Presented at the 94th AMS Annual Meeting, Atlanta, GA, Feb 2-6, 2014

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DETERMINATION OF THE ROUGHNESS LENGTH AND VON KARMAN CONSTANT USING METEOROLOGICAL TOWERS AT THE NWTC

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1. Introduction.

In neutral conditions wind profiles are strictly linked with the roughness length and with the Von Karman constant. While the roughness length is determined by using different methods, the Von Karman constant is generally considered as a constant parameter.

In complex terrain, the roughness length Z_0 is linked with the other fundamental parameter d_0. The role of d0 is to correct the neutral log-law valid in flat terrain.

In urban area and neutral atmosphere, Z_0 and d_0 can be obtained by using morphometric methods (Macdonald et al. (1988), Grimmond and Oke (1999), Di Sabatino et al. (2010), Kastner-Klein and Rotach (2004)). In flat terrain, the roughness length can easil[1]y be estimated by land-use categories Stull (1988) or in terms of the Reynolds number (Frenzen and Voegel (1995)) and the Rossby number (Tennekes (1973)).

All these methods are based on the obstacles height or on the local urban characteristics, and no direct measurements of wind are request for the calculations of Z_0.

The constant k is generally calculated from the flux relationships using neutral or near-neutral turbulence conditions Businger et al. (1971) in flat terrain. The flux methods are based on the knowledge of two or more measurements of horizontal wind at different heights.

Another methods for the determination of k are the wind profile methods.

The wind profile methods may be considered as an alternative approach with respect to the gradient one. The profile methods assume a theoretical formulation to reproduce the wind at different heights.

In literature k is in general considered as a constant (Oncley et al. (1990)) (ONC90), and the most common value is k=0.40. Usually the assumption of its constancy is crucial in many fields. With regard to the constancy of k there is a lively debate (ONC90 and Hogstrom (1996)-HOG96).

k can depend by the Rosby number and it can be associated in general with the local roughness (HOG96).

Here the Von Karman constant k is evaluated applying the wind profile methods in neutral conditions. The connections between the Von Karman and the roughness Reynolds number has been evaluated for the same dataset in Pelliccioni (2014).

The focal point of this work is that profile methods involve as experimental parameter to be determined, other than the Z_0, also the Von Karman constant and the estimation of Von Karman derive directly as result of regression models to the wind neutral profiles.

2. Materials and methods

2.1. NREL site

Different data from meteorological towers are collected at National Wind Technology Center (NWTC). Data referring to year 2012 have been analyzed. The National Renewable Energy Laboratory is located on the eastern side of the NWTC grounds. The NWTC is approximately 8 km south of Boulder, Colorado (USA) and 36 km north west of Denver at an elevation of approximately 1850 m above sea level. A long-term wind time series of turbulence variables (as the L, TKE, U*, etc) is available from the M5 tower at different heights (15m, 30m, 50m, 75m, 100m,131m) (Clifton (2013)).

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As evident by figure 1, the site is characterized by a zero displacement height so that conventional log-law has been chosen for the neutral conditions.

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The average value u* is very high (u*=1.08±0.37 m/s) and a good correlation between u* with σ_W and wind speed has been observed (Figure 2).
In literature, σ_W and u* are correlated and the constant of proportionality may depend on the knowledge of mixing height and of stress Stull (1988).

Figure 1: View of wind park at NREL

Averaging on all levels up to 75m, the following relationship between u* and σ_W is obtained (fig 3):

σ_W =1.319 u* (1)

The correlation is high (R=0.93) and the coefficient 1.319 is within the typical range between 1.3 and 1.5 as in literature.

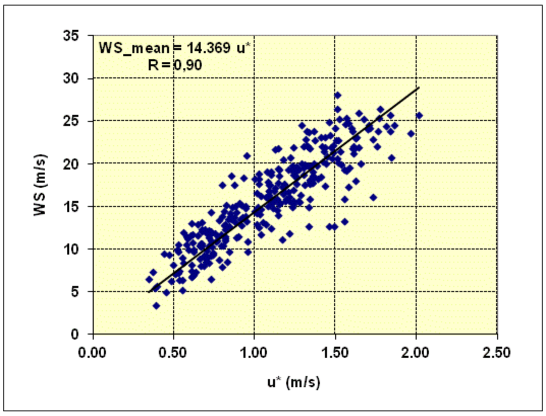

Figure 2: Correlation between wind speed and friction velocity for M5 tower: average values.

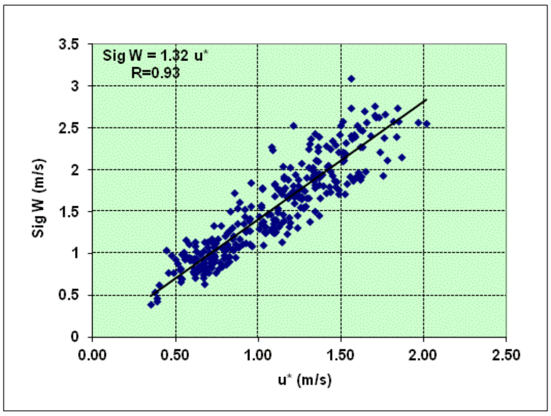

Figure 3: Correlation between vertical wind standard deviation and friction velocity for M5 tower

2.2. The selection of neutral profiles

We selected wind profiles from data having wind direction and u* constant along Z. The work was concentrated on neutral conditions. These neutral profiles are extracted by one year data assuming:

1- │Z/L│≤0.01
2- The variations along Z of wind direction is lesser than 1% of the observed average
3- The variation along Z of u* is lesser than 15% of the observed average u*

The last criteria is very important because it assures the vertical homogeneity of u*, and so of the constancy of mechanical turbulence during the selected neutral conditions.

The equation used for the wind profile method is the neutral log law:

$$\mathbf{u(Z)} = \frac{\mathbf{u}_*^{\mathbf{15m}}}{\mathbf{k}} \cdot \mathbf{ln}\left(\frac{\mathbf{Z}}{\mathbf{Z_0}}\right) \qquad (2)$$

Where u^{15}_m is the representative value of friction velocity calculated using the sonic anemometer height corresponding to the lower level at 15m.
Note that the basic equation (2) links u* with k through the ratio u*/k. This ratio introduces a slight error during the regression process. To separate the contribution of u* by k, it has been used the non-dimensional equation as follow:

$$\frac{\mathbf{u(Z)}}{\mathbf{u}^*_{\mathbf{15m}}} = \frac{\mathbf{1}}{\mathbf{k}} \cdot \mathbf{ln}\left(\frac{\mathbf{Z}}{\mathbf{Z_0}}\right) \qquad (3)$$

In the non-dimensional formulation (3), the direct correlation between $u(z)/\overline{u*}$ with k and Z0 parameters can be evaluated.

2.3. Near- neutral correction

Equation (3) is valid only for strictly neutral conditions. In open area, the classic neutral conditions are never verified during the field campaigns because they correspond to the asymptotic values of Z/L =0. Each profile is influenced by an error due to the presence of near-neutral conditions. Andreas et al. (2006) (AND06) have proposed a correction (named as stratified correction) for near-neutral conditions. Starting from the solution of k it is possible to obtain a new estimation of kuc using the used values of Z/L. In the present work such correction will be considered and the corrected kuc will be considered as the best estimation for the Von Karman parameter.

3. **Results**

We analyzed data using above criteria 1)-2)-3) to select the wind profiles. The number of neutral profiles for each month are shown in table 1. The total neutral profiles number is 255.

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	oct	Nov	Dec
55	24	20	11	9	10	8	10	16	10	38	44

Table 1: number of neutral profiles selected for the analysis

We note that maximum neutral conditions happen during winter seasons. Conversely, the minimum neutrals profiles are during the summer.
Equation (3) reproduces the selected profiles quite well. The correlation is R=0.985±0.017, with a minimum of 0.888 and maximum of 0.999 (Figure 4). For an higher quality of the k values, a more stringent selection has been applied on the selected data. The profiles with correlations lesser than R=0.99 are not be considered. In such a way, the total number of profiles considered for the further evaluation is of 198. These profiles have been considered as representative of homogeneous turbulence and wind direction conditions. The filtered profiles satisfy equation (3) with an excellent correlation (R=0.995±0.003).

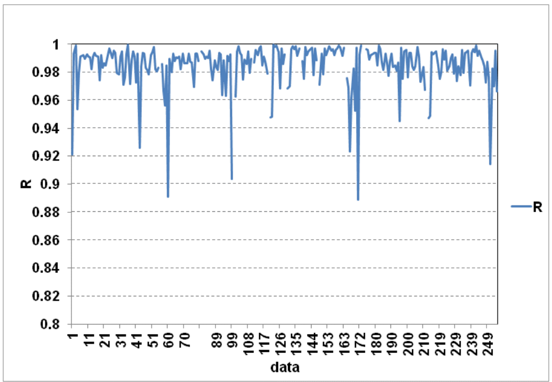

Figure 4: Correlation (R) for the neutral log-law (3) for all 255 selected profiles.

The average of the roughness length on all data is Z_0=4.1±4.8cm, and this value is in agreement with the expected site characteristics. The Z_0 shows skew distribution, with a marked modal value at 2.5cm for all seasons. The main sector is along the W-NW direction (Figure 5), with average values of 3.1±5.0cm, while in NNW-W direction few other values of 2.8±1.9cm are observed.

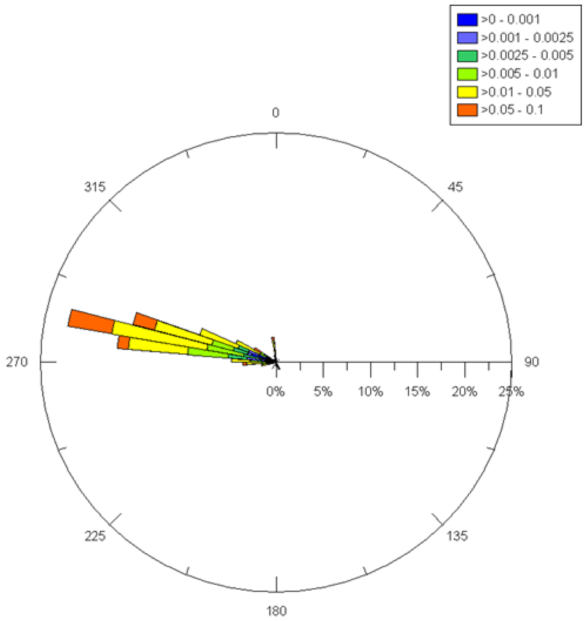

Figure 5: Z_0 wind sector distribution.

The observed Z_0 are in agreement with the assumption of displacement height equal to zero and the hypothesis of flat terrain was confirmed by the results of theoretical regression model for the log-law.

The values of the Von Karman calculated from equation (3) is k=0.52±0.12, a quite different value from that in literature.
This difference may be explained by the presence of near-neutral conditions in the selected data.
The stratified method has been applied to these values obtaining the values of k_{uc}=0.47±0.12.
The pdf of k and k_{uc} are skewed and the modal values are quite different. From the k distribution, the modal value of 0.5 is observed. From the k_{uc} distribution, the modal value is 0.40, coincident exactly with the literature one.
The application of wind profile methods without any near-neutral correction seems to produce an overestimation of the Von Karman values. The stratified correction is able to reduce the original values of k towards more expected values.
In Figure 5 are shown the k_{uc} as function of the observed Z_0. As evident, it seems to exist a non linear relationship between k and Z_0.
By the Figure 6, the average k values can be connected with Z_0 by following power law:

$$k_{uc} = \alpha \cdot \ln(Z_0) + \beta \qquad (4)$$

With α= -0.0508 and β=0.2712. The correlation for equation (4) is high (R=0.97) using the bin analysis. The classic k value (k=0.4) can be valid only in the cases of high observed values of Z_0

($Z_0 \geq 0.07$m). In cases of low Z_0 values (Z0 ≈ 1cm) the k assume an average values 0.50.

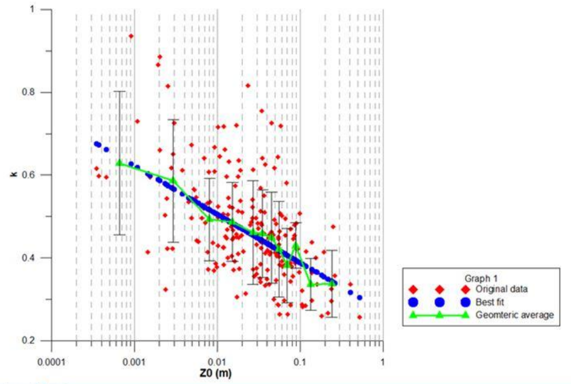

Figure 6: k_{uc} vs Z_0 as calculated at NREL site by regression. BIN analysis.

4. Conclusions

The application of wind profile methods seem very promising for the evaluation of Z0 and of the Von Karman constant.

As expected, the NREL field campaigns suggest that Z_0 is not constant, being linked to the seasons effect and to wind direction. The other important results concern the values of k, that increase with the decrease of Z_0. The observed roughness length is compatible with the site characteristic.

The choice of the non-dimensional equation (5) to calculate k and Z_0 from experimental profiles seems to be promising. The stratified correction as suggested by AND06 seems to be an efficient tool to adjust data in an open area. The observed Von Karman (0.47± 0.13) is greater than the conventional value. The distribution of k_{uc} is very similar to that observed in literature and the modal values is perfectly coincident with the classical values of 0.40.

These results seem to suggest how to address the study of the Von Karman values in an open area. Equation (4) has to be confirmed in more precise experiments, where it the influence of turbulence fluctuations must be minimizing, more data must be available, and the near-neutral correction can be applied.

Acknowledgments

I thank Andrew Clifton for the dataset concerning the NREL site.

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