

THE INFLUENCE OF WAVES ON THE WIND RESOURCE IN NEAR-SHORE WATERS

Bernhard Lange and Jørgen Højstrup*

Risø National Laboratory, P.O.Box 49, DK-4000 Roskilde, Denmark, e-mail: bernhard.lange@risoe.dk

*NEG Micon, Alsvej 21, DK8900 Randers, Denmark, email: jho@neg-micon.dk

Summary

Sea surface roughness plays a key role in the momentum exchange process between wind and waves and thus in air-sea interaction in general. For predicting the offshore wind climate it is therefore important to establish and refine models for the description of the sea surface roughness. Aim of the paper is to describe and compare available models of different complexity, which are interesting for wind energy applications. The analysis is confined to conditions of near neutral stability. The models are validated with data from the Rødsand measurement in the Baltic Sea, where a large database of simultaneous wind and wave data is available. Finally the models are compared with each other and the measurement in their capability to predict the 10 m wind speed from measured friction velocity. Significant differences in input requirements as well as accuracy exist between the models. Compared to the simple assumption of a constant sea surface roughness a large improvement can already be achieved with the Charnock relation. A significant further improvement is found for a more complex model that explicitly takes influences of the wave field into account.

1 Introduction

The favourable wind resource at offshore compared to land sites is caused by the very low surface roughness of the sea. The development of models describing the sea surface roughness is therefore of major importance for offshore wind power utilisation. The surface roughness length for land surfaces is typically in the order of centimetres to meters. For sea surfaces the value is typically below one millimetre. Also, for land surfaces it is usually taken as a constant depending only on the surface, i.e. independent of the wind flow. For water surfaces the roughness length depends on the wave field present, which in turn is dependent on the wind speed and other parameters like fetch, current, water depth, etc. Describing the sea surface roughness for wind resource studies has the aim of finding a simple empirical description for this complex dependency. Furthermore, the description should only depend on parameters usually available in wind resource studies, i.e. preferably not on parameters of the wave field.

2 Modelling sea surface roughness

The wind resource estimation model WAsP (Mortensen et al., 1993) of the European Wind Atlas (Troen and Petersen, 1989) is the standard method for wind resource estimations on land as well as offshore. WAsP assumes a constant value of 0.2 mm for the sea surface roughness. No dependency on wind speed or other parameters is taken into account.

Widely used in meteorological applications is the description by (Charnock, 1955), relating sea surface roughness to friction velocity by means of a single empirical constant:

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

where g is the gravitational acceleration and z_{ch} the so-called Charnock parameter. It works well for open ocean sites, but is problematic in coastal areas since it does not take into account fetch influences. The traditional way of fixing this problem has been to use increasing values of the Charnock parameter when approaching the coast. Experimental studies determined the Charnock parameter to approximately 0.011-0.014 for the open sea with fully developed waves. However, it has been found to be higher for coastal waters with values of 0.018 or more. The physical explanation for the increased roughness of near coastal waters is based on the fact that wind driven waves are most efficient in taking energy out of the mean flow when they are 'young', i.e. in the phase when they are growing rapidly.

From the point of view of offshore wind power utilisation the uncertainty in the Charnock parameter for coastal waters is unsatisfactory since this is the area most interesting for wind farm development. Many attempts have been made to refine the description of the sea roughness by including additional parameters, which better describe the wave field. We use the model developed by (Johnson et al., 1998), using an expression for the Charnock constant z_{ch} as a function of wave age c_p/u_* , where c_p is the phase velocity of the dominant wave component:

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

The constants were found to be $A=1.89$ and $B=-1.59$. Using (1) and (2), the sea surface roughness is calculated as:

$$z_0 = A \left(\frac{c_p}{u_*} \right)^B \frac{u_*^2}{g} \quad (3)$$

Measured wave data are necessary to apply the wave age dependent roughness model. Since these often are not available in practical applications, the empirical relation by (Hasselmann et al., 1973) is used to relate the wave age to fetch (defined as distance to the nearest upwind coastline):

$$\frac{f_p u_{10}}{g} = C \left(\frac{xg}{u_{10}^2} \right)^D \quad (4)$$

Here f_p is the peak frequency, x the fetch in metres and u_{10} the wind speed at 10 m height. The constants were found to be $C=3.5$ and $D=-0.33$. Using the deep water approximation of the dispersion relation and the logarithmic wind profile leads to an expression for the wave age:

$$\frac{u_*}{c_p} = C \cdot \frac{\kappa}{\ln\left(\frac{10}{z_0}\right)} 2\pi \left(\frac{xg}{u_{10}^2} \right)^D \quad (5)$$

We combine equations (3) and (5) to:

$$z_0 = AC^{-B} (2\pi)^{-B} \kappa^{2-B} g^{-BD-1} \left[\ln\left(\frac{10}{z_0}\right) \right]^{B-2} \frac{u_{10}^{2+2BD}}{x^{BD}} \quad (6)$$

This implicit equation can be used to determine the sea surface roughness solely from u_* and fetch.

3 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).



Figure 1: Rødsand measurement site

Simultaneous wind and wave measurements are performed since April 1998. The measurement is part of a Danish study of wind conditions for proposed offshore wind farms. For a description of the measurement and the data analysis see (Lange and Højstrup, 2000). For this analysis data have been selected for near neutral stability ($-0.5 < z/L < +0.3$ with $z=50\text{m}$) and a single peaked wave spectra (bandwidth < 0.25). This excluded about 60% of the

available data. The remaining 2300 half-hourly records were used for comparison with different models (chapters 4 and 5) and for the application test (chapter 6).

4 Wave age dependent sea surface roughness

To validate the approach by (Johnson et al., 1998) (equation 3) the Charnock parameter z_{ch} and the wave age have been derived from each measurement record.

A comparison of measurement and model is difficult since the data show large scatter, especially for small inverse wave ages, i.e. old waves. For a comparison with the model the data have therefore been sorted into bins with respect to their inverse wave age. The parameters u_{10n} , u_* and c_p are averaged within each bin. This is done since these parameters are physical quantities and the spreading of the values due to statistical processes can be assumed to approximately follow a normal distribution. This would not be the case for e.g. the sea surface roughness or the Charnock constant. From these averages the bin values of z_{ch} are derived for each bin. The standard deviation of the means of u_{10n} and u_* have been used to estimate a standard deviation of the mean of the bin value of z_{ch} . The result is shown in Figure 2. Also shown is the relation from (Johnson et al., 1998) (equation 3). The agreement is excellent.

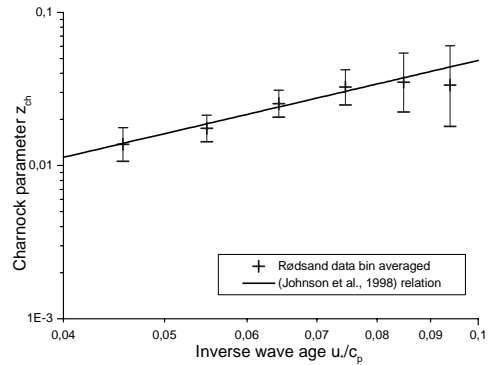


Figure 2: Charnock constant versus wave age from Rødsand data; bin averages with respect to wave age are shown in comparison with the relationship proposed by (Johnson et al., 1998).

5 Fetch dependent sea surface roughness

For the described model of wave age dependent sea surface roughness it is necessary to know the wave age. This requires wave measurements, which are often not available. An empirical description relating the wave age to fetch has been proposed by (Hasselmann et al., 1973). Their approach is to assume a power law between the dimensionless fetch and the dimensionless peak frequency (equation 4).

The two models of wave age dependent sea surface roughness and fetch dependent wave age can be combined to a fetch dependent sea surface

roughness model. This allows to estimate the roughness from wind speed and fetch alone. The 3 models which do not require wave parameters as input are compared in Figure 3: The constant roughness model, the Charnock relation and the fetch dependent model. For the fetch dependent model results for the two fetches of 10 km and 100 km are shown. Two parameterisations are compared: One where the parameters are taken from literature (Hasselmann et al., 1973), (Johnson et al., 1998) and (Troen and Petersen, 1989) and one with parameters fitted to the Rødsand data set.

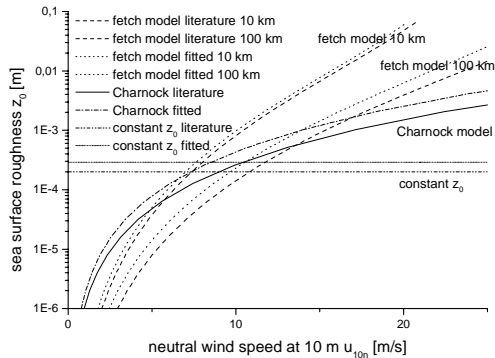


Figure 3: Comparison of different models of sea surface roughness versus neutral wind speed at 10 m height; shown are the constant roughness model, the Charnock model and the fetch dependent model for the two fetches 10 km and 100 km; results are shown for original constants taken from literature as well as for constants fitted to the data set

Using model constants fitted to the measurement data does not lead to large differences in the modelled roughness. The values of the constants used are shown in Table 1. The fitted constants lead to higher roughness in all models.

For the most frequent wind speeds between 5 and 10 m/s the difference between the different models is small. The largest difference between the Charnock relation and the fetch dependent formulation is found for the shorter fetches and high wind speeds, where the fetch dependent model predicts a higher roughness.

Figure 4 shows the sea surface roughness versus neutral wind speed at 10 m height for the Rødsand data set. The data have been sorted with respect to wind speed, the averages of wind speed and friction velocity have been built and bin values of sea surface roughness have been calculated for each bin from these averages. The data are compared to the Charnock relation, the fetch dependent model and a constant roughness. Parameters from literature have been used for the models. For the fetch dependent model the two extreme fetches of 10 and 100 km are shown.

Generally, a large roughness is measured at low wind speeds. At 7 m/s it reaches a minimum. At low wind speeds effects of smooth flow and capillary waves become dominant, which are not modelled by the models used here.

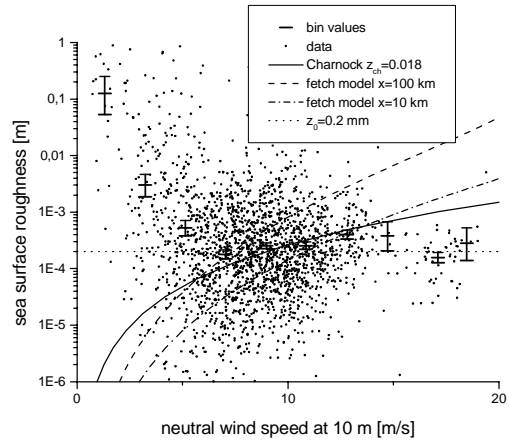


Figure 4: Sea surface roughness versus neutral wind speed at 10 m height from the Rødsand measurement; data, bin values for the data with standard deviation of the mean, Charnock relation, fetch dependent relation and constant roughness model are shown

For wind speed bins from 7 to 11 m/s the measured values are very close to the results of all three models. For 13 and 15 m/s the Charnock relation seems to be closest to the measured bin values, while for even higher wind speeds the constant roughness of 0.2 mm is closest. However, only very few data are available for wind speeds above 14 m/s and conclusions can not be based on these.

6 Test of different models

Due to the large scatter in the measurement data a direct comparison of the different models with the measurement is unsatisfactory. Therefore the models have been used to predict the wind speed at 10 m height from the measured friction velocity and wave speed c_p or fetch. This has been done for each measurement record and the difference between predicted and measured wind speed has been compared statistically by their root mean square error and correlation coefficient r^2 . The results are shown in Table 1.

The constant roughness model shows the highest rms error of 2.21. Using constants fitted to the Rødsand data decreases the rms error by 4%. Using the simple Charnock relation decreases the rms error by 18% (literature constants) and 20% (fitted constants). The winner of this test is the (Johnson et al., 1998) relation with a decrease of rms error of 28% independent of the set of constants used. However, when no wave measurement is available and the model is extended to a fetch dependent model the improvement is reduced to 21% (literature constants) and 23% (fitted constants). Generally it can be seen that differences between the models are large compared to differences between different sets of constants from literature and from a fit to the data.

Table 1: Test of different models for sea surface roughness: time series of measured and modelled neutral wind speed at 10 m height are compared by their root mean square error and correlation coefficient; measured parameters are used as input to the models; the constants used in the different models are taken from literature and from a fit to the measured data

model	constants	r^2	rms
WAsP	literature: $z_0=0.2$ mm	0.64	2.21
	Rødsand fit: $z_0=0.289$ mm	0.64	2.12
Charnock (eq. 1)	literature: $z_{ch}=0.018$	0.67	1.81
	Rødsand fit: $z_{ch}=0.0273$	0.67	1.77
(Johnson et al, 1998), (eq.3)	literature: A=1.89 B=-1.59	0.72	1.60
	Rødsand fit: A=2.86 B=-1.70	0.72	1.59
(Johnson et al, 1998) and (Hasselmann et al, 1973), (eq. 6)	literature: A=1.89 B=-1.59 C=3.5 D=-0.33	0.67	1.75
	Rødsand fit: A=2.86 B=-1.70 C=1.68 D=-0.23	0.67	1.71

7 Conclusion

Aim of the paper is to describe, validate, test and compare models for the sea surface roughness, which might be useable for offshore wind energy applications. The analysis has been confined to the case of near neutral stability and locally generated wind waves and focused on wind speeds above 5 m/s. Simultaneous wind and wave measurements from the meteorological mast Rødsand in the Danish Baltic Sea have been used to validate and test the models. Two approaches have been followed: First, a direct comparison of the measured and modelled sea surface roughness or Charnock parameter has been made. Secondly, the capability of the different models to predict the neutral wind speed at 10 m height from the measured input parameters has been tested and compared statistically. The following conclusions can be drawn:

1. A comparison of bin averaged values of measured Charnock parameters with values modelled by the wave age dependent model showed an excellent agreement. However, the statistical scatter in the measured data is enormous.
2. The comparison of the different models with measurement data on the basis of bin averages for wind speeds did not yield a conclusive result. The scatter in the measurements is much larger than the differences between the different models.
3. As expected from the different complexity of the models the test of wind speed prediction showed significant differences between the models. Compared to the constant roughness model the

Charnock relation yields a reduction rms error of about 19%, the wave age dependent model of about 28% and the fetch dependent model of about 22%. As expected, the Charnock relation is an improvement compared to the assumption of a constant roughness. The wave age dependent model again improves the prediction significantly compared to the Charnock model, while the fetch dependent model only yields minor improvements.

4. For each of the models different sets of constants have been compared: the performance with typical constants taken from literature was compared with that using constants fitted to the measurement data. The difference between different sets of constants is small (0-4%) compared to the differences between the models.

8 Acknowledgements

The Rødsand measurement was funded by the Danish Energistyrelsens Udviklings-programmet for Vedvarende Energi in the 'Offshore wind resources' project (contract no: UVE J.nr. 51171/96-0040). The work of one of the authors (B. Lange) is funded by the European Commission through a Marie Curie Research Training Grant.

9 References

- Charnock, H.: Wind stress over a water surface. in: Quarterly Journal of the Royal Meteorological Society, Vol. 81, pp.639-640, 1955
- Hasselmann, K., T. P. Barnett, E. Bouws, H. Carlson, D. E. Cartwright, K. Enke, J. A. Ewing, H. Gienapp, D. E. Hasselmann, P. Kruseman, A. Meerburg, P. Müller, D. J. Olbers, K. Richter, W. Sell and H. Walden: Measurements of Wind-Wave Growth and Swell Decay during the Joint North Sea Wave Project (JONSWAP). in: Deutsche Hydrogr. Zeits., Reihe A, Vol. 12, No.8; 1973
- Johnson, H.K., J.Højstrup, H.J.Vested, S.E.Larsen: On the dependence of sea surface roughness on wind waves. in: Journal of Physical Oceanography, Vol.28, pp.1702-1716; 1998
- Lange, B. and J. Højstrup: The influence of waves on the offshore wind resource. in: Proceedings of the European Seminar OWEMES, Sicily (Italy) 2000: pp. 491-503
- Mortensen, N.G., L.Landberg, I.Troen and E.L.Petersen: Wind Atlas Analysis and Application Program (WAsP). Risø National Laboratory, Roskilde, Denmark. 1993
- Troen, I., E.L. Petersen: European Wind Atlas. Risø National Laboratory, Roskilde, Denmark. 1989