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A Comparative Study on Design Wind Speed Using Extreme Value Type-1 Distribution and IS875 Approach

N. Vivekanandan
Central Water and Power Research Station, Pune, Maharashtra, India

Abstract-: **Assessment of wind speed in a region is a pre-requisite while designing tall structures viz. cooling towers, stacks, transmission line towers, etc. This can expediently be carried out by Extreme Value Analysis (EVA) of hourly wind speed (HWS) data using probability distribution, or by using standard procedures available under Bureau of Indian Standards code of practices (IS 875) for building and structures. This paper details a study on EVA of HWS data recorded at India Meteorological Department observatories of Delhi and Visakhapatnam adopting five parameter estimation methods of Extreme Value Type-1 (EV1) distribution. The adequacy of fitting of EV1 distribution was quantitatively assessed by Goodness-of-Fit (GoF) tests such as Anderson-Darling and Kolmogorov-Smirnov, and diagnostic test using root mean squared error. The GoF and diagnostic tests results present the order statistics approach (OSA) is better suited amongst five methods adopted for estimation of wind speed for Delhi and Visakhapatnam. The results of 3-second average wind speed obtained from EVA of hourly rainfall adopting EV1 (using OSA) distribution are compared with IS 875 approach for arriving at a design wind speed. Based on the results obtained from EV1 distribution and IS 875 approach, the recommendations are made and presented in the paper.**

Keywords**: Anderson-Darling, Extreme Value Type-1 distribution, Kolmogorov-Smirnov, Order Statistics Approach, Wind speed.**

I. INTRODUCTION

Wind forces, and their static and dynamic effects, need to be taken into account while designing buildings, structures and their components thereof. If a structure is tall and slender, the effect of wind on the structure can be critical. The distribution of wind speed is also important in determining the serviceability of buildings [1-3]. The basic wind speed is arrived by considering 3-second (sec) average wind speed at a standard height of 10m. Research reports on wind studies indicated that the Mean+SE (where Mean denotes the estimated wind speed, SE the Standard Error and Mean+SE upper confidence limit will represent the value that will not be exceeded by 84.13% of the events having a desired return period) value is generally used to arrive at the design load that a structure must withstand during its lifetime [4-6]. For arriving at such design values, a standard procedure is to analyse hourly wind speed (HWS) data over a period of time and arrive at statistical estimates. A theoretical analysis of extreme hydrologic phenomena has led researchers to identify Extreme Value Type-1 (EV1) distribution as a standard distribution for extreme value analysis of meteorological data such as rainfall, temperature, wind speed, evaporation, etc.; and hence used in the present study. Standard analytical procedures viz., Method of Moments (MoM), Maximum Likelihood Method (MLM), Method of Least Squares (MLS), Order Statistics Approach (OSA) and Probability Weighted Moments (PWM) are commonly available for determination of parameters of EV1 (i.e., Gumbel) distribution. Number of studies has been carried out by different researchers on analyzing the characteristics of the parameter estimation methods of EV1 distribution. Research reports indicated that the MoM is a natural and relatively easy parameter estimation method. MLM is considered the most efficient method, since it provides the smallest sampling variance of the estimated parameters and hence of the estimated quantiles compared to other methods. But, the method has the disadvantage of frequently giving biased estimates and often failed to give the desired accuracy in estimating extremes from hydrological data [7-9]. PWM and MLS are much less complicated, and the computations are simpler. Parameter estimates from small samples using PWM and MLS are sometimes more accurate than the MLM estimates for EV1 distribution. On the other hand, OSA estimators are unbiased and having minimum variance [10-12]. Since there is no general agreement in applying particular method for a region because of the characteristics of the parameters, an attempt is made to apply all five methods of EV1 distribution for analyzing the HWS data recorded at the India Meteorological Department observatories of Delhi and Visakhapatnam. Goodness-of-Fit (GoF) tests viz., Anderson-Darling (AD) and Kolmogorov-Smirnov (KS) are employed for checking the adequacy of fitting of EV1 distribution to the recorded data. Diagnostic test using Root Mean Squared Error (RMSE) is adopted for the selection of suitable method of EV1 distribution for estimation of wind speed. In this paper, the Mean+SE values given by the suitable method of EV1 distribution (using GoF and diagnostic tests) are compared with the values obtained from IS 875 approach to arrive at a design wind speed for the regions under study. The methodology adopted in estimation of design wind speed using EV1 distribution and IS 875 approach are briefly described in the following sections.

II. METHODOLOGY

The Cumulative Distribution Function [CDF; F(x)] of EV1 distribution is given by:

$$F(x) = e^{-e^{-(x_i-\alpha)/\beta}}, \; x_i, \; \beta>0 \qquad \ldots (1)$$

Where, α and β are location and scale parameters of the distribution [13]. The parameters are computed by five different methods and used to estimate wind speed (x_T) for different return periods from

$$x_T = \alpha + Y_T\beta \qquad \ldots (2)$$

Where, Y_T is the reduced variate and defined by Y_T=-ln(-ln(1-(1/T))). Theoretical descriptions of the methods adopted in determination of parameters of EV1 distribution are as follows:

A. Method of Moments

$$\alpha = \bar{x} - 0.5772157\,\beta \text{ and } \beta = \left(\sqrt{6}/\pi\right)S_x \qquad \ldots (3)$$

Where, $\bar{x}$ and Sx are the mean and standard deviation of the recorded data.

B. Maximum Likelihood Method

$$\beta = \bar{x} - \left[\sum_{i=1}^{N} x_i \exp(-x_i/\beta) \Big/ \sum_{i=1}^{N} \exp(-x_i/\beta)\right] \qquad \ldots (4)$$

$$\alpha = -\beta \ln\left[\sum_{i=1}^{N} \exp(-x_i/\beta) \Big/ N\right] \qquad \ldots (5)$$

C. Method of Least Squares

$$\beta = \frac{\left(\sum_{i=1}^{N} x_i\right)^2 - \left(N \sum_{i=1}^{N} x_i^2\right)}{\left(N \sum_{i=1}^{N} x_i(\ln(-\ln(P_i)))\right) - \left(\sum_{i=1}^{N} x_i\right)\left(\sum_{i=1}^{N} \ln(-\ln(P_i))\right)} \qquad \ldots (6)$$

$$\alpha = \bar{x} + \left(\left(\sum_{i=1}^{N} \ln(-\ln(P_i))\right)\beta \Big/ N\right) \qquad \ldots (7)$$

Where, P_i=(i-0.44)/(N+0.12) and ln(-ln(P_i)) defines the cumulative probability of non-exceedance for each x_i [14].

D. Order Statistics Approach

The determination of Gumbel distribution using OSA is as follows:

$$\alpha = r^{*}\alpha_M^{*} + r'\alpha_M' \text{ and } \beta = r^{*}\beta_M^{*} + r'\beta_M' \qquad \ldots (8)$$

Where, r^* and r' are proportionality factors, which can be obtained from the selected values of k, n and n' using the relations as follows:

$$r^{*} = kn/N \text{ and } r' = n'/N \qquad \ldots (9)$$

Here, N is the sample size containing the basic data that are divided into k sub groups of n elements each leaving n' remainders. α_M^* and β_M^* are the distribution parameters of the groups, and α_M' and β_M' are the parameters of the remainders, if any. These can be computed from Eq. (10), as follows:

$$\alpha_M^{*} = (1/k)\sum_{i=1}^{n} \alpha_{ni} S_i \text{ and } \alpha_M' = \sum_{i=1}^{n'} \alpha_{n'i} x_i$$

$$\beta_M^{*} = (1/k)\sum_{i=1}^{n} \beta_{ni} S_i \text{ and } \beta_M' = \sum_{i=1}^{n'} \beta_{n'i} x_i \qquad \ldots (10)$$

Where, $S_i = \sum_{i=1}^{k} x_{ij}$, j=1,2,3,..,n.

The weights of α_{ni} and β_{ni} used in determining the parameters of EV1 by OSA are presented in Table 1.

Table 1: Weights of and used in determining the parameters of EV1 by OSA

α_{ni} or β_{ni}	i					
	1	2	3	4	5	6
α_{2i}	0.916373	0.083627				
α_{3i}	0.656320	0.255714	0.087966			
α_{4i}	0.510998	0.263943	0.153680	0.071380		
α_{5i}	0.418934	0.246282	0.167609	0.108824	0.058350	
α_{6i}	0.355450	0.225488	0.165620	0.121054	0.083522	0.048867
β_{2i}	-0.721348	0.721348				
β_{3i}	-0.630541	0.255816	0.374725			
β_{4i}	-0.558619	0.085903	0.223919	0.248797		
β_{5i}	-0.503127	0.006534	0.130455	0.181656	0.184483	
β_{6i}	-0.459273	-0.035992	0.073199	0.126724	0.149534	0.145807

E. Probability Weighted Moments

$$\alpha = M_{100} - 0.5772157\beta \text{ and}$$

$$\beta = (M_{100} - 2M_{101})/\ln 2 \ldots \quad (11)$$

$$M_{100} = \bar{x} \text{ and } M_{101} = \sum_{i=1}^{N} x_i(N-i)/(N(N-1)).$$

Here, 'i' is the rank assigned to each sample arranged in ascending order [15].

F. Computation of Standard Error

The values of SE of the estimated wind speed by MoM, MLM, MLS and PWM may be computed from Eq. (12):

$$SE = \left(\beta/\sqrt{N}\right)\left(A + BY_T + CY_T^2\right)^{0.5} \qquad \ldots (12)$$

The values of A, B and C [16] used in computation of SE by MoM, MLM, MLS and PWM are presented in Table 2. The SE of estimated wind speed by OSA is computed from:

$$SE = \left(r^{*}x_n + r'x_{n'}\right)^{1/2} \qquad \ldots (13)$$

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Where, $r^* = (1/k)(kn/N)^2$ and $r' = (n'/N)^2$. x_n and $x_{n'}$ are defined by general form as $x_n = (A_n Y_T^2 + B_n Y_T + C_n)\beta^2$. The values of A_n, B_n, and C_n [17] used in computing the SE by OSA, are presented in Table 3.

TABLE 2: VALUES OF A, B, AND C USED IN COMPUTATION OF SE BY MOM, MLM AND MLS

Parameter Estimation Method	Coefficients of A, B and C used in computation of SE		
	A	B	C
MoM and MLS	0.34472	0.04954	0.40286
PWM	0.22528	0.06938	0.29346
MLM	0.16665	0.06798	0.23140

TABLE 3: VALUES OF An, Bn AND Cn USED IN COMPUTATION OF SE BY OSA

n	A_n	B_n	C_n
2	0.71186	-0.12864	0.65955
3	0.34472	0.04954	0.40286
4	0.22528	0.06938	0.29346
5	0.16665	0.06798	0.23140
6	0.13196	0.06275	0.19117

G. Goodness-of-Fit Tests

The AD and KS tests statistic are defined by:

$$AD = (-N) - (1/N)\sum_{i=1}^{N}\left\{\begin{matrix}(2i-1)\ln(Z_{(i)}) + \\ (2N+1-2i)\ln(1-Z_{(i)})\end{matrix}\right\} \quad \ldots (14)$$

$$KS = \underset{i=1}{\overset{N}{Max}}\left(F_e(x_i) - F_D(x_i)\right) \quad \ldots (15)$$

Where, $Z_{(i)}=F(x_i)$, for $i=1,2,3,\ldots,N$ and $x_1<x_2< \ldots x_N$. Also, $F_e(x_i)=(i-0.44)/(N+0.12)$ is the empirical CDF of x_i and $F_D(x_i)$ is the computed CDF of x_i. If the computed values of GoF tests statistic given by the distribution (or method) are less than that of theoretical values at the desired significance level, then the distribution (or method) is considered to be adequate for modelling of HWS data [18].

H. Diagnostic Test

Theoretical description of RMSE [19] is given by:

$$RMSE = \left((1/N)\sum_{i=1}^{N}(x_i - x_i^*)^2\right)^{1/2} \quad \ldots (16)$$

where x_i and x_i^* are the recorded and estimated wind speed of i^{th} observation. The method having minimum RMSE is considered as better suited method for estimation of wind speed.

I. IS 875 Approach

Following IS 875 procedure, the basic wind speed (x_b) for a region can be determined, and subsequently modified to account for different effects and get design wind speed (x_z) at height z(m) for the chosen class of structure [20]. The relationship between x_b and x_z can be expressed by:

$$x_z = x_b k_1 k_2 k_3 \quad \ldots (17)$$

Where, k_1 is the probability-factor/ risk-coefficient, k_2 the terrain and height factor and k_3 the topography factor. Value of k_1 for different classes and mean probable design life of structures can be computed from the equation given by:

$$k_1 = \left(A - B\left[\ln\left\{-\frac{1}{NYR}\ln(1-P_{NYR})\right\}\right]\right)\Big/(A+4B)$$

$$P_{NYR} = 1-(1-(1/NYR))^{0.5} \quad \ldots (18)$$

Here, NYR is the mean probable design life (year) of the structure, P_{NYR} the risk level in NYR, and A and B are appropriate coefficients for the basic wind speed zone.

III. RESULTS AND DISCUSSIONS

A. Estimation of Wind Speed Using EV1 Distribution

By adopting the methodology described above, a computer program was developed and used to estimate wind speed for Delhi and Visakhapatnam regions. HWS data recorded at Delhi for the period 1991 to 2003 and Visakhapatnam for the period 1987 to 1997 was used. By using the nomogram (Figure 1) on normalized wind speed, the recorded 3-sec average wind speed is obtained by multiplying the factor of 1.52 with hourly wind speed data. The derived series of 3-sec average wind speed is further used to estimate the design wind speed adopting EV1 distribution (using MoM, MLM, MLS, OSA and PWM).

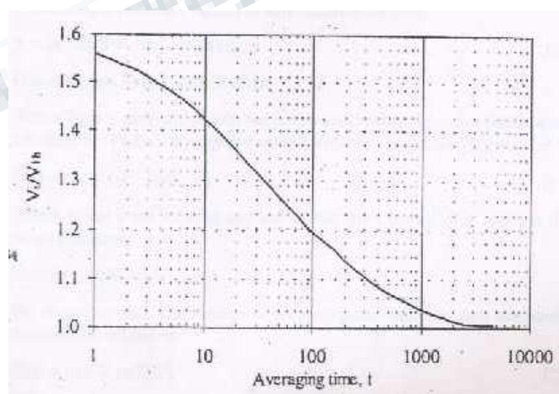

FIG. 1: NOMOGRAM FOR CONVERSION OF HOURLY WIND SPEED DATA INTO SHORT DURATION (SEC) WIND SPEED DATA

Table 4 gives the statistical parameters of the recorded 3-sec average wind speed of Delhi and Visakhapatnam. Tables 5 and 6 give the estimates of 3-sec average wind speed for different return periods computed by five different methods of EV1 distribution for Delhi and Visakhapatnam. From Tables 5 and 6, it may be noted that the estimated wind speed

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by OSA are consistently higher the corresponding values of other four methods for both the regions.

TABLE 4: STATISTICAL PARAMETERS OF RECORDED 3-SEC AVERAGE WIND SPEED OF DELHI AND VISAKHAPATNAM

Region	Statistical parameters			
	Average (km/hr)	SD (km/hr)	CS	CK
Delhi	87.7	18.8	0.599	-0.476
Visakhapatnam	89.0	24.9	0.191	-1.188
SD: Standard Deviation; CS: Coefficient of Skewness; CK: Coefficient of Kurtosis				

B.Analysis Based on GoF Tests

GoF tests statistic were computed by using the parameters of EV1 distribution and the results are presented in Table 7. From GoF tests results, it is noticed that the computed values of GoF tests statistic by five different parameter estimation methods of EV1 distribution are less than the theoretical values ($AD_{0.05}$=0.757; $KS_{0.05,11}$=0.410; $KS_{0.05,13}$=0.377) at five percent significance level, and at this level, all five methods are suitable for determination of parameters of EV1 distribution for the regions under study.

TABLE 5: 3-SEC AVERAGE WIND SPEED ESTIMATES WITH SE USING FIVE METHODS OF EV1 DISTRIBUTION FOR DELHI

Return period (year)	Estimated 3-sec average wind speed (km/hr) by EV1 distribution using									
	MoM		MLM		MLS		OSA		PWM	
	X_T	SE	X_T	SE	X_T	SE	X_T	SE	X_T	SE
2	84.7	4.7	84.5	4.7	84.8	5.2	84.4	5.5	84.4	5.0
5	101.2	8.1	101.2	7.3	103.1	8.8	103.1	8.7	102.0	8.2
10	112.2	10.8	112.2	9.4	115.1	11.9	115.5	11.6	113.7	10.8
20	122.7	13.7	122.8	11.6	126.6	15.0	127.4	14.3	124.9	13.4
50	136.3	17.5	136.5	14.3	141.5	19.3	142.7	18.2	139.5	16.9
100	146.5	20.4	146.7	16.4	152.8	22.5	154.3	21.1	150.3	19.5

TABLE 6: 3-SEC AVERAGE WIND SPEED ESTIMATES WITH SE USING FIVE METHODS OF EV1 DISTRIBUTION FOR VISAKHAPATNAM

Return period (year)	Estimated 3-sec average wind speed (km/hr) by EV1 distribution using									
	MoM		MLM		MLS		OSA		PWM	
	X_T	SE	X_T	SE	X_T	SE	X_T	SE	X_T	SE
2	85.0	6.8	84.8	7.3	85.1	7.6	84.8	8.1	84.5	7.6
5	106.9	11.6	108.1	11.1	109.6	12.9	110.5	12.8	108.7	12.3
10	121.4	15.7	123.4	14.3	125.9	17.5	127.4	16.9	124.8	16.1
20	135.4	19.8	138.2	17.5	141.4	22.0	143.8	21.0	140.3	19.9
50	153.5	25.2	157.2	21.7	161.4	28.1	164.9	26.4	160.2	25.1
100	167.2	29.5	171.5	24.9	176.6	32.7	180.7	30.6	175.1	29.0

TABLE 7: GOF TESTS RESULTS OF EV1 DISTRIBUTION FOR DELHI AND VISAKHAPATNAM

Region	GoF tests results of EV1 distribution by									
	MoM		MLM		MLS		OSA		PWM	
	AD	KS	AD	KS	AD	KS	AD	KS	AD	KS
Delhi	0.295	0.173	0.293	0.173	0.271	0.160	0.285	0.169	0.274	0.168
Visakhapatnam	0.449	0.205	0.372	0.195	0.322	0.182	0.302	0.186	0.331	0.190

C. Analysis Based on Diagnostic Test

The RMSE values were computed by five methods of EV1 through Eq. (16) and presented in Table 8.

TABLE 8: RMSE VALUES OF FIVE METHODS OF EV1

Region	RMSE (km/hr) given by				
	MoM	MLM	MLS	OSA	PWM
Delhi	4.84	4.82	4.19	4.12	4.44
Visakhapatnam	6.77	6.13	5.49	5.19	5.73

From Table 8, it is noticed that the RMSE value given by OSA is minimum when compared to other four methods of EV1. Therefore, OSA is identified as the best suitable method for estimation of design wind speed for both the regions. The plots of recorded and estimated 3-sec average wind speed by EV1 (using OSA) distribution together with 84.13% and 95% confidence limits for Delhi and Visakhapatnam are presented in Figures 2 and 3. From Figures 2 and 3, it can be seen that the recorded 3-sec average wind speed data are within 95% confidence limits of the estimated wind speed by EV1 (using OSA). The Correlation Coefficient (CC) between the recorded and estimated wind speed by all five methods of EV1 is computed as 0.971 for Delhi and 0.979 for Visakhapatnam.

D. Estimation of Wind Speed using IS 875 Approach

According to the wind speed map given in IS 875, the basic wind speed for Visakhapatnam region is 50 m/s; and the coefficients of A and B corresponding to the basic wind speed is 88.8 and 22.8 respectively. For Delhi region, the coefficients of A and B, corresponding to the basic wind speed of 47 m/s, are 88.0 and 20.5 respectively.

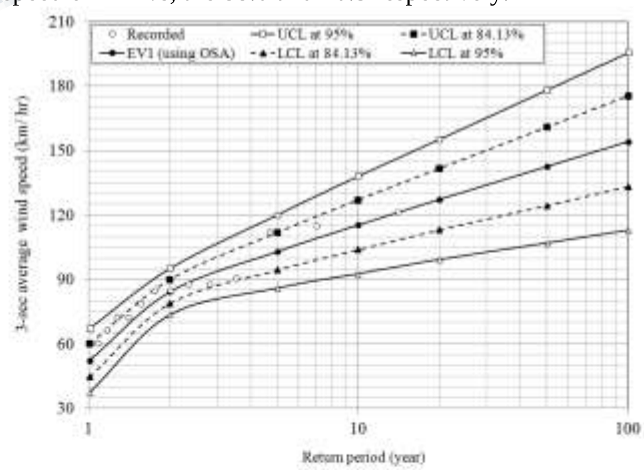

FIG. 2: PLOT OF ESTIMATED 3-SEC AVERAGE WIND SPEED BY EV1 (OSA) WITH CONFIDENCE LIMITS FOR DELHI

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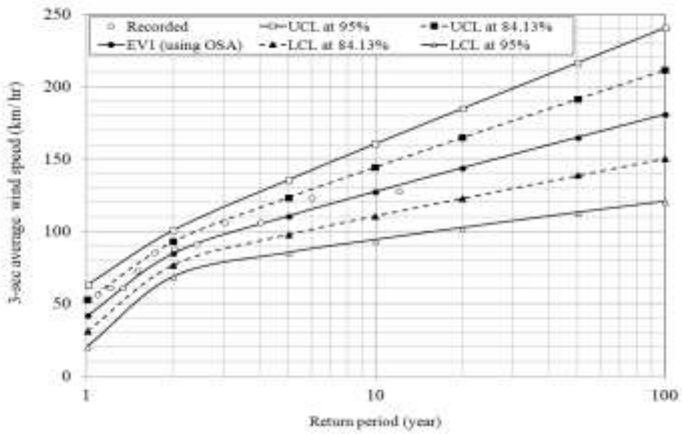

FIG. 3: PLOT OF ESTIMATED 3-SEC AVERAGE WIND SPEED BY EV1 (OSA) WITH CONFIDENCE LIMITS FOR VISAKHAPATNAM

Since Delhi and Visakhapatnam region are considered to be a Terrain Category 1, i.e. exposed open terrain with few or no obstructions and in which the average height of any object surrounding the structure is less than 1.5m, the values of k2 and k3 are considered as 1.05 and 1.00 respectively. The values of k1 for 50-year and 100-year return periods are computed from Eq. (18). By using the values of xb, k1, k2 and k3, the values of design wind speed (xz), at a standard height of 10m, for different return periods are computed from Eq. (17). Table 9 gives a comparison of 3-sec average wind speed obtained from EV1 (using OSA) distribution and IS 875 approach for Delhi and Visakhapatnam.

TABLE 9: COMPARISON OF ESTIMATED 3-SEC AVERAGE WIND SPEED BY EV1 (OSA) AND IS 875 APPROACH

Return period (year)	IS 875 approach (at standard height 10m)		Estimated 3-sec average wind speed (m/s) by EV1 (using OSA) distribution			
	Delhi	Visakhapatnam	Delhi		Visakhapatnam	
			Mean	Mean+SE	Mean	Mean+SE
2	27.6	28.4	23.5	25.0	23.6	25.8
5	34.5	35.7	28.7	31.1	30.7	34.3
10	39.0	41.0	32.1	35.3	35.4	40.1
20	43.4	45.7	35.4	39.4	40.0	45.8
50	49.4	52.5	39.7	44.7	45.8	53.2
100	52.8	56.7	42.9	48.8	50.2	58.7

From Table 9, it may be noted that the estimated 50-year and 100-year return period 3-sec average wind speed by IS 875 approach is consistently higher than the corresponding values given by EV1 (using OSA) distribution for Delhi and Visakhapatnam regions. Also, from Table 9, it may be noted that the percentages of variation on Mean+SE values of the estimated 3-sec average wind speed, with reference to design wind speed corresponding to 50-year and 100-year are 9.5% and 7.6% respectively for Delhi. Similarly, the percentages of variation on Mean+SE values of the estimated 3-sec average wind speed with reference to design wind speed corresponding to 50-year and 100-year are 1.3% and 3.5% respectively for Visakhapatnam. The study suggested that the Mean+SE values of 3-sec average wind speed of 48.8 m/s (175.4 km/hr) and 58.7 m/s (211.3 km/hr) related to 100-year return period may be considered for design purposes while designing hydraulic structures with design life of 100-year in Delhi and Visakhapatnam regions respectively.

IV. CONCLUSIONS

The paper presented a computer aided procedure for assessment of design wind speed for Delhi and Visakhapatnam regions adopting EV1 distribution (using MoM, MLM, MLS, OSA and PWM). IS 875 approach was also used to determine the design wind speed using basic wind speed for the regions, and the results are compared with the corresponding values obtained from EV1 distribution. From the results of the data analysis, the following conclusions were drawn from the study:

i) GoF tests results confirmed the suitability of all five methods for parameter estimation of EV1 distribution for modelling of HWS data.

ii) Diagnostic test results (using RMSE) indicated the OSA is better suited method for estimation of wind speed.

iii) CC values computed by all five methods of EV1 distribution for Delhi and Visakhapatnam are 0.971 and 0.979 respectively.

iv) The estimated 50-year and 100-year return period 3-sec average wind speed using IS 875 approach are higher than the values given by EV1 (using OSA) distribution.

v) The study suggested that the 100-year return period Mean+SE values of 3-sec average wind speed of 48.8 m/s and 58.7 m/s could be considered for design purposes while designing hydraulic structures with design life of 100-year return period in Delhi and Visakhapatnam.

vi) However, considering the data length made available for the study, it was cautioned to use the 3-sec average wind speed for return periods beyond 25-year because of uncertainty in the estimated values.

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