COMPARISON OF SEA SURFACE ROUGHNESS MODELS FOR OFFSHORE WIND POWER UTILISATION

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ABSTRACT: Sea surface roughness z_0 is one of the key parameters for the description of the marine atmospheric boundary layer. Four different relations for its estimation are compared here. The first is the simple assumption of a constant z_0. The second is the commonly used Charnock relation. The third is a wave age dependent relation aiming to improve the Charnock relation by including the influence of the wave field. The last is a simplification of this wave age model, using fetch instead of wave parameters as input.

The wave age dependent relation is investigated closer with data from the Rødsand measurement program. Good agreement is found for the parameterisation proposed by (Johnson et al., 1998). However, it is also shown that self-correlation is a problem of this type of relation and that the relation does not scale completely.

In a test application the neutral 10 m wind speed is predicted with the four models for the Rødsand data. The models show differences in their biases, while the rms-errors seems to be dominated by measurement errors ad do not vary much. If only data selected for nearly stationary situations is used, the models performance is as expected: the wave age model shows the best result, followed by the fetch dependent model, the Charnock relation and finally the constant roughness assumption. If also instationary data are included the performance of all models deteriorate. The constant roughness assumption performs relatively better, outperformed only by the wave age model. Furthermore, atmospheric stability was found to have an important impact on the performance of all models.

1 INTRODUCTION

Large offshore wind farms are being built in several countries in Europe. The economic viability of such projects depends on the favourable wind conditions of offshore sites, since the higher energy yield has to compensate the additional installation and maintenance cost. A reliable prediction of the wind resource is therefore crucial. The main reason for the high wind speeds offshore is the low surface roughness of the sea. However, the roughness is not constant with wind speed like for land surfaces, but depends on the wave field present, which in turn depends on wind speed, upstream fetch, water depth, etc.

The sea surface roughness z_0 is usually determined from friction velocity u_* with the Charnock relation as $z_0=z_{ch}u_*^2/g$, where g is the gravitational acceleration and z_{ch} the empirical Charnock parameter. This was originally meant to be a constant, but it turned out to be site specific for sites with coastal influence. In these near coastal areas it has been found that quantities other than the friction velocity (or wind speed) also play an important role. The reason is that the sea state is not only determined by the wind speed, but also significantly by upstream fetch.

Numerous attempts have been made to find an empirical relation for the sea surface roughness with an improved description of the wave field. No consensus on the most suitable scaling groups has emerged yet. Different relations have been tested with the Rødsand data (Lange et al., 2001a), and the only relation showing a significant correlation was a power law between the Charnock parameter $z_{ch}= z_0 g / u_*^2$ and the ratio of peak wave velocity c_p and friction velocity u_*, the so called wave age c_p/u_* is proposed. (Johnson et al., 1998).

This model requires measurements of the peak wave velocity, which is often not available for wind power applications. A fetch dependent model has therefore been developed, where the wave age has been replaced by utilising an empirical relation between wave age and fetch.

In section 2 the field measurement program Rødsand is briefly presented. The four sea surface roughness models are described in the folowing section. The wave age model is closer investigated in section 4. All relations are than tested in their capability to predict the wind speed at 10 m height from measured quantities in section 5. Finally, conclusions are given in the last section.

Figure 1: Rødsand measurement site

2 THE RØDSAND MEASUREMENT

A 50 m high meteorological measurement mast has been established at Rødsand in October 1996. It is situated about 11 km south of the coast of Lolland (see Figure 1).

Simultaneous wind and wave measurements were performed from 1998 to 2001. For a description of the measurement and the quality control of the data see (Lange et al., 2001). For this analysis data from 1998 to 2000 have been used. Extreme situations of atmospheric stability (0>L>-20m and 0<L<50m, with L= Monin-Obukhov-length) and broad or double peaked wave spectra (wave spectrum bandwidth>0.25) were excluded. Wind speeds were corrected for flow distortion of the mast and booms with a method described in (Højstrup, 1999). Records with wind speed sensors in the shade of the mast were excluded. The final data set consisted of about 2400 half-hourly records.

A data subset was selected for nearly stationary conditions by limiting gradients for wave velocity and wind speed to 20% per hour, for friction velocity to 30% per hour and for wind direction to 40º per hour. 67% of the data were rejected in this selection.

3 DESCRIPTIONs OF SEA SURFACE ROUGHNESS MODELS

Constant roughness

For land surfaces the aerodynamical roughness can usually be assumed to be a independent of wind speed. This is not the case for the sea surface roughness. Nevertheless the approximation of a constant sea surface roughness is often used, e.g. in the WAsP program of teh European Wind Atlas (Troen and Petersen, 1989). It is therefore included here. The WAsP value of z_0=0.2 mm is used for modelling.

Charnock relation

Based on dimensional reasoning, Charnock (1955) proposed a relationship for the sea surface roughness z_0, friction velocity u_* and gravitational acceleration g:

$$z_0 = z_{ch} \frac{u_*^2}{g} \qquad (1)$$

z_{ch} is an dimensionless empirical parameter, which was meant to be a constant. A value of z_{ch}=0.0185 (Wu, 1980) is used here.

Wave age model

However, measurements at sites with coastal influence revealed that the Charnock parameter is site specific. Several approaches have been proposed to improve the Charnock relation by including properties of the wave field. Here the wave age dependent roughness model by (Johnson et al., 1998) is used. It uses a power law relation between the Charnock parameter z_{ch} and wave age c_p/u_*. The coefficients are A=1.89 and B=1.59.

$$z_{ch} = A\left(\frac{u_*}{c_p}\right)^B \qquad (2)$$

Fetch dependent model

The wave age used in the above relation is often not available for wind power studies. Therefore a relation is needed to determine it from fetch, which is an easily available parameter. (Kahma and Calkoen, 1992) found the following empirical relation between the dimensionless peak frequency and the dimensionless fetch:

$$\frac{u_*}{g}\omega_p = C\left(\frac{g}{u_*^2}x\right)^D \qquad (3)$$

Here ω_p is the peak wave frequency and x the fetch in metres. The coefficients were found to be C=3.08 and D=-0.27.

The influence of fetch on wave parameters in this relation has been determined by field experiments with winds blowing approximately perpendicular to a straight coastline. To use these relations for an arbitrary coastline the effective fetch x_{eff} is used as defined in (Lange et al., 2001a).

With the assumption of deep water conditions the left hand side of eq. (3) can be identified as the inverse wave age u_*/c_p using the dispersion relation. This relation can then be used to eliminate the wave age from eq. (3):

$$z_0 = \frac{u_*^2}{g} A C^B \left(\frac{g}{u_*^2}x_{eff}\right)^{BD} \qquad (4)$$

4 INVESTIGATION OF WAVE AGE MODEL

4.1 Comparison with measurements

A comparison of the Rødsand data with the wave age model is shown in Figure 2. The Charnock parameter is plotted versus inverse wave age. Individual 30-min averaged records as well as their and bin-values averaged with respect to inverse wave age are shown. It can be seen that the bin averaged values agree well with the proposed relation, but there is a large scatter in the measured data.

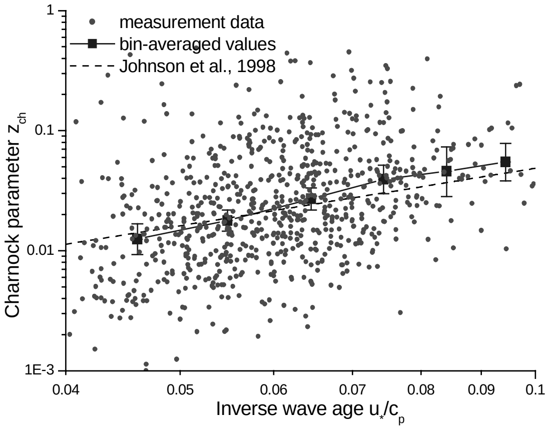

Figure 2: Charnock parameter versus inverse wave age for Rødsand measurement data; individual 30-min averaged records and bin-values averaged with respect to inverse wave age; also shown is the Johnson et al., 1998 relation

4.1 Self-correlation

The two scaling groups of the wave age model, Charnock parameter and wave age, contain common variables, especially since the sea surface roughness z_0 can not be measured independently, but has to be derived from measured data by assuming a log-linear wind profile:

$$z_0 = \frac{z}{\exp\left(\frac{\kappa u_{z,n}}{u_*}\right)} \qquad (5)$$

Here κ is the von Karman constant (κ=0.4), u_{10n} the neutral wind speed at 10 m height and u_* the friction velocity. The neutral wind speed is calculated from $u_{z,n}$ = $u_*/\kappa\ \Psi_m(z/L)$, where Ψ_m is the Businger/Dyer flux-profile relationship for momentum.

Common variables can lead to self-correlation effects, which influence the correlation found between the groups. The question arises, if the use of the peak wave velocity to model the Charnock parameter can improve its prediction. To do so, it needs to change the correlation, which is already present due to the presence of friction velocity in both scaling groups.

This question has been investigated by a numerical experiment. A data set is prepared, where the measured wave data are exchanged by random values, which only follow the probability distributions of the measured peak wave velocity, but are completely uncorrelated. The random data have been analysed in the same way as the measured data.

Figure 3 shows a comparison between the real Rødsand data and the ‘data’ with random wave velocities. The data have been bin-averaged with respect to inverse wave age. The Charnock parameter is plotted versus inverse wave age.

The difference between both graphs shows that the relation is not only due to self-correlation, i.e. that there is a physical dependency of Charnock parameter on wave age. However, differences between the two relations are small and the improvement of the Charnock equation by including wave age is smaller than what could be expected at first sight.

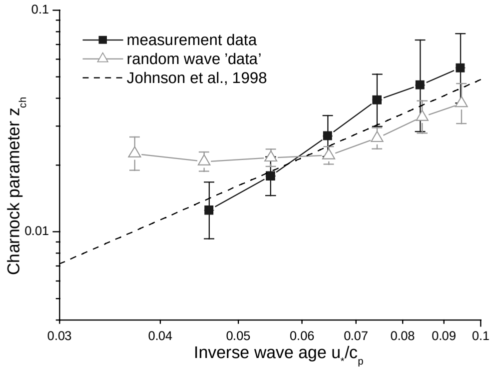

Figure 3: Comparison of Rødsand measurement data and ‘data’ with random peak wave velocity: Charnock parameter versus inverse wave age

4.2 Influence of wind speed distribution

For ideal scaling parameters the remaining scatter in the data around the line given by the power law should be independent of other physical quantities. This can be tested by stratifying the data into different classes with respect to one quantity, e.g. the 10 m wind speed, and comparing the correlation between the scaling groups for the different classes.

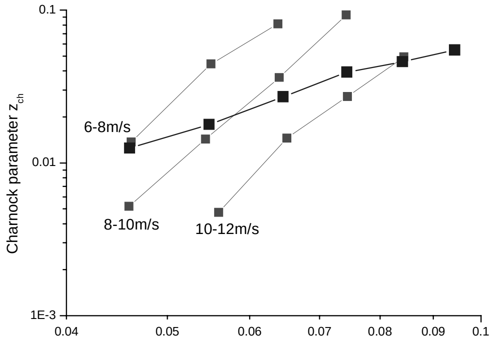

Figure 4: Charnock parameter versus inverse wave age; for the line with crosses all data have been used, the other lines are for data selected for wind speed

This is shown for wind speed classes and the Charnock parameter versus inverse wave age relation in Figure 4. The data have been bin-averaged with respect to inverse wave age. For the line with crosses all data have been used, the other lines are for data stratified according to wind speed. For an ideal scaling all points should collapse onto one line. This is clearly not the case. It can be seen that the steepness of the relations of the single wind speed classes is larger that that of the total data set, where the bin-averaging has been made irrespective of wind speed.

This means that the wind speed probability distribution has an influence on the result of the analysis. A narrow wind speed distribution of only 2 m/s width would e.g. result in a much larger steepness.

5 TEST APPLICATION

To test the prediction capabilities of the different models they were used to model the neutral wind speed at 10 m height from the measured quantities needed in the relations. The logarithmic wind profile was used. The data set seleted for stationary conditions has been used. The bias and root mean square error of modelled and measured data was calculated. It is given in the left two columns of Table 1.

The assumption of a constant sea surface roughness leads to the highest bias and rms-error. The use of the Charnock relation improves both values. Compared to the Charnock relation the wave age model leads to a decrease in bias, but yields only a small decrease in rms-error. When fetch is used instead of measured wave age the bias and rms-error increase again, but are still slightly lower than those obtained with the Charnock relation.

The data were also divided into cases with stable and unstable atmospheric conditions (see Table 1). The Monin-Obukov-length L, used for the selection, was determined from sonic anemometer measurements with the eddy-correlation method. It can be seen that the bias is very different between both conditions, while the rms-error does not show much difference.

Table 1: Bias and root mean square error of modelled and measured neutral wind speed at 10 m height for different sea surface roughness models; subset of nearly stationary data

	all data		stable data		unstab. data	
(all in%)	bias	rms	bias	rms	bias	rms
Constant	-3.2	12.2	0.3	12.2	-6.5	11.3
Charnock	-2.6	10.9	0.8	10.3	-5.8	10.4
Wave age	-0.7	10.3	2.3	9.6	-3.7	10.0
Fetch	-1.9	10.7	1.3	10.1	-5.0	10.4

So far the data set selected for nearly stationary conditions has been used. For the application in the context of wind resource prediction all conditions have to be considered. The analysis has therefore been repeated with the unselected data set (Table 2).

Bias and rms-error are significantly increased compared to the stationary data set. For the assumption of a constant sea surface roughness the increase in bias is smaller than for the other models and only the wave age model has a slightly lower bias. The difference between stable and unstable conditions remains.

Table 2: Bias and root mean square error of modelled and measured neutral wind speed at 10 m height for different sea surface roughness models; data not selected for stationarity

	all data		stable data		unstab. data	
(all in%)	bias	rms	bias	rms	bias	rms
Constant	-4.7	16.3	-0.6	16.3	-7.6	15.6
Charnock	-5.2	14.9	-1.5	14.8	-7.8	14.4
Wave age	-3.7	14.4	-0.5	14.2	-5.9	14.0
Fetch	-4.9	14.8	-1.5	14.7	-7.2	14.3

The dependence of the model bias on stability can also be seen in the example time series shown in Figure 5. Atmospheric stability is plotted along with the measured and modelled wind speeds for a period of about 4 days. Atmospheric stability, shown in the upper part of the graph, changes from slightly stable at the beginning to slightly unstable at the end of the period. This is reflected in the deviations of the model results from the measured wind speeds. The models tend to underpredict wind speeds at the beginning and overpredict at the end.

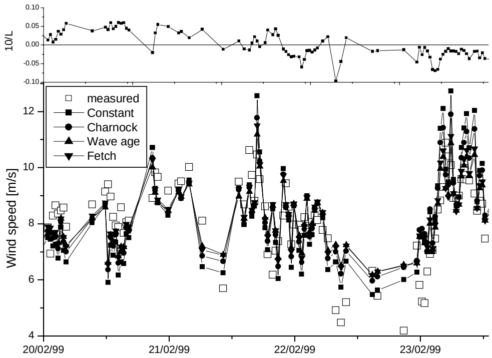

Figure 5: Time series plot of atmospheric stability (expressed as 10/L with L= Monin-Obukhov length) and measured and modelled neutral wind speeds at 10 m height

6 CONCLUSIONS

Different models to determine the sea surface roughness have been described. These are:

1. The simple assumption of a constant roughness, often used in wind power applications (e.g. WAsP).
2. The commonly used Charnock relation.
3. The wave age model, which aims to improve the Charnock relation by including effects of the wave field.
4. The fetch dependent model, which simplifies the wave age model for wind power applications by replacing the wave age by fetch, which is easy to determine.

Data from the Rødsand field measurement program in the Danish Baltic Sea have been used to investigate the potential of the wave age model and to test all models for their capability to predict the neutral 10 m wind speed.

The wave age model compares well with the measurement, although with a lot of scatter. However, self-correlation effects were found to have an influence on the observed relation. The possible improvement of the Charnock equation by including wave age is therefore smaller than what could be expected at first sight. Simultaneous bin-averaging of wave age and wind speed shows that the scaling of the relation is incomplete since it has a dependency on wind speed.

The different models were tested in their capability to predict the neutral wind speed at 10 m height from measured quantities. Differences were found in the bias of the different models, while the rms-error seems to be dominated by measurement errors and does not differ much between the models. For data selected for nearly stationary conditions the model performance is as expected: the wave age model performed best, followed by the fetch dependent model, the Charnock equation and finally the simple assumption of a constant sea surface roughness.

The picture changes if also non-stationary data is considered. The results deteriorate for all models, since now temporal changes in the geophysical conditions influence the relation between wind speed and friction velocity. The constant sea surface roughness performs relatively better and is only outperformed by the wave age model. This model does not have the dependency on the square of the friction velocity of the Charnock relation, which makes it robust in situations where the physical description of the Charnock relation breaks down due to non-stationary conditions.

Comparing conditions with different atmospheric stability shows that a large part of the deviation of all models is stability dependent. An improved modelling of the atmospheric stability is necessary.

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