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Numerical Investigation of Vertical Canopy Structure Effects on Shelterbelt Windbreak Performance Using LES

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SUMMARY
Conventional simulations of shelterbelts commonly adopt porous canopy models with uniform aerodynamic resistance, thereby neglecting the vertical variation of canopy structures and introducing discrepancies in the estimation of windbreak effectiveness. In this study, a novel modeling strategy based on the Alpha Blending algorithm is proposed to quantify the vertical profiles of canopy porosity and aerodynamic resistance coefficients. Comparisons between the conventional and the proposed strategies demonstrate that the vertical variation of canopy aerodynamic resistance is necessary for obtaining accurate predictions, particularly at the top and middle canopy heights.

Keywords: shelterbelts; windbreak effectiveness; porous canopy model; canopy structure

1. INTRODUCTION

Accurate simulation of shelterbelt windbreak effectiveness is essential for meteorological wind field prediction (Lyu et al., 2020). However, the irregular structures of tree canopies pose challenges for numerical modeling, such as the trade-off between computational cost and results accuracy. To address this challenge, previous numerical studies represent shelterbelts as rectangular porous media models with a uniform aerodynamic resistance coefficient, denoted as K. However, most natural trees exhibit vertical variations in canopy diameter, leaf density, and porosity, denoted as β. This simplification of the conventional *Uniform-K* strategy leads to biases, including underestimation of wind reduction in the mid-canopy region, where foliage density is high, and overestimation at the top of trees, where crown diameter is small.

To address this limitation, and inspired by the Alpha Blending algorithm widely used in computer graphics for transparency rendering, this study proposes a *Nonuniform-K* strategy to quantify the vertical distribution of canopy porosity and aerodynamic resistance. Large-Eddy Simulation, LES, is employed to evaluate the discrepancies introduced by the conventional Uniform-K strategy.

The results indicate that neglecting the vertical variation of canopy structure leads to significant errors in the prediction of shelterbelt windbreak effectiveness. The proposed *Nonuniform-K* strategy provides a more accurate representation of near-surface wind fields behind shelterbelts, thereby improving the reliability of local wind field prediction for meteorological applications.

2. METHODS

2.1. *Uniform-K* Strategy

We first introduce the conventional porous canopy model with *Uniform-K* strategy, i.e., the porous media model with uniform aerodynamic resistance. This approach has been validated for shelterbelts whose canopy is pruned into a rectangular shape, such as the *Tsuijimatsu* shelterbelt shown in Fig. 1 (a). Good agreement between measured and simulated velocity profiles, shown in Fig. 1 (b) to (e), indicates that the *Uniform-K* approach provides acceptable accuracy when the canopy geometry is consistent with the assumed porous representation.

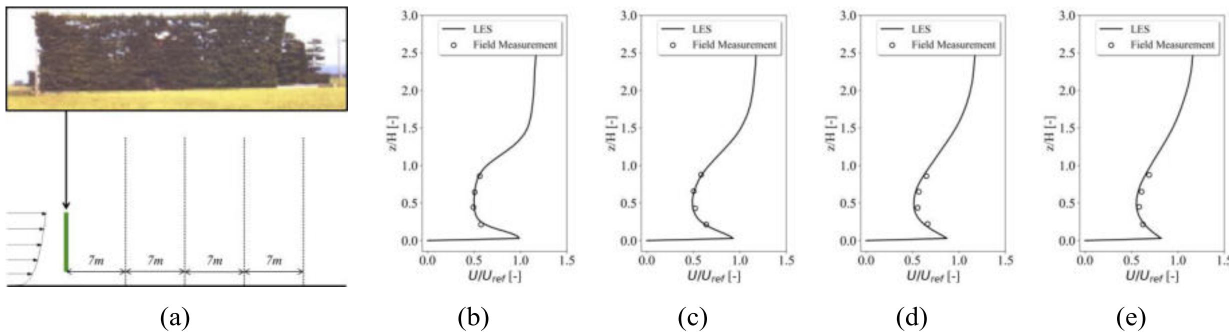


Figure 1. Time-averaged velocity magnitude results downstream of the *Tsuijimatsu* shelterbelt with a rectangular pruned canopy. (a) Schematic of the sampling layout; (b) to (e) Velocity profiles measured at downstream distances of 7 m, 14 m, 21 m, and 28 m, respectively.

2.2. *Nonuniform-K* Strategy

For most natural shelterbelts, the aforementioned *Uniform-K* strategy is not able to capture the vertical variations of their canopy structures and diameters. One possible solution is explicitly modeling the canopy shape, i.e. using the *Nonuniform-K* strategy, which allows consideration of the non-uniform distribution of aerodynamic resistance (Wang et al., 2024). As shown in Fig. 2(a) and Fig. 2(b), significant differences in the downstream velocity fields of shelterbelts are observed. These differences become negligible among Fig. 2(b) to (d), where similar coefficients of aerodynamic resistance are adopted across all heights.

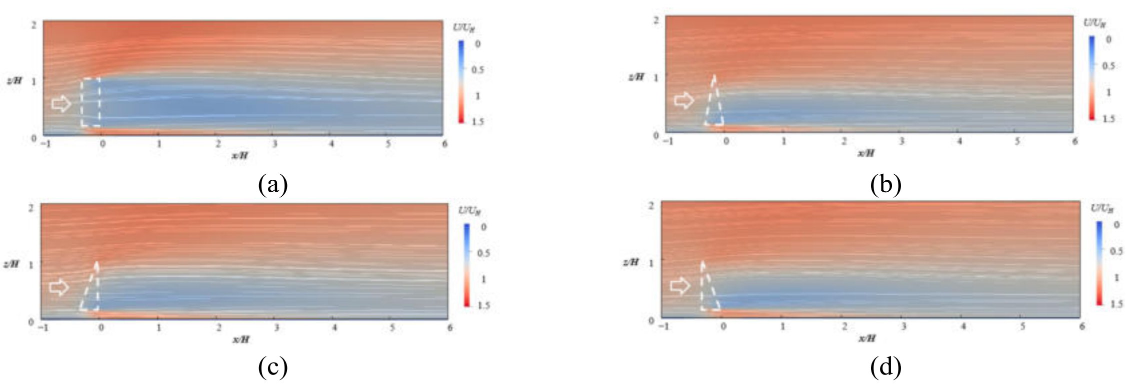
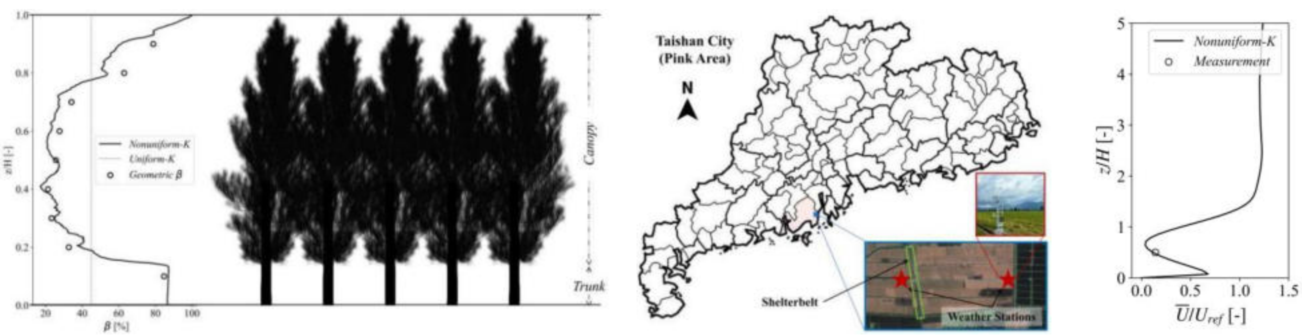


Figure 2. The velocity fields downstream of shelterbelts modeled by explicitly using the *Nonuniform-K* strategy as (a): rectangle, (b): symmetrical triangle, (c): windward triangle and (d): leeward triangle porous media, respectively (Wang et al., 2024).

However, for canopies with irregular leaf and branch distribution, explicit geometric modeling of complex canopies is constrained by mesh resolution requirements and computational costs. To address this limitation, this study proposes a parameterized alternative in which aerodynamic resistance is defined as a height-dependent variable within the *Nonuniform-K* strategy. For this purpose, two major challenges must be addressed for practical implementation: first, the irregular three-dimensional canopy geometry makes direct measurement of vertical porosity profiles difficult; second, existing relationships between aerodynamic resistance and porosity are primarily derived for thin porous fences, requiring further calibration for tree shelterbelts.

For the first challenge, a novel method based on the Alpha Blending algorithm is developed to estimate canopy porosity. This algorithm discretizes the canopy into a series of vertical translucent layers, where grayscale values are used to represent foliage density (which is inversely related to local porosity). It leverages principles from volume rendering and stratified image analysis to simulate light transmission through the canopy matrix, thereby enabling the quantification of vertical porosity variations. Unlike traditional optical porosity, which represents only two limiting states, namely fully transparent and fully solid, the proposed method incorporates the aerodynamic resistance of three-dimensional canopy structures through the calculation of cumulative opacity. An application of this approach to calculate the porosity profiles of *metasequoia* shelterbelts is shown in Fig. 3 (a), where good agreement can be found between the geometric porosity and the results obtained from this algorithm.



(a) (b) (c)

Figure 3. (a): The porosity (β) profiles of the adopted shelterbelt obtaining using the *Nonuniform-K* and *Uniform-K* approaches, where the geometric porosity at several heights are added as reference, (b): the locations of shelterbelt and automatic weather stations for measuring the wind velocity at the height of 4m and (c): the comparisons between numerical and measured results of wind velocity at the western automatic weather station.

For the second challenge, although a positive correlation remains between the above-mentioned porosity and the aerodynamic resistance coefficient, the corresponding mathematical model still requires further study. This entails, for instance, conducting LiDAR scans on target tree species and measuring velocity reduction of wind through canopies. In this study, a preliminary model is developed by recalibrating an existing *K-β* model (Xu et al., 2020). The calibration dataset is derived from a field measurement and a LES study to reproduce these velocity fields (Kurotani, 2002; Wang et al., 2024). The resulting model is further validated using wind observations from two automatic weather stations located in Taishan City, China, with a shelterbelt positioned between them, shown in Fig. 3 (b). The comparisons between the calibrated model and field measurement, demonstrated in Fig. 3 (c), indicate good agreement.

3. RESULTS

The velocity fields on the central vertical plane of a shelterbelt simulated using the *Uniform-K* and *Nonuniform-K* strategies are respectively shown in Fig. 4 (a) and (b), where noticeable differences can be observed at trunk and top-canopy heights. Further comparison on horizontal planes at canopy-top height, shown in Fig. 4 (c) and (d), indicates that the *Uniform-K* strategy significantly overestimated the windbreak effectiveness of the shelterbelt in this region.

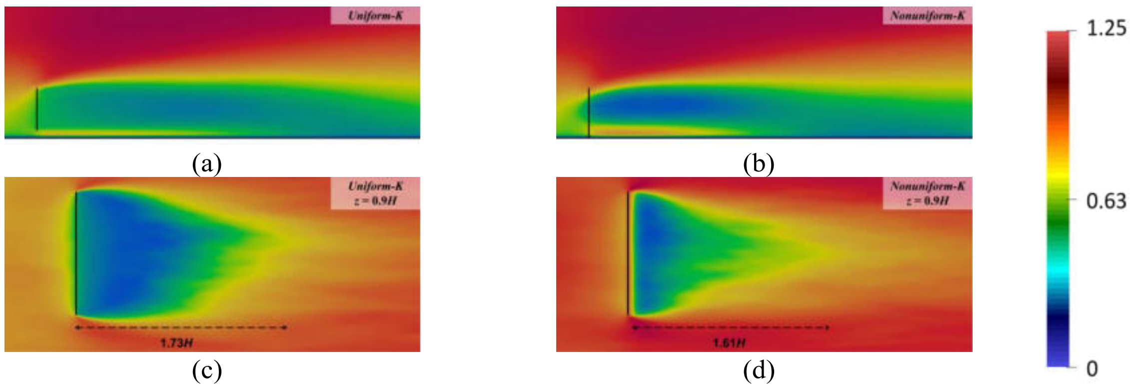


Figure 4. The fields of time-averaged velocity, U/U_{ref}, on (a): the middle vertical plane of *Uniform-K* case and (b): the the middle vertical plane *Nonuniform-K* case, (c): the horizontal plane at top-canopy height of *Uniform-K* case and (d): the horizontal plane at top-canopy height of *Nonuniform-K* case, respectively.

4. CONCLUSIONS

This study proposes a novel strategy to parameterize the vertical profiles of aerodynamic resistance for shelterbelts in numerical simulations, incorporating the vertical variation of canopy structural properties. Results from large-eddy simulations demonstrate that the conventional porous canopy model with uniform resistance introduces significant discrepancies in predicting windbreak effectiveness. The findings highlight the necessity of accounting for vertical variations in canopy diameter and foliage density when representing shelterbelts using porous media models, the relationship between canopy porosity and aerodynamic resistance coefficients requires further investigation.

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REFERENCES

Kurotani, Y. (2002). Windbreak effect of tsuijimatsu in izumo part. 2. Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan (AIJ), Environmental Engineering, 745–746.

Lyu, J.; Wang, C. M.; Mason, M. S. (2020). Review of models for predicting wind characteristics behind windbreaks. Journal of Wind Engineering and Industrial Aerodynamics, 199, 104117.

Wang, J., Patruno, L., Chen, Z., Yang, Q., Tamura, Y. (2024). Windbreak effectiveness of single and double-arranged shelterbelts: A parametric study using large eddy simulation. Forests, 15(10), 1760.

Xu, M.; Patruno, L.; Lo, Y. L.; de Miranda, S. (2020). On the use of the pressure jump approach for the simulation of separated external flows around porous structures: A forward facing step. Journal of Wind Engineering and Industrial Aerodynamics, 207, 104377.