ARTICLES

Determination of Basic Wind Pressure for Structural Design in Saudi Arabia

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Abstract:

The results of extreme value analysis of wind speed data from twenty-four meteorological stations in Saudi Arabia together with five stations in five other neighbouring countries are presented. The objective of this work is to present the design wind speeds and basic wind pressures corresponding to 50 and 100 year recurrence periods at an altitude of 10 m for Saudi Arabia. The chosen recurrence periods are corresponding to a certain limit of risk acceptance criteria. These wind speeds are averaged over a time of fifteen minutes. The results are presented in a table to provide the wind speeds and basic wind pressures for structural design purposes in Saudi Arabia.

1- Introduction:

The design of safe and serviceable building structures requires assessment of the largest loads likely to be experienced in the expected lifetime of each structure. The first step in this assessment is the estimation of extreme wind climate of the site from the available meteorological records. Analysis of the wind climate is conventionally performed in terms of the order statistics of annual maxima, as reviewed in [1,2,3,4 and 5]. Often these analyses are used indirectly in the form of code specified wind speeds. However, in recent years, more detailed analyses are often undertaken in support of particular major

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projects. Various methods have been developed for statistical analysing such records to arrive at estimates of the wind speeds corresponding to particular recurrence interval or risk level deemed suitable for design purposes. Such analysis for Saudi Arabia has not been performed before. This paper reports the application of the approach provided in [6,7,8,9 and 10] to a comprehensive analysis of the Saudi extreme wind climate. The results are used to provide the 50 year and 100 year wind speed for structural design purposes.

2. Discussion:

2.1 Extreme wind climatology in well-behaved climates:

Infrequent winds (e.g., hurricanes) that are meteorologically distinct from and considerably stronger than the usual annual extremes are referred to herein as extraordinary winds. Climates in which extraordinary winds may not be expected to accur, are referred to as well-behaved (this is the case in Saudi Arabia). In such climates, it is reasonable to assume that each of the data in series of largest annual wind speeds contributes to the description of the probabilistic behavior of the extreme winds. A statistical analysis of such a series can therefore be expected to yield useful predictions of long-term wind extremes. Thus in a well-behaved climate, at any given station a random variable may be defined, which consists of the largest yearly wind speed. If the station is one for which wind records over a number of consecutive years are available, then the cumulative distribution function (CDF) of this random variable may be estimated to characterise the probabilistic behavior of the largest annual wind speeds. The basic design wind speed is then defined as the speed corresponding to a specific value p of the CDF or, equivalently, to a specific mean recurrence interval N (note that $N = 1/(1-p)$). A wind speed corresponding to an N-year mean recurrence interval is commonly referred to as the N-year wind speed (Usually the recurrence period used in building codes is 50 years).

2.2 Probabilistic Modelling of largest yearly wind speeds:

Several probability distributions have been proposed to model extreme wind behavior. These include the Type I distribution of largest values, Eq. (1), and the Type II distribution of largest values, Eq. (2). The cumulative distribution function for Type I distribution of the extreme values (also referred to as th Gumbel distribution) is:

$$P(x) = exp\{-exp[-(x-\mu)/\sigma]\} \tag{1}$$

In Eq. (1) μ and σ are referred to as the location and scale parameters, respectively. The cumulative distribution function for Type II distribution of the extreme values (also referred to as the generalized Frechet distribution) is:

$$P(x) = exp\{-[x-\mu/\sigma]^{-\gamma}\}, \tag{2}$$

Where, μ, σ and γ are the location, the scale and the shape or tail length parameters, respectively. In the particular case when $\mu = 0$, eq. (2) is referred to as the Frechet (not generalized Frechet) distribution.

Eqs. (1) and (2) may be inverted to yield the so-called percent point function, that is the x value of the random variable that corresponds to any given value of cumulative distribution function. In the case of Type I distribution:

$$x(P_I) = \mu - \sigma\ In(-In\ P_I), \tag{3}$$

Whereas for Type II distribution

$$x(P_{II}) = \mu + \sigma(-In\ P_{II})^{-1/\gamma} \tag{4}$$

It is convenient to denote the cumulative distribution function value P_I or P_{II} by p and the corresponding random variables $x(P_I)$ or $x(P_{II})$ by $G_X(p)$. Then, for Type I distribution.

$$G_X(p) = \mu - \sigma\ In(-In\ p) \tag{5}$$

And for Type II distribution

$$G_X(p) = \mu + \sigma(-In\ p)^{-1/\gamma} \tag{6}$$

Let the random variable X represent the extreme annual wind speed at some given location. From the definition of p, it follows that the probability $(X > x) = 1 - p$. Each year many them be viewed as a trial in which the event that the wind speed X will exceed some value x has the probability of occurrence $1 - p$. If the return period (or the mean recurrence interval) is N, N is equal to $1/(1 - p)$. Thus the wind speed x corresponding to a mean recurrence interval N is equal to the value of the percent point function of X corresponding to

$$p = 1 - 1/N \tag{7}$$

Extreme wind speed that inferred from any given sample of wind speed data depends on the type of distribution on which the inferences are based. For large mean recurrence intervals $(N > 50)$ estimates based on the assumption that Type II distribution is valid are higher than corresponding estimates obtained by using Type I distribution, while estimates based on a Weibull distribution [11]with tail length parameter $\gamma \geq 2$ are lower.

According to [12], extreme winds in well-behaved climates may be assumed to be best modelled by Type II distribution with $\mu = 0$ and $\gamma = 9$. However, subsequent research has shown that this assumption is not borne out by analyses of extreme wind speed data [13,14,15].

In Ref. [13], a 37 years series of the 5 minute largest yearly speeds measured at stations with well-behaved climates was subjected to the probability plot correlation coefficient test to determine the tial length parameter of the best fitting distribution of the largest values. Of these series, 72% were best fit by Type I distributions or by Type II distributions with $\gamma = 13$ (which differs insignificantly from Type I distribution); 11% by Type II distributions with $7 \leq \gamma < 13$; and 17% by Type II distribution with $2 \leq \gamma < 7$. Virtually the same percentages were obtained from the analysis of sets of 37 wind speed data generated by Monte Carlo simulation from a population with Type I distribution On the other hand, the analysis of sets generated by Monte Carlo simulation from a Type II distribution with tail length parameter $\gamma = 9$ led to percentages differing significantly from those corresponding to the actual wind speed data. On the basis of these results there is a high degree of probability that in a well-behaved climate, extreme wind speeds are modelled more realistically by Type I than by Type II distribution with $\gamma = 9$. This conclusion was reinforced by studies reported in [14], in which techniques similar to those of [13] were used in conjunction with wind speed data at 100 US weather stations obtained from [16]. Also a Type I distribution, in most cases, is likely to be more conservative according to Ref. [17].

2.3 Estimation of N-year wind speeds and confidence intervals:

It is shown in [11] that, given a set of data with a Type I extreme value distribution, several techniques can be used to estimate the parameters of the distribution and, hence, the value of the variant corresponding to given mean recurrence interval. However, inherent in these estimates are sampling errors. A measure of the magnitude of the latter can be obtained by calculating confidence intervals of the quantity being estimated, that is, intervals of which it can be stated that they contain the true unknown value of the quantity. Techniques that can be used to estimate the N-year wind, and the confidence intervals for the N-year wind, are discussed in [11]. One of these techniques is presented below.

Using the approximation $-In[-In(1 - 1/N)] = In\,N$, the estimated value of the N-year wind speed, V_N is:

$$V_N \approx \overline{X} + 0.78(In\,N - 0.5772)s, \qquad (8)$$

Where $\overline{X}$ and s are, respectively, the sample mean and the sample standard deviation of the largest yearly wind speeds for the period of record.

As previously noted, inherent in the estimates of V_N are sampling errors. The standard deviation of the sampling errors in the estimation of V_N can be written as:

$$SD(V_N) \approx 0.78\,[1.64 + 1.46(In\,N - 0.5772) + 1.1(In\,N - 0.5772)^2]^{1/2}\frac{s}{\sqrt{n}}, \qquad (9)$$

Where n is the sample size.

As indicated previously, in engineering calculation it is prudent to assume the validity of Type I distribution Eq. (1). This is the adopted technique in developing the 50-year wind speed map (fastest mile wind speed at 10 m above ground in open terrain) for the US-ANSI-A58.1 standards, BBC [18], SBC[19] and UBC[20].

As shown in [11], the probabilities that V is contained in the intervals $V_N \pm SD(V_N)$, $V_N \pm 2SD(V_N)$ and $V_N \pm 3SD(V_N)$ are approximately 68%, 95% and 99% confidence intervals for V. It is also shown in [11], that the width of the confidence intervals can be reduced if a more efficient estimator is used; however, the intervals cannot be narrower than those obtained by using the Cramer Rao (C.R.) lower bound [11].

2.4 Estimation of Extreme Wind Speeds from Short Term Records:

A practical procedure for estimating extreme wind speeds at locations where long-term data are not available is described in [21]. The method that was tested for a large number of US weather stations, makes it possible to infer the probabilistic behavior of extreme winds from data consisting of the largest monthly wind speeds recorded over a period of three years or longer. Estimates based on the monthly speeds, denoted by, V_m, are obtained by rewriting Eq. (8) as follows:

$$V_{Nm} \approx X_m + 0.78[In(12\,N) - 0.5772]s_m\ , \qquad (10)$$

Where X_m and s_m are, respectively, the sample mean and the sample standard deviation for the largest monthly wind speed data, and N is the mean recurrence interval in years.

The standard deviation of the sampling error in the estimation of V_N is obtained from Eq. (9) as:

$$SD(V_{Nm}) \approx 0.78\{1.64 + 1.46[In(12N) - 0.5772] + 1.1[In(12N) - 0.5772]^2\}^{1/2} \frac{S_m}{\sqrt{n_m}}\ , \quad (11)$$

where n is the sample size.

Similar calculations carried out for 67 sets of records taken at 36 stations are reported in [21], where it was found that the difference

$V_{50m} - V_{50}$ where V_{50} is the 50-year speed estimated long term largest yearly data, were less than $SD(V_{50m})$ in 66% of the cases and less than twice the value of $SD(V_{50m})$ in 95% of the cases. This remarkable result, confirmed by additional calculations reported in [8], indicates that the estimates based on the largest monthly wind speeds recorded over three years or more provide a useful description of the extreme wind speeds in regions with a well- behaved wind climate.

Inferences concerning the probabilistic model for the extreme wind climate have also been attempted from data consisting of the largest daily wind speeds [21], or wind speeds measured at 1-hour interval [9]. One problem that arises in this respect is that data recorded on two successive days are generally strongly correlated. Nevertheless, as shown in [9], in practice such correlation has a negligible effect on the statistical estimates, and the assumption of statistical independence among the data can therefore be used. However, a second and more serious problem is that the daily (or hourly) data reflect a large number of events (e.g. morning breezes) that are altogether unrelated meteorologically to the storms associated with the extreme winds. These events can be viewed as noise that obscures the information relevant to the description of the extreme wind climate. Indeed, it was verified in [21] that estimates of the extreme winds based on daily data differ significantly from estimates obtained for long-term records of largest yearly speeds. This conclusion is true for the inferences based on the hourly data.

2.5 Wind Directionality:

Wind has effects on various structures and components not only depending on the magnitude of the wind speeds, but also on the associated wind directions as well. For this reason, knowledge of continuous joint probability distributions of extreme wind speed and directions would be useful for design and code development purposes.

There are important practical applications in which information is needed on the univariate probability distributions of the largest yearly wind speeds associated with each of the principal compass directions, and on the correlation coefficients for the largest yearly winds blowing from any two directions. In well-behaved climate the largest yearly wind speeds for any given wind direction are in most cases, thought not always, best fitted by Type I distribution of the largest values. As indicated in [14], the correlation between wind speeds occurring in two of the eight principal compass directions is in most cases weak.

An important problem faced by the designer is obtaining the largest yearly wind speed data for each of the eight principal compass directions for Saudi Arabia. The source of data is the National Oceanic and Atmospheric Administration (NOAA) in the United States. Their data do not include maximum wind speeds and directions for all the data obtained and used in this study, so wind directionality will be the objective of future work.

2.6 Wind Speed Data:

Twenty-nine surface stations, twenty-three in Saudi Arabia, one in Qatar, one in Oman, one in Kuwait, one in Abu-Dhabi and one in Bahrain, were chosen to provide data for this study, (see map1) The selection was based mainly on the following consideration:

1 - The Station should, as far as possible, provide coverage for all Saudi Arabia territories.

2 - The study should usefully extend to some neighboring regions in Kuwait, Qatar, Oman, Bahrain and Abu-Dhabi.

The choice was also restricted by the distribution of stations providing reasonably lengthy and continuous records, the availability of the data and the time and cost required for processing.

Station descriptions including position (longitude and latitude) and period of reading are given in Table 1. These data are extracted from the World-wide Data CD-ROM provided by the National Oceanic and Atmospheric Administration (NOAA).

Table 1
Some information about stations being used in the study

Name of Station	Latitude	Longi-tude	Period of Reading	Name of sta-tion	Latitude	Longi-tude	Period of Reading
Abha	18 14° N	42 39° E	1979-1993*	Rafha	29 38° N	34 29° E	1973-1993*
Abu Dhabi (UAE)	24 26° N	54 39° E	1982 - 1993	Riyadh	24 43° N	46 43° E	1973-1993*
Al Ahsa	24 17° E	49 29° E	1973-August 1990	Sharurah	17 28° N	47 07° E	1984-August 1990
Al Baha	20 18 ° N	41 38° E	1983 - 1993*	Tabuk	28 22° N	36 38° E	1973 - 1993*
Bahrain	26 16° N	50 39° E	1973 - 1993	Taif	21 29° N	40 33° E	1973-1993*
Bishah	19 59° N	42 37° E	1976 - 1993*	Turaif	31 41° N	38 40° E	1974-1993*
Dhahran	26 16° N	50 09° E	1973 - 1993*	Al Wajh	26 12° N	36 28° E	1973 - 1993*
Al Jawf	29 47° N	40 06° E	1976 - 1993*	Yanbu Al	24 09° N	38 04° E	1973 - 1993*
Fahud (Oman)	22 21° N	56 29° E	1988 - 1990	Kuwait (Kuwait)	29 13° N	47 59° E	1973 - 1993*
Hafar Al Ba-ten	28 20° N	46 07° E	1973 - 1993*	Mecca	21 29° N	39 50° E	1984 - 1993*
Hail	27 26° N	41 41° E	1973 - 1993*	Medina	24 33° N	39 42° E	1973 - 1993*
Jeddah	21 40° N	39 09° E	1973 - 1993*	Nejran	17 37° N	44 26° E	1980-August 1990
Judayyidat Arar	30 55° N	41 08° E	1973 - 1993*	Al Qasim	26 18° N	43 46° E	1981 - 1993*
Khamis Mushait	18 18° N	42 48° E	1973 - 1993*	Doha (Qatar)	25 15° N	51 34° E	1973 - 1993*

* The recording stops during the period August 1990 to January 1991.

2.7 Format of the data:

The one-minute extreme wind speeds in every month, during the period from 1973 to 1993, are provided in tables for fifteen stations only. These stations are Bahrain in Bahrain, Kuwait in Kuwait, Dhahran, Hail, Judayyidat Arar, Medina, Rafha, Riyadh, Tabuk, Taif, Turaif, Al Wajh and Yanbu Al Bahr in Saudi Arabia and Doha in Qatar. The annual extreme wind speed is also provided. Some of these data are accompanied by the direction of these wind extremes but these data are insufficient to provide the necessary database for wind directionality study.

In the remaining station, measurements were not continuous during the 1973 - 1993 period but at least three years of continuous recordings of wind speeds, and sometimes directions, are available in all these stations. Annual extremes are provided for all stations during the period of recording. It should be mentioned that many records were continuous during the period 1973 - 1993 except the period from August 1990 to February 1991.

2.8 Extreme wind speeds:

On the basis of Type I distribution, the distribution of the extreme wind speeds corresponding to recurrence of 50 and 100 years for Saudi Arabia and the other selected stations have been obtained. The standard deviations of the sampling errors of these speeds on the moment method and C-R method are calculated. Table 2 presents design speeds and the two standard deviations of the sampling errors. Table 2 presents the 50-year and 100-year recurrence wind speeds averaged over fifteen minutes. The design wind speed can be transformed to dynamic wind pressure, q, using the following equation.

$$q = \frac{1}{2} \rho_a V_{20}^2 \qquad (in\ N/m^2) \qquad (12)$$

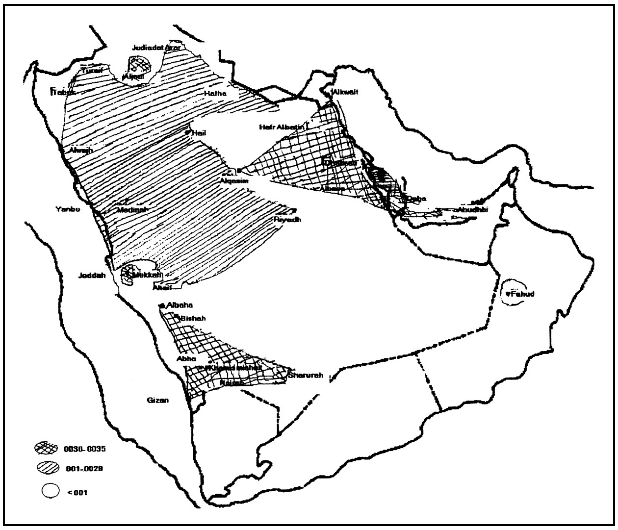
Where ρ_a is the air density (1.23 kg/m^2). Table 2 gives the design pressure for the studied meteorological stations corresponding to 50 and 100 years recurrence periods. These values again are for open territories and at a height of 10 m above ground.

If it desired to transform the wind speed averaging time from one minute to one hour averaging time Table 3 is very beneficial to calculate the new wind speed.

Table 2
Design wind speed and standard deviation of the sampling errors (m/sec)

Name of Station	Design Wind Speed (m/s)		Method of moments r.m.s (m/s)		C-R method r.m.s (m/s)		Design Pressure (KN/m2)	
	50-yr	100-yr	50-yr	100-yr	50-yr	100-yr	50-yr	100-yr
Abha	23.23	25.67	1.32	1.53	1.07	1.23	0.014	0.016
Abu Dhabi (UAE)	21.13	23.38	1.32	1.35	0.94	1.09	0.013	0.014
Al Ahsa	26.88	29.80	1.73	2.02	1.41	1.62	0.017	0.018
Al Baha	21.67	23.83	1.46	1.70	1.19	1.36	0.013	0.015
Bahrain	40.54	43.02	5.37	5.93	4.22	4.64	0.025	0.027
Bishah	23.01	25.62	1.29	1.51	1.05	1.21	0.014	0.016
Dhahran	40.69	43.64	6.53	7.22	5.13	5.64	0.025	0.027
Al Jawf	24.53	27.00	1.22	1.43	1.00	1.15	0.015	0.017
Fahud (Oman)	13.99	14.92	0.97	1.12	0.79	0.90	0.008	0.009
Hafar Al Baten	33.00	36.00	3.00	3.50	2.42	2.83	0.020	0.022
Hail	42.63	45.01	5.29	5.84	4.16	4.57	0.26	0.028
Jeddah	40.06	42.27	4.91	5.42	3.86	4.23	0.025	0.026
Judayyidat Arar	40.57	42.96	5.30	5.85	4.17	4.57	0.025	0.026
Khamis Mushait	18.88	20.78	0.88	1.02	0.72	0.82	0.012	0.013
Kuwait	21.00	22.00	1.75	1.92	1.33	1.50	0.013	0.014
Mecca	22.90	25.71	2.05	2.38	1.67	1.92	0.014	0.016
Medina	47.83	50.74	6.47	7.14	5.08	5.58	0.029	0.031
Nejran	22.55	25.08	1.43	1.66	1.16	1.33	0.014	0.015
Al Qasim	22.55	24.90	1.40	1.64	1.14	1.31	0.014	0.015
Doha (Qatar)	42.19	44.92	6.06	6.68	4.76	5.23	0.026	0.028
Qizan	25.61	28.63	1.49	1.74	1.22	1.40	0.016	0.018
Rafha	41.96	44.31	5.22	5.77	4.11	4.51	0.026	0.027
Riyadh	31.26	33.24	4.40	4.86	3.46	3.80	0.019	0.020
Sharurah	27.88	31.13	2.59	3.02	2.11	2.43	0.017	0.019

Name of Station	Design Wind Speed (m/s)		Method of moments r.m.s (m/s)		C-R method r.m.s (m/s)		Design Pressure (KN/m2)	
	50-yr	100-yr	50-yr	100-yr	50-yr	100-yr	50-yr	100-yr
Tabuk	38.59	40.89	5.13	5.66	4.03	4.42	0.24	0.025
Taif	42.33	44.80	5.48	6.05	4.31	4.73	0.026	0.028
Turaif	52.17	55.55	7.50	8.28	5.89	6.47	0.032	0.034
Al Wajh	40.69	42.75	4.58	5.06	3.60	3.96	0.025	0.026
Yanbu Al Bahr	42.46	45.18	6.02	6.65	4.73	5.20	0.026	0.028



Map 1 The location of the stations being used in the study, illustrating their Design Pressure (KN/m2)

Table 3
Approximate ratios of wind speeds averaged over a time to mean hourly wind speed

t (sec)	2	5	10	30	60	100	200	500	1000	3600
V_t'/V_{3600}	1.53	1.47	1.42	1.28	1.24	1.18	1.13	1.07	1.03	1.00

3. Conclusion:

The design wind speeds and pressures for Saudi Arabia and some other selected places are provided according to data from twenty-nine meteorological stations in Saudi Arabia and some neighbouring locations. Some stations have continuous readings for twenty-one years whereas some have at least three years of continuous readings. This gives good reliability and credibility for the results. These values present the design wind speeds for structures corresponding to 50 and 100-year recurrence periods at an altitude of 10 meters above ground level. These values will enable the designer to determine the actual basic dynamic wind pressure without over or underestimation. The accurate determination of wind forces will result in reduction in the building cost, safety of structures and economy of construction sector.

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