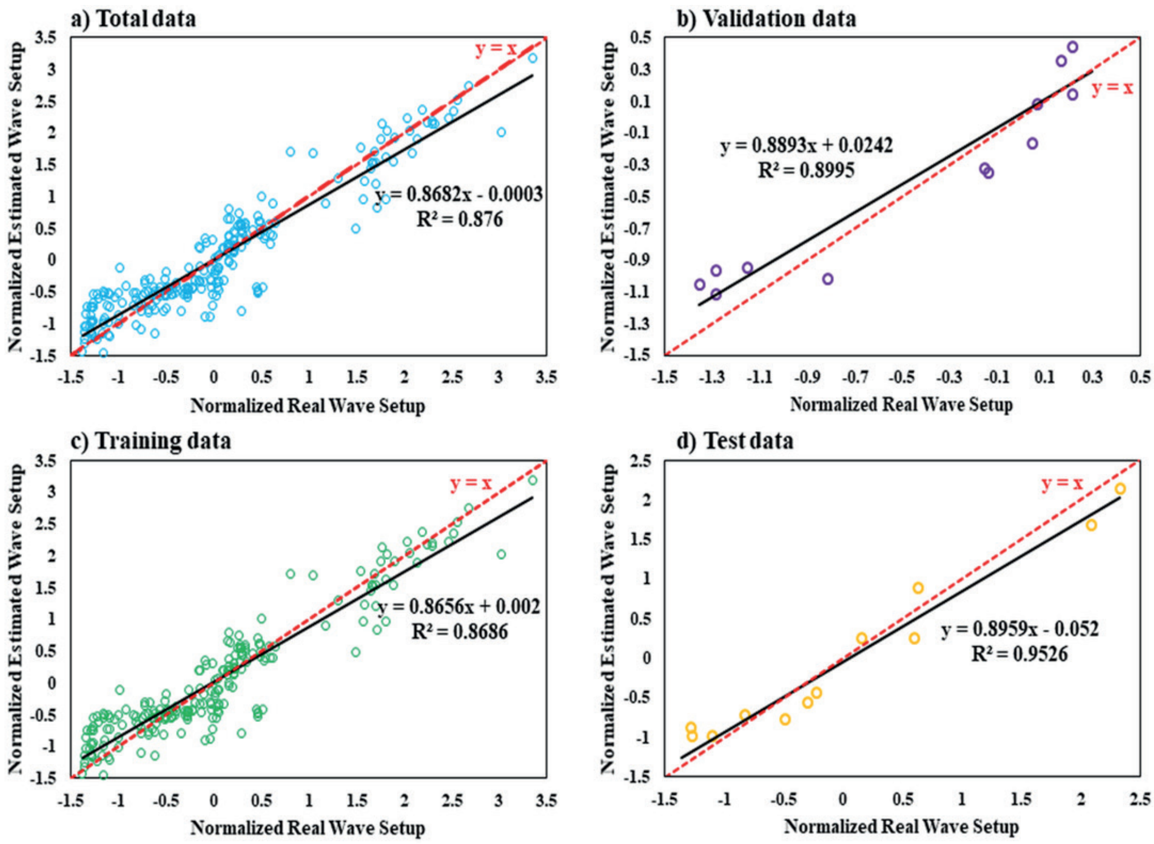

Figure 4. Correlation between normalized real wave set-up and normalized estimated wave setup a) total data, b) validation data, c) training data, and d) test data

Diagrams in Figure 4 show that there is a good correlation between real data and the neural network outputs. In other words, the neural network has been well trained. Particularly as seen, the best result is from the test data, which is also desirable in the research, because of the highest value of R^2 for the test data (0.95) in comparison with the rest results.

3.2. Comparison of the ANN results with common equations

After training the neural network model by the existing data bank, in this section, for the input data which are not used in the training and validation of the neural network model, in other words, the test data, the predicted results of the obtained neural network are compared with the results of the common equations presented in section 2 to calculate the amount of wave set-up. Figure 5 shows the distribution of the predicted wave set-up by the ANN and the results from equations relative to real values.

Figure 5 shows that the estimated results are closer to actual results. In order to more accurately evaluation of the results, dispersion diagrams are plotted for each of the estimated results and the calculated results against the actual data (Figure 6).

Figure 6 shows that the correlation and closeness of estimated data in the neural network to actual values is more than the data obtained from the equations. For a better comparison, Figure 7 indicates the comparison between the statistical

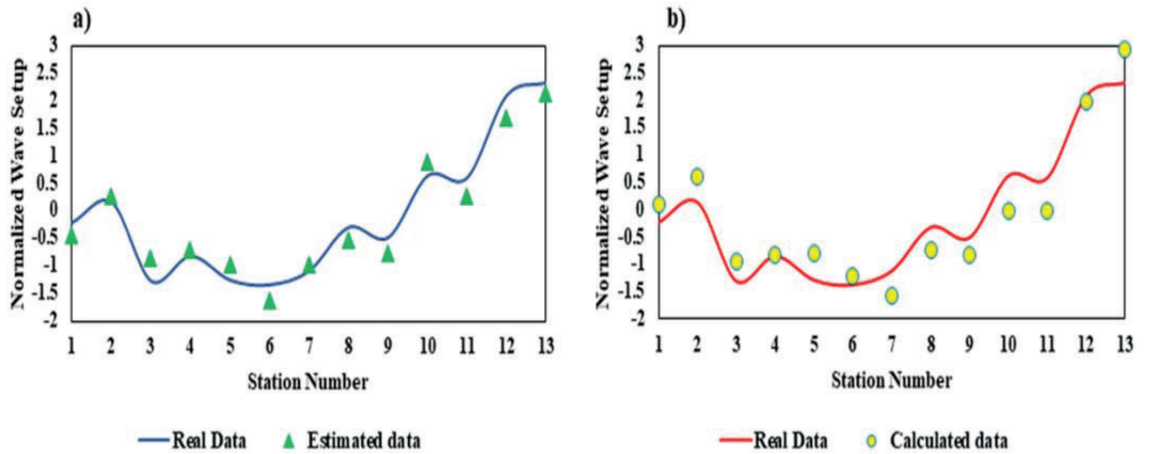

Figure 5. Comparison of the real data with a) Estimated data from the ANN model, b) Calculated data from Equations (3-8) in 13 stations

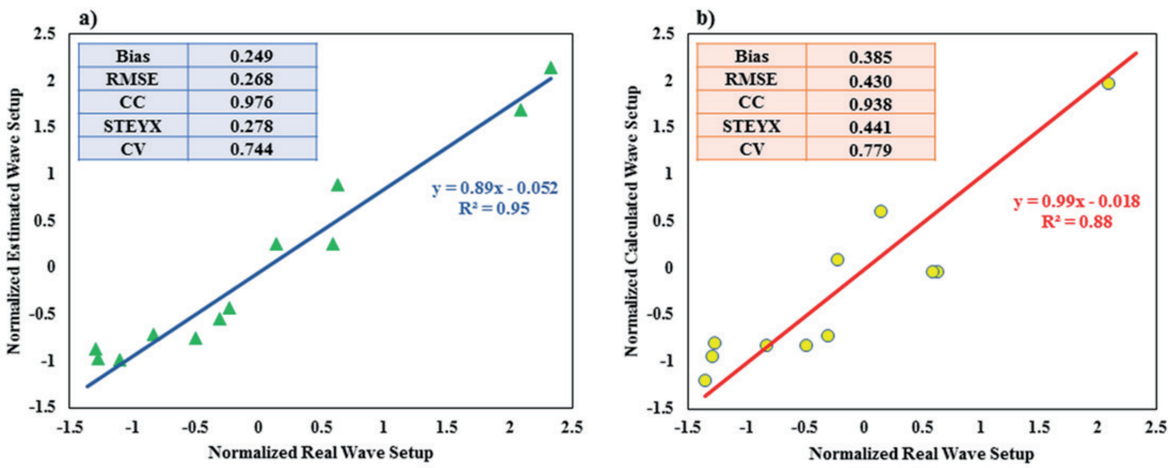

Figure 6. Correlation between the real data and a) Estimated data from the ANN, b) Calculated data from the equations

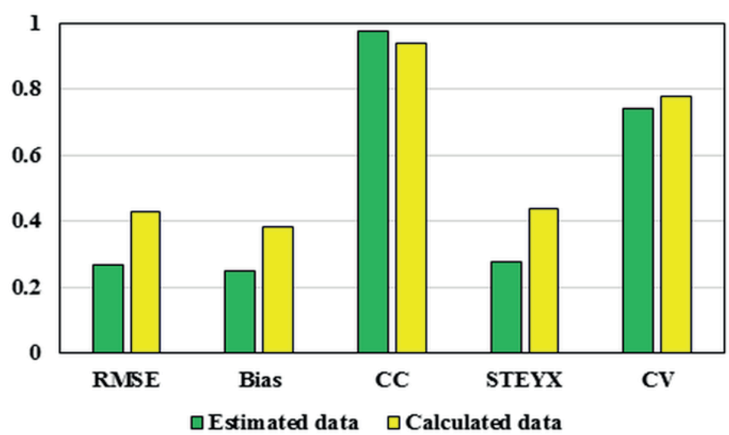

Figure 7. Comparison of the statistical parameters of estimated and calculated results

parameters, which represents the accuracy of the two series of data adaptations.

As it can be seen, the parameters that are related to the error rate (Bias, RMSE, STEYX, and CV) for the values obtained from the equations are greater than the values obtained from the neural network method. For example, the RMSE in the method of this research (estimated data) is 60% less than the ones obtained from the formulas (calculated data). Also, the correlation coefficient parameter (CC) for the estimated data is larger than the calculated data. This indicates the superiority of the approach of this research for estimating of wave set-up.

Conclusion

In this paper, we tried to provide a more precise estimation of the wave set-up phenomenon by presenting a new approach based on the ANN model. In this regard, after collecting data from the Iranian coast of the Caspian Sea, the Persian Gulf, and the Oman Sea, the wave set-up was calculated at various stations in accordance with the equations in the codes. And in the next step, the ANN training estimated the wave set-up for those various stations.

By comparing these two methods with actual wave set-up in accordance with the ISWM report, it was observed that the results of the artificial network approach are closer to real values than the ones from the existing relationships. So that, the correlation of results in the results of ANN model is about 4% more than the calculated results, and also the Bias and the RMSE of the ANN model are about 54 and 60% less than the calculated results. These numbers clearly show that the neural network, despite the fact that it does not know the reason for the phenomena, however, show acceptable results even in the presence of an abnormal phenomenon.

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