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PERFORMANCES OF PARAMETRIC LAWS FOR COMPUTING THE WIND SPEED PROFILE IN THE URBAN BOUNDARY LAYER. COMPARISON TO TWO-DIMENSIONAL BUILDING WATER CHANNEL EXPERIMENT

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Abstract: The wind flow above the urban canopy depends strongly on the geometry of the buildings and other roughness elements that characterize the city. Given the high variability of real urban textures, the estimation of the wind speed is a rather difficult task, even for relatively simple building geometries. This problem is currently handled by means of similarity laws. This study analyzes some of the laws generally adopted to determine the vertical profile of the wind speed above the canopy layer in neutral conditions. The performance of such laws is tested against water-channel data simulating a two-dimensional array of regular buildings.

Key words: *Building; Canopy layer; Friction velocity; Logarithmic law; Roughness sub-layer depth.*

INTRODUCTION

Obstacles such as buildings, vegetation and other features determines largely the state of the urban boundary layer (UBL), i.e. the portion of atmosphere in which the surface properties greatly affect turbulent exchanges of mass, momentum, heat, moisture and pollutants. Observational networks in the urban area are generally too coarse to resolve in detail the space variations of the variables of interest for UBL studies (e.g. Pelliccioni et al., 2000; Cantelli et al., 2015; Gariazzo et al., 2015). This is the main reason why both laboratory experiments and numerical models have recently focused attention on flow and turbulence in the UBL. Nonetheless, important issues still remain unresolved. One of these is the determination of the wind speed profile, u(z). The main difficulty is due to the vertical structure of the UBL, whose components are (i) the urban canopy layer (from the ground up to the average building height, H); (ii) the roughness sublayer (RSL), of thickness (2-5)H, which comprises the z-range where the flow is strongly influenced by the roughness elements and hence spatially inhomogeneous and (iii) the inertial sublayer (ISL), where the turbulent fluxes are nearly constant and the effect of the buildings is negligible. Several papers (e.g. Grimmond and Oke, 1999) report formulations capable of predicting the wind field in both the RSL and ISL and discussions on its dependence on the variables generally used to describe the urban texture. Such variables can be expressed in terms of suitable parameters such as H, the plan areal fraction λ_P (the ratio between the plan area of roughness elements to the total surface area) and the frontal area index λ_F (areas of building facets facing the wind direction to the total surface area). For two-dimensional building arrays, three flow regimes describe the urban canopy as a function of the interelement spacing: (1) the skimming flow, when the building separation is small and the flow skims over the urban canyon; (2) the wake-interference regime, when the distance between each building is larger and the wakes of adjacent buildings interfere and (3) the isolated regime, when the interaction between individual building wakes is absent or negligible. The expression generally used to determine the wind-speed profile above the canopy is based on the log-law:

$$\bar{u}(z) = \frac{u_*}{k} \ln\left[\frac{z - d_0}{z_0}\right] \qquad (1)$$

where $\bar{u}$ is the average wind velocity, k=0.4 the von Karman constant, u_* the friction velocity, while z_0 and d_0 are the roughness length and displacement height, respectively. These are generally estimated on the basis of the morphometric or the anemometric methods (see the recent review by Kent et al., 2017), while u_* is usually referred to the ISL. The former method uses algorithms that relate z_0 and d_0 to geometric parameters such as H, λ_P and λ_F, while in the latter one z_0 and d_0 are calculated from (1) given the wind speed taken at two or more heights within the ISL. Kastner-Klein and Rotach (2004) proposed expressions for z_0 and d_0 derived from a dataset collected in the wind-tunnel and adopted H and λ_P as morphometric parameters. More recently, Pelliccioni et al. (2015) proposed an alternative formulation for the wind speed profile based on a dataset collected during a field campaign. These authors found an appreciable improvement of the results with respect to those obtained using the canonical log-law. The aim of this work is to compare wind speed profiles determined using (1) and the formulation proposed by Pelliccioni et al. (2015) with experimental data measured in the water-channel.

EXPERIMENTAL SETUP, FLOW PARAMETERS AND MORPHOMETRIC METHODS

The experiments are performed using a closed-loop water-channel facility. The channel is 35 cm high, 25 cm wide, 740 cm long. A constant head reservoir feds the flume. The water depth and the freestream velocity are 16 cm and U=0.33 m s^{-1}, respectively. The Reynolds number based on the friction velocity, $Re_\tau=u_*H/\nu$, is around 400, ($u_*=(-\overline{u'w'})^{0.5}$, u and w are the streamwise and the vertical velocity components, prime is the fluctuation around the mean, indicated with bar, H=0.02 m is the building height and ν is the kinematic viscosity of water). For all details on the experimental setup we refer the reader to Di Bernardino et al. (2015a, 2015b). The modelled urban canopy consists of an array of 2D parallelepipeds of height H made of black PVC glued onto the channel bottom, orthogonally to the streamwise direction. Four arrays with AR=1, 1.5, 1.75 and 2 are considered for the experiments. In terms of plan areal fraction, they correspond to λ_P=0.5, 0.4, 0.36 and 0.33. Note that from the point of view of two-dimensional flows, AR=1 and 1.5 belong to the skimming flow, while AR=1.75 and 2 belong to the wake interference regime. In contrast, by using λ_P, generally adopted for three-dimensional urban textures, only the case λ_P=0.33 (AR=2) falls into the wake interference regime.

We consider two classes of morphometric methods currently adopted in UBL studies, in particular (i) methods that use H; (ii) methods that use H and λ_P. In the first, simpler method, also known as to the height-based approach, z_0 and d_0 are calculated as a fraction of the average building height, viz.:

$$\begin{cases} z_0 = f_0 H \\ d_0 = f_d H \end{cases} \quad (2)$$

where f_0 and f_d are empirical coefficients derived from laboratory and field observations. Several choices of this couple of coefficients have been proposed in the literature; one of the most utilized, i.e. f_0=0.1 and f_d=0.7, was proposed by Grimmond and Oke (1999), GO99, as representative of numerous field studies and wind tunnel experiments. Among the parameterizations based on the method (ii), we use the one attributed to Kutzbach (1961), K61, based on field experiments:

$$\begin{cases} z_0 = (\lambda_P)^{1.13} H \\ d_0 = (\lambda_P)^{0.29} H \end{cases} \quad (3)$$

and that proposed by Counihan (1971), C71,who determined the two parameters:

$$\begin{cases} z_0 = (1.082\lambda_P - 0.08)H & (4a) \\ d_0 = (1.4352\lambda_P - 0.0463)H & (4b) \end{cases}$$

on the basis of wind-tunnel experiments. Equation (4a) is valid only for $0.1<\lambda_P<0.25$. C71 reported a curve for z_0 that ranges from λ_P=0 to λ_P=0.5. Using this curve, we extend the validity of the law by means of the polynomial expression valid for $0.25<\lambda_P<0.5$:

$$z_0 = (C_1 + \sum_{j=2}^{j=4} C_j (\lambda_P)^{j-1}) H \quad (4c)$$

where we determined the coefficients C_1=0.366, C_2=0.377, C_3=-3.201 and C_4=2.919 by fitting the original curve proposed by C71. One of the expressions for z_0 and d_0 based on the second method is that proposed by Kastner-Klein and Rotach (2004), KR04, obtained by using wind-tunnel data:

$$\begin{cases} z_0 = 0.072\lambda_P\{\exp[-2.2(\lambda_P - 1)] - 1\}H \\ d_0 = \{0.4\lambda_P \exp[-2.2(\lambda_P - 1)] + 0.6\lambda_P\}H \end{cases} \quad (5)$$

We also test the formulation by Pelliccioni et al. (2015), PML15, who proposed a new form of (1):

$$\bar{u}(z) = \frac{u_*}{k}\ln\left[\frac{z - d_0}{z_{0L}(z)}\right] \quad (6)$$

where:

$$z_{0L}(z) = \alpha\exp[-z/L_C] + \gamma \quad (7)$$

is a local length scale. PML15 calculated α=3.25 m, L_C=62.5 m and γ=0.35 m on the basis of a field campaign conducted in Rome, Italy. Since they did not give the triad (α, L_C, γ) in terms of suitable scale variables, their model cannot be used in other sites. To overcome this problem, in this work we assume that the average building height (H=18 m) representative of the site considered by PML15 can be used to make the three quantities non-dimensional. Thus, the non-dimensional counterparts of (α, L_C, γ), viz.:

$$\begin{cases} K_\alpha = H/\alpha = 5.54 \\ (L_C' = L_C/H = 3.47 \\ K_\gamma = H/\gamma = 51.54 \end{cases} \quad (8)$$

will be used when applying (7) instead of the original values. Therefore, (7) now reads:

$$z_{0L}(z) = \left\{\frac{1}{K_\alpha}\exp\left[-\frac{z}{L_C'H}\right] + \frac{1}{K_\gamma}\right\}H + \gamma \quad (9)$$

Although model equation (9) belongs to the class of the height-based approach – no information on the city density is requested – its formulation must be considered as alternative to those based on the the canonical form (1). In fact, the role played by the couple z_0 and d_0 in (1) is taken in (6) by the sole parameter $z_{0L}(z)$. More discussion on the meaning of $z_{0L}(z)$ can be found in Pelliccioni et al. (2016).

RESULTS

The parameters of each formulation have been calculated on the basis of H and λ_P referred to the water channel (Tables 1 and 2). In particular, z_0 and d_0 obtained using the formulations mentioned above, have been considered to determine $\bar{u}$ by adopting (1), while $z_{0L}(z)$ has been used to calculate $\bar{u}$ with equation (6). The values of u_* for the four λ_P reported in Table 1 correspond to the Reynolds stress maxima measured along the vertical profiles (Figure 1a).

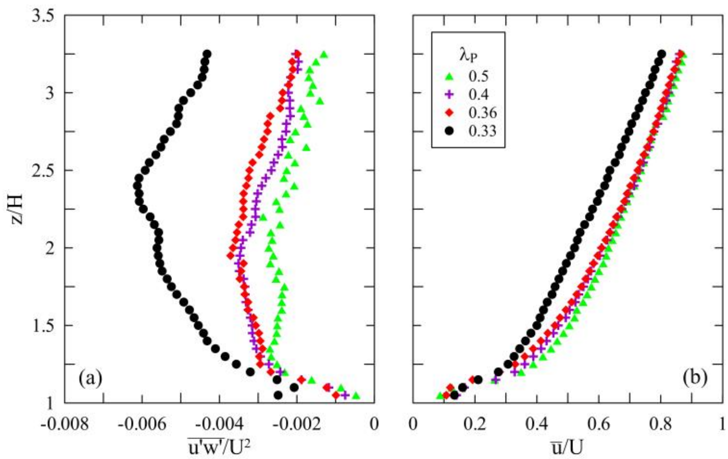

Figure 1. (a) Measured vertical profiles of the non-dimensional Reynolds stress for the four λ_P. (b) as in (a), but for the non-dimensional horizontal mean velocity.

These have been determined by performing a spatial averaging along the streamwise direction in the area overlaying the canyon top and one rooftop. Note that $-\overline{u'w'}/U^2$ does not change much passing from

λ_P=0.5 to λ_P=0.36, while, in contrast, it grows nearly by a factor of two going from λ_P=0.36 to λ_P=0.33. In other words, the latter case (AR=2) differs substantially from the other three. This fact suggests that the transition between the skimming flow and the wake interference regime coincides with that of the 3D flow (λ_P=0.35), rather than with that conventionally recognised for 2D flows (AR=1.5, i.e. for λ_P=0.4). The different structure of the flow patterns between the case λ_P=0.33 and the others can also be discerned looking at the vertical profiles of the mean horizontal velocity (Figure 1b). A substantial lowering of the velocity for λ_P=0.33 is apparent. Figure 2 depicts observed and modelled vertical profiles of $\bar{u}/U$ for λ_P=0.5 and λ_P=0.33. For the case λ_P=0.5 (skimming flow), all the models underestimate observations for most of the vertical profiles. Overall, K61 shows the larger discrepancy between modelled and observed velocity; the other four models overestimate the measurements close to the canopy layer, while they show a large underestimation above it. A similar behaviour holds for the cases λ_P=0.4 and λ_P=0.36 (not shown). In contrast, for λ_P=0.3 (Figure 2b) a substantial lowering of the gap with observations occurs for all the five models, both close to the canopy and at higher levels. The agreement improves particularly for GO99, KR04 and PML15, while K61 and C71 show again a general underestimation of the velocity.

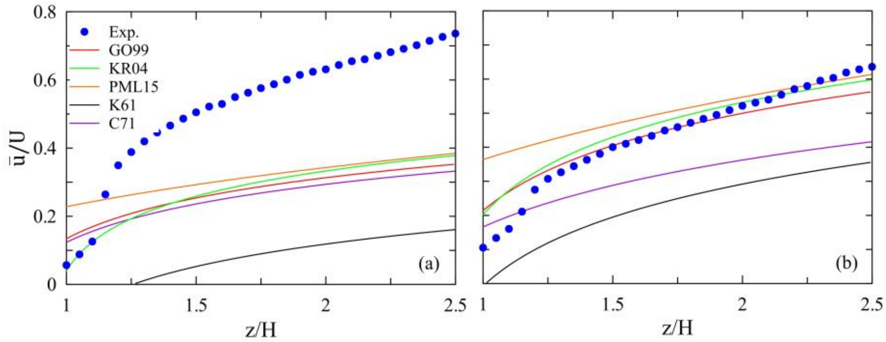

Figure 2. Modelled and observed non-dimensional horizontal velocity vs. z/H for (a) λ_P=0.5 and (b) λ_P=0.33.

Table 1. z_0 and d_0 calculated with the morphometric methods based on H and λ_P. The corresponding friction velocities u_* based on the profiles shown in Figure (2) are also reported.

	λ_P	0.5	0.4	0.36	0.33
	u_* (m/s)	0.0221	0.0255	0.0265	0.0335
KR04	z_0 (m)	0.0014	0.0016	0.0016	0.0016
	d_0 (m)	0.0180	0.0168	0.0162	0.0155
K61	z_0 (m)	0.0910	0.0071	0.0064	0.0057
	d_0 (m)	0.0160	0.0150	0.0149	0.0145
C71	z_0 (m)	0.0024	0.0038	0.0044	0.0049
	d_0 (m)	0.0134	0.0105	0.0095	0.0085

Table 2. z_0 and d_0 calculated with the morphometric methods based on H.

G099	z_0 (m)	0.002
	d_0 (m)	0.014
PML15	α (m)	0.00361
	L_C (m)	0.06944
	γ (m)	0.00038

To quantify in more detail the ability of the models to reproduce the velocity profile, we test the horizontal velocity computed using the five models against observations via the reproducibility parameter, $RP = [\overline{|u_0 - u_M|} / \overline{u_0}]100$, where u_0 and u_M are the observed and the modelled velocities, respectively. Figure 3 depicts RP for each of the five models as a function of λ_P. The agreement with observation is reasonably good (RP<15%) for GO99, KR04 and PML15 when λ_P=0.33, while large errors occur for K61 and C71. The agreement deteriorates as λ_P grows, even though RP remains acceptable for

GO99, KR04 and PML15 when λ_P<0.4. In other words, all models work reasonably well for low λ_P, i.e. for the wake interference regime. This may be partially explained by the fact that the experiments in the water channel refer to regular arrays of two-dimensional buildings, while the parameters of the similarity laws were obtained in real-world urban areas or in wind tunnels simulating actual urban areas, characterized by buildings of random heights. It is generally recognised that arrays of buildings with different heights are more rough than one with similar heights. Moreover, the inhomogeneity of the building height produces certainly a deepening of the RSL depth and, therefore, should cause a decrease of the wind speed therein. It is plausible that this effect is more important for large λ_P (i.e. skimming flows) than for small λ_P, where the stronger exchanges of momentum between the cavity and the outer flow characterizing those regimes presumably mask the effect mentioned above. Further work is needed to analyse the sensitivity of the results to the building height inhomogeneity and to investigate the performance of the similarity laws in three-dimensional geometries.

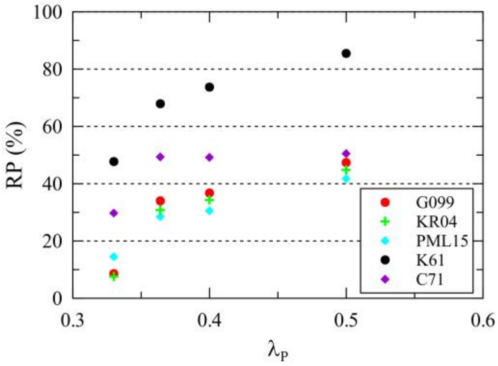

Figure 3. Reproducibility parameter as a function of λ_P for the five formulations based on (1) and (6).

REFERENCES

Counihan, J., 1971: Wind tunnel determination of the roughness length as a function of fetch and density of three-dimensional roughness elements. *Atmos. Environ.*, **5**, 637-642.

Cantelli, A., P. Monti, G. Leuzzi, 2015: Numerical study of the urban geometrical representation impact in a surface energy budget model. *Environ. Fluid Mech.*, **15**, 251-273.

Di Bernardino, A., P. Monti, G. Leuzzi and G. Querzoli, 2015a: A laboratory investigation of flow and turbulence over a two-dimensional urban canopy. *Boundary-Layer Meteorol.*, **155**, 73-85.

Di Bernardino, A., P. Monti, G. Leuzzi and G. Querzoli, 2015b: On the effect of the aspect ratio on flow and turbulence over a two-dimensional street canyon. *Int. J. Environ. Pollut.*, **58**, 27–38.

Di Bernardino, A., P. Monti, G. Leuzzi and G. Querzoli, 2017: Water-channel estimation of Eulerian and Lagrangian time scales of the turbulence in idealized two-dimensional urban canopies. *Boundary-Layer Meteorol.*, **165**, 251-276.

Gariazzo, C. et al., 2015: Assessment of population exposure to Polycyclic Aromatic Hydrocarbons (PAHs) using integrated models and evaluation of uncertainties. *Atmos. Environ.*, **101**, 235-245.

Grimmond, C. S. B. and T. R. Oke, 1999: Aerodynamic properties of urban areas derived from analysis of urban surface form. *J. Appl. Meteorol.*, **38**, 1261-1292.

Kastner-Klein, P. and M. W. Rotach, 2004: Mean flow and turbulence characteristics in an urban roughness sublayer. *Boundary-Layer Meteorol.*, **111**, 55-84.

Kutzbach, J., 1961: Investigation of the modifications of wind profiles by artificially controlled surface roughness. M.S. thesis, University of Wisconsin-Madison.

Kent, C. W., C. S. B. Grimmond,·J. Barlow, D. Gatey, S. Kotthaus,·F. Lindberg and C. H. Halios, 2017: Evaluation of urban local-scale aerodynamic parameters: implications for the vertical profile of wind speed and for source areas. *Boundary-Layer Meteorol.*, **164**, 183-213.

Pelliccioni, A. And U. Poli, 2000: Use of neural net models to forecast atmospheric pollution. *Environ. Monit. Assess.*, **65**, 297-304.

Pelliccioni, A., P. Monti and G. Leuzzi, 2015: An alternative wind profile formulation for urban areas in neutral conditions. *Environ. Fluid Mech.*, **15**, 135-146.

Pelliccioni, A., P. Monti and G. Leuzzi, 2016: Wind-speed profile and roughness sub-layer depth modelling in urban boundary layers. *Boundary-Layer Meteorol.*, **160**, 225-248.