EVALUATION OF EXTREME WIND SPEEDS IN RELATION TO THE DESIGN OF COASTAL STRUCTURES IN TANZANIA

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Abstract

Five distribution functions, FT-I and Weibull with the exponent k = 0.75, 1.0. 1.4 and 2.0 respectively, have been applied to 25-year wind data collected between 1972 and 1996 at Tanga, Dar Es Salaam, Zanzibar and Mtwara Meteorological stations. One maximum value for every year from the full data record was drawn to constitute the annual maxima series for each station. For each of the stations, 2-100-year return wind speeds with corresponding 90% confidence intervals were computed. The distribution functions were fitted to the data by the Least Squares Method. Results from the study show that FT-I and the Weibull distribution with k = 1.0 and 2.0 have the highest correlation coefficient and the smallest sum of the squares of residuals. The 50- and 100-year return wind speeds are respectively 26 and 27 knots for Tanga, 27 and 28 knots for Dar Es Salaam, 29 and 30 knots for Zanzibar and 36 and 37 knots for Mtwara.

Introduction

Meteorological conditions play an important role in the design and operation of marine and coastal structures. Wind has multiple effects on ocean circulation, waves and sea level. In near-shore zones, waves and currents play a major role in sediment movement and the resulting natural beach geometry. The wave climate of a given location will depend on the speeds of the winds, their fetch and duration. It is wind that determines the wave height, wave period and the predominant or resultant wave direction. The steepness and direction of the approaching waves are the major parameter in the generation of long-shore currents, their corresponding long-shore littoral drift and the orientation of a beach.

When wind blows over the sea surface, it induces a steady movement of the upper few hundred meters. This movement is generally known as wind-induced current which flows in the same general direction of the wind. The relationship between the surface current and wind speed is [1]:

$$V_o = \frac{0.0127}{\sqrt{\sin|\Phi|}} W \qquad (1)$$

where $\Phi > 10^{\circ}$ is the location latitude and $W > 6$ m/s is the wind speed. Surface current is typically 3 % of the wind speed so that at 10 m/s wind is expected to give rise to $V_o \approx 0.3$ m/s. The drifting of floating matter such as oil slick, buoys, ships, and sewage solids is the result of this water movement due to winds.

The tangential stress on the surface water leads to accumulation (if winds blow towards land) or depletion (if winds blow away from the coast) of water and the development of surface slopes. The surface slopes create a horizontal pressure gradient from which currents are produced superimposing on the initial wind drift. The piling of water at the coast as a result of this process is known as wind set-up.

If wind blows parallel to the coast, and say towards the equator at the eastern boundary of an ocean, water in the surface layer will tend to move away from the coast in either hemisphere and will have to be replaced by water upwelling from below. Since the upwelled water is cooler than the original surface water, a characteristic band of low temperatures will develop close to the coast. Also, since the upwelled water has greater concentration of nutrients, e.g. phosphates, nitrates and silicates, than the original surface water, upwelling is important for replenishing the

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surface layer with nutrients needed for biological production.

A successful control of beach erosion requires the knowledge of all factors which are most effective in beach processes. The design data for coastal protective structures, such as mounds, revetments and groins include near-shore bathymetry, water levels, waves and currents, structural data on soils, strength and the availability of building materials.

Wind speeds and their directional distribution can be used to evaluate directional properties of waves, currents and sea level in the absence of wave in a given location. In Tanzania the design engineer will frequently be restricted by the absence, not only of wave data, but also of good wind data specific to a given site. Lwambuka [2] compiled 18-year wind data of several locations in Tanzania including Tanga, Zanzibar, Dar Es Salaam and Mtwara. Using the method of moments, he fitted only the FT-I distribution function and found 50-year extreme gust speeds (1.9 x extreme wind speed) to be 30 m/s for Tanga, 29 m/s for Zanzibar, 27 m/s for Dar Es Salaam and 38 m/s for Mtwara. In this paper, extreme wind speeds, which would be required in the evaluation of wave climate, currents and sea level on the coastline of Tanzania, are evaluated by fitting five distribution functions and choosing the best fit.
In this paper, extreme wind speeds, which are normally used in the determination of the design wave climate, currents and water level, are evaluated.

Methodology

Wind data records for Tanga, Dar Es Salaam, Mtwara and Zanzibar for the period between 1972 and 1996 were collected. These are 3-hourly records of wind speeds and direction at airport stations recorded by a rotating cup anemometer mounted at the top of a 10 meter high tower.

The annual maxima series was constructed by drawing the maximum value in every year from the full data record. No data of some years with low wind activity were omitted. Five candidate distribution functions, viz. Fisher-Tippett Type I and Weibull with the exponent k ranging from 0.75 to 2.0 are fitted to the input array of wind speeds following the approach developed by Goda [3]. This approach provides estimates of wind speeds for various return periods and the corresponding confidence intervals. It has been assumed that only one severe storm per year will occur. The distribution functions are:

- Fisher-Tippett Type I (FT-I) Distribution given as:

$$F(V) = \exp(-\exp(-(V - B) / A) \quad (2)$$

and

- The Weibull Distribution given as:

$$F(V) = 1-\exp[-\{(V-B)/A\}^k] \quad (3)$$

where $F(V)$ is the probability of non-exceedance of the statistical wind speed variable V, $B \geq V$ is the location parameter, A is the scale parameter and $k > 0$ is the shape parameter.

The input data is then arranged in descending order of magnitude from the largest to the smallest of the wind speeds and a probability or plotting position is assigned to each wind speed using Gringorten formula [4] for FT-I and the modified formula (by Goda [3]) of Petruaskas and Aagaard [5] as follows:

$$\left.\begin{aligned} F(V_m) &= 1-\frac{m-0.44}{N_T+0.12} && \text{for FT-I} \\ F(V_m) &= 1-\frac{m-0.20-\frac{0.27}{\sqrt{k}}}{N_T+0.20+\frac{0.23}{\sqrt{k}}} && \text{for Weibull} \end{aligned}\right\} \quad (4)$$

where $F(V_m)$ is the probability of the m-th value of wind speed not being exceeded, m is the rank of the wind speed. N_T is the total number of events during the length of a record, which in our case, has been taken to be equal to the number of input wind speeds.

The scale and location parameters A and B in Equations (1) and (2) are related linearly as

$$V_m = AY_m + B, \quad m = 1, 2, \ldots\ldots, N \qquad (5)$$

where V_m is the *m-th* largest value of the wind speed and Y_m is the reduced variate for the *m-th* value of the wind speed. This reduced variate is related to $F(V_m)$ as:

$$\left.\begin{aligned} Y_m &= -\ln[-\ln F(V_m)], \quad \text{for FT-I} \\ Y_m &= \{-\ln[1 - F(V_m)]\}^{\frac{1}{k}} \text{ for Weibull} \end{aligned}\right\} \qquad (6)$$

The parameters A and B are evaluated using the Least Squares Method applied between the ordered pair of V_m and its reduced variate Y_m for the five candidate distribution functions.

The return period is defined as the average time interval between successive events of an extreme wind speed being equalled or exceeded. For example, the 25-year wind speed can be expected to be equalled or exceeded an average of once every 25 years. Wind speeds for various return periods are calculated by the following equations [3]:

$$V_r = Ay_r + B \qquad (7)$$

where

v_r = wind speed with return period T_r

$$\left.\begin{aligned} y_r &= -\ln\left[-\ln\left(1 - \frac{1}{\lambda T_r}\right)\right] \quad \text{for FT-I} \\ y_r &= \left[\ln(\lambda T_r)\right]^{\frac{1}{k}} \quad \text{for Weibull} \end{aligned}\right\} \qquad (8)$$

λ = N_T/K = average number of events per year = 1 in this analysis.

T_r = return period in years and K = length of record in years

Since the period of a record is short and the level of uncertainty in extreme estimates with long return periods is high, confidence intervals are calculated to give a quantitative indicator of the level of uncertainty in the estimated extreme wind speeds. Here, the approach of Goda [3] for estimating standard deviation of return values when the true distribution is known is used. The normalised standard deviation is calculated by

$$\sigma_{nr} = \frac{1}{\sqrt{N}}\left[1.0 + a(y_r - c + \varepsilon \ln \nu)^2\right]^{\frac{1}{2}} \qquad (9)$$

where

σ_{nr} = normalised standard deviation of wind speed with return period r

N = number of input wind speed

$a = a_1 e^{a_2 N^{-1.3} + k\sqrt{-\ln \nu}}$

a_1, a_2, c, ε, κ = empirical coefficients as suggested by Goda [3] and shown in Table 1.

Table 1. Coefficients of Empirical Standard Deviation Formula for Extreme Wind speeds [3]

Distribution	a_1	a_2	κ	c	ε
FT-I	0.64	9.0	0.93	0.0	1.33
Weibull (k =0.75)	1.65	11.4	-0.63	0.0	1.15
Weibull (k =1.0)	1.92	11.4	0.00	0.3	0.90
Weibull (k =1.4	2.05	11.4	0.69	0.4	0.72
Weibull (k=2.0)	2.24	11.4	1.34	0.5	0.54

The absolute magnitude of the standard deviation of wind speed is calculated by

$$\sigma_r = \sigma_{nr}\,\sigma_m \qquad (11)$$

where σ_r is the standard error of wind speed with return period r and σ_m is the standard deviation of input wind speed.

Confidence intervals are calculated by assuming that wind speed estimates at any particular return period are normally distributed about the assumed distribution function. Table 2 gives factors by which the standard error given by Equation (10) is multiplied to get bounds with various levels of confidence.

The five distribution functions considered in this analysis are sufficiently different that only one or two provide a good fit distribution function to any particular data set. In order to select the best fit distribution function, the

Table 2. Confidence Interval Bounds for Extreme Wind speeds

Confidence Level (%)	Confidence Interval Bounds Around V_r	Probability of Exceeding Upper Bound (%)
80	$\pm 1.28\sigma$	10.0
85	$\pm 1.44\sigma$	7.5
90	$\pm 1.65\sigma$	5.0
95	$\pm 1.96\sigma$	2.5
99	$\pm 2.58\sigma$	0.5

correlation between variables in the linear Equation (5) and the sum of the squares of residuals are used. The sum of the squares of residuals is the is given as:

$$\sum_{m=1}^{N}\left[V_m-\left(AY_m+B\right)\right]^2 \tag{13}$$

The distribution function that gives the highest correlation and the smallest sum of the squares of residuals has been selected.

Results

Tables 3 through 6 show that for Tanga, Dar Es Salaam and Mtwara winds the Weibull distribution with k = 1.0, 2.0 and 2.0 respectively are found to have the highest correlation coefficient and the smallest sum of the squares of residuals. For Zanzibar winds, the FT-I distribution has the highest correlation while the Weibull distribution with k = 2.0 has the least sum of residuals. The corresponding 100-year extreme wind speeds for these distributions are 30.07 knots for Tanga, 27.76 knots for Dar Es Salaam, 31.09 knots for Zanzibar (taking the value for the highest correlation) and 37.24 knots for Mtwara.

Figures 1 through 4 show the distribution functions fitted to wind speed data points and the expected extreme wind speeds with 90% confidence limits.

Table 3. Tanga winds

N = 25 STORMS, NT = 25 STORMS, NU = 1.00, K = 2 YEARS, LAMBDA = 1.00 STORM PER YEAR , MEA OF SAMPLE DATA = 20.20 KNOTS, STD = 2.70 KNOTS					
Distribution Function	FT-I	Weibull Distribution			
		k = 0.75	k = 1.0	k = 1.4	k = 2.0
A	2.056	1.730	2.736	4.026	5.529
B	19.047	18.150	17.472	16.535	15.302
Correlation	0.9330	0.9435	0.9559	0.9449	0.9182
Sum Square of Residuals	0.2739	0.5444	0.2016	0.2447	0.3159
Return Period	V_r	V_r	V_r	V_r	V_r
2	19.80	19.21	19.37	19.63	19.90
5	22.13	21.41	21.88	22.19	22.32
10	23.67	23.41	23.77	23.84	23.69
25	25.62	26.37	26.28	25.81	25.22
50	27.07	28.82	28.17	27.20	26.24
100	28.51	31.41	30.07	28.52	27.17

Table 4. Dar Es Salaam winds

N = 24 STORMS, NT = 24 STORMS, NU = 1.00, K = 24 YEARS, LAMBDA = 1.00 STORM PER YEAR , MEAN OF SAMPLE DATA = 20.00 KNOTS, STD = 2.828 KNOTS					
Distribution Function	FT-I	Weibull Distribution			
		k = 0.75	k =1.0	k =1.4	k = 2.00
A	2.246	1.712	2.809	4.312	6.161
B	18.742	17.973	17.199	16.074	14.541
Correlation	0.9747	0.8914	0.9382	0.9678	0.9787
Sum Square of Residuals	0.1206	0.5731	0.1908	0.1394	0.1091
Return Period (Yr)	V_r	V_r	V_r	V_r	V_r
2	19.57	19.02	19.15	19.39	19.67
5	22.11	21.20	21.72	22.13	22.36
10	23.80	23.18	23.67	23.90	23.89
25	25.93	26.11	26.24	26.01	25.60
50	27.51	28.52	28.19	27.50	26.73
100	29.08	31.09	30.13	28.91	27.76

Table 5. Zanzibar winds

N = 24 STORMS, NT = 24 STORMS, NU = 1.00, K = 24 YEARS, LAMBDA = 1.00 STORM PER YEAR, MEAN OF SAMPLE DATA = 21.458 KNOTS, STD = 3.007 KNOTS					
Distribution Function	FT-I	Weibull Distribution			
		$k = 0.75$	$k = 1.0$	$k = 1.4$	$k = 2.0$
A	2.385	1.885	3.030	4.577	6.467
B	20.123	19.226	18.437	17.292	15.729
Correlation	0.9733	0.9234	0.9521	0.9662	0.9662
Sum Square of Residuals	0.1165	0.2523	0.2059	0.1322	0.1142
Return Period (Yr)	Vr	Vr	Vr	Vr	Vr
2	21.00	20.38	20.54	20.81	21.11
5	23.70	22.78	23.31	23.72	23.93
10	25.49	24.96	25.41	25.60	25.54
25	27.75	28.18	28.19	27.84	27.33
50	29.43	30.85	30.29	29.42	28.52
100	31.09	33.87	32.39	30.92	29.61

Table 6. Mtwara winds

N = 24 STORMS, NT = 24 STORMS, NU = 1.00, K = 24 YEARS, LAMBDA = 1.00 STORM PER YEAR, MEAN OF SAMPLE DATA = 27.292 KNOTS, STD = 3.712 KNOTS					
Distribution Function	FT-I	Weibull Distribution			
		$k = 0.75$	$k = 1.0$	$k = 1.4$	$k = 2.0$
A	2.875	2.137	3.525	5.463	7.894
B	25.682	24.760	23.777	22.318	20.298
Correlation	0.9503	0.8480	0.8970	0.9342	0.9554
Sum Square of Residuals	0.1240	0.3303	0.2301	0.1653	0.1161
Return Period (Yr)	V_r	V_r	V_r	V_r	V_r
2	26.74	26.07	26.22	26.52	26.87
5	29.99	28.79	29.45	29.99	30.31
10	32.15	31.26	31.89	32.23	32.28
25	34.88	34.92	35.12	34.91	34.46
50	36.90	37.93	37.57	36.79	35.91
100	38.91	41.13	40.01	38.58	37.24

Discussion and Conclusion

The results presented in Tables 3 through 6 show that the 50- year and 100-year extreme wind speeds for the Weibull distribution function with $k = 2.0$ and the FT-I have the highest correlation coefficient and the least sum of the squares of residuals. When the five distribution functions are fitted to the extreme wind data, the Weibull distribution with k = 0.75 predicts the largest

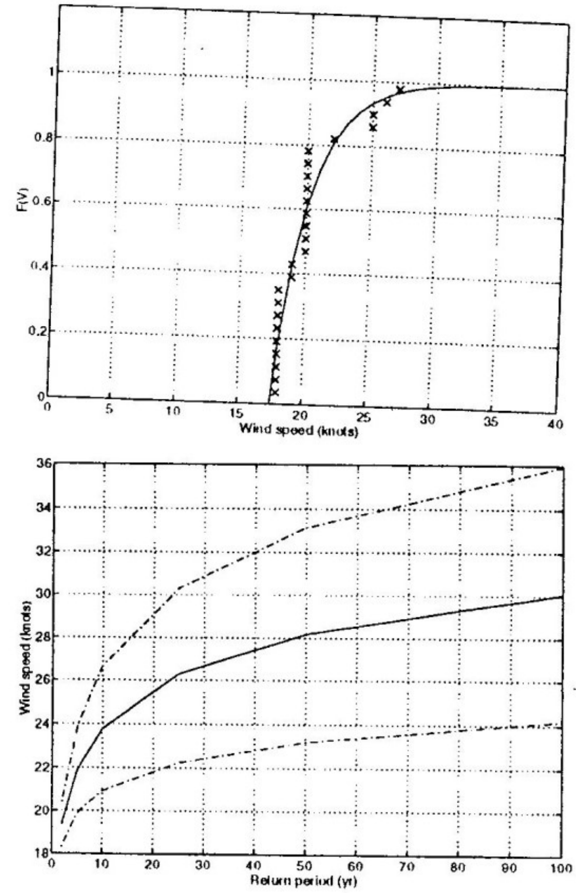

Figure 1. Tanga winds. Weibull Distribution (k =1.0) and expected extreme wind speeds with 90% confidence limits. (——— Weibull distribution, xx data points, ------- 90% confidence interval bounds).

return speeds and the Weibull distribution function with k =2.0 the smallest. The FT-I distribution function predicts values between those of the Weibull with k =1.0 and 1.4.

Although the extreme wind speed analysis can predict the return extreme wind speeds, the true return wind speeds are unknown because the winds and significant wave heights are random variables. It is, therefore, up to the design value engineer to make a decision to select a certain value within the predicted confidence interval shown in Figures 1 through 4. The selection of a certain value will depend mainly on the safety margin of the structure and the extent of the damages that would be incurred by a possible failure of the structure under design.

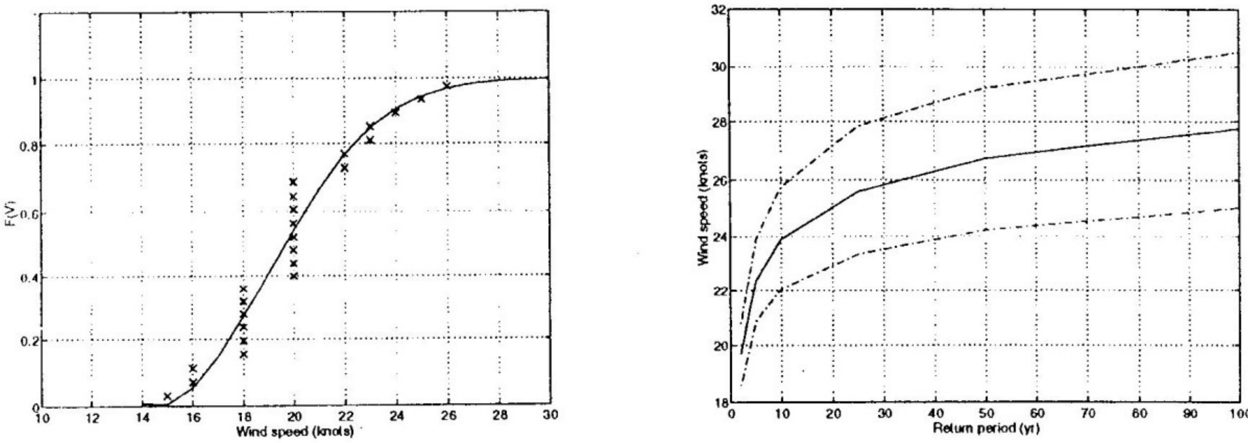

Figure 2. Dar Es Salaam winds. Weibull distribution ($k = 2.0$) and expected extreme wind speeds with 90% confidence limits. (——— Weibull distribution, xx data points, ------ 90% confidence interval bounds).

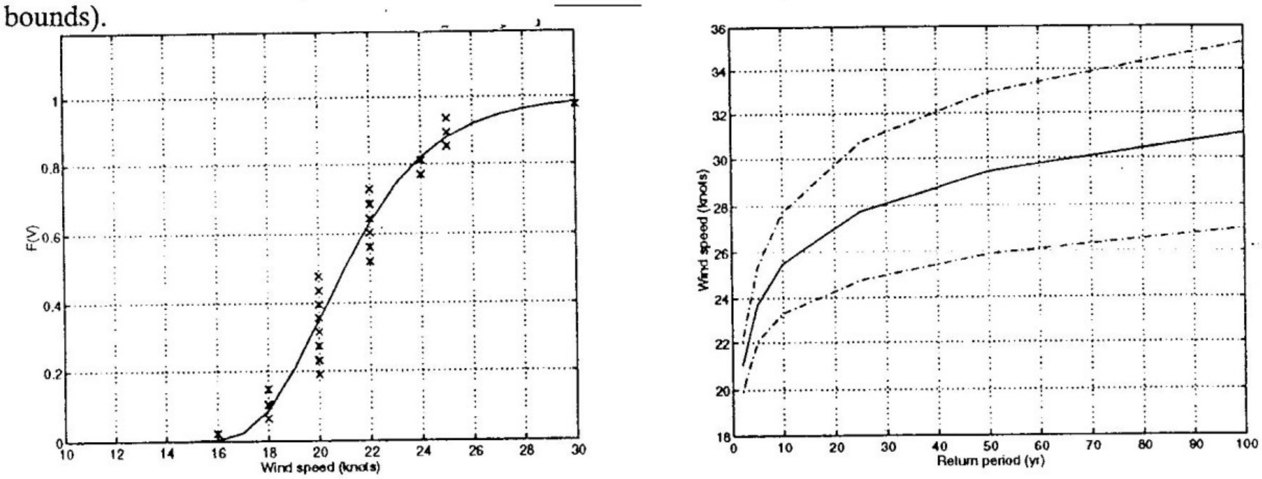

Figure 3. Zanzibar winds. Fisher-Tippet I and expected extreme wind speeds with 90% confidence limits. (_______ Weibull distribution, xx data points, ------ 90% confidence interval bounds).

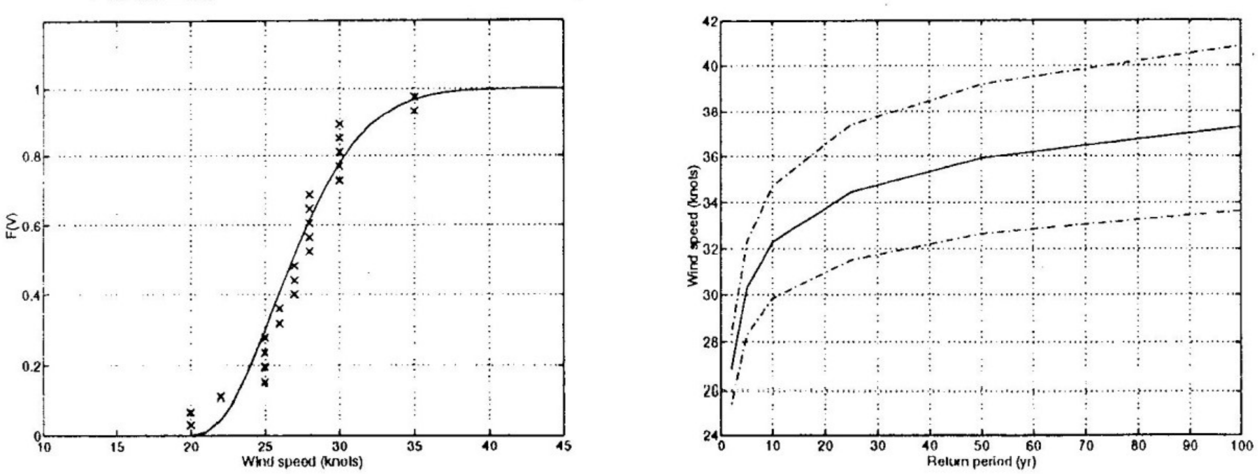

Figure 4. Mtwara winds. Weibull distribution ($k = 2.0$) and expected extreme wind speeds with 90% confidence limits. (——— Weibull distribution, xx data points, ------ 90% confidence interval bounds).

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