ON THE ROLE OF THE ROUGHNESS LENGTH IN URBAN BOUNDARY LAYERS

Armando Pelliccioni[1], Paolo Monti[2] and Giovanni Leuzzi[1]

[1]INAIL-DIPIA, Via Fontana Candida 1, 00040 Monteporzio Catone, Roma (Italy)
[2]Dipartimento di Ingegneria Civile Edile e Ambientale, Università di Roma "La Sapienza", Via Eudossiana 18, 00184 Roma (Italy)

Abstract: In an attempt to develop an improved model for the wind-speed profile valid for urban boundary layers (UBLs), the meaning of the roughness length z_0, i.e. the constant of integration of the vertical gradient of the wind speed, is extended. z_0 is assumed here as a "dynamic" variable rather than as a "geometric" parameter independent of the flow properties. On the basis of experiments conducted in a park located within the city of Rome and in the laboratory, it is found that in neutral conditions the "vertical" profile of the roughness length shows a nearly exponential decrease with height.

Key words: *MOST, Vertical profile, SODAR, Canopy layer, Roughness length, CEDVAL.*

INTRODUCTION

The aerodynamic roughness (buildings and other structures), moisture availability and surface thermal properties (albedo, heat capacity, thermal conductivity, among others) differentiate urban areas from their rural surroundings. This leads to the formation of a region characterized by higher temperatures, defined as the urban boundary layer (UBL). Monin-Obukhov similarity theory (MOST) is an useful tool for the investigation of the atmospheric boundary layer (ABL) over rural and flat terrain. In contrast, little progress has been made in the case of the UBL because of the difficulty intrinsic of the urban environment investigation (Roth, M., 2000).

One of the problems in UBL studies is that in the roughness sublayer (RSL) the MOST fails. In the inertial sublayer (ISL), i.e. the layer overlying the RSL, the mean horizontal velocity u as a function of the height z does not follow the classical log-law prescribed by the MOST. This problem is usually overcome extending the canonical Prandtl logarithmic law valid for flat terrain and by defining a suitable displacement height d_0:

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

where the x-axis is aligned with the mean wind, z_0 is the roughness length, $u_* = \left|\overline{u'w'}\right|^{1/2}$ the friction velocity (w is the vertical velocity component), k=0.4 the von Karman constant, u=0 at $z=(z_0+d_0)$. The universal dimensionless function $\psi[z/L]$, where L is the Obukhov length, takes into account deviations from adiabatic conditions, i.e. ψ is a function that equals zero when $z/L \rightarrow 0$. In equation (1) the quantities z_0, d_0 and u_* are variables to be estimated by means of some assumptions or by measurements. While u_* can be determined experimentally, z_0 and d_0 are not measurable parameters which must then be obtained in an indirect way. Furthermore, given the high spatial variability of turbulent fluxes, their estimation is not straightforward in the case of the urban environment. For example, morphometric methods allow to determine z_0 and d_0 on the basis of surface morphometry (among others MacDonald, R.W. et al., 1998; Grimmond, C.S.B. and T.R. Oke, 1999). In the case of neutral atmosphere, Kastner-Klein, P. and M.W. Rotach (2004) estimated z_0 and d_0 based on a morphometric method, while u_* was not measured, but calculated from equation (1). Those authors found a reasonable agreement between their model and wind tunnel measurements also within the RSL. More recently, Harman I.N and J.J. Finnigan (2007) developed profile functions, tested in vegetated canopies, which do not show discontinuity at the interface between RSL and ISL. In particular, they found a relationship for the vertical profile of the wind speed that is comprised of a canopy model coupled to a modified surface-layer model, formulated through the mixed layer analogy for the flow at a canopy top. In essence, their model consists of an extension of the canonical log-law where the influence of the RSL is taken into account by introducing an additional function.

To develop improved models for the wind-speed profile, we propose here a new parameterization where the roughness length z_0, i.e. the constant of integration of the vertical gradient of the wind-speed, is no longer assumed as a "static" parameter independent of the flow properties, but rather as a "dynamic" variable. We conjectured that z_0 may not be constant and that it may be assumed as a variable, which values depend not only on the surface cover but on the flow characteristics and the height too. The analysis is conducted using mainly a set of meteorological data taken from a site located within the city of Rome, Italy. We also utilized data taken from the CEDVAL compilation of wind tunnel datasets provided by the Environmental Wind Tunnel Laboratory (EWTL) of the Meteorological Institute of Hamburg University.

DATASETS

The urban data set is from a field campaign at the Villa Pamphili urban Park (VP) (Figure 1a) conducted during the period June 2005-July 2006. That large park, situated in the northeast part of the city of Rome, (41° 53' N, 12° 26' E, 70 m above the mean sea level), interrupts built-up zones. The measurements were made away from buildings and trees and hence the data can be considered as free from the immediate effects of obstacle wakes.

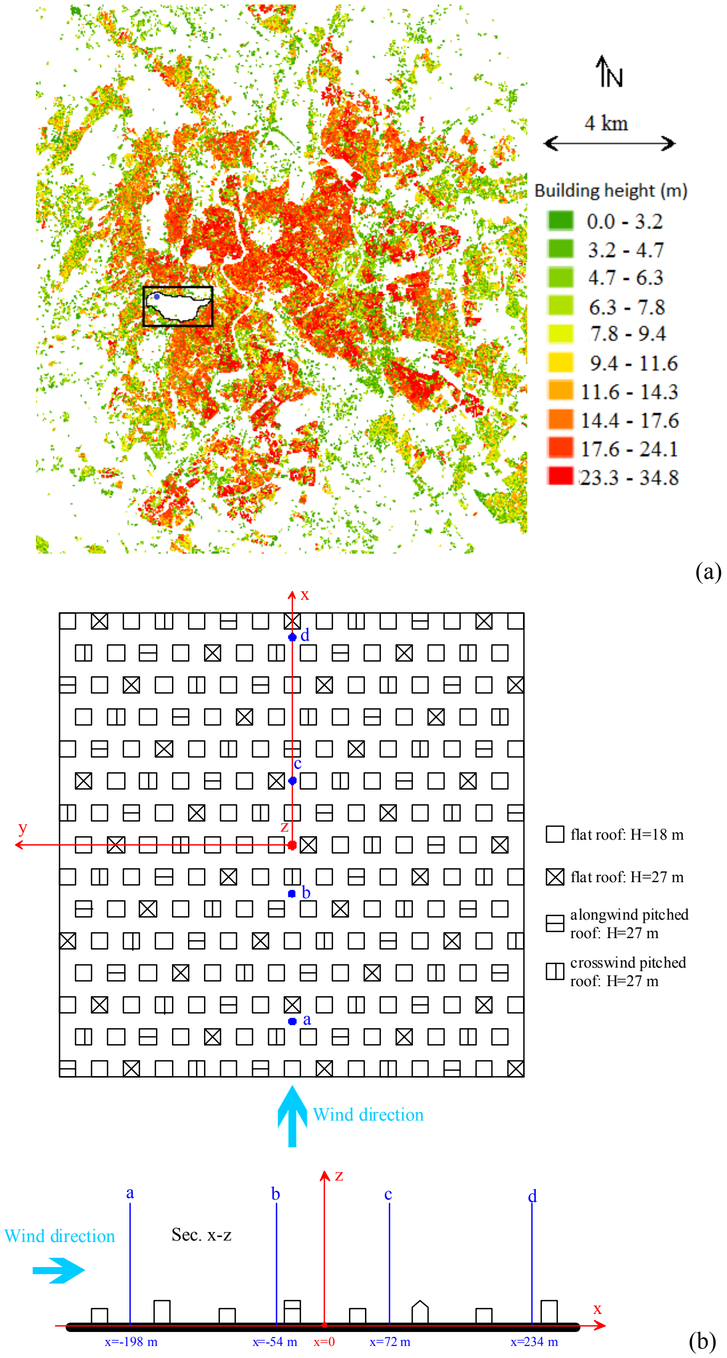

Figure 1. Rome area. Colors are building heights. The black line indicates VP park, the blue circle the position of the site. (b) CEDVAL experimental apparatus. The profiles a-d are those used for the analysis.

The meteorological instruments included a 10 m mast equipped with two triaxial ultrasonic anemometers mounted at z=5.5 m and z=10 m above ground level (agl) in order to measure the three velocity components u, v and w, respectively positive along east, north and the vertical, with a sampling rate of 4 Hz. In addition, two thermistors placed at z=1.6 m and z=10 m agl provided measurements of the air temperature T. A SODAR/RASS system was used to acquire the three components of the wind velocity and the virtual air temperature up to height of ~400 m. The system provided the vertical profiles of velocity and temperature averaged every 10 min. Since the analysis regards the neutral boundary layer, a stringent criterion to select neutral conditions is adopted in order to minimize uncertainties in the estimation of L, used as an indicator of the flow stability. In particular, only the vertical profiles corresponding to $|z/L| \leq 0.01$ m are considered as representative of the statically neutral UBL, for a total number of ~165 vertical profiles relevant to the analysis.

The second dataset is from the wind tunnel campaign CEDVAL. A detailed description of the experimental set-up and measurement techniques can be found at the internet site www.mi.uni-hamburg. The CEDVAL experiment was conducted in the WOTAN wind tunnel of the Environmental Wind Tunnel Laboratory (EWTL) at the Meteorological Institute of the University of Hamburg (Germany). In particular, the flow data considered in the present work refers to an array of cube houses with flat and slanted roofs (case BL3-2). Laser Doppler Anemometry was used to carry out at different sites wind velocity and components of the shear stress tensor. In particular, 4 vertical profiles taken along the wind direction were used for the present analysis (Figure 1b).

THE CONCEPT OF THE DYNAMIC ROUGHNESS LENGTH

The canonical definition of z_0 derives from the integration of the similarity law and its value has not a strict physical meaning (i.e. it does not coincide with the height at which wind speed vanishes); by definition its role regards the modulation of the wind profile as height varies. In our dataset, we found that the roughness length can be considered as a dynamic variable, $z_{0z}(z)$, which depends not only on the surface characteristics but also on the height, we need to define a suitable function z_{0z}, bearing in mind that it might be also a function of the flow. In this context, the canonical definition of z_0 should be considered as a zero-order approach, where it is assumed as invariant with height, viz.:

$$\frac{dz_{0z}}{dz} = 0 \tag{2}$$

from which results $z_{0z}=z_0=k_0$, where k_0 is a value independent of the height. In case of height dependent roughness length z_{0z}, the right hand side of equation (2) is no longer zero, but is a function at least of the height, whose expression is not straightforward. For guidance we may look at the work of Pelliccioni A. et al. (2012), who found optimal values for the classical roughness length at the surface and elevated levels for the VP site. With the constraint of a simple form for z_{0z}, it can be shown that the first order approach respect to equation (2) gives:

$$z_{0z}(z) = \alpha \cdot exp[-\beta \cdot z] + \gamma \tag{3}$$

The quantity β incorporates the effects of the roughness elements on the upper air levels, while α is a parameter depending on the roughness length at the ground level. In particular, the dynamical roughness length z_{0z} consists of two parts: one takes into account the effects of the roughness elements (the higher β the higher the complexity of the terrain) and a second one, corresponding to an asymptotic roughness length related to the city considered as a whole. It is worth noticing that the concept of dynamic roughness length can be viewed in terms of an additional contribution to the vertical gradient of the wind speed with respect to the classic law where the roughness length is constant.

VERTICAL PROFILES OF z_{0z}

Vertical profiles of z_{0z} for the Villa-Pamphili dataset

For the calculation of the parameters α, β, and γ, which come into play in the equation of z_{0z}, 16 wind sectors surrounding the VP measurement site were considered, each of them equal to 22.5°. Two sectors were selected for the analysis. The first, S1 (22.5°-45°), corresponds to a highly urbanized area, the second, S2 (202.5°-225°), identifies a more vegetated area, characterized by lower buildings height (Figure 1a). The average value of the buildings height is nearly H=14 m for S1 and H=9 m for S2. Only the profiles that obey the condition of constancy of the wind direction along the vertical were considered for the analysis. In this way, 36 and 12 vertical profiles were selected for the sectors S1 and S2, respectively. From those, we calculated the vertical profiles of z_{0z} by rearranging equation (1):

$$z_{0z}(z) = \frac{z}{exp\left[\frac{u(z)\cdot k}{u_*}\right]} \tag{4}$$

where u_* is measured at z_{ref}=10 m. Differently from equation (1), equation (4) does not contain the displacement height d_0 since it can be incorporated together with z_0 in an effective roughness, z_{eff}, once introduced an origin translation along the z-axis. In practice, from an operational point of view, the two classical parameters d_0 and z_0 can be related by means of the identity:

$$\frac{z^*-d_0}{z_0} = \frac{z^*}{z_{eff}} \tag{5}$$

where z* is an arbitrary reference height (Pelliccioni A. et al., 2012). For S1, the profiles of z_{0z} were grouped into 4 classes of values of u_* plus a fifth one referred to the mean profile obtained regardless of the value of u_*. Similarly, for S2 we considered 3 classes of u_* plus a fourth one, calculated regardless of u_*. The mean profiles shows that z_{0z}, on average, is larger at low z-levels (around 2.9 m and 2.4 m for the sectors S1 and S2, respectively). As height increases lower z_{0z} is observed, until it reaches a minimum nearly equal to 0.4 m and 0.6

m, respectively for S1 and S2, at z=200 m. In Figure 2, the experimental z_{0z} profiles are given as coming from the VP site.

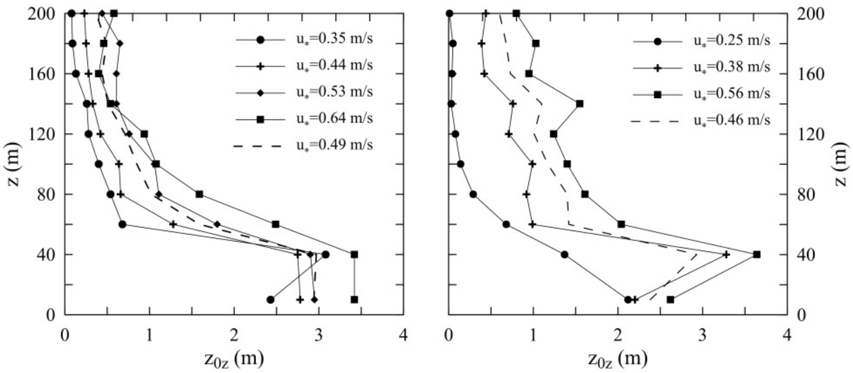

Figure 2. Vertical profiles of z_{0z} for classes of u_* for the sector S1 (left panel) and S2 (right panel).

Vertical profiles of z_{0z} for the CEDVAL dataset

The hypothesis that the decrease with height of z_{0z} observed for the VP dataset is not the consequence of a decrement of u_* with z, can be tested by analyzing the vertical profiles of u_* available in the CEDVAL dataset. In particular, to determine whether in the calculation of z_{0z} is more appropriate to consider measures of u_* for each height, or, instead, if it is sufficient the knowledge of $u_*(z_{ref})$, we consider a generalization of equation (4), where $u_*(z)$ is the friction velocity at height z:

$$z_{0z}^*(z) = \frac{z}{exp\left[\frac{u(z)\cdot k}{u_*(z)}\right]} \tag{6}$$

By comparing the roughness length profiles calculated by applying equation (4) (open circles in Figure 3) and equation (6) (full circles), it is clear that the two formulations provide similar profiles in correspondence of the larger fetch, despite $u_*(z)$ changes with z also in those locations. z_{0z} maxima of order 3 m at lower levels occur, while z_{0z} gradually decreases as height grows, until reaching a minimum value in the range 1-1.5 m for z>100 m. In contrast, in the other two locations z_{0z} shows very different behaviors. We tend to consider that for the first two locations the flow is not in equilibrium with the coverage, contrary to what might happen for the last two profiles, considerably far from the leading edge of the building group (see Figure 3). In conclusion, the variability of u_* with z seems to play a secondary role if the boundary layer is in equilibrium with the terrain.

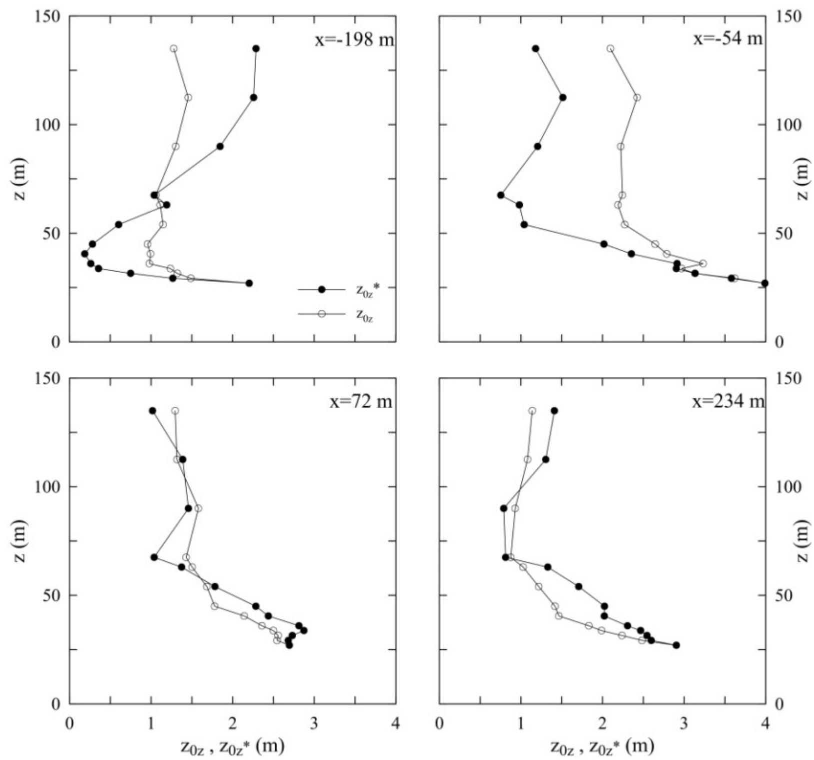

Figure 3. Vertical profiles of the roughness length from equation (4) and (6).

FINAL DISCUSSION AND CONCLUSIONS

The new model removes the restriction strictly linked to the land cover and attempts to provide a physically based method to determine the vertical profile of z_{0z}. Figure 4 shows the dependence of z_{0z} on u_* measured at z_{ref} at VP for the sectors S1 and S2. z_{0z} is averaged along z and grouped based upon the classes of u_* as defined above. The figure shows that a linear correlation between z_{0z} and u_* could exists. The proposed method proves to be sensitive and able to model the effects associated with the interaction of the wind with the obstacles. The importance of the concept of the dynamic roughness lies in the fact that it is an useful tool for evaluating wind profiles up to the ISL. The parameters α, β and γ can be calculated from z_{0z} and u_* using interpolating methods by adopting equation (3) as a parametric equation (not shown here).

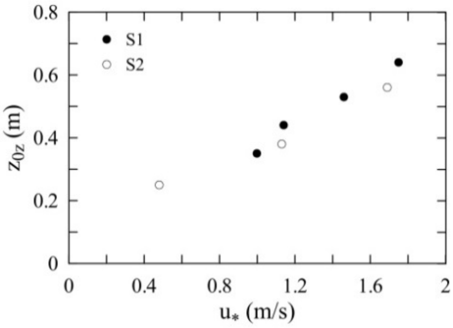

Figure 4. z_{0z} averaged over the whole vertical profile as a function of u_* for the sectors S1 and S2.

REFERENCES

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.

MacDonald, R.W., R.S. Griffiths and D.J. Hall, 1998: An Improved Method for the Estimation of Surface Roughness of Obstacle Arrays. *Atmos. Environ.* **32**, 1857–1894.

Roth, M., 2000. Review of atmospheric turbulence over cities. *Q. J. Roy. Meteorol. Soc.*, **126**, 941-990.

Pelliccioni, A., P. Monti, C. Gariazzo and G. Leuzzi, 2012: Some characteristics of the urban boundary layer above Rome, Italy, and applicability of Monin-Obukhov similarity. *Environ. Fluid. Mech.*, **12**, 405-428.

Harman I.N and J.J. Finnigan, 2007: A simple unified theory for flow in the canopy and roughness sublayer. *Boundary-Layer Meteorol.*, **123**, 339–363.