Abstract

This thesis presents a comprehensive study of flow dynamics over rough and vegetated surfaces. The work is structured in two parts addressing the hydrodynamics of flows over canopy-like roughness elements and the statistical structure of vertical velocity in turbulent boundary layers.

Part I focuses on the drag mechanisms induced by surface roughness and vegetation-like canopies under various conditions from steady uniform to unsteady fully three-dimensional flows. Firstly, an analytical framework for drag partitioning based on Raupach's (1992) model is re-examined using stochastic averaging methods and scaling arguments, offering new insights into wake interactions and shelter effects at various roughness densities. Validation against two decades of experimental and numerical data confirms the model's applicability across a range of roughness types and densities. Secondly, the transient drag behavior in rod-canopied sloping channels following a two-dimensional dam break events is investigated. Flume experiments combined with image-based reconstructions and load cell measurements show significantly reduced drag coefficients ($C_d \approx 0.4$) near the advancing front, compared to the steady-uniform case. This finding suggests that drag reduction mechanisms associated with transients and flow disturbances are more likely to play a dominant role when compared to conventional sheltering. Finally, to three-dimensional dam-break flows and canopy-like surfaces is studied. Based, on preliminary investigation of the smooth bed case results, a novel a normalization framework that collapses front dynamics and water depth across conditions is proposed. Both theoretical and empirical models to predict front position in the smooth case is also proposed. In canopy cases, anisotropic propagation is observed and interpreted using a directional frontal solidity parameter $\lambda_{f,k}$, showing that wave fronts preferentially follow low-drag paths. In these directions, front velocities can equal or exceed those over smooth beds due to structural channeling.

Part II focuses on vertical velocity skewness S_w in near-neutral atmospheric boundary layer (ABL) turbulence. A broad picture of the vertical profile of S_w above smooth, rough, and permeable walls using wind tunnel and flume experiments, absent buoyancy and Coriolis effects is proposed. The observations are analyzed using diagnostic models based on cumulant expansions and realizability constraints, as well as third-order prognostic models. The inability of flux-gradient relations to capture S_w from $\partial \sigma_w^2 / \partial z$ is addressed by proposing energy-transport-based corrections. Links between diagnostic and prognostic models are established, and co-spectral properties of normalized vertical velocity fluctuations are presented to identify dominant turbulence scales in both inner and outer layers. A close-looking analysis provides empirical evidence that S_w in the inertial sublayer of adiabatic turbulent flows over smooth walls is nearly universal, constrained within $S_w \approx 0.1$–0.16 across various configurations and Reynolds numbers. The theoretical model proposed to explain this behavior and its bounded variability, highlighting why S_w cannot be captured by traditional down-gradient closure methods. The model suggests an alternative formulation suitable for large-scale meteorological and climate applications.