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Determining wind gusts using mean hourly wind speed

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This paper presents a way of defining the speed of the strongest gusts in days with long-lasting, relatively strong wind at the Split-Marjan meteorological station. The gusts have been defined on the basis of the maximal mean hourly values of wind speed on the same day at the Split-Marjan location. The relations derived are of a strictly local character while the methodology used to define them could be used generally. This methodology is suitable for the development of a meteorological background to support Croatian standards in designing overhead power-transmission lines.

Keywords: wind gust, mean hourly wind speed, European standards, Croatian standards

1. Introduction

Croatia has been developing a wind load meteorological background to support Croatian standards. Wind impact is one of the major loads affecting buildings and other constructions, among which the most affected are the power-transmission pylons of the electrical energy network which can be seriously damaged by wind, resulting in serious collateral damage in different areas. Croatia has to harmonise its standards with European standards and one of its biggest problems is that there is an insufficient number of locations with long-term continuous measurements of wind direction and speed averaged to 10-minute intervals. Namely, the pre-drafts of European standards (ENV 1991.2.4, 1995; CENELEC/TC 11 (SEC) 40, 1997) recommend the use of 10-minute averaged wind speed in the calculation of many parameters. In Croatia, such data are available from 21 locations, for periods longer than three but shorter than ten years. They have been used as the basis for the development of a meteorological background for Croatian standards. However, within this project, for the estimation of locally expected maximal wind speeds, it has been decided to also use wind speed and direction averaged over hourly periods. Hourly averaged data for longer periods are available at another 24 locations and they are particularly useful to achieve better territorial coverage of the Croatian area observed. Up to the present, based on the example of data from the Novalja meteorological station, the relation of wind speeds averaged at different intervals has been analysed (Bajić and Peroš, 2001). Further investigations of such relations (for all available locations) have been suggested as well as the division of Croatian territory on the basis of similar relations.

This paper presents a direct application of hourly averaged wind speed data (instead of the recommended 10-minute average) for defining the maximal local instantaneous wind speed (wind gust). Such application has been researched on the example of hourly data from the Adriatic location of Split-Marjan, where some of the strongest Croatian gusts had been measured.

In Croatia, the strongest gusts are usually witnessed on the Adriatic coast during *bura* or *jugo.* A lot of research has been done on these two winds, both to investigate their origin and for statistical purposes (Koračin, 1982, Trošić, 1983; Bajić, 1989; Vučetić, 1993; Jurčec et al., 1996; Ivančan-Picek and Vučetić, 1996; Brzović, 1997; Tutiš, and Ivančan-Picek, 1991). In weather situations with *bura* or *jugo,* gusts are not always of the same intensity nor of the same frequency and the wind force usually results in substantial material damage on those days when strong wind blows over longer periods (Jurčec and Vukičević, 1996). It is therefore important to know the persistency of strong wind (Poje, 1992). To define the wind conditions at the Split-Marjan location that might jeopardise the power-transmission lines, an analysis has been made of the wind speed data for one day in each month when two kinds of maximal monthly speeds were identified for the same month. These are the maximal monthly mean hourly wind speed and the maximal monthly instantaneous wind speed. The relationship of these two maximal speeds has been analysed. The analysis has been performed by a methodology derived from the methodology for defining gusts based on mean ten-minute wind speeds as recommended by the pre-draft of European standards for building European power-transmission lines. The simplest form of the relations has been applied to get a first insight into the local gust characteristics and computations.

Generally, in attempting to define the local characteristics of gusts in detail, many kinds of analyses have been applied so far. For instance, for an Argentinean location, gusts have been computed for different averaging intervals, their variation with height and the time of year has been analysed, the general form of the vertical wind profile and its dependence on stability conditions have been analysed and compared with those of typical episodes of severe winds (Labraga, 1994). One of the newest physically based parameterisation schemes for the computation of wind gusts has been implemented in a numerical Canadian regional climate model (Goyette et al, 2003). A parameterisation scheme has been developed in order to use the quantities available at each model time step, including the wind gust computation for each of these time steps. There have been many attempts to relate wind gusts to mean wind speeds averaged over different time scales, and even to mean daily wind speeds (Weggel, 1999, Jungo et al., 2002). Statistically based prediction methods for gusts are used more often than numerical ones (Connor et al., 2003).

2. Data and methodology

Split is situated in the central part of the Eastern Adriatic coast. The Split-Marjan station (φ = 43° 31' N, λ = 16° 26' E, H_S = 122 m) is located on the forested Marjan Hill (178 m high), in the western part of the Split Peninsula. The largest green surfaces of the entire Split area are on Marjan Hill. This area is separated from the continental hinterland by the Dinaric mountain ranges of Kozjak (779 m high) and Mosor (1339 m high). The western part of Mosor and Kozjak, with their hinterland, belongs to the municipality of Split. The narrow pass of Klis cuts between these two mountains. Because of the geographical and topographical position of Split, strong *bura* and *jugo* winds are not rare at the Split location (Jurčec, 1981; Tutiš, and Ivančan-Picek, 1991; Jurčec and Vukičević, 1996).

At the Split-Marjan station, for the period 1958-2000, 288 monthly pairs were available of maximal monthly instantaneous speeds and maximal monthly mean hourly wind speeds for the same day of a particular month. The months in which the maximal monthly gust and the maximal monthly mean hourly speed did not occur on the same day were not included. As earlier research suggested that *bura* and *jugo* should be considered separately for the purpose of supporting standards (Bajić et al., 2001), the analysis has been performed on two separate groups of pairs. The first group included data collected for N-ENE winds and the second included data relating to E-SSW winds. Among the strong N-ENE winds, the prevailing ones are those of *bura* direction, and among the strong E-SSW winds, the prevailing ones are those of *jugo* direction (Jurčec and Vukičević, 1996; Penzar et al., 2001). In this paper all the winds of N-ENE directions are nominated *bura*, and all the winds of E-SSW directions are nominated *jugo*. A separate investigation of wind gusts under different weather systems is very common (Jungo et al., 2002; Choi and Hidayat, 2002).

Thus, wind occurrences were chosen for *bura* and *jugo* directions on days when wind speed, except in the short period of gusts, was on the average relatively high over a longer period, *i.e.* at least over an hour. The days thus chosen are days when substantial material damage can be expected due to the great strength and relatively long duration of strong wind, and this was the main reason for this research.

For application to the building of electrical power-transmission equipment in Europe, the estimation of wind gusts based on mean ten-minute wind speed values has been initially suggested to be processed as follows (CENELEC/TC 11 (SEC) 40):

$$V_g = k_g V_{mean} \tag{1}$$

where V_g is the gust speed (m s^{-1}), *i.e.* the instantaneous maximal wind speed in a measuring interval (T) of 2 seconds, V_{mean} is the mean ten-minute wind speed (m s^{-1}) and k_g is the gust factor. The gust factor is defined as:

$$k_g = 1 + \frac{2.28}{\ln\left(\frac{z}{z_0}\right)}, \tag{2}$$

where z (m) is the height above ground and z_0 is the roughness length (m), which depends on terrain characteristics. At the Split-Marjan location, wind measurements are performed at the usual height above ground, *i.e.* z = 10 m. The value of the roughness length, z_0, has been taken as 0.3 m, which is the value defined in most European countries for woodland areas like the Split-Marjan area observed.

In equation (2), the log wind profile is used to define the gust. The mean wind speed as a function of height above the ground can be computed by the logarithmic profile

$$V_{mean} = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right), \tag{3}$$

where k is the von Karman constant, approximately equal to 0.4; u_* is the friction velocity; z_0 is the surface roughness length; and z is the height above the ground.

The peak gust speed (V_g) at height z is computed using Durst's statistical model (Durst, 1960) as follows:

$$V_g(z) = V_{mean}(z) + g(T)\sigma_v(z), \tag{4}$$

where T is the averaging period, $g(T)$ is the gust peak factor which is a function of T and $\sigma_v(z) = \sqrt{\beta} u_*$ is the root-mean-square value of the longitudinal fluctuating wind speed at height z, in which β is a terrain dependent coefficient (Zhou et al., 2002a). For $g(T)$, the Eurocode uses alternatively factors of 3.7 and 3.5. (Zhou et al., 2002b). By including equations (3) and (4) into equation (1), the following gust factor equation is obtained:

$$k_g = \frac{V_g}{V_{mean}} = 1 + g(T)I(z), \tag{5}$$

where $I(z)$ is the longitudinal turbulence intensity and $I(z)$ is defined as (Zhou et al., 2002a):

$$I(z) = \frac{\sigma_v(z)}{V_{mean}(z)}. \tag{6}$$

Equations (4), (5) and (6) indicate that the constant 2.28 in (2) is calculated as:

$$2.28 = g(T)\sqrt{\beta}k. \tag{7}$$

Assuming the applicability of the logarithmic wind profile, Wieringa (1976) has shown another (statistical) kind of gust factor derivation. A description of the vertical wind speed profile by power-law is also in use (Labraga, 1994; Hsu, 2003). The assumed dependence of the power-law exponent upon atmospheric stability (Davenport, 1965) results in a gust factor definition as a function of stability, instead of a logarithmic wind profile and a fixed gust factor value (equation (2)) as suggested in the pre-draft of European standards (CENELEC/TC 11 (SEC) 40). The relationship between the exponent of the power-law wind profile, friction velocity and the gust factor has been investigated and is already available for engineering applications (Hsu, 2003). However, only a revision of the convenience of the wind gust calculation recommended in the pre-draft of European standards (CENELEC/TC 11 (SEC) 40, 1997) is shown in this paper.

It is well known that *bura* and *jugo* gusts in Croatia are among the strongest gusts in Europe (Heimann, 2001). Strong gusts have been assumed to characterise the daily weather conditions which significantly affect the values of the individual mean hourly wind speeds during the whole day and not only the value of the mean ten-minute speed at the time of the gust. Because of this assumption, and because there are no ten-minute data available for many locations in Croatia, the recommended equation (1) has been modified and the following modification has been tested:

$$V_g = k_g \overline{V_{MAX}}, \tag{8}$$

where k_g is the same parameter value as in equation (2), $\overline{V_{MAX}}$ is the maximal mean hourly speed for a particular month and V_g is the expected maximal gust on the same day.

3. Results

The first step in the analysis of the measured gusts and the maximal mean hourly wind speeds was the analysis of their averaged values (*AG* and *AV*, respectively). Each pair of maximal measured monthly instantaneous speed (G) and maximal monthly mean hourly wind speed ($\overline{V_{MAX}}$) for the same day was grouped in one of the predefined classes. The classes were determined on the basis of the values of $\overline{V_{MAX}}$. *The* $\overline{V_{MAX}}$ classes and the speed range have been defined in such a way that each particular $\overline{V_{MAX}}$ speed class corresponds to the adequate wind strength class of the Beaufort scale. For each class, all $\overline{V_{MAX}}$ values have been averaged (the result of averaging is the AV value), as well as all the »associated« G values (the result of averaging is the AG value).

The analysis of the average measured gusts (AG) and the average maximal mean hourly wind speeds (AV) per maximal mean hourly speed class has shown that a relative (AG/AV) difference is remarkable during *bura* and *jugo*. However, their absolute difference ($AG–AV$) is also remarkable – the difference is considerably greater in the case of *bura* than in the case of *jugo* (Tables 1 and 2). For particular wind speed classes, the average gust and average maximal mean hourly wind speed ratio (AG/AV) showed to be, on the average, higher by about 20% for *bura* than for *jugo*. The absolute difference ($AG–AV$) in the particular speed classes reaches a maximum average of 16.5 m s^{-1} for *bura* and 11.2 m s^{-1} for *jugo*.

The values of the maximal monthly gusts estimated on the basis of equation (8) have been compared with the measured maximal monthly gusts. It has been established that this equation should be further modified for all maximal mean hourly wind speed classes, for both *bura* and *jugo*. The modification of equation (8) has been carried out for all wind speed classes. All equations, derived individually for every maximal mean hourly wind speed class, have the following form:

$$V_g = k_g\overline{V_{MAX}}+C \tag{9}$$

where C is the constant, which is different for each particular wind speed class and for the same wind speed class in the case of *bura* and *jugo* (Tables 1 and 2).

Constant C represents the mean difference between the individual measured wind gusts in the particular speed class considered and the associated wind gusts calculated by using equation (8). In the *bura* and *jugo* cases, constant C values differ substantially from speed class to speed class. Its values are much greater in the case of *bura* than in the case of *jugo*, which indicates that during *bura* a short-lasting gust speed is much higher than the highest mean hourly speed characterising the same day. For *bura*, positive constant C values have been established for all speed classes, except for the strong storm class, which is the only case when the gust speed is slightly lower than the one calculated by equation (8). For *jugo*, the values of the mean hourly speeds in the strong storm category have not been established at the Split-Marjan location and when using equation (8) the gust speed values are overestimated already for the very strong wind class and also for the stronger

Table 1. The means of the maximal hourly values of measured wind speed (AV; m s^{-1}), measured wind gusts (AG; m s^{-1}), AG/AV ratio and AG–AV difference, and the constant C value (m s^{-1}) in the gust equation (9), per particular speed class, with N cases of bura of which in n per cent of cases (%) the calculated gust was considerably weaker than the measured one. Split-Marjan, 1958–2000.

class range (m s^{-1})	N	mean values *AG*	*AV*	*AG/AV*	*AG–AV*	con-stant *C*	n
wind of medium intensity 8.0–10.7	5	19.8	9.9	2.0	9.9	3.4	0
strong wind 10.8–13.8	37	23.8	12.7	1.9	11.1	2.9	3
very strong wind 13.9–17.1	46	27.4	15.4	1.8	12.0	2.0	11
gale 17.2–20.7	41	32.6	18.8	1.7	13.8	1.6	7
storm 20.8–24.4	26	37.6	22.6	1.7	15.0	0.3	12
violent storm 24.5–28.4	5	44.2	27.7	1.6	16.5	–1.4	0

Table 2. Same as Table 1, but for jugo.

class range (m s^{-1})	N	mean values *AG*	*AV*	*AG/AV*	AG–*AV*	con-stant C	n
wind of medium intensity 8.0–10.7	2	17.1	10.2	1.7	6.9	0.3	0
strong wind 10.8–13.8	16	21.7	12.8	1.7	8.9	0.5	13
very strong wind 13.9–17.1	46	25.0	15.6	1.6	9.4	–0.8	7
gale 17.2–20.7	46	30.0	18.8	1.6	11.2	–1.0	7
storm 20.8–24.4	18	31.6	22.1	1.4	9.5	–4.9	11

wind classes. Therefore, constant *C* values in (9) are negative for the speed classes mentioned.

For the period 1958–2000, at the Split-Marjan location observed, a percentage (n) is presented of the cases which have been modelled (using equation (9)) as substantially lower, *i.e.* at least 5 m s^{-1} lower than the corresponding measured wind gusts (Tables 1 and 2). The percentage of theoretical gusts that have been underestimated compared with the measured gusts is mainly below 10% per particular speed class. By accepting such correspondence of theoretical and measured wind gust speeds we have only initially and roughly validated these experimentally derived relations. Namely,

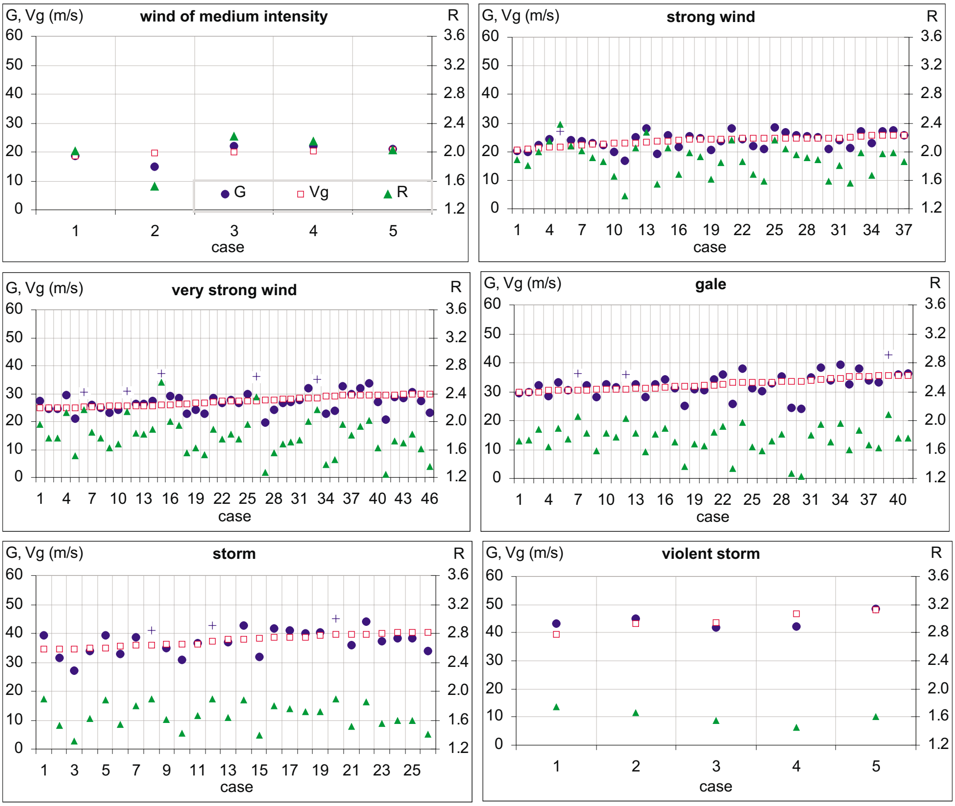

Figure 1. The speed of the measured (G) and modelled (V_g) gusts and the ratio between the measured gust and the maximal hourly mean (V_{MAX}) of measured wind speed ($R=G/V_{MAX}$) during *bura*. Measured gusts which were stronger by 5 m s^{-1} or more than the calculated ones are marked with a plus (+). Split-Marjan, 1958–2000.

further research at more locations on the Adriatic will make it possible to define the currently chosen threshold (5 m s^{-1} for all wind speed classes) more accurately for particular speed classes. Figures 1 and 2 present, separately for *bura* and *jugo*, per speed class, the measured and calculated wind gusts and the ratio (R) between the measured wind gusts and the corresponding maximal hourly means of the measured wind speed used to calculate the gust speeds. In each class, the cases are arranged on the basis of the values of the calculated gust speeds (in ascending order). Measured gusts stronger by 5 m s^{-1} or more than the calculated ones have been additionally marked by »+«.

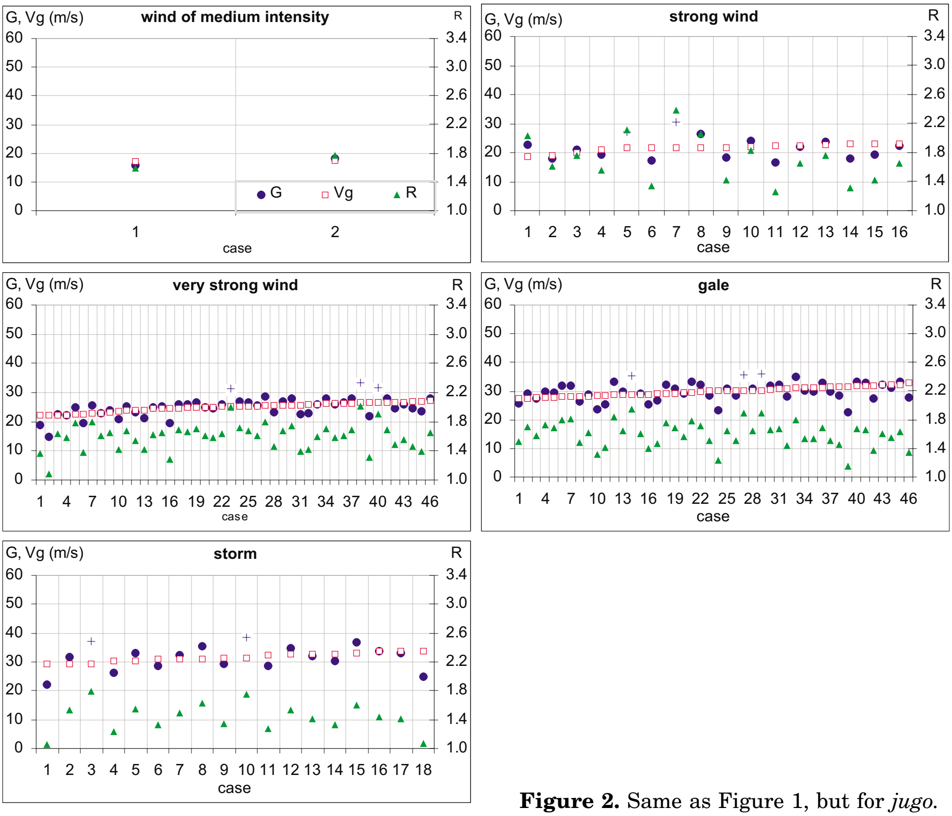

Figure 2. Same as Figure 1, but for *jugo.*

4. Discussion and conclusion

The Split-Marjan location is the first Croatian location for which a modelling of wind gust speed has been made by modified forms of the model recommended by the pre-draft of European standards for application in the designing of power-transmission systems. European standards allow for national modifications if they are necessary because of the specific natural or other conditions of particular countries. In this case, we tried to develop a modification which would allow the modified forms to remain as similar to the recommended pre-draft of standards as possible. The results of this effort have shown the modifications were usable, resulting in an acceptable presentation of the meteorological background to Croatian standards in designing overhead power-transmission lines.

Both steps of the modification developed proved usable. In the first step, the mean ten-minute wind speed data input in the pre-draft of the European standard model was replaced by a mean hourly data input, because of the availability of long-term hourly averaged data for a large part of the Croatian territory. Long-term data provide an insight in the climatological characteristics of the location observed. Therefore, in the few cases where the derived relations for Split-Marjan proved unsuitable (20 cases marked by »+« in Figures 1 and 2), they point at a cluster of cases which have to be taken as locally exceptional and rare but possible. These cases can be categorised as exceptional due to their small amount in the data cluster observed which, in turn, represents rather rare occurrences. For Croatian locations where only shorter-term gust series and ten-minute wind data are available it is not possible to single out locally exceptional gusts reliably enough.

The constants introduced in the second step of the modification have made it possible to define more reliably the gust speeds at the Split-Marjan location. The constants, and therefore the modified models, are only locally applicable but it can be assumed that this experimental way of defining a connection between the maximal mean hourly speed on a particular day and the strongest wind gust on the same day can be generally applied to the territory on the Croatian side of the Adriatic.

In further wind gust investigations some other forms of relationship between gust speed and mean hourly speed will be investigated for the Split-Marjan location. The intention is to find a universally applicable form of wind gust calculation.

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SAŽETAK

Određivanje udara vjetra pomoću srednjih satnih brzina

Lidija Cvitan

Rad prikazuje jedan način definiranja brzine najjačih udara vjetra u danima u kojima i dugotrajno puše relativno jak vjetar na meteorološkoj postaji Split-Marjan. Udari su definirani na temelju maksimalnih srednjih satnih vrijednosti brzine vjetra iz istog dana na lokaciji Split-Marjana. Izvedene relacije su izrazito lokalnog karaktera, a primijenjena metoda njihovog određivanja bi se mogla općenito primijeniti. Metoda je prikladna za izradu meteorološke podloge za potrebe hrvatskih norma u gradnji dalekovoda.

Ključne riječi: udar vjetra, srednja satna brzina vjetra, europske norme, hrvatske norme

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