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SIMULATION OF THE EFFECT OF WINDBREAKS ON AIRFLOW WITH THE WASP ENGINEERING PROGRAM

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Abstract

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A number of technical complications go hand in hand with the reality of research on the effectiveness of windbreaks. Direct wind measuring in the windbreak area must be linked to specific meteorological situations that are not very frequent. A limiting factor for more frequent field measuring is also the development of surrounding areas of windbreaks. It is for these reasons that indirect methods are becoming more important. This work simulates the effect of several windbreaks in Southern Moravia (Czech Republic, Central Europe), on the modification of wind speed with the aid of the WAsP Engineering program. The windbreaks were defined in the program environment as a three-dimensional obstacles which some parameters – primarily porosity – amended as necessary during the calculation. The model results were compared with data on the wind speed from field measuring under the conditions of fresh flow perpendicular to the windbreak. The average absolute values of differences between the measured and model-calculated wind speed round about the windbreaks varied from 0.4 till 0.9 $m.s^{-1}$, the greatest differences were located very close to the windbreaks (typically 50 m on leeward side). Data about the windbreak's optical porosity based on digital photographs, obtained during performed measuring of wind speed, were also used.

Keywords: wind erosion, windbreak, wind modelling, WAsP Engineering, obstacle, optical porosity

INTRODUCTION

Wind erosion in the Czech Republic primarily threatens dry areas with sandy soils, but also has some significance on areas with clay or loamy soils (Podhrázská *et al*., 2013). One of the most commonly used biotechnical strategies is the planting of windbreaks. The meteorological dictionary (Sobíšek *et al*., 1993) defines a windbreak as a strip comprised of trees and shrubs, planted to protect an area of interest from the harmful effects of wind. They are primarily planted in drier climatic areas that are predominantly flat and treeless in order to reduce the speed of drying winds and limit the removal of soil particles or snow from fields. However, the effect of windbreaks on the surrounding area is complex and concerns other microclimate parameters as well.

Two main parameters are used to assess the effectiveness of windbreaks: the height of the windbreak and its porosity (permeability), which is usually specified as either aerodynamic or optical. Aerodynamic porosity can be defined by various methods, most often as the ratio between the amount of air that passes through the windbreak and the amount that is dispersed above the windbreak (Středová *et al*., 2012). Guan *et al*. (2003) define the aerodynamic porosity as the ratio between the average wind speed measured on the leeward side of the windbreak and the average speed in the open area. Optical porosity is defined as the ratio between the spaces in the windbreak to its total area through the aid of a digitalized photograph of the windbreak. The effectiveness of a windbreak further depends on the speed and direction of flow, the stability conditions in the ground layer of the atmosphere and details of the shape of the windbreak.

WAsP Engineering (WEng) is a computer program with the primary purpose of estimating the effect of certain parameters of wind (load cost by wind) on wind turbines and various objects in a moderately complex terrain. WEng is an independent accessory of the basic model WAsP – the Wind Atlas Analysis and Application Program (Mortensen *et al*., 1993), which is the primary tool for the estimation of wind power potential.

The WEng program concentrates mainly on the following wind parameters: extreme values of average wind speed, wind shears, and vertical wind and turbulence profiles. The program implicates the effects caused by moderately complex terrain (slopes to approx. 20°, i.e. except for rugged mountain locations) and surface roughness. It also partly takes into account obstacles – with the exception of the turbulence analysis. Obstacles are generally understood to be three-dimensional objects such as buildings, trees, etc. situated relatively close to the area of interest (to the order of 10^1 to 10^2 m) which, thus, might distort the wind speed values. Like WAsP, it assumes stability conditions of near-neutral during use. However, it is different in a number of technical aspects and approaches. It is more realistic – and also more sensitive to the detailed terrain description – in the layer closest to the earth's surface. Unlike WAsP, it cannot perform extrapolations from the entire statistic file of input data regarding the speed and direction of the wind, but only from one entered wind vector value that can be either a value measured at the meteorological station on a specific day and hour, a value of geostrophic wind, or a value of modified geostrophic wind (Mann *et al*., 2002).

The obstacle model of the WEng program is, much like the basic WAsP product, based on correlations obtained by modeling and experiments in the wind tunnel, published by Perera (1981). In the WEng, as well as WAsP program, the obstacle is clearly defined by the following parameters: the angle between north and the first closest corner of the obstacle (°), the angle between north and the second closest corner of the obstacle (°), the distance of the first closest corner of the obstacle (m), the distance of the second closest corner of the obstacle (m), the height of the obstacle (m), the depth of the obstacle (m), the porosity (permeability against flow).

The angles are measured from the north in the direction of azimuth. The porosity in WAsP is defined as the ratio of the area of the windbreaks "pores" to its total area and is entered as a decimal number between zero and one. For an object that is entirely wind permeable, porosity equals one. For an object entirely wind non-permeable (a wall, a building), porosity is zero. The porosity of trees may vary depending on the species, season, foliage, etc. (Dellwik *et al*., 2005).

The goal of this work was to verify the possibilities of the WEng model for simulation of the effect of windbreaks on the speed of wind in their surrounding area. A windbreak was defined in the model as a three-dimensional obstacle with certain porosity; the porosity is obtained by local investigation, and the resulting speed modification for selected wind episodes was compared with field measurements taken.

MATERIAL AND METHODS

Since 2005, in frame of the activities of the Czech Hydrometeorological Institute (CHMI), approximately 15 field measurements of the wind speed by windbreaks, including the determination of optical porosity, were conducted in Southern Moravia. This data served as a comparative set for the model calculations presented here.

Windbreaks Description

Windbreaks in the areas of interest of the municipalities of Micmanice (Znojmo district) and Suchá Loz (Uherské Hradiště district) were selected to measure the horizontal profile of the wind speed.

The windbreak in Suchá Loz area is oriented east–west; it is at ground level 4 m wide and approximately 22 m high. It consists of two levels, with the upper level being formed by two rows (in four meters distance) of adult Canadian poplar trees (*Populus × canadensis*). For the most part, their crowns are connected. There are juvenile summer oak trees (*Quercus robur*) and little-leaf linden (*Tilia cordata*) with disseminated European ash trees (*Fraxinus excelsior*) in the lower level.

Micmanice municipality windbreak is oriented southwest-northeast; it is at ground level 7 m wide and approximately 14 m high. It consists of well-engaged woody vegetation of various ages. The main level consists of ash-leaf maple trees (*Acer negundo*), sycamore maples (*Acer pseudoplatanus*), Norway maples (*Acer platanoides*) and European ash trees (*Fraxinus excelsior*). The windbreaks are described in detail by Středa *et al*. (2008).

Measurement of Wind Speed

The wind speed measurements were carried out with the aid of schemes with type W1 and W2 mobile cup anemometers from the C.T.M. Praha Company. Range of sensors W1 a W2 is 0.7–30 $m.s^{-1}$. The devices were calibrated by Metrological and calibration laboratory of the Czech Hydrometeorological Institute. The W2 sensors are further equipped with a wind direction indicator. The data were stored into the data-logger. The effect of the windbreak on the wind horizontal profile was usually determined in distances of 50, 100, 150 and 200 m in front (windward side; WW), as well as behind (leeward side, LW) the windbreak, 2 m above the surface. At the same time, there was always one control sensor measuring on the windward side at the distance of 150 m. Optimal meteorological conditions – fresh flow 10 m above the terrain with an average minimum speed of 4 to 8 $m.s^{-1}$ in a direction roughly perpendicular to the windbreak were preferred. Occasionally was as a compromise performed field measuring even in cases when the flow was slightly weaker (average speed 3 to 6 m.s^{-1}).

Optical Porosity Evaluation

While measuring the wind speed, a digital camera was used to take a series of images of the windbreak from the same spot. Digital camera Olympus Camedia C-55 ZOOM was used for snapping. Optical porosity was evaluated for same transect where the measurement of wind speed was carried out. To evaluate the optical porosity was used methodology of Litschmann *et al.* (2007). In order to determine the optical porosity, a processing method was used in which the selected images were broken down into individual squares (grids), with the number of squares determined by the size of the windbreak in the relevant image. In most cases, 10 to 14 columns and 5 to 8 rows were assessed. The optical porosity was determined for each of these squares.

Simulation of Obstacle Element

The windbreak was defined in the WEng environment as a three-dimensional obstacle which some parameters – primarily porosity – amended as necessary during the calculation. The attenuation of the speed can be approximately quantified in a certain distance from the obstacle; in close vicinity, the wind speed is already strongly affected by the obstacle's geometry; therefore, it is impossible to expect realistic model results (Mortensen *et al.*, 1993). Not every terrain obstacle can be defined in all its details and, therefore, must be schematized and simplified in a certain way.

A profile (transect) corresponding with the position of the measured profile was defined, although the model transect was, in some cases, longer and segmented in more detail. Any and all calculations in the transect were set at 2 m above the terrain, in order to be able to compare them with the ambulant measurements. The model horizontal resolution for calculations was set at 15 to 20 m. The underlying orography was created with the aid of a global digital model of the terrain (digital elevation model, DEM), obtained by the radar interferometry method during the mission of the space shuttle Endeavour in February 2000 (Shuttle Radar Topography Mission, SRTM). Individual source data files for the area of Central Europe, known as type SRTM3, cover an area defined by one degree of latitude and one degree of longitude with a horizontal resolution 3", i.e. about 90 meters. A more detailed description of the SRTM mission is presented by e.g. Farr and Kobrick (2000). The SRTM hypsography, as the control measurement, was compared by superimposing with other suitable map documentation, including maps from the portal of the public administration of the Czech Republic and, for the given purpose, it is possible to state these products has good conformity. Because the WEng model requires a more detailed description of the area immediately adjacent to the calculation locations (Mortensen and Petersen, 1998), the hypsography was locally supplemented, according to needs, from detailed maps with contour lines in a step smaller than 10 meters from the built-in map editor, WAsP MapEditor. This instrument was also used for detailed digitalization of the roughness parameter z_0, according to a methodology used during the creation of the European wind atlas (Troen and Petersen, 1989). The values of roughness were in case of need completed according to Google Earth and Czech National Geoportal.

Micmanice (May 2006), planted crop was maize (8 cm height); Suchá Loz (November 2008) the surface was ploughed.

RESULTS AND DISCUSSION

Detailed results for typical meteorological situations in two locations, in which the measuring around the windbreaks was performed during almost ideal wind conditions are presented: by Micmanice on May 4th, 2006 (a case with fairly little windbreak porosity) and by Suchá Loz on November 11th, 2008 (higher porosity).

On May 4th, 2006, the Czech Republic was experiencing a strong south-east to south flow around an anticyclone centered over the Baltic in front of an undulating cold front that was advancing slowly eastward across Western Europe. At the reference CHMI station in Kuchařovice, located at a distance of about 14 km from the Micmanice windbreak, the average wind speed at 10 m above the terrain during the field measurement (at approximately 9–14 h CET) was between 7 to 9 m.s^{-1}. The vector of the wind input value entered into the program was 140°/8 m.s^{-1}. The obstacles at the Kuchařovice station were considered, but their effect on model calculations for this station is negligible. In various parts of the windbreak, optical porosity reached values from 14 to 35% (Tab. I); the average for the entire windbreak is 25%, for the profile analyzed by us, approximately 30%.

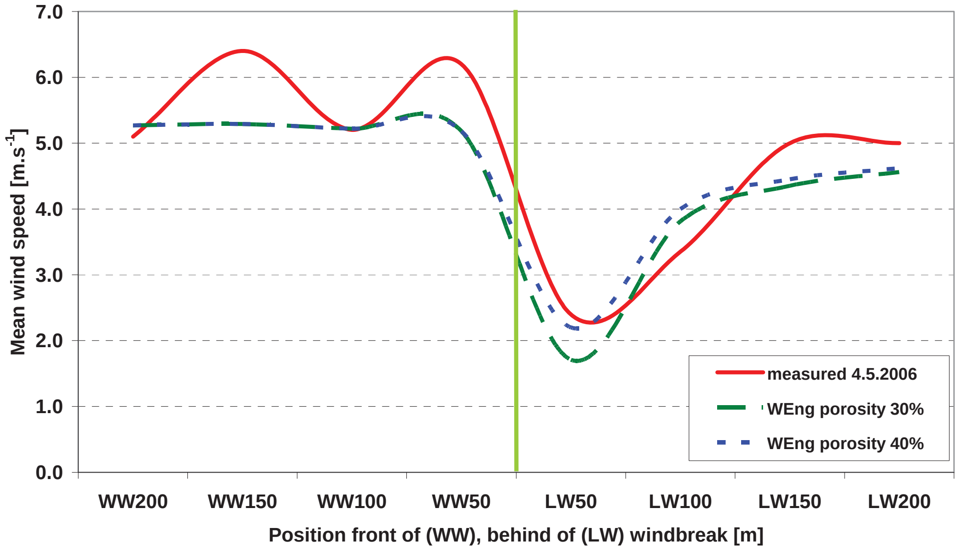
Fig. 1 shows a comparison of the measuring and model calculation results. The difference between the measured wind speed values and those calculated by the model for a windbreak with a porosity of 30% are positive, as well as negative; nonetheless, the positive outweigh the negative, i.e. the measured data are rather higher than assumed by the model. Maximum differences are in absolute value around 1 m.s^{-1} (in distance 50 and 150 m on the windward side); the differences are lower when leeward – up to 0.7 m.s^{-1}. Optimum results were achieved when the model porosity of the obstacle was increased to 35 or 40%, which is, of course, a higher value than one found during the field determination of the optical porosity of the windbreak.

At relatively low porosity, the attenuation of wind speed is generally quite apparent, especially

I: *The windbreak's optical porosity values (%), Micmanice, May 4th, 2006*

Row No.	Column No.														Mean (%)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
6	97	58	20	25	47	66	35	34	27	38	41	55	65	72	**49**
5	34	3	14	11	9	7	16	34	39	27	26	28	54	19	**23**
4	19	5	14	23	12	9	24	23	36	26	30	48	42	33	**25**
3	9	2	20	25	15	28	15	19	29	15	10	12	21	11	**17**
2	16	10	19	20	10	17	6	12	19	21	30	21	16	5	**16**
1	3	4	3	18	33	26	20	22	22	15	33	29	12	22	**19**
mean 1–6 (%)	30	14	15	20	21	26	19	24	29	24	28	32	35	27	**25**
mean 1–5 (%)	16	5	14	19	16	17	16	22	29	21	26	28	29	18	**20**

Note: Rows: horizontal heterogeneity of optical windbreak porosity, columns: vertical heterogeneity of optical windbreak porosity



1: *Field measured data and modeled wind speed values (m.s⁻¹) at 2 m a.g.l., ranging from 200 m in front of the windbreak (WW200) to 200 m on the leeward side (LW200), Micmanice May 4th, 2006*

in the area 50 m on the leeward; the measured and model-calculated average speed fluctuates around 2 m.s^{-1} here: therefore, it is only around 35% of the average speed in the area 150 m in front of the windbreak. In the area 100 m on leeward side the windbreak, an average speed of 3.4 m.s^{-1} was measured, which is already 53% of the unaffected value in front of the windbreak. In this zone, the model assumes an even greater increase of speed, already approximately 4 m.s^{-1} (75% of model speed in front of the windbreak). The same average speed of 5 m.s^{-1} was measured (78% unaffected) further on leeward the windbreak (150 and 200 m); here, the model allows for a speed of only around 4.6 m.s^{-1} (87% of the model speed in front of the windbreak).

An episode from November 11th, 2008, at the windbreak by Suchá Loz was selected as the second typical case, when the flow in the relevant area was also fresh, south-east to south, front a cold front advancing from the west. At the reference CHMI station in Strání, located at a distance of about 6.5 km, the average wind speed at the time of the field measurements (12–15 h CET) at 10 m above the terrain ranged between 5 and 9 m.s^{-1}. The vector of the wind input value entered into the program is 140°/ 7 m.s^{-1}. The effect of obstacles with a fairly major impact on the model calculations in Strání was considered.

The numerical values of the optical porosity (%) of the windbreak in Suchá Loz, according to the situation on November 11th, 2008 are stated in Tab. II. Optical porosity for Suchá Loz windbreak (November 11th, 2008) was plotted on Fig. 2 to graphics demonstration of the method. The overall medium optical porosity of the windbreak is 50%, respectively 43% (without the highest layer, row no. 8). As in the previous case, the optical porosity of the windbreak is not constant over its entire horizontal face. The average optical porosity changes in individual areas (columns 1 to 11) from 40 to 60%; about 50% for the profile analyzed.

The difference between the measured and model-calculated wind speed values for a windbreak with 50% porosity are also positive, as well as negative

II: *The windbreak's optical porosity values (%), Suchá Loz, November 11th, 2008*

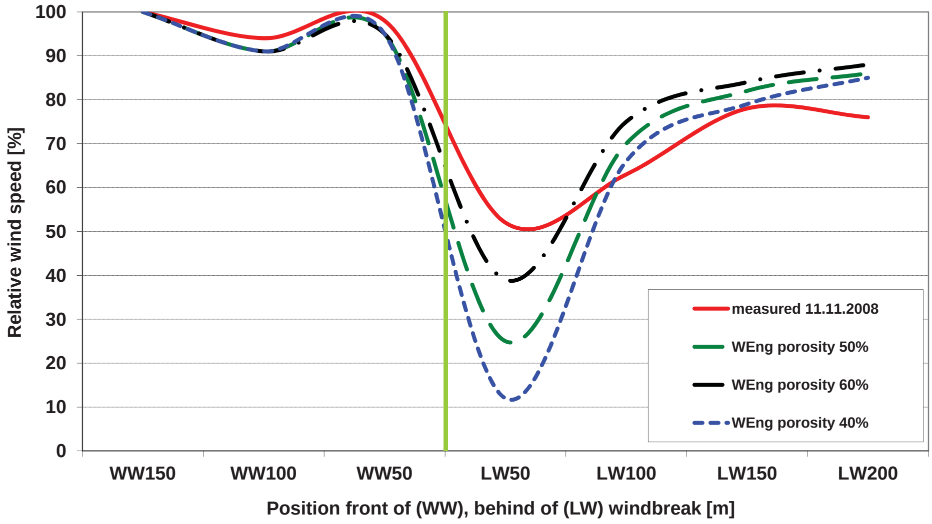
Row No.	Column No.											Mean (%)
	1	2	3	4	5	6	7	8	9	10	11	
8	94	96	95	84	96	93	92	96	97	96	100	94
7	50	51	44	48	81	70	68	83	69	75	92	66
6	46	35	40	51	75	60	65	75	50	38	34	52
5	46	42	50	38	62	52	58	58	47	35	47	49
4	56	32	39	33	42	38	46	56	49	42	42	43
3	48	26	35	18	40	26	30	56	38	45	23	35
2	35	35	42	24	29	34	26	34	29	52	34	34
1	26	23	19	23	20	25	16	20	31	38	30	25
mean 1–8 (%)	50	42	46	40	56	50	50	60	51	53	50	50
mean 1–7 (%)	44	35	38	34	50	44	44	55	45	46	43	43

Note: Rows: horizontal heterogeneity of optical windbreak porosity, columns: vertical heterogeneity of optical windbreak porosity

2: *Suchá Loz windbreak, November 11th, 2008 – optical porosity (%)*

(Fig. 3). On the windward side of the windbreak and in the 100 m zone and further on the leeward side, the differences are minimal. In an absolute value up to approximately 0.3 m.s^{-1} (to 5%). The biggest recorded difference between the measurements and the calculation is 50 m on the leeward side, where field measurements are higher than those modeled by 1.5 m.s^{-1} at a porosity of 50% and correspond more with a porosity of 70% in this area.

Due to the time of the year and, therefore, the windbreak already having relatively large wind porosity, the overall wind speed attenuation is less than in the case described above. In the area 50 m on the leeward, an average speed of 2.8 m.s^{-1} was measured, which is about 52% of the average speed in the area 150 m in front of the windbreak. The wind speed predicted by the model, for a porosity of 50% is only 1.3 m.s^{-1} (25% of unaffected model speed 150 m windward). In the area 100 m to 200 m on leeward side, where the measured average speed ranged between 3 to 4 m.s^{-1} (63 to 78% of the unaffected value measured in front of the windbreak), the model assumes speeds higher by approximately



3: *Field measured and modeled values of mean wind speed at 2 m a.g.l., ranging from 150 m in front of the windbreak (WW150 = 100%) to 200 m on the leeward side (LW200), Suchá Loz, November 11th 2008*

III: *Medium and ultimate absolute difference values (m.s^{-1}) between measured and WEng model-calculated wind speeds in the surrounding windbreak areas, during fresh flow (average speed 3 to 8 m.s^{-1}) perpendicular to the windbreak, ranging from 150 m in front of the windbreak (WW150) to 200 m on the leeward (LW200)*

Side and distance	Difference (m.s^{-1})		
	minimum	average	maximum
WW150	0.0	0.4	1.2
LW50	0.2	0.9	1.7
LW100	0.2	0.6	0.9
LW150	0.2	0.5	0.8
LW200	0.1	0.4	1.0

0.5 m.s^{-1} (70 to 86% of the model speed in front of the windbreak). Ian *et al.* (2009) determined for practical uses that porosity did determine wind speed and the degree of shelter is roughly similar to windbreak density i.e. a windbreak with 30% porosity would reduce wind speed to 70% of the open-field speed at the most sheltered location. Exact formula of wind speed reduction in dependence on distance from the windbreak and its optical porosity states Středová *et al.* (2012).

If, in addition to the two above described cases, we also assess other usable field measurements (a total of approximately 15 cases), with the average wind speed during measuring at 3 m.s^{-1} or more, and with the direction of wind approximately perpendicular to the windbreak, then the results do not considerably differ from the values obtained in the above analyzed cases (Tab. III).

CONCLUSION

The WEng program was used to model the effect of windbreaks on the flow speed and to compare with field measured data in selected locations in the Czech Republic. Data about optical porosity which were determined based on digital photographs of windbreaks during performed measuring were also used at the same time.

In all the positions on windward and leeward side of windbreak, the differences between the measured and the model data in various episodes were positive, as well as negative. Thus, no systematic deviation was recorded in either the positive or negative sense for the entire file of comparison data. As expected, wind speed attenuation is greatest in the area closest on the leeward the windbreak (50 m leeward); this is also where the greatest differences exist between the model calculation and the measured data. The average absolute value of differences is about 0.9 m.s^{-1}; in an extreme case, it was between 1 and 2 m.s^{-1}. The option with a higher measured wind speed is slightly more prevalent than the model states. The relative attenuation of wind speed in comparison with unaffected data ranges in this area depends on the height and porosity of the windbreak, usually from 25 to 50%. In distances of 100 m on the leeward, the average difference decreases to approximately 0.6 m.s^{-1}; conversely, this area has slightly more numerous cases in which the model speed is higher in comparison to the field measured speed. The relative attenuation of the wind speed in comparison with unaffected data to the side of the windbreak reaches 50 to 75%. In greater distances on leeward (150 to 200 m), the differences between the field measuring and the model outputs are lowest (0.4 to 0.5 $m.s^{-1}$, on average), the values of the relative attenuation of flow speed usually falls in interval of 80 to 90%. In all cases, the stated results are related to the conditions of fresh flow with an average speed of 3 to 8 $m.s^{-1}$ and with the porosity of the obstacle corresponding with the optical porosity value evaluated for the relevant episode.

There can be more than one cause for the differences between the measured data and the model-calculated data. There are not many suitable meteorological situations; other reasons are primarily technical – during the vegetation season it is often impossible to make measurements, due to growing crops, even during very good meteorological conditions. Therefore, it is necessary to settle for performing measurements in very few cases, which usually take 4 to 6 hours.

Another potential source of differences is the heterogeneity of windbreaks: their actual porosity at any given moment is more or less variable, in the horizontal as well as vertical planes; in this respect, however, the model must greatly simplify the obstacle, because there is no possibility of more detailed local specifications of obstacle porosity in the model. In suitable cases, the windbreak was simulated, at least as a compound obstacle (two obstacles with different heights and porosities placed one behind the other) but the results were not considerably better. Other factors that contribute to the conception of deviations between the reality and the model are the inaccuracies of the digital description of the terrain, as well as the imperfection of the model itself; mainly when it comes to the calculation model of the effect of the obstacle on the speed of flow. Despite regularly performed calibration and control, it is impossible to eliminate even minor errors in the terrain measuring process, where the demand for the precision and maintenance of devices is higher than during the measuring process in the standard meteorological station.

SUMMARY

The goal of this work was to verify the possibilities of the WEng model for simulation of the effect of windbreaks on the speed of wind in their surrounding area. A windbreak was defined in the model as a three-dimensional obstacle with certain porosity; the porosity is obtained by local investigation, and the resulting speed modification for selected wind episodes was compared with field measurements taken.

It is safe to say that the WEng model, although primarily designed for other purposes, can be used with an acceptable degree of precision in typical cases with a significant flow, even for the estimation of the effect of windbreaks on the wind speed in the surrounding area. The average absolute values of differences between the measured and model-calculated wind speed round about the windbreaks varied from 0.4 till 0.9 $m.s^{-1}$. The only results that require greater caution for evaluation are those very close to the windbreak (up to approx. 50 m). A considerable advantage of the WEng model application is the possibility of also simulating calculations in cases where the terrain in the windbreak area would otherwise be inaccessible.

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