Analysis of the terrain specifics and roughness factor on the wind shear over complex terrains

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Abstract. Wind power production depends mainly on the distribution of wind speed over the terrain. Wind behaviour is a function of terrain features, the roughness of the terrain - the complexity of the relief (the presence of mountain ranges, hills or valleys) and the presence of natural or artificial obstructions along the wind’s path (shrubs, trees, small and large buildings). In order to assess the factors influencing the distribution of the wind shear, long-term measurements with high meteorological masts installed on complex terrain were carried out. The masts are equipped with calibrated equipment to measure wind parameters. A numerical solution has been carried out with specialized software, which also supplied information about the velocity field on the site. A comparison was made between the results of the numerical solution and the experimental ones. An adjustment was proposed to change the initial conditions in order to refine the results of numerical solutions.

1. Introduction

Determining the wind shear for a complex terrain is a difficult task. It depends not only on the roughness factor of the relief, but also on its orography. Details such as "speed up" of winds over valleys, mountain peaks, natural strains between mountain ranges, etc., should be included here. Figure 1 schematically presents the types of boundary layers formed by wind flow over complex terrains.

![Figure 1](image)

**Figure 1.** Boundary layers and sublayers over complex terrains.

The presence of a complex surface leads to large horizontal differences in the structure of the boundary layer. The impact of different mountain structures on the behavior of the boundary layer is well illustrated in [1, 2].
The strength of winds along mountain ranges, apart from orography, is influenced by local features (such as temperature inversions, for example). As stated in [3], several hours are required to establish a stable wind profile in mountains and valleys. The windy part of the mountains is 3 hours after sunset and in the valleys 3 hours after sunrise [4]. In addition, wind direction in the valleys is influenced by wind warming and cooling, which is more efficient in the high and narrow sections compared to the lower parts [5].

Unlike flat terrain, wind behavior over complex terrain can vary, so a common analytical methodology cannot be proposed. However, analytical approximations are known in the literature, which can even predict such behavior. The non-linear nature, such as detaching the eddy from the main wind flow and vortexing, cannot be predicted with regular mathematical models, and nonlinear numerical relations have to be used [6]. A simplified model for a numerical solution is proposed in [7]. In conclusion, one of the most famous commercial products used to analyze wind flows over flat and low complex terrain uses linear analytical approximation [8].

2. Modeling of terrain orography

The exact interpretation of topography and orography is an essential prerequisite for correct determination of the wind shear.

The most primary and labor-intensive way of building a relief surface is by using topographic maps. For the territory of Bulgaria, such maps are available both in the web and in the specialized institutes. Depending on the desired accuracy of the relief surface, maps are available at a scale of 1: 5 000, 1:10 000, 1:25 000, 1:50 000. In order to determine the wind potential parameters for a given location, it is advisable to use the most detailed maps (1: 5 000), while for areas over 5 km from the site in question, less detailed maps can be used.

For the purpose of the present study, the chosen site is located in the municipality of Ruen, Central Eastern Bulgaria (Figure 2). The 3D map (Figure 2) is prepared using Surfer software. Due to the complex topography of the relief, measurements of the wind parameters are made in three points, using three meteorological masts - 30, 70 and 80 m.

The area is characterized by a complex terrain displacement of 100 to 600 m, which is a prerequisite for a significant change in the wind behavior above the ground.

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**Figure 2.** Topology of terrain and position of measuring masts.

In order to analyze the potential, a measurement of 30 m mast was initially carried out in the period December 2007 - September 2009. Measurements with a 70 m mast start in March, 2010 and end January, 2011. Measurements with a 80 m mast start in November, 2010 and end January, 2012.

Five different sensors have been used during the on-site measurements – anemometers, wind vanes, temperature, humidity and pressure sensors. Summarized technical information concerning the measuring equipment is presented in table 1. The equipment is calibrated in certified laboratory and it is installed on the mast according to the current standards for performing wind measurements.
Table 1. Technical specification of the measuring equipment.

| Sensor               | Model              | Range          | Accuracy                                      |
|----------------------|--------------------|----------------|-----------------------------------------------|
| Anemometer           | Thies Clima 4.3350 | 0-75 m/s       | <1% of means value (0.3÷50 m/s) or ±0.2 m/s   |
| Wind vane            | Thies Clima 4.3150 | 0-360°         | ±1°                                           |
| Humidity sensor      | Vaisala HMP 50     | 0-90%          | ±3%                                           |
| Temperature sensor   | Vaisala HMP 50     | -40 ÷ +60 °C   |                                               |
| Pressure sensor      | Setra 276          | 600 ÷ 1 100 hPa| ±0.25%                                        |

Obviously, for both tall masts, the measurement period overlaps, so an analysis of the wind shear can be made. In the 30 m mast the measurements started earlier, so it is necessary to make a correlation with the wind rose data. Due to the above, in Figure 3 is information about the wind rose for the three masts. It can be seen that the prevailing directions are two: north-northeast and south-southwest. The correlation between data is very good, which is an indicator of reliability in data analysis.

Figure 3. Wind rose for: a) 30 m mast, b) 70 m mast, c) 80 m mast.

Figure 4 presents information on the wind speed at height obtained using power law and logarithmic law wind shear profiles.

According to Figure 4 roughness factor of the terrain in front of the 70 m mast is 0.862 while for the 30 m mast is 0.485. The position of the 80 m mast also implies a lower roughness factor, namely 0.102. Given that 70 and 30 m masts are installed on the same plateau, the behaviour of wind speed at altitude is very close. The orography of the 80 m mast differs from that of the two masts, which is why the wind shear is also different (sharper), which implies the lower roughness factor. The power law and logarithmic profiles (Figure 4) are obtained on the basis of the following equations 1 and 2:

\[
U(z) = \begin{cases} 
\frac{U_0}{k} \ln \left( \frac{z}{z_0} \right), & \text{if } z > z_0 \\
0, & \text{if } z < z_0 
\end{cases}
\]

(1)

where: \( U(z) \) - wind speed at some height above ground \( z \), \( m/s \); \( z_0 \) - surface roughness, \( m \); \( k \) - von Karman’s constant (0.4); \( U_0 \) - friction velocity, \( m/s \).
\[ U(z) = u(z_1) \left( \frac{z}{z_1} \right)^\alpha \]  

where: \( U(z) \) - wind speed at some height above ground \( z \), m/s; \( z_1 \) - height of the known wind speed, m; \( \alpha \) - power law exponent.

The visualization of the wind profile in view of the orography of the terrain is presented in Figure 5. It shows the height profiles for the 70 and 80 m masts for the North direction, which coincides with both the prevailing wind directions and the highest sector frequency. The difference between the two wind profiles is clearly visible - at the 70 m mast, the terrain ahead of the mast in the direction of the wind is significantly more complex (with greater displacement in altitudes), which is also the reason for the greater velocity gradient. However, for the 80 m mast, due to the smaller difference in displacement, the wind profile is significantly "sharper". The main conclusion that can be drawn from the comparison between the two profiles is that at the same altitude on the hill, at a significantly more complex terrain before the hill, the wind speed can be increased by up to 10%, only due to the orographic features of the terrain.

**Figure.** 4 Wind profiles for all masts.
Figure 5. Wind profiles at a height of 70 and 80 m in prevailing north wind direction.

A cross-sectional view of the topography of the terrain in the vicinity of 70 and 80 m masts is shown in Figure 6.

Figure 6. Cross-sectional topography of the terrain in the vicinity of 70 and 80 m masts.

3. Numerical study

Various commercial software products are used for engineering calculations. Some of them are specialized, focusing on wind flow study (WAsP WindPro, WindSim), while others can be "tailored" to wind power (Fluent / Ansys). WAsP commercial software [9] is a linear model that combines two models: physical model (atmospheric stability, factor roughness, natural change in geography of relief, etc.) and statistical model (Weibull wind parameters distribution). The physical model is used to determine the wind profile.

With the development of computing techniques, in recent years there has been an increasing interest in modelling of flows in semi-confined spaces [10 - 15]. In [16] is presented modelling of flows over complex terrains using different turbulent models.

In order to study the influence of orography and the roughness factor of the relief on the wind velocity profile, the following approaches are used:

- **Case 1**: A 30 m mast is used as the basis for the numerical simulations, after which the results of the numerical solutions are compared with those obtained from the 70 m mast.
- **Case 2**: A 70 m mast is used as the basis for numerical simulations, then the results are compared with those obtained from a 30 m mast;

This way an analysis will be made regarding the interpretation of data obtained from measurements with the high masts and their interpretation near the site through numerical simulations.

Case 1. Using a low mast to predict the wind flow.

Figure 7 shows information about the input meteorological data used in the numerical simulations for a 30m mast and in Figure 8 for a 70 m mast. The numerical simulations are performed using the specialized software product WAsP.
Comparison of data shows that there is a good correlation (60%) between data in terms of directional distribution. In addition, the correlation between the frequency distribution in directions for 30 and 80 m masts is over 87%.

The results of the numerical solution using two masts as main ones are presented in Figure 9 and 10, there is a very good match between the numerical results of using the two masts.

An analysis of the results of the numerical simulations for case 1 is presented below. Table 2 is about the frequency distribution of wind parameters as well as average wind speed by sectors for a 30 m mast (on-site measurements) as well as the same wind characteristics obtained by numerical simulations near a 70m mast. The last column also shows the RIX index (Roughness index). This index shows the probability of
turbulence of the wind flow by sector, resp. accelerating or delaying the flow caused by the roughness factor of the relief.

The information presented in Table 3 is of great interest. A comparison was made between the results of a numerical solution obtained with the use of a 30 m mast and real ones, using a high mast. Correlation of wind speed data by direction is 54.5%, which is not very satisfactory.

Table 2. Main mast and numerical simulation results.

| Sector | Angle, ° | Frequency, % | Average speed, m/s | Frequency, % | Average speed, m/s | RIX, % |
|--------|----------|--------------|--------------------|--------------|--------------------|--------|
| 1      | 0        | 13.9         | 7.17               | 13.9         | 7.98               | 11.2   |
| 2      | 30       | 6.8          | 5.39               | 6.1          | 5.80               | 13.2   |
| 3      | 60       | 5.7          | 4.72               | 5.5          | 5.49               | 3.7    |
| 4      | 90       | 4.5          | 4.76               | 4.8          | 5.56               | 3.0    |
| 5      | 120      | 7.7          | 5.39               | 7.6          | 6.27               | 1.3    |
| 6      | 150      | 6.2          | 4.87               | 7.8          | 6.33               | 2.4    |
| 7      | 180      | 9.9          | 6.33               | 9.2          | 6.98               | 7.0    |
| 8      | 210      | 12.0         | 6.58               | 9.9          | 7.18               | 7.9    |
| 9      | 240      | 4.8          | 5.63               | 5.9          | 6.79               | 5.2    |
| 10     | 270      | 3.5          | 6.35               | 3.9          | 7.07               | 0.6    |
| 11     | 300      | 7.5          | 5.93               | 10.2         | 7.42               | 8.6    |
| 12     | 330      | 17.5         | 6.74               | 15.2         | 7.84               | 7.5    |
| ALL    |          | 6.10         | 6.98               | 6.76         |                   | 6.0    |

The difference between numerical and experimental data is clearly visible in figure 11. At 10 m above the ground, the difference in wind speeds obtained from the numerical and experimental data is 28.5%. At 20 m height, this difference drops to 16.8%, and at 30 m - to 11.1%, which is within the allowable range. The main conclusion that can be made here is that the software product does not take sufficient account of the orography of the terrain, the size of the boundary layer, which is why there is also an error in the wind shear. At a height of 100 m, however, the difference between numerical and experimental studies is 0.5%. Along with the above the software package has the potential for user intervention by setting the corresponding roughness factor of the relief. However, this factor may be established if there are at least two speed measurements within and outside the boundary layer in the vicinity of the site. Experience shows that the error in numerical research decreases in determining the roughness.
Case 2. Using a tall mast to predict the wind flow.

The main purpose of the study is based on data from the 70 m mast measurement to predict the wind parameters measured with a 30 m mast. Wind input parameters are similar to those shown in Figure 8.

Table 4 presents information on the wind parameters of 30 m mast - experimental and numerical surveys.

Table 4. Comparison between results from numerical and experimental solutions.

| Sector | Angle, ° | 70 m mast (numerical simulation) | 70 m mast (on site measurements) |
|--------|----------|---------------------------------|---------------------------------|
|        | Frequency, % | Average speed, m/s | Frequency, % | Average speed, m/s |
| 1      | 0         | 21.0 | 6.95 | 13.9 | 7.17 |
| 2      | 30        | 7.8  | 5.59 | 6.8  | 5.39 |
| 3      | 60        | 5.0  | 5.18 | 5.7  | 4.72 |
| 4      | 90        | 3.2  | 4.84 | 4.5  | 4.76 |
| 5      | 120       | 6.9  | 5.64 | 7.7  | 5.39 |
| 6      | 150       | 9.8  | 5.96 | 6.2  | 4.87 |
| 7      | 180       | 12.7 | 6.34 | 9.9  | 6.33 |
| 8      | 210       | 8.9  | 6.43 | 12.0 | 6.58 |
| 9      | 240       | 5.1  | 5.52 | 4.8  | 5.63 |
| 10     | 270       | 3.8  | 4.77 | 3.5  | 6.35 |
| 11     | 300       | 4.9  | 5.24 | 7.5  | 5.93 |
| 12     | 330       | 10.7 | 6.00 | 17.5 | 6.74 |

Correlation of wind speed data in directions is 61%, which is no better than when using a 30 m mast. Meanwhile, the difference in average speeds is 1.2%, in favour of the higher mast.

Figure 12 shows the wind shear in the vicinity of 30 m masts (numerical and experimental surveys). At 10 m above the ground, the difference in wind speeds obtained by the numerical and experimental research is 15.5% (the speed is higher in the numerical studies). At 20 m height, this difference decreases to 6.1%, and to 30 m - it is 0.3%, i.e. as the high of the taken measurements increases, the interpolation of data to the ground is more accurate. Velocity values at height greater than 30 m are extrapolated using the logarithmic velocity profile and numerical simulations. It is seen that at a height of 70 m the difference in speeds is 9.3%, the real one closer to the numerical research.
Figure 12. Wind shear (numerical results and experimental studies).

4. Conclusions
On site measurements carried out with meteorological high masts installed in the vicinity of the site provide reliable information on the velocity distribution. The specialized software used in the experiment does not take into account the peculiarity of the relief, so the results obtained may differ from the real ones.

The results from the performed study shows that at least two meteorological masts are needed in measurements on complex terrain and should be equipped with the respective for the site equipment.

It is important to determine the thickness of the boundary layer, because it has the most significant influence on the wind shear. For this type of complex terrains, the thickness of the boundary layer exceeds 20 m, indicating that measurements of the wind parameters at the specified height are required. Together with measurements at a height of 20 meters, measurements of at least two points are required.

The use of a second measuring mast serves as a reference source of information to analyze the results obtained from the numerical solution. As can be seen from the analysis made, due to the use of linear models in the numerical solution, the error between numerical and experimental results may exceed 10%. The specified error can be reduced by making adjustments in roughness factor of the terrain adopted in numerical model.

The terrain orography characteristics obtained can be used to configure the turbines (micro-sitting) in the park as well as to fine-tune energy production.

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