Codification of mean wind and turbulence profiles over the ocean with roughness saturation

John D. Holmes[1*]
[1]JDH Consulting
Mentone, Victoria, Australia
* *john.holmes@jdhconsult.com*

1 INTRODUCTION

Reliable and robust models of strong winds over the open seas and oceans are essential for structural design and operation of structures such as offshore oil and gas platforms, and their renewable energy counterparts – offshore wind turbine towers. These models should include wind speeds expected in the extreme winds of tropical cyclones, including hurricanes and typhoons. In this paper, a revised model for strong winds over the open oceans is proposed, incorporating saturation or 'capping' of the surface roughness and the related turbulence intensity.

Although the length of the extended abstract does not permit a full discussion here, full details of the proposed and other wind models in design codes and standards for offshore structures, are given in a report and submitted paper (Holmes, [1]).

2 HISTORY AND BACKGROUND

Charnock [2] used dimensional arguments in applying the classic logarithmic law to the atmospheric boundary layer over water surfaces. The Charnock relation can be written in the form of an effective, velocity-dependent, roughness length (Eq. (1)):

$$z_o = \frac{a{u_*}^2}{g} \tag{1}$$

where a is the more common form of Charnock's 'constant'. u_* is the friction velocity, and g is the gravitational constant.

Subsequent research has usually replaced the roughness length z_0 with the closely-related surface drag coefficient, $C_{d,10}$, normalized by the mean wind speed at a height of 10 metres above the water surface, $\overline{U}_{10}$. The Charnock relation of Eq. (1) leads to a relation between $C_{d,10}$ and $\overline{U}_{10}$ which is close to linear over a wide range of wind speeds; an example is shown in Fig. 1. This graph illustrates an important characteristic of over-water winds compared with those overland – a dependency of roughness parameters, and hence wind profiles, on the wind speed itself.

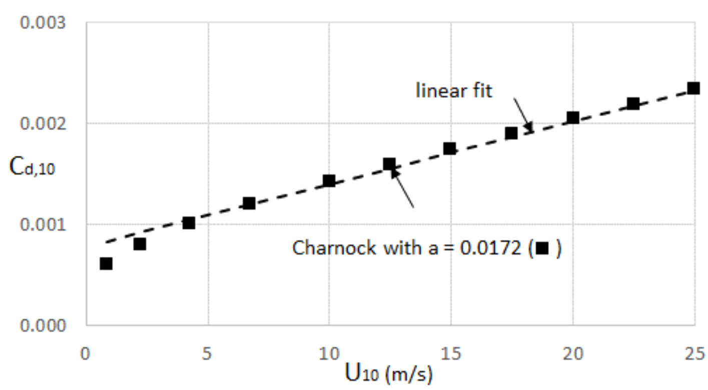

Figure 1, Surface drag coefficient versus mean wind speed - linear fit to Charnock model

Many measurements of wind drag and profiles of open water were made up to about 1990, for wind speeds up to about 20 m/s, and usually with linear $C_{d,10}$ versus $\overline{U}_{10}$ fits. However, virtually none were made over the open ocean and for a range of wind speeds relevant to the design of offshore structures.

DOI 10.5258/WES/P0027

In an attempt to rectify this, the Norwegian state oil company (Statoil) sponsored extensive tower measurements from the island of Frøya, between 1988 and 1989. Measurements of mean wind speeds and turbulence were made from three different towers, for heights up to 100m. The sites were exposed to gales from the west and south-west over the Atlantic Ocean. The sites and instrumentation on Frøya were discussed by Andersen and Lovseth [3], and the results were summarized by Andersen and Lovseth [4].

Powell *et al*. [5] analysed wind profiles from dropwindsonde measurements by the National Hurricane Center of the United States, obtained from aircraft flying into Atlantic hurricanes. The trajectories of the probes were tracked using GPS satellites enabling wind profiles to be obtained, based on the dropwindsondes moving with the local wind speed. Although there are questions about the response of the probes to atmospheric turbulence, averaging the profiles over many drops enables mean wind profiles in the strong winds of hurricanes to be assessed. In an attempt to

Saturation, or 'capping', of the surface drag coefficient and roughness length was identified by Powell *et al*. [5]. Although there was some scatter in the values obtained, the data indicates a levelling off, and even a reduction, in the surface drag coefficient, for mean wind speeds greater than about 30m/s. Powell *et al*. noted: "*surface winds above hurricane force (34 m/s) create streaks of bubbles on the sea surface combined with patches of foam 20-50m wide caused by steep wave faces breaking and being sheared off by the wind. As the wind approaches 50 m/s, the sea becomes completely covered by a layer of foam*". Images in the paper show large areas of near-flat white water corresponding to low surface roughness.

3 PROPOSED MODEL OF SURFACE DRAG COEFFICIENTS AND TURBULENCE FOR STRONG WINDS

Unlike those in international standards, the proposal here is for a model that is suitable for both extra-tropical and tropical synoptic-scale storms. However, it is not an appropriate model for non-synoptic, convective, windstorms that may occur in tropical and sub-tropical oceans.

The proposed model is essentially a 'fine tuning' of the model in ISO 19901-1 [6], with extension to wind speeds in excess of the Frøya data, and incorporating capping of the surface drag coefficient and roughness length at a mean wind speed, $\overline{U}_{10}$, of 25 m/s. Some modification and capping of the ISO expression for turbulence intensity is also proposed.

3.1 Surface drag coefficient and mean profile

The proposed model for surface drag coefficient is given by Equation (2):

$$C_{d,10} = 0.000525[1 + 0.1505\,\overline{U}_{10}] \qquad \overline{U}_{10} \leq 25\ m/s$$
$$C_{d,10} = 0.0025 \qquad \overline{U}_{10} > 25\ m/s \tag{2}$$

The first equation coincides with that in the ISO Standard, but there is no wind-speed limit in [6]. Fig. 2 shows Eqs. (2) (solid black line), plotted with the Frøya data. The version in ISO 19901-1 is shown dashed in Fig. 2.

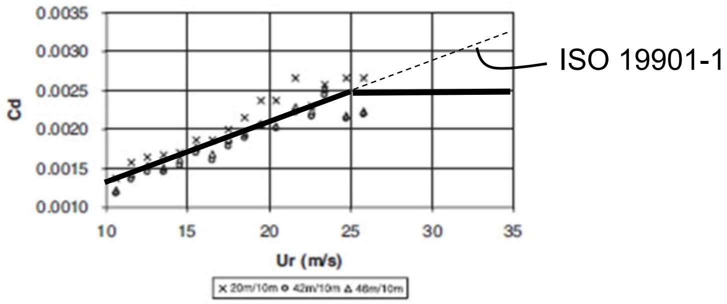

Figure 2, Proposed surface drag coefficient versus mean wind speed – Eqn. (2) versus Frøya data

DOI 10.5258/WES/P0027

The agreement of the data in Fig. 2 with Eq. (2) is good, if the data influenced by near-shore conditions (shown by '×'in the Figure) are ignored. As noted by Andersen and Løvseth [4]: *"..for the highest wind speeds the data indicate saturation."* This is represented in Eqs. (2) by a constant value of $C_{d,10}$ of 0.0025 for wind speeds above 25 m/s.

The logarithmic law, Eq. (3), can be used to give a relation between roughness length and surface drag coefficient, Eq. (4). k is von Karman's Constant (~0.4), and $C_{d,10} = \frac{{u_*}^2}{{\bar{U}_{10}}^2}$.
Together with Eqs. (2), these define the mean velocity profile above ocean surfaces up to a height of at least 100m.

$$\bar{U}_z = \frac{u_*}{k} \ln \frac{z}{z_0} \tag{3}$$

$$\sqrt{C_{d,10}} = \frac{k}{\ln\left(\frac{10}{z_0}\right)} \tag{4}$$

From Eqs. (2) and (4), the saturated value of roughness length, z_0, for wind speeds exceeding 25 m/s, is 3.35 mm.

3.2 Turbulence intensity

25 m/s is an appropriate value of $\bar{U}_{10}$ for capping the surface drag coefficient, as shown in Fig. 2, and logically the turbulence intensity should also be capped at that wind speed. Then the proposed equations for turbulence intensity become:

$$I_u = 0.06[1 + 0.050\, \bar{U}_{10}] \left(\frac{z}{10}\right)^{-0.22} \qquad 10\, m/s \leq \bar{U}_{10} \leq 25\, m/s$$

$$I_u = 0.135 \left(\frac{z}{10}\right)^{-0.22} \qquad \bar{U}_{10} > 25\, m/s \tag{5}$$

The first of Eq. (5) is a modification of that in the ISO Standard [6] with '0.050' replacing the value of '0.043' in [6]. The ISO equation for turbulence intensity is also uncapped, as it is in the surface drag coefficient versus $\bar{U}_{10}$ function.

The I_u versus height relation in Eq. (5) is compared with the available recorded data at high wind speeds (> 25 m/s) in Fig. 3. This figure includes some unpublished data from oil platforms in the Atlantic during hurricanes, values derived from gust factors during the land-falling of Tropical Cyclone 'Yasi' on the Queensland coast [7], values recorded by Shiotani and Arai [8] on the coast of Shikoku Island, Japan, during landfall of typhoons, and recent data from gales in the North Sea recorded at the FINO1 and FINO3 meteorological towers, (Jeans, [9]). The agreement with Eq. (5) in Fig. 3 is very reasonable, allowing for the scatter in the measurements, the scatter to be expected as the data are all based on individual 10- or 60- minute samples.

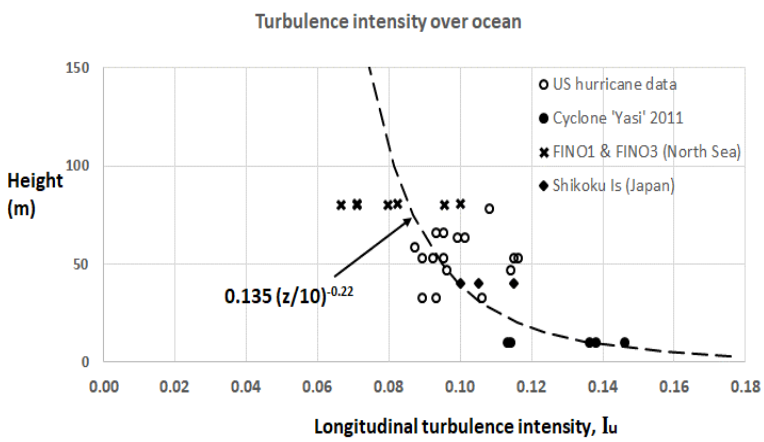

Figure 3, I_u vs. z – Eqn. (5b) compared with recorded data for $\bar{U}_{10}$ > 25 m/s

DOI 10.5258/WES/P0027

Another comparison is shown in Fig. 4, in which recorded turbulence intensities at an average elevation of 46m (+/-13m) are plotted as a function of mean speed at 10m. Eq. (5), with capping at $I_u = 0.0965$ for $\overline{U}_{10} \geq 25$m/s provides a good fit to the data. Based on Figs. 3 and 4, Eq. (5) gives a better fit to recorded data on turbulence intensity than those in current codes and standards.

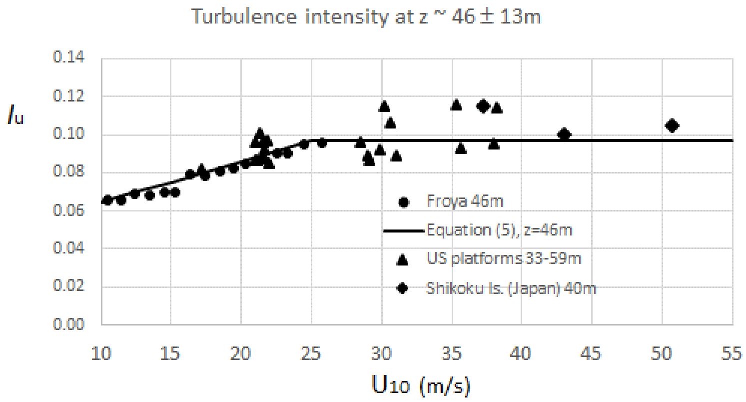

Figure 4, I_u vs. $\overline{U}_{10}$ *- Eq. (5) compared with recorded data at ~ 46m height*

4 CONCLUSIONS

Based on the good-quality wind data recorded on the coast of the island of Frøya (Norway) in the 1980s, and supported by later dropwindsonde profiles in hurricanes, this paper shows that 'capping' of the surface drag coefficient becomes apparent at a mean wind speed, at 10m height, of about 25 m/s. The upper limit of the surface drag coefficient is about 0.0025.

Revised models are proposed for surface drag coefficients, aerodynamic roughness lengths and turbulence intensities for design of offshore structures, valid for all mean wind speeds, incorporating the observed 'capping' beyond a threshold of 25 m/s. The proposed model for longitudinal turbulence intensity is well supported by individual measurements from gales and tropical cyclones (including hurricanes and typhoons) at several different locations.

REFERENCES

[1] Holmes, J.D. (2024), *Mean wind and turbulence profiles over the ocean with roughness saturation*, JDH Consulting Report 24/1R, July 2024, (manuscript submitted to *Wind and Structures*).

[2] Charnock, H. (1955), "Wind stress on a water surface", *Quart. J. Roy. Met. Soc.* **81**, 639-640.

[3] Andersen, O.J., and Løvseth, J.L. (1995), "Gale force maritime wind. The Frøya database", *J. Wind Eng. Ind. Aero.* **57**, 97-109.

[4] Andersen, O.J., and Løvseth, J.L. (2006), "The Frøya database and maritime boundary-layer description", *Marine Structures.* **19**, 173-192.

[5] Powell, M.D., Vickery, P.J., and Reinhold, T.A. (2003), "Reduced drag coefficients for high wind speeds in tropical cyclones", *Nature* **422**, 279-283.

[6] International Organization for Standardization (2015), Petroleum and natural gas industries – Specific requirements for offshore structures. Part 1 Metocean design and operating considerations, International Standard, ISO 19901-1:2015, ISO, Geneva, Switzerland.

[7] Holmes, J.D. (2017), "Roughness lengths and turbulence intensities for wind over water", *9th Asia-Pacific Conference on Wind Engineering*, Auckland, New Zealand, December 3-7.

[8] Shiotani, M. and Arai, H. (1967), "Lateral structures of gusts in high winds", *2nd International Conference on Wind Effects on Buildings and Structures*, Ottawa, Canada, September 11-15

[9] Jeans, G. (2023), "Converging profile relationships for offshore wind speed and turbulence intensity", *Wind Energy Science Discussions.* Preprint, *doi.org/10.5194/wes-2023-35*.

DOI 10.5258/WES/P0027