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Accuracy of assessment of wind speed in the built environment

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ABSTRACT

Wind climate in the built environment is assessed with wind tunnel simulations and criteria for wind discomfort and safety. Probability of occurrence of local winds with regard to speed, direction and time are derived from the wind tunnel results and data from an appropriate meteorological station. The present paper discusses error sources in the various steps. It is shown that at least a 20% standard deviation in the estimated local wind speeds has to be accounted for. This error has impact on the application of the various criteria.

1. INTRODUCTION

In the Netherlands a program has started for standardisation of the assessment of wind climate in building plans. Among the goals are standard criteria for wind discomfort and standard rules for wind tunnel investigations, CFD calculations and for use of climatological data. The program incorporates literature surveys and experience during three decades of wind comfort assessment with wind tunnel simulations. The standard for the assessment of wind discomfort and wind hindrance is meant as a document, available for incorporation in a building program and it is expected to become an important tool for authorities. It is necessary to determine the accuracy of the mentioned methods.

2. METHODOLOGY

In current practice in the Netherlands wind tunnel investigations yield the ratio $C_{V,WT}$ between the hourly mean wind speed V_{PED} at pedestrian height and the hourly-mean wind speed V_{REF} at some reference height Z_{REF} . In a perfect wind tunnel simulation $C_{V,WT}$ is the same in the wind tunnel as the value $C_{V,IS}$ in situ. We assume that $C_{V,WT}$ has no systematic errors, but only a random error with standard deviation δC_V . So:

$$C_{V,WT} = \frac{V_{PED,WT}}{V_{REF,WT}}, \quad C_{V,IS} = \frac{V_{PED,IS}}{V_{REF,IS}} \quad C_{V,WT} = C_{V,IS} \pm \delta C_V, \quad (1)$$

$V_{REF,IS}$ is discussed in section 4. It is defined as an in situ wind speed at a height Z_{REF} . The flow is assumed stationary and homogeneous. The flow corresponds

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with a z_0 -value that is representative for the oncoming flow at the investigated building site as function of wind direction.

In literature an effective wind speed V_{EFF} is defined, in which the effects of wind gusts on wind discomfort and danger are accounted for. The definition of an effective wind speed V_{EFF} in non-dimensional form is

$$C_{V,EFF} = C_V \cdot (1 + K \cdot I_U) \quad (2)$$

I_U is the longitudinal turbulence intensity and K has a value varying in literature between 0 to 3.5. With a typical value of $I_U = 0.20$ (i.e. 20%), the difference between applying $K=0$ and $K=3.5$ results in a 70% difference in the $C_{V,EFF}$ value; this affects of course greatly the further results of the assessment. Wind tunnel test data may incorporate turbulence characteristics directly (the rms-value of the time signal of the wind speed sensor is measured) or indirectly (the time-mean value of the sensor output will be higher as a result of turbulence). This means that a proper choice of K should depend on the applied sensor in the wind tunnel. The heated thermistors as used in the Netherlands are expected to respond mainly on the time-mean wind speed and a high K -value should then be used to define V_{EFF} . The matter of an effective wind speed coefficient and the corresponding error due to turbulence is further left out of discussion here.

To calculate the in situ wind speed at pedestrian height from a $C_{V,WT}$ -value, we have to calculate $V_{REF,LS}$ from the hourly mean wind speed V_{METEO} at 10m height at a nearby meteorological station. Assuming a ratio T with a standard error δT , we may write:

$$\frac{V_{REF,LS}}{V_{METEO}} = T \pm \delta T \text{ and } V_{PED,LS} = (C_{V,WT} \pm \delta C_V) \cdot (T \pm \delta T) \cdot V_{METEO} \quad (3)$$

$$\text{if } C_{V,LS} = C_{V,WT} \pm \delta C_V$$

The standard error δC_V will be discussed in section 3, δT in section 4 and the effect on the accuracy of the calculated wind speeds at pedestrian height in section 5. In section 6 the consequences for the assessment of the wind climate will be discussed.

3. ACCURACY OF THE WIND SPEED COEFFICIENT

The standard error δC_V in equations 1 and 3 is caused by technical and simulation errors. These errors may originate from e.g.:

- Wind tunnel characteristics (short and long term change of the flow with time, drift of sensor accuracy and sensor sensitivity);

- Extent of details in the model and in the surrounding area;
- Response of sensors to highly turbulent flow conditions (wind speed variations and flow angle variations);
- Differences between the simulated atmospheric boundary layer (ABL) and the in situ ABL (in wind tunnel experiments the ABL profile does not, or seldom change with wind direction);
- Choice of the reference height.

In 1992 a round-robin test was performed between three independently operating wind tunnels in the Netherlands.

Figure 1. Result of the round robin test. The ratio of $C_{V,WT}$ determined with wind tunnel A to $C_{V,WT}$ determined with wind tunnel B, for 52 positions as function of $C_{V,WT}$ determined with wind tunnel A.

An imaginary built environment was defined and modelled on scale 1:250. The same physical model was used by all three parties and tested under a simulated ABL, as used by the separate wind tunnels for $z_0 = 0.03\text{m}$. At 52 positions $C_{V,WT}$ was calculated for 24 wind directions (step size 15°). The results of one wind tunnel had a systematic deviation; this will not be discussed further, as a systematic error might be solved in principle. For the present discussion the random errors are of interest. Comparing any two wind tunnels resulted in a similar conclusion. Figure 1 gives the result for wind tunnels “A” and “B”. The ratios between the C_V -values at similar wind direction from the two wind tunnels are plotted along the vertical axis and the C_V -values for wind tunnel “A” along the horizontal. The results show a bandwidth of approximately 50 per cent. A standard deviation of 12% was calculated.

The round-robin test only covers a part from the above-summarised possible technical and simulation errors. The remaining errors may have considerable effects, especially a mismatch in the velocity profile. Although generally, the building location is characterised by different upstream surface roughness at varying wind directions, routine wind simulations use one surface roughness for all wind directions. A description of the upstream roughness will easily be one class off in the roughness classification (Wieringa 1992), with noticeable effects on wind speed and turbulence characteristics. If for example $z_0 = 1\text{ m}$ or 0.5 m and if the displacement length $d = 10\text{ m}$, the longitudinal turbulence intensity I_U at height $z = 50\text{ m}$ is either 27% or 22%. The integral turbulence length scale L_X is inversely proportional to $(I_u)^2$. If the wind speed V_{REF} is kept constant, L_X varies then a factor 1.5. Moreover, the integral turbulence length scale varies a factor 4 with stability (Tieleman 2001). The effect of a miss-modelled integral turbulence length scale on separation in the flow might be considerably. We have no information on the magnitude of this error with regard to pedestrian level wind tests.

It is suggested (ASCE 1999) that the effect of stability may be compensated by climatologically averaging. For the effect of a non-realistic roughness length this may not be expected. Stability will also significantly affect the wind characteristics.

The present authors estimate that apart from the round robin test the errors discussed will cause an extra standard deviation in C_V of at least the same order of magnitude, i.e. another 12%. The total standard deviation is then at least 15%, i.e. $\delta C_V / C_V = 0.15$.

4. ACCURACY OF THE REFERENCE WIND

The ratio T in equation 3 represents the transfer from the documented wind speed at a nearby meteorological station to the wind speed at reference height. An estimate of T based on values for the surface roughness at varying wind direction and an internal boundary layer growth model in a neutral atmosphere. This estimate incorporates errors.

De Wit et al (2001) analysed wind measurements over Eindhoven. They found that the error in the calculated T -value had a standard deviation of about 9%. They also found a random wind speed variation at a reference height of 42 m with a standard deviation of 0.7 m/s. At wind speeds relevant in wind comfort studies (threshold wind speeds of 5 m/s) this is almost 15%. An additional error in the source data of V_{METEO} of say 10% will also affect the $V_{\text{REF,LS}}$ for another 10%. For the time being, the present authors estimate from above considerations the standard error in T as 15%, i.e. $\delta T/T = 0.15$.

5. ACCURACY OF THE PEDESTRIAN LEVEL WIND SPEED

The estimates of $\delta C_V = 15\%$ and $\delta T = 15\%$ mean that according to equation 3 the in situ pedestrian level wind speed $V_{PED,IS}$ can be estimated within a standard deviation of about 20%.

Isyumov (1995) compared in a study at the campus of the University of Western Ontario the mean wind speed coefficients measured in situ $C_{V,IS}$ with wind tunnel coefficients $C_{V,WT}$. The $V_{REF,IS}$ was estimated from V_{METEO} and a reference anemometer at another location of the campus. The present authors estimate that these data show a range for $C_{V,IS}/C_{V,WT}$ of 0.4 to 1.6, with at $C_{V,WT}=0.5$ a standard error of about 20%. The small amount of data is in line with the present error estimate.

Visser and Cleijne (1994) measured $V_{REF,IS}$ for a low-rise location in wooded countryside in the Netherlands and estimated the roughness lengths z_0 of the foreland. The authors studied four locations. At an optimal choice of z_0 they found values of $C_{V,IS}/C_{V,WT}$ of 0.8 to 1.2 in a winter half-year and of 0.6 to 1.0 in a summer half-year. For all four locations together they found $C_{V,IS}=0.06+0.93 C_{V,WT}$ (correlation coefficient $r=0.87$) in winter and $C_{V,IS}=0.12+0.70C_{V,WT}$ ($r=0.78$) in summer. These data are also in line with the present error discussion.

Williams and Wardlaw (1992) studied the wind regime in the city of Ottawa. The wind speed V_{LOC} at a 213-m high measuring point was found to be 1.226 times the V_{METEO} value. They required 1250 hours of data to get this ratio within a 10% of the mean value and 2935 hours for a better than 0.5%. This information indicates that the standard deviation of this ratio is surprisingly great. The correlation coefficient between $C_{V,IS}$ (with V_{REF} being the gradient wind) and $C_{V,WT}$ was only 0.7, indicating that the wind tunnel simulation could not explain half of the variance. However, the ratios of the pedestrian level winds and the wind speeds at the closest tower as determined in situ and in the wind tunnel correlated very well. The study of Williams and Wardlaw illustrates very well the difficulty in the calculation of T in equation 3, even if the wind tunnel simulation is completed with in situ measurements.

Murakami et al (1979) compared $C_{V,IS}$ (with V_{REF} at 120m height) and $C_{V,WT}$. From their scatter diagram the present authors conclude to a standard error of 40% at $C_{V,IS}=0.2$ to 10% at $C_{V,IS}=0.8$.

6. CODIFICATION OF WIND COMFORT

More than 25 years ago it was already recognised that thermal comfort and the cooling effects from wind should be considered in the assessment of wind discomfort. Recent work from Sasaki et al. (2000) and Stathopoulos et al. (1999) renewed this attention to thermal effects. In this paper the assessment of wind discomfort is restricted to the probability P_i for a location i that a local wind speed $V_{PED,IS}$ exceeds a certain threshold value V_{THR} .

$$P_i = \sum_n P_i (V_{PED,LS} > V_{THR}) = \sum_n P_i \{ (C_{V,WT} \pm \delta C_V) \cdot (T \pm \delta T) \cdot V_{METEO} > V_{THR} \} = P_{AVG,i} \pm SD_i \quad (4)$$

n being the number of wind direction classes in the wind tunnel simulation. Because of the climate of the region and the geometry of the built environment $P(U_{REF} > X)$ and C_V are both a function of wind direction. Therefore, a generalised answer on the value of SD_i is impossible. We performed a test with a wind tunnel generated set of $C_{V,WT}$ for 76 measuring points in a model of a 19th century quarter with additional high rise. For each measuring point P_i has been calculated with wind climate data of Amsterdam airport. To demonstrate the effect of $\delta C_V = 15\%$ and $\delta T = 15\%$ we chose randomly 10 numbers from a normal distribution with a standard deviation of 20%. From the 11 numbers for every measuring point a mean $P_{AVG,i}$ and a standard deviation SD_i has been calculated. Figure 2 and 3 present $P_{AVG,i}$ and corresponding SD_i values for $V_{THR} = 5$ and 15 m/s respectively.

Figure 2 and 3. $P_{AVG,i}$ and SD_i values in percent for 76 measuring points. Wind climate of Amsterdam Airport. $\delta C_V = \delta T = 15\%$. Figure 2: $V_{thr} = 5$ m/s; Figure 3: $V_{thr} = 15$ m/s.

To implement a wind comfort criterion in building practice, which consists of a value for V_{THR} and a maximum probability P_{MAX} for P_i , we have to choose the probability that

$$P_i - P_{MAX} > 0 \quad (5)$$

This means that we have to choose the level of certainty, which we can claim for our evaluation of the quality of the wind climate in the building project. Let us assume that it will be required that $P_i - P_{MAX}$ will only be positive with a probability less than 3.6%. This means that if we apply a normal distribution

$$P_{AVG,i} + 1.8 SD_i < P_{MAX} \quad (6)$$

If we choose $SD_i=3\%$ for comfort assessment (figure 2) and require that the local velocity is greater than 5 m/s in less than 20% of the time, the above discussion implies that a wind tunnel simulation should demonstrate that $P_{AVG,i}<15\%$ to meet this requirement.

Moreover, if we adapt the safety requirement that V_{PED} only exceeds 15 m/s in 0.5% of the time and see from figure 3 that now SD_i is 0.4% we find that a wind tunnel simulation should demonstrate that $P_{AVG,i}<0.5-1.8 \times 0.4$ or $P_{AVG,i}=0$.

7. CONCLUSION

A conservative estimate of the standard error of the pedestrian level wind speed in the built environment is 20%. Consequently, the standard error in the probability that the local wind speeds exceed a threshold value is given by figures 2 and 3.

A complete discussion of the accuracy of wind tunnel simulation of local wind speed is not possible. In particular the technical and aerodynamical errors involved in the simulation are not sufficiently documented. Also the uncertainty in the threshold values for wind comfort and safety as well as the determination of the local turbulent intensity are neglected in the present discussion. A tentative conclusion is that an evaluation of a building plan with a wind tunnel simulation is feasible, but the errors involved should be taken into account while formulating the required probability that local wind speed exceeds a threshold value.

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