Surface roughness for offshore wind energy

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Abstract. The Northeastern coast of the U.S. is expected to increase its offshore wind capacity from 30 MW today to 86 GW by 2050. Measurements of wind speeds are available near sea level, but not at hub height, thus extrapolation is often required using the surface roughness, $z_0$. The focus of this study is to estimate the surface roughness length off the Northeastern coast of the U.S. using field measurements from Nantucket Sound, MA, with three methods: 1) analytical, dependent on friction velocity and atmospheric stability, 2) the Charnock relationship between $z_0$ and friction velocity, and 3) a statistical method, based on wind speed observations at three heights. The main results of this paper are: a comparison of the three methods, a comprehensive error analysis of each method, a regional $z_0$ value of $10^{-3}$ m, and a new mathematical interpretation of surface roughness.

Keywords: Surface roughness, Charnock, offshore wind, logarithmic profile, wind farm

1. Introduction

The planned offshore wind sites along the East Coast of the U.S. have a potential capacity of 2,000 gigawatts (GW). This amount is about two times the combined energy generation from all electric power plants in the entire United States [1]. Also, the U.S. East Coast has the potential to provide its own electricity from offshore wind farms better than from any other form of energy generation [1]. So far, however, there is only one offshore wind farm in the U.S., at Block Island, off the coast of Rhode Island. Constructed in 2016, it is a 30-megawatt (MW) project which includes five 6-MW turbines.

The power production of wind turbines is directly proportional to the cube of wind speed at the turbine hub height [2]. Therefore, a precise prediction of wind speed at hub height will lead to precise estimates of energy production. In general, measurements of wind speeds at hub height are not available. Therefore, it is necessary to explore methods to predict wind speeds accurately from other available measurements. Aerodynamic surface roughness, $z_0$, is a critical parameter to extrapolate the wind velocity, measured at a reference height, to the hub height [3].

Surface roughness length is generally smaller in marine environments compared to inland. Over the ocean, surface roughness length depends on the wave height and length in such a way that steeper waves result in higher surface roughness lengths [4]. Kim et al. [5] concluded in their study that, while using wind measurements at higher elevations can result in smaller prediction errors, an inaccurate $z_0$ value would not have as significant an impact on wind speed calculations. Similarly, Lange et al. [6] suggest that a constant $z_0$ value is sufficient, since it may result in differences between the wind speed profiles and observations only at higher elevations, where the wind profile is relatively flat. On the other hand, other studies disagree on the importance of the surface roughness lengths. Wave characteristics were considered by Ueo and Deushi in their
calculations of surface roughness [7]. Similarly, water depth was reported to be an important factor in surface roughness calculations in the simulations done by Jimenez and Dudhia [8].

Frank et al. [9] concluded that, in near-neutral and stable conditions in offshore flows, the wind speeds are underestimated at higher elevations above the water. Results of the current study are in agreement with their findings only for stable conditions. Archer et al. [10] also found that atmospheric stability impacts wind shear in the atmospheric boundary layer and is an important factor in designing wind farms.

Displacement height is another factor that has been considered for $z_0$ calculations. For instance, Kim et al. [5] reported that, when the sea surface level varies significantly, a displacement height should be considered in calculations to compensate. Tidal variations were considered by Khan et al. and Elkinton et al. [11, 12]. The former found that the wind speed ratios at two heights were dependent on tidal variations, whereas the latter reported no impacts of tides on the wind profiles.

Lackner et al. [13] used the power law and the log law to predict the wind profiles at different sites and concluded that using a shear correction factor reduced the RMSE significantly. Elkinton et al. [12] recommended a value of 0.1 m for surface roughness length in the Nantucket sound area using data from two heights. Their method to calculate $z_0$ was similar to the equation derived for $z_0$ by Archer and Jacobson [14], which was also used as the statistical method in our previous study [15] based on three measurement heights. There we suggested a value of $6 \times 10^{-3}$ (m) for the Nantucket sound region using the statistical method, which is discussed further in this study.

In our previous study [15], the best estimates of the $z_0$ value were obtained based on data available from three different field campaigns using three different methods. Then, using the $z_0$ values, the wind velocity profiles were predicted. As an extension of the previous study, this paper focuses on the error analysis and accuracy of each of the three methods.

This paper is organized as follows. First, the datasets collected during the three field campaigns are introduced, followed by a short explanation of each of the three methods. Next, the error analysis results are presented for each method. This includes the correlation between estimated and actual wind speed, as well as time series of prediction errors and effects of stability.

2. Data and methodology

This study uses three datasets. The first was measured at the Cape Wind (CW) meteorological tower at three levels, 20, 41, and 60 m AMSL, in 2003–2007 and contains approximately 227,000 records. The CW dataset consists of 10-minute observations of meteorological variables, such as wind speed and direction, heat and momentum fluxes, temperature etc. The second dataset includes high-frequency wind and flux measurements at 12 m AMSL, measured at the same CW platform but during the IMPOWR campaign in 2013–2014 and includes approximately 105,000 10-minute measurements. The third dataset was measured in Lewes, Delaware and is from the VERTEX campaign. It includes 10-minute wind speed observations from 5 heights: 10, 25, 33, 42, and 49 m, with approximately 19,500 records. More information about the first two datasets can be found in [10, 15].

The wind speed at higher elevations can be fit to the so-called “log law” as follows:

$$U(z) = U(z_0) + \frac{u_*}{k} \log \left( \frac{z - d}{z_0} \right) - \psi,$$

where $U(z)$ is the wind speed at height $z$ AMSL, $U(z_0)$ is the surface current, $d$ is the displacement height, $\psi$ is the stability correction factor, and $u_*$ is the friction velocity, which is related to the shear stress at the surface [16]. Friction velocity is a function of observed turbulent momentum fluxes as follows:

$$u_* = \sqrt{u'w'^2 + v'w'^2}$$
where $\overline{u'w'}$ and $\overline{v'w'}$ are the covariances of the observed turbulent momentum fluxes. As the region of focus for this study is a marine environment, $d$ is assumed to be negligible. Due to the lack of observations of surface current speed, we neglected the term $U(z_0)$. As such, $U(z_0)$ is assumed to be zero in this study, just like inland.

An alternative form of the log law that is independent of $u_*$ is given by:

$$U(z) = U(z_R) \frac{\log \left( \frac{z}{z_0} \right)}{\log \left( \frac{z_R}{z_0} \right)},$$

(3)

where $z_R$ is a reference height. We will refer to this second form of the log law in Eq. 3 as “simplified log law” since it does not require any flux measurements or stability information. Both equations are functions of $z_0$. However, the simplified log law does not include the impact of stability on the wind profile.

Three approaches were used in this study to calculate surface roughness: 1) Charnock relation, 2) analytical solution, and 3) statistical method.

**Charnock method**

The Charnock relation is given by:

$$z_0 = \alpha \frac{u_*^2}{g},$$

(4)

where $\alpha$ is the Charnock parameter, which mostly depends on the wave age [6, 7]. Many studies have calculated $\alpha$ with different methods, including fitting field data [17]. For instance, Frank et al. [9] suggested a value of 0.018 for coastal areas and 0.011 for open seas, while Lange et al. [6] used a value of 0.0185 for their calculations. However, a review by Garratt [18] concluded that the average value for $\alpha$ in the literature is 0.0144, which was therefore used in this study and in Van Wijk et al. [19].

With this method $z_0$ is a function of friction velocity $u_*$ and is independent of atmospheric stability. However, since a 3D sonic anemometer can provide both $u_*$ and stability information, either Eq. 1 or Eq. 3 can be used to calculate $U(z)$ once the estimate for $z_0$ from Charnock is obtained. With the Charnock relation, $z_0$ can be interpreted as the result of wave disturbances on the water surface.

**Analytical method**

In the analytical method, the log law (Eq. 1) was solved for $z_0$ using the measured values of the physical parameters (wind speed, friction velocity, and atmospheric stability) at each time. Rearranging Eq. 1 results in a relation for $z_0$:

$$z_0 = \frac{z_R}{\exp \left( \frac{\kappa U(z_R)}{u_*} + \psi \right)},$$

(5)

where $\kappa$ is the Von Karman constant, 0.40, and $\psi$ is the stability function.

**Statistical method**

A statistical method to extrapolate wind speed data to hub height was derived by Archer and Jacobson [14,20]. The statistical method, which is based on the least-square-error approach, fits wind speeds at various heights to a log profile and it is therefore a purely mathematical construct. This means that the estimates for $z_0$ may necessarily have a physical interpretation. In some cases $z_0$ may be orders of magnitude larger or smaller compared to those obtained with other methods. Despite the possibility of non-physical $z_0$ values, this method results in the most
accurate predictions for wind speed. The equation to calculate $z_0$ using data from heights $i = 1, 2, \ldots, N, N \geq 3$ is:

$$\ln(z_0) = \frac{U(z_R) \left\{ \sum [\ln(z_i)]^2 - \ln(z_R) \sum \ln(z_i) \right\} - \ln(z_R) \sum \left[ U_i \ln \left( \frac{z_i}{z_R} \right) \right]}{U(z_R) \sum \ln(z_i) - \sum \left[ U_i \ln \left( \frac{z_i}{z_R} \right) \right] - N \cdot U(z_R) \ln(z_R)},$$

where $U_i$ and $z_i$ are the wind speed and height at data point $i$ at a single time instance.

The statistical method requires measurement data at least from three different heights. It effectively incorporates the impact of stability, the friction velocity and surface currents using the least-square-error approach and is therefore appropriate to use with equation 3.

3. Error analysis

Using the three methods described above, $z_0$ values were calculated at every time step. Then, wind speed profiles were predicted for each record using the specific $z_0$ value. A summary of the time averaged predicted wind profiles versus the observations was provided in Fig. 1, taken from [15], which shows the average of all wind profiles from stable, unstable, and neutral atmospheric conditions. The ultimate goal of this study is to characterize the accuracy of each method in predicting wind speed at the turbine hub height.

![Average wind speed profiles](image)

Figure 1: Mean wind speed profiles predicted using $z_0$ values obtained with the three methods presented here. The observations are displayed with solid circles. The figure is obtained from [15].

From the results summarized in Fig. 1, it was deemed necessary to take a closer look at the error distribution for each method.

One concern with analyzing the average profiles was the large overall uncertainty. An average of the errors may result in a small overall error, since positive and negative values can cancel out during the averaging process. Despite the fact that the statistical method gives the lowest average error, the average may not be representative of the actual wind profiles. Therefore, an in-depth error analysis was deemed necessary to confirm our previously published findings [15].

In principle, to predict the wind speed profile offshore, five physical characteristics of a surface are relevant: surface roughness length, wind speed at a reference height, atmospheric stability, friction velocity, and the surface current. The focus of this work is on surface roughness,
which, from a physical interpretation, represents an average height of the obstacles in the area. Therefore, it is a constant value over the land; it could, however, vary with time offshore and in ocean environments due to the waves in the area. In this definition, surface roughness has a physical meaning and is a physical parameter.

Meanwhile, another definition for the surface roughness is purely mathematical, i.e., $z_0$ is the y-intercept of the wind profile with the height axis. This corresponds to the height where wind speed becomes zero. In this definition, $z_0$ is no longer a physical parameter, but just a mathematical constant that contains information about all five physical parameters. As the wind profile is dependent on the other four factors, and $z_0$ depends on the wind profile, we can infer that $z_0$ also depends on these same parameters. In the latter definition of $z_0$, no physical meaning for $z_0$ may be sought and it should be treated as a mathematical parameter which minimizes the prediction error for wind speeds at the turbine hub height. With this interpretation, and unlike all other methods, no bounds on the value of $z_0$ are required.

In cases with non-monotonic wind profiles, i.e., in which wind speed does not increase monotonically with height, but either decreases or zig-zags, the resulting $z_0$ may be very large or very small. These cases are neglected when using other methods, as they would invalidate the physical meaning of surface roughness length. However, in the statistical method, where $z_0$ is found through an error minimization problem, we will not seek any physical meaning for these values and therefore we will use all available data in the analysis. This approach may lead to concerns, as the time-averaged wind profile may not be representative of the wind profile at any particular time. Further error analysis performed in this study will reveal the nature of each method and quantify their prediction accuracy.

Results

Wind speed prediction errors

A correlation between observed and predicted wind speeds at 60 m for each method is given in Fig. 2. Equations 4 – 6 were used to calculate $z_0$ by each method. The wind speed at 60 m was then predicted by using this surface roughness in Eq. 1 for Charnock and analytical methods and Eq. 3 for the statistical method.

![Figure 2: Correlation between measured wind speeds at 60 m and calculated wind speeds at 60 m by each method used in this study.](image-url)
It can be seen from Fig. 2 that the Charnock method is more scattered compared to the other two methods, which implies that it is not as reliable at predicting the wind speed. This is especially true at higher wind speeds, which are most relevant for wind energy applications. On the other hand, the analytical and statistical methods show a much stronger correlation, with a slope near one. This indicates a good correlation between the predictions by these two methods and the observations. Between these two methods, the statistical method appears the most promising.

Fig. 3 shows the error time series for each method. It is clear from the figure that the Charnock method (Fig. 3a), as discussed above, results in the highest prediction errors, especially at 60 m, which is near the hub height of modern wind turbines. In addition, the error magnitude appears to increase with height. Therefore, for modern turbines with hub heights approaching 100 meters, a significant error is expected.

Fig. 3b shows the error of the analytical method. The range of errors is much smaller compared to the Charnock method. The error at 20 m is nearly zero, since the analytical method is directly using the observations at the 20-m reference height to calculate $z_0$.

Fig. 3c is the prediction by the statistical method. The statistical method results in much smaller errors compared to the other two methods. This result is in agreement with our previously published work and confirms our previous findings. This is expected, as the statistical method requires data from at least three heights to calculate $z_0$. Similar to the analytical method, the error at 20 m is close to zero.

Note that, with the Charnock method, the calculated $z_0$ values are not a function of wind speed at the reference height $U(z_R)$, but are a function of $u_*$ only, which was measured by the sonic anemometer (Eq. 2). Therefore, the error occurring at the reference height by Charnock method is not zero and can be high. By contrast, in the analytical and statistical methods, the $z_0$ values are a function of $U(z_R)$ and the resulting fitted profiles are forced to go through $U(z_R)$. Therefore, there should be no error in the wind speed at the reference height with the analytical and statistical methods.

To quantify the range of prediction error for each method, the 90th percentile of the absolute error was taken for each method. The 90th percentile of prediction error resulting from the Charnock method is approximately 2.7 m/s, meaning that 90% of the time the error is below 2.7 m/s. By contrast, the 90th percentile for the analytical and statistical methods at CW are 0.9 m/s and 0.2 m/s respectively.

As another comparison, the percentage of wind speeds within an acceptable range was calculated. In wind farm applications, a 5% uncertainty is considered to be the acceptable range for wind speed prediction errors [21]. With an average wind speed of 9 m/s at 60 m height, this corresponds to an error of ± 0.5 m/s. The percentage of all predictions falling within this range are given in Table 1.

Effect of stability

Atmospheric stability is an important physical parameter in wind speed calculations, and as such it plays an important role in the wind profile’s shape. The Obokhove length $L$, is used to estimate the stability. $L$ represents the height at which the turbulence production by buoyancy dominates over that by mechanical effects, such as shear and friction [22], and it is calculated as follows:

$$L = -\frac{u_*^3}{\kappa g T_s}$$

where $w'T_s$ is the sonic heat flux, $\kappa$ is the von Kármán constant ($\kappa = 0.41$), $g$ is gravity, and $T_s$ is the near-surface sonic temperature. Note that we use sonic temperature (from the lowest-level anemometer) as an approximation for virtual temperature [10].
Figure 3: Error resulting from: a) Charnock, b) analytical and c) statistical methods at 20, 41 and 60 m. The reported error is in m/s for each time step during 2003–2007.

The value of $L$ is infinite in a neutral atmosphere. Conversely, in both stable and unstable conditions, the magnitude of $L$ is small and the sign is positive and negative, respectively. However, in practice the measured heat flux is never exactly zero and therefore thresholds for $L$ in neutral conditions have been proposed in the literature. Here we use $|L| > 500$ m, following Archer et al. [10]. Since $L$ can vary by orders of magnitude, an alternative is to use the stability parameter $\zeta$:

$$\zeta = \frac{z_s}{L},$$

where $z_s$ is the height of the sonic anemometer, thus 20 m for CW and 12 m for IMPOWR. Based on the stability parameter, the atmospheric stability is assessed as follows:

- Stable: $\zeta > \frac{z_s}{500}$
- Unstable: $\zeta < -\frac{z_s}{500}$
- Neutral: $|\zeta| \leq \frac{z_s}{500}$
High and positive $\zeta$ values correspond to stable atmospheric conditions, while large negative $\zeta$ values correspond to unstable conditions. Unstable cases are dominant in the study region [10, 15].

Next, the three different methods are partitioned by stability and evaluated (Fig. 4). Similar to the prior analysis, the Charnock method has the largest variance in accuracy over all stabilities. However, it appears to systematically underestimate the wind speeds in stable cases. The wider scatter in unstable cases indicates higher uncertainty in wind speed predictions by the Charnock method in unstable conditions, which unfortunately are dominant at this offshore location. The analytical and statistical methods show a much lower variance compared to the Charnock method.

The statistical method, however, is by far the most accurate and shows a very narrow range of errors. Additionally, the statistical method does not underestimate the wind speed under stable conditions, unlike the Charnok and analytical methods. Across all three methods, the neutral stability case is the most accurately predicted.

![Figure 4](image)

Figure 4: Percent prediction error versus stability parameter at 60 m for: (a) Charnock (b) analytical and (c) statistical methods. A large positive and negative stability parameter represent more stable and unstable cases, respectively, whereas in neutral cases $\zeta$ is approximately zero.
The results so far clearly indicate the higher accuracy of the statistical method. However, Fig. 3c is a result of calculating $z_0$ values using observations from all three levels, including 60 m, while the other two methods are not using the 60 m observations. This may raise another concern with the accuracy of the statistical method, as the predicted wind speeds are using the $z_0$ values which were calculated using the observations from 60 m themselves. To address this concern, a third dataset, VERTEX, from a meteorological tower in Lewes, Delaware has been used for further analysis on statistical method. As previously noted, the statistical method requires measurements from at least three levels above the ground. Here, we have data from five different heights, which allows us to calculate the $z_0$ values using data from the lowest three levels and estimate the wind speed at the higher two. Using the calculated $z_0$ values, we can predict the wind speed at 42 and 49 meters using data collected at 10, 25, and 33 m. In this case 10 m is taken as the reference height.

![Figure 5: Error by the statistical method with respect to stability using VERTEX data with 10 m as the reference height. The first three lowest heights, i.e., 10, 25, and 33 m, were first used to calculate $z_0$ with the statistical method. These $z_0$ values were then used to predict wind speeds at 42 and 49 meters, where observations were available to make a comparison. This figure corresponds to 42 m.](image)

Fig. 5 illustrates the same error analysis on the VERTEX data set at 42 m for the statistical method. Here we observe a slightly wider range of errors compared to the statistical method at CW. With the analytical method, the error is similar to CW but with slightly better performance; however, there is no systematic underestimation for the stable cases (not shown). The 90th percentile error for the statistical method on data from the VERTEX campaign at 42 and 49 m is found to be 0.45 m/s and 0.8 m/s respectively. The 5% accuracy of this data-set is also given at Table 1.

The 16% accuracy maybe low for the Charnock method, however other studies have worked to improve the prediction accuracy of this method. A few studies [9,17,23,24] propose to modify the Charnock coefficient $\alpha$, either through optimization, fitting, or relation to other physical parameters related to the ocean. However, analyzing the accuracy of all these cases is beyond the scope of this paper.
Table 1: Error analysis results. Error range corresponds to the 90th percentile of error and accuracy corresponds to the percentage of prediction errors within 0.5 m/s for the CW campaign and 0.3 m/s for the VERTEX campaign.

| Method     | Campaign | Height | Accuracy within 5% error | Error range (90th percentile) |
|------------|----------|--------|---------------------------|-------------------------------|
| Charnock   | CW       | 60 m   | 16%                       | 2.67 m/s                      |
| Analytical | CW       | 60 m   | 40%                       | 0.87 m/s                      |
| Statistical| CW       | 60 m   | 95%                       | 0.17 m/s                      |
| Statistical| CW       | 41 m   | 98%                       | 0.24 m/s                      |
| Statistical| VERTEX   | 42 m   | 81%                       | 0.45 m/s                      |
| Statistical| VERTEX   | 49 m   | 67%                       | 0.78 m/s                      |

Conclusions

With the analysis presented in this study, we obtained $z_0$ values with three methods: Charnock’s relationship, analytical, and statistical methods. The $z_0$ values were then used to predict the wind speed at 60 m, which is the height where measurements of wind speeds were available. Each method gave an average error that was less than 1 m/s for wind speed predictions at 60 m; however, the statistical method showed the least error overall. These results showed that the statistical and analytical methods show a significantly better prediction for wind speed compared to the observations at 60 m than the Charnock method. This confirmed the previous findings. Also, the statistical method resulted in the least error overall.

The Charnock and analytical methods are more likely to underestimate wind speeds in stable cases. Moreover, the Charnock equation presents higher uncertainty in wind speed predictions in unstable conditions, that are dominant at this offshore location in the Nantucket Sound.

This study recommends $z_0 = 6.1 \times 10^{-3}$ as a representative value of surface roughness for wind energy applications in the Nantucket Sound region. This value was determined by taking the median $z_0$ from the statistical method, as the median is a more robust statistic than the mean.

This study concludes that the statistical method may result in non-physical $z_0$ values due to its mathematical nature. However, $z_0$ values calculated with the statistical method give the most accurate estimates of wind speed at hub height. Therefore, if the goal is to predict the most accurate wind speeds at hub height, the statistical method should be used, as it results in the smallest error overall. Otherwise, when seeking a physical meaning for $z_0$, or if multi-level wind speeds are not available, the analytical method is recommended over the Charnock method.

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