# Performances of parametric laws for computing the wind speed profile in the urban boundary layer. Comparison to two-dimensional building water channel experiment.


Annalisa Di Bernardino[1], Armando Pelliccioni[2], Paolo Monti[1], Giovanni Leuzzi[1] and Fabio Sammartino[1]

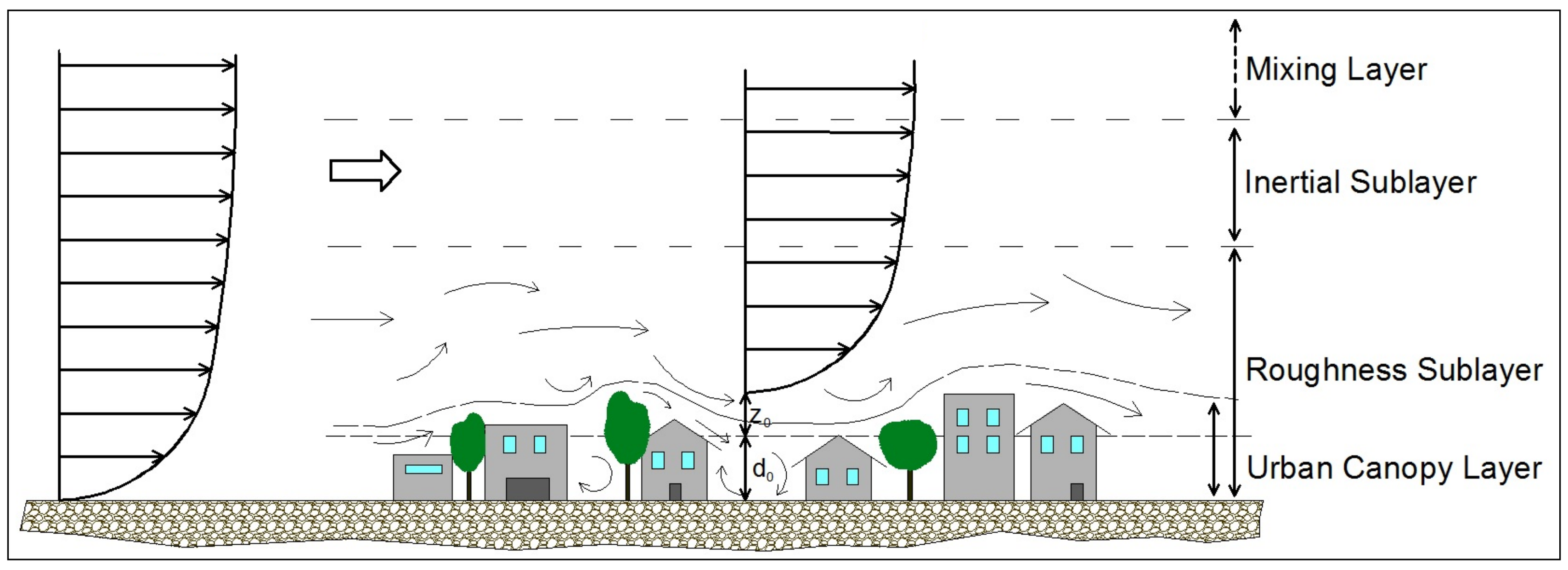
[1] Dipartimento di Ingegneria Civile Edile e Ambientale, Università di Roma "La Sapienza". Via Eudossiana 18 - 00184, Roma, Italy.

[2] INAIL-DIMELA, Monteporzio Catone, Rome, Italy.

SAPIENZA UNIVERSITÀ DI ROMA

DICEA - DIPARTIMENTO DI INGEGNERIA CIVILE, EDILE ED AMBIENTALE


## ① 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 (Fernando, 2010). The UBL is studied numerically and experimentally but important issues still remain unresolved. One of these is the determination of the wind speed profile, u(z).

Where obstacles are present, the UBL shows a well-define vertical structure:

(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 is spatially inhomogeneous;

(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 $\lambda_P$ (the ratio between the plan area of roughness elements to the total surface area) and the frontal area index $\lambda_F$ (areas of building facets facing the wind direction to the total surface area).

The expression generally used to determine the wind speed profile above the canopy is based on the log-law in (1):

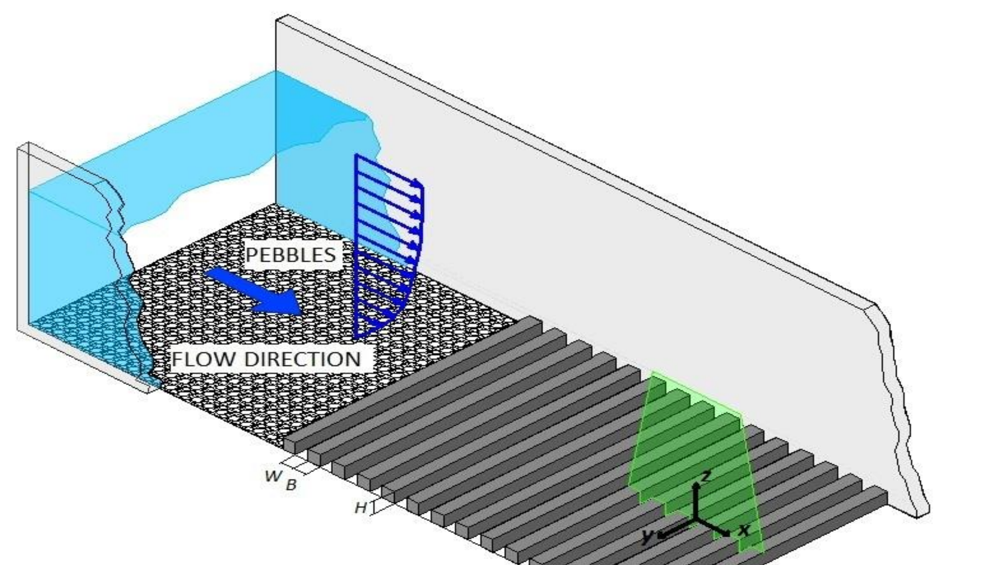
$$\bar{u}(z) = \frac{u_*}{k}\ln\left[\frac{z-d_0}{z_0}\right] \quad (1)$$

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, while $u_*$ is usually referred to the ISL. In what follows, algorithms that relate $z_0$ and $d_0$ to geometric parameters such as H, $\lambda_P$ and $\lambda_F$ are investigated.

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.

## ② Experiments




❖ **FLOW CHARACTERISTICS**

- height: 0.35 m
- width: 0.25 m
- length: 7.40 m
- water depth: 0.16 m

The test section is located 5.0 m downwind of the inlet, where the boundary layer under neutral conditions is fully-developed.
This condition is realized thanks to small pebbles that cover the channel bottom upstream the building.

- obstacle: **B=L=H=0.02 m** in the middle section of the channel (y=0)
- free stream velocity (U): 0.33 m $s^{-1}$
- Reynolds number: ≅ **400** (considering the friction velocity)

❖ **GEOMETRICAL CONFIGURATIONS**

- AR = 1 and 1.5 ($\lambda_P$ = 0.5 and 0.4) ➡ skimming flow
- AR = 1.75 and 2 ($\lambda_P$ = 0.36 and 0.33) ➡ wake interference regime

## ③ Morphometric methods

Two classes of morphometric methods are considered: (i) methods that use H (height-based approach); (ii) methods that use H and $\lambda_P$.

In the first, simpler method, $z_0$ 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. 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.**
Among the parameterizations based on the second method, the one by Kutzbach (1961), **K61**, based on field experiments, viz.:

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

That proposed by Counihan (1971), **C71**, basis of wind-tunnel experiments viz.:

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

on the. Equation (4a) is valid only for $0.1<\lambda_P<0.25$. C71 reported a curve for $z_0$ that ranges from $\lambda_P$=0 to $\lambda_P$=0.5. Using this curve, the validity of the law can be estended 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 the coefficients $C_1$=0.366, $C_2$=0.377, $C_3$=-3.201 and $C_4$=2.919 are determined 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:

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

is a local length scale. PML15 calculated $\alpha$=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 ($\alpha$, $L_C$, γ) in terms of suitable scale variables, their model cannot be used in other sites. To overcome this problem, in this work the average building height (H=18 m), assumed as representative of the site considered by PML15, can be used to make the three quantities non-dimensional. Thus, the non-dimensional counterparts of ($\alpha$, $L_C$, 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:

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

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 $z_{0L}(z)$.

## ④ Results

Figure 1:
(a) Experimental vertical profiles of the non-dimensional Reynolds stress for the four $\lambda_P$.
(b) As in (a), but for the non-dimensional horizontal mean velocity.

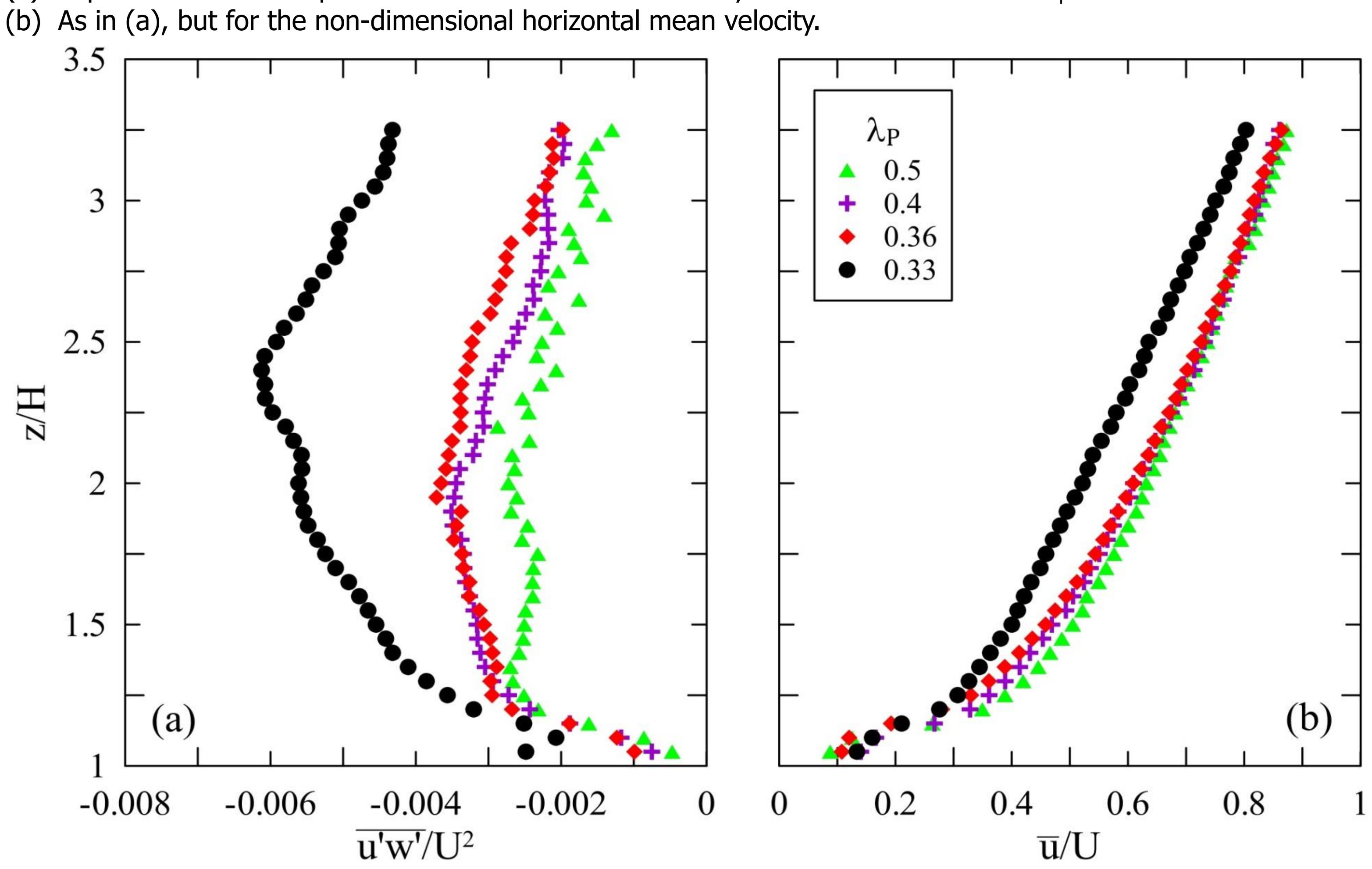



Table 1:
$z_0$ and $d_0$ calculated with the morphometric methods based on H and $\lambda_P$. The corresponding friction velocities based on the profiles shown in Figure 1 are also reported.

| | $\lambda_P$ | 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** | $\alpha$ (m) | 0.00361 |
| | $L_C$ (m) | 0.06944 |
| | γ (m) | 0.00038 |

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

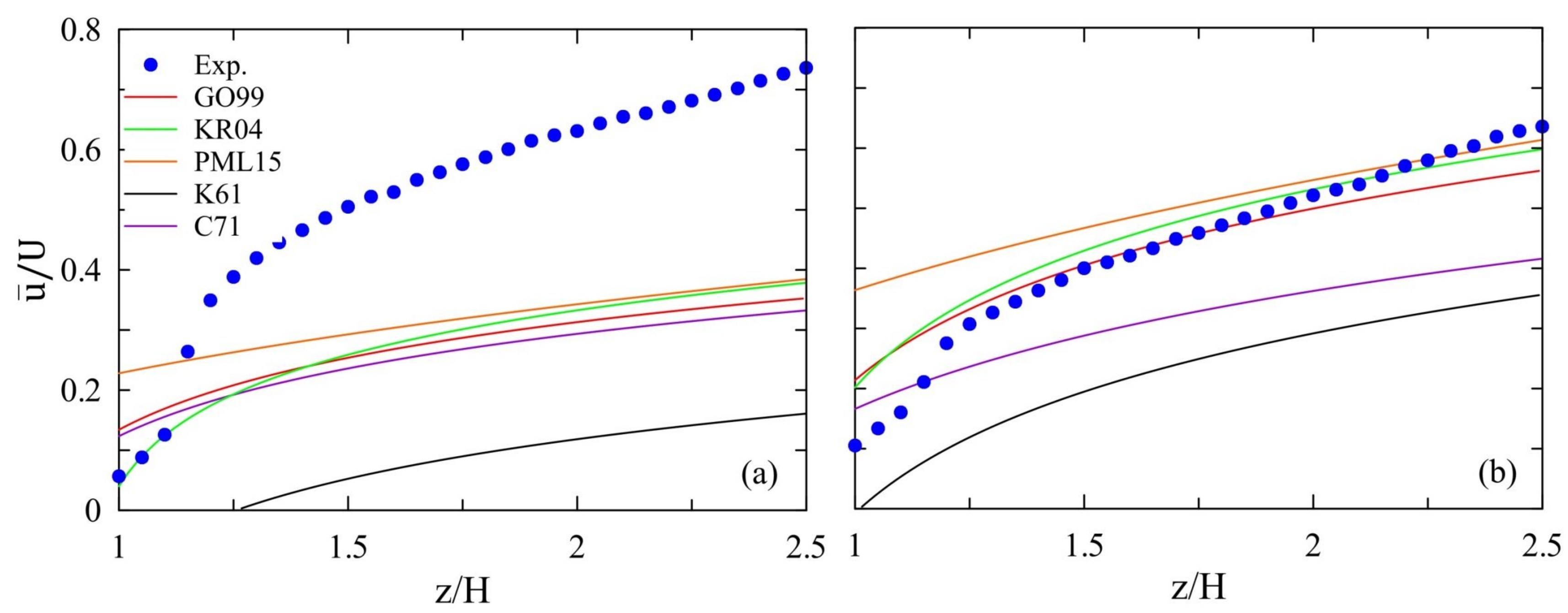
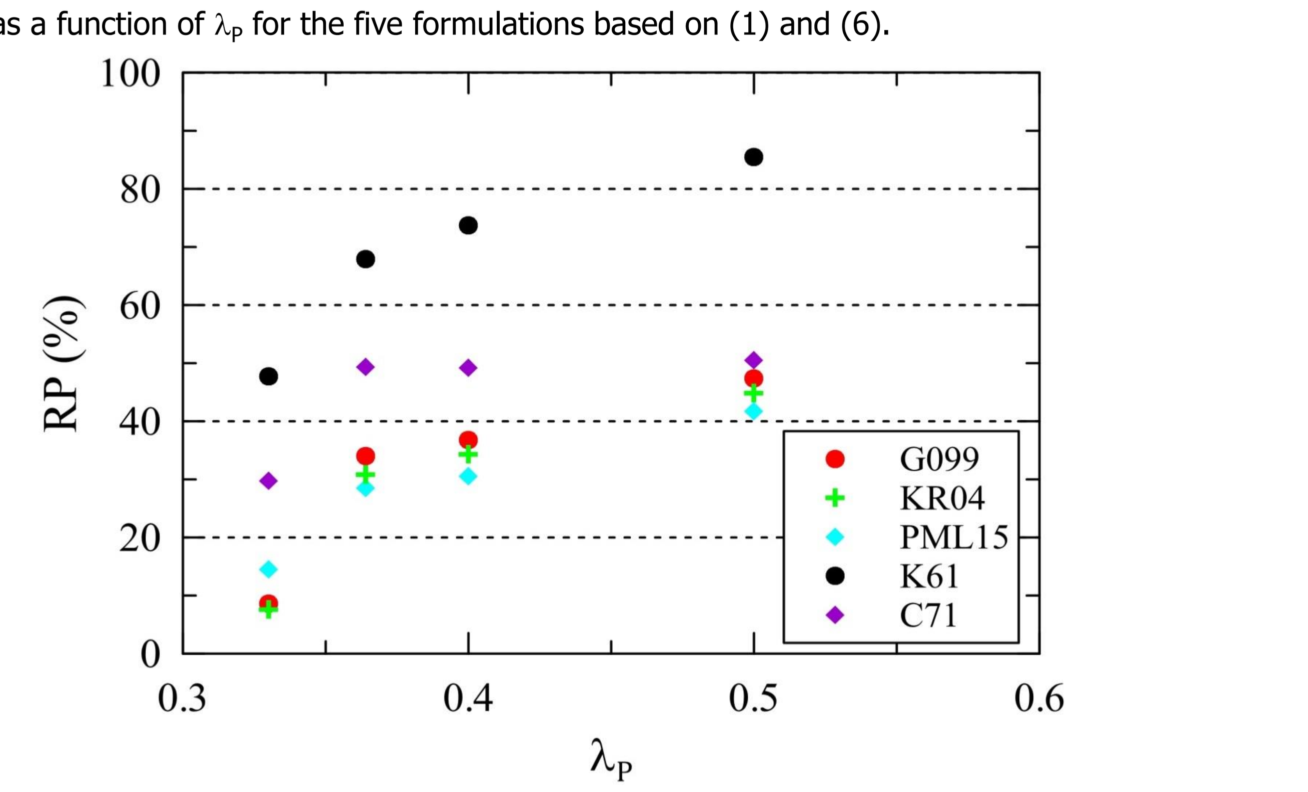



Figure 3:
Reproducibility parameter as a function of $\lambda_P$ for the five formulations based on (1) and (6).

$$RP = [\overline{|u_0 - u_M|}/\overline{u_0}]100$$




## ⑤ Conclusions

Trends for AR=2 differs substantially from the others: it suggests that the transition between the skimming flow and the wake interference regime coincides with that of the 3D flow ($\lambda_P$=0.35), rather than with that conventionally recognised for 2D flows (AR=1.5, i.e. for $\lambda_P$=0.4)
For $\lambda_P$=0.5 (skimming flow), all the models underestimate observations. 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. In contrast, for $\lambda_P$=0.3 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.
The agreement with observation is reasonably good (RP<15%) for GO99, KR04 and PML15 when $\lambda_P$=0.33, while large errors occur for K61 and C71. It means that all models work reasonably well for low $\lambda_P$, i.e. for the wake interference regime.

## References


- Fernando, H. J. S., 2010: Fluid dynamic of urban atmospheres in complex terrain. *Annu. Rev. Fluid Mech*, **42**, 365-389.
- Pelliccioni, A., P. Monti and G. Leuzzi, 2015: An alternative wind profile formulation for urban areas in neutral conditions. *EFM*, **15**, 135-146.
- Counihan, J., 1971: Wind tunnel determination of the roughness length as a function of fetch and density of three-dimensional roughness elements. *AE*, **5**, 637-642.
- Kastner-Klein, P. and M. W. Rotach, 2004: Mean flow and turbulence characteristics in an urban roughness sublayer. *BLM*, **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.
- Grimmond, C. S. B. and T. R. Oke, 1999: Aerodynamic properties of urban areas derived from analysis of urban surface form. *JFM*, **38**, 1261-1292.