A new combined approach for wind profile calibration in urban environments

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SUMMARY

Accurate modelling of mean wind profiles is a key point for the reliable evaluation of wind actions on structures, especially within complex urban areas featured by heterogeneous building configurations and significant vertical variability. Standard anemometric and morphometric methods exhibit significant limitations, including substantial uncertainty in the determination of displacement height and limited applicability across different urban morphologies. Within this topic, a new combined morphometric–anemometric approach for the calibration of logarithmic mean wind profiles in urban environments is described. The displacement height is defined through a physically consistent morphometric formulation, whereas the roughness length is estimated by anemometric measurements. The influence of urban canopy heterogeneity is incorporated by adopting a representative height derived from the statistics of building heights. The application to mean wind profiles derived by LiDAR measurements in two urban sites shows reduced uncertainty in roughness-parameters estimation and improved agreement with logarithmic profiles compared with purely anemometric methods.

Keywords: mean wind profile, wind actions, roughness height, displacement height, LiDAR measurements

1. INTRODUCTION

The modelling of the mean wind profile is a pivotal aspect in the assessment of wind actions on structures. Several models are available for structural design (Simiu and Scanlan, 1996), among which the Logarithmic Law is generally regarded as suitable for representing the mean wind flow in the Surface Layer (SL) up to heights of about 200 m (Kent et al., 2017). Nevertheless, its validity throughout the entire SL has been questioned in the lower part of SL, the Roughness Sublayer (RSL), where the wind flow is influenced by urban texture and individual buildings (Grimmond and Oke, 1999). In practice, these effects are often neglected by assuming that the Logarithmic Law, valid in the upper part of the SL, namely Inertial Sublayer (ISL), extends downwards into RSL (Millward-Hopkins et al., 2011). Under this assumption, the vertical variation of the mean wind speed is described by a roughness parameter, namely the roughness length z_0, while a location parameter is introduced to account for the upward displacement of the profile relative to the ground level, defined as the zero-plane displacement height z_d. Accurate estimation of the mean wind profiles therefore requires an appropriate calibration of both z_0 and z_d (Sepe et al., 2023) for the site of interest and for each wind direction.

A combined morphometric–anemometric approach is described here for the characterization of logarithmic wind profile parameters in complex urban environments. The methodology is first introduced, including both the morphometric model and the anemometric calibration procedure. Its performance is then discussed, and the approach is finally applied to LiDAR measurements collected at two urban sites. For more details see Avossa et al. 2026.

2. METHODOLOGY

Within the assumption of validity of the logarithmic wind profile, the mean wind speed above the urban canopy layer is evaluated as:

$$v(z) = \frac{u_*}{\kappa} log\left(\frac{z-z_d}{z_0}\right) \quad (1)$$

where κ = 0.4 is the von Karman constant, u_* is the friction velocity, and z_0 and z_d are the roughness parameters to be calibrated for the specific site. Calibration of logarithmic wind profile parameters in complex urban environments is affected by significant uncertainty when anemometric methods are applied alone, mainly due to the subjective treatment of the displacement height as a fitting parameter. To address this issue, the presented approach adopts a sequential combination of morphometric and anemometric methods.

In the first step, the displacement height is estimated using a morphometric method grounded on the physical definition introduced by Jackson (1981). The presented morphometric model to assess the displacement height is given by:

$$\frac{z_d}{H_{rep}} = 0.37 + 0.9 \cdot \lambda_p \quad (2)$$

where λ_p is the plan area index, and H_{rep} is the representative height equal to the building height H in idealised urban environments and to $0.85 \cdot H_{95}$ for complex urban environments, being H_{95} the 95th percentile of the building height distribution. The morphometric parameters including the plan area index λ_p, the mean building height H_m, and descriptors accounting for building height variability can be evaluated from Digital Elevation Models (DEMs) and Digital Terrain Model (DTM) within a GIS-based procedure. In particular, the DTM and DSM can be pre-processed subtracting the former from the latter to derive the Roughness-Element Surface Model (RESM) providing the heights H of the roughness elements.

Once the value of the displacement height is set, the anemometric analysis is performed to estimate the remaining parameter of the logarithmic wind profile. Anemometric inputs consist of N mean wind profiles obtained from field measurements, together with the corresponding measurement heights and wind directions. It is reasonable to assume that the roughness parameters z_0 and z_d, for a given mean wind direction, are the same for each wind profile associated with that direction. In this case, the Constrained Optimisation Problem (COP) can be formulated (Picozzi et al., 2025), which requires solving the minimisation problem:

$$\{\boldsymbol{u}, z_0, z_d\}_{opt} = \arg\min \frac{1}{N} \sum_{i=1}^{N} C_i(u_*, z_0, z_d) \quad (3)$$

The solution of the COP includes N friction velocities and a single pair of optimum roughness parameters $\{z_0, z_d\}_{opt}$ defined as the values minimising the Mean Square Error (MSE). In the (z_0, z_d) domain, a locus corresponding to the minimum MSE is identified and can be defined as:

$$z_0 = Z(z_d) = \arg\min \frac{1}{N} \sum_{i=1}^{N} C_i(z_0 | z_d) \quad (4)$$

which provides the minimum MSE for a given value of the displacement height z_d. The function defined by Eq. (4) is termed Skeleton Curve of Roughness parameters (SCR) and depends on the input datasets of the available measurements for the investigated site and wind direction. The SCR defines a family of wind profiles equally representative of the dataset, for which the MSE is almost equal and lower than the measurement error. The definition of this curve reveals a substantial uncertainty in the definition of the mean wind profile at low elevation. This uncertainty primarily stems from the difficulty in identifying a unique physically meaningful value of the displacement height z_d within the range of admissible solutions defined by the SCR parameters. Thus, selecting a single displacement height remains inherently ambiguous when based solely on anemometric fitting, reflecting the limited information content of measurements at low elevation.

Thus, wind profiles can be calibrated using a morphometric-anemometric approach, in which morphometric information used to constrain the estimation of the displacement height z_d is expressed in terms of plan area index λ_p according to Eq. (2). By reducing the dimensionality of the anemometric problem, this approach limits the sensitivity of the calibrated parameters to measurement height selection and fitting assumptions.

3. EXPECTED RESULTS

Two sites in Aversa (southern Italy), denoted as LAS-1 and LAS-2, are investigated using a LiDAR wind profiler. Both are characterised by almost flat terrain and dense built-up areas. Measurements were collected from October 2015 to December 2016 and from February 2020 to June 2021, respectively. The system recorded data at 10 measurement heights between 50 and 200 m. For more details see Avossa et al. 2026.

From the raw LiDAR measurements, a dataset of 10-min averaged wind profiles corresponding to neutral atmospheric stability conditions is derived. Specifically, the value of 6.0 m/s suggested by Pasquill (1961) at 10 m height under standard conditions is projected to the height z_{min} = 50 m, resulting in threshold wind speed equal to 10 m/s adopted to identify wind profiles associated with strong wind conditions. After pre-processing, a total of 386 and 223 wind profiles is retained for dataset LAS-1 and LAS-2, respectively. The wind profiles are finally grouped into twelve sectors, each spanning 30°, numbered clockwise, with Sector I centred on the North. Once the heights of the roughness elements are derived from DSM and DTM models, the morphometric analysis is performed evaluating the plan area index λ_p and building height statistics, including the mean value H_m, the standard deviation σ_H, the maximum value H_{max} and the 95th percentile H_{95}.

Results summarised in Table 1 highlight marked differences between the roughness parameters obtained through the pure anemometric method and those derived from the combined approach referring to four representative sectors characterized by distinct behaviours and displacement height estimation. Further insight into the differences between the pure anemometric calibration and the presented combined approach is provided in Figure 1. For each case, experimental data are shown in terms of mean wind speed values and associated variability at the measurement height, together with the wind profiles calibrated using the anemometric method and the combined approach. Figure 1a refers to Sector II of LAS-1, which represents a case where the two approaches yield comparable results. In this sector, the displacement height estimated through the anemometric calibration is close to that obtained using combined approach, and both profiles are in good agreement with the experimental data. This case confirms that when anemometric fitting

Table 1. Roughness parameters estimated using pure anemometric method and proposed combined approach

							Anemometric		Combined		
Site	Sector	λ_p	H_m (m)	σ_H (m)	H_{max} (m)	H_{95} (m)	z_d (m)	z_0 (m)	z_d (m)	z_0 (m)	$z_{d,comb}/z_{d,an}$
LAS-1	II	0.58	10.0	5.3	34.6	20.7	14.8	0.66	15.7	0.59	1.1
	X	0.45	7.7	3.8	35.5	13.5	26.5	0.11	8.9	0.63	0.3
LAS-2	II	0.59	10.5	6.3	41.6	20.6	4.5	4.63	15.8	2.98	3.5
	VIII	0.46	12.9	9.3	60.3	27.2	23.0	0.98	18.1	1.94	0.8

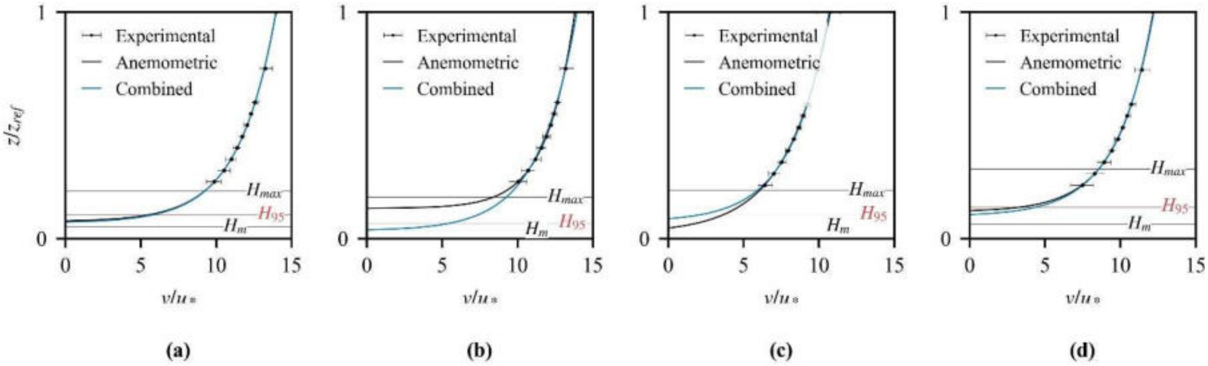

Figure 1. Measured wind profiles and corresponding calibrated profiles: (a) Sector II of LAS-1; (b) Sector X of LAS-1; (c) Sector II of LAS-2; (d) Sector VIII of LAS-2. The reference height z_{ref} is set equal to 200 m.

yields plausible z_d, both approaches agree. Figure 1b shows Sector X of LAS-1, where the anemometric method yields a displacement height approximately twice the value of H_{95}. This is not consistent with the physical interpretation of the displacement height in relation to the urban canopy height distribution. In this case, the combined approach constrains z_d to a value compatible with the representative building height, leading to a wind profile that remains in good agreement with the experimental data, avoiding physically questionable extrapolations at low elevations. Figure 1c illustrates Sector II of LAS-2, which is characterised by an anemometric estimate of z_d that is of the same order of magnitude as z_0. This combination of roughness parameters suggests an inconsistency between the estimated value of z_d and the overall morphological characteristics of the site. The combined approach mitigates this issue by providing a larger and more physically meaningful value of z_d, resulting in a wind profile that better reflects the expected influence of the urban canopy. Finally, Figure 1d refers to Sector VIII of LAS-2, where the urban morphology is dominated by a single tall building with a height of 60.3 m, occupying less than 5% of the total plan area. In this configuration, the use of the maximum building height as a reference scale would lead to an overestimation of z_d. By contrast, the combined approach, based on the representative height H_{95}, effectively filters out the isolated feature and yields a displacement height that is more representative of the bulk urban morphology, while still reproducing the measured wind profile above the canopy.

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