A procedure for calculation of single-fetch dependent mean and gust wind profiles based on an update of the ESDU (Harris and Deaves) strong-wind model.

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1.0 Introduction

A long-standing problem with the roughness fetch dependent Harris and Deaves (H+D) strong wind model is that it does not deal rigorously with the prediction of turbulence. In the ESDU Wind Engineering Data items curve-fitting methods were used in an attempt to match measurements but it was clear that, outside the range of the measurements, there might be significant discrepancies.

In dealing with this problem for codification, NJ Cook used a procedure where the turbulence intensity near the ground was assumed to be the same as for a fully developed wind profile, until the resulting gust speeds exceeded those of the less rough exposure preceding the roughness change. There are technical problems with this in that the matching depends on the gust peak factor used and also that, while conservative for smooth to rough surface transitions, it is quite non-conservative for rough to smooth transitions.

The following is based on a more fundamental theory following thoughts provided by Wieringa on the idea of height dependent local properties of wind shear and roughness length.

The majority of this note is based on hourly-mean windspeeds which are the statistical basis of the H+D and ESDU theory. A proposal for practical adjustment for 10-minute means is included.

The methodology has also been simplified by first removing effects of Coriolis and then adding it back after the main calculation. Apart from the benefit for the calculation process, this has little practical effect on the calculated wind pressures.

2.0 Background to Methodology

2.1 Log-Law profiles

This is intended as a limited summary of the simplified procedures. For more detailed background please read the original papers or the relevant ESDU Wind Engineering data items.

The basic form of boundary layer development close to a surface, beyond a limited surface distance, is a logarithmic variation of wind speed associated with a relatively constant shear stress. This profile is characterised by a velocity, u^*, which is related to the shear stress as $\tau = \rho u^{*2}$ and a surface roughness length (boundary layer thickness scaling parameter), z_0.

For a height $z > 2.5\ z_0$ the velocity, v'_{mz}, without Coriolis, is given as

$$v'_{mz} = 2.5\ u^* \ln(z/z_0)$$

2.2 Harris and Coriolis

Over greater heights, the Harris model shows how this is modified by effects of planetary spin (Coriolis), which also has the effect of changing the wind direction with height, and how these effects result in the decay of the wind shear to zero at a gradient height of typically about one to two kilometres in strong winds, i.e. with neutral atmospheric stability.

The full equation can be simplified so that for strong winds up to ~500m, the Coriolis correction may be marginally conservatively described as an addition to the log-law wind speed of '~ $z \sin|\lambda|/80$'. For UK latitudes with $\lambda \approx 52°$, this is $\approx 0.01z$ m/s. Note that effects of variations for latitudes, e.g. between 35° and 65°, are not highly significant.

To use the logarithmic formulas consistently, the Coriolis effect should be removed from basic reference speeds at 10m height, e.g. as provided in UK wind loading codes of practice, by subtracting 0.1 m/s (= 10 x 0.01) (or a more accurate correction depending on latitude) before further calculation. This is added back at the end of the calculation.

2.3 Deaves and the Effect of Changes to Surface Roughness

When the ground roughness changes, a new wind shear immediately occurs at the surface depending on the new roughness length but the effect of this takes some time and distance to work its way through the full atmospheric boundary layer depth. The relationship between the original and new values of u_1^* and u^* (respectively) is given by Deaves paper as a ratio depending on the ratio of the surface roughnesses, z_{01} and z_0, and the upwind distance (fetch), X, of the new local roughness. The formula below is intrinsic but relatively easy to solve iteratively, and polynomial fits are also practical.

$$u_X^*/u_1^* = 1 - \frac{\ln(z_{01}/z_0)}{0.42 + \ln m_0}$$

$$m_0 = \frac{0.32\ X/z_0}{\ln m_0 - 1}$$

Using the Deaves model, it is assumed that the mean windspeeds are the same at a matching height, z_X, where $v_{mz}(z_X) = 2.5\ u_X^* \ln(z_X/z_0) = 2.5 u_1^* \ln(z_X/z_{01})$, and the first part of this equation is used for heights up to z_X and the second part for greater heights. The resulting windspeed relationship with height is used in the current model and is therefore as the Deaves model for mean windspeeds.

While it might initially appear from the above that, z_X, is a function of fetch and both surface roughnesses, the effect of the upstream roughness, z_{01}, cancels in these equations so that the match height depends on the site roughness length, z_0, and fetch, X, only.

2.4 Long-fetch correction

For long fetches the Deaves model as above does not converge on the equilibrium result in a sufficiently rapid way. This appears to be associated with the relationship between the matching height, which increases with fetch, and the gradient height, and can be thought of as a filling process as the new turbulence remains trapped below the new gradient height.

A model has been developed by the author where the logarithm of the far-fetch surface roughness, z'_{01}, is adjusted as ratio of the matching height, z_X, divided by the twice equilibrium value of the gradient height. e.g.

$$\ln z_{01} = \ln z'_{01} + \ln(z_0/z'_{01}) \cdot \min\left(1, \frac{z_X}{2z_G}\right)$$

The factor of two has been calibrated against the discrepancy in the simplified Deaves model noted in ESDU 82026. See Sketch A2.2.

Note that this correction has little effect on speeds for fetches of a few kilometres.

Full convergence is achieved in about 100 km, compatible with previous models although, for practical purposes, the gust speeds near ground level change little from about half this distance.

(The above has been calibrated for a smooth-to-rough fetch transition. Further calibration work is needed to verify applicability to a rough-to-smooth transition.)

2.5 Wieringa and Variation of Properties with Height

The physical impossibility of actually having two values of u^* (a step change in wind shear) just above and below the match height ought to be clear. At the match height $u^* = u_1^*$ and must be associated with z_{01}. Similarly, at the surface ($z = 2.5\ z_0$) there are no options except $u^* = u_X^*$ and z_0.

Methods of dealing with what happens in between are less clear. ESDU, Cook and others have speculated about a region near the ground in full-equilibrium with the new roughness and proposed various arbitrary (but calibrated) fits in between, but with no consistent theory.

Following a suggestion by Wieringa, the use of height varying properties of u^* and z_0 was investigated by the author.

The best fit for $u^*(z)$ to achieve the Deaves variation of mean speeds with height is a linear variation with $\ln z$ between the two values above, and the value of $\ln(z/z_0(z))$ is adjusted as needed to achieve the predicted mean speeds. $\ln z_0(z)$ is approximately parabolic with $\ln z$, but this assumption is not necessary.

From first principles, the u^*relationship is expected from consideration of wind shear stresses which also can only have discontinuities at the surface and at the limit of the developing new shear layer at z_X.

The effect of using the resulting $u^*(z)$ and $z_0(z)$ on turbulence properties has been investigated and gives a good match to the ESDU calibrations both for smooth to rough and rough to smooth transitions, but eliminates the clearly artificial variations resulting from the ESDU use of arbitrary sinusoidal curve-fits.

3.0 Practical procedure for a single fetch change

a) Calculate basic constants.

i) The Coriolis frequency, f_c, may be taken as 1.15e-4 for the UK, or calculated from the latitude, λ, as 1.454e-4 $\sin \lambda$.

ii) The hourly-mean reference windspeed, v_r (e.g. at 10m height in open country exposure) is $v_b/1.06$, where the basic 10-min mean windspeed, v_b, is from the UK NA to EN1991-1-4.

iii) The reference friction velocity u_r^* is calculated as

$$u_r^* = \frac{(v_r - 0.1)}{2.5\ \ln(10/z_{0r})}$$

z_{0r} may be varied but is taken as 0.03m in the UK.

NB The Coriolis correction of 0.1 m/s is good for the UK but may be replaced by $(10 \sin|\lambda|/80)$ for latitudes different from ~52°.

iv) Calculate u^* for fully converged fetch using roughness length z_0.

$$u^* = \frac{u_r^* \ln(10^5/z_{0r})}{\ln(10^5/z_0)} \quad \text{(ESDU 82026)}$$

v) Calculate fully converged gradient height as

$$z_G = u^*/\ 6f_c$$

b) **Solve the intrinsic equation**

$$m_0 = \frac{0.32\ X/z_0}{\ln m_0 - 1}$$

This is used below as a Divisor in the form '$0.42 + \ln m_0$' for which a good cubic solution is

$$\text{Divisor} = \left[\left(\left(-0.000944 \ln\left(\frac{X}{z_0}\right) + 0.039\right)\ln\left(\frac{X}{z_0}\right) + 0.366\right)\ln\left(\frac{X}{z_0}\right) + 0.8545\right]$$

c) Calculate the match height, z_X

$$z_X = z_0\ e^{Divisor}$$

NB This is a function of X and z_0 only.

d) Correct the far-field roughness length, z'_{01} for long-fetch effects

$$\ln z_{01} = \ln z'_{01} + \ln(z_0/z'_{01}) \cdot \min(1, z_X/2z_G)$$

e) Calculate u_1^*

$$u_1^* = \frac{u_r^* \ln(10^5/z_{0r})}{\ln(10^5/z_{01})}$$

f) Calculate u_X^*

$$u_X^* = u_1^* \left(1 - \frac{\ln(z_{01}/z_0)}{\text{Divisor}}\right)$$

g) Calculate v'_{mz} and v_{mz} for heights below z_X as

$$v'_{mz} = 2.5\, u_X^* \ln(z/z_0)$$

For heights above z_X use

$$v'_{mz} = 2.5\, u_1^* \ln(z/z_{01})$$

Apply the Coriolis correction

$$v_{mz} = v'_{mz} + 0.01z$$

NB The 0.01 may be replaced by (sin $|\lambda|$ /80) for latitudes different from ~52°.

h) Calculate $u^*(z)$ for heights below z_X as

$$u^*(z) = u_X^* + (u_1^* - u_X^*) \ln(0.4\, z/z_0) \,/\, \ln(0.4\, z_X/z_0)$$

For heights above z_X use

$$u^*(z) = u_1^*$$

i) Calculate $z_0(z)$ for heights below z_X using

$$\ln(z/z_0(z)) = 0.4\, v'_{mz}/u^*(z)$$

NB Use v'_{mz} in this equation – not the Coriolis corrected speed.

For heights above z_X use

$$z_0(z) = z_{01}$$

j) Calculate turbulence velocities, u_z as

$$u_z = \frac{7.5u^*(z)}{1 + 0.156 \ln(u^*(z)/(f_c\, z_0(z)))} \cdot (1 - 6zf_c/u^*(z)) \cdot \left(0.538 + 0.09 \ln\left(\frac{z}{z_o(z)}\right)\right)^{\left[(1-6zf_c/u^*(z))^{16}\right]}$$

where $f_c = \frac{\pi \sin|Lat|}{21600} = 1.15 \cdot 10^{-4}$ for $Lat \approx 52°$ (UK)

NB The formula above avoids use of a variable 'gradient height', which is replaced by $u^*(z)/6f_c$.

k) Calculate turbulence intensities I_{uz} as

$$I_{uz} = u_z / v_{mz}$$

l) Calculate gust speeds, v_{pz}, as

$$v_{pz} = v_{mz}(1 + 3.5 I_{uz})$$

NB The peak factor of 3.5 is the expected value in one-hour using an 0.8 second time average. 3.0 is the corresponding value in 10-minutes.

m) Calculate 10-minute mean speeds, $v_{mz,10min}$, as

$$v_{mz,10min} = v_{pz} / (1 + 3 I_{uz})$$

4.0 Multiple Roughness Changes

Deaves original paper does not cover multiple roughness changes.

While similar methods to those used by ESDU might be employed, for the UK NA, the wind pressure exposures are precalculated based on single roughness changes from Sea to Country ($z_{01} = 0.003$m to $z_0 = 0.03$m), from Country to Urban ($z_{01} = 0.03$m to $z_0 = 0.3$m) and directly from Sea to Urban ($z_{01} = 0.003$m to $z_0 = 0.3$m) and these are used together for sea-country-urban transitions.

Writing the single fetch-change values as $q_{sc}(X_s)$, $q_{su}(X_s)$, and $q_{cu}(X_c)$, where X_s is the distance from site to sea/water and X_c is the distance to country from an urban site, and q_{su}, as an example, represents a wind pressure transition from sea exposure to urban, and $q_{su}(X_s)$ represents mean or gust pressures at any height as a function of distance to sea, then the resulting pressure profile is calculated as

$$q_{scu} = \left(\frac{q_{cu}(X_c)}{q_{cu}(0)}\right) \cdot q_{sc}(X_s) \text{ but } \geq q_{su}(X_s)$$

The first term here represents the effect of urban terrain on a fully developed country wind profile, $q_{cu}(0)$, and the second includes the effect of proximity to sea on the country wind profile. The condition at the end is necessary when the extent of country fetch, $(X_s - X_c)$, is small, in which case the sea to urban transition may be more onerous and should be used.

NB It is necessary to use X_s for the check above, but, when the check using $q_{su}(X_s)$ is critical, consider also the use of the more onerous values obtained using $q_{su}(X_c)$.

5.0 Conclusions

The above represents an improvement and simplification of the model given in the ESDU Wind Engineering Data Items, based on applying an idea obtained from Wieringa of height varying friction velocity and roughness length to the original model of Harris and Deaves.

The results have been compared (ref.) with ESDU spreadsheet calculations and with previous UK codified models from BS6399-2 and from the UK NA to EN1991-1-4, and while there are no major systematic changes, the model is clearly an improvement on the Cook model, taking it closer to ESDU, but it eliminates a random effect of the sinusoidal fits used by ESDU.

In principle the method can be further used to derive the other wind turbulence properties in lateral and vertical directions, including spectra, using the ESDU Wind Engineering models. This is not discussed further here.

The correction to 10-minute mean speeds is not required on any theoretical grounds. The measured ratio of 10-minute mean speeds (i.e. 6 no. measurements per hour) to hourly-mean speeds varies with turbulence intensity. The 1.06 proposed by Cook for the UK NA is good for a turbulence intensity of about 18% as expected in standard open country reference condition with surface roughness length of 0.03m. The author has made various attempts to simplify the formulas but these either complicate the calculation of at least one of the variables, or result in systematic variations of peak gust pressure with turbulence intensity compared to the hourly-mean calculation. The simplest alternative is to readopt the use of hourly-mean wind profiles and use hourly gust-speed peak factors like 3.5 rather than 10-minute peaks like 3 (0.8s).

The basic single roughness change model has been implemented as a single page spreadsheet with input and calculations as below. (Macros are not strictly needed, as shown, but the spreadsheet does contain one for calculation of the turbulence velocities.) It is intended that this is model is published in the UK PD6688-1-4.

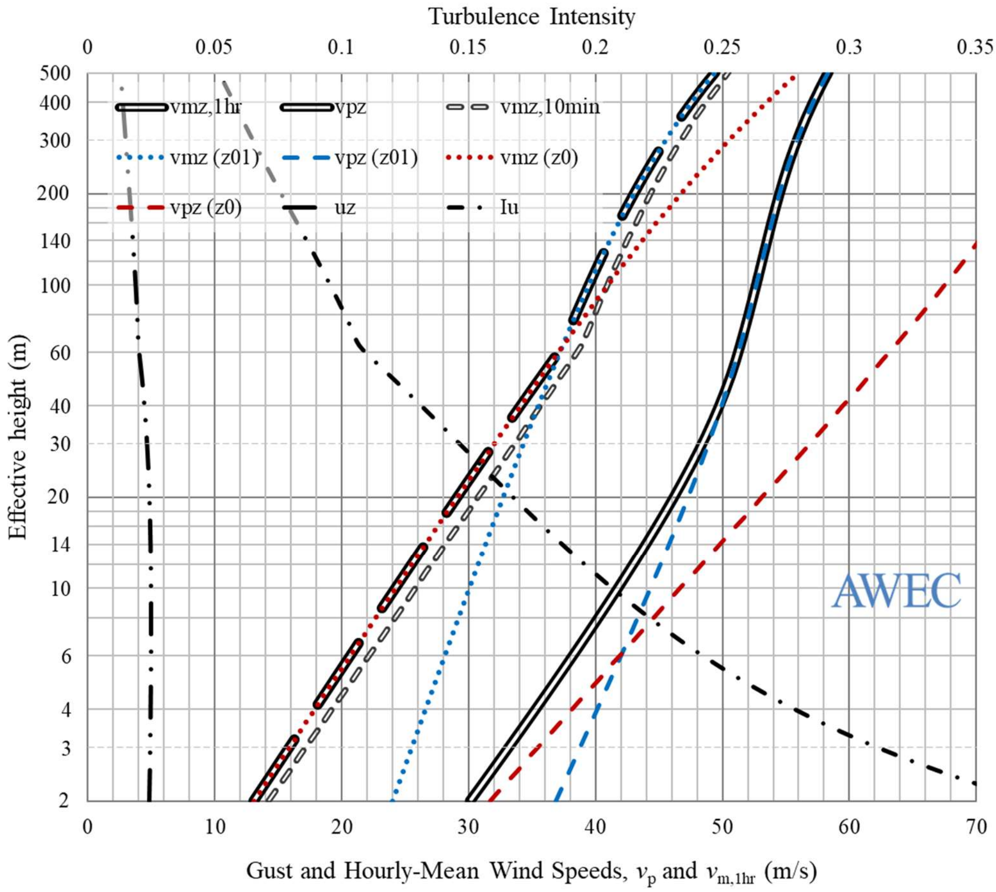
Wind Profiles - Single Roughness Change - valid up to 500 m

11th December 2025

Reference hourly wind speed	v_r	24.89	m/s	Coriolis (/s)			
Latitude	λ	52	deg	Sin(λ)	0.788		
Ref Zo	z_{0r}	0.03	m/s	$f_c(\lambda)$	0.0001146		
Ref height	z_r	10	m	$f_c(\lambda=90)$	0.0001454		
Far Field roughness length	z'_{01}	**0.003**	m	from ESDU	86.253	For q_p = 1 kPa pressure at 10m in open country	
Site roughness length	z_0	**0.3**	m	Vadd-const	79.7 ≈ 80	1.06 v_r	26.387 m/s
Fetch	X	**500**	m			v_r	24.893 m/s
		Valid Zo				$v_{b,10min}$	26.331 m/s
				Equilibrium limit for large X			
a)	u^*_r	1.707	m/s	u^* (m/s)	2.016		
				z_G (m)	2932		
b)	Divisor	5.331	$= [-0.000944\,(\ln(X/z_0))^3 + .039\,(\ln(X/z_0))^2 + 0.366\,\ln(X/z_0) + 0.8545]$				
c)	z_X	62	m (a function of X and z_0 only)			chart title	Hourly Wind Profile for Zo1, 0.003m, Zo, 0.3m, Fetch, 0.5km
d)	z_{01}	0.00315	m (fetch modified value, ln(z_{01}) varies with 0.5(z_X/z_G))				
e)	u^*_1	1.485	m/s				
f)	u^*_X/u^*_1	1.855	-				
	u^*_X	2.753	m/s			t (s)	0.8
						$g_{t,1hr}$	3.50
Increment	0.05	20.0 steps per decade				$g_{t,10min}$	3.00
Rows	49						

	Eff. Height (m)	g)	Hourly	h)	i)		j)		k)	l)	m)		$v_{b,10min}$ 26.4	m/s	Comparison profiles			
	z (m)	(m/s)	(m/s)	(m/s)	(m)	(-)	(m/s)	(m/s)	(-)	(m/s)	(m/s)		(-)	(-)	Far Field		Near Field Factored	
		v'_{mz}	$v_{mz,1hr}$	$u^*(z)$	$z_0(z)$	$(1\text{-}6z\, f_c/u^*)$	7.5 u^* etc.	u_z	I_u	v_{pz}	$v_{mz,10min}$	v_{10min}/v_{1hr}	$c_r^2 = c_{em}$	c_e	$v_{mz}(z_{01})$	$v_{pz}(z_{01})$	$v_{mz}(z_0)$	$v_{pz}(z_0)$
Formulas	2.00	13.1	13.1	2.471	0.2416	0.999	6.67	4.87	0.3723	30.1	14.2	1.088	0.291	1.303	24.0	36.9	13.1	31.7
	2.24	13.9	13.9	2.438	0.2313	0.999	6.57	4.89	0.3525	31.0	15.1	1.086	0.326	1.379	24.4	37.4	13.9	32.7
	2.52	14.6	14.7	2.405	0.2205	0.999	6.47	4.91	0.3348	31.9	15.9	1.084	0.363	1.458	24.8	37.9	14.7	33.8
	2.83	15.4	15.5	2.372	0.2092	0.999	6.37	4.93	0.3188	32.7	16.7	1.081	0.402	1.537	25.3	38.5	15.5	34.9
	3.17	16.2	16.3	2.339	0.1976	0.999	6.26	4.95	0.3042	33.6	17.6	1.080	0.443	1.619	25.7	39.0	16.3	36.0
	3.56	17.0	17.1	2.306	0.1857	0.999	6.16	4.96	0.2909	34.4	18.4	1.078	0.485	1.702	26.1	39.6	17.1	37.0
	3.99	17.8	17.9	2.273	0.1736	0.999	6.05	4.98	0.2787	35.3	19.2	1.076	0.530	1.787	26.6	40.1	17.9	38.1
	4.48	18.6	18.7	2.240	0.1614	0.999	5.94	4.99	0.2675	36.1	20.0	1.074	0.576	1.873	27.0	40.6	18.7	39.2
	5.02	19.4	19.4	2.207	0.1492	0.998	5.84	5.00	0.2570	36.9	20.9	1.073	0.625	1.960	27.4	41.2	19.4	40.2
	5.64	20.2	20.2	2.174	0.1372	0.998	5.73	5.01	0.2473	37.8	21.7	1.071	0.675	2.049	27.9	41.7	20.2	41.3
	6.32	21.0	21.0	2.141	0.1253	0.998	5.62	5.01	0.2382	38.6	22.5	1.069	0.728	2.139	28.3	42.2	21.0	42.4
	7.10	21.8	21.8	2.107	0.1138	0.998	5.51	5.02	0.2296	39.4	23.3	1.068	0.782	2.230	28.7	42.8	21.8	43.5
	7.96	22.6	22.6	2.074	0.1026	0.997	5.39	5.02	0.2215	40.2	24.2	1.067	0.838	2.321	29.2	43.3	22.6	44.5
	8.93	23.4	23.4	2.041	0.0918	0.997	5.28	5.01	0.2138	41.0	25.0	1.065	0.896	2.414	29.6	43.8	23.4	45.6
	10.02	24.2	24.3	2.008	0.0816	0.997	5.17	5.01	0.2065	41.8	25.8	1.064	0.956	2.507	30.0	44.3	24.3	46.7
	11.25	24.9	25.1	1.975	0.0719	0.996	5.05	5.00	0.1994	42.5	26.6	1.062	1.018	2.600	30.5	44.8	25.1	47.8
	12.62	25.7	25.9	1.942	0.0629	0.996	4.94	4.98	0.1927	43.3	27.4	1.061	1.082	2.693	30.9	45.3	25.9	48.8
	14.16	26.5	26.7	1.909	0.0545	0.995	4.82	4.96	0.1861	44.0	28.3	1.060	1.147	2.787	31.4	45.8	26.7	49.9
	15.89	27.3	27.5	1.876	0.0468	0.994	4.70	4.94	0.1798	44.8	29.1	1.058	1.215	2.879	31.8	46.3	27.5	51.0
	17.83	28.1	28.3	1.843	0.0398	0.993	4.59	4.91	0.1736	45.5	29.9	1.057	1.285	2.971	32.2	46.8	28.3	52.1
	20.00	28.9	29.1	1.810	0.0336	0.992	4.47	4.88	0.1675	46.2	30.7	1.056	1.356	3.061	32.7	47.3	29.1	53.1

Hourly Wind Profile for Zo1, 0.003m, Zo, 0.3m, Fetch, 0.5km



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In the ‘10-minute’ mean version below the reference speed was increased by 6% without any other change of calculation for mean speeds and the peak speeds are calculated using a peak factor of 3 using the original turbulence intensities. The result is a systematic increase of peak gust speeds with turbulence less than 18% at higher heights, which is a conseqence of the overestimated mean speeds, compared to the hourly-mean based figure above. The reverse happens when turbulence is higher than 18%.

10-min Wind Profile for Zo1, 0.003m, Zo, 0.3m, Fetch, 0.5km