Calibrating a CFD canopy model with the EC1 vertical profiles of mean wind speed and turbulence

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1 INTRODUCTION

According to the Eurocode 1 (EC1), part 1-4: Wind Actions (EN 1991-1-4:2005E), the wind pressure w acting on a surface is obtained from the reference peak velocity pressure $q_p(z)$ at height z and the pressure coefficient c_p by the expression $w=q_p(z)c_p$. The exposure coefficient $c_e(z)$ relates the peak velocity pressure to the reference wind speed with the relationships:

$$q_p(z) = c_e(z)\rho v_b^2 / 2 \tag{1}$$

$$c_e(z) = [1 + 7I_v(z)][c_r(z)c_o(z)]^2 \tag{2}$$

where ρ is the air density, $I_v(z)$ the turbulence intensity, $c_r(z)$ the roughness coefficient and $c_o(z)$ the orography coefficient.

In case of standard homogeneous and flat terrains EC1 gives formula to estimate the roughness coefficient and the turbulence intensity.

However, in some heterogeneous and complex terrains, it is frequent to develop a more accurate estimate, by performing CFD computations. In this case, the CFD method should reproduce EC1 profiles, when applied to the standard terrains.

TopoWind is a CFD code developed by Meteodyn, and especially dedicated to the computation of atmospheric flows over complex terrains (Delaunay et al. 2004). It includes the efficient coupled multi-grid solver MIGAL (Ferry, 2002). We present here the calibration of the canopy model used in TopoWind for high roughness cases (roughness length greater than 30 cm).

2 THE NUMERICAL METHOD

The code TopoWind solves the full Reynolds-Averaged Navier-Stokes equations with a turbulence closure scheme obtained by the prognostic equation on the turbulent kinetic energy (TKE) k, and a mixing length approach for the dissipation term. Indeed, it was pointed out by Katul et al.(2004) that such schemes give better results in atmospheric flows than the two equation k-ε model.

As the application concerns strong winds, the thermal stratification is supposed to be neutral. Then the isothermal equations are solved and the turbulent viscosity formulations are considered for the neutral case.

In momentum equation, surface drag is applied to the ground cells as:

$$f_S = -C_S \left|\overline{u_1}\right| \overline{u_1} / h_1 \tag{3}$$

where h_1 is the cell height, and C_S a surface drag coefficient computed as a function of the local roughness and the cell height.

TopoWind tests show that the surface drag coefficient method works well in the neutral homogenous low roughness terrain, with 4 m minimum vertical resolution for the mesh. This value is also considered for the present calibration.

When a surface drag is applied at the ground boundary, the turbulent kinetic energy at the ground cell is computed by considering the hypothesis of no flux through the bottom surface, and by assuming that the turbulence production is equal to its dissipation.

For higher roughness lengths, a volume drag force is added in the momentum equations:

$$f_V = -C_D \left|\overline{u_1}\right| \overline{u_1} \tag{4}$$

where C_D is a volume drag coefficient depending on the forest density, vertical leaf area profile. Here we consider C_D = 0.005, which represents a leaf area index of about 0.4.

Inside the canopy, both the production term and dissipation term are enhanced, thus additional terms are added into the TKE equation in which production and dissipation terms become:

$$P_k = \nu_T \left(\frac{\partial \overline{u_l}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) \frac{\partial \overline{u_i}}{\partial x_j} + \beta_p C_D \left|\overline{u}\right|^3 \tag{5}$$

$$\varepsilon = \frac{0.015 k^{3/2}}{L_T} + \beta_D C_D \left|\overline{u}\right| k \tag{6}$$

where ν_T is the eddy viscosity, and L_T is the turbulence length scale given by L_T=0.55*l*, *l* being the mixing length as computed in eq. (9). Following Liu (1996), we consider β_p =1.0 and β_d = 4.0

If we call h_c the canopy height h_c and h_{RSL} the depth of the roughness sublayer which is the region where the canopy directly impinges on the flow (Kaimal, 1994). We write:

$$h_{RSL} = k_r h_c \tag{7}$$

$$h_c = k_c z_0 \tag{8}$$

For the calibration, k_r is fixed at 2, and k_c is evaluated as a function of the roughness.

Then the mixing length is modeled as follow:

$$\begin{aligned} & z<h_c && l^{-1} = l_0^{-1} + l_f^{-1} \\ & h_c<z<h_{RSL} && l^{-1} = (1-\alpha)(l_0^{-1} + l_f^{-1}) + \alpha(l_0^{-1} + 1/\kappa z) \\ & z>h_{RSL} && l^{-1} = l_0^{-1} + 1/\kappa z \end{aligned} \tag{9}$$

with $\alpha = (z-h_c)/(h_{RSL}-h_c)$, l_f = 2 m and l_0 =100 m is introduced so that *l* approaches a constant value at higher level.

The tests were made by homogenous terrain, with a computation domain length of 6000 m and roughness length of 0.2 m, 0.3 m, 0.5 m and 1.0 m, under neutral thermal stability. The horizontal resolution of the mesh is set up at 100 m, and the vertical resolution is 4 m. The inlet wind and turbulence profiles are EC1 profiles.

In the low vegetation cases (z_0<0.4 m), surface drag is applied while for the higher roughness, the canopy model is applied.

One the turbulent kinetic energy k is computed, it is necessary to link this value with the turbulent intensity which is used in EC1. By definition we have:

$$k = (\sigma_u^2 + \sigma_v^2 + \sigma_w^2)/2$$

According Panofsky and Dutton (1984) relationships, we know that in a flat homogeneous terrain, we can write σ_v=0.80σ_u and σ_w = 0.52σ_u, which leads to I_v = 1.02 $k^{1/2}$

3 RESULTS

The numerical tests have led to values of k_c=12.5 for z_0 = 0.5 m and k_c=10 for z_0=1 m. The computed velocity and turbulence intensity profiles are shown in Figure 1 to figure 4, from 5 m to 200m above ground, and compared with EC1 profiles. The velocity is normalized with reference wind, which is defined as 10 m/s at 10m height. The absolute errors are less than 0.02 for normalized velocity and 0.006 for turbulence intensity.

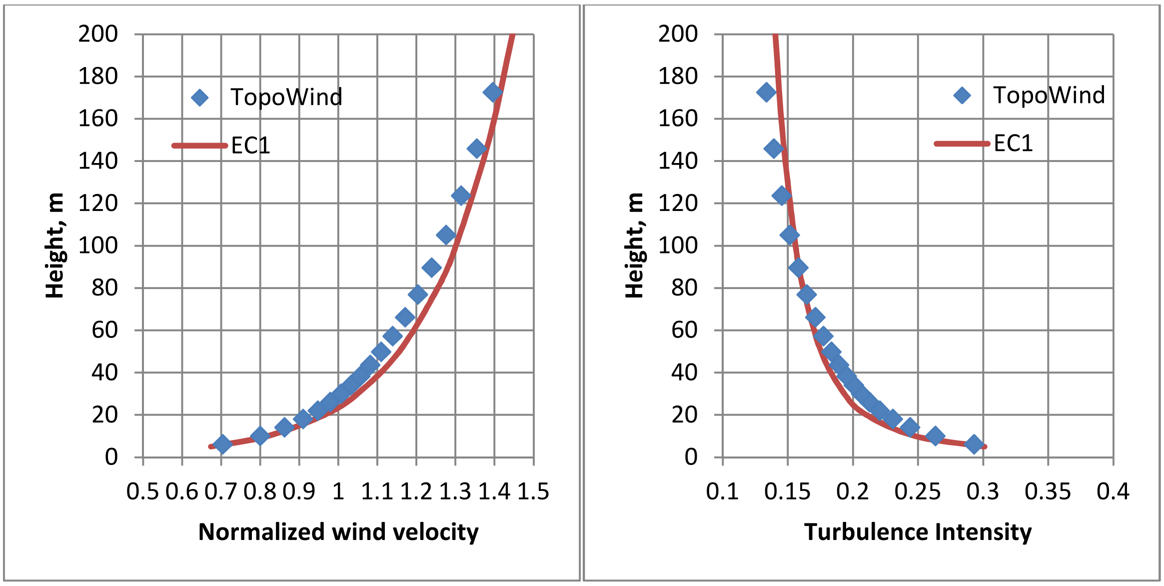

Figure 1. Velocity and turbulence intensity profiles for z_0 = 0.2 m

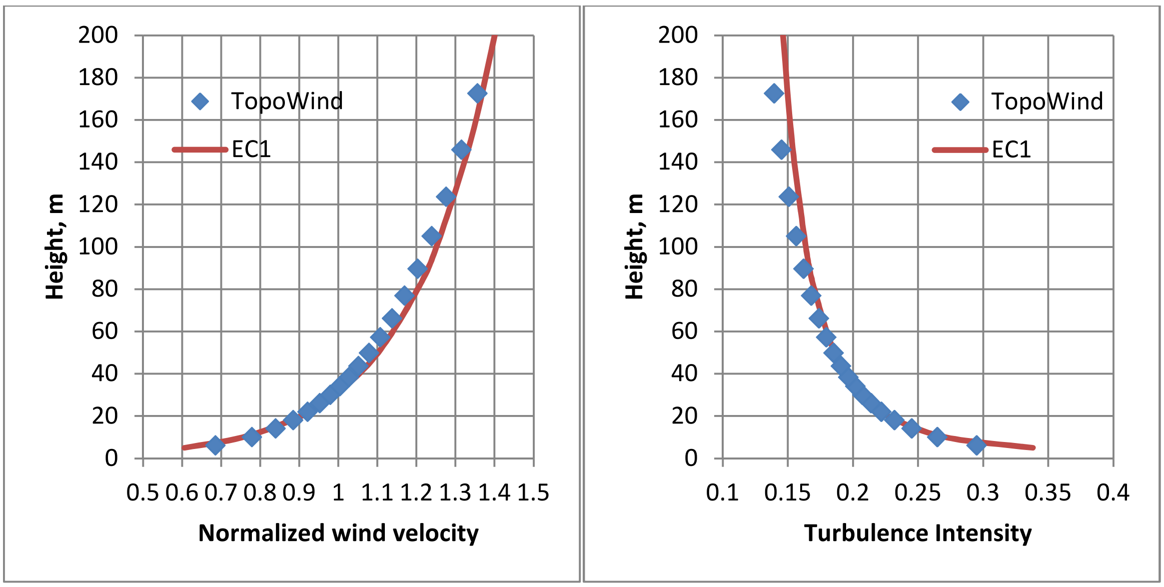

Figure 2. Velocity and turbulence intensity profiles for z_0 = 0.3 m

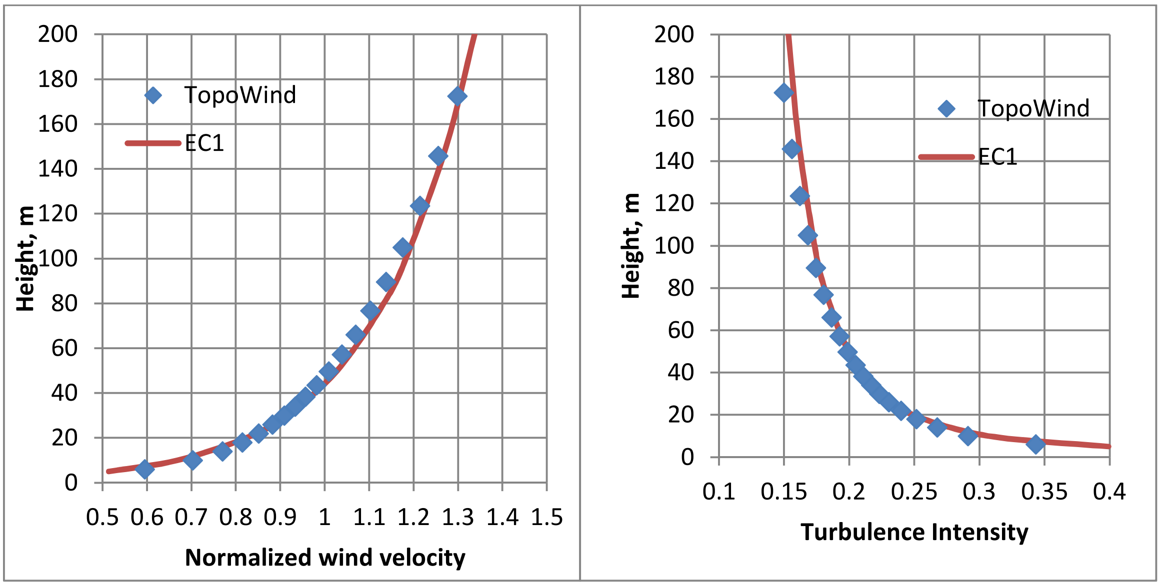

Figure 3. Velocity and turbulence intensity profiles for z_0 = 0.5 m

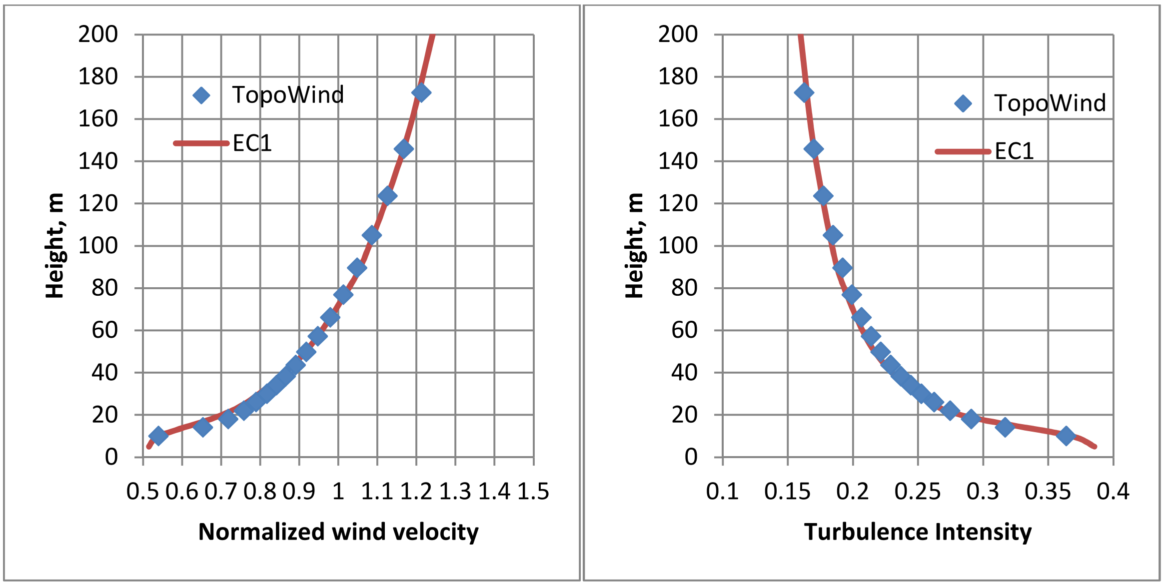

Figure 4. Velocity and turbulence intensity profiles for z_0 = 1.0 m

4 EXAMPLE OF APPLICATION

We present the case of the wind model elaboration for designing the “Grand Stade du Havre” in Normandy, France. This is a typical case where applying the EC1 recommendations can lead to either overestimation of the reference wind speed, or its underestimation.

The figure 5 shows the location of the stadium in its environment. The terrain is very heterogeneous and is composed of sea, water surfaces, urban constructions, industrial zones, and open terrains. The height *h* of the stadium roof top is 32 m above ground level

Figure 5. Location and Environment of the “Grand Stade du Havre”

According to the National Annex of France the upwind distance to consider for the definition of the terrain roughness category is $R=23\ h^{1.2}$ = 1472 m. If we consider for instance the South-West direction, the distance to the sea is 3000 m. So, applying the French National Annex leads to consider a a roughness category of IIIb (z_0=0.5 m), which would lead to a 50-yr mean wind speed of 22.3 m/s at 32 m height and to a peak velocity pressure of 776 N/m².

However, for some building control officers, it can be difficult to admit that in such a case the sea proximity has no influence on the value of wind speed at 32 m height.

If we consider the Annex A of EC1, in case of transitions between different upwind roughness classes, it is recommended (procedure 2 of paragraph A.2, normative in Belgium) in case of a transition between lakes (category 1) and urban zones, to consider a distance of 10 km where picking the lower roughness. Moreover the CSTB study that has defined the basic wind velocity map for France (Sacré C. et al, 2005), was based on corrections of measured wind speed at 10 m height, by considering the terrain roughness up to a distance of 5 km.

If we apply the procedure 2 of Annex A, we should consider the roughness of the sea, which would lead to a reference wind speed of 34.0 m/s and a peak pressure of 1275 N/m², i.e. a value 64% higher than applying the French National Annex.

In this case the proposed solution, agreed by the Control Officer was to perform micro-scale computational fluid dynamics (CFD) computations, at the necessary condition that the CFD code was calibrated obtains the EC1 profiles for the homogeneous terrain cases.

The figure 6 shows the computational domain and the roughness map that were used. A roughness length map of the site was carried out by using the European Data Base Corine Land Cover and checking them by a visit on the site. The orography was taken into account with a resolution of 30 m. The horizontal spatial resolution of the computations is 25 m.

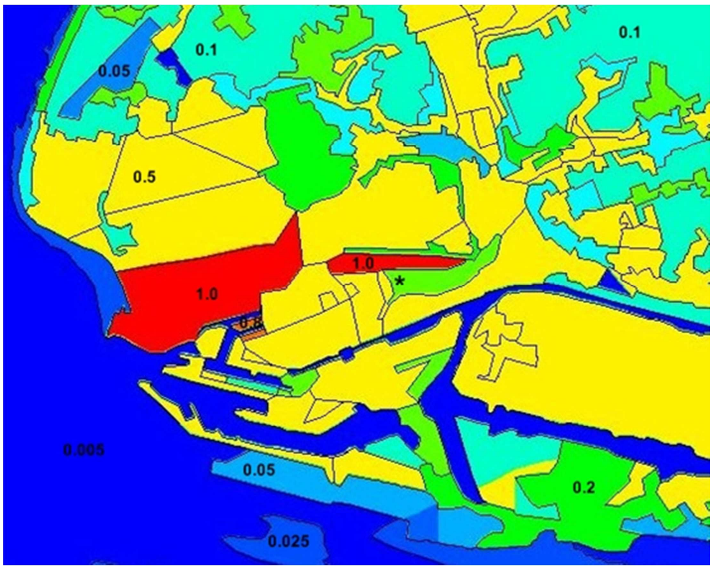

Figure 6. Computational domain and roughness length map for the TopoWind (picture width = 12 km)

The TopoWind computations take into account all topographical effects as a whole, i.e. both roughness and orography effects. In this case, orography impacts northerly winds due to the presence of a plateau of 80 m height, 600 m Northwards of the site. Moreover westerly or easterly winds could be accelerated by channeling effects that cannot be handled by EC1 rules.

Then, in this case, the advantage of adopting a CFD method lays in an objective approach both for roughness and orography effects. The engineer has not to define the pertinent characteristics of the orography. Moreover it allows taking into account the coupling between roughness and orography: It is evident, for instance, that if a forest lays upwind the site at the bottom of a valley at a much lower altitude than the site, it has a lesser effect than the same forest in a flat terrain.

Finally the Table 1 give reference wind peak pressures at 32 m height at the stadium location for the several approaches than could be chosen.

Table 1. Mean wind speed and peak wind pressures according the different hypothesis

Hypothesis	Peak wind pressure (N/m²)
Homogeneous terrain category 0	1275
Homogeneous terrain category IIIb	776
Real terrain – TopoWind computations	952

It can be seen that the TopoWind computations lead to a peak wind pressure larger by 23%, compared to the EC1 – France National Annex. It appears also that the distance to the sea has reduced the peak wind pressure by 25%. Choosing one single roughness as it is recommended in EC1 would have led in both cases (taking into account sea roughness or not) to an important error, either in overestimation, or underestimation of the wind loads.

5 CONCLUSION

For some projects, applying the basic rules of EC1 is not sufficient, and it is required to get a more accurate estimation of the wind speed on the construction site. This can be done by using computational fluid dynamics codes which have the advantage, both to take into account of the terrain inhomogeneity and to calculate 3D orographic effects. In this way, the orography and roughness effects are coupled as they are in the real world.

However, applying CFD computations must be in coherence with EC1 code. Then it is necessary to calibrate the ground friction for low roughness terrains as well as the drag force and turbulence production in case of high roughness lengths due to the presence of a canopy (forests or built areas). That is the condition for such methods to be commonly used and agreed by Building Control Officers.

In this mind, TopoWind has been developed especially for wind design applications and can be a very useful, practical and objective tool for wind design engineers. The canopy model implemented in TopoWind has been calibrated in order to get the mean wind and turbulence profiles as defined in the EC1 for standard terrains. In this way, TopoWind computations satisfy the continuity between the EC1 values for homogeneous terrains and the more complex cases involving inhomogeneous roughness or orographic effects.

6 REFERENCES

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