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Title
HANDBOOK ON OBSTACLE EFFECTS RELATED TO
WIND TURBINE SITING

ANNEX: VALIDATION OF THE WAKE PREDICTION
METHOD

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1. INTRODUCTION

In this annex validation experiments carried out to establish the usefulness of the wake prediction method for actual obstacle situations at a wind turbine site, are reported.

The wake prediction method is based on experimental data regarding simple obstacle shapes in atmospheric wind, which have the following shortcomings when applied to wind power estimates:

- For houses, there is only a very limited amount of data, the most extensive and well-documented being the work of Woo [1]. Besides, the basic experiments have been carried out almost exclusively in wind tunnels.
- Much experimental work has been performed on trees (hedges) because of the economical importance of wind shelter for crops, prevention of soil erosion etc. Besides, wind screens natural or artificial are also widely used for protection of highways or harbours from strong winds. Experiments on natural wind fences have been performed mostly on full scale, because of the difficulty to simulate trees and hedges properly on model scale.

A limitation with respect to wind power application however, is that wind screen research concentrates on the lower levels close to the ground.

In fact wind shelter is often presented by a wind shelter factor R , which is the ratio between the velocity at 1.4 m height (crops) or at 1 m (traffic) and the undisturbed wind velocity at the same height.

However for wind turbines the wake flow behaviour at much larger heights is important.

- Results of wake measurements on dikes are very scarce. Experiments reported, almost exclusively deal with the speed-up phenomenon.

Also the validity of schematizations used in the method need to be determined.

The reported studies of DMI [2], CSTB [3] and TNO [4] are used for validation of the handbook method for houses, trees and complex obstacle situations, respectively.

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2. DMI – HOUSES

2.1 Abstract

This chapter presents the results of full scale measurements of the wake behind a building.

The full-scale measurements have been carried out on a farm situated Sjarllands Odde, Denmark in the period from October 1987 to September 1988.

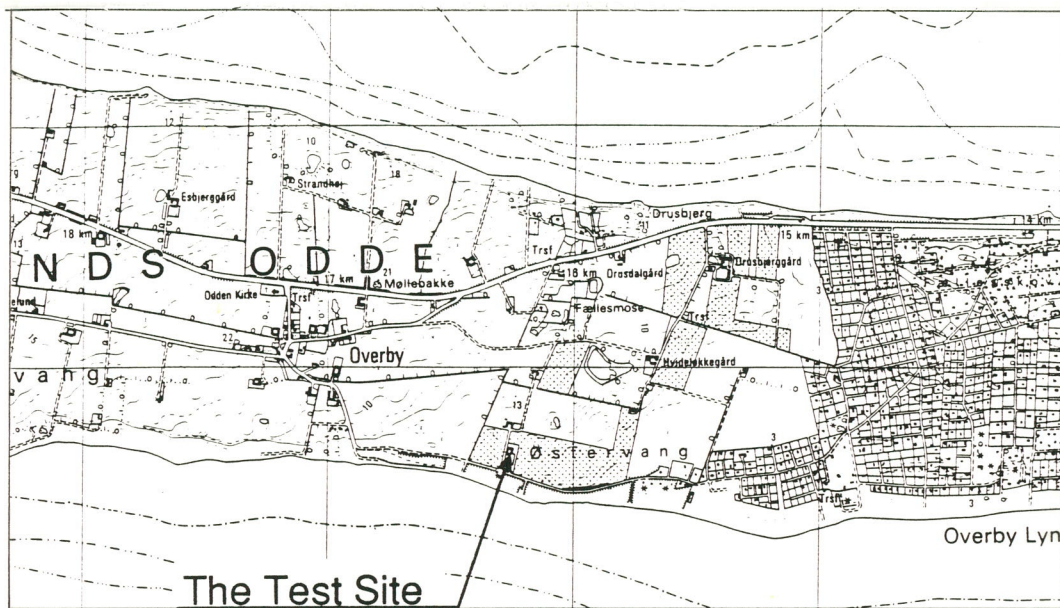
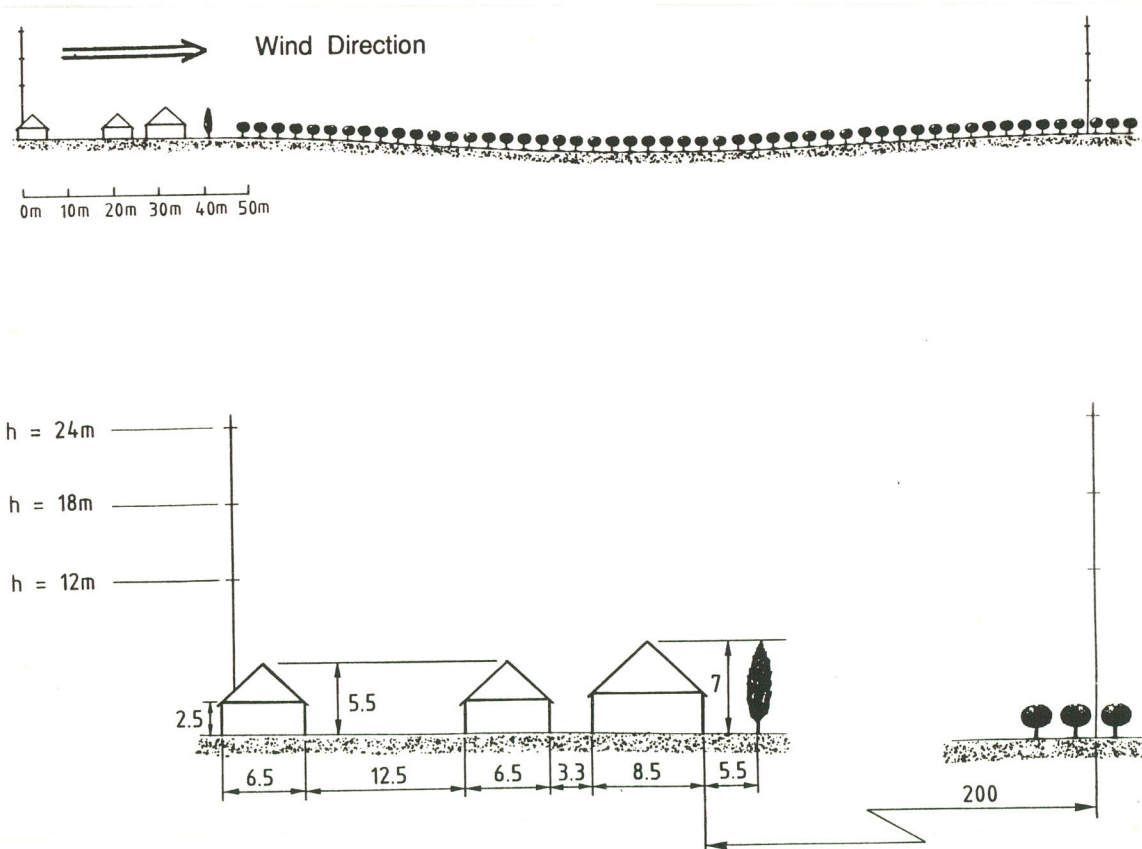
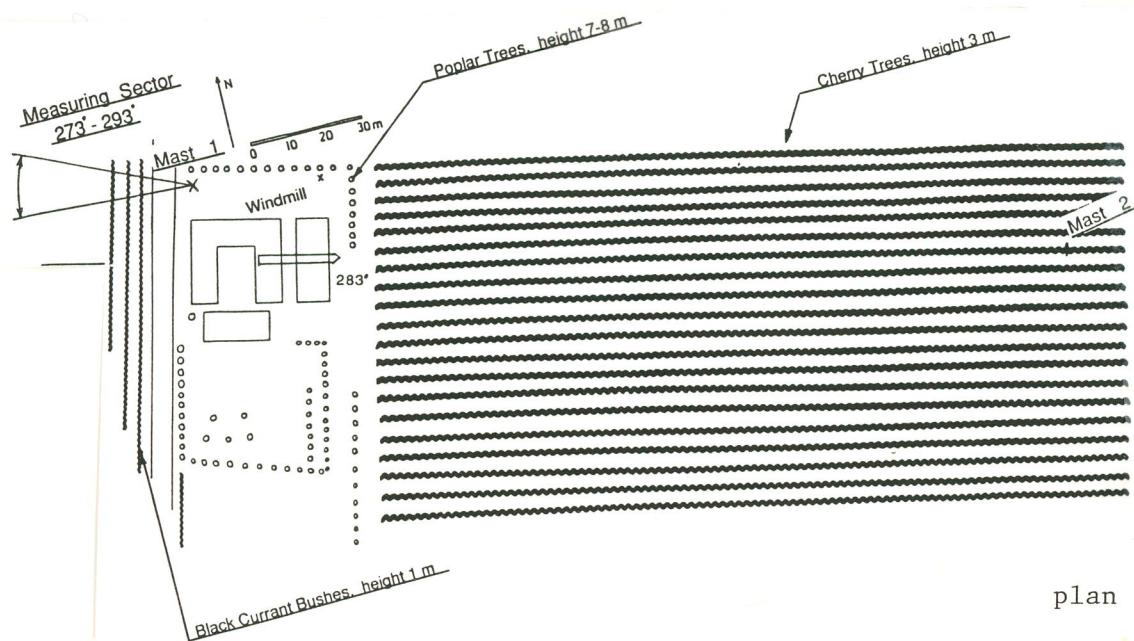


Figure 1 The wind turbine test site in Denmark

The wind speed, turbulence and wind direction have been measured at three heights 24 m, 18 m and 12 m on two positions, one upwind in front of the farm buildings and one 200 m downwind behind the farm buildings.

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Enlarged scale

Figure 2 Details of terrain occupation at the test site

Sideview

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2.2 Test site

The test site is situated on the peninsula Sjaellands Odde in the eastern part of Denmark. The exact location is shown in the figures 1 and 2.

2.3 Measurements

The wind speed and wind directions have been measured simultaneously on the two masts. Mast 1 is the upwind mast placed at the north-west corner of the farm. Mast 1 measures the undisturbed wind. Mast 2 is down wind and placed at 200 m distance from the farm buildings. The wind direction perpendicular to the farm buildings is 283 deg. and corresponds to the sideview on fig. 2. Wind data are only accepted in a sector 283 deg. $\pm$ 10 e.g. 273 deg. - 293 deg. The measurements have been performed in three heights: 24 m, 18 m and 12 m. Zero-level is defined as the ground-level of the courtyard in front of the farm, where mast 1 is placed.

The following measurements have been made at the three heights:

wind speed,M1 : 10 minutes mean wind speed at mast 1, sampled with a frequency of 1 Hz.

wind direction,M1: 10 minutes mean wind direction at mast 1 sampled with a frequency of 0.5 hz. Accept range: 273-293 deg.

standard deviation V1: statistical standard deviation of wind speed at mast 1 in 10 minutes periodes.

turbulence,M1 : turbulence at mast 1 defined as standard deviation/mean wind speed. Standard deviation and wind speed are 10 minutes values.

Wind speed,M2 : 10 minutes mean wind speed at mast 2, sampled with a frequency of 1 Hz.

Wind direction,M2: 10 minutes mean wind direction at mast 2, sampled with a frequency of 0.5 Hz.

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Standard deviation V2: statistical standard deviation of wind speed at mast 2 in a 10 minutes periodes.

Turbulence, M2 : turbulence at mast 2 defined as standard deviation/mean wind speed. Standard deviation and wind speed are 10 minutes values.

$V2/V1 = C_B$: Ratio between wind speeds at mast 1 and mast 2; values correspond to 10 minutes mean values.

2.4 Analysis of measurements

Time series of the measured values (10 min. values) have been plotted, one plot "for each" week of measurement.

The data from each week have been sorted in order to eliminate measurements outside the measuring range (273-293 deg.) and measurements from the same height have been summarized in order to be presented together in the plots.

The turbulence and $V2/V1$ (wind speed ratio C_B) have been analysed by the Method of Bins (MOB), with the reference wind speed at mast 1.

Methods of Bins sorts the data in wind speed intervals: 0-1 m/s, 1-2 m/s and calculates the average value of the measured values in each interval. The results from Method of Bins have been plotted.

2.5 Results

In the following figures the wind speed reduction is shown at the three heights, which is considered the primary result of the measurements. Besides the turbulence at the various heights is presented.

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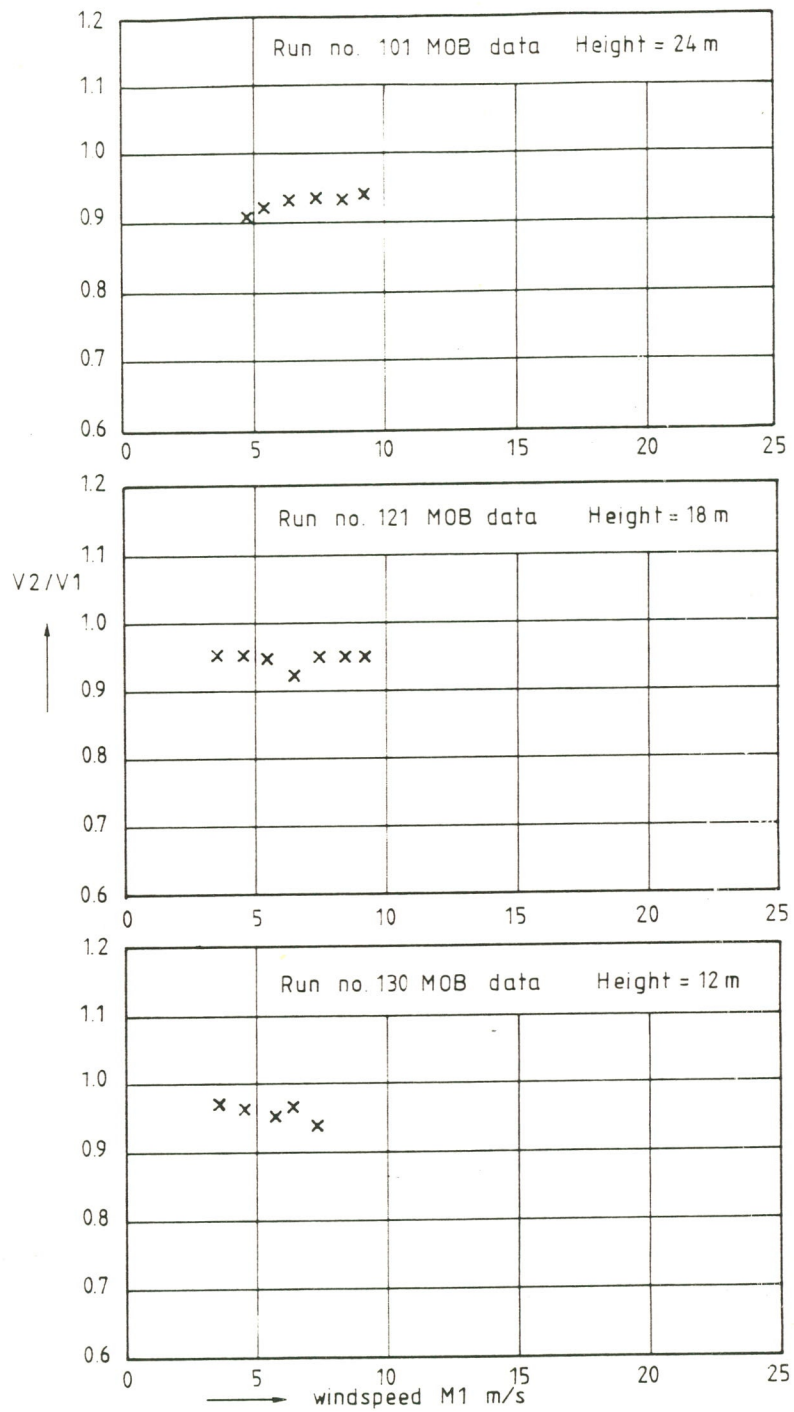


Fig. 3 Wind velocity in the far wake of the farm at $z = 12$ m, 18 m and 24 m.

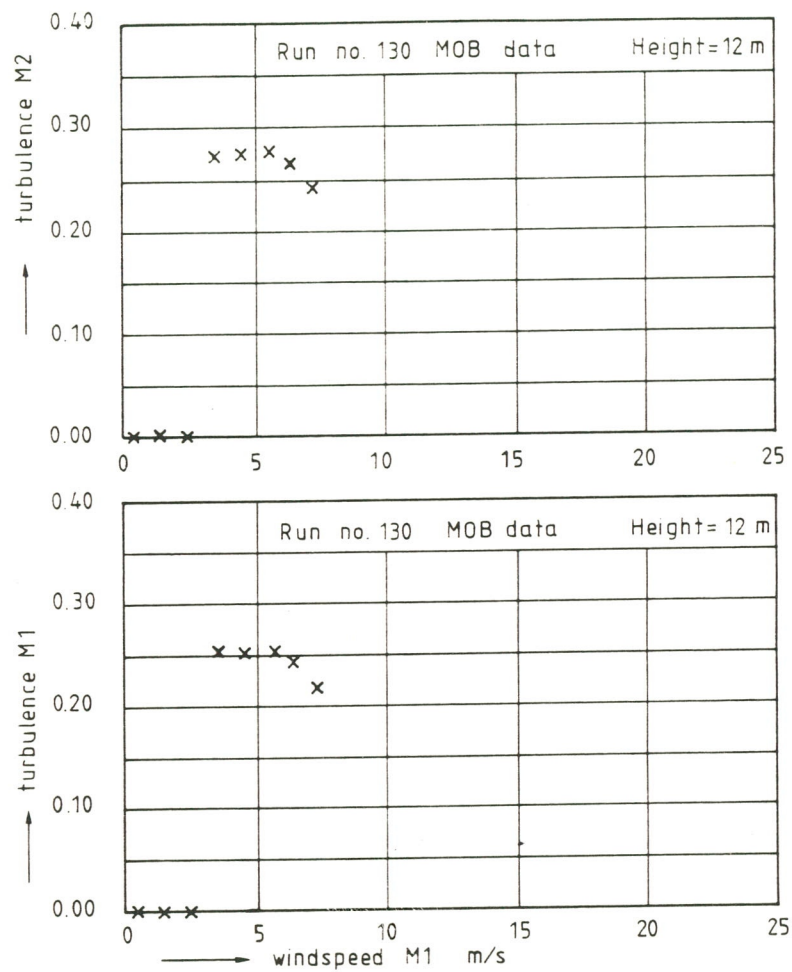


Fig. 4 Turbulence (M2) in the far wake of the farm at $z = 12$ m, compared to undisturbed flow (M1).

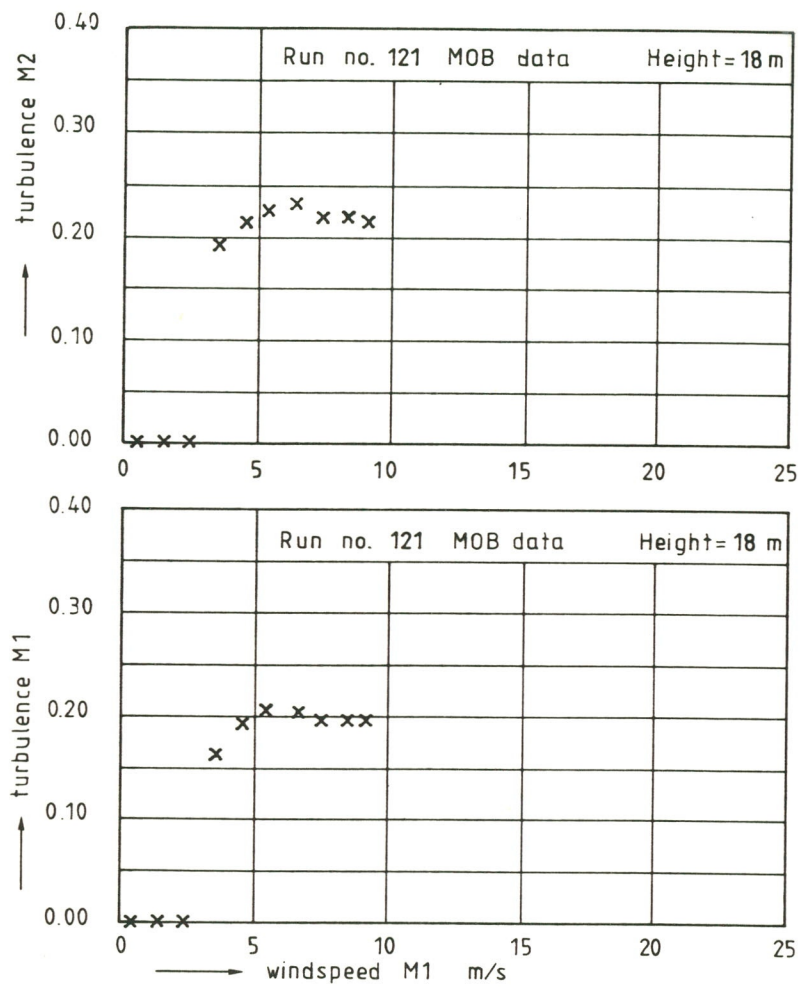


Fig. 5 Turbulence (M2) in the far wake of the farm at $z = 18$ m, compared to undisturbed flow (M1).

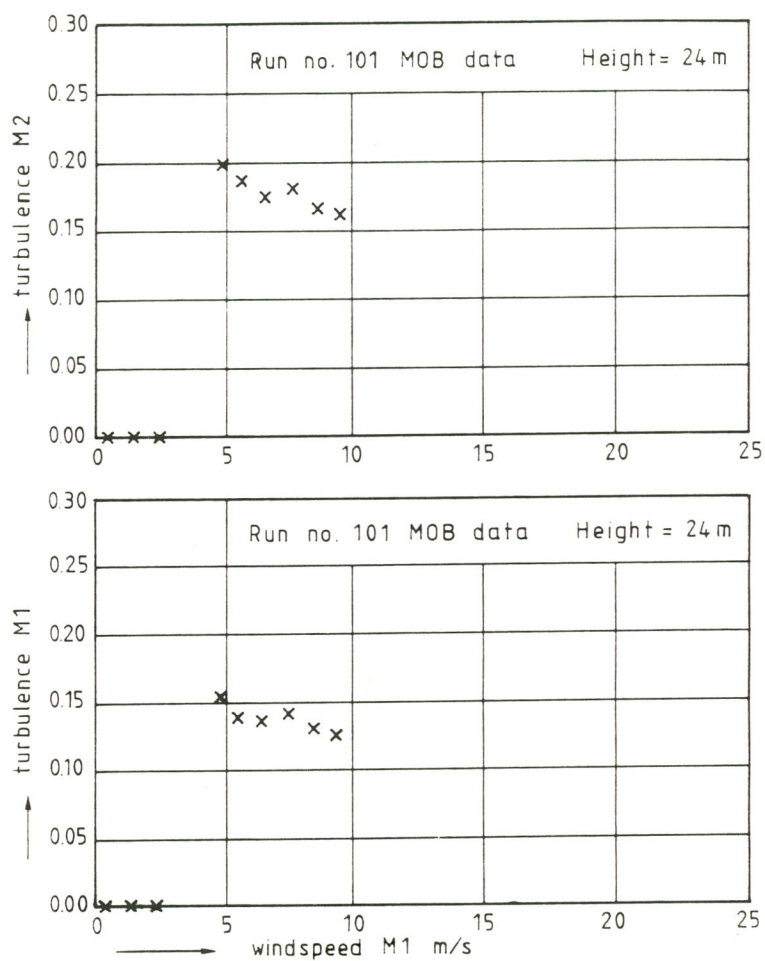


Fig. 6 Turbulence (M2) in the far wake of the farm at $z = 24$ m, compared to undisturbed flow (M1).

2.6 Discussion of results

In 2.5 it can be seen that the wind reduction factor does not change significantly at the different heights. This can be explained by the fact that the shape of the logarithmic wind profiles at the two measuring points are similar, but the buildings and the cherry trees have lifted the profile. The lifted wind profile will give a rather constant wind reduction factor.

A factor beyond control which may have influenced the results, is the fact that the black-currant bushes (height 1 m) in front of the farm buildings were gradually removed (a work period of 10 days) during the measurements at 18 m height. The results at 18 m height have been examined, for a possible effect but no significant changes have been found.

2.7 Comparison with handbook method

The obstacle situation is not a simple one and can probably best be described - for the wind direction sector involved - as an intermediate form between a dense 2-dimensional hedge and a 2-dimensional house.

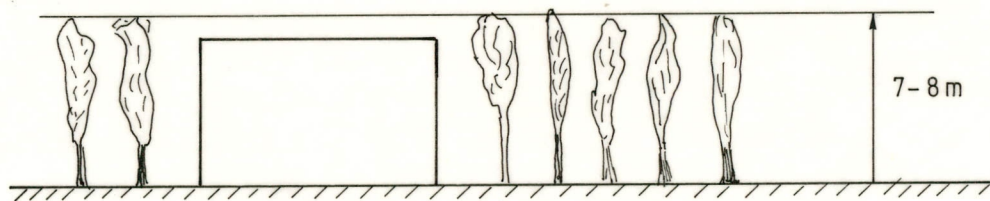


Figure 7 The complex obstacle situation at the DMI-site

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The C_B factors measured of 0.90-0.95 at $\frac{x}{h} = 35$ and $\frac{z}{h} = 1-4$ lie within the range given by the main graphs of the handbook. The smaller C_B value at greater height is remarkable.

A small increase of turbulence has been measured, which corresponds with the handbook. The results do not make a firm conclusion possible whether or not the handbook graphs should be adjusted. This is due to the complex nature of the obstacle and the limited amount of measuring stations used. The site available for this particular validation experiment turned out not to be characteristic for an isolated house-obstacle situation, but results are certainly not in conflict with handbook predictions.

3. CSTB-HEDGE

3.1 Description of the experiment

The hedge to be chosen for the validation experiment should have the following characteristics:

- straight line
- relatively constant height
- homogeneous porosity
- long enough
- normal to the prevailing wind
- flat homogeneous terrain.

The selected site corresponds to these requirements to a far extent. The hedge is a row of oaks, with a mean height of 8.5 m and a length of 110 m. The terrain is free of hedges or trees 350 m upwind and 500 m downwind of the hedge.

Figure 8 shows the topography of the area surrounding the test site, estimated z_0 -values. On the fields immediately upwind and downwind of the hedge, maize has been seeded just at the beginning of the measurements. Up to the 11th of June, the maize height increased to 30 cm, but this increase has not induced a strong modification of the value of the roughness parameter. Measurements have also been made in October when the height of maize was 2.5 m.

The porosity of the hedge has changed during the experiment. Table 1 gives characteristics of the foliage and estimated porosities. Pictures of the hedge are given in figure 8.

When the wind is normal to the hedge ($\beta = 210$ deg), all the measurements can be used. But the greatest deviation of the wind from the perpendicular that can be allowed is 16° for the third mast, 30° for the second mast and 50° for the first mast. Beyond these angles, the wind does not come from the hedge (see figure 10).

Only 10 minutes runs with an adequate level of stationarity have been selected. The prescribed conditions are that the variations of the mean

wind speed and mean wind direction at the reference mast location for successive runs are less than 10% and 15 degrees respectively.

3.2 The "undisturbed" flow

The vertical profile of mean windspeed

The undisturbed wind is measured on the reference mast at 4 heights $h/2$ to $5h/2$ where h is the height of the hedge ($h=8.5$ m)

The logarithmic law fits reasonably well to the data. Nevertheless, the values of z_0 deduced from the profiles are not in accordance with the type of terrain surrounding the site. The variation of wind with height is very low between 4.5 m and 20.8 m.

This profile shape can be explained by a roughness change at 300 m upwind of the reference mast (from $z_0=0.30$ m to $z_0=0.02$ m when the maize has not grown), which increases windspeed at low levels. Calculations carried out with a two-dimensional numerical model (Sacré, 1981) has confirmed this hypothesis. The same model has shown that the influence of this roughness change on the ratios between windspeeds on the masts downwind the hedge and on the reference mast is less than 3%. This effect of roughness change disappears when the maize is high.

The values of z_0 calculated from turbulence intensity I with the relation $z_0=z \exp (-1/I)$ are given in table 4, for different wind directions and heights of maize. The turbulence intensity is taken at the height of 8.5 m, which is the hedge height. The values of z_0 calculated from turbulence intensity at other heights do not differ very much.

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Table 1 Approach flow and hedge conditions at full scale wake measurements

Date	Number of runs 10 min. runs	Wind		Terrain	Hedge	Foliage
		Wind direction* (deg)	mean windspeed (m/s)	z ₀ from turbulence (cm)	Foliage	Porosity
04/29	2	196-210	8.0	3.3	without	60%
04/30	4	242-250	5.7	1.5		
04/30	4	254-258	5.3	0.8		
05/14	14	231-239	7.6	3.1		
05/14	7	240-250	7.7	3.6		
05/26	3	208-218	5.9	1.8	light	50%
05/26	3	254-260	8.7	2.3		
06/02	6	226-239	6.2	3.8	total	30%
06/02	4	240-253	6.6	5.1		
06/06	9	195-225	6.5	4.3		
06/06	4	226-239	6.7	2.1		
06/10	4	195-225	8.4	6.1		
06/11	3	195-225	5.8	4.0		
06/11	1	226-239	4.9	3.4		

It can be seen that the roughness length, calculated from turbulence intensity corresponds to arable land and that the low maize, in June, increases it slightly. So, assuming a constant roughness length, the periods of measurements have been divided into three parts corresponding to the different hedge porosities.

* Normal direction to the hedge is 210 deg.

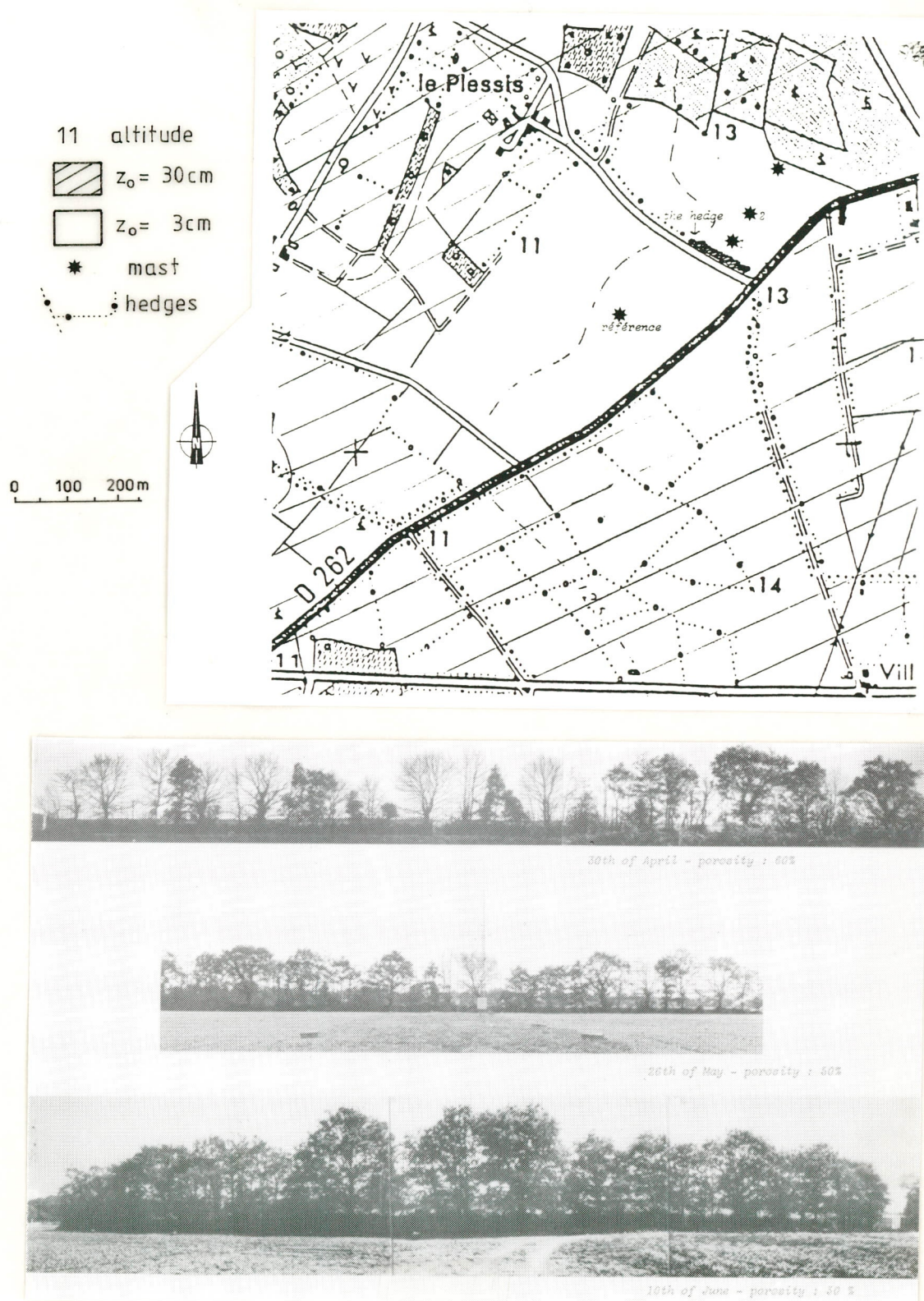


Fig. 8 The hedge and its location

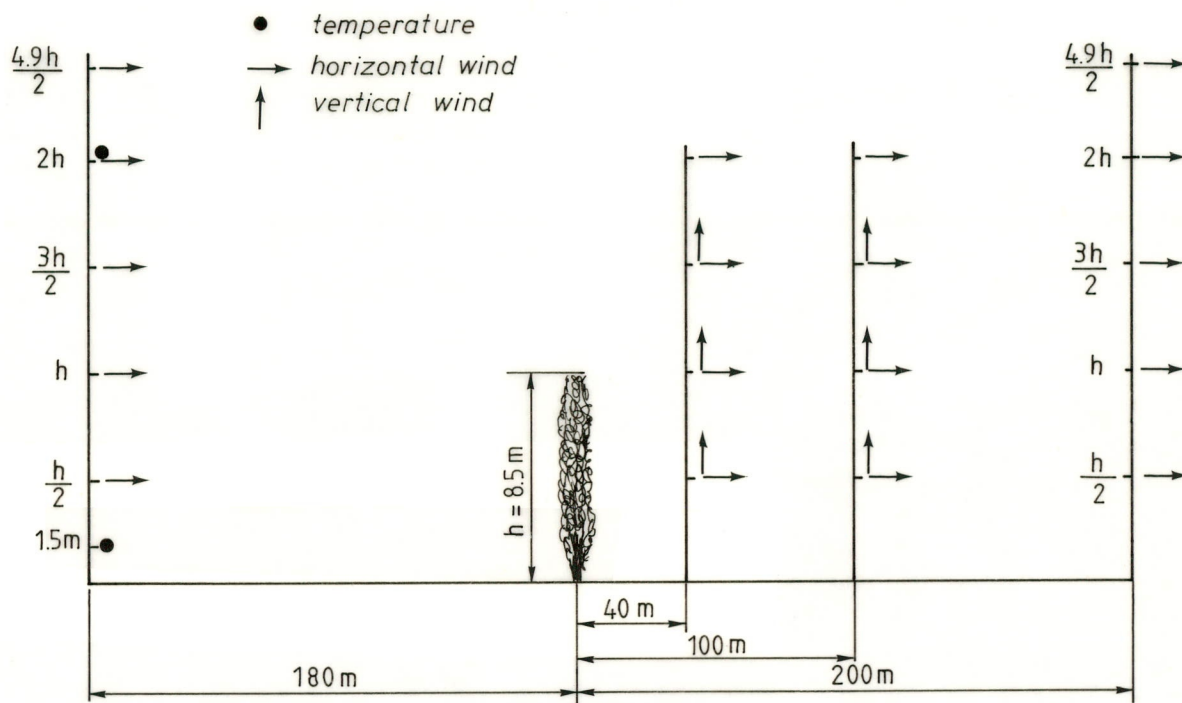


Fig. 9 The measuring stations

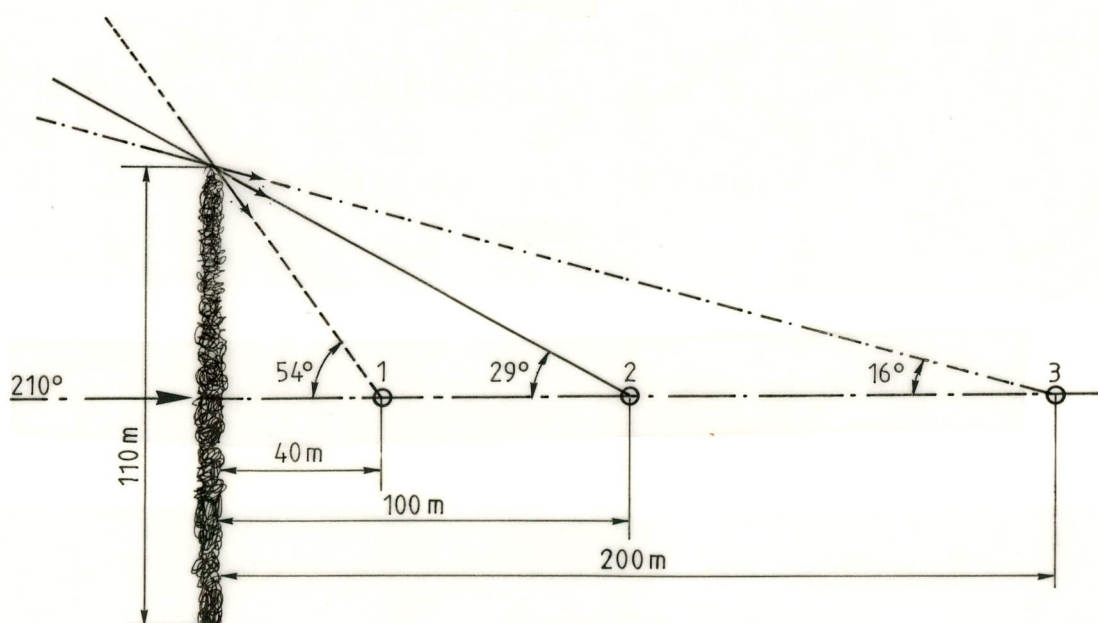


Fig. 10 Maximum allowable deviation of wind direction from normal to the hedge for each mast

3.3 Comparison with handbook

3.3.1 Mean flow

The figures 11 to 13 show the curves of wind velocity distribution behind a row of trees, as they are given in the handbook. They correspond to hedge porosities of 20% and 50%. For comparison, the mean values of measured C_B coefficients have been transferred on these graphs in spite of the fact that the porosity is not exactly the same in this experiment (30% and 60%).

Moreover, in the handbook model, the effect of oblique winds, with deviation β from the perpendicular to the hedge, is taken into account by using an effective distance to the hedge given by $x_e = x/\lambda_\beta$ (λ_β given by the handbook). So, measurements with oblique winds have also been transferred on the graphs, with this effective distance in abscissa.

It appears that the measured wake is shorter than the prediction of the model and that there is an effect of overspeed at proximity of the hedge and at a height of twice the height of the hedge, which has not been taken into account in the model.

The effect of oblique winds seems to be correctly considered with the concept of effective distance.

3.3.2 Turbulence

Figure 14 shows the spatial distribution of the handbook coefficient for turbulence increase (CTI). Results of the measurements have been transferred for the cases of normal winds. The measured values are in accordance, except at low heights ($z < h$) where the curves overestimate the turbulence and at greater heights ($z = 2h$) near the hedge where the turbulence is underestimated.

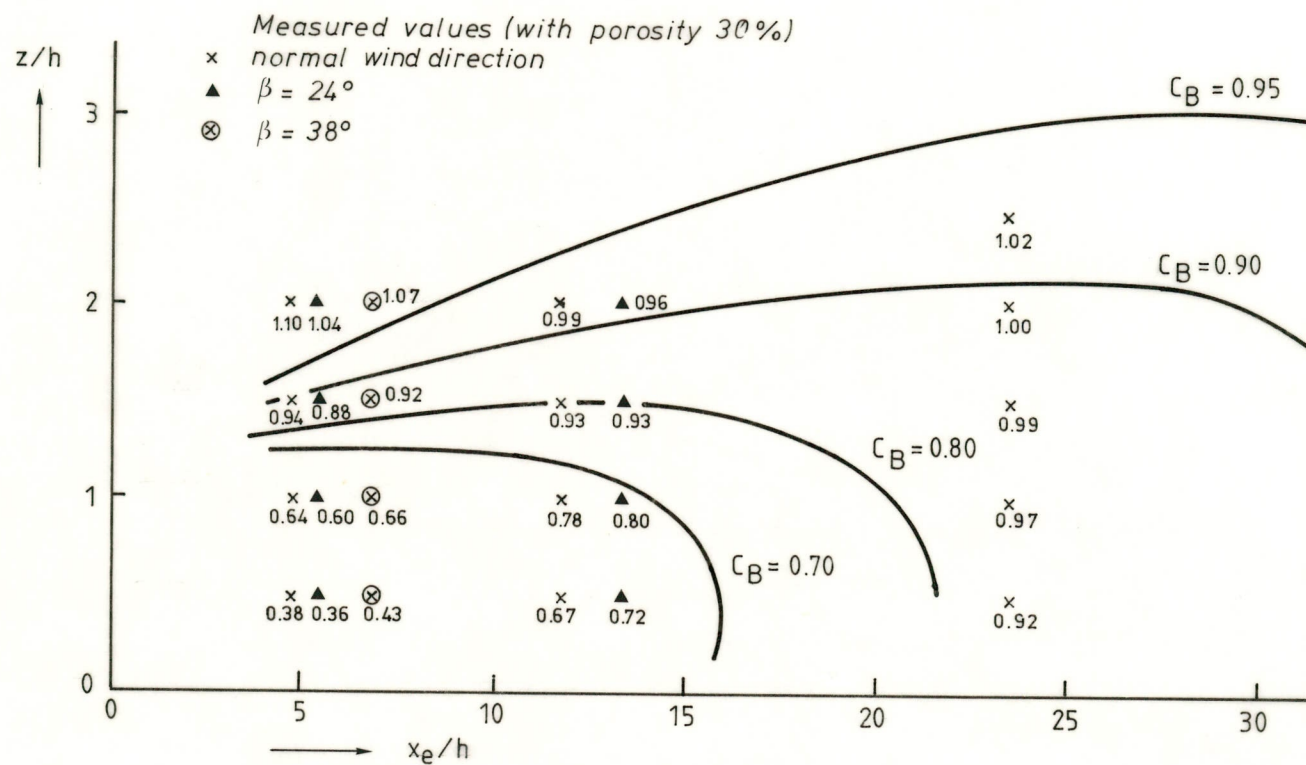


Fig. 11 Comparison between experimental results and original handbook graphs. (Note: The final graphs for trees in the handbook were slightly modified to account for the full scale results of CSTB)

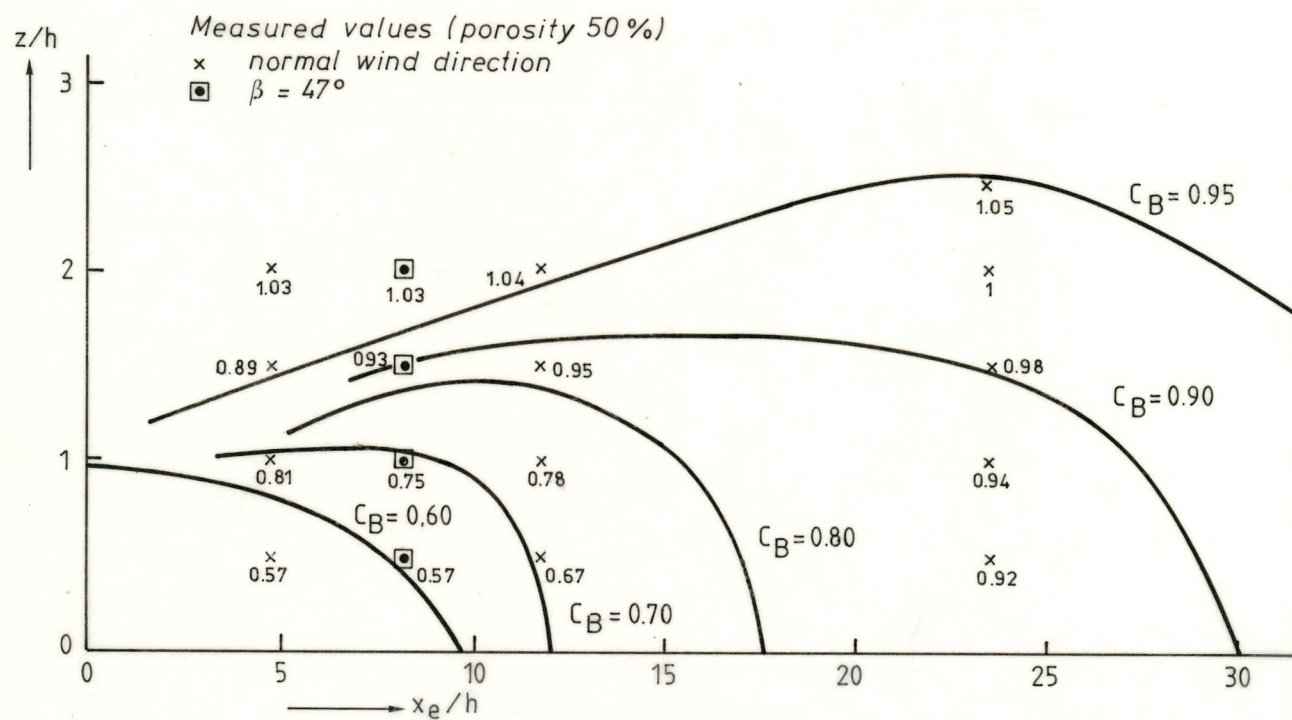


Fig. 12 The wind velocity distribution in the mid-plane behind a 50% open row of trees at normal wind direction.
 Comparison of experimental results original handbook graph, (Note: final handbook graph modified)

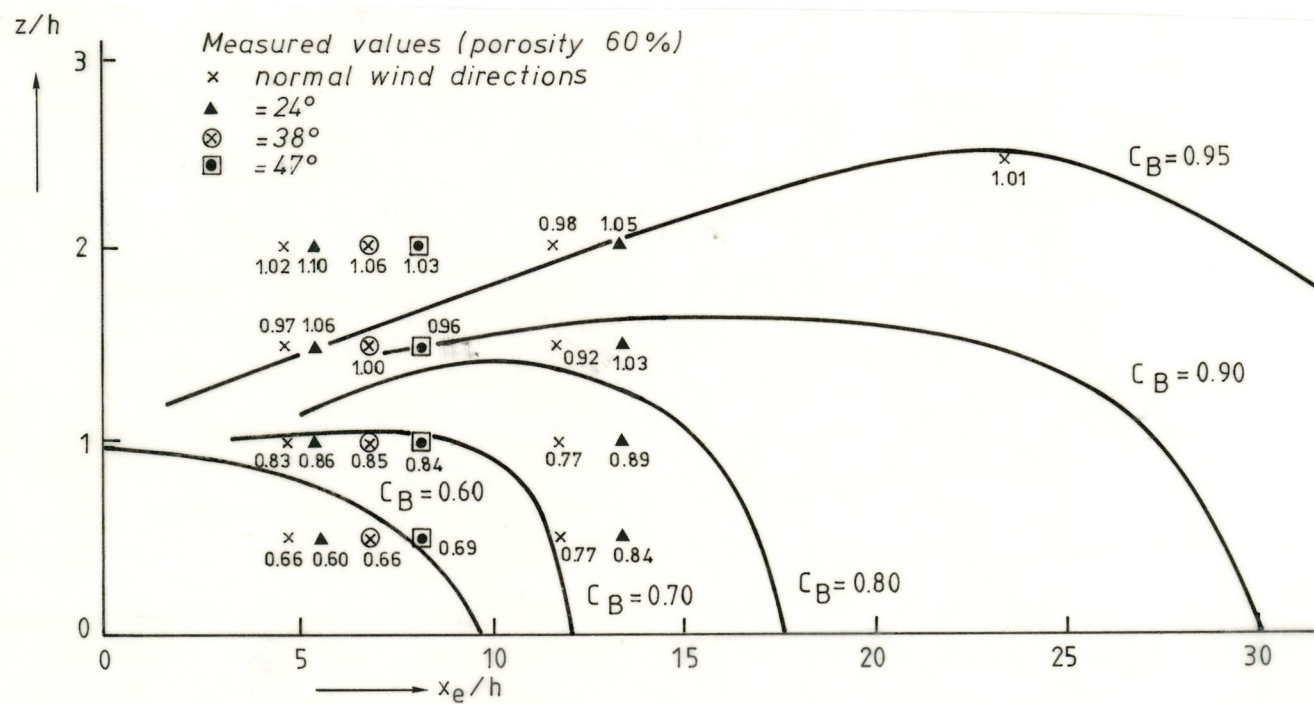


Fig. 13 The wind velocity distribution in the mid-plane before and behind a 50% open row of threes at normal wind direction. Comparison of experimental results and original handbook graph, (Note: final handbook graph modified)

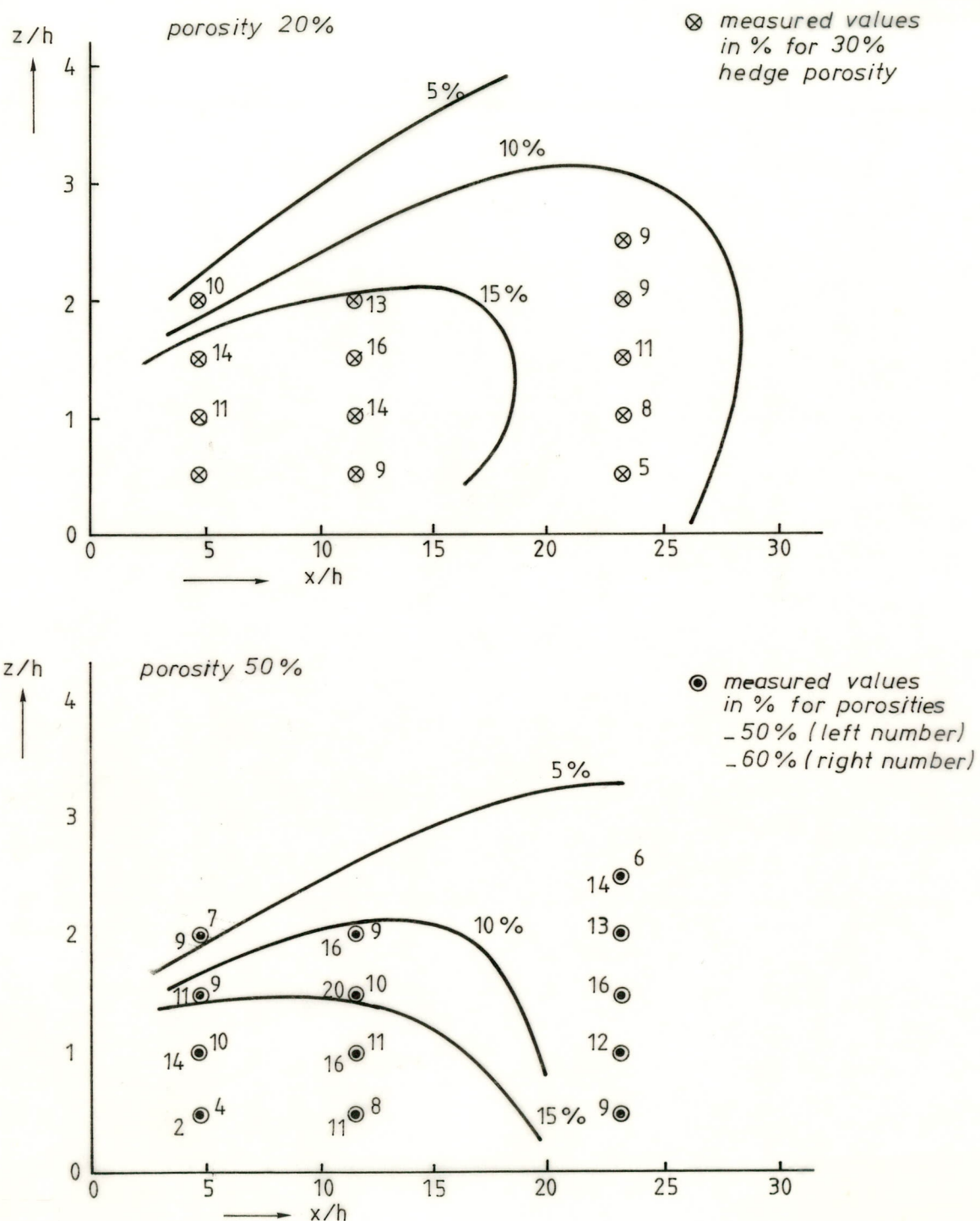


Fig. 14 Spatial distribution of the coefficient of turbulence increase comparison with original handbook graphs
(Note: final handbook graph modified)

4. TNO-COMPLEX OBSTACLE SITUATIONS

4.1 Introduction

Within the framework of the National Development Program Wind Energy fase II TNO performed wind tunnel studies on several wind turbine sites. Five sites which lie near the West coast of the Netherlands will be discussed here after.

The wind turbine sites while mostly in flat terrain comprise in general rather complex obstacle situations. For each location a short site description will be given and then model results and Handbook estimates will be compared.

4.2 Results

Camperduin

Site description:

The two 18 m high and 10.6 m diam. wind turbines are situated behind a small 10 m high wood (fig. 15).

Flat polderland extends North and East but at the South a group of residential houses, to which the electric power from the wind turbines is delivered, is situated. Still further southward a dune landscape begins.

The closest obstacle to the West side is the well-known 5 km long, 11 m high "Hondsbosche Zeewering" at 850 m distance, being a substitute for the locally missing dunes.

In figure 16 wind tunnel results on velocity defect and handbook estimates are compared. For the handbook method the group of houses has been considered as a wall 250 m South-West of the wind turbine site.

There is a fair agreement between measured and predicted CB-values. The influence of the sea-dike on the flow is not noticeable at the site, the latter lying some 80 obstacle heights downwind.

The graphs dealing only with retarding effects on the flow in obstacle wakes, the $CB > 1$ at $300 < \beta < 360$ deg. was not predicted. Keeping in mind however, the speeding up of the flow outside the wake boundary, due to

flow confinement by the wake, this effect of the adjacent wood is not surprising.

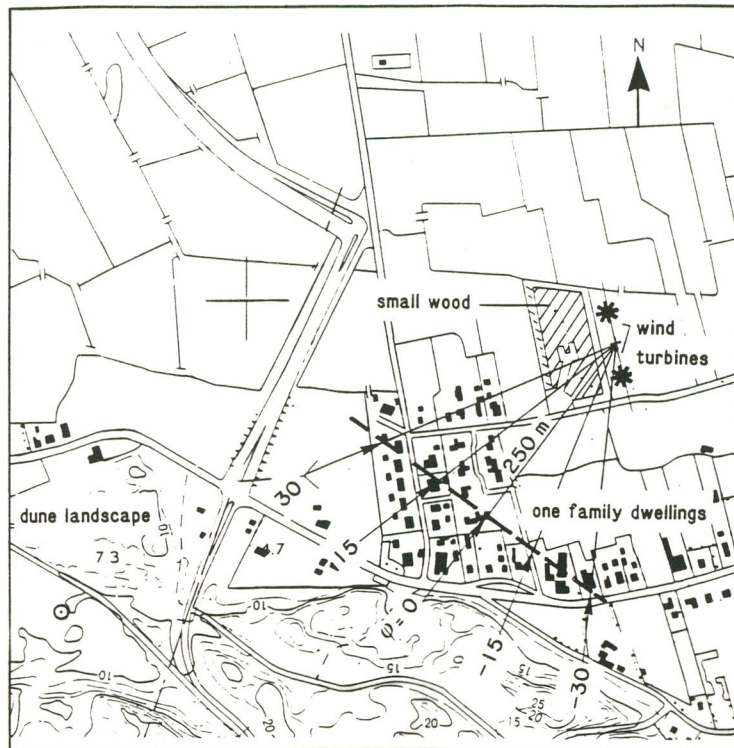


Figure 15 Wind turbine site Camperduin

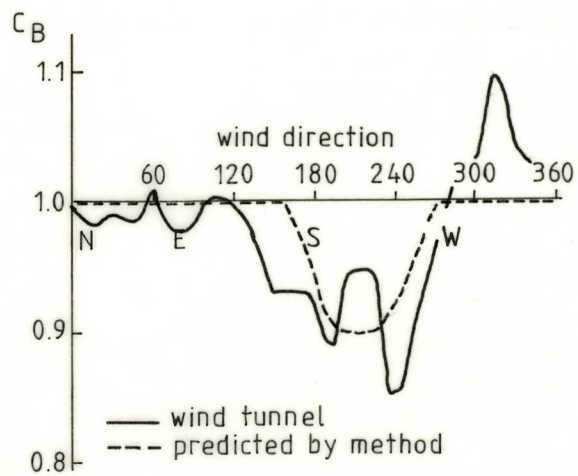


Figure 16 Mean C_B of the two wind turbines at hub height

2. Oudkarspel

Site description:

This wind turbine test site is located in flat polderland.

The wind turbine ($h=24$ m, $d=16$ m) stands at 10 m distance from the east-side of a large factory hall ($h=10$ to 12 m). At large distance, 250 m to the Southwest lies a ribbon of 8 m high residential houses (fig.17).

Model results

Windtunnel measurements of velocity and turbulence as a function of wind direction are presented in fig. 18 and 19.

At most wind directions (45 deg. to 255 deg.) a small velocity increase of maximal 5% was measured. A maximal velocity reduction was measured at $\beta = 45$ deg. and $\beta = 270$ deg: $C_B = 0.92$.

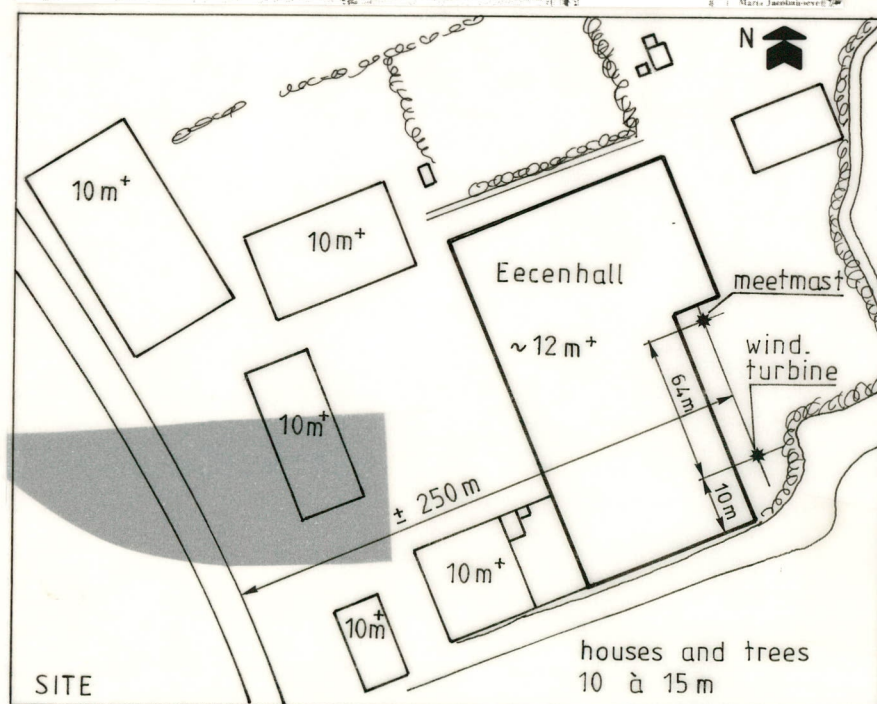
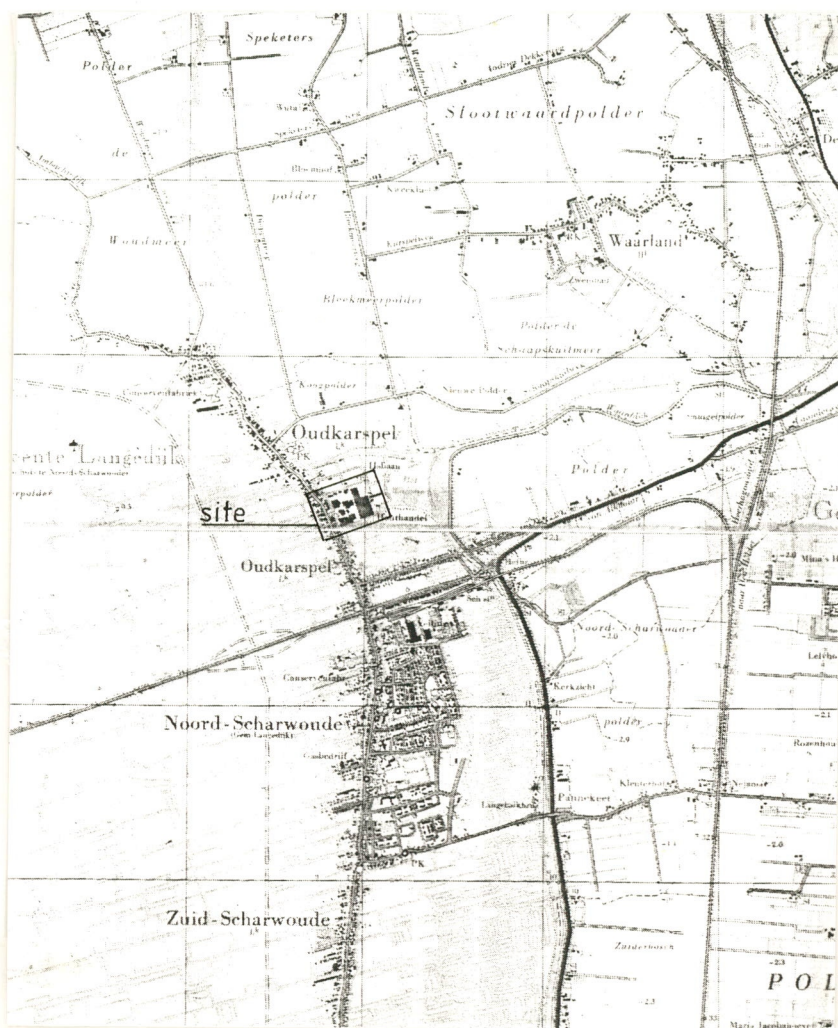
At the same wind direction the turbulence increase is maximal 9%.

Handbook

The largest wake effect of the factory may be expected at $\beta = 255$ deg. For $\frac{z}{h} = 2.4$ and $\frac{x}{h} = 1$, $C_B = 1$, which is 8% higher measured.

The maximal turbulence increase is 20% which is more than twice as high as measured. So the velocity decrease is underestimated and the turbulence increase overestimated some 10% by the Handbook method.

The reason for this is not clear.





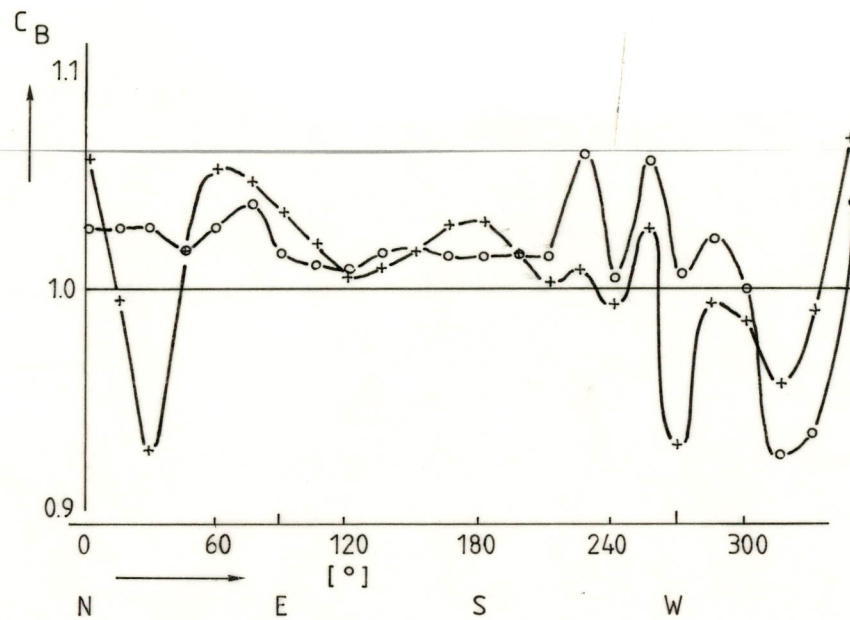


Fig. 18 Velocity reduction factor C_B as a function of wind direction.
(+) with and (o) without nearby EECEN-building

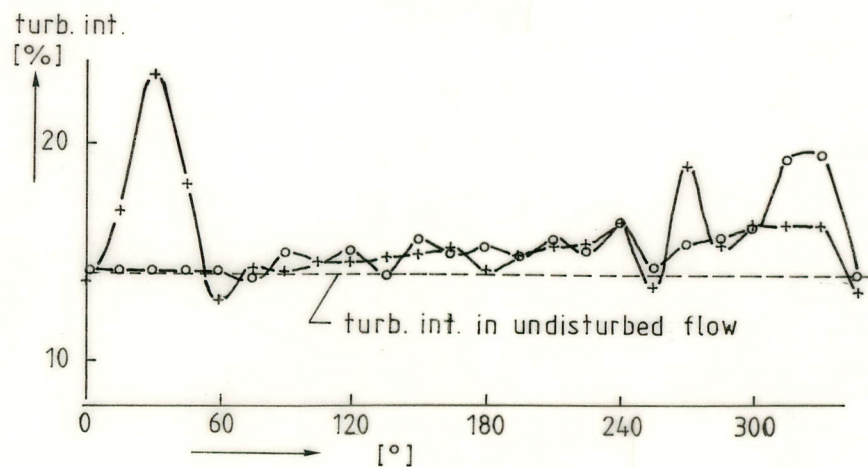


Fig. 19 The turbulence intensity at hub height + with and o without nearby EECEN-building

3. Den Helder

Den Helder is a Navy harbour in the northwest of the Netherlands. The obstacle is a 6 m high isolated swimming hall with the roof lifted to 11.5 m above the swimming pool (fig. 20).

Three locations for the wind turbine ($h=18$ m, $d=14$ m) will be considered.

Model results.

In location 1 close to the swimming hall maximal velocity decreases occur at wind directions of $\beta = 225$ deg. and $\beta = 285$ deg. of $C_B = 0.92$ and 0.91 respectively.

In location 2 the maximal velocity decrease is $C_B = 0.9$ at $\beta = 255$ deg.

In location 3 the maximal velocity decrease measured is $C_B = 0.95$ at $\beta = 285$ deg. Turbulence increases at all stations about 15%.

Handbook

The maximum velocity decrease in location 1 is expected at $\beta = 210^\circ$.

For $\frac{x}{h} = \frac{56}{11.5} \approx 5$ and $\frac{z}{h} = \frac{18}{11.5} \approx 1.6$ $C_B = 0.68$ and the turbulence-increase is 30%.

For location 2 wind decrease is expected at wind directions $\beta = 240^\circ - 300^\circ$

$$\frac{x}{h} = \frac{78}{6.5} \approx 12 \quad \frac{z}{h} = \frac{18}{6.5} \approx 2.8 \rightarrow C_B = 0.9$$

In location 3 the protected windsector is from $\beta = 270^\circ - 300^\circ$.

$$\frac{x}{h} = \frac{170}{6.5} \approx 26 \quad \frac{z}{h} = 2.8 \quad C_B = 0.88$$

So it appears that at larger distance from the obstacle the correspondence between measurements and handbook graphs is good. In the near wake however the correspondance is bad, with a strong overestimate of the obstacle effect.

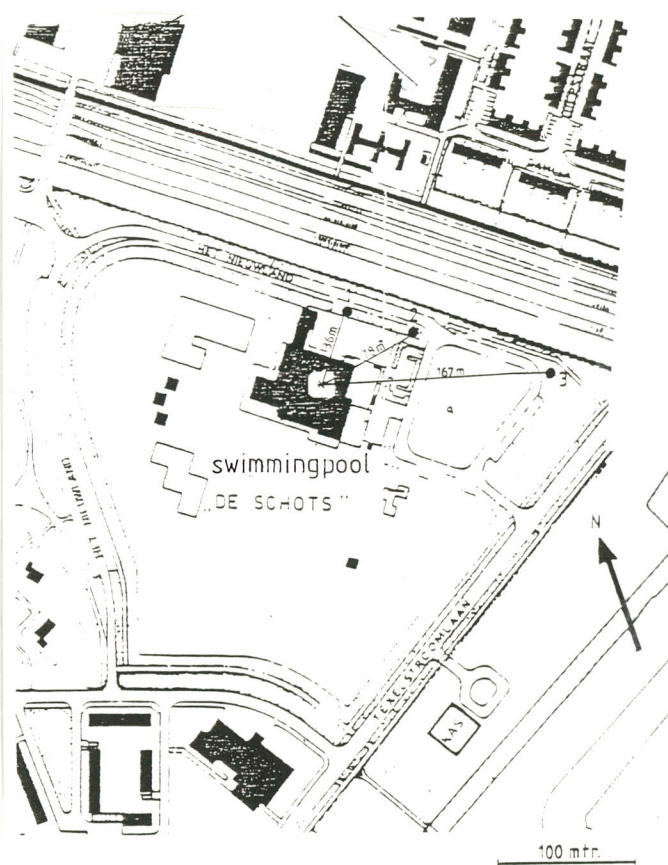
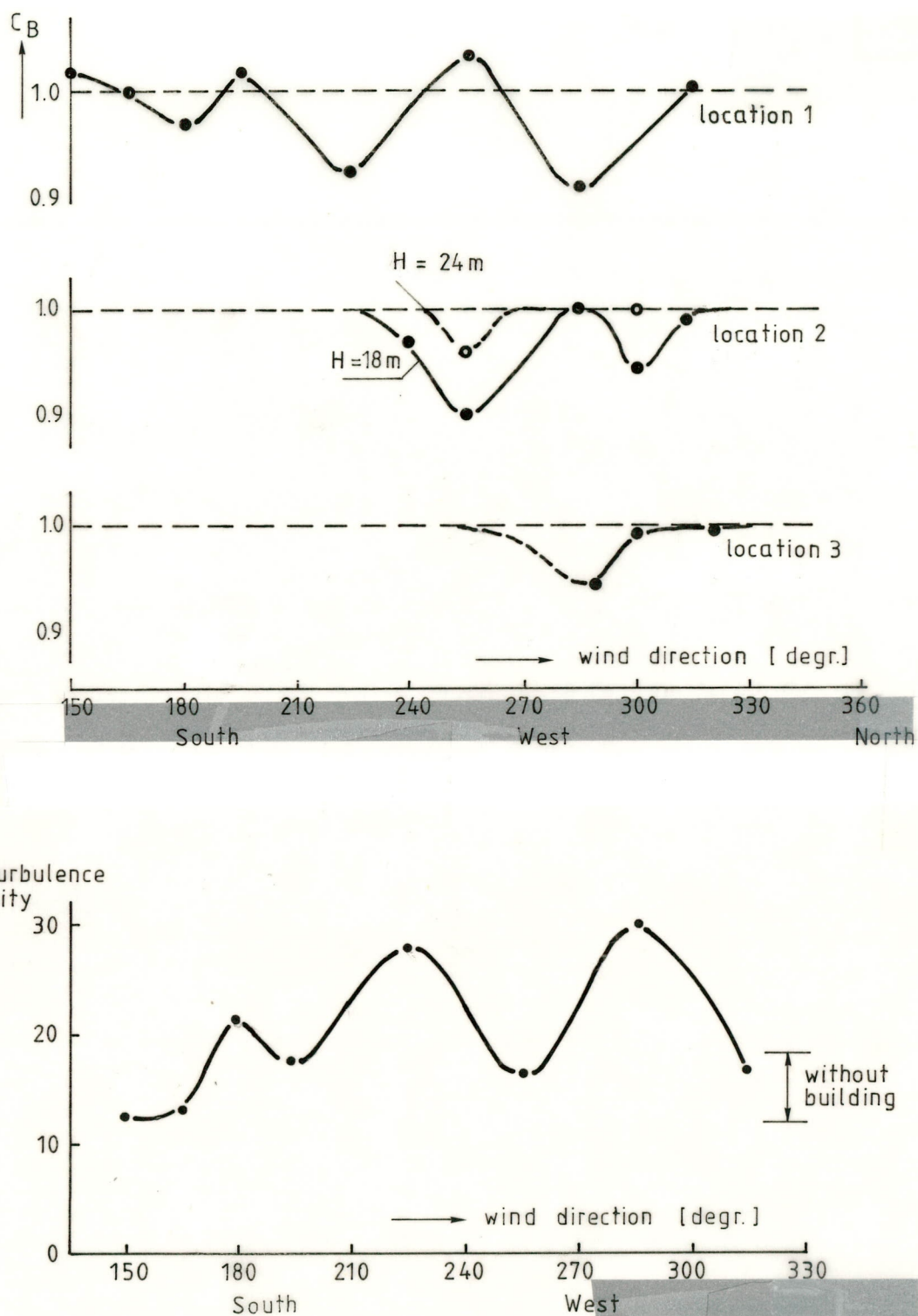


Fig. 20 The site at den Helder



b) Turbulence intensity at location 2

Fig. 21 Wind velocity reduction C_B and turbulence intensity increase at hub height, as a function of wind direction

20 180 160 140 120 100 80 60 40 20 0
South West North

21

4. Dronten

The windturbine (h=24 m, d=10.6 m) location Dronten is in very flat pol-derland (fig. 22).

The obstacle situation is not simple. To the north the location is free to the wind, but to the south there are rows of trees and at greater distance a schoolbuilding and to the east a sporthall. The trees are about 15 m high and the buildings 7 m.

Model results

For south-westerly to north-easterly winds the wind turbine location is just upstream of the obstacle group which causes an increase of wind velocity up to 8%.

When the wind turbine is downstream of the obstacle group the velocity decreases to a maximum of 15% ($C_B=0.85$) at $\beta=210$ deg. At $\beta=90$ deg also a decrease $C_B=0.92$ occurs.

Turbulence increase is 13% at southwesterly wind, while obstacle east of the location cause 20% turbulence increase.

Handbook

- 15 m high small wood at the SW-side. The maximum wind reduction is expected at $\beta \approx 205$ deg.

For $\frac{x}{h} = 16$ and the model wood porosity of 34% $C_B = 0.87$ which is close to the measured value of 0.85.

The turbulence increase is estimated at maximal 15%, which is also close to the measured value of 13%.

- Of all obstacles east of the wind turbine the sport hall appears to be predominant.

For $\frac{x}{h} = 11$ $\frac{z}{h} = 3.2$ and $\frac{w}{h} = 5$ the wake elongation factor $\lambda_w = .7$.

So $\left(\frac{x}{h}\right)_e = \frac{11}{0.7} = 16$ and $C_B = 0.92$

The maximum is expected at $\beta = 105$ deg.

Comparison with measured value shows that there is a good agreement especially with regard to C_B .

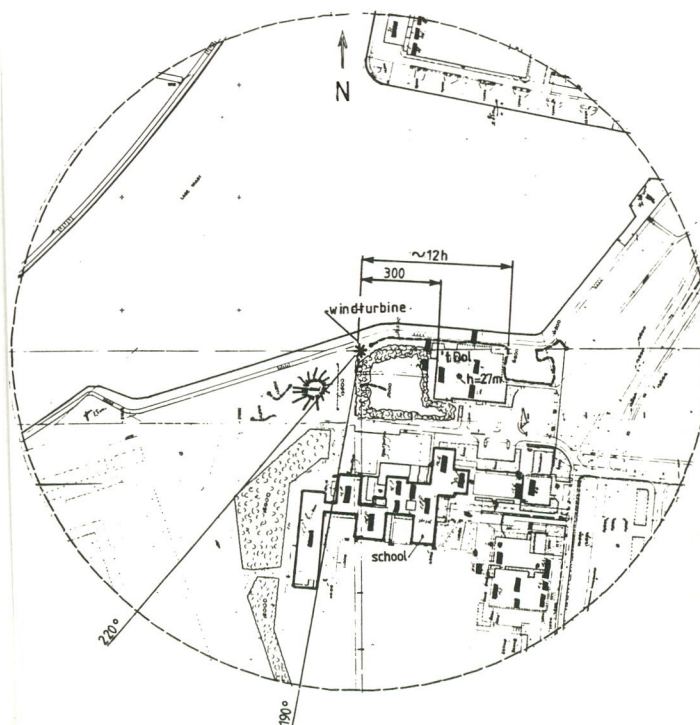


Fig. 22 Wind turbine site Dronten

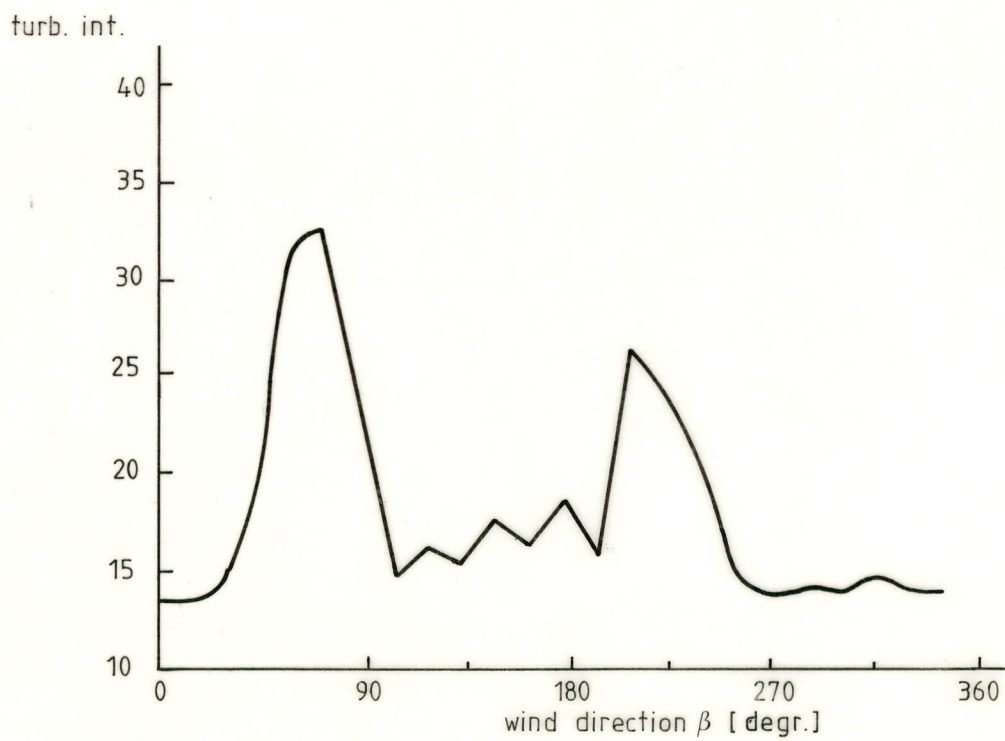
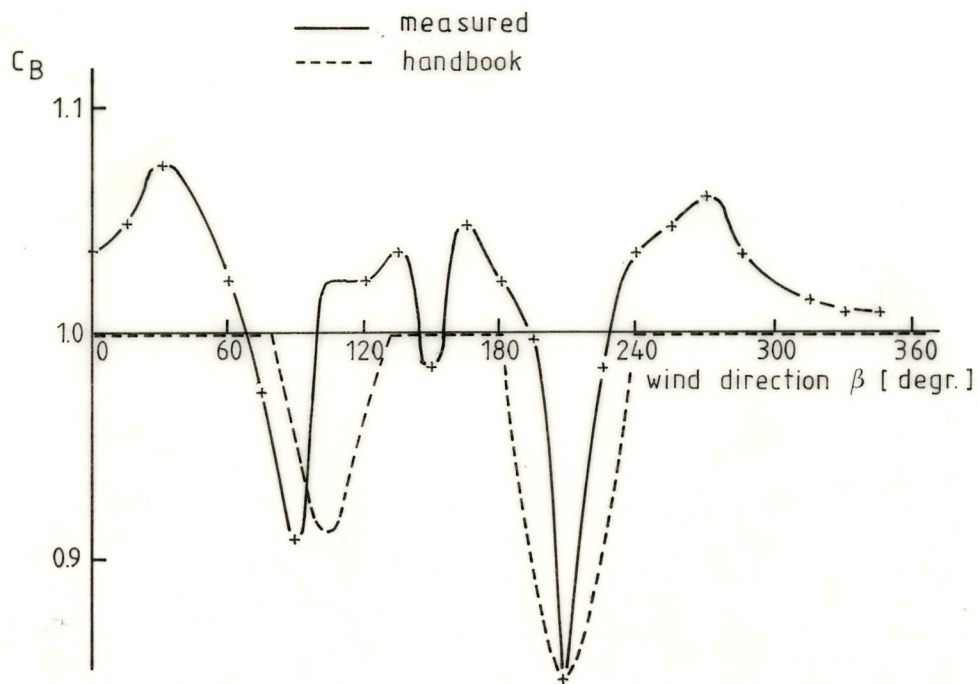


Fig. 23 Wind velocity decrease and turbulence increase at the Dronten site

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5. Cornwerd

A windturbine (h=26 m, d=15 m) is located at 80 m distance from an isolated church. The nave of the church is 16 m high and the tower 43 m (fig. 24).

Model results

Velocity has been measured at the windturbine axis height when the church is upwind only.

The velocity coefficient $C_B = 0.79$ and the turbulence increase is 17%.

Handbook

For the effect of the church (without tower) $\frac{x}{h} = 4.5$ and $\frac{z}{h} = 1.5$.

The wake elongation factor, due to small w/h is $\lambda_w = 0.22$ giving $x_e = 20 h$.

The C_B -value given by the Handbook is $C_B = 0.82$ what corresponds greatly with the measured value.

The (longitudinal) turbulence increase has not been measured.

The method predicts no effect of the slender tower on the wind velocity at hub height, which is confirmed by the measurements.

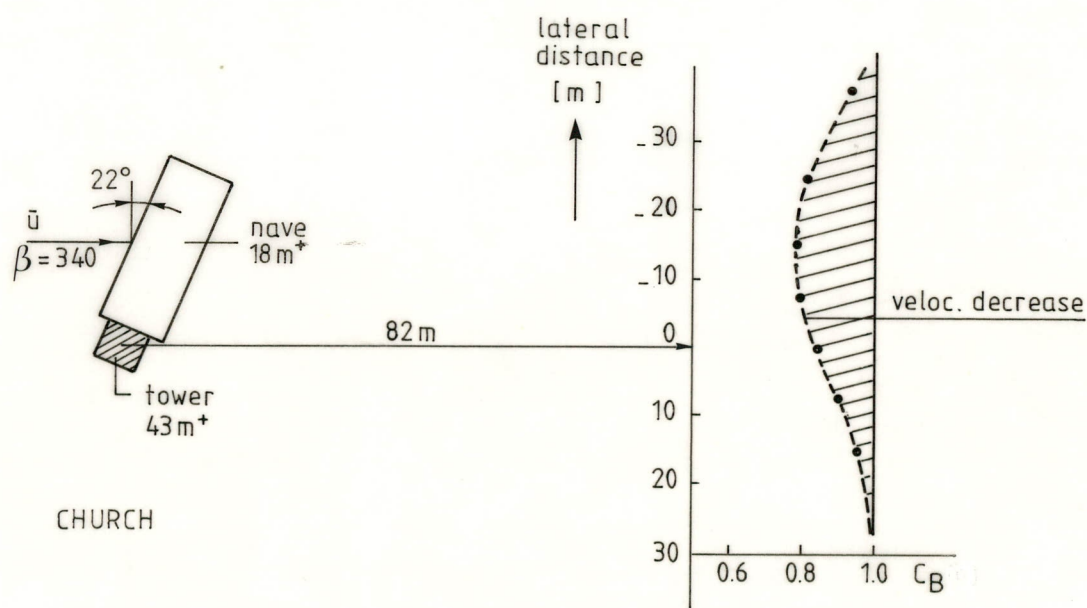


Fig. 24 The wind turbine site Cornwerd

4.3 Conclusions

The velocity decrease as well as the turbulence increase in the far wake of an obstacle (Camperduin, Dronten, Cornwerd, Den Helder) is well predicted by the handbook method.

Considering a small obstacle group as a wall with the same main dimensions as the group is justified (Camperduin).

In the near wake ($x/h < 5$) large differences are found between measurement and prediction (Oudkarspel, Den Helder-spoorthall).

5. GENERAL CONCLUSION

Velocity decrease and turbulence increase in the wake of an earth bound obstacle are reasonably well predicted by the determination method of the Handbook, except for small $x/h < 5$.

Full scale measurements of CSTB behind a nominally 2 dimensional hedge suggest the predicted values of the velocity decrease to be lightly at the conservative side, while at low heights ($z < h$) the turbulence increase is overestimated and at greater heights ($z > 2h$) the turbulence increase is underestimated.

The final handbook graphs for trees have been modified slightly to account for the CSTB results.

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