THE INFLUENCE OF WAVES ON THE OFFSHORE WIND RESOURCE

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ABSTRACT: With the growing interest in offshore wind resources, it has become increasingly important to establish and refine models for the interaction between wind and waves in order to obtain accurate models for the sea surface roughness. The simple Charnock relation that has been applied for open sea conditions does not work well in the shallow water near-coastal areas that are important for offshore wind energy. A model for the surface roughness of the sea has been developed based on this concept, using an expression for the Charnock constant as a function of wave age [1], and then relating the wave 'age' to the distance to the nearest upwind coastline. The data used in developing these models originated partly from analysis of data from the Vindeby site, partly from previously published results. The scatter in the data material was considerable and consequently there is a need to test these models further by analysing data from sites exhibiting varying distances to the coast. Results from such analysis of recent data are presented for sites with distances to the coast varying from 10km to several hundreds of km. The model shows a good agreement also with this data.
Keywords: Wind resource, Off-shore, Meteorology, Waves

1. INTRODUCTION

The favourable wind resource at offshore sites is caused by the very low surface roughness of water areas. The development of models describing the sea surface roughness is therefore of major importance for offshore wind power utilisation. Widely used is the model by Charnock [2]. 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 constant in the Charnock relation when approaching the coast. 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.
The model by Johnson et al [1] is based on this concept and gives an explicit description of the sea surface roughness depending on wave age. Using an equation by Hasselmann et al [3] relating wave age to fetch, this model can be utilised to predict the sea surface roughness depending on wind speed and fetch only. It has been developed using data from the Vindeby site and from literature. Here it is tested further by analysing data from the two sites Rødsand and Östergarnsholm in the Baltic Sea. Fetches at these sites are in the range of 10 to 200 km. Published results from two other stations are included for comparison. The results are compared with the Charnock model and the model by Johnson et al.

2. MODELING THE SEA SURFACE ROUGHNESS

The surface roughness is used to describe the influence of the surface on the logarithmic vertical wind speed profile. For neutral atmospheric stability it can be written as:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \qquad (1)$$

where u(z) is the mean wind speed at height z, u_* the wind friction velocity, κ the von Karman constant and z_0 the surface roughness length.
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 the surface roughness length usually is 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 to find 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.
Widely used is the description by Charnock [2], relating the sea surface roughness to the friction velocity by means of a single empirical constant:

$$z_0 = A_C \frac{u_*^2}{g} \qquad (2)$$

where g is the gravitational acceleration and A_C the so-called Charnock constant. Experimental studies determined the Charnock constant to approximately 0.011 for the open sea with fully developed waves. However, the 'constant' has been found to be somewhat higher for coastal waters with a value of 0.018 (or more) usually assumed here.
The uncertainty in the Charnock constant for coastal waters is unsatisfactory from the point of view of offshore wind power utilisation since this is the area most interesting for wind farm development. Johnson et al [1] showed that the Charnock constant can be described ass a function of the 'wave age':

$$A_C = 1.89\left(\frac{c_p}{u_*}\right)^{-1.59} \qquad (3)$$

where c_p is the phase velocity of the dominant wave component. The term c_p/u_* is called wave age. Since the wave age or c_p usually are not available for wind power studies, a relation between wave age and fetch is needed. Hasselmann et al [3] found the following relation from the JONSWAP data:

$$\frac{u_*}{c_p} = \frac{3.5}{2\pi}\left(\frac{xg}{u_{10}^{\;2}}\right)^{-1/3} \qquad (4)$$

where x is the fetch in metres and u_{10} the wind speed at 10 m height. We approximate equation (3) by:

$$A_C = 1.54\left(\frac{c_p}{u_*}\right)^{-3/2} \qquad (5)$$

and combine equations (2), (4) and (5) to:

$$z_0 = 0.64\frac{u_*^2\,u_{10}}{x^{1/2}g^{3/2}} \qquad (6)$$

using equation (1) to eliminate u_{10} yields:

$$z_0 = 0.64\frac{u_*^3}{x^{1/2}g^{3/2}\kappa}\ln\left(\frac{10}{z_0}\right) \qquad (7)$$

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

3. SEA SURFACE ROUGHNESS DETERMINED FROM MEASUREMENTS

3.1 Determination of the sea surface roughness

The surface roughness length is defined as the intercept of the turbulent wind speed profile with the height axis. This is a mathematical concept and z_0 does not have a physical existence. Therefore it can not be measured directly, but has to be derived from atmospheric measurements by theoretical considerations. Different approaches are possible here. The most direct determination is from the measured wind profile, i.e. wind speeds at different heights. The problem of this method for determining very small roughnesses is its sensitivity for errors in the wind speed measurements. Even very small errors lead to a large deviations in the resulting values for z_0. Another possiblity is the use of a measured friction velocity. Equation (1) can be rewritten as:

$$z_0 = \frac{z}{\exp\left(\frac{u(z)\kappa}{u_*}\right)} \qquad (8)$$

The difficulty is the large uncertainty usually involved in the measurement of the friction velocity. Here a third method is employed: It is assumed that the standard deviation of the wind speed σ_u is proportional to the friction velocity u_*:

$$u_* = C\sigma_u \qquad (9)$$

The constant C is usually taken as 2.5. Taking 0.4 for the von Karman constant while substituting u* in (8) by (9) yields:

$$z_0 = \frac{z}{\exp\left(\frac{u(z)}{\sigma_u}\right)} \qquad (10)$$

This is in the following used for a determination of z_0. This approach is of course restricted to neutral (or near neutral) atmospheric stability.

3.2 Rødsand measurement

Wind and atmospheric measurements are performed at the offshore mast Rødsand south of the Danish island Lolland (see figure 1) since October 1996. The measurement is a part of a Danish study of wind conditions for proposed offshore wind farms (see[4]). Wind speed measurements are performed at heights 10, 30 and 48m by cup anemometers and at 43 m height by a sonic anemometer. Wave and current data are also collected as well as several atmospheric parameters. Data are collected as half hourly averages. They have been quality checked and records with possible mast shading have been excluded. About 10000 records are available for the analysis.

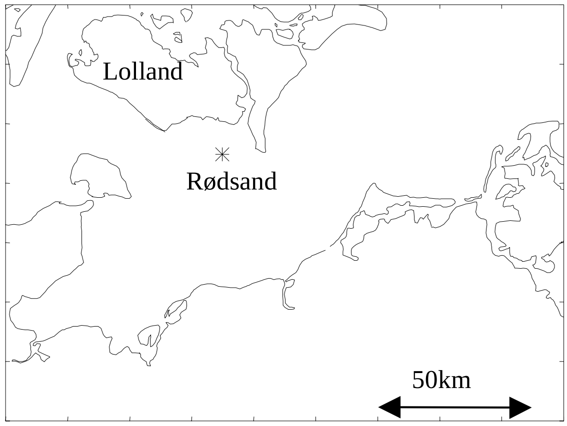

Figure 1: *Rødsand measurement site*

A data subset has been selected containing only near neutral data. Richardson numbers have been used to determine the near neutral cases. Data with $-0.3<Ri<0.02$ have been selected. This leaves about 2500 records for the analysis. Wind direction sectors corresponding to different fetches have been selected. For each sector the data were bin-averaged according to wind speeds. The sea surface roughness was calculated from the averaged wind speeds and standard deviations at 10 m height according to equation (10).

3.3 Östergarnsholm measurement

Wind and atmospheric measurements at the measurement station Östergarnsholm were performed by the Department of Meteorology, Uppsala, in the BALTEX (Baltic sea Experiment) experiment [5]. Measurements took place on the island Östergarnsholm, which is located west of the bigger Swedish island Gotland in the Baltic Sea.(see figure 2). Wind measurements were performed at a mast situated on the southernmost tip of the flat island. For a more detailed description of the measurement see [5]. For this study data from two campaign measurements were available. The first took place from 19th to 25th September 1996, the second from 29th April to 10th May 1997. Among other measurements wind speeds were measured at 5 heights from 6.7 to 28.6m. Data are collected as 10 minute averages.

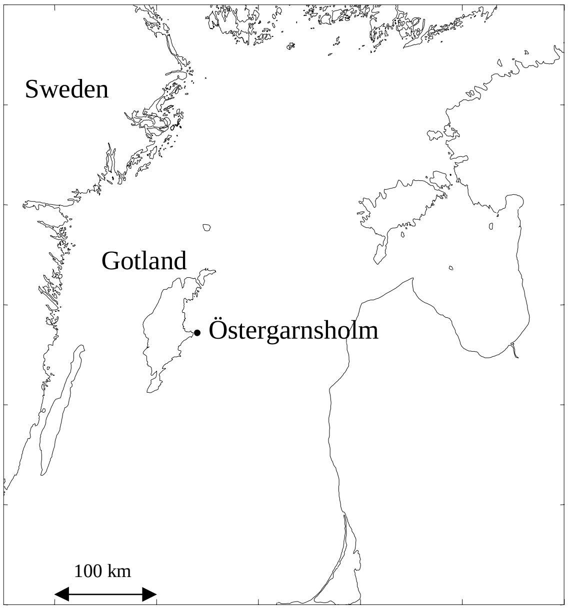

Figure 2: *Östergarnsholm measurement site*

Richardson numbers have been calculated to select near neutral data. As for Rødsand, data with -0.3<Ri<0.02 have been allowed. The Östergarnsholm measurement contains mainly unstable data for the first measurement period and mainly stable or very stable data during the second period (see also [2]). Therefore only 340 records were left for the analysis. One wind direction sector with undisturbed sea fetch of more than 150 km has been used for the analysis. Analysis was done as for Rødsand, but for a wind speed measurement at 6.7 m height. Figure 3 shows the result.

3.4 Comparison with Nibe and Vindeby measurements

The sea surface roughnesses found from the Rødsand and Östergarnsholm measurements are compared with earlier published results from the Nibe and Vindeby measurements [6], [7]. The sea surface roughness was calculated with the same method as described above for near neutral data. Wind directions with upstream fetches over water of 7-15 km were used in both cases. Figure 3 shows the results of all four measurements. Two wind direction sectors with different fetches were used for the Rødsand measurement.

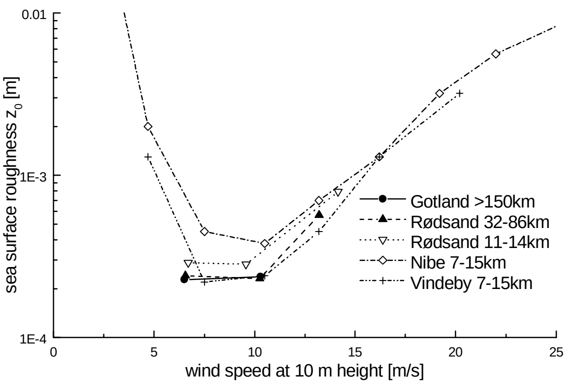

Figure 3: *Sea surface roughness versus wind speed for different fetches at the sites Rødsand, Östergarnsholm, Nibe and Vindeby for different fetches*

The measured values for the sea surface roughness are very close to each other with the exception of Nibe which gives slightly higher results. For low wind speeds <10 m/s the z0 values determined from the measured standard deviations are very large. This is probably due to instationary situations with fluctuating wind speeds and does not reflect the surface roughness.

4. COMPARISON WITH MODELS

A comparison of the measured and modelled sea surface roughness over wind speed is shown in figures 4 and 5. The measured data from figure 3 is plotted together with values calculated with the Charnock model (eq. 2) and the model based on Johnson et al (eq. 7).

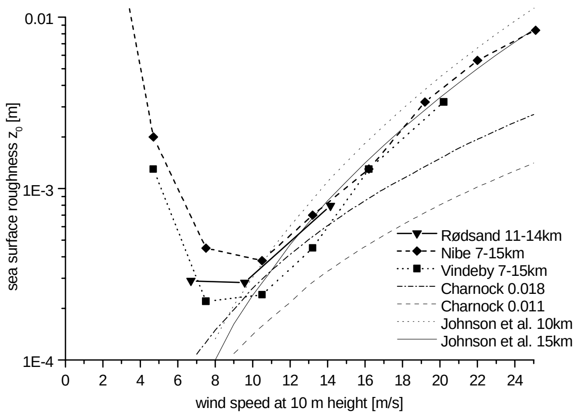

Figure 4: *Measured and modelled sea surface roughness versus wind speed for medium fetches*

Figure 4 shows the results for medium fetches of 10-20 km. Both models are close to each other in the range of wind speeds where new measurements are available and agree well with the measurements The Charnock model (with A_C=0.018) (eq.2) compares slightly better to the new data, while the model by Johnson et al (eq. 7) performs clearly better for the Nibe and Vindeby data.

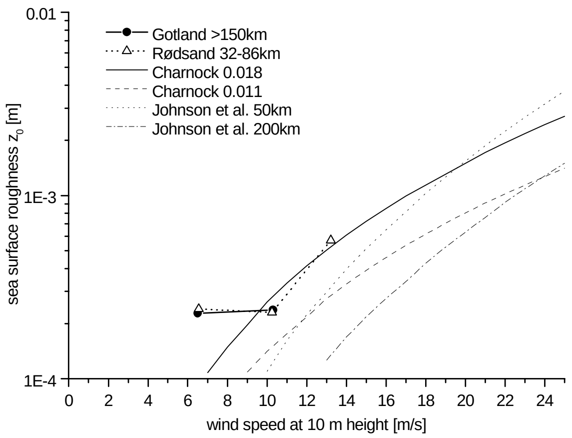

Figure 5*: Measured and modelled sea surface roughness versus wind speed for long fetches*

Figure 5 shows the results for long fetches of more than 30 km. Unfortunately only very few measured data are available for this situation.

Despite the difference in fetch are the data from Gotland with fetch exceeding 150 km and those from Rødsand with fetches of 32-86 km very close to each other.
Both models fit well to the three data points available for higher wind speeds. The slope of the measurements is fitted slightly better by the Johnson et al model. For the Charnock model the coastal value (0.018) fits best. However, more data points are needed to compare the models for these fetch situations.

5. CONCLUSION

The sea surface roughness has been determined from measurements from the sites Rødsand (south of Lolland, DK) and Östergarnsholm (west of Gotland, Sweden). The values found compare well with the published results from the Nibe and Vindeby sites.
The sea surface roughness has been determined from the measured standard deviation of the wind speed. This method gives rise to high values for the sea surface roughness at low wind speeds, which probably stem from instationarities and stability effects and do not reflect the surface roughness.
Results of the Charnock and the Johnson et al models are compared to the measurements. For medium fetches the model by Johnson et al. is in good agreement with the measurements from Nibe and Vindeby for higher wind speeds, while the few data available from the new measurement at Rødsand fit slightly better to the Charnock model (with constant 0.018). Only few measured data are available for long fetches. The two data sets from Östergarnsholm and Rødsand are very close to each other despite their different fetches. The Charnock model with a constant between 0.011 (open sea value) and 0.018 (coastal water value) as well as the Johnson et al. model for 50 km fetch agree well with the data.

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