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Wind tunnel investigation of mean and fluctuating wind flow downstream of a terrain roughness discontinuity

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SUMMARY
The ERIES-WhICH ROUGH project investigates the development of neutral atmospheric boundary-layer flows downstream of terrain roughness discontinuities, and its implications on the wind loading of tall buildings. Wind tunnel experiments were conducted at the Eindhoven University of Technology (TU/e), where three equilibrium configurations representing terrains with increasing roughness, and their associated smooth-to-rough transitions were reproduced, resulting in twenty-seven roughness setups. Instantaneous wind speed measurements were taken along a vertical alignment, just upstream the location where the model of a tall building was then placed for pressure measurements. Profiles of the mean wind velocity and of the relevant turbulence characteristics were thus available, providing information on how and how fast the modifications in the flow propagate downstream the discontinuity. The findings from the experimental campaign are expected to provide a consistent description of transition boundary-layer profiles and support a more realistic evaluation of wind actions under non-equilibrium conditions.

Keywords: Atmospheric boundary layer; Surface roughness; Roughness transitions; Wind tunnel experiments; Turbulence characteristics; Wind actions

1. INTRODUCTION

The assessment of wind actions on structures requires modelling the mean wind speed profile within the Atmospheric Boundary Layer (ABL). In engineering practice, this profile is typically described using three formulations: the power law proposed by Hellman and adopted by Davenport (Davenport, 1960), the logarithmic law derived from boundary layer theory and the analytical model introduced by Deaves and Harris (Deaves and Harris, 1978). These models are generally calibrated under neutral atmospheric stratification and assume equilibrium conditions over long upstream fetches with uniform terrain roughness. In practical applications, terrain exposure is classified into discrete roughness categories and model parameters are assigned through reference-based, morphometric, or anemometric methods. However, these approaches involve considerable uncertainty, especially in complex urban environments. Moreover, equilibrium conditions are rarely satisfied in reality because terrain roughness often changes abruptly due to variations in land use. When wind encounters a roughness discontinuity, such as between sea and coastline or rural and urban areas, the flow cannot immediately adjust to the new surface conditions. Instead, an Internal Boundary Layer (IBL) develops and grows downstream, creating a stratified structure composed of: (*i*) a lower region adjusted to the downstream terrain; (*ii*) an upper region still governed by upstream conditions; and (*iii*) an intermediate transition layer where momentum and turbulence gradually redistribute. Analytical descriptions of this process were developed several decades ago (Picozzi et al., 2025) and later incorporated, in simplified form, into engineering recommendations and design standards. However, codified procedures often require very long fetch distances to reach equilibrium conditions, sometimes extending to several tens of kilometres, which is rarely compatible with real terrain configurations. The ERIES-WhICH ROUGH research project (Rizzo et al., 2026) investigates the behaviour of atmospheric boundary-layer flows downstream of terrain roughness changes through an extensive wind tunnel campaign. The present study focuses on the analysis of mean wind velocity and turbulence profiles for both equilibrium conditions and smooth-to-rough transitions. The experimental configurations allow a direct observation of how the flow adjusts downstream of a roughness discontinuity and how this adjustment varies with height. The collected data provide a description of the development of the internal boundary layer under non-equilibrium conditions. In particular, three values of uniform roughness were tested as a reference, corresponding categories II, III and IV of Eurocode 1 (CEN, 2026), together with three sets of roughness transitions were examined, corresponding to the changes from Category II to III, from Category III to IV and from Category II to IV. For each transition, eight intermediate configurations were defined by progressively modifying the roughness downstream a discontinuity line, thus covering a wide range of development stages of the IBL. For each configuration, instantaneous wind speed measurements were taken along a vertical alignment, just upstream the location where the model of a tall building was then placed for pressure measurements. Profiles of the mean wind velocity and of the relevant turbulence characteristics were thus available, providing a consistent and detailed description of how both mean flow and turbulence evolve across different transition scenarios.

2. EXPERIMENTAL CAMPAIGN

The research is mainly based on an experimental campaign conducted in the closed-circuit Atmospheric Boundary Layer Wind Tunnel (ABLWT) at Eindhoven University of Technology (TU/e), featuring a 27 m long test section that allows the natural development of the boundary layer under controlled conditions. Boundary layer conditions were reproduced using modular L-shaped metallic roughness elements magnetically fixed to the tunnel floor, allowing controlled simulation of different terrain exposures and their transitions without the use of spires or additional turbulence-generating devices.

Three equilibrium roughness configurations were generated, representing terrains with increasing roughness through the use of 20×20 mm, 40×40 mm, and 60×60 mm roughness elements. In a scale of 1:492, these produced equilibrium profiles corresponding to values of the roughness length of z_0=0.056 (profile A), z_0=0.30 (profile B) and z_0=0.627 (profile C), meant to reproduce categories II, III and IV of Eurocode 1. In addition, smooth-to-rough transitions were simulated by progressively replacing roughness elements from downstream to upstream, thus increasing the fetch length between the discontinuity and the section of measurement. Fetch lengths corresponding to approximately 1–8 km full scale were obtained, resulting in a total of twenty-seven flow configurations. Flow measurements were performed using a Cobra multi-hole probe mounted on an automated traversing system, with high-frequency acquisition to capture turbulence characteristics. Figure 1 shows the experimental setup, including the distribution of modular roughness elements and the measurement system.

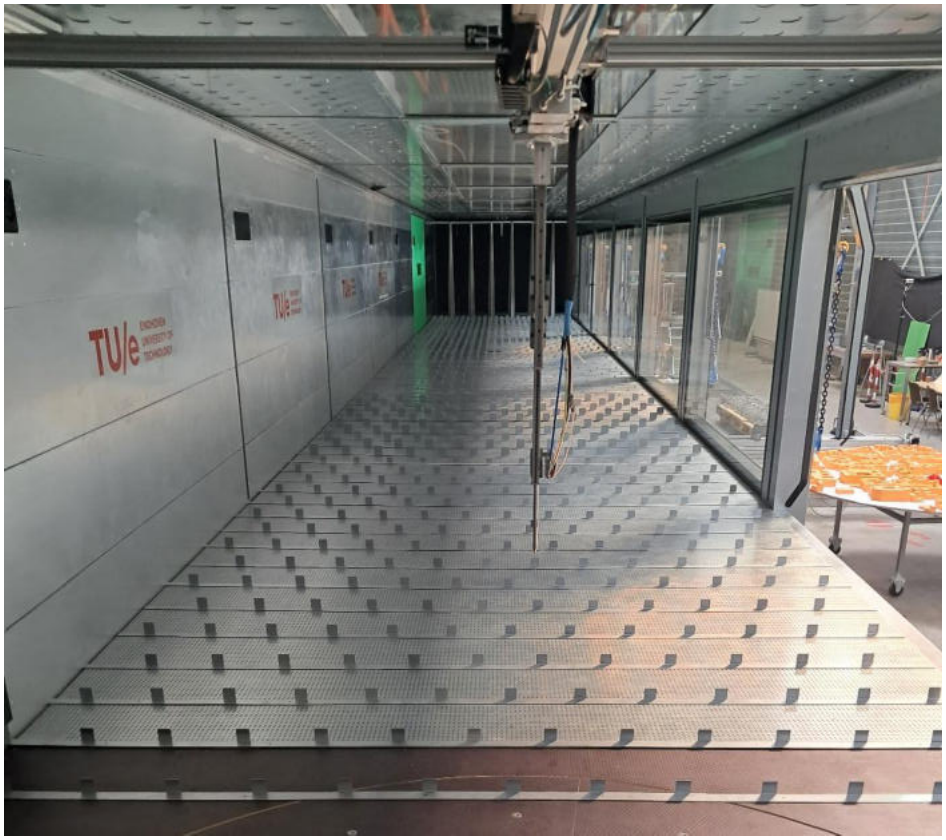

Figure 1. Experimental setup in the wind tunnel

3. MAIN RESULTS

Figures 2a and 2b show the measured profiles of mean wind velocity and turbulence intensity for the three transitions considered, namely A → B, B → C and A → C, each described through a sequence of intermediate configurations associated with increasing fetch downstream the discontinuity. In the A → B discontinuity it is observed that for the shortest fetch of 1.2 km, no full adjustment of the mean wind profile to the downstream roughness occurs, and the transition between the upstream and downstream profiles extends from the ground to a height of about 70 m; above that equilibrium profile A is unaffected by the roughness change. On the other hand, for the longest fetch of 8.1 km, the mean wind profile fully adjusts to the downstream roughness up to 100 m from the ground, and the transition ends at 250 m. A similar observation can be made for the transition from roughness B to C for the shortest fetch, where the transition ends at about 60 m from the ground; however, for just only longer fetches, starting from 1.5 km adjustment to roughness C seems to be have been reached up to 50 m from the ground. Above that, transition starts, and its extension depends on the fetch downstream the discontinuity. Finally, for transition from roughness A to C due to the more pronounced discontinuity in roughness, the transition zone is deeper; it extends from the ground to about 150 m for a fetch length of 1.2 km, and for 50 m to 300 m for a fetch length of 8.1 km.

The turbulence intensity profiles in Figure 2b confirm the observations above. For transition from roughness A to B, with a fetch of 1.2 km transition between the equilibrium intensity profiles A and B occurs below 70 m; for a fetch of 8.1 km, the turbulence intensity is fully adjusted to that of roughness B up to 150 m, and transition takes place between 150 m and 300 m. For Transition B to C, with a fetch of 1.2 km transition between the equilibrium intensity profiles also takes place up to 70 m, but also in this case it is observed that for even just longer fetches, starting at 1.5 km, the intensity profile is adjusted to that of the downstream roughness up to 50 m from the ground, and transition take place above that. Finally, the transition of the intensity profile for a roughness discontinuity from A to C fully confirms what observed concerning the mean speed profiles.

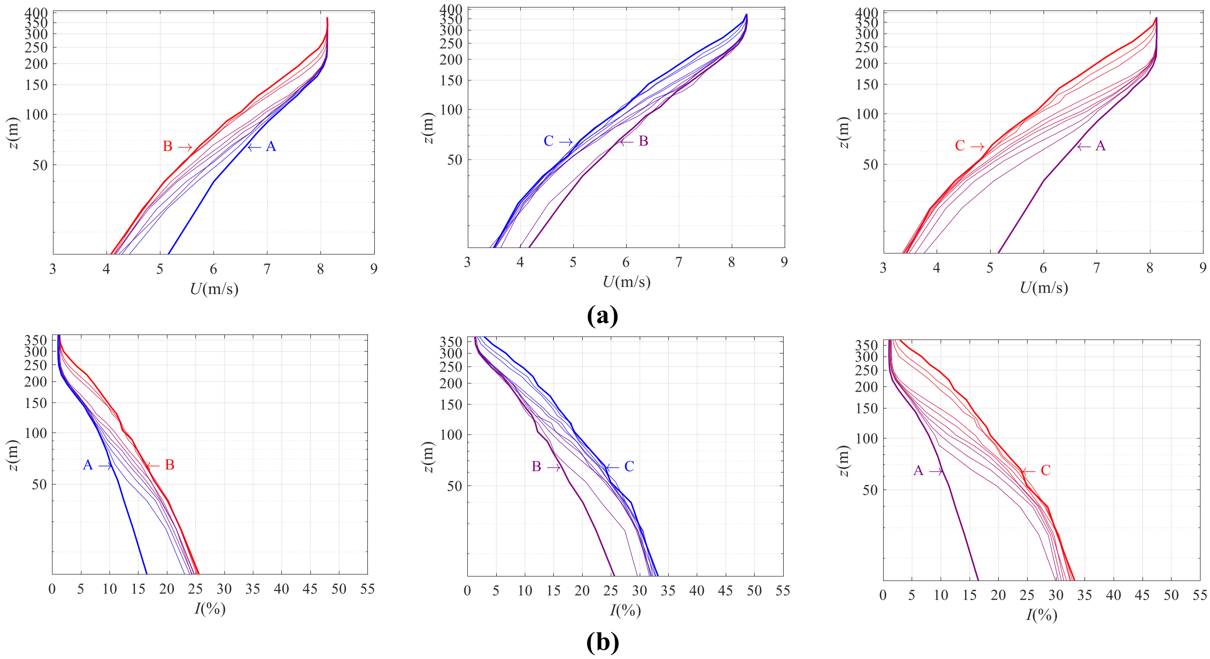

Figure 2. Transition of flow characteristics downstream the discontinuity: mean wind speed (a) and turbulence intensity (b) profiles.

4. CONCLUSIONS AND PERSPECTIVES

The study provides an experimental characterization of atmospheric boundary-layer flows downstream of terrain roughness changes, considering three transition types. The results show that both mean wind velocity and turbulence adjust progressively with downstream distance, with a clear vertical stratification: rapid adaptation near the ground and delayed response at higher elevations. The extension of the transition region increases with the magnitude of the roughness change, with the A → C case exhibiting the most pronounced effects. These findings highlight the relevance of non-equilibrium conditions in the modelling of wind profiles over heterogeneous terrain for the purpose of the assessment of wind loads on structures. The possibility of developing a mathematical model for the flow downstream the discontinuity will allow establishing consistent rules for the definition of wind loads.

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