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Topographical Effects on Downburst-Induced Wind Loads: A BIM-Based CFD Analysis in Hilly Terrain

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Summary

Downbursts are intense downdraft events characterized by strong, divergent near-ground outflows that pose significant risks to structures, particularly in hilly terrain where topographic features can amplify wind intensity. Unlike atmospheric boundary layer winds, downburst flows are highly transient and localized, generating concentrated near-surface gusts and distinctive loading conditions. This study investigates the influence of hilly terrain on downburst-induced wind flow characteristics using a Building Information Modeling (BIM)–based Computational Fluid Dynamics (CFD) framework. Full-scale simulations of impinging jet–type downburst flows are conducted within a three-dimensional cylindrical computational domain using an unsteady Reynolds-averaged Navier–Stokes (URANS) approach. The results demonstrate that terrain slope and elevation significantly affect downburst wind structures, with steeper slopes producing pronounced flow acceleration and localized speed-up near hill crests. These findings highlight the importance of explicitly accounting for terrain effects in downburst wind hazard assessment and structural design.

Keywords: *Downburst Wind, Hilly Terrain Effects, Wind Load Analysis, CFD, BIM, URANS*

1 INTRODUCTION

Severe wind events pose a significant threat to the built environment, causing substantial structural damage and economic losses worldwide. Among these, downbursts, intense and localized downdrafts that produce damaging surface winds, are particularly destructive due to their high gust speeds and sudden onset (Wilson and Wakimoto, 2001). These events have been responsible for numerous building failures, power line collapses, and other infrastructure damage, often exceeding the forces considered in standard design codes (Loredo-Souza et al., 2019). A typical downburst, illustrated in Fig. 1, develops when a concentrated downdraft of cool air impinges on the ground and spreads radially outward.

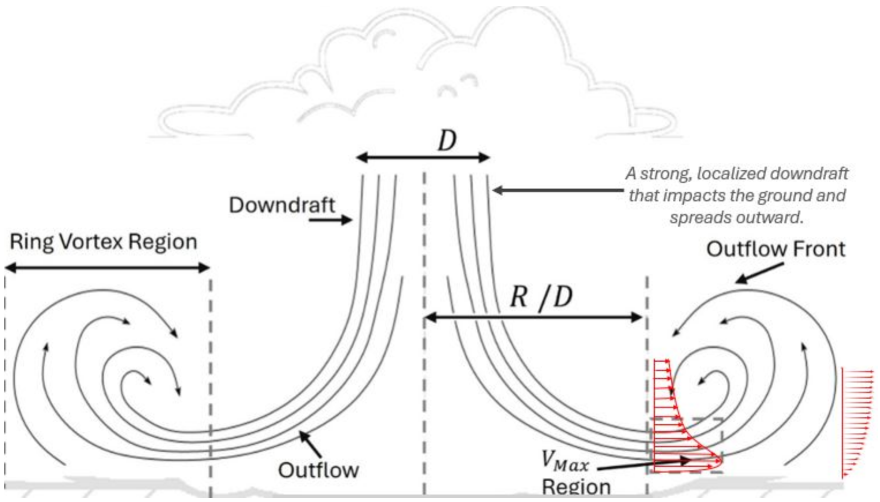

Figure 1: Downburst outflow structure

The leading edge of this outflow, known as the gust front, forms a nose-shaped profile characterized by a sharp acceleration in wind speed (Kim and Hangan, 2007). Circulating structures, referred to as ring vortices, often appear along this front, influencing the turbulent behavior of the flow. Their highly localized nature and short duration make monitoring and field measurements challenging, motivating extensive research through analytical, experimental, and numerical approaches (Solari, 2020). Despite these advances, the interaction of downbursts with hilly terrain remains insufficiently understood. The present study addresses this gap by by combining CFD simulations with BIM (Younis et al., 2023) to evaluate downburst wind loads in hilly terrain, characterizing both mean and turbulent wind components and providing practical insights.

2 METHDOLOGY

This study employs a full-scale CFD model to simulate downburst outflows generated by an impinging jet. The simulations are conducted within a three-dimensional cylindrical computational domain (CD), as illustrated in Fig. 2. The domain dimensions were selected to adequately capture both the jet development and the interaction of downburst winds with topographical features. The radial and vertical extents of the CD are set to $10D_j$ and $5D_j$, respectively, where D_j is the jet nozzle diameter. This configuration is slightly larger than those used in previous studies (Aboshosha et al., 2015), ensuring that boundary effects do not influence the near-surface flow field.

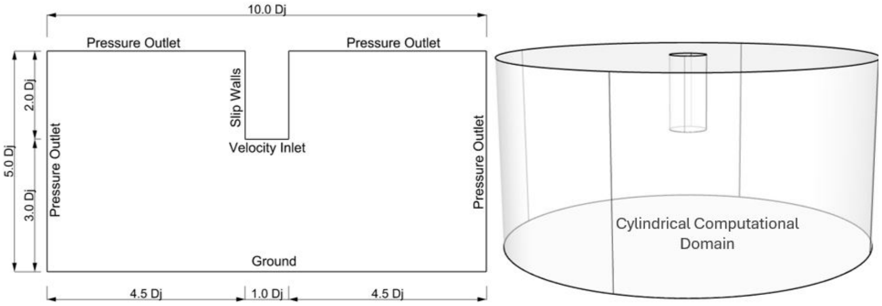

Figure 2: Computational domain and boundary conditions

The hills were modeled as idealized three-dimensional geometries defined by height (H) and half-width (L), representing two slope categories (steep and shallow). Three representative configurations were considered: a small steep hill with $H = 250\,\text{m}$ and $L = 0.5D_j$; a large steep hill with $H = 500\,\text{m}$ and $L = 1.0D_j$; and a shallow hill with $H = 250\,\text{m}$ and $L = 1.0D_j$.

The hill profile is described using the following equation:

$$y = \frac{H}{2}\left[\cos\left(\frac{\pi x}{L}\right) + 1\right],$$

where x is the horizontal coordinate. This formulation provides a smooth, bell-shaped profile that has been widely used in previous studies of flow over topography. In all test cases, the downburst center (the impinging jet touchdown point) was fixed, and the hills were positioned at different radial offsets R measured from that center. Hills were placed at $R = 1.0D_j, 1.2D_j, 1.5D_j, 1.6D_j, 2.0D_j$, and additional intermediate positions. The numerical simulations of downburst interactions with hilly terrain were performed in `STAR-CCM+` using an unsteady Reynolds-averaged Navier–Stokes (URANS) approach with the SST k–ω turbulence model. This choice reduces memory cost and ensures robustness for large parametric sweeps, while capturing key flow features such as separation, reattachment, and terrain-induced speed-up. Boundary conditions were defined based on full-scale downburst characteristics. The impinging jet had a diameter of $D_j = 1000\,\text{m}$ and an inlet velocity of $40\,\text{m/s}$, positioned $3D_j$ above the ground to allow sufficient development of the downdraft core before surface impact.

3 RESULTS AND DISCUSSION

3.1 Model Validation

Prior to analyzing the influence of hills on downburst flows, the CFD model was validated against benchmark data from the literature to ensure accuracy and reliability. Figure 3 presents a comparison of the radial velocity profiles obtained in this study with experimental and numerical results reported in the literature. The results show good agreement, particularly in capturing the location and magnitude of the peak radial velocity, confirming that the simulation approach accurately reproduces key downburst flow features.

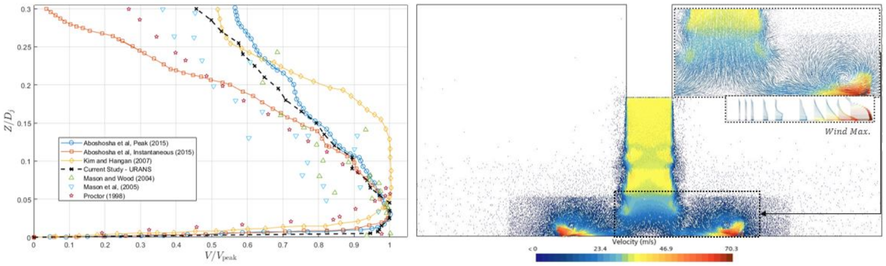

Figure 3: Velocity profile comparisons for the open exposure

3.2 Downburst Flow in Empty and Hilly Domains

Having validated the CFD model, the empty-domain case was first analyzed to establish baseline radial velocity, turbulence characteristics, and downburst vorticity field Figure 4. This reference condition enables evaluation of how terrain modifies near-surface flow behavior. Subsequently, the influence of hill placement and geometry on downburst outflow was examined by introducing different hills at various radial distances from the downburst center.

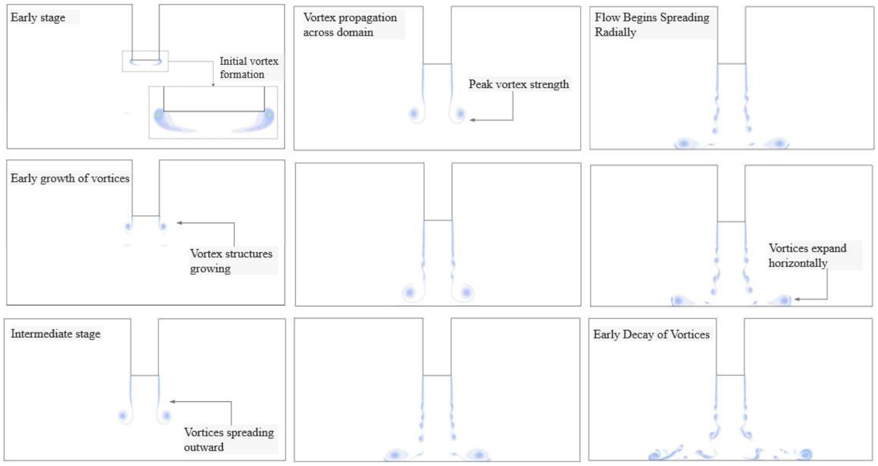

Figure 4: Time evolution of downburst vorticity field

4 CONCLUSIONS

This study investigated the influence of hilly terrain on downburst-induced wind flow characteristics using a BIM-based CFD framework. Numerical simulations were performed using an URANS approach to examine the interaction between impinging jet–type downburst flows and terrain features. The results demonstrate that terrain geometry plays a significant role in modifying downburst wind structures, with increased slope and elevation leading to localized flow acceleration and pronounced speed-up near hill crests (Fig. 5). These terrain-induced effects result in elevated near-surface wind intensities compared to flat-terrain conditions, which may impose critical loading demands on exposed structures.

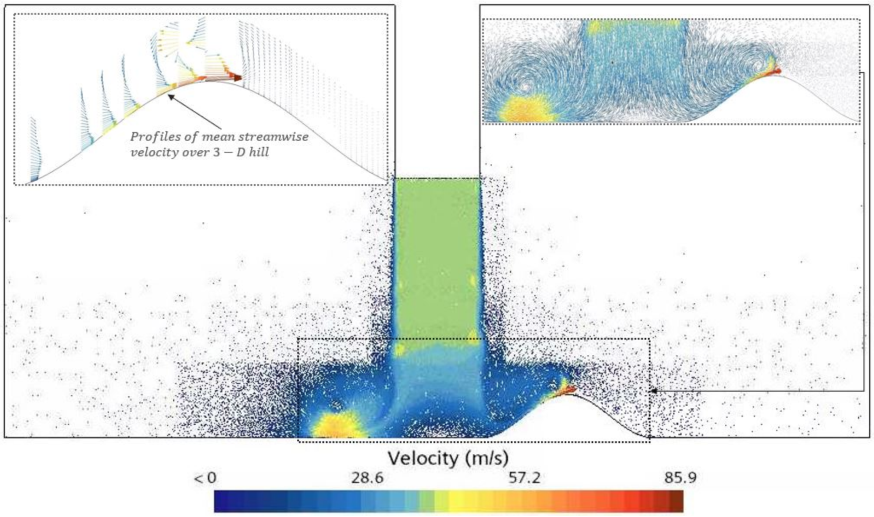

Figure 5: Time evolution of downburst vorticity field

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