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On The Prediction of Wave Parameters Using Simplified Methods

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ABSTRACT

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Wind induced waves are the most important phenomenon to be considered in the coastal and offshore activities. Therefore, in this study the performance of three simplified methods for predicting the wave height in lakes are investigated. The data set used in this study comprises of wave data and over water wind data gained from Lake Ontario and Lake Erie. CEM, Wilson and SMB methods were used to predict the hourly significant wave height. The predicted and measured wave heights were then compared and their skills were evaluated using statistical measures. Results indicate that the simplified methods are more accurate in the fetch limited condition than in the duration limited condition. Comparison of the methods also shows that the SMB method is more accurate than the other methods. In addition, it is discussed that in the CEM method, the proposed equation for calculation of equivalent fetch length and minimum wind duration for prevailing fetch limited condition are not compatible. Hence, a modified CEM method is suggested to increase the accuracy in prediction of wave height.

ADITIONAL INDEX WORDS: *Simplified methods, Coastal engineering manual, SMB, Wilson*

INTRODUCTION

The knowledge of wind wave characteristics is the most important issue for almost any engineering activity in inland and coastal waters. In many applications, it is necessary to use long-term wave data. However, in many areas, long-term measurements are not available and it is necessary to use wave prediction models for wave hindcasting.

During the past decades some empirical and numerical models have been developed for wave prediction. Numerical models solve the energy balance equation throughout grid points over the water, where active wave generation is taking place (eg. BOOIJ *et al.* 1999, KAZEMINEZHAD *et al.*, 2007 and MOEINI and ETEMAD-SHAHIDI, 2007,). These models require abundant bathymetric, meteorological and oceanographic data. In some regions, these data are not available and numerical modeling is both difficult and expensive (BROWNE *et al.*, 2007). Moreover, for first estimates in many cases, the use of these models is not economically justified (GODA, 2003). Therefore, in these cases engineers tend to use simplified wave prediction methods that are based on interrelationships between dimensionless analyses. These are accurate enough for preliminary estimates and also in simple situations where local effects are small (U.S. Army, 2006).

Several simplified wave prediction methods have been developed in the past decades, such as SMB (BRETSCHNEIDER, 1970), Wilson (WILSON, 1965), JONSWAP (HASSELMAN *et al.*, 1973), Donelan (DONELAN, 1980), SPM (U.S. Army, 1984) that has been superseded recently by CEM (U.S. Army, 2006). SMB method has been proposed in the U.S. Army (1977) and British Standard (1993) while the Wilson method proposed in Japan's ports and harbor standards (Ocadij, 2002).

Some of these methods have been investigated only in fetch limited conditions. Donelan, SMB and JONSWAP methods have been evaluated in Lake Ontario (BISHOP, 1983). He found that the accuracy of the Donelan method is slightly superior to those of the JONSWAP and SMB methods. CEM method has been also evaluated in Lake Ontario for fetch limited condition (KAZEMINEZHAD *et al.*, 2005). Results showed the CEM method overestimates the wave height.

The aim of this study is to compare the performance of CEM and other simplified methods, which have been proposed in different coastal and maritime standards, in the Great lakes. Therefore, SMB and Wilson methods are also used to hindcast the wave height. The predicted and measured wave heights are compared and accuracy of each method is determined and discussed.

STUDY AREA

The data set used in this study comprises of wave data and over-water wind data gained from Lake Ontario from April to November, 2004 and further from September to November, 2003. The data set was gathered by National Data Buoy Center (NDBC) in station 45012 at 43°37′09′′N and 77°24′18′′W, where water depth is 145 m (Figure 1). Since maximum measured peak spectral period, was 10 s, the minimum ratio of the water depth to the wave length was 0.93 and most of the observed waves were deep water waves.

Wind and wave data were collected using 3 meter discus buoy. Wave data was collected for 20 min at 1 hour intervals and a sampling frequency of 2.56 HZ. Wind data was also collected for 8 min at 1 hour intervals, at a frequency of 1.28 HZ. The wind speed, U, at buoy was measured at a height of 5 meter above the mean sea level. The buoy measured and transmitted barometric pressure, wind direction, speed, and gust, air and sea temperature, and wave energy spectra.

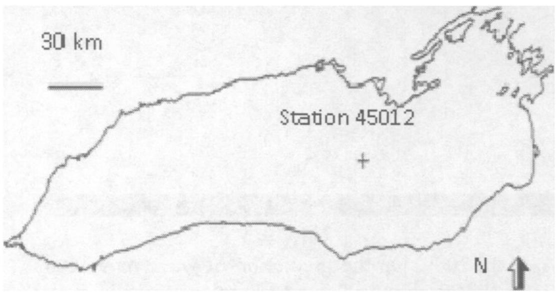

Figure 1. Map of the Lake Ontario and location of NDBC buoy 45012

METHOD

CEM Method

In the CEM method (U.S. Army, 2006) the fetch length for a certain direction was calculated by constructing 30 radials from the point of interest (at 1 degree intervals) and extended them until they first intersect the coastline (BISHOP *et al.*, 1992). The fetch length X was calculated as arithmetic average of extended radials.

To determine the duration of winds, definition of constant wind was used (U.S. Army, 2006). In this way, wind duration at i^{th} hourly data point was considered to be equal to number of preceding consecutive and acceptable hours which satisfies following conditions (KAZEMINEZHAD *et al.*, 2005):

$$\left|U_i - \overline{U}\right| < 2.5 \quad ms^{-1} \tag{1}$$

$$\left|D_i - \overline{D}\right| < 15^{\circ} \tag{2}$$

where $\overline{U}$ and $\overline{D}$ are the average of preceding consecutive and acceptable hourly wind speed and direction, respectively. U_i and D_i are the wind speed and direction at i^{th} hourly data point.

The minimum wind duration for accomplishing fetch limited condition is expressed as:

$$t_{\min} = 77.23 \frac{X^{0.67}}{U^{0.34}\, g^{0.33}} \tag{3}$$

where, U is the wind speed at 10 m above the sea surface (m/s). In the fetch limited condition, the equation for prediction of non dimensional wave height is:

$$\frac{g H_S}{u_*^2} = 4.13 \times 10^{-2} \left(\frac{g X}{u_*^2}\right)^{\frac{1}{2}} \tag{4}$$

where, u_* is the friction velocity (m/s) estimated as:

$$u_* = U \left(C_D\right)^{\frac{1}{2}} \tag{5}$$

where, C_D is the drag coefficient which is defined as:

$$C_D = 0.001\,(1.1 + 0.035U) \tag{6}$$

In duration limited conditions, equivalent fetch length is calculated as:

$$\frac{g X}{u_*^2} = 5.23 \times 10^{-3} \left(\frac{g t}{u_*}\right)^{\frac{3}{2}} \tag{7}$$

In this equation t is the wind duration (s). The fetch length estimated from this equation must then be substituted into equation (4) to obtain estimates of wave height in duration limited condition.

SMB method

To determine the fetch length in the SMB method, cosine average method was used. Based on this method 15 radials were extend in the upwind direction ± 45 degree (at 6 degree intervals). Then fetch length was calculated as:

$$X = \frac{\sum_{i=1}^{15} X_i \cos\theta_i}{\sum_{i=1}^{15} \cos\theta_i} \tag{8}$$

According to this method, for accomplishing fetch limited condition, the wind duration must be greater than t_{min}, that is:

$$\frac{g t_{\min}}{U} = 6.5882 \exp\left\{\left[\left(0.0161\left(\ln\left(\frac{gX}{U^2}\right)\right)^2 - 0.3692\left(\ln\left(\frac{gX}{U^2}\right)\right) + 2.2024\right]^{0.5} + 0.8798\left(\ln\left(\frac{gX}{U^2}\right)\right)\right\} \tag{9}$$

In the fetch limited condition, the equations for predicting wave height is:

$$\frac{gH_S}{U^2} = 0.283 \tanh\left[0.0125\left(\frac{gX}{U^2}\right)^{0.42}\right] \tag{10}$$

If wind duration is smaller than t_{min}, the condition is called duration limited. In this condition, equivalent fetch must be calculated by substituting the wind duration into the equation (9). Then, wave heights are estimated by substituting the equivalent fetch into the equation (10).

Table 1: Error statistics of simplified methods in the prediction of H_S

Methods	Conditions	No. of Data	H_S bias (m)	H_S SI (%)
SMB	All	2530	-0.21	51.0
	F.L.*	365	0.13	26.3
	D.L.*	2165	-0.27	56.7
Wilson	All	2530	-0.21	51.2
	F.L.	346	0.08	24.7
	D.L.	2184	-0.25	56.6
CEM	All	2530	-0.36	67.7
	F.L.	282	0.03	27.9
	D.L.	2248	-0.42	73.8

*F.L.: Fetch Limited; *DL: Duration Limited

WILSON method

For fetch length computation in Wilson method utilization of SAVILLE (1954) method has been recommended in Japan's ports and harbor standards (Ocadij, 2002). According to this method, for calculating fetch length in a certain direction, 15 radials were extended in the upwind direction ± 45 degrees and fetch length was calculated as:

$$X = \frac{\sum_{i=1}^{15} X_i \cos^2 \theta_i}{\sum_{i=1}^{15} \cos \theta_i} \tag{11}$$

In this method, the minimum duration for the full growth at a given fetch length is approximately calculated by (WILSON, 1965):

$$t_{\min} = 43 \frac{X^{0.73}}{U^{0.46}\, g^{0.27}} \tag{12}$$

In the fetch limited condition, the significant wave height is expressed as:

$$\frac{gH_S}{U^2} = 0.30\left\{1 - \left[1 + 0.004\left(\frac{gX}{U^2}\right)^{0.5}\right]^{-2}\right\} \tag{13}$$

In the duration limited condition, equivalent fetch must be calculated. The wave height can then be estimated by substituting equivalent fetch in the equation (13).

RESULT AND DISCUSSION

The observed wind speed at any level, z, was adjusted to 10 m level. The simple approximation for level adjustment is (U.S. Army, 1984):

$$U = U_z \left[\frac{10}{z}\right]^{1/7} \tag{14}$$

where U_z is the wind speed at level z. A factor of 1.104 has been used for converting the measured wind speed to 10 m level. To evaluate the performance of CEM and other methods, significant wave height was predicted using wind of year 2004. Predicted and measured wave data were compared for waves with significant wave height greater than 0.3 m.

For statistical comparison of predicted and observed wave heights, bias and scatter index were used. The bias and scatter index (SI) were calculated as follows:

$$bias = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \tag{15}$$

$$SI = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2}}{\frac{1}{N}\sum_{i=1}^{N} O_i} \tag{16}$$

where, O_i is the observed value, P_i is the predicted value and N is the number of observations.

Table 1 shows the error statistics of calculated wave parameters in all, fetch limited and duration limited conditions. Calculated biases show that the simplified methods underestimate the wave height in all conditions. As can be seen, the CEM method has the highest bias in the prediction of wave parameters (-0.36 m for H_S) while the SMB method has the lowest one (-0.21 m for H_S).

Comparison of calculated SI in all conditions shows that the SMB method is generally more skillful than the other ones in this lake, while the CEM method is the poorest method.

To investigate the performance of these methods in different conditions, the error statistics of them are also presented in table 1. As can be seen, in fetch limited condition, the simplified methods predicted the wave heights more accurate than in duration limited condition. Note that the numbers of occurrence of fetch limited and duration limited conditions in different methods are not the same. This is due to the different equations presented by the simplified methods for calculation of t_{min}.

For a better inter comparison of methods, an equal number of fetch limited and duration limited cases were selected. To provide an equal number of fetch limited cases for all methods, the largest values of t_{min} calculated by different methods were used to select the data set. Similarly, to provide an equal number of duration limited cases the smallest values of t_{min} calculated by different methods were used to select the data set. In this way, 272 data points were selected for fetch limited case and 2122 data points for duration limited case. Table 2 shows the accuracy of simplified methods in the prediction of wave heights in fetch limited condition. In this condition, all methods overestimate the wave height. This is in line with the results obtained by BISHOP *et al.* (1992) in Lake Ontario and other places where the SMB method overestimated the wave height. As shown in the fetch limited

Table 2. Error statistics of simplified methods in the prediction of wave parameters in different conditions after selecting equal number of data points for all methods

Method	fetch limited		duration limited	
	bias (m)	*SI* (%)	bias (m)	*SI* (%)
SMB	0.12	24.6	-0.28	57.2
Wilson	0.07	23.0	-0.26	57.7
CEM	0.04	28.0	-0.44	76.4

Table 3. Error statistics of the CEM method in the prediction of wave height using equation (3) to estimate the equivalent fetch length.

Conditions	H_S	
	bias (m)	SI (%)
All	-0.29	62.5
F.L.	0.03	27.9

condition, the Wilson method is the best method for wave height prediction with a bias of 0.07 m and *SI* of 23.0%. The CEM method is the poorest one for prediction of the wave height in the fetch limited condition.

Table 2 also shows the error statistics of simplified methods in the prediction of wave parameters in the duration limited condition. As can be seen in duration limited condition, all simplified methods underestimate the wave height. In this condition the SMB method is the best method to predict the wave parameters while the CEM method is the poorest one. Comparison of the results in duration and fetch limited conditions shows that the simplified methods are more accurate in fetch limited condition than in duration limited condition.

As shown simplified methods underestimate the wave parameters in duration limited condition. In this condition, wave growth is limited by wind duration and therefore, wind duration calculation is of great importance. To investigate the effect of wind duration in the prediction of wave parameters in duration limited condition, errors of the simplified methods are shown against wind duration. Fig. 3 displays the *SI* of methods in prediction of wave height versus the wind duration in duration limited condition. As can be seen, the errors in prediction of H_S decrease as wind duration increases. These errors vary from 100% to 77% for 1 hour wind duration and from 38% to 22% for 8 hours wind duration. In most cases, the SMB method outperforms other methods. This is in line with the recent results obtained in Lake Erie and Michigan (MOEINI 2006, ZANGANEH 2006).

Modification of the CEM method

As seen the CEM method underestimates the wave height in duration limited condition. The errors of this method in prediction of wave height in the mentioned condition can be partly due to the proposed equation for equivalent fetch calculation. In the CEM,

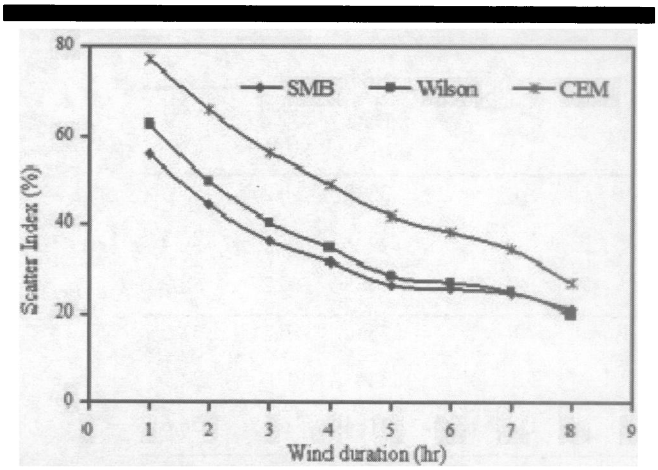

Figure 2. Scatter index of simplified methods in prediction of H_S versus wind duration in the duration limited condition

equations (3) and (7) are used to calculate the time required to accomplish fetch limited wave development and the equivalent fetch length in duration limited condition, respectively. These equations should give the same t_{min} when the wave growth becomes duration limited. However, since equation (7) uses friction velocity u_* and equation (3) uses U, the obtained t_{min}s are only the same when $u_*= 0.0794U$ (U=148.7 m/s), that is not acceptable.

In similar conditions, equation (3) results in to a larger equivalent fetch than what equation (7) results in. If equation (3) is used to calculate the equivalent fetch, better results can be obtained in the prediction of wave parameters. Table 3 shows the error statistics of the CEM method using equation (3) to estimate the equivalent fetch. Comparison of tables 1 and 3 shows that use of equation (3) in equivalent fetch calculation decreases errors of CEM method in duration limited condition.

The CEM method was then modified for Lake Ontario. Non dimensional equation of significant wave height was used as follows:

$$\frac{gH_S}{u_*^2} = a_1\left(\frac{gX}{u_*^2}\right)^{b_1} \quad (17)$$

Using 1500 wind and wave data gained from Lake Ontario in 2003, a_1 and b_1 values were determined by best fitting as:

$$\frac{gH_S}{u_*^2} = 13.48\left(\frac{gX}{u_*^2}\right)^{0.1342} \quad (18)$$

To evaluate these modified equations, significant wave height was predicted using data of year 2004.

Error statistics of predicted values are presented in Table 4. As can be seen using the modified equations leads to lower error in the prediction of wave height. The scatter index of the H_S decreased from 67.7% to 49.6% and also leads to unbiased predictions.

The modified equations were also evaluated using Lake Erie data to investigate how well the modified equation performs in other lakes. In this way, 2700 hourly wave parameters of Lake Erie (station 54132) were predicted using the modified CEM

Table 4. Error statistics of the Modified CEM method in the prediction of wave parameters.

Methods	Lake Ontario		Lake Erie	
	bias (m)	*SI* (%)	bias (m)	*SI* (%)
Modified CEM	0.088	49.6	0.11	53.3
CEM	-0.36	67.7	-0.29	59.4

method. Table 4 shows the error statistics of the methods in the prediction of wave parameters in Lake Erie. It can be seen that the accuracy of the modified method in Lake Erie is better than that of the CEM method.

SUMMARY AND CONCLUSION

In this study the performance of simplified methods for prediction of wave parameters were investigated. The SMB, Wilson and CEM methods were used to predict the wave height in fetch limited and duration limited conditions in Lake Ontario. Results show that the simplified methods generally underestimate the wave parameters and the SMB method results in more accurate predictions than the other methods. The scatter indexes of the SMB method in H_S predictions was 51%. Since the CEM method is the most recent wave prediction method, it was expected that this method results in more accurate predictions. However, results showed that the CEM method is the poorest method for wave predication in Lake Ontario. This is in line with the recent results obtained in Lake Erie and Michigan (MOEINI 2006, ZANGANEH 2006). The accuracy of simplified methods was also separately investigated in duration limited and fetch limited conditions. It was found that the methods are more accurate in fetch limited condition than in duration limited condition. In fetch limited condition, the Wilson method performed better in hindcasting of *Hs* while the CEM method was the poorest one in the prediction of wave height. In duration limited condition, all methods underestimated the wave parameters and the SMB method performed better than others in hindcasting wave parameters in this lake. Results showed that in duration limited condition, the observed errors of the CEM method are partly due to the proposed equation for equivalent fetch calculation. The CEM equations were also modified to results in more accurate predictions in Lake Ontario. Results indicate that using modified equations decreases the scatter index of H_S predictions to 49.6%. The modified equations were also evaluated using Lake Erie data. Here, the scatter Index of wave height prediction was reduced from 59.4% to 53.3% which is still high.

LITERATURE CITED

BISHOP, C.T., 1983. Comparison of manual wave prediction models. *Journal of Waterway, Port, Coastal and Ocean Engineering*, ASCE 109(1), 1-17

BISHOP, C.T.; DONELAN, M.A., and KAHMA, K.K. 1992., Shore protection manual's wave prediction reviewed. *Coastal Engineering*, 17, 25-48

BOOIJ, N.; RIS, R.C., and HOLTHUIJSEN, L.H., 1999. A third generation wave model for coastal regions. 1. Model description and validation. *Journal of Geophysical Research,* 104, 7649–7666

BRETSCHNEIDER, CL., 1970. Wave forecasting relations for wave generation. *Look Lab, Hawaii*, 1(3)

British Standard, Maritime Structures, 1993. Part 1: Code of practice for general criteria. BS 6349-1:200.

BROWNE, M.; CASTELLE, B.; STRAUSS , D.; TOMLINSON, R.; BLUMENSTEIN, M., and LANE, C., 2007. Near-shore swell estimation from a global wind-wave model: Spectral process, linear, and artificial neural network models. *Coastal Engineering,* 54, 445–460.

Donelan, M.A., 1980. Similarity theory applied to the forecasting of wave heights, periods and directions. *Proceedings of Canadian Coastal Conference*, National Research Council of Canada, pp. 47-61.

GODA, Y., 2003. Revisiting Wilson's Formulas for Simplified Wind-Wave Prediction. *Journal of Waterway, Port, Coastal and Ocean Engineering*, ASCE 129(2), 93-95.

HASSELMANN, K.; BARNETT, T.P.; BOUWS, E.; CARLSON, H.; CARTWRIGHT, D.E.; ENKE, K.,;WEING, J.A.; GIENAPP, H.; HASSELMANN, D.E.; KRUSEMAN, P.; MEERBURG, A.; MULLER, P.; OLBERS, K.J.; RICHTER, K.; SELL, W., and WALDEN, W.H., 1973. Measurements of Wind-Wave Growth and Swell Decay During the Joint North Sea Wave Project (JONSWAP). *Deutsche Hydrograph, Zeit., Erganzung-self Reihe*, A 8(12).

KAZEMINEZHAD, M.H.; ETEMAD-SHAHIDI, A., and MOUSAVI S.J, 2005. Application of fuzzy inference system in the prediction of wave parameters. *Ocean Engineering*, 32, 1709-1725.

KAZEMINEZHAD, M.H.; ETEMAD-SHAHIDI, A., and MOUSAVI S.J, 2007. Evaluation of Neuro Fuzzy and Numerical Wave Prediction Models in Lake Ontario. Journal of Coastal Research Special Issue No. 50, pp. 317-321.

MOEINI, M.H. 2006, Prediction of wind-wave parameters in lakes using the SWAN model. Iran: Iran University of science and technology, Master's thesis, 120p.

MOEINI, M.H. and ETEMAD-SHAHIDI, A., 2007. Application of two numerical models for wave hindcasting in Lake Erie. Applied Ocean Research, 29(3), 137-145

Overseas Coastal Area Development Institute of Japan, 2002. Technical standards and commentaries for port and harbor facilities in Japan. Japan, 664p.

SAVILLE, T., 1954. *The effect of fetch width on wave generation.* U.S. Army Corps of Engineers, Beach Erosion Board, Technical Memo (7).

U.S. Army, 1977. Shore Protection Manual. Washington, DC: U.S. Army Engineer Waterways Experiment Station, U.S. Government Printing Office, Washington, D.

U.S. Army, 1984. Shore Protection Manual. Washington, DC: U.S. Army Engineer Waterways Experiment Station, U.S. Government Printing Office.

U.S. Army, 2006. Coastal Engineering Manual. Chapter II-2, Meteorology and Wave Climate. Washington, DC: Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers.

WILSON, B.W., 1965. Numerical prediction of ocean waves in the North Atlantic for December, 1959. *Deutsche Hydrograph. Z*, 18 (3), 114-130.

ZANGANEH, M., 2006. A combined fuzzy inference system-genetic algorithm model for wind wave prediction and its comparison to ANFIS and CEM methods. Iran: Iran University of science and technology, Master's thesis, 140p.