Comparative study of Eurocode 1, ISO and ASCE procedures for calculating wind loads

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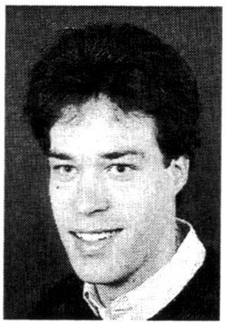

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SUMMARY

This paper contains a comparative study of the basic parameters involved in the prediction of the wind loads with Eurocode 1, ISO DIS 4354 and ASCE 7 standards: reference wind velocity; V_{ref}, exposure factor; C_{exp}, turbulence intensity at height z; I(z), gust factor; C_{gust}, spectral density functions of Davenport, Solari and von Karman for along-wind gustiness and peak factor for calculating the largest extreme value of velocity pressure.

Davenport and Solari spectra. The hierarchy of spectra remains the same for z=150m.

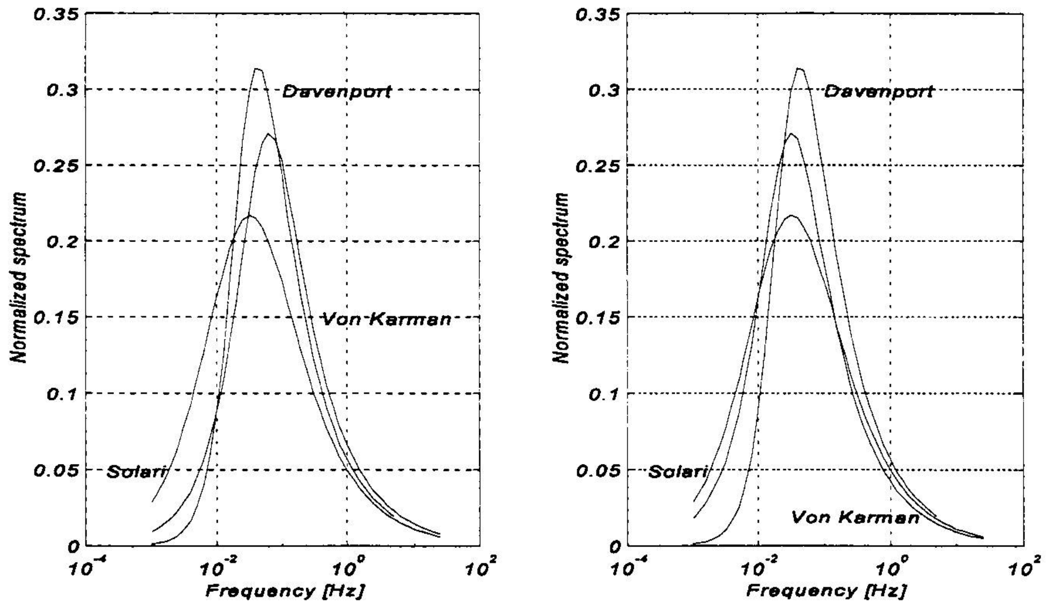

Fig. 4. Davenport, Solari and von Karman spectra at z=10m, z_0=0.05m, V_{ref}=30m/s, with 2 lengths of integral scale of turbelence in the von Karman spectrum; left:ESDU, right:Couniham.

4. Conclusions

In spite of complexity involved in evaluating the wind effects on buildings there is a clear need for an international harmonization of calculating methods for the building response to strong winds. We hope that the IABSE Colloquium in Delft will give the opportunity for an EC1/ISO/ASCE Liaison Committee on Actions, or at least on wind action to come up with recommendations for an unified calculating format for wind loads.

5. References

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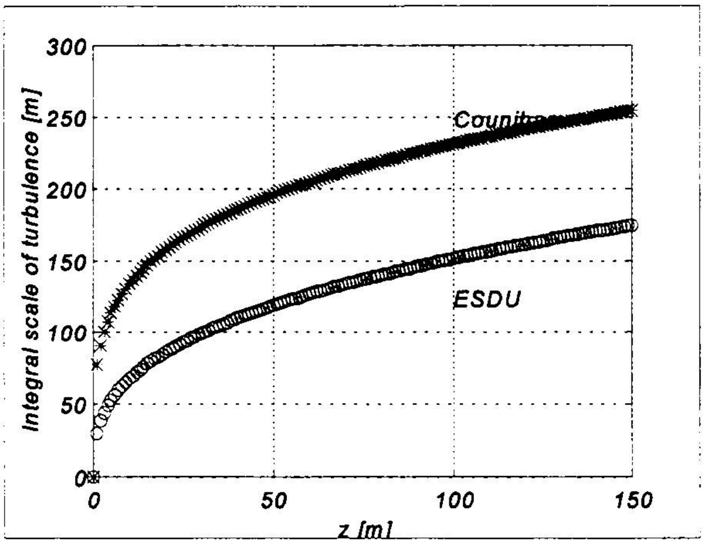

i) The length of the integral scale of turbulence from Couniham, used by Solari for EC1:

$$L_u^C(z)=300(z/300)^{0.46+0.074\ln z0}$$

ii) The length of the integral scale of turbulence after ESDU:

$$L_u^{ESDU}(z)=25z^{0.35}z_0^{-0.063}$$

Fig. 3. ESDU and Couniham integral scale of turbulence (z_0=0.05).

3.4 Graphical analysis of the spectra

The following table forms the basis of this section:

z [m]	V(z)		L_u^C [m]		L_u^{ESDU} [m]		x_C		x_{ESDU}	
	Open	Urban	Open	Urban	Open	Urban	Open	Urban	Open	Urban
10	**30.0**	23.1	133	85	68	60	4.4n	3.7n	2.2n	2.6n
30	36.5	30.4	173	128	99	89	4.8n	4.2n	2.7n	2.9n
90	42.7	37.6	225	192	146	130	5.3n	5.1n	3.4n	3.5n
150	45.6	41.0	254	232	174	156	5.6n	5.7n	3.8n	3.8n

Tabel 7. Spectrum parameter $x=nL_u/V$ for different heights above the ground and integral scale of turbulence (Couniham and ESDU)

Note the difference in the values of spectral parameter x for different integral scales of turbulence. Using this table, we can easy examine the differences in the spectra due to the height above the ground and/or the choice of the turbulence length. Solari spectra in Fig.4 are represented with Couniham length of integral scale of turbulence. Von Karman spectrum in Fig.4 (left) is represented with ESDU length of integral scale of turbulence. For the frequency range of interest its values are higher than that of Davenport and Solari spectra. Von Karman spectrum in Fig. 4 (right) is represented with Couniham length of integral scale of turbulence. For the frequency range of interest for buildings and structures its values are lower than that of

Urban and suburban z_0=0.3m

		z=10m				z=150m		
		Dav.	Solari	v.Kar.		Dav.	Solari	v.Kar.
V_{ref}=20m/s	v_0	0.079	0.087	0.07	V_{ref}=20m/s	0.15	0.12	0.10
V=15.4m/s	μ_g	*2.98*	*3.02*	*2.96*	V=27.4m/s	*3.19*	*3.12*	*3.06*
$n_{cut\text{-}off}$=5Hz	σ_g	*0.46*	*0.46*	*0.47*	$n_{cut\text{-}off}$=9Hz	*0.43*	*0.44*	*0.45*
V_{ref}=20m/s	v_0	0.13	0.15	0.13	V_{ref}=20m/s	0.22	0.17	0.16
V=15.4m/s	μ_g	*3.15*	*3.19*	*3.15*	V=27.4m/s	*3.31*	*3.24*	*3.21*
$n_{cut\text{-}off}$=10Hz	σ_g	*0.43*	*0.43*	*0.43*	$n_{cut\text{-}off}$=18Hz	*0.41*	*0.42*	*0.43*
V_{ref}=40m/s	v_0	0.18	0.20	0.17	V_{ref}=40m/s	0.30	0.24	0.20
V=30.8m/s	μ_g	*3.25*	*3.28*	*3.23*	V=54.8m/s	*3.40*	*3.33*	*3.28*
$n_{cut\text{-}off}$=10Hz	σ_g	*0.42*	*0.41*	*0.42*	$n_{cut\text{-}off}$=18Hz	*0.40*	*0.41*	*0.42*

Table 6b. Comparison of the 3 spectra in urban area.

The main conclusions from these tables are:

i) The v_0 is extremely sensitive for a change in the cut-off frequency. The reason for this is that except for the 0^{th} spectral moment, all other spectral moments are divergent. In the definition of v_0, we have the 2^{nd} moment to divide by the 0^{th} moment (a constant). If we increase the cut-off frequency, the v_0 will increase consequently. Spectral bandwidth measures, like ϵ, don't show this behaviour because the divergence of the spectral moments compensate eachother.

ii) The mean peak factor is an increasing function especially of the cut-off frequency and the reference velocity; and consequently also of the height above the ground.

iii) The σ_g parameter is almost insensitive for changes in the reference velocities, cut-off frequencies, height and terrain roughness. The σ_g stays between 0.42 and 0.47.

iv) There is not so much sensitivity to the roughness of the terrain on the μ_g and σ_g.

v) Eurocode 1 proposes a mean peak factor of 3.5. It roughly corresponds to the mean peak factor added with one standard deviation. The mean peak factor can be obtained artificially high by increasing the cut-off frequency.

3.3 Length of integral scale of turbulence

In this paper we have distinguished 2 different lengths of the integral scales of turbulence, Fig.3:

V_{ref} [m/s]	z [m]	z_0 [m]	V(z) [m/s]	NBC of Canada (Davenport'70)	EC1 (Solari'93)
20	10	0.05	20	3.6	20.0
40	10	0.05	40	7.2	40.0
20	150	0.05	30.2	5.4	15.2
40	150	0.05	60.4	10.9	30.4
20	150	0.3	35.5	4.9	13.7
40	150	0.3	70.9	9.9	27.4

Table 5. Summarization of the recommended cut-off frequencies [Hz]

Note the differences in the recommended cut-off frequencies. In comparison with the cut-off frequencies used in earthquake engineering (maximum 20-40 Hz), we must comment that the recommended cut-off frequencies by Eurocode 1 for wind engineering applications seems to be quite large. The cut-off frequencies used in full scale measuremens of wind effects on structures are usually taken around a few Herz. With the newest techniques like ultrasonic anemometers it becomes possible to resolve frequencies up to 30 Hz, but the energy content in these frequency ranges will be extremely low and uninteresting for wind loads on buildings.
The spectral peak factor of the 3 different spectra were compared. The comparisons were made at different heights (z=10 and 150m), different terrain roughnesses (z_0 = 0.05 and 0.3m), for different reference velocities (V_{ref} = 20 and 40m/s) and different cut-off frequencies; Tables 6a-b. (L_u^C in the von Karman spectrum).

Open country z_0=0.05m

		z=10m				z=150m		
		Dav.	Solari	v.Kar.		Dav.	Solari	v.Kar.
V_{ref}=20m/s	ν_0	0.079	0.075	0.069	V_{ref}=20m/s	0.12	0.094	0.09
$n_{cut-off}$=5Hz	μ_g	*2.98*	*2.97*	*2.93*	V=30.2m/s	*3.13*	*3.04*	*3.01*
	σ_g	*0.46*	*0.47*	*0.47*	$n_{cut-off}$=7.5Hz	*0.44*	*0.45*	*0.46*
V_{ref}=20m/s	ν_0	0.14	0.14	0.12	V_{ref}=20m/s	0.19	0.15	0.13
$n_{cut-off}$=10Hz	μ_g	*3.18*	*3.17*	*3.13*	V=30.2m/s	*3.27*	*3.19*	*3.16*
	σ_g	*0.43*	*0.43*	*0.44*	$n_{cut-off}$=15Hz	*0.42*	*0.43*	*0.43*
V_{ref}=40m/s	ν_0	0.18	0.17	0.16	V_{ref}=40m/s	0.25	0.19	0.17
$n_{cut-off}$=10Hz	μ_g	*3.25*	*3.24*	*3.21*	V=60.4m/s	*3.34*	*3.26*	*3.23*
	σ_g	*0.42*	*0.42*	*0.43*	$n_{cut-off}$=15Hz	*0.41*	*0.42*	*0.42*

Table 6a. Comparison of the 3 spectra in open country.

$$\lambda_i = \int_0 G_u(n) n^i dn$$

and the 0[th] moment is given by σ_u^2.
Analytically, for Davenport spectrum one finds ϵ=1.0. Numerically, for any spectra (in the case of usual cut-off frequencies), ϵ=0.98-0.99.
The mean and standard deviation of the peak factor for computing the largest extreme gust are given by Davenport as:

$$\mu_g = \sqrt{2 \ln \nu_0 t} + \frac{0.5772}{\sqrt{2 \ln \nu_0 t}} \qquad \sigma_g = \frac{\pi}{\sqrt{6}} \frac{1}{\sqrt{2 \ln \nu_0 t}}$$

where ν_0 is the mean frequency of zero upcrossings:

$$\nu_0 = \frac{1}{2\pi} \sqrt{\frac{\lambda_2}{\lambda_0}}$$

3.2 Cut-off frequency

Calculating spectral moments and peak factors are done numerically. A question of importance is the choice of integration interval and in particular the cut-off frequency. It appears that the calculation of the spectra parameters is extremely sensitive to the cut-off frequency: Table 4. If we study for example the influence on the mean peak factor (using a Davenport wind spectrum), we see the following results:

Mean peak factor, μ_g	2.72	2.77	3.22	3.67
Cut-off frequency [Hz] (V_{ref}=30m/s)	1	1.5	10	100

Table 4. The mean peak factor as a function of the cut-off frequency in a Davenport spectrum

In the next table, we summarize the different recommendations for the cut-off frequencies:

3. Power spectral density for along-wind gustiness

3.1 Spectrum types

From numerous proposals for the spectral density of along-wind gustiness: Karman (1948), Panovski (1964), Davenport (1967), Harris (1968), Flicht (1970), Kaimal (1972), Simiu (1974,1975), ESDU (1976, 1985), Naito (1978, 1983), Kareem (1985), Solari (1987,1993) were selected that of Davenport, Solari and von Karman. Attention will be paid to their spectral density functions, to the notion of cut-off frequency and integral scales of turbulence. A sensitivity study will be performed to study the influence of the terrain roughness, the reference velocity and the height above the terrain.

Davenport in NBC of Canada	Solari in Eurocode 1	von Karman in JCSS and CIB codes
$\frac{nG_u(n)}{\sigma_u^2}=\frac{0.667x^2}{(1+x^2)^{\frac{4}{3}}}$	$\frac{nG_u(n)}{\sigma_u^2}=\frac{6.868x}{(1+10.32x)^{\frac{5}{3}}}$	$\frac{nG_u(n)}{\sigma_u^2}=\frac{4x}{(1+70.8x^2)^{\frac{5}{6}}}$
x=1200 n / V(z) Mean spectrum for 10 < z < 150m	$x=L_u\, n / V(z)$, where: $L_u^C=300(z/300)^{0.46+0.074\ln z0}$	$x=L_u\, n / V(z)$ where $L_u^C=300(z/300)^{0.46+0.074\ln z0}$ or $L_u^{ESDU}=25z^{0.35}z_0^{-0.063}$

Table 3. Power spectra of the along-wind gust velocity.

The Longuett-Higgens indicator of the frequency bandwidth of the gust velocity process is:

$$\epsilon=\sqrt{1-\frac{\lambda_2^2}{\lambda_0\lambda_4}}$$

where the spectral moments for i=1,2,... are defined by:

2.3 The gust factor

The gust factor is the ratio of the peak velocity pressure to the mean pressure of the wind:

$$C_{gust}(z) = \frac{q_{peak}(z)}{Q(z)} = \frac{Q(z) + g\sigma_q}{Q(z)} = 1 + gV_q \approx 1 + g[2I(z)]$$

Where Q(z) is the mean value of the wind velocity pressure, σ_q the root mean square value of the along wind velocity pressure fluctuations from the mean, g the peak factor and V_q the coefficient of variation of the velocity pressure fluctuations. V_q is approximately equal (second moment order formats) to the double of the intensity of turbulence I(z); Table 2. The recommended values of the peak factor are 2.8 (ASCE7-93), 3.0 (ISO) and 3.5 (Eurocode 1). The V_q is given as a logarithmic law in Eurocode 1 and ISO and as a power law in ASCE. In figure 2, we show the differences of the gust factor recommended by the different codes.

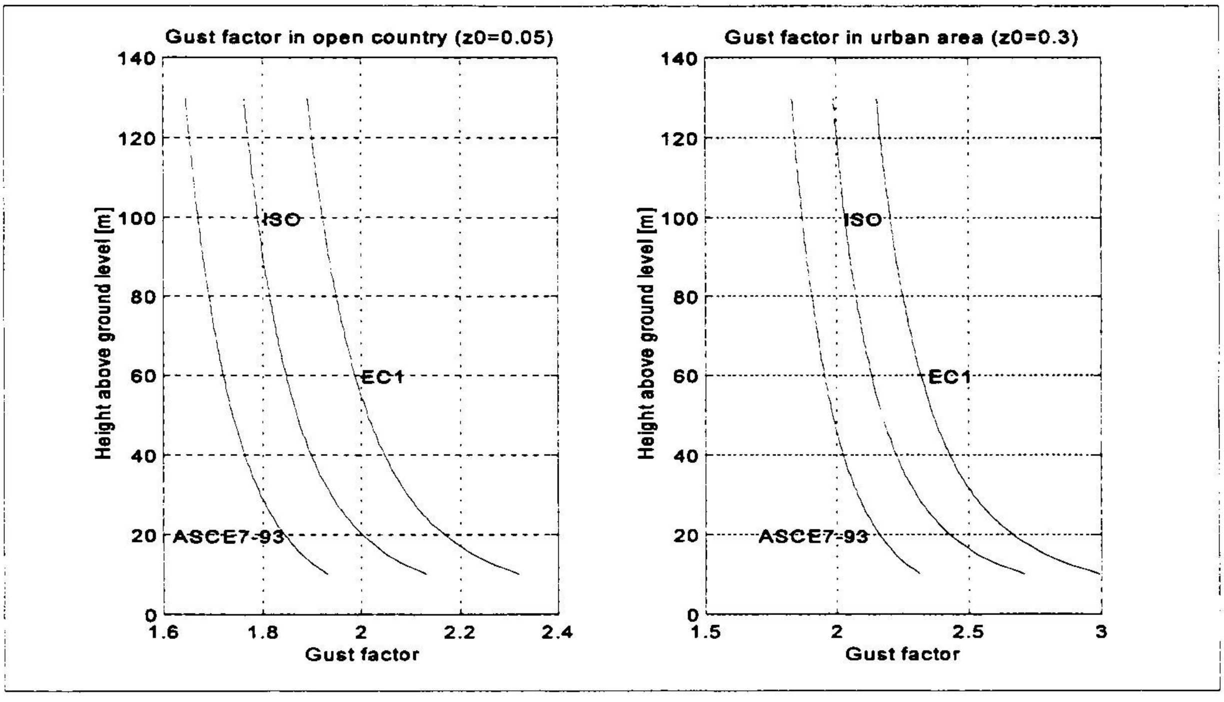

Fig. 2. Gust factor for velocity pressure averaged on 10 min, $C_{gust}(z)$.

	ASCE 7-93	ISO DIS 4354	Eurocode 1	ASCE Report	ASCE 7-95 draft
Open country	16.6	17.2	18.8	19.7	20
Suburban, urban	23.5	28.5	28.5	25.1	30

Table 2. Intensity of turbulence at 10m, I(10) - percent.

Terrain category	Logarithmic law				Power law			
	EUROCODE 1		ISO DIS 4354				ASCE 7-93	
	$k_r^2(z_0)(\ln\frac{z}{z_0})^2$		$A(z_0)(\ln\frac{z}{z_0})^2$		$B(\frac{z}{10})^{2\alpha}$		$2.58(\frac{z}{z_g})^{2\alpha}$	
	k_r	z_0 (m)	z_0 (m)	$A(z_0)$	B	α	α	z_g (m)
Open sea, flat area	0.17	0.01	0.003	0.021	1.4	0.11	1/10	213
Open country	0.19	0.05	0.03	0.030	1.0	0.14	1/7	274
Suburban, urban	0.22	0.3	0.3	0.041	0.5	0.22	1/4.5	365
Large city center	0.24	3	3	0.058	0.16	0.31	1/3	457

Table 1. Exposure factor, C_{exp}.

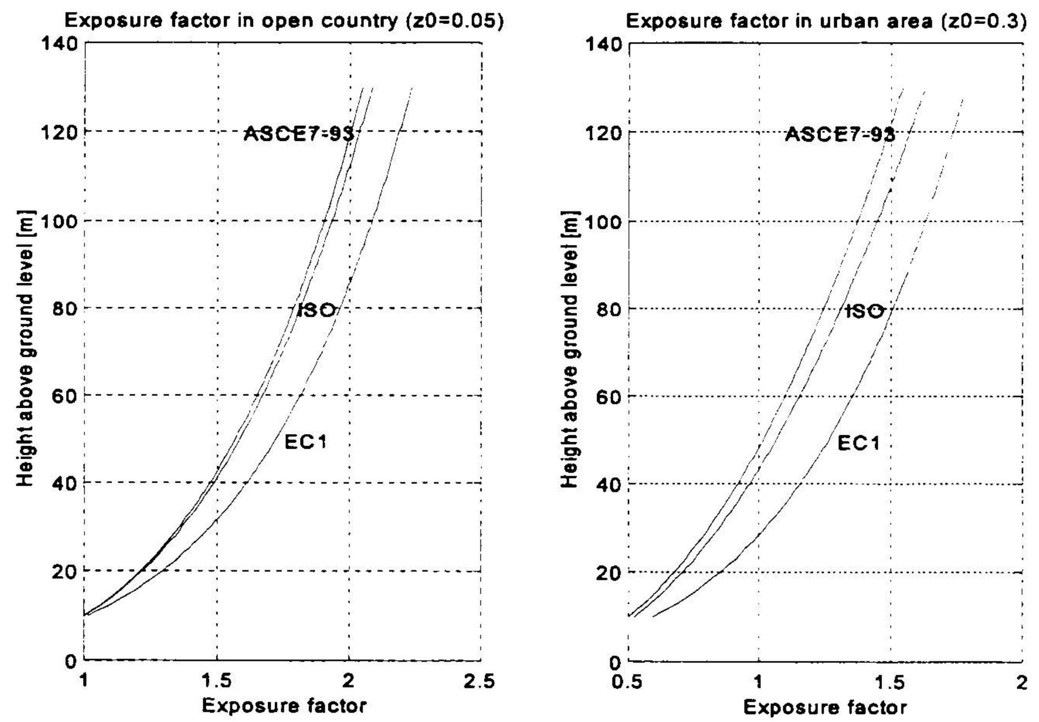

Fig. 1. Exposure factor (ASCE, ISO) or roughness factor (EC1), $C_{exp}(z)$.

1. Introduction

The Eurocode 1, Part 2-4: Wind actions (ENV 1991-2-4: 1994), the ISO Draft International Standard 4354, Wind actions on structures, 1990 and the ASCE 7-93 (or the proposed revisions from ASCE 7-95), the American standard for minimum building design loads, contain accurate stochastic procedures for calculating wind effects on building and structures. However, this latest generation of standards prove the lack of international harmonization of meteorological, structural and aerodynamical data used for calculating static and dynamic design wind loads. The differences in definition of the basic parameters for the wind loading on structures create significant difficulties for unifying the formats recommended by EC1, ISO and ASCE standards for prediction of the wind loads. Additional difficulties arise in training students to apply wind standards.

2. Basic parameters for wind loads

2.1 The reference wind velocity

According to EC1 and ISO code, the reference wind velocity is the mean velocity of the wind averaged over a period of 10 min, determined in open terrain exposure at an elevation of 10 m and having 0.02 annual probability to be exceeded (50 yr mean recurrence interval). According to ASCE7-93 code the averaging time interval of the wind velocity is about 1 min (fastest mile speed); in ASCE7-95 draft a 3 second gust speed is used. After ISO-code for different averaging time intervals, a conversion of the wind velocity is possible using the relation (in open terrain):

$$1.05V_{ref}^{1h} = V_{ref}^{10min} = 0.84V_{ref}^{1min} = 0.67V_{ref}^{3sec}$$

2.2 The exposure factor

The exposure factor describes the variation of the velocity pressure with height above ground and terrain roughness as function of reference velocity pressure:

$$C_{exp}(z) = \frac{q(z)}{q_{ref}}$$

The roughness length z_0 in metres plays an important role in this; Table 1 and Fig. 1.