

Wind driven rain: a parametric study on bus stop canopy

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SUMMARY

Wind driven rain (WDR) exposure on semi-outdoor space considerably influence pedestrian comfort but received few attentions. Through a parametric study of a stand-alone canopy and Shanghai meteorological data, this paper compares several typical aerodynamic measures on reducing WDR exposure impact, which are expected to be applicable in other semi-outdoor scenarios. First, according to the typical layout, the study analysed different orientations and identified the potential risks of WDR exposure. Subsequently, the effectiveness of different aerodynamic measures including canopy length and canopy angle has been evaluated. The results show that canopy can shelter large raindrops while provide few helps on smaller raindrops. Increasing the canopy angle can significantly reduce the exposure of smaller raindrops, although the effect will be less significant as the canopy angle become larger. Meanwhile, extending the canopy length is more effective in blocking larger raindrops. Hence, slightly increasing the canopy angle will be the most effective way.

Keywords: wind-driven rain; pedestrian comfort; aerodynamic measures; parametric study

1. INTRODUCTION

Wind-driven rain (WDR), which is the rain affected by the wind direction and velocity, is generally considered to have a significant impact on building façade. Current studies mostly focus on the WDR loading assessment. However, for semi-outdoor area, as shown in the Fig 1., it also plays a major role on pedestrian comfort but only few papers focus on it. Most of the scholars are based on a stadium to study the canopy and seat arrangement according to the WDR exposure. Ooi et al. (2020) conducted a comparison on horizontal and vertical barriers for a specific corridor located in Singapore, but during the numerical simulation, the context of the whole school has been considered, which may be unapplicable in other projects.

Therefore, to mitigate the impact of WDR exposure, this study evaluates the efficacy of various aerodynamic design strategies, such as adjusting canopy length and angle. Bus stops represent a typical semi-outdoor environment where such measures are applicable.

As a coastal city, Shanghai experiences over 140 rainy days per year, with frequent WDR exposure during the rainy season. However, as illustrated in Figure 1, the current design of bus stop canopies in Shanghai offers limited protection against WDR. Hence, through a parametric study of a stand-alone canopy, this paper compares several typical aerodynamic measures on reducing WDR exposure impact, which are expected to be applicable in other semi-outdoor scenarios.

2. METHODOLOGY

2.1. Meteorological parameters

Mu (2019) has detailly summarized the characteristics of wind driven rain in Shanghai. Generally, the most frequent wind direction during rainfall event is Northeast. Although the wind velocity

will be larger during rainfall event, the differences are not obvious. Therefore, the following simulations will be based on the same wind velocity.

As for the rainfall intensities, the majority of the rainfall intensities is smaller than 0.1mm/h or between 0.1mm/h and 5mm/h. Therefore, based on the raindrop distribution proposed by Best (1950), the raindrop sizes adopted in this study will be 0.5mm, 1mm and 2mm.

2.2. Model settings

2.2.1. Model geometry

According to CJJ/T15-2011(Code for design of urban road public transportation stop, terminus and depot engineering), the standard geometry for a bus stop is specified as follows: a height of 2.5 m, a length of 5 m along the road, and a flat canopy length of 1.5 m. Although a typical bus stop features an opening at its base, this opening is considered negligible in terms of WDR exposure. Therefore, the wall behind the bus stop is modeled as a continuous surface as shown in Figure 2. In the following study, typical aerodynamic measures including modifying the canopy angle and canopy length will be evaluated. The detailed configurations of the parametric models are summarized in the Table 1.

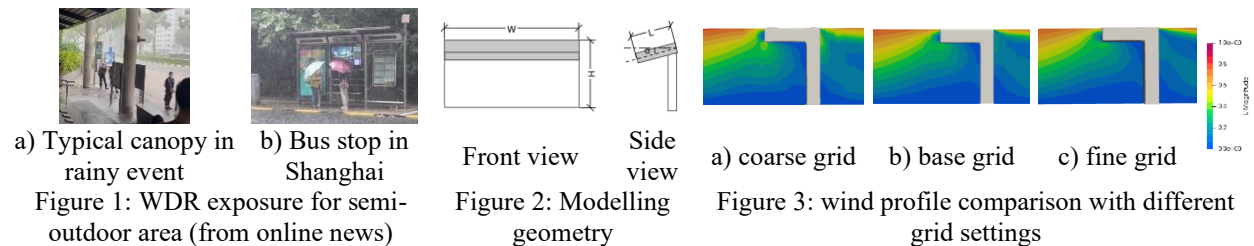
Table 1: Modelling geometry summary

Model	L(mm)	$\alpha(^{\circ})$	H(mm)	W(mm)
Prototype	1500	0	2500	5000
Small slope	1500	15	2500	5000
Medium slope	1500	30	2500	5000
Large slope	1500	45	2500	5000
Long canopy	2000	0	2500	5000
Extra-long canopy	2500	0	2500	5000
Double extra-long canopy	3000	0	2500	5000

2.2.2. Grid sensitive study

The grid sensitive results have been conducted based on the prototype of bus stop. Considering the computation cost, the grid sensitive study will only conduct for the wind velocity.

The wind profile along the bus stop is shown in the Figure 3. The coarse grid cannot capture the turbulence due to canopy while the base grid shows few differences with the fine grid. Therefore, the base grid will be adopted in the following analysis.



2.2.3. Computation domain and boundary conditions

Using OpenFOAM v2206, this study utilized the RANS approach with the RNG k- ϵ turbulence model coupled with the Eulerian Multiphase (EM) model. The SIMPLE algorithm is adopted for pressure-velocity coupling in the wind flow field simulation and the windDrivenRainFOAM is adopted for the The computation domain is 130 x 70 x 30 m³ (L x B x H), as shown in Figure 4,

with a blockage ratio of 0.6%. There are approximately 2 million cells, with local refinement around the target bus stop achieving a minimum cell size of 0.0625 m.

For the wind phase, a logarithmic law velocity inlet profile is applied. The reference velocity is set to 3.4 m/s at 10 m height, based on statistical analysis of wind velocities during rainy events (Mu, 2019). A roughness height of 1.0 m is specified, corresponding to typical urban terrain conditions.

For the rain phase, the boundary condition (at both inlet and top) are prescribed from Eq. (1). The splash and accumulation are not considered in the following simulations.

$$\alpha_d = \frac{R_h f_h(R_{h,d})}{V_t(d)} \quad (1)$$

Where R_h is the rainfall intensity, $f_h(R_{h,d})$ is the raindrop size distribution and $V_t(d)$ is the terminal velocity of a raindrop with diameter = d mm.

2.3. Validation study

To validate the WDR simulation, a verification study based on Kubilay et al. (2013) was conducted. To quantify WDR intensity on building facade, the specific catch ratio, proposed by Blocken and Carmeliet (2004), has been widely adopted. Based on a historical building, the comparison of the specific catch ratio is shown in Figure 5 and Figure 6. The results demonstrate overall good agreement across different raindrop size classes.

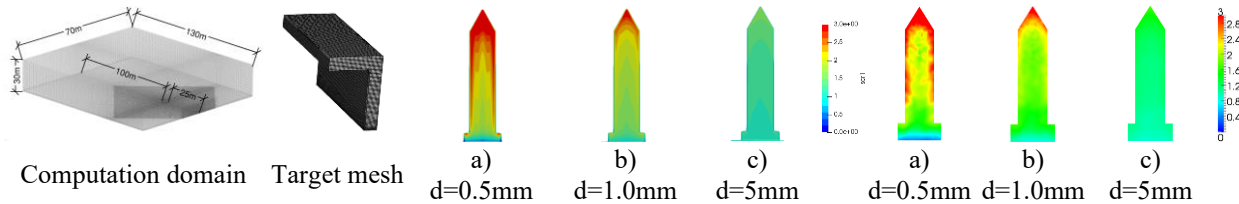


Figure 4: Computation domain and mesh. Figure 5: Specific catch ratio verification. Figure 6: Specific catch ratio from Kubilay et al., (2013)

3. RESULTS

3.1. Potential risk study

The road network in Shanghai is oriented along north-south and east-west axes, with the bus stops generally aligned accordingly. Further considering geometry symmetry, two scenarios were defined for analyze. Figure 7 illustrates the wind profile at the centerline along the canopy length. Among all the scenarios, the first scenario shows the highest risk of WDR, with significant higher wind velocity. Hence, the subsequent parametric study will focus on this case.

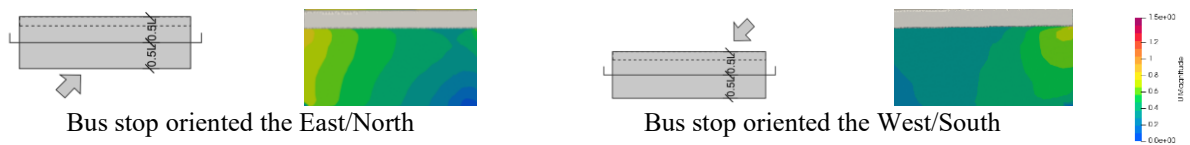


Figure 7: Wind profile of bus stop with different orientations

3.2. Comparison of effectiveness of canopy angle

Based on a parametric study on a stand-alone canopy, Figure 8 summarizes the specific catch ratio on the bottom of bus stop with different canopy angle. Generally, the canopy is more effective to block larger raindrops. The parametric results show that increasing the canopy angle can significantly reduce the exposure of smaller raindrops. However, as the canopy angle becomes larger, the effect will diminish, and the edge will be exposed to more raindrops.

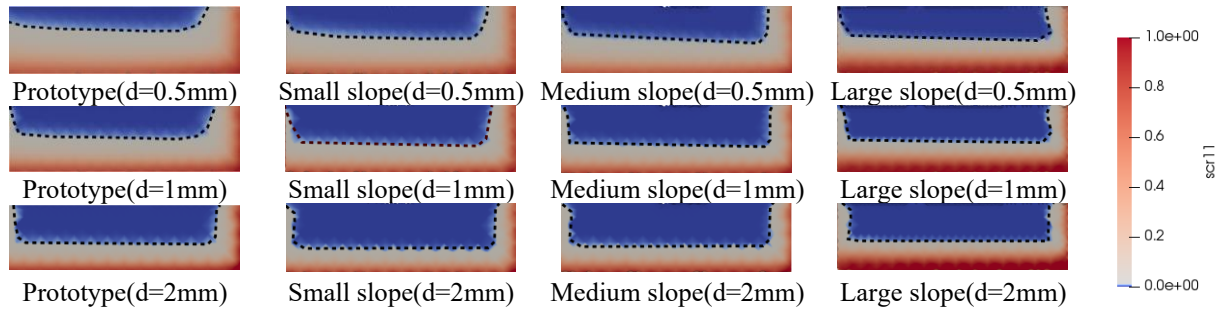


Figure 8: Specific catch ratio of different canopy angle

4. CONCLUSION

Through a parametric study of a stand-alone canopy, this paper compares several typical aerodynamic measures on reducing WDR exposure impact. Conclusion can be summarized:

- 1) Combine with the meteorological data and typical road layouts, the simulations under two scenarios have been conducted. According to the wind profile at the center of the canopy length, it shows that the wind from the corner of bus stop is the most critical case.
- 2) Generally, canopy itself can shelter large raindrops while provide few helps on smaller raindrops. Increasing the canopy angle can significantly reduce the exposure of smaller raindrops, although the effect will be less significant as the canopy angle become larger.
- 3) Extending the canopy length is more effective for blocking larger raindrops.

This study has focused on evaluating the impact of various aerodynamic measures on bus stops. Future research will extend these principles to investigate WDR in semi-enclosed spaces of buildings.

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