WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2023.146077
ARCHIVES OF CIVIL ENGINEERING
Vol. LXIX ISSUE 3 2023

pp. 217 – 237

Research paper

Characteristic velocity of strong wind for wind engineering purposes

Tomasz Lipecki[1], Mariusz Gaczek[2], Adam Goliger[3], Grzegorz Kimbar[4], Wojciech Węgrzyński[5]

Abstract: Eurocode standard recommends using fundamental basic wind velocity (characteristic velocity) as the design value in civil engineering. There are different approaches to estimate this value depending on the climate features of the given area and the quality of environmental data. The estimation of the characteristic value requires statistical analysis of historical data regarding wind velocities measured throughout the country at meteorological stations. The results of the analysis are probability density distributions of this random variable for each meteorological station. On this basis, values of characteristic wind velocity with a mean return period of 50 years are determined. The zones with uniform velocities are delineated on the map of the country. In the case of Poland the last evaluation of wind zones took place over 15 years ago. Higher quality of measurement data on the one hand, and the introduction of the second generation of Eurocode standards on the other hand, create a need to check and update these zones. This work presents theoretical basis for the estimation of characteristic values of random variables in the context of wind velocity, comprehensively reviews practical methods used for this purpose and summarizes current situation in Poland, finally discusses the issues related to the heterogeneity of wind data, illustrating them with an example.

Keywords: characteristic wind velocity, Gumbel, GEV, GPD, wind map, wind code, BLUE

---

[1] DSc., PhD., Eng., Lublin University of Technology, Nadbystrzycka 40, 20-618 Lublin, Poland, e-mail: t.lipecki@pollub.pl, ORCID: 0000-0002-2867-773X

[2] DSc., PhD., Eng., Poznan University of Technology, Piotrowo 5, 60-965 Poznań, Poland, e-mail: mariusz.gaczek@put.poznan.pl, ORCID: 0000-0003-1349-2676

[3] DSc., PhD., Eng., Firelab, Pretoria, South Africa, e-mail: adam.goliger@gmail.com

[4] DSc., PhD., Eng., Building Research Institute, Filtrowa 1, 00-611 Warszawa, Poland, e-mail: g.kimbar@itb.pl, ORCID: 0000-0003-0500-4062

[5] DSc., PhD., Eng., Building Research Institute, 00-611 Warszawa, Poland, e-mail: w.wegrzynski@itb.pl, ORCID: 0000-0002-7465-0212

1. Introduction

Wind load in all design standards in civil engineering is based on the concept of characteristic wind velocity. In Eurocode [1], it is called a fundamental basic wind velocity, $v_{b,0}$. This value may be exceeded in a given area of the country only once in 50 years on average. Therefore, the probability that the characteristic velocity will occur during a single year is about 2%. This is called a 50-year return period. Characteristic velocities are determined on the basis of long-term measurements performed at meteorological stations scattered throughout the country. The requirements of World Meteorological Organization and the recommendations of Eurocode [1] harmonizing the characteristic wind velocities throughout Europe, indicate that these values should be based on 10-minute mean wind velocities irrespective of wind direction, measured at a height of 10 m above flat open terrain.

The estimation of $v_{b,0}$ is based on the probability density function (PDF) of the wind velocity. Denoting each registered record of the 10-minute mean wind velocity as a random variable y and taking into account the period of measurements as long as possible, the entire population can be approximated with so-called parent distribution. Each set of random values y can be described with PDF – $f(y)$ and cumulative distribution function (CDF) – $F(y)$. The general relationship between PDF and CDF for continuous functions is:

$$F(y) = \int_{-\infty}^{y} f(t)\,\mathrm{d}t = P\,(Y \leq y) \tag{1.1}$$

where $P(Y \leq y)$ denotes the probability that the Y is less than or equal to y.

The estimation of the characteristic velocity with a specific (large) return period may be burdened with a considerable inaccuracy when based on parent distribution. A more precise approximation can be obtained using extreme value distribution of a random variable x. In this approach, the measurement data are divided into epochs, usually, of the length of one year each. Maximum values of 10-minute mean velocity in consecutive epochs, denoted as $y_1, y_2, \ldots, y_n$, create the data set of the random variable x.

The main problem with using the extreme value distribution of the random variable x is usually short measurement period that results in relatively small amount of data. Practices introduced in various countries show that it is reasonable to use extreme distribution based on several/many data points from one measurement epoch.

This paper summarizes approaches used to determine the characteristic value of wind velocity based on: Generalized Extreme Value (GEV) distribution and Generalized Pareto Distribution (GPD). Moreover, modified approaches based on single annual maxima are described: Modified Gumbel distribution, FT1 penultimate distribution and Process (a.k.a. level-crossing) analysis. Finally, approaches based on multiple annual maxima are considered: R-largest values, Peaks Over Threshold (POT) and Method of Independent Storms (MIS). Another issue mentioned in the paper is the choice of the method for determining the values of parameters of the given distribution. The practical application of the following methods is described: Least Squares Method (LSM), Method of Moments (MOM), Maximum Likelihood Method (ML), Probability Weighted Moments Method (PWM, similar to Method of L-Moments – MLM), method recommended by Eurocode and based on Best Linear Unbiased Estimators (BLUE, similar to Generalized Least Squares Method – GLM), and de Haan method in the case of GPD. Finally, the current situation and problems related to the inconsistency of wind data in Poland are discussed and illustrated with a computational example.

The paper is structured as follows: Section 2 briefly describes approaches used in wind engineering, based on single and multiple annual maxima; Section 3 discusses the methods for determining distributions parameters; finally, Section 4 summarizes the current situation in Poland with regard to the characteristic wind velocity and presents sample results.

2. Distributions of data

2.1. Generalized extreme value and generalized pareto distributions

An Extreme value analysis is used to determine the characteristic values of environmental parameters. According to Fischer–Tippett distribution [2–6] properly prepared random variables x of extreme values can converge to only one of the three distributions: Gumbel (Fischer–Tippett type I – FT1), Fréchet (FT2) and Weibull (FT3). Typically, Gumbel distribution is used as the extreme value distribution when long measurement periods are available, i.e. there is a large number of annual extrema. If the measurement period is short and only a small amount of data is available, Weibull distribution for parent data can be used.

The PDF and CDF for Gumbel, Fréchet and Weibull distributions are given by:

$$\begin{aligned} f(x) &= \frac{1}{\alpha}\exp\left[\frac{\beta-x}{\alpha}-\exp\left(\frac{\beta-x}{\alpha}\right)\right], \\ F(x) &= \exp\left[-\exp\left(\frac{\beta-x}{\alpha}\right)\right], \end{aligned} \qquad -\infty < x < \infty \tag{2.1}$$

$$\begin{aligned} f(x) &= \frac{k\alpha}{(x-\beta)^2}\exp\left[-\left(\frac{\alpha}{x-\beta}\right)^k\right]\left(\frac{\alpha}{x-\beta}\right)^{k-1}, \\ F(x) &= \exp\left[-\left(\frac{\alpha}{x-\beta}\right)^k\right], \end{aligned} \qquad x > \beta \tag{2.2}$$

$$\begin{aligned} f(x) &= \frac{k}{\alpha}\exp\left[-\left(\frac{x-\beta}{\alpha}\right)^k\right]\left(\frac{x-\beta}{\alpha}\right)^{k-1}, \\ F(x) &= 1-\exp\left[-\left(\frac{x-\beta}{\alpha}\right)^k\right], \end{aligned} \qquad x > \beta \tag{2.3}$$

In above equations: α, β, and k are scale, location and shape parameters, respectively. The values of α and k are positive. All distributions are presented in Fig. 1.

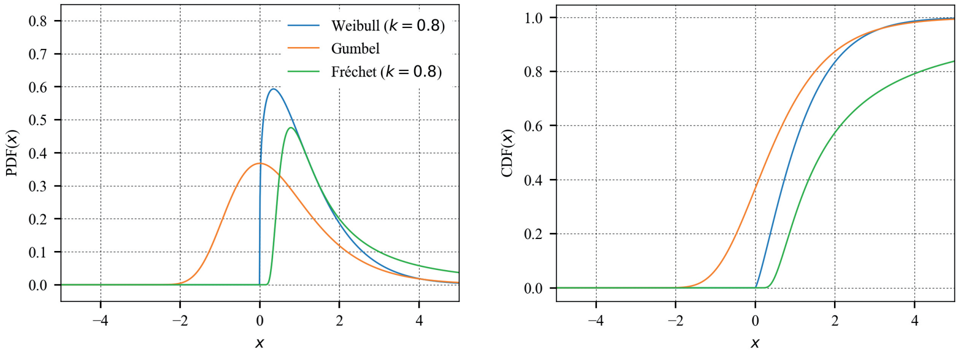


Fig. 1. PDFs and CFDs of Gumbel, Weibull, Fréchet distributions

These distributions were combined into Generalized Extreme Value distribution (GEV), which is equivalent to its location-scale family. GEV was described by von Mises (in English: [7]) and recently by: [2, 4–6, 8–10]. The PDF and CDF are given by:

$$
\begin{aligned}
f(x) &= \begin{cases} \exp\left[-\left(1-\kappa\dfrac{x-\beta}{\alpha}\right)^{\frac{1}{\kappa}}\right]\left[1-\kappa\dfrac{x-\beta}{\alpha}\right]^{\frac{1}{\kappa}-1}\dfrac{1}{\alpha} \\ \exp\left[-\exp\left(\dfrac{\beta-x}{\alpha}\right)\right]\exp\left(\dfrac{\beta-x}{\alpha}\right)\dfrac{1}{\alpha} \end{cases} \\
F(x) &= \begin{cases} \exp\left[-\left(1-\kappa\dfrac{x-\beta}{\alpha}\right)^{\frac{1}{\kappa}}\right] & \kappa \neq 0 \\ \exp\left[-\exp\left(\dfrac{\beta-x}{\alpha}\right)\right] & \kappa = 0 \end{cases}
\end{aligned}
\tag{2.4}
$$

The shape parameter κ determines the type of extreme distribution. For $\kappa = 0$ it is Gumbel distribution, for $-k = \kappa < 0$ and $x \geq \beta + \alpha/\kappa$ it is Fréchet distribution, and for $k = \kappa > 0$ and $x \leq \beta+\alpha/\kappa$ it is reverse ("flipped" around vertical axis) Weibull distribution. GEV distribution could relate to maxima (Eq. (2.4)) and to minima.

Generalized Pareto Distribution (GPD) is used for the description of data which outstand over a given threshold [2, 4, 6]. The PDF and CDF for maxima are given by:

$$
f(x) = \begin{cases} \dfrac{1}{\alpha}\left(1-\dfrac{\kappa x}{\alpha}\right)^{\frac{1}{\kappa}-1} \\ \dfrac{1}{\alpha}\exp\left(-\dfrac{x}{\alpha}\right) \end{cases}, \qquad F(x) = \begin{cases} 1-\left(1-\dfrac{\kappa x}{\alpha}\right)^{\frac{1}{\kappa}} & \kappa \neq 0, \quad 1-\dfrac{\kappa x}{\alpha} \geq 0 \\ 1-\exp\left(-\dfrac{x}{\alpha}\right) & \kappa = 0 \end{cases}
\tag{2.5}
$$

where α and κ are scale and shape parameters, respectively. The PDFs and CDFs are presented in Fig. 2 for different distribution parameters.

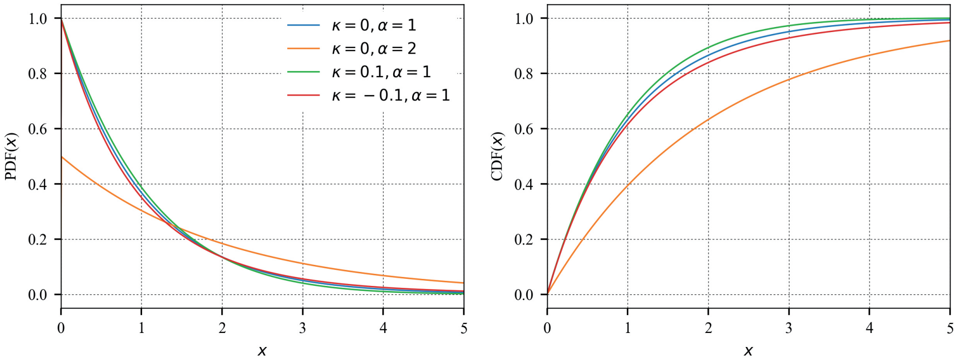


Fig. 2. PDFs and CDFs of GPD

2.2. Modified approaches based on single annual maxima

1. Modified Gumbel distribution. Harris [11] proposed an amendment to Gumbel distribution, suggesting that the square of velocity instead of velocity should be used to calculate the characteristic value. The main goal was to accelerate the convergence of distribution to asymptotic Gumbel distribution. The main disadvantage was systematic increase of possible data error, associated with the second power of velocity, which rises for the highest values. To avoid these problems, Harris proposed the use of Weighted Least Squares or Lieblein BLUE (Best Linear Unbiased Estimators) methods [12] to determine distribution parameters. The approach was described by: [8, 11, 13, 14], and latter method in slightly modified version is recommended by the second generation Eurocode [15].

2. FT1 penultimate distribution. The approach consists in determining some parameters based on parent Weibull distribution, and others based on Gumbel extreme value distribution [9, 16, 17]. It is recommended if the parent distribution is known. The estimation based on Weibull distribution is often used in wind power engineering, when looking for not extreme but average values.

3. Process (a.k.a. level-crossing) analysis. The set of parent data is used in the process analysis [9, 10, 18, 19]. The approach allows to estimate maximum wind velocity based on parent distribution which is assumed to be of Weibull type. It is possible to use short measurement periods of at least two years. The parameters describing Weibull distribution are determined separately for each measurement period, and then their average values are calculated. The parameters are corrected by referring to the data from the nearest station performing long-term measurements. Afterwards, appropriate equations and tables allow calculation of Gumbel distribution parameters. The approach can be used for return periods up to 20 years and should not be used as a primary approach in climates with various mechanisms causing strong winds.

2.3. Approaches based on multiple annual maxima

1. R-largest values (r-los – r largest order statistics). In this approach r-largest values in one epoch are selected [8, 9, 14, 20]. GEV is used for their description. According to the fundamental GEV assumption, extreme values must be independent of each other. This means that the time interval between successive maxima within the single epoch should ensure that they are not the result of the same front or storm. Consequently, the number of maxima in the single epoch, r, should be relatively low. The number of independent events within one epoch is usually in the range of 3–10.
2. Peaks Over Threshold (POT). The approach takes into account all values high enough to exceed the certain threshold [8, 9, 13, 19, 21–25]. GPD is used for their description. The variable x in Eq. (2.5) should be substituted with $x - \xi$ which is the exceedance of the given threshold ξ. The selection of a sufficiently high threshold means that the number of exceedances in the analysed time period is low and has Poisson distribution with the rate parameter λ. It can be assumed that $\lambda = n/T$, where n and T are the total number of exceedances and the number of measurement years, respectively. The requirement of POT approach is the independence of subsequent exceedances above the threshold. Thus, the threshold level and the minimum time interval between successive exceedances should be controlled accordingly. Incorrect setting of these parameters may result in inclusion of data from the same event.
3. Method of Independent Storms (MIS). This approach is similar to r-LOS and POT in the fundamental assumption that the number of independent maxima in one epoch should increase [8, 9, 13, 14, 26–28]. Several variants of MIS were developed over the years, but the original was elaborated by Cook [26]. The main idea was to identify independent storms from the entire parent data set and then take the highest values from independent storms in each separate epoch for analysis. Cook [26] stated that about 10 storms per year are needed to provide a reliable estimate of the characteristic value with the 50-year return period. The approach was developed to IMIS [27] by applying Weighted Least Squares method in the procedure of determining distribution parameters. However, the new form did not provide good enough estimate for data sets containing a large number of extremes. Finally, Harris [28] removed these limitations and developed XIMIS.

3. Methods of determining distribution parameters

The basic problem with the estimation of characteristic values of any random variable is the selection of the appropriate parent or extreme distribution and then determining the parameters of this distribution. The distributions of parent and extreme data sets depend on 1, 2 or 3 parameters (e.g. in the case of GEV, there are 3 parameters: α, β, κ). The determination of these parameters allows to describe PDF, CDF and quantiles of the considered distribution. It is said that x_T is a quantile with the return period T if the probability of its occurrence is $F(x_T) = 1 - (1/T)$. The value of x_T can be considered as the characteristic value which can be exceeded only once during the time period T

(eg. 50 years). This means that the probability of its occurrence in a year is approximately $1/T$. The x_T quantile of GEV distribution is given by:

$$x_T = \begin{cases} \beta + \dfrac{\alpha}{\kappa}\left[1 - \left[-\ln\left(1 - \dfrac{1}{T}\right)\right]^{\kappa}\right] & \kappa \neq 0 \\ \beta - \alpha \ln\left[-\ln\left(1 - \dfrac{1}{T}\right)\right] & \kappa = 0 \end{cases} \tag{3.1}$$

The value of x_T is obtained by transforming $F(x)$. For example, in the case of $\kappa = 0$ in GEV, a logarithm of $F(x)$ in Eq. (2.4) should be done twice and from the transformed equation the value x corresponding to x_T should be determined. In the case of Gumbel distribution ($\kappa = 0$) only parameters α and β should be determined, while in the case of two other distributions ($\kappa \neq 0$) the additional parameter κ should be also determined.

In the case of GPD, for the threshold ξ and the rate parameter λ, the quantile is given by:

$$x_T = \begin{cases} \xi + \dfrac{\alpha}{\kappa}\left[1 - (\lambda T)^{-\kappa}\right] & \kappa \neq 0 \\ \xi + \alpha \ln(\lambda T) & \kappa = 0 \end{cases} \tag{3.2}$$

Since the threshold is assumed, only two parameters have to be determined: λ and κ.

Practical methods for determining the parameters of GEV-FT1 (Gumbel) and GPD distributions are described below, these are: LSM, MOM, ML, PWM, BLUE, and de Haan method.

1. Least Squares Method (LSM). The method consists in minimizing the function measuring the deviation of the linear model from the measured values. Differentiating the obtained function with respect to distribution parameters, e.g.: α and β leads to a system of two equations with α and β as variables.

In the case of Gumbel distribution (Eq. (2.1) or Eq. (2.4), for $\kappa = 0$) the data set containing maximum annual 10-minute mean velocities, should be prepared. Putting instead of x in Eq. (2.1) and next performing double logarithm operation, we get:

$$\overline{u} = \alpha\left(-\ln\left[-\ln\left(F\left(\overline{u}\right)\right)\right]\right) + \beta \Rightarrow \overline{u} = \alpha x + \beta \tag{3.3}$$

where $-\ln\left[-\ln\left(F\left(\overline{u}\right)\right)\right]$ is an argument of the linear function. LSM can be used for determine the parameters of the trend line.

In the case of GPD in POT approach the relationship between the decreasing value of the mean excess and the increasing threshold is calculated. Mean excess is defined as the difference between the mean velocity values above the threshold minus this threshold. In practice, to get enough data for a linear trend, the threshold is increased by the given step and the mean excess for the new threshold is calculated. By using this procedure, the approximating line with the negative slope can be found, $y = ax + b$, and then GPD parameters can be calculated:

$$\kappa = -\frac{a}{1+a}, \quad \alpha = b(1+\kappa) \tag{3.4}$$

2. Method of Moments (MOM). In this method consecutive moments of assumed distribution and calculated from the data set are compared. The method is quite simple

when only two parameters are to be determined. Mean and variance of Gumbel distribution (maximal), $\overline{x}$ and s^2, and resulting distribution parameters are given by:

$$\overline{x} = \beta + 0.57721\alpha, \quad s^2 = \frac{\pi^2\alpha^2}{6} \quad \text{and} \quad \alpha = \sqrt{\frac{6s^2}{\pi^2}}, \quad \beta = \overline{x} - 0.57721\alpha \tag{3.5}$$

These values are compared with and s^2 calculated from the data set of annual maxima.

The parameters of GPD can be estimated in similar procedure:

$$\kappa = \frac{\overline{x}^2 - s^2}{2s^2}, \quad \alpha = \frac{\overline{x}\left(\overline{x}^2 + s^2\right)}{2s^2} \tag{3.6}$$

3. Probability Weighted Moments method (PWM). The data set of annual maxima is arranged in ascending [22, 29, 30] or descending [8, 31] order and consecutive weights j are assigned. The unbiased estimators for the data set of size N are given in Eq. (3.7) and subsequently, the parameters of Gumbel distribution can be estimated from Eq. (3.8):

$$\begin{aligned} b_0 = \overline{x}_j = \text{mean}, \quad b_1 &= \sum_{j=1}^{N-1} x_j \frac{(N-j)}{N\,(N-1)} \ \text{(descending)}, \\ b_1 &= \sum_{j=2}^{N} x_j \frac{(j-1)}{N\,(N-1)} \ \text{(ascending)} \end{aligned} \tag{3.7}$$

$$\begin{cases} \alpha = 2.8854b_1 - 1.4427b_0 & \beta = 1.8327b_0 - 1.8327b_1 \quad \text{(descending)} \\ \alpha = (2b_1 - b_0)\,/\ln(2) & \beta = b_0 - 0.57721\alpha \quad \text{(ascending)} \end{cases} \tag{3.8}$$

In this approach, more attention is put to a long tail of the distribution, than to the low-end values. Therefore, the single extreme values, are less likely to be outliers of the model.

The parameters of GPD can be derived in similar procedure:

$$\kappa = \frac{4p - \overline{x}}{\overline{x} - 2p}, \quad \alpha = \frac{2\overline{x}p}{\overline{x} - 2p} \quad \text{for} \quad p = \frac{1}{N}\sum_{j=1}^{N}\left(1 - \frac{j - 0.35}{N}\right)x_j \tag{3.9}$$

4. Maximum Likelihood method (ML). The method consists in creation a likelihood function for the given data set based on probability density function (e.g.: [2]). Thus, the likelihood function depends on the parameters describing the distribution. These parameters are estimated such that the likelihood function takes its global maximum value. Partial derivatives of the likelihood function (or its logarithm) with respect to particular parameters of the distribution should be computed and compared to zero. The solution of the obtained system of equations requires iteration.

A simplified estimation can be used for Gumbel distribution and for a data set of size N:

$$\alpha \leftarrow \bar{x}_j - \frac{\sum\limits_{j=1}^{N} x_j \exp\left(-\dfrac{x_j}{\alpha}\right)}{\sum\limits_{j=1}^{N} \exp\left(-\dfrac{x_j}{\alpha}\right)}, \qquad \beta \leftarrow -\alpha \cdot \ln\left[\frac{1}{N}\sum_{j=1}^{N} \exp\left(-\frac{x_j}{\alpha}\right)\right] \tag{3.10}$$

An initial value of α must be given from e.g.: MOM. Then, the sums in Eq. (3.10) are calculated and the improved values of α and β are found. The entire procedure is repeated for the new value of α. The iteration continues until the parameter values converge accordingly.

5. BLUE method. The method is a modification of Gumbel distribution introduced for wind engineering by Harris [11] to facilitate calculation of Gumbel distribution parameters using the Lieblien BLUE [12]. Relatively short data sets can be used, although data sets shorter than 10 years are not recommended. The method uses two BLUE coefficients $A(m)$ and $B(m)$, where m is the rank of coefficients, ranging from 1 for the lowest value of the velocity-squared to N for the highest value. The coefficients $A(m)$ and $B(m)$ are given for N from 10 to 30 in increments of 1 [15]. Originally, Lieblien method reported BLUE coefficients up to $N = 16$. In the case of longer data set subsequent coefficients can be determined based on known BLUEs for e.g. $N = 16$ years or can be obtained from [12, 15, 19]. This approach will be probably recommended for use in Europe to harmonize wind velocity maps [15].

6. De Haan method. The method is based on the data above the given threshold and ordered in descending order. The values of M_i are calculated (Eq. (3.11)) and in consequence parameters κ and α of GPD can be defined (Eq. (3.12)) [32]:

$$M_i = \frac{1}{k}\sum_{j=1}^{k}\left(\ln(x_j) - \ln(t)\right)^i \tag{3.11}$$

$$\kappa = M_1 + 1 - \frac{1}{2\left(1 - M_1^2/M_2\right)}, \qquad \alpha = \frac{tM_1}{\rho}, \qquad \rho = \begin{cases} 1 & \kappa \geq 0 \\ 1/(1-\kappa) & \kappa < 0 \end{cases} \tag{3.12}$$

where: $i = 1, 2$, k – number of data x_j over the given threshold t.

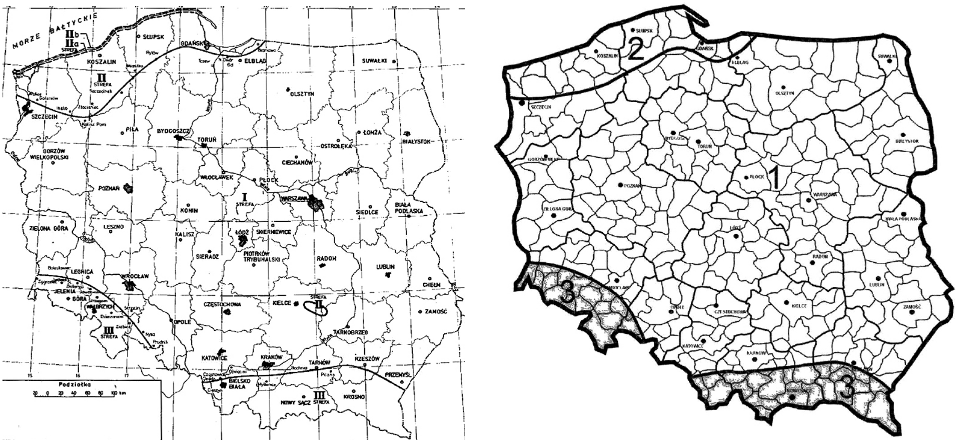
4. Velocity of strong winds in Poland

4.1. Current regulations

Many measurements are carried out around the world to determine the environmental conditions at the construction sites of future engineering structures or investments related to, among others, wind energy, e.g.: [33–37]. This type of research applies only to local conditions in the area intended for the investment. Undoubtedly, such measurements can provide a lot of information about wind characteristics. However, they cannot be used to analyse wind conditions for larger areas and to calculate characteristic value. To perform such analysis, it is necessary to collect long-term data on wind velocity and direction from a network of meteorological stations scattered throughout the country. Wind conditions in a given country were, and still are one of the main issues raised by researchers in wind engineering. Recently, such works have been carried out in various countries – [38–57]. These works use different time periods of data, different approaches to the description of parent and extreme data distributions, and different methods for estimating parameters of these distributions.

The climate in Poland can be classified as mixed [58] and is influenced by marine and continental climates. Strong and extreme wind velocities can be caused by: (a) deep cyclones (mid-latitude cyclones) causing violent winds accompanying the transition of the front system and occurring mainly in winter, (b) foehn winds (mountain winds) occurring locally, (c) storm events: gust fronts, downbursts, derechos, tornados, and gust front vortexes [38, 59–63].

A huge work on statistics of parent and extreme distributions of wind velocity and direction was done in Poland by prof. Jerzy Żurański [38]. Żurański used Weibull parent and Gumbel extreme value distributions in relation to wind velocity with and without division into 12 directional sectors. His research made it possible to develop the wind velocity map of Poland, which was included in the Polish standard [64], and later in its updated version in the national annex to Eurocode [1]. Żurański determined characteristic values of wind velocity with the return period of 50 years and respective directional coefficients of wind. He considered 33 meteorological stations and data since 1961. Fig. 3a shows the zones based on research carried out up to the 1970s, while Fig. 3b shows these zones verified on the basis of next 25 years of data. The last update of the values of $v_{b,0}$ was around 2005. It is worth mentioning that the future introduction of the second generation Eurocode [15] requires further updating of the wind maps in Poland.



(a) (b)

Fig. 3. Wind velocity maps in Poland: a) [64], b) [1]

4.2. Available wind data – problems and solutions

In the case of Poland, the meteorological data provider is Polish Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB). The current measurement-observation network of IMGW-PIB includes synoptic and climate stations that are equipped, or may be equipped in the case of climate stations, with automatic devices recording wind velocity and direction in an hourly mode. The scope of data collected at both types of stations is different, much less information is provided at climate stations. IMGW-PIB reports the total number of 67 synoptic and 339 climate stations that were installed in Poland since 1951. At the end of 2021, 58 synoptic and 57 climate stations reported measurements. Some stations were closed or changed location over the years. In authors' opinion, based on the compilation of public data from IMGW-PIB, roughly about 58 synoptic and 119 climate stations can be considered when estimating the characteristic wind velocity. These numbers include stations that have closed in the last few years, but have performed measurements over a 30-year period. Currently, the maximum available time period is 72 years for some stations.

Both types of stations record wind velocity and direction. At synoptic stations, wind velocity is recorded with the resolution of 1 m/s and the direction is recorded with the resolution of 10° that was corrected a few years ago to 1°. The values are recorded hourly, with the 10-minute mean value over the last 10 minutes being measured before each UTC clock hour. The value of maximum 2–3-second gust in the last 10 minutes of each hour is measured, roughly since 1995. It is recorded if the value exceeds the 10-minute mean by at least 5 m/s [38]. Maximum hourly gusts are recorded since 2005. In initial time period data was recorded 4 times a day at 0:00, 6:00, 12:00, 18:00. Data were captured 24 times a day since 1966, but in some periods number of measurements was reduced to 8 per day, every 3 hours at 0:00, 3:00, 6:00 etc. At climate stations, wind velocity and direction is recorded 3 times a day at 6:00, 12:00, 18:00 with the resolution of 1 m/s in 16 directional sectors (N, NNE, etc.).

Sufficiently long measurement time does not ensure correct determination of the characteristic velocity. In addition, several requirements regarding measurements at different stations should be met, they are: the same method of data recording; the same methodology of measurements; the location of station in the terrain with low roughness corresponding to the open area; the location of station in the terrain with similar low surrounding orography; the same installation height of the measuring devices (10 m).

In practice, these requirements are not met simultaneously or none of them are met throughout the station's lifetime. Over the years, the recording methods evolved by switching from manual to automatic registration and by introducing more modern anemometers. Another methodology was used, 2-minute mean velocities were recorded until December 31, 1975, and after January 1, 1976, the values changed to 10-minute means. The number of records per day in various periods was different: 3, 4, 8 or 24 records a day. Usually, stations were/are located in accordance with the abovementioned requirements for topography and orography, however, during the years, the surrounding area was/is built-up. Sometimes the location of the station was even moved due to the intensive development of areas around it.

Most of changes can be fairly easy accounted in calculation. The transition between different averaging times from 2-minute means to 10-minute means can be based on the guidelines given by e.g. [65–68]. Values of factors by which 2-minute means should be multiplied to obtain 10-minute means are 0.903 for the open terrain, 0.879 for the terrain with low vegetation and buildings, and 0.817 for the built-up terrain (comp. [65, 67]).

When calculating the characteristic velocity, wind gusts should be taken into account, if they were measured. Especially maximum hourly gusts can increase the characteristic velocity quite significantly. In order to obtain 10-minute means, the values of 2-second gusts should be multiplied by: 0.689 for the open terrain, 0.636 for the terrain with low vegetation and buildings, and 0.515 for the built-up terrain (comp. [65, 67]).

More precisely, the conversion of values between different averaging times can be done by determining the ratio of gust velocity to 10-minute mean velocity recorded at the same time, as long as both measurements are carried out simultaneously. This way the gust factor for the given meteorological station can be obtained. The determined gust factor values allow to assess the topography of the area around the station. The stable value over the years proves that the area has not changed much, while significant changes most often indicate an increase in the density and height of land development.

If, on the basis of the documentation from the meteorological services in the given country or on the basis of changes in the gust factor value, it was found that the area around the station was built-up, then the transition from the built-up terrain to the open terrain should be done. Appropriate conversion factors being in accordance with the vertical wind velocity profile should be applied. Considering Eurocode [1] assumption that the terrains assigned to the 2nd and 3rd category are open and built-up terrains, respectively, and taking into account logarithmic vertical profile of wind velocity, the wind velocity at height z can be recalculated from category 3 (u_3) to category 2 (u_2) according to:

$$u_2(z) = \frac{k_{r,2} \ln\left(z/z_{0,2}\right)}{k_{r,3} \ln\left(z/z_{0,3}\right)} u_3(z) \tag{4.1}$$

where k_r is the terrain factor depending on the roughness length for the given terrain, z_0.

A similar conversion, consistent with the vertical wind velocity profile, should be performed when sensor installation height was changed. The conversion performed for the terrain category 2 between velocities at two heights z_1 and z_2 is:

$$u_2(z_2) = \frac{\ln\left(z_2/z_{0,2}\right)}{\ln\left(z_1/z_{0,2}\right)} u_2(z_1) \tag{4.2}$$

4.3. Sample results

The solution of problems resulting from the data heterogeneity is shown on the example of synoptic stations located in central Poland. Poznań-Ławica station (code: 330) located in Poznań, in the wind zone 1, was selected for analysis. Figure 4 shows the data set for this station since 1966 when it started operating as the synoptic station. The following notations are introduced: $v_{m,\max}$ – maximum 10-minute mean velocity measured in the last

10 minutes of each hour; v_{g1} – velocity of 10-minute gusts, i.e. maximum velocity of gusts measured in the last 10 minutes of each hour; v_{g2} – velocity of hourly gusts, i.e. maximum velocity of gusts measured over an hour; v_m – 10-minute mean velocity averaged over the year. Between 1961–1965, 4 sets of data were registered, at 0:00, 6:00, 12:00, 18:00, since 1966 – 24 measurements were made. This number was limited to 8 measurements per day between 1986–1992 when they were taken at 0:00, 3:00, 6:00 etc. The 10-minute gusts and hourly gusts were recorded since 1993 and 2005, respectively. The terrain conditions around the station remained, more or less, unchanged during its use. The height of the anemometer installation changed. It was 13 m until June, 1965, 16.5 m until May, 1984, and 10 m until now. Wind data for other stations located in wind zone 1 are also shown in Fig. 4: Warszawa-Okęcie (code: 375), Siedlce (code 385), Kozienice (code: 488). The period of operation, the number of daily measurements and the time of the first registration of gusts were the same as at Poznań–Ławica station with the following differences: there were 8 measurements a day until 1993 and 24 since 1994 in the case of 385 and 488; moreover station 488 operated since 1977.

Preliminary analysis shows a downward trend in the values of v_m and $v_{m,\max}$. Table 1 presents equations of linear trends from Fig. 4. The greatest decrease of $v_{m,\max}$ occurs for station 385; according to the equation the velocity would drop by approx. 3 m/s by 2050. Most likely, the downward trend indicates the gradual development of the area around the stations.

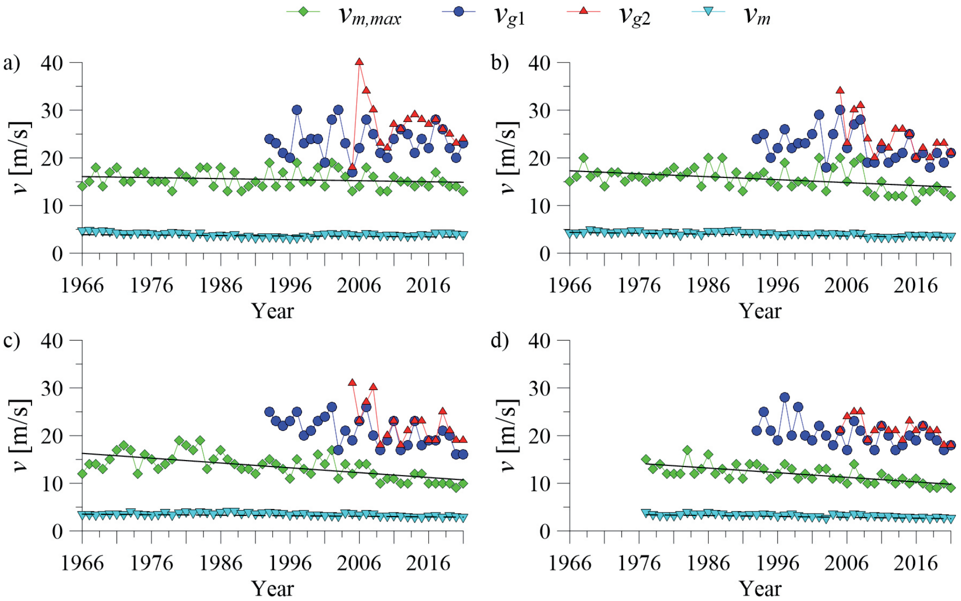


Fig. 4. Annual maximum and mean wind velocities at stations: a) 330, b) 375, c) 385, d) 488

Wind velocities from Poznań–Ławica station were the input data to determine the characteristic velocity, $v_{b,0}$. The calculations were made for two data sets: 1) containing

Table 1. Linear trend of wind velocity

Station	330	375	385	488
v_m	$y = -0.009x + 22.109$	$y = -0.019x + 41.819$	$y = -0.011x + 25.910$	$y = -0.019x + 40.128$
$v_{m,\max}$	$y = -0.022x + 58.609$	$y = -0.062x + 138.838$	$y = -0.101x + 215.439$	$y = -0.097x + 206.039$

maximum 10-minute mean velocities – $v_{m,\max}$, and 2) supplemented with the maximum gusts from the periods in which they were measured – $v_{\max}$. Of course, 2-second gusts were converted to 10-minute means. The input data is shown in Fig. 5a,b.

Both data sets were modified. Subsequent modifications were made in three steps: 1) 2-minute means were converted to 10-minute means in the time periods that require it. The variants $v_{m,\max_1}$ and $v_{\max_1}$ were obtained (Fig. 5a,b). 2) Velocities were recalculated due to the changes in the mounting height of the anemometer. The variants $v_{m,\max_2}$ and $v_{\max_2}$ were obtained (Fig. 5a, b). 3) Terrain category changes were additionally examined. In this case, it was assumed that in the last 10 and 20 years the area around the station was built-up and could be classified as terrain category III. The variants with indexes 3 and 4 were obtained (Fig. 5c, d). Variants 1 and 2 take into account the actual changes in the averaging time and the height of the anemometer, while options 3 and 4 take into account theoretical changes of roughness.

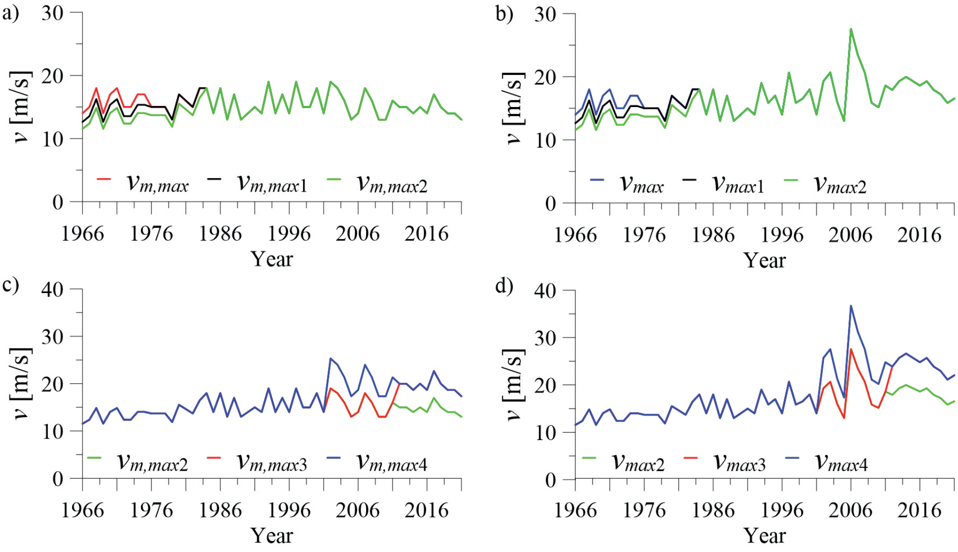


Fig. 5. Modifications of wind velocities at station 330 according to: a–b) averaging time and height of measurement, c–d) terrain roughness

Characteristic wind velocity was determined with Gumbel distribution of annual maxima. Various methods were considered to estimate distribution parameters: LSM, MOM, ML, PWM and BLUE. Figure 6 shows the values of $v_{b,0}$ estimated in 5 variants of data sets described above. The data set based on 10-minute means gave the lowest estimate in variant 2 when the data were recalculated from 2-minute means and changes of the mounting height of anemometer were taken into account ($v_{m,\max_2}$). Considering data sets supplemented by gusts the variant of original data usually gave the lowest estimate ($v_{\max}$). It is logic because changes of averaging time and anemometer height took place in early years of the station operation when gusts were not measured.

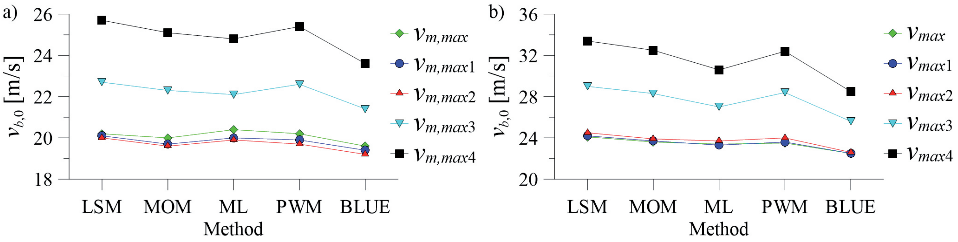


Fig. 6. Values of $v_{b,0}$ for station 330, for data sets: a) based on means, b) supplemented by gusts

The analysis carried out for station 330 shows that taking into account the time conversion from 2-minute to 10-minute means and changes in the mounting height of the anemometer does not cause large changes in the value of $v_{b,0}$. The changes with respect to the initial values of $v_{m,\max}$ and $v_{\max}$, in dependence on the method used to estimate the distribution parameters, are in the range from –0.9% to –2.3% and from –0.2% to 1.8%, respectively for two data sets. Negative values mean a decrease of velocity whereas positive its increase. The theoretical change of the terrain category causes a significant increase of $v_{b,0}$. In the case of upgrading the terrain category to category 3 during the last 10 years, the increase in $v_{b,0}$ is at the level of 10% and 20%, respectively in variants $v_{m,\max_3}$ and $v_{\max_3}$. The extension of the roughness change period to 20 years, i.e. in variant 4, causes the increase over 20% and 30%, respectively. Large changes of the values of $v_{b,0}$, especially taking into account gusts, are caused by the fact that gusts were measured in periods corresponding to the theoretical changes in roughness, and not in the initial years. To sum up, while changes in the averaging time and the height of anemometer assembly do not significantly affect the value of $v_{b,0}$, changes in the roughness of terrain around the station may have a very large impact. It should be emphasized that the modification of the terrain category is artificial and in practice these changes will occur gradually, not suddenly, so their impact on the characteristic velocity will be lower.

When analysing the methods, BLUE provided the lowest estimate of $v_{b,0}$ for both data sets in all variants. On the other hand, the highest estimate was calculated most often with LSM.

The range of differences in the values of $v_{b,0}$ in relation to the value determined using BLUE ranges from 1.9% to 4.1% in the case of the data set including means and input variant ($v_{m,\max}$) and variants taking into account real changes ($v_{m,\max_1}$, $v_{m,\max_2}$). In the case of the data set supplemented with gusts and similar variants ($v_{\max}$, $v_{\max_1}$, $v_{\max_2}$), the range of changes is from 3.9% to 8.7%. Taking into account the rounding of the value of $v_{b,0}$ to the total value used in the designing of structures, the choice of the method may result in a change of this value by 1 m/s and in the extreme case by 2 m/s (LSM vs BLUE in $v_{\max_2}$ variant).

The peak factor can be used to determine the real changes in terrain roughness around the station. Figure 7 shows values of peak factor determined by dividing the gust velocity during the last 10 minutes of each hour by the 10-minute mean velocity measured during that time.

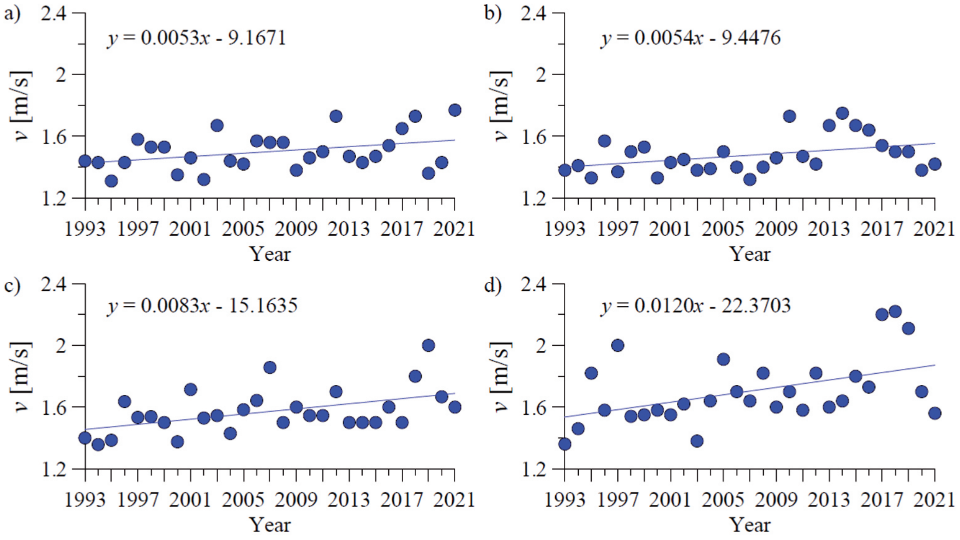


Fig. 7. Peak factor values and trend lines for stations: a) 330, b) 375, c) 385, d) 488

The highest annual means and corresponding gusts from the same time were selected. The values of peak factor averaged over the entire measurement period are respectively: 1.500, 1.477, 1.572 and 1.702 for subsequent meteorological stations. The first three values correspond more or less to the values measured in nature and recommended by Eurocode [1, 65–67] for the terrain category 2, i.e. the standard terrain. The fourth value is much higher and indicates changing roughness of the terrain. The linear trend equation related to time changes of the peak factor is also shown in Fig. 7. All slope coefficients are positive, which indicate probable development of the area around the station over the years. A smaller slope of the linear trend indicates smaller changes in the roughness.

5. Conclusions

Changes in the network of meteorological stations in Poland, modernisation of recording devices, development of the terrain roughness, and above all, constantly extended measurement period indicate the need to analyze wind velocity and direction and update the knowledge in this field. At present, the analysis can be based on quite long, up to 70 years measurement periods. This is the significant quantitative (in the number of records) as well as qualitative (quality of automatic measurements, gust recording) difference compared to the research carried out several years ago. Data from the last 20 years, which includes gusts, deserve particular attention. In addition, questionable quality of some results from the initial measurement period related to different recording methods, different averaging times and the human factor, may affect the estimation of $v_{b,0}$. In connection with above comments, it is necessary to check the influence of the measurement period length on the obtained estimate. Żurański in Poland used Weibull distribution for parent data and Gumbel distribution based on one maximum per one epoch for extreme value distribution. The method of determining wind velocity with 50-year return period recommended by the second generation Eurocode based on Gumbel distribution and BLUE coefficients [15] is slightly different from the approach used by Żurański. Perhaps the use of different methods or measurement periods caused discrepancies in the values of $v_{b,0}$ observed along the Polish border with Germany, Lithuania and Slovakia indicated in the draft of new Eurocode. Probably, the incompatibility along the western border of Poland is the result of an arbitrary decision to increase wind velocity, which is written into the German standard. Research carried out by Kasperski [39] indicated velocity only 0.5 m/s higher than in the border area in Poland. A few years ago, Żurański increased wind velocity at Lithuanian border to 26 m/s, which resulted in a difference of 2 m/s, but upwards. He also proposed to increase characteristic values in submontane and mountainous regions at altitudes of more than 300 m asl, which should provide a better correlation with the velocity in Slovakia to 700 m asl. Żurański did not manage to publish these results and they also need to be checked and supplemented by new data. Worldwide practices also suggest other approaches to estimate the value of $v_{b,0}$, including modified Gumbel distribution, MIS, POT or r-los. Especially the latter methods should be considered in estimating $v_{b,0}$ as more advanced and well adapted to the mixed climate that prevails in Poland. Although BLUE is the recommended method in Europe, all other methods should be constantly applied to the available data and cross-validated. Any discrepancies between them should be explained due to the fundamental uncertainty and sparsity of weather-related measurements. In addition, the statistical analyses carried out in various measurement periods will allow to determine possible climate changes related to the maximum values of wind velocity.

References

[1] PN-EN 1991-1-4:2008 Eurocode 1: Actions on structures – Part 1–4: General actions – Wind actions. Brussels, Belgium: CEN, 2008.

[2] E. Castillo, A.S. Hadi, N. Balakrishnan, and J.M. Sarabia, *Extreme value and related models with applications in engineering and science*. New Jersey: John Wiley and Sons, 2005.

[3] E.J. Gumbel, *Statistics of extremes*. New York: Columbia University Press, 1958.

[4] S. Coles, *An introduction to statistical modeling of extreme values*. London: Springer-Verlag, 2004.

[5] L. de Haan and A. Ferreira, *Extreme value theory. An Introduction*. Springer, 2006.

[6] R.D. Reiss and M. Thomas, *Statistical analysis of extreme values: With applications to insurance, finance, hydrology and other fields*, 3rd ed. Birkhäuser Verlag, 2007.

[7] A.F. Jeckinson, "The frequency distribution of the annual maximum (or minimum) values of meteorological elements", *Quarterly Journal of the Royal Meteorological Society*, vol. 81, pp. 158–171, 1955, doi: 10.1002/qj.49708134804.

[8] J.P. Palutikof, B.B. Brabson, D.H. Lister, and S.T. Adock, "A review of methods to calculate extreme wind speeds", *Meteorological Applications*, vol. 6, pp. 119–132, 1999, doi: 10.1017/S1350482799001103.

[9] A. Torrielli, M.P. Repetto, and G. Solari, "Extreme wind speeds from long-term synthetic records", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 115, pp. 22–38, 2013, doi: 10.1016/j.jweia.2012.12.008.

[10] R. Chiodi and F. Ricciardelli, "Three issues concerning the statistics of mean and extreme wind speeds", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 125, pp. 156–167, 2014, doi: 10.1016/j.jweia.2013.12.009.

[11] R.I. Harris, "Gumbel re-visited – A new look at extreme value statistics applied to wind speeds", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 59, no. 1, pp. 1–22, 1996, doi: 10.1016/0167-6105(95)00029-1.

[12] J. Lieblein, "Efficient methods of Extreme-Value methodology. Raport NBSIR 74-602", USA: National Bureau of Standards, 1974.

[13] Y. An and M.D. Pandey, "A comparison of methods of extreme wind speed estimation", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 93, no. 7, pp. 535–545, 2005, doi: 10.1016/j.jweia.2005.05.003.

[14] Y. An and M.D. Pandey, "The r largest order statistics model for extreme wind speed estimation", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 95, no. 3, pp. 165–182, 2007, doi: 10.1016/j.jweia.2006.05.008.

[15] EN 1991-1-4 SC1.T3; Second Draft EN 1991-1-4 'Wind Actions' April 2019; CLEAN, 2020.

[16] N.J. Cook and R.I. Harris, "Exact and general FT1 penultimate distributions of extreme wind speeds drawn from tail-equivalent Weibull parents", *Structural Safety*, vol. 26, no. 4, pp. 391–420, 2004, doi: 10.1016/j.strusafe.2004.01.002.

[17] N.J. Cook and R.I. Harris, "Postscript to 'Exact and general FT1 penultimate distributions of extreme wind speeds drawn from tail-equivalent Weibull parents", *Structural Safety*, vol. 30, no. 1, pp. 1–10, 2008, doi: 10.1016/j.strusafe.2006.04.001.

[18] L. Gomes and B.J. Vickery, "On the prediction of extreme wind speeds from the parent distribution", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 2, no. 1, pp. 21–36, 1977, doi: 10.1016/0167-6105(77)90003-4.

[19] ESDU 87034 World-wide extreme wind speeds. Part 1: Origins and methods of analysis. London: ESDU International, 1987.

[20] I. Weissman, "Estimation of parameters and large quantiles based on the k largest observations", *Journal of the American Statistical Association*, vol. 73, no. 364, pp. 812–815, 1978, doi: 10.1080/01621459.1978.10480104.

[21] J. Pickands, "Statistical inference using order statistics", *Annals of Statistics*, vol. 3, no. 1, pp. 119–131, 1975, doi: 10.1214/aos/1176343003.

[22] J. Abild, E. Andersen, and D. Rosbjerg, "The climate of extreme winds at the Great Belt", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 41, no. 1–3, pp. 521–532, 1992, doi: 10.1016/0167-6105(92)90458-M.

[23] D. Walshaw, "Getting the most from your extreme wind data: a step by step guide", *Journal of Research of the National Institute of Standards and Technology*, vol. 99, no. 4, pp. 399–411, 1994.

[24] E. Simiu and N.A. Heckert, *Extreme wind distribution tails: a 'Peaks Over Threshold' approach*. NIST Building Science Series 174, 1995.

[25] J.D. Holmes and W.W. Moriarty, "Application of the generalized Pareto distribution to extreme value analysis in wind engineering", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 83, no. 1–3, pp. 1–10, 1999, doi: 10.1016/S0167-6105(99)00056-2.

[26] N. J. Cook, "Towards better estimation of wind speeds", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 9, no. 3, pp. 295–323, 1982, doi: 10.1016/0167-6105(82)90021-6.

[27] R.I. Harris, "Improvements to the 'Method of Independent Storms", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 80, no. 1–2, pp. 1–30, 1999, doi: 10.1016/S0167-6105(98)00123-8.

[28] R.I. Harris, "XIMIS, a penultimate extreme value method suitable for all types of wind climate", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 97, no. 5–6, pp. 271–286, 2009, doi: 10.1016/j.jweia.2009.06.011.

[29] J.R.M. Hosking, J.R. Wallis, and E.F. Wood, "Estimation of the Generalized Extreme Value distribution by the method of Probability-Weighted Moments", *Technometrics*, vol. 27, pp. 251–261, 1985, doi: 10.1080/00401706.1985.10488049.

[30] T.S. Gubareva and B.I. Gartsman, "Estimating distribution parameters of extreme hydrometeorological characteristics by L-moments method", *Water Resources*, vol. 37, no. 4, pp. 437–445, 2010, doi: 10.1134/S009780 7810040020.

[31] J.R. Stedinger, R.M. Vogel, and E. Foufoula-Georgiou, "Frequency analysis of extreme events", in *Handbook of Hydrology*. New York: McGraw Hill, 1993, p. 68.

[32] E. Simiu and D.H. Yeo, *Wind effects on structures. Modern structural design for wind*. John Wiley & Sons Ltd., 2019.

[33] P. Breuer, T. Chmielewski, and P. Górski, "Dynamic response of the Stuttgart TV tower measured by classical instruments and GPS technology", *Archives of Civil Engineering*, vol. 67, no. 1, pp. 7–38, 2021, doi: 10.24425/ace.2021.136459.

[34] X. Yang, C. Milliren, M. Kistner, C. Hogg, J. Marr, L. Shen, and F. Sotiropoulos, "High-fidelity simulations and field measurements for characterizing wind fields in a utility-scale wind farm", *Applied Energy*, vol. 281, art. no. 116115, 2021, doi: 10.1016/j.apenergy.2020.116115.

[35] S. Laima, H. Feng, H. Li, Y. Jin, F. Han, and W. Xu, "A Buffeting-Net for buffeting response prediction of full-scale bridges", *Engineering Structures*, vol. 275, art. no. 115289, 2023, doi: 10.1016/j.engstruct.2022.115289.

[36] Y.W. Wang and Y.Q. Ni, "Full-scale monitoring of wind effects on a supertall structure during six tropical cyclones", *Journal of Building Engineering*, vol. 45, art. no. 103507, 2022, doi: 10.1016/j.jobe.2021.103507.

[37] B. Li, C. Li, Q. Yang, Y. Tian, and X. Zhang, "Full-scale wind speed spectra of 5 year time series in urban boundary layer observed on a 325 m meteorological tower", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 218, art. no. 104791, 2021, doi: 10.1016/j.jweia.2021.104791.

[38] J.A. Żurański, *Influence of climatic and terrain conditions on wind loads on building structures*. Warsaw: Scientific papers of the Building Research Institute, 2005 (in Polish).

[39] M. Kasperski, "A new wind zone map of Germany", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 90, no. 11, pp. 1271–1287, 2002, doi: 10.1016/S0167-6105(02)00257-X.

[40] C. Sacré, J.M. Moisselin, M. Sabre, J.P. Flori, and B. Dubuisson, "A new statistical approach to extreme wind speeds in France", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 95, no. 9–11, pp. 1415–1423, 2007, doi: 10.1016/j.jweia.2007.02.013.

[41] H.P. Hong, T.G. Mara, R. Morris, S.H. Li, and W. Ye, "Basis for recommending an update of wind velocity pressures in Canadian design codes", *Canadian Journal of Civil Engineering*, vol. 41, no. 3, pp. 206–221, 2014, doi: 10.1139/cjce-2013-0287.

[42] F.T. Lombardo and A.S. Zickar, "Characteristics of measured extreme thunderstorm near-surface wind gusts in the United States", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 193, art. no. 103961, 2019, doi: 10.1016/j.jweia.2019.103961.

[43] O. Karpa and A. Naess, "Extreme value statistics of wind speed data by the ACER method", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 112, pp. 1–10, 2013, doi: 10.1016/j.jweia.2012.10.001.

[44] P. Patlakas, G. Galanis, N. Barranger, and G. Kallos, "Extreme wind events in a complex maritime environment: Ways of quantification", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 149, pp. 89–101, 2016, doi: 10.1016/j.jweia.2015.11.006.

[45] L. Pop, Z. Sokol, and D. Hanslian, "A new method for estimating maximum wind gust speed with a given return period and a high areal resolution", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 158, pp. 51–60, 2016, doi: 10.1016/j.jweia.2016.09.005.

[46] M.B. Vallis, A.M. Loredo-Souza, V. Ferreira, and E. de L. Nascimento, "Classification and identification of synoptic and non-synoptic extreme wind events from surface observations in South America", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 193, art. no. 103963, 2019, doi: 10.1016/j.jweia.2019.103963.

[47] L.O. Almeida, M.G. Lima, I.C.A. Esteves, G.S. Munhoz, and R.A. Medeiros-Junior, "Updating the Brazilian wind speed map for structural design", *Structural Engineering and Mechanics*, vol. 79, no. 5, pp. 557–564, 2021, doi: 10.12989/sem.2021.79.5.557.

[48] A.C. Kruger, J.V. Retief, and A.M. Goliger, “Strong winds in South Africa: Part 1 Application of estimation methods”, *Journal of the South African Institution of Civil Engineering*, vol. 55, no. 2, pp. 29–45, 2013.

[49] A.C. Kruger, J.V. Retief, and A.M. Goliger, “Strong winds in South Africa: Part 2 mapping of updated statistics”, *Journal of the South African Institution of Civil Engineering*, vol. 55, no. 2, pp. 47–58, 2013.

[50] A.C. Kruger, J.V. Retief, and A.M. Goliger, “Development of an updated fundamental basic wind speed map for SANS 10160-3”, *Journal of the South African Institution of Civil Engineering*, vol. 59, no. 4, pp. 12–25, 2017, doi: 10.17159/2309-8775/2017/v59n4a2.

[51] F.P. Bakker, N. De Koker, and C. Viljoen, “Preconditioning wind speeds for standardised structural design”, *Engineering Structures*, vol. 238, art. no. 111856, 2021, doi: 10.1016/j.engstruct.2021.111856.

[52] S. Zhang, G. Solari, Q. Yang, and M.P. Repetto, “Extreme wind speed distribution in a mixed wind climate”, *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 176, pp. 239–253, 2018, doi: 10.1016/j.jweia.2018.03.019.

[53] A.A. Safaei Pirooz, R.G.J. Flay, and R. Turner, “New Zealand design wind speeds, directional and lee-zone multipliers proposed for AS/NZS 1170.2:2021”, *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 208, art. no. 104412, 2021, doi: 10.1016/j.jweia.2020.104412.

[54] P. Ceppi, P.M. Della-Marta, and C. Appenzeller, “Extreme Value Analysis of wind speed observations over Switzerland”, *Arbeitsberichte der MeteoSchweiz*, vol. 219, p. 48, 2008.

[55] I. Yu, J. Kim, and S. Jeong, “Development of probability wind speed map based on frequency analysis”, *Spatial Information Research*, vol. 24, no. 5, pp. 577–587, 2016, doi: 10.1007/s41324-016-0054-6.

[56] M.R. Abdillah, et al., “Extreme wind variability and wind map development in western Java, Indonesia”, *International Journal of Disaster Risk Science*, vol. 13, no. 3, pp. 465–480, 2022, doi: 10.1007/s13753-022-00420-7.

[57] A. Sarkar, S. Deep, D. Datta, A. Vijaywargiya, R. Roy, and V.S. Phanikanth, “Weibull and Generalized Extreme Value distributions for wind speed data analysis of some locations in India”, *KSCE Journal of Civil Engineering*, vol. 23, no. 8, pp. 3476–3492, 2019, doi: 10.1007/s12205-019-1538-4.

[58] J.A. Żurański and A. Sobolewski, “An analysis of snow and wind loads combinations based on meteorological data”, *Archives of Civil Engineering*, vol. 62, no. 4, pp. 205–230, 2017, doi: 10.1515/ace-2015-0117.

[59] J.D. Holmes, *Wind loading of structures*, 3rd ed. CRC Press, 2017.

[60] J.A. Żurański, M. Gaczek, and S. Fiszer, “Charakter i występowanie wiatrów katastrofalnych w Polsce / The nature and occurrence of catastrophic winds in Poland”, in *Konferencja Naukowa KILiW PAN i KN PZITB Kielce – Krynica*. 2009, pp. 697–704 (in Polish).

[61] T. Chmielewski, B. Kaleta, and H. Nowak, “Estimation of critical wind speed on the basis of roof blow-off”, *Archives of Civil Engineering*, vol. 66, no. 3, pp. 391–405, 2020, doi: 10.24425/ace.2020.134404.

[62] T. Chmielewski and H. Nowak, “Proposed classification for all types of wind storms in Poland”, *Archives of Civil Engineering*, vol. 66, no. 4, pp. 183–200, 2020, doi: 10.24425/ace.2020.135216.

[63] A. Goliger, J. Żurański, M. Giżejowski, M. Gaczek, J. Retief, A. Kruger, P. Dunaiski, S. Fiszer, and M. Ćwik, “Comparative study between Poland and South Africa wind climates, the related damage and implications of adopting the eurocode for wind action on buildings”, *Archives of Civil Engineering*, vol. 59, no. 1, pp. 51–95, 2013, doi: 10.2478/ace-2013-0003.

[64] PN-77/B-02011 Loads in static calculations. Wind loads. Warsaw, Poland: PKN, 1977 (in Polish).

[65] E.L. Deacon, “Wind gust speed: averaging time relationship”, *Australian Meteorological Magazine*, vol. 51, pp. 11–14, 1965.

[66] C.S. Durst, “Wind speeds over short periods of time”, The *Meteorological Magazine*, vol. 89, pp. 181–186, 1960.

[67] M. Gaczek, “Oddziaływanie wiatru na dachy budynków / Wind action on building roofs”, *Materiały Budowlane*, vol. 6, no. 562, pp. 6–9, 2019 (in Polish).

[68] ISO-4354:2009 Wind actions on structures. Geneva, Switzerland: ISO, 2009.

Prędkość charakterystyczna silnego wiatru do celów inżynierii wiatrowej

Słowa kluczowe: charakterystyczna prędkość wiatru, Gumbel, GEV, GPD, mapa prędkości, norma wiatrowa, BLUE

Streszczenie:

Eurokod zaleca stosowanie podstawowej bazowej prędkości wiatru (prędkości charakterystycznej) jako wartości projektowej w inżynierii lądowej. Istnieją różne metody szacowania tej wartości, zależne od cech klimatycznych danego obszaru oraz jakości rejestrowanych danych środowiskowych. Oszacowanie wartości charakterystycznej wymaga analizy statystycznej danych historycznych na temat prędkości wiatru mierzonej na stacjach meteorologicznych na terenie całego kraju. Wynikiem analizy jest rozkład gęstości prawdopodobieństwa i w konsekwencji wartość charakterystyczna prędkości wiatru w danej lokalizacji. W normach projektowych, przeważnie jest to prędkość o tzw. okresie powrotu wynoszącym 50 lat. Końcowym efektem jest wyznaczenie na mapie kraju stref o jednakowych prędkościach wiatru. W przypadku Polski ostatnia aktualizacja stref wiatrowych miała miejsce ponad 15 lat temu. Znacznie dłuższe okresy pomiarowe i dobra jakość danych rejestrowanych na stacjach w ostatnich latach oraz wprowadzenie w niedalekiej przyszłości drugiej generacji norm Eurokod stwarza potrzebę sprawdzenia tych stref i ewentualnej ich korekty. W pracy przedstawiono podstawy teoretyczne estymacji wartości charakterystycznych zmiennych losowych w kontekście prędkości wiatru, dokonano kompleksowego przeglądu praktycznych metod stosowanych w tym celu oraz podsumowano obecną sytuację w Polsce. Omówiono również zagadnienia związane z niejednorodności danych wiatrowych rejestrowanych na stacjach meteorologicznych, ilustrując je przykładem.

Received: 2023-03-10, Revised: 2023-05-23